An Illustrated Dictionary of Optoelectronics and Photonics: Important Terms and Effects

Safa Kasap

University of Saskatchewan, Canada

Harry Ruda

University of Toronto, Canada

Yann Boucher

École Nationale d'Ingénieurs de Brest, France

Ali Javan and his associates William Bennett Jr. and Donald Herriott at Bell Labs were first to successfully demonstrate a continuous wave (cw) helium-neon laser operation (1960). (Courtesy of Bell Labs, Lucent Technologies.)

Concise Second Student Edition
Version 1.3.1 (February 2002)

PREFACE

The title *An Illustrated Dictionary of Important Terms and Effects in Optoelectronics and Photonics* reflects exactly the contents of this dictionary. It is not meant to be an encyclopedia in this field but rather a self-contained semiquantitative description of terms and effects that frequently turn up in optoelectronics and photonics courses at the undergraduate level. We have missed many terms but we have also described many; though, undoubtedly, our own biased selection. In our own view there is very little difference between optoelectronics and photonics, except that in the latter there may not be any electronics involved. Today, photonics is a more fashionable term than the old optoelectronics term which usually conjectures images of LEDs, solar cells, optoisolators *etc*, whereas photonics is closely associated with optical communications and optical signal processing.

Please feel free to email us your comments for improving the dictionary for its next edition. Although we may not be able to reply individually, we do read all our email messages and take note of suggestions and comments.

S.O. Kasap,
Saskatoon, Canada

H. Ruda,
Toronto, Canada

Y. Boucher,
Brest, France

"I know you believe you understand what you think I said, but I am not sure you realize that what you heard is not what I meant"

Alan Greenspan
Chairman of US Federal Reserve

Version 1.3 (October 2000)

Absorption coefficient α characterizes the loss of **photons** as light propagates along a certain direction in a medium. It is the fractional change in the intensity of light per unit distance along the propagation direction, that is,

$$\alpha = -\frac{\delta \mathcal{I}}{\mathcal{I} \delta x}$$

where $\mathcal{I}$ is the intensity of the radiation. The absorption coefficient depends on the photon energy or wavelength λ. Absorption coefficient α is a material property. Most of the photon **absorption** (63%) occurs over a distance $1/\alpha$ and $1/\alpha$ is called the **penetration depth** δ.
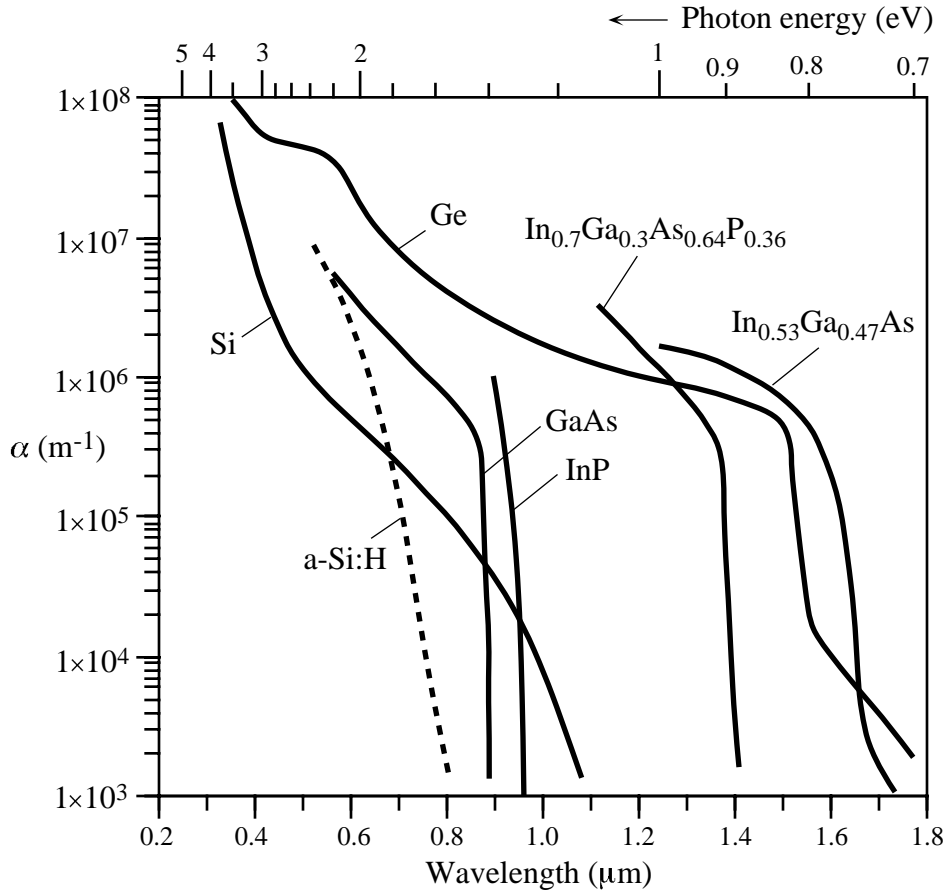
Absorption coefficient (α) vs. wavelength (λ) for various semiconductors
(Data selectively collected and combined from various sources.)

Absorption is the loss in the power of an electromagnetic radiation that is traveling in a medium. The loss is due to the conversion of light energy to other forms of energy, *e.g.* **lattice** vibrations (heat) during the polarization of the molecules of the medium, local vibrations of impurity ions, excitation of electrons from the **valence band** to the **conduction band** *etc*.

Acceptance angle, or the maximum acceptance angle is the largest possible light launch angle from the fiber axis. Light waves within the acceptance angle that enter the fiber become guided along the fiber **core**. If *NA* is the **numerical aperture** of a **step index fiber**, and light is launched from a medium of **refractive index** n_o, then maximum acceptance angle α_{max} is given by

$$\sin \alpha_{max} = \frac{NA}{n_o}$$

Total acceptance angle is twice the maximum acceptance angle and is the total angle around the fiber axis within which all light rays can be launched into the fiber.

Acceptance cone is a cone with its height aligned with the fiber axis and its apex angle twice the **acceptance angle** so that light rays within this cone can enter the fiber and then propagate along the fiber.

Acceptance cone

$2\alpha_{max}$ Optical fiber
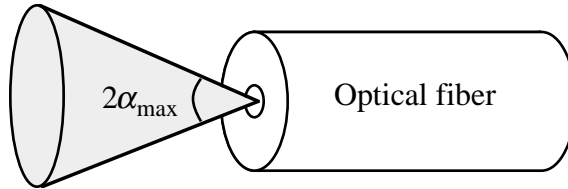
Acceptor atoms are dopants that have one less valency than the host atom. They therefore accept electrons from the **valence band** (VB) and thereby create holes in the VB which leads to $p > n$ and hence to a p-type **semiconductor**.

Acousto-optic modulator makes use of the **photoelastic effect** to modulate a light beam. Suppose that we generate traveling acoustic or ultrasonic **waves** on the surface of a piezoelectric **crystal** (such as $LiNbO_3$) by attaching an interdigital electrodes onto its surface and applying a modulating voltage at radio frequencies (RF). The *piezoelectric effect* is the phenomenon of generation of **strain** in a crystal by the application of an external electric field. The modulating voltage $V(t)$ at electrodes will therefore generate a *surface acoustic wave* (SAW) via the piezoelectric effect. These acoustic waves propagate by rarefactions and compressions of the crystal surface region which lead to a periodic variation in the density and hence a periodic variation in the **refractive index** in synchronization with the acoustic wave amplitude. Put differently, the periodic variation in the strain S leads to a periodic variation in n owing to the photoelastic effect. We can simplistically view the crystal surface region as alternations in the refractive index. An incident light beam will be *diffracted* by this periodic variation in the refractive index. If the acoustic wavelength is Λ, then the condition that gives the angle θ for a diffracted beam to exist is given by the **Bragg diffraction condition**,

$$2\Lambda\sin\theta = \lambda/n$$

where n is refractive index of the medium.

Suppose that ω is the angular frequency of the incident optical wave. The optical wave reflections occur from a moving **diffraction** pattern which moves with a velocity $v_{acoustic}$. As a result of the **Doppler effect**, the diffracted beam has either a slightly higher or slightly lower frequency depending on the direction of the traveling acoustic wave. If Ω is the frequency of the acoustic wave then the diffracted beam has a Doppler shifted frequency given by

$$\omega' = \omega \pm \Omega$$

When the acoustic wave is traveling towards the incoming optical beam, then the diffracted optical beam frequency is up-shifted, *i.e.* $\omega' = \omega + \Omega$. If the acoustic wave is traveling away from the incident optical beam then the diffracted frequency is down-shifted, $\omega' = \omega - \Omega$. It is apparent that we can modulate the frequency (wavelength) of the diffracted light beam by modulating the frequency of the of the acoustic waves. (The diffraction angle is then also changed.)
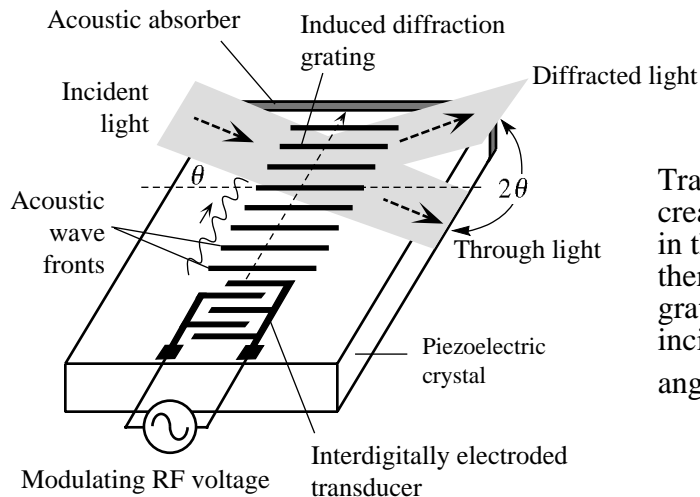
Traveling acoustic waves create a harmonic variation in the refractive index and thereby create a diffraction grating that diffracts the incident beam through an angle 2θ.
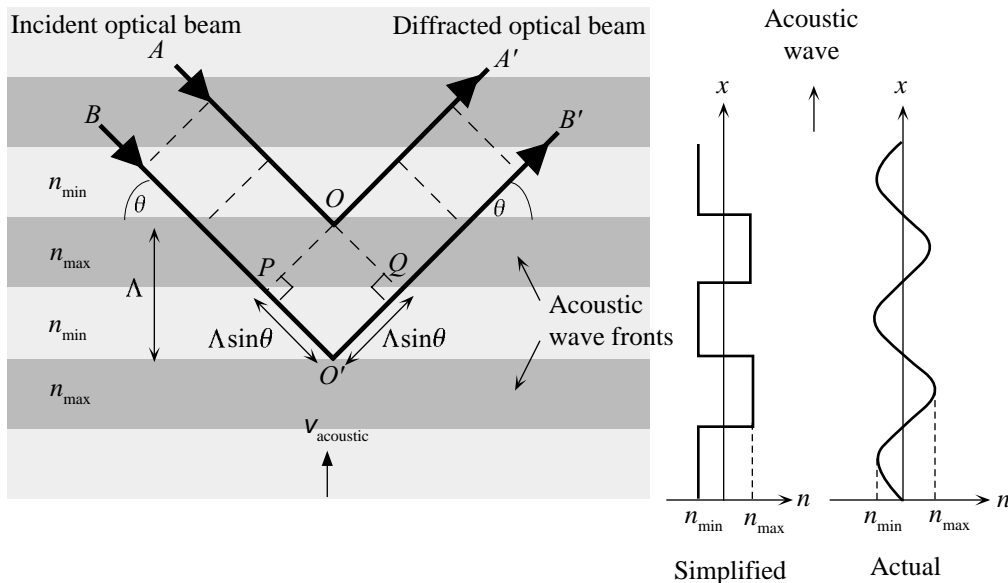
Consider two coherent optical waves A and B being "reflected" (strictly, scattered) from two adjacent acoustic wavefronts to become A' and B'. These reflected waves can only constitute the diffracted beam if they are in phase. The angle θ is exaggerated (typically this is a few degrees).

Activation energy is the potential energy barrier that prevents a system from changing from state to another. For example, if two atoms A and B get together to form a product AB, the activation energy is the potential energy barrier against the formation of this product. It is the minimum energy which the reactant atom or molecule must have to be able to reach the activated state and hence form the product. The probability that a system has an energy equal to the activation energy is proportional to the Boltzmann factor: $\exp(-E_A/kT)$, where E_A is the activation energy, k is the **Boltzmann constant** and T is the temperature (Kelvins).

**Active device** is a device that exhibits gain (current or voltage or both) and has a directional function. Transistors are active devices whereas resistors, capacitors and inductors are passive devices.

Active region is the region in a medium where direct electron hole pair (EHP) **recombination** takes place. For LEDs it is the region where most EHP recombination takes place. In the **laser diode** it is

the region where **stimulated emissions** exceeds **spontaneous emission** and **absorption**. It is the region where coherent emission dominates.

Airy disk is the central white spot in the **Airy ring** pattern

Airy rings represent a **diffraction** pattern from a circular aperture illuminated by a coherent beam of light. The central white spot is called the **Airy disk**, its radius corresponds to the radius of the first dark ring.
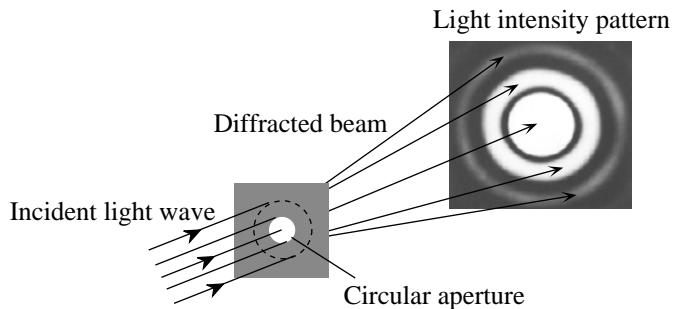

A light beam incident on a small circular aperture becomes diffracted and its light intensity pattern after passing through the aperture is a diffraction pattern with circular bright rings (called Airy rings). If the screen is far away from the aperture, this would be a Fraunhofer diffraction pattern.

Amorphous solid exhibits no crystalline structure or long range order. It only posses a short range order in that the nearest neighbors of an atom are well defined by virtue of chemical bonding requirements. See **glass**.

Angstrom (Å) is 10^{-10} meters.

Anisotropy (optical) refers to the fact that the **refractive index** n of a **crystal** depends on the direction of the electric field in the propagating light beam. The velocity of light in a crystal depends on the direction of propagation and on the state of its **polarization**, *i.e.* the direction of the electric field. Most noncrystalline materials such as glasses and liquids, and all cubic crystals are *optically isotropic*, that is the refractive index is the same in all directions. For all classes of crystals excluding cubic structures, the refractive index depends on the propagation direction and the state of polarization. The result of optical anisotropy is that, except along certain special directions, any unpolarized light ray entering such a crystal breaks into two different rays with different polarizations and phase velocities. When we view an image through a calcite crystal, an optically anisotropic crystal, we see two images, each constituted by light of different polarization passing through the crystal, whereas there is only one image through an optically isotropic crystal. Optically anisotropic crystals are called **birefringent** because an incident light beam may be doubly refracted. Experiments and theories on "most anisotropic crystals", *i.e.* those with the highest degree of anisotropy, show that we can describe light propagation in terms of *three* refractive indices, called **principal refractive indices** n_1, n_2 and n_3, along three mutually orthogonal directions in the crystal, say x, y and z called **principal axes**. These indices correspond to the polarization state of the **wave** along these axes. Crystals that have three distinct principal indices also have *two* optic axes and are called *biaxial crystals*. On the other hand, *uniaxial crystals* have two of their principal indices the same ($n_1 = n_2$) and only have *one* **optic axis**. Uniaxial crystals, such as quartz, that have $n_3 > n_1$ and are called *positive*, and those such as calcite that have $n_3 < n_1$ are called *negative* uniaxial crystals.
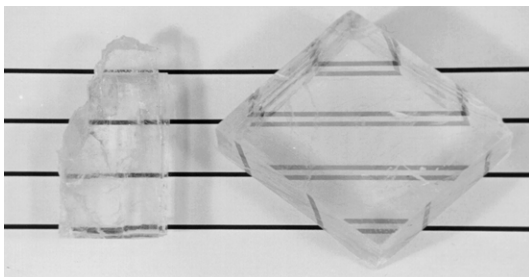
A line viewed through a cubic sodium chloride (halite) crystal (optically isotropic) and a calcite crystal (optically anisotropic).

Annealing point of **glass** is the temperature at which the **viscosity** of a glass is about 10^{12} Pa s (or 10^{13} dPa s; dPa is decipascals) . For example, for fused **silica glass** this is about 1180 °C. Viscosity of glass is strongly temperature dependent and decreases steeply as the temperature increases. At the annealing point, the viscosity is sufficient to relieve internal stresses.

Antireflection (AR) coating is a thin dielectric layer coated on an optical device or component to reduce the reflection of light and increase the transmitted light intensity.
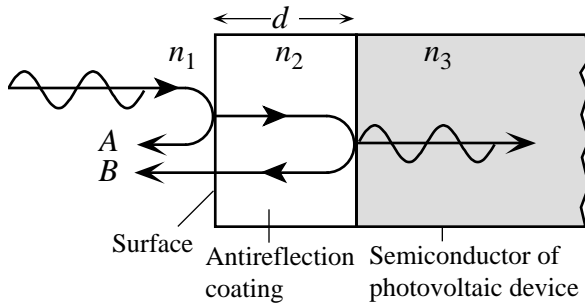

Illustration of how an antireflection coating reduces the reflected light intensity

Consider a thin layer of a **dielectric** material such as Si_3N_4 (silicon nitride) on the surface of a **semiconductor** optoelectronic device such as a **solar cell**. If this antireflection coating has an intermediate **refractive index** then the thin dielectric coating can reduces the reflected light intensity. In this case n_1(air) = 1, n_2(coating) ≈ 1.9 and n_3(Si) = 3.5. Light is first incident on the air/coating surface and some of it becomes reflected. Suppose that this reflected **wave** is *A*. Wave *A* has experienced a 180° phase change on reflection as this is an **external reflection**. The wave that enters and travels in the coating then becomes reflected at the coating/semiconductor surface. This wave, say *B*, also suffers a 180° phase change since $n_3 > n_2$. When wave *B* reaches *A*, it has suffered a total delay of traversing the thickness *d* of the coating twice. The phase difference is equivalent to $k_c(2d)$ where $k_c = 2\pi/\lambda_c$ is the **wavevector** in the coating and is given by $2\pi/\lambda_c$ where λ_c is the wavelength in the coating. Since $\lambda_c = \lambda /n_2$, where λ is the free-space wavelength, the phase difference $\Delta\phi$ between *A* and *B* is $(2\pi n_2/\lambda)(2d)$. To reduce the reflected light, *A* and *B* must interfere destructively and this requires the phase difference to be π or odd-multiples of π, $m\pi$ where $m = 1,3,5,\ldots$ is an odd-integer. Thus

$$\left(\frac{2\pi n_2}{\lambda}\right)2d = m\pi \qquad \text{or} \qquad d = m\left(\frac{\lambda}{4n_2}\right)$$

Thus, the thickness of the coating must be multiples of the quarter wavelength in the coating and depends on the wavelength. To obtain a good degree of **destructive interference** between waves *A* and *B,* the two amplitudes must be comparable. It turns out that we need $n_2 = \sqrt{(n_1 n_3)}$. When $n_2 = \sqrt{(n_1 n_3)}$ then the **reflection coefficient** between the air and coating is equal to that between the coating and the semiconductor. In this case we would need $\sqrt{(3.5)}$ or 1.87. Thus, Si_3N_4 is a good choice as an antireflection coating material on Si **solar cells**. Generally an AR coating operates at one or over a narrow range of wavelengths.

Ar ion laser can provide powerful CW visible **coherent radiation** of several watts. The laser operation is achieved as follows: The Ar atoms are ionized by electron collisions in a high current electrical discharge. Further multiple collisions with electrons excite the argon ion, Ar^+, to a group of $4p$ energy levels ~35 eV above the atomic ground state. Thus a **population inversion** forms between

the 4*p* levels and the 4*s* level which is about 33.5 eV above the Ar atom ground level. Consequently, the stimulated radiation from the 4*p* levels down to the 4*s* level contains a series of wavelengths ranging from 351.1 nm to 528.7 nm. Most of the power however is concentrated, approximately equally, in the 488 and 514.5 nm emissions. The Ar$^+$ ion at the lower laser level (4*s*) returns to its neutral atomic ground state via a radiative decay to the Ar$^+$ ion ground state, followed by **recombination** with an electron to form the neutral atom. The Ar atom is then ready for "**pumping**" again. The **Doppler broadened linewidth** of the 514.5 nm radiation is about 3500 MHz ($\Delta\upsilon$) and is between the half-intensity points. Typically the argon-ion laser the discharge tube is made of Beryllia (Beryllium Oxide).
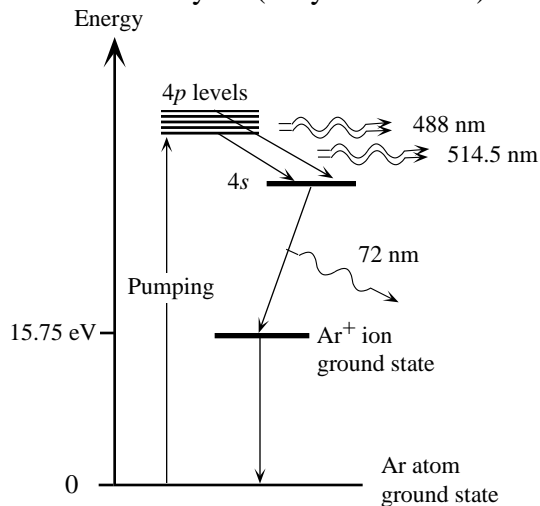
The Ar-ion laser energy diagram

Armoring is the protective "cover" made of metal wires or bands, that is put around the cable sheath; it provides protection against harsh external environments.

Arrhenius temperature dependence implies that the rate of change in a physical or chemical process, or the particular property under observation, has an exponential temperature dependence of the form

$$\text{Rate} = C \exp\left(-\frac{\Delta H}{RT}\right)$$

where C is a constant, R is the gas constant, T is the temperature (in Kelvins) and ΔH is the **activation energy** of associated with the process, in J mol^{-1}.

Asynchronous signal is not synchronized to any one time reference signal. A synchronous transmission does not use a common clock signal between the transmitter and receiver.

Attenuation is the decrease in the **optical power** of a traveling **wave**, or a guided wave in a dielectric waveguide, in the direction of propagation due to absorption and scattering. If P_o is the optical power at some location O, and if it is P at a distance L from O along the direction of propagation then the attenuation coefficient is defined by $\alpha = 10L^{-1}\ln(P/P_o)$. In terms of attenuation measured in **decibels**

$$\alpha_{dB} = \frac{10}{\ln(10)}\alpha = 4.34\alpha$$

Avalanche breakdown is the enormous increase in the reverse current in a *pn* junction when the applied reverse field is sufficiently high to cause the generation of electron hole pairs by **impact ionization** in the space charge layer.

Avalanche multiplication factor M of an **avalanche photodiode** (APD) is defined as

$$M = \frac{\text{Multiplied photocurrent}}{\text{Primary unmultiplied photocurrent}} = \frac{I_{ph}}{I_{pho}}$$

where I_{ph} is the APD photocurrent that has been multiplied and I_{pho} is the **primary or unmultiplied photocurrent**.

Avalanche noise is the excess noise in the photocurrent of an **avalanche photodiode** due to the statistics of the multiplication process occurring in the avalanche region. The avalanche process does nor occur continuously and smoothly in time but as discrete events whose frequency of occurrence fluctuates in the avalanche region about some mean value. Thus the multiplication M fluctuates about a mean value. The result of the statistics of **impact ionization** is an excess noise contribution, called *avalanche noise*, to the multiplied **shot noise**. The noise current in an avalanche photodiode (APD) is given by,

$$i_{n\text{-APD}} = [2e(I_{do} + I_{pho})M^2 FB]^{1/2}$$

where F is called the *excess noise factor* and is a function of M and the impact ionization probabilities (called coefficients). Generally, F is approximated by the relationship $F \approx M^x$ where x is an index that depends on the **semiconductor**, the APD structure and the type of carrier that initiates the avalanche (electron or hole). For Si APDs, x is 0.3 - 0.5 whereas for Ge and III-V (such as InGaAs) alloys it is 0.7 - 1.

Avalanche photodiode (APD) is a **photodiode** with a depletion region in which the field is sufficiently large for an avalanche multiplication of photogenerated charge carriers by **impact ionization**. The avalanche process in the APD occurs over a limited region of the **depletion layer** and the photodiode design allows only the multiplication of one type of carrier for example electrons for Si.

Avogadro's number N_A is the number of atoms in exactly 12 grams of Carbon-12. It is 6.022×10^{23}. Since atomic mass is defined as $^1/_{12}$ of the mass of the carbon-12 atom, N_A number of atoms of any substance has a mass equal to the atomic mass, M_{at}, in grams.

Axial or longitudinal modes are allowed EM stationary **waves** that exist along the optical cavity length whose electric field patterns are determined by the length L of the optical cavity, *e.g.*

$$m\left(\frac{\lambda}{2n}\right) = L$$

where λ is the free-space wavelength, n is the refractive index of the cavity medium and m is an integer, 1, 2, … Longitudinal modes of an optical cavity are normally associated with transverse modes of the cavity. Each transverse mode has many longitudinal modes.

Azimuthal mode number (l) is one of two integers that are normally used to characterize propagating modes in a **step index fiber** (or more generally in a cylindrical waveguide). It characterizes the azimuthal field distribution. In a step index fiber, there are $2l$ number of maxima in the light intensity around a circle center on the fiber axis.

Backscattered technique, see **optical time domain reflectometry.**

Bandwidth, or optical bandwidth, is the range of modulation frequencies up to some maximum frequency f_{op} where the optical transmission characteristic of the fiber falls by a factor of 3dB. The optical bandwidth is very roughly the same as the bit rate capacity B. Similarly to BL, the product $f_{op}L$, called the bandwidth-length product, remains very roughly constant and a property of the fiber. Strictly, however, BL is not constant (especially for single mode fibers) and one should compare BL products of fibers of comparable length. Frequently, the bandwidth-distance product is expressed as $BL^\gamma = $ constant where γ is an index that is typically between 0.6 and 1.

Baud is a measure of the rate of digital signal transmission in terms of transitions per second.

Beam diameter, see **Gaussian beam**.

Beam splitter is an optical device that split an incoming beam into two beams that are traveling in different directions. Beam splitter cubes typically use **frustrated total internal reflection** to split an incident beam.
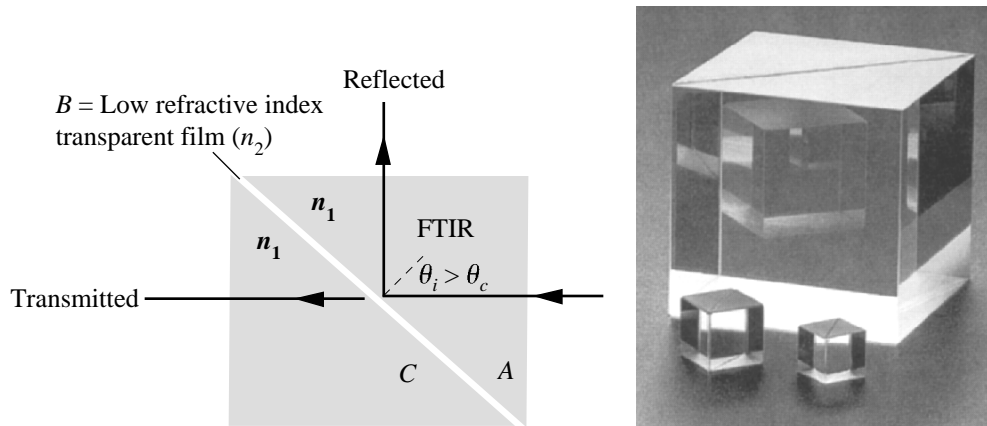
Left : Two prisms separated by a thin low refractive index film forming a beam-splitter cube. The incident beam is split into two beams by frustrated total internal reflection (FTIR).
Right: Beam splitter cubes (Courtesy of Melles Griot)

Bend loss or bending loss is the **attenuation** in an **optical fiber** as a result of the bending of the fiber. See **microbending loss** and **macrobending loss.**

Bend radius is the local radius of the fiber axis when the fiber is bent, that is, the fiber axis follows a curvature. Typically **attenuation** increases exponentially with decreasing bend radius. Minimum bend radius is the shortest radius of curvature to which a fiber can be bent without the induced **stress** in the fiber exceeding the allowed stress.

BER, see **bit error rate**

Bessel function $J_n(x)$ of order n is a mathematical function that is a solution to the differential equation
$$x^2 y'' + xy' + (x^2 - n^2)y = 0$$
where prime represents differentiation with respect to x, *i.e.* $y' = dy/dx$, and n is a constant (independent of x and y). Bessel functions are either tabulated or graphed for various orders. $J_n(x)$ looks like a damped sinusoidal wave. The electric field in cylindrical waveguides, coaxial cables, step index optical fibers, are generally described by Bessel functions. For example, for **step index fibers**, zeros of the Bessel function $J_n(x)$ point to those values of the **V-number** at which various modes, with the exception of the **fundamental mode**, are cut-off (cannot propagate). For example, the LP_{11} ($l = 1$, $m = 1$) mode is cut off when $J_0(x) = 0$ or when $V = 2.405$.

Bias is a term used to describe the application of a continuous (dc) voltage across, or a current through, a device that puts the device in a desirable operating condition. For example, applying a reverse dc voltage across a *pin* photodiode establishes the necessary electric field and puts the *pin* into a desirable operating condition.

Biaxial crystals, see **anisotropy.**

Bipolar junction transistor (BJT) is a transistor whose normal operation is based on the injection of **minority carriers** from the **emitter** into the base region and their **diffusion** to the collector where they give rise to a collector current. The voltage between the base and the emitter controls the collector current; this is the transistor action.

Birefringent crystals such as calcite are optically anisotropic which leads to an incident light beam becoming separated into ordinary (*o*-) and extraordinary (*e*-) **waves** with orthogonal

polarizations; incident light becomes doubly refracted because these two waves experience different refractive indices n_o and n_e. There is no double refraction for light propagation along the **optic axis**. If we were to cut a plate from a calcite **crystal** so that the optic axis (along z) would be parallel to two opposite faces of the plate, then a ray entering at normal incidence to one of these fa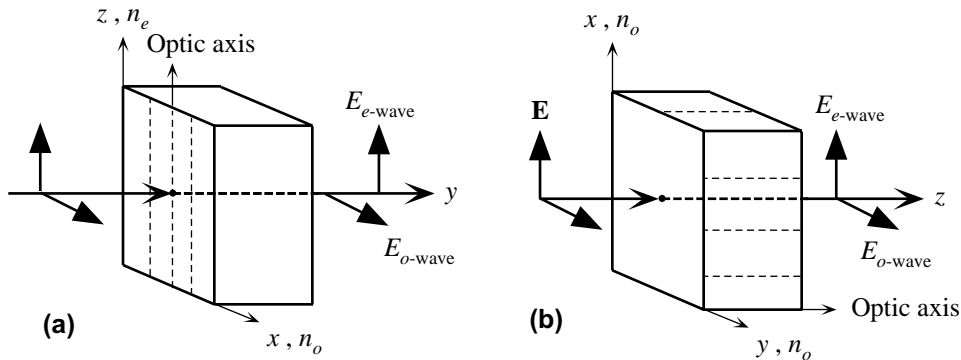ces would not diverge into two separate waves. The o- and e-waves would travel in the same direction but with different speeds. The waves emerge in the same direction as well which means that we would see no double refraction. This optical arrangement is used in the construction of various optical retarders and polarizers as discussed below. If we were to cut a plate so that the optic axis was perpendicular to the plate face, then both the o and e-way would be traveling at the same speed and along the same direction which means we would not again see any double refraction (see also **anisotropy**)
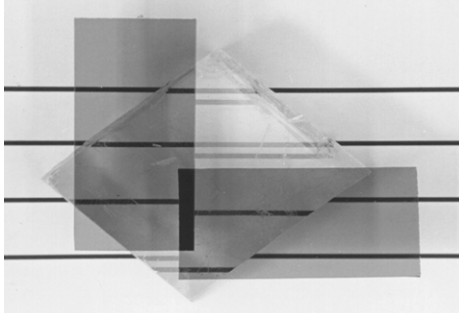
Two polaroid analyzers are placed with their transmission axes, along the long edges, at right angles to each other. The ordinary ray, undeflected, goes through the left polarizer whereas the **extraordinary wave**, deflected, goes through the right polarizer. The two waves therefore have orthogonal polarizations.

Optic axis

Incident ray

Principal section

e-ray

o-ray

A calcite rhomb

Principal section

$E_{//}$

e-wave

o-wave

Incident wave

$E_\perp$

Optic axis
(in plane of paper)
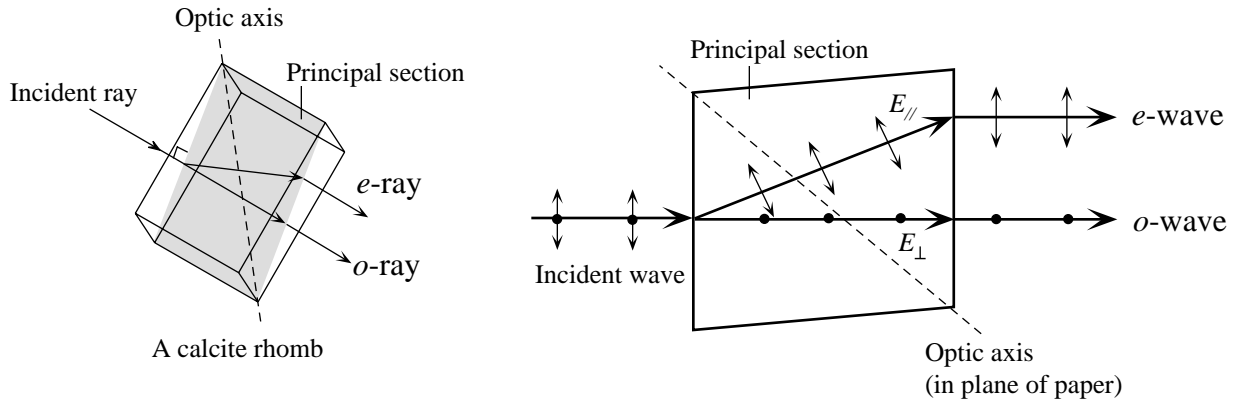
An EM wave that is off the optic axis of a calcite crystal splits into two waves called ordinary and extraordinary waves. These waves have orthogonal polarizations and travel with different velocities. The *o*-wave has a polarization that is always perpendicular to the optical axis.

z , n_e

Optic axis

$E_{e\text{-wave}}$

y

$E_{o\text{-wave}}$

(a)

x , n_o

x , n_o

E

$E_{e\text{-wave}}$

z

$E_{o\text{-wave}}$

Optic axis

(b)

y , n_o

(a) A birefringent crystal plate with the optic axis parallel to the plate surfaces. (b) A birefringent crystal plate with the optic axis perpendicular to the plate surfaces.

Birefringent prisms are prisms made from **birefringent crystals** for producing a highly polarized light **wave** or **polarization** splitting of light. The Wollaston prism is a polarization splitter in which the split beam has orthogonal polarizations. Two calcite (or quartz) right angle prisms A and B are placed with their diagonal faces touching to form a rectangular block. Various Wollaston prisms with typical beam splitting angles of 15 - 45° are commercially available.

e-ray

B

A

o-ray

Optic axis

Optic axis

Optic axis

Optic axis

A

E_1

e-ray

E_1

E_2

E_1

E_2

θ
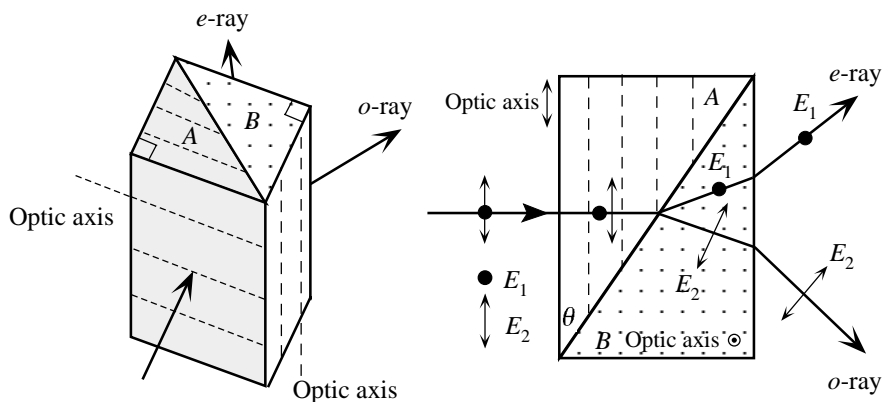
B Optic axis ⊙

o-ray

The Wollaston prism is a beam polarization splitter. E_1 is orthogonal to the plane of the paper and also to the optic axis of the first prism. E_2 is in the plane of the paper and orthogonal to E_1. *e*-ray is the *extraordinary* wave and *o*-ray is the *ordinary wave*.

Commercial Wollaston prisms. The actual prism is held inside a cylindrical housing (Courtesy of Melles Griot)

Bit error rate (BER) is the fraction of all **bits** that are wrong (corrupted) within a long series of bits of information received over a long period of time. Stated differently, it is the ratio of errors to the total number of bits transmitted during a long digital transmission period. The lower the BER. the better is the transmission system.

Bit is the basic unit of information in **digital communication** systems and corresponds to the presence or absence of pulses.

Bit rate is the rate at which **bits** are transmitted in a **digital communications** system. Maximum rate at which the digital data can be transmitted along the fiber is the bit rate capacity, B (bits per second), and is directly related to the **dispersion** characteristics of the fiber.

Bit rate × distance (BL) is the product of the bit rate capacity and fiber length and is a measure of the information carrying capacity of a fiber. Generally, the **dispersion** or time spread of an optical pulse increases with distance and the bit rate capacity consequently decreases with distance. In **multimode fibers**, B decreases approximately linearly with L so that BL is nearly constant and fiber characteristic. Strictly, however, BL is not constant (especially for single mode fibers) and one should compare BL products of fibers of comparable length. See **bandwidth.**

Black body is a hypothetical (an ideal) body that absorbs all the electromagnetic radiation falling onto it and therefore appears to be black at all wavelengths. When heated, a black body emits the maximum possible radiation at that temperature. A small hole in the wall of a cavity maintained at a uniform temperature emits radiation that approximately corresponds to that from a black body .
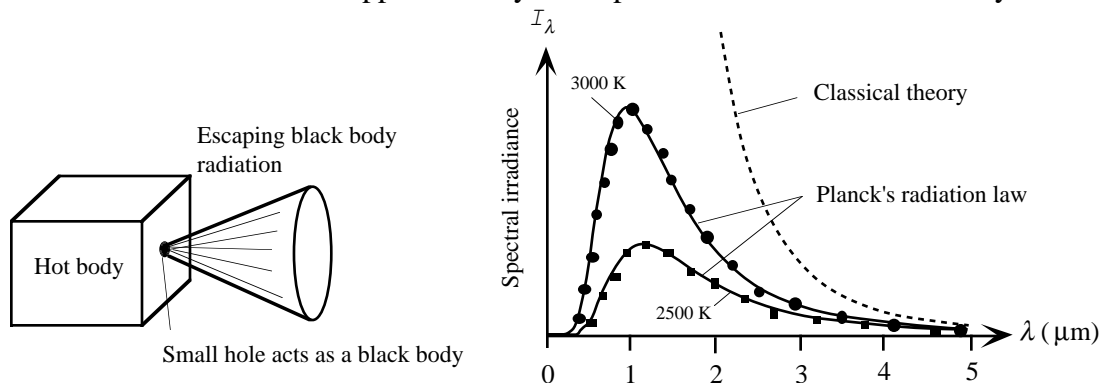
Schematic illustration of black body radiation and its characteristics. Spectral irradiance vs wavelength at two temperatures (3000K is about the temperature of the incandescent tungsten filament in a light bulb).

Black body radiation is the distribution of radiation energy as a function of wavelengths emerging from a hot **black body** such as a small hole in a cavity. The maximum amount of radiation intensity that can be emitted by an object is called the black body radiation. Although, in general, the radiated

intensity depends on the material's surface, a radiation emitted from a cavity with a small aperture is independent of the material of the cavity and corresponds very closely to black body radiation. Spectral irradiance $\mathcal{I}_\lambda$ is the emitted radiation intensity (power per unit area) per unit wavelength so that $\mathcal{I}_\lambda d\lambda$ is the intensity in a small range of wavelengths, $d\lambda$. *Planck's black body radiation law* describes the wavelength dependence of $\mathcal{I}_\lambda$ as

$$\mathcal{I}_\lambda = \frac{2\pi hc^2}{\lambda^5 \left[\exp\left(\frac{hc}{\lambda kT}\right) 1 \right]}$$

where k is the **Boltzmann constant**, T is the temperature (Kelvins), h is the Planck constant, c is the speed of light.

Boltzmann energy distribution, see **Boltzmann statistics.**

Boltzmann statistics describes the behavior of a collection of particles (*e.g.* gas atoms) in terms of their energy distribution. It specifies the number of particles, $N(E)$, with an energy E through $N(E) \propto \exp(-E/kT)$ where k is the Boltzmann constant and T is the temperature (Kelvins). The description is non-quantum mechanical in the sense that there is no restriction to how many particles can have the same **state** (the same **wavefunction**) with an energy E. It applies when there are only a few particles compared with the number of possible states so that the likelihood of two particles having the same state becomes negligible. This is generally the case for thermally excited electrons in the **conduction band** of a **semiconductor** where there are many more states than number of electrons. The kinetic energy distribution of gas molecules in a tank obeys the Boltzman statistics.
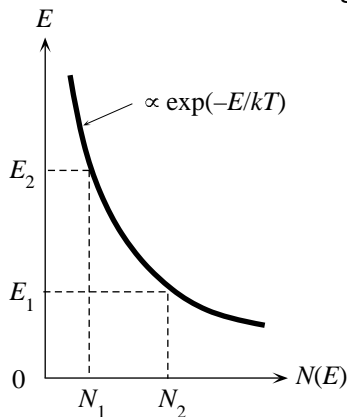

The Boltzmann energy distribution describes the statistics of particles, *e.g.* electrons, when the particles do not interact with each other, *i.e.* when there are very few electrons compared with the number of available states.

Boltzmann's constant k is the gas constant per atom or per molecule, that is, the gas constant divided by **Avogadro's number** ($k = R/N_A$); $k = 1.38 \times 10^{-23}$ J K^{-1}. ($\frac{3}{2}kT$ is the mean kinetic energy associated with the translational motions of gas molecules in a gas cylinder at temperature T).

Boron trioxide (B_2O_3) is added to **silica glass** to form B-doped silica to modify (decrease) the **refractive index**.

Boundary conditions relate the normal and tangential components of the electric field next to the boundary. The tangential component must be continuous through the boundary. Suppose that E_{n1} is the normal component of the field in medium 1 at the boundary and ε_{r1} is the relative permittivity in medium 1. Using a similar notation for medium 2, then the boundary condition is $\varepsilon_{r1}E_{n1} = \varepsilon_{r2}E_{n2}$.
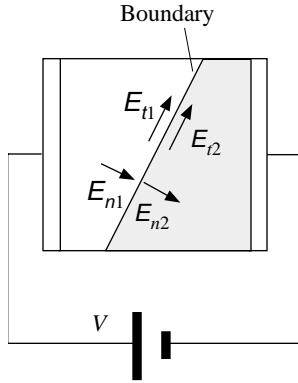
Boundary conditions between dielectrics. E_t is the tangential and E_n is the normal electric field to the boundary Subscripts 1 and 2 refer to dielectrics 1 and 2.
$\varepsilon_{r1}E_{n1} = \varepsilon_{r2}E_{n2}$ and $E_{t1} = E_{t2}$

Bragg diffraction condition, see **diffraction grating.**

Bragg wavelength is a particular wavelength λ_B of electromagnetic radiation that satisfies the **Bragg diffraction condition**,

$$q\frac{\lambda_B}{n} = 2\Lambda\sin\theta$$

where Λ is the periodicity of the diffracting structure, n is the **refractive index** of the medium diffracting the **waves** and θ is the diffraction angle, and q is an integer (1,2,…), so that the electromagnetic radiation becomes diffracted.

Brewster's angle or polarization angle (θ_p) is the angle of incidence which results in the reflected **wave** having no electric field in the plane of incidence (plane defined by the incident ray and the normal to the surface). The electric field oscillations are in the plane perpendicular to the plane of incidence. When the angle of incidence of a light wave is equal to the polarization angle θ_p, the field in the reflected wave is then always perpendicular to the plane of incidence and hence well-defined. The reflected wave is then plane polarized. This special angle is given by

$$\tan\theta_p = \frac{n_2}{n_1}$$

In addition, the transmitted (the refracted) wave has a greater field amplitude in the plane of incidence. By using a pile of **glass** plates inclined at the Brewster angle, one can construct a polarizer that provides a reasonable polarized light with the field in the plane of incidence.
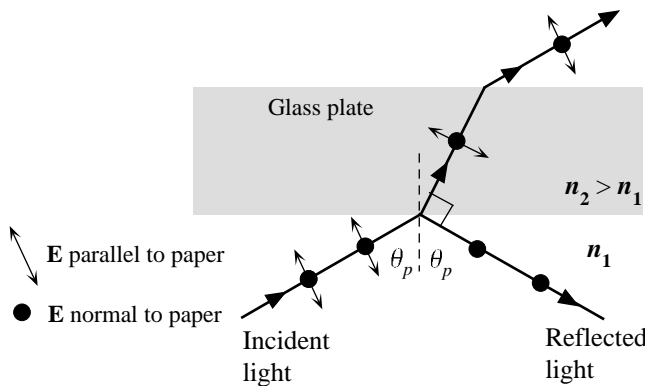
When an unpolarized light wave is incident at the Brewster angle, the reflected wave is polarized with its optical field normal to the plane of incidence, that is parallel to the surface of the glass plate. The angle between the refracted (transmitted) beam and the reflected beam is 90°.
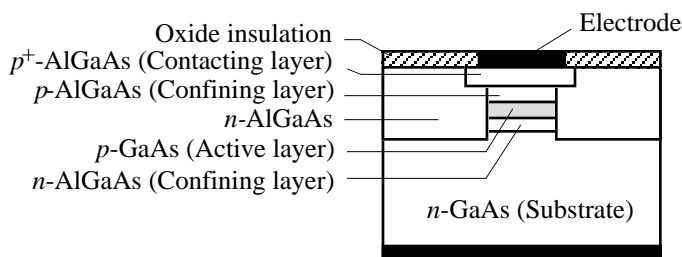
David Brewster (1781-1868), a British physicist, formulated the polarization law in 1815. He was a Professor of Physics at St. Andrew's University and later the Principal of the University of Edinburgh. (Courtesy of AIP Emilio Segrè Visual Archives, Zeleny Collection.)

Brillouin scattering is the **scattering** of **electromagnetic waves** in a non-linear medium by high frequency acoustic ('sound") or ultrasonic generated in that medium. The frequency of the scattered **wave** is shifted by an amount equal to the frequency of the sound wave.

Built-in voltage (V_o) is the voltage across a *pn* junction, going from *p* to *n*-type **semiconductor**, in an open circuit. It is not the voltage across the **diode** which is made up of V_o as well as the contact potential at the metal electrode to semiconductor junctions.

Buried double heterostructure laser diode is a double heterostructure **semiconductor laser** device that has its **active region** "buried" within the device in such a way that it is surrounded by low **refractive index** materials rendering the active region as a waveguide.

Oxide insulation
Electrode
p^+-AlGaAs (Contacting layer)
p-AlGaAs (Confining layer)
n-AlGaAs
p-GaAs (Active layer)
n-AlGaAs (Confining layer)
n-GaAs (Substrate)

Schematic illustration of the cross sectional structure of a buried heterostructure laser diode.

Butt jointed optical fibers are two fibers that are placed end-to-end with their flat ends as close as possible to allow light exiting one fiber to enter the other fiber.

Carrier confinement is the restriction of injected charge carriers to a small volume to increase the carrier concentration. The restriction of injected carriers is achieved by using a **heterojunction** so that there is a step change in the **conduction band** edge (ΔE_c) or a step change in the **valence band** edge (ΔE_v).

Cathode-ray tube (CRT) is a vacuum tube device that uses an electron beam to provide an image on a luminous screen. Thermionically emitted electrons from a heated cathode at one end of the tube are accelerated by ring shaped anodes (hollow cylinders) which form an electrostatic lens system to focus the beam. Electrons pass through the anode rings and form a beam that strikes the enlarged end of the tube. The latter is coated on the inside with a fluorescent material (a phosphor) so that the region struck by the electron beam becomes luminous. A negative voltage applied to a grid between the cathode and the anode controls the intensity of the electron beam. The cathode (including the filament), grid and the anode assembly is termed an electron gun. The electron beam from the electron gun can be deflected by *x* and *y*-deflection plates or by magnetic coils.

Cathodoluminescence, see **luminescence**.

**Centrosymmetric crystals** have a unit cell with a center of symmetry. If we draw a vector **r** from point O to any charge and then reverse the vector, *i.e.* make it −**r**, we will find the same charge. If, on the other hand, we do *not* find the same charge when we reverse the vector, then the unit cell is *non-centrosymmetric.*; **r** and −**r** point on to different ions. Non-centrosymmetric crystals exhibit

piezoelectricity.
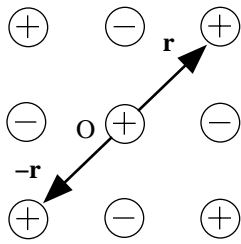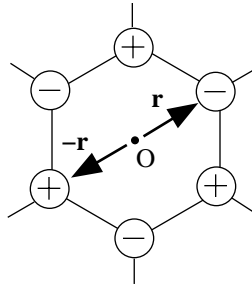
(a) Centrosymmetric   (b) Non-centrosymmetric

Chemical potential μ **or Gibbs free energy per atom** G of a system or a substance is the potential energy per atom for doing non pV (non-mechanical) work, for example electrical or magnetic work. It is the change in the chemical potential (or change in Gibbs free energy per atom) that results in non-pV work to be done. For example in a battery, the EMF, V, that is available is the change $\Delta\mu$. The term chemical potential (potential energy) is used because the work comes about typically through chemical changes.

Chemical vapor deposition (CVD) is a chemical process by which reaction between gaseous reactants results in products that are deposited as solid.

Chip is a piece (or a volume) of a semiconductor **crystal** which contains many integrated active and passive components to implement a circuit.

Chirp, see **optical Kerr effect**.

Chromatic dispersion coefficient D_{ch} is time spread of a propagating optical pulse in an optical guide per unit length and per unit spectral wavelength width due to the wavelength dependence of all the guide properties. If $\delta\lambda$ is the spread of the excitation wavelengths coupled into the fiber, $\delta\tau$ is the spread in propagation times of these different wavelengths, L is the fiber length then,

$$D_{ch} = \frac{1}{L}\frac{\delta\tau}{\delta\lambda}$$

The overall chromatic dispersion coefficient can be written as

$$D_{ch} = D_m + D_w + D_p$$

where D_m, D_w and D_p are the material, waveguide and **profile dispersion** coefficients.
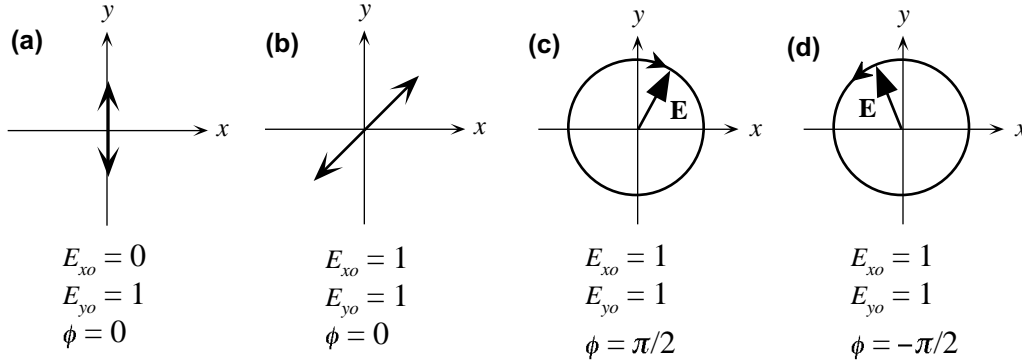
Chromatic dispersion is due to the **dispersion** of a traveling pulse of light along an **optical fiber** as a result of the wavelength dependence of the propagation characteristics and waveguide properties but excluding multimode dispersion. Chromatic dispersion arises as a result of the range of wavelengths in the emission **spectrum** of the **emitter** (*e.g.* LED or **laser diode**) that are coupled into the fiber. It is the combination of **material dispersion** and **waveguide dispersion**.

Circularly birefringent crystal is a medium in which the right and left handed circularly polarized waves propagate with different velocities and experience different refractive indices; n_R and n_L. Since optically active materials naturally rotate the **optical field**, it is not unreasonable to expect that a **circularly polarized light** with its optical field rotating in the same sense as the **optical activity** will find it easier to travel through the medium. Thus, an optically active medium possesses different refractive indices for right and left handed circularly polarized light and exhibits circularly birefringence.

Circularly polarized light has the magnitude of the field vector **E** constant but its tip at a given location on direction of propagation, *e.g. z* -direction, traces out a circle by rotating either in a clockwise sense, *right circularly polarized*, with time, as observed by the receiver of the **wave**, or in a counterclockwise sense, *left circularly polarized*.
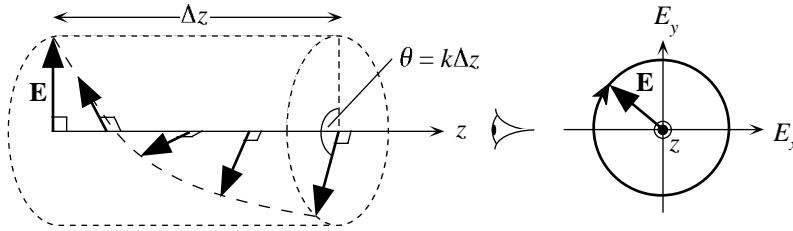
A *right circularly polarized light*. The field vector **E** is always at right angles to z, rotates clockwise around z with time, and traces out a full circle over one wavelength of distance propagated.

(a)	(b)	(c)	(d)
$E_{xo} = 0$	$E_{xo} = 1$	$E_{xo} = 1$	$E_{xo} = 1$
$E_{yo} = 1$	$E_{yo} = 1$	$E_{yo} = 1$	$E_{yo} = 1$
$\phi = 0$	$\phi = 0$	$\phi = \pi/2$	$\phi = -\pi/2$

Examples of linearly, (a) and (b), and circularly polarized light (c) and (d); (c) is right circularly and (d) is left circularly polarized light (as seen when the wave directly approaches a viewer)

Cladding is the **dielectric** layer that surrounds the dielectric core of an **optical waveguide**.

Cleaved-coupled-cavity (C^3) laser device, two different pumped laser optical cavities L and D (different lengths) are coupled in such a way that only modes that satisfy both cavities can exist for the whole system (of two cavities). The two lasers are pumped by different currents . Only those **waves** that can exist as modes in *both* cavities are now allowed because the system has been coupled. The modes in L are more closely spaced than modes in D. These two different set of modes coincide only at far spaced intervals. This restriction in possible modes in the combined cavity and the wide separation between the modes, results in a single mode operation.
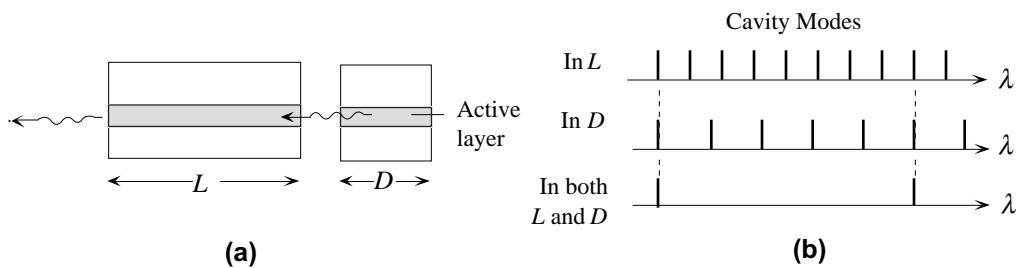
Cleaved-coupled-cavity (C^3) laser

Coherence length l is the spatial distance over which any two points P and Q on a waveform at a given instant can be correlated, one can be predicted from the other. Suppose that a **wave** train has a **coherence time** Δt then its *coherence length $l = c\Delta t$*.

Coherence time Δt is the longest time period over which any two points P and Q at a given location can be correlated, one can be predicted from the other. When a sine **wave** is chopped, truncated, so that it exists only over the time period Δt, then it is not a perfect sine wave and contains a distribution of frequencies. The **spectral width** $\Delta \upsilon$ and the **temporal coherence** Δt are related by $\Delta \upsilon = 1/\Delta t$.
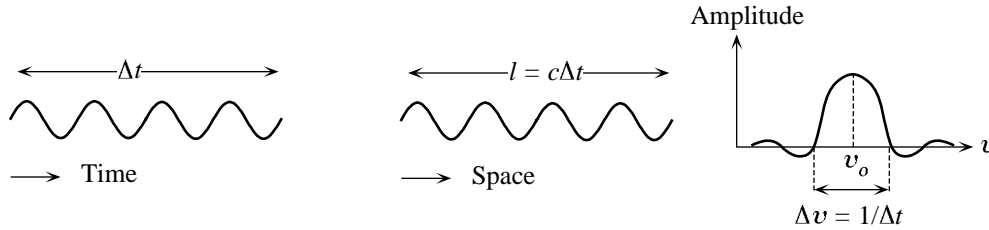
A finite wave train lasts for a duration Δt and has a length l. Its frequency spectrum extends over $\Delta \upsilon = 1/\Delta t$. It has a coherence time Δt and a coherence length l.

Coherent radiation (or light) consists of **waves** that have the same wavelength and always have the same phase difference with respect to each other at all times.

Compensated semiconductor contains both donors and acceptors in the same **crystal** region which compensate for each other's effects. For example, if there are more donors than acceptors, $N_d > N_a$, then some of the electrons released by donors are captured by acceptors and the net effect is that $N_d - N_a$ number of electrons per unit volume are left in the **conduction band**.

Complex refractive index characterizes the propagation of a light wave in a medium in which there is a loss of energy, that is, the electromagnetic wave experiences attenuation, due to various loss mechanisms such as the generation of phonons (lattice waves), photogeneration, free carrier absorption, scattering, etc. If N is the complex refractive index, then $N = n - jK$, where the real part n, the refractive index, represents the effect of the medium on the phase velocity, and the imaginary part, K, called the extinction coefficient, represent the attenuation suffered by the wave as it travels along a well-defined propagation direction. N can be defined in terms of the *complex relative permittivity* $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$ by

$$N = n - jK = \sqrt{\varepsilon_r} = \sqrt{(\varepsilon_r' - j\varepsilon_r'')}$$

By squaring both sides we can relate n and K directly to ε_r' and ε_r''. The final result is

$$n^2 + K^2 = \varepsilon_r' \quad \text{and} \quad 2nK = \varepsilon_r''$$

Optical properties of materials are typically reported either by showing the frequency dependences of n and K or ε_r' and ε_r''. The complex relative permittivity and the complex refractive index of crystalline silicon in terms of the photon energy $\hbar\omega$ (or frequency) are shown below. For photon energies below the bandgap energy, both ε_r'' and K are negligible and n is close to about 3.7. Both ε_r'' and K increase and change strongly as the photon energy becomes greater than 3 eV; far beyond the bandgap energy (1.1 eV). Notice that both ε_r' and n peak around $\hbar\omega \approx 3.5$ eV. The optical properties n and K can be determined by measuring the reflectance from the surface of a material as a function of polarization and the angle of incidence (based on Fresnel's equations). The reflection and transmission coefficients that are normally given by Fresnel's equations are based in using a real refractive index, that is, neglecting losses. We can still use the Fresnel reflection and transmission coefficients if we simply use the complex refractive index N instead of n. For example, consider a light wave traveling in free space incident on a material at normal incidence ($\theta_i = 90°$). The reflection coefficient is now,

$$r = \frac{N-1}{N+1} = \frac{n-jK-1}{n-jK+1}$$
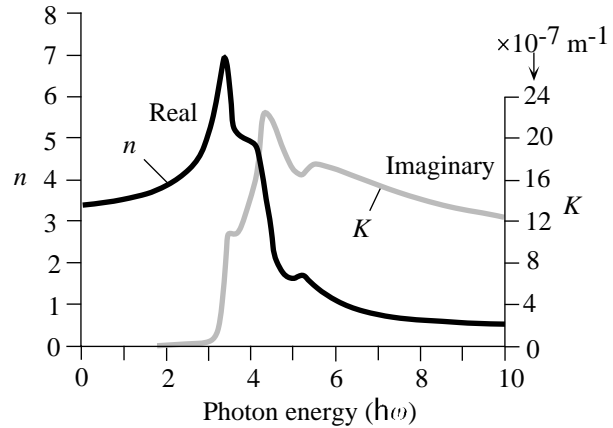
The reflectance is then

$$R = \left|\frac{n-jK-1}{n-jK+1}\right|^2 = \frac{(n-1)^2 + K^2}{(n+1)^2 + K^2}$$

which reduce to the usual forms when the extinction coefficient $K = 0$.
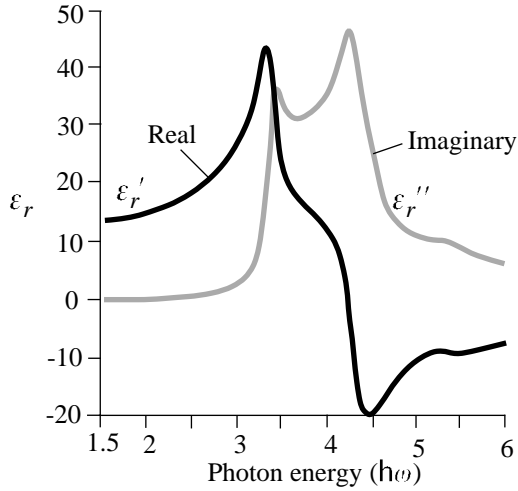
Complex relative permittivity of a silicon crystal as a function of photon energy plotted in terms of real (ε_r') and imaginary (ε_r'') parts.

Optical properties of a silicon crystal vs. photon energy in terms of real (n) and imaginary (K) parts of the complex refractive index.

Complex relative permittivity ($\varepsilon_r' + j\varepsilon_r''$) has a real part ($\varepsilon_r'$) that determines the charge storage ability and an imaginary part (ε_r'') that determines the energy losses in the material as a result of the polarization mechanism. The real part determines the capacitance through $C = \varepsilon_o \varepsilon_r' A/d$ and the imaginary part determines the electric power dissipation per unit volume as heat by $E^2 \omega \varepsilon_o \varepsilon_r''$, where E is the electric field, ω is the angular frequency and ε_o is the absolute permittivity.

Complex propagation constant ($k' - jk''$) describes the propagation characteristics of an **electromagnetic wave** that is experiencing **attenuation** as it travels in a lossy medium. If $k = k' - jk''$ is the complex propagation constant, then the electric field component of a **plane wave** traveling along z in a lossy medium can be described by

$$E = E_o\exp(-k''z)\exp j(\omega t - k'z)$$
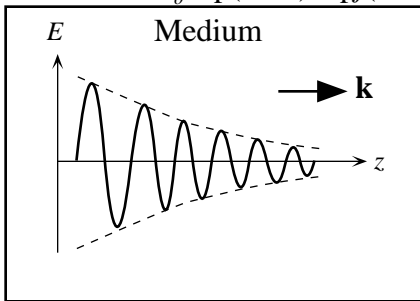
Attenuation of light in the direction of propagation.

The amplitude decays exponentially while the **wave** propagates along z. The **real** k' part of the complex propagation constant (**wavevector**) describes the propagation characteristics, *e.g.* **phase velocity** $v = \omega/k$. The *imaginary* k'' part describes the rate of attenuation along z. The intensity $\mathcal{I}$ at any point along z is

$$\mathcal{I} \propto |E|^2 \propto \exp(-2k''z)$$

so that the rate of change in the intensity with distance is

$$d\mathcal{I}/dz = -2k''\mathcal{I}$$

where the negative sign represents attenuation. Suppose that k_o is the **propagation constant** in vacuum. This is a real quantity as a plane wave suffers no loss in free space. The **complex refractive index** N with real part n and imaginary part K is defined as the ratio of the complex propagation constant in a medium to propagation constant in free space

$$N = n - jK = k/k_o = (1/k_o)[k' - jk'']$$

$$n = k'/k_o \qquad \text{and} \qquad K = k''/k_o$$

The real part n is simply and generally called the **real refractive index** and K is called the **extinction coefficient**. In the absence of attenuation,

$$k'' = 0, \; k = k' \; \text{and} \; N = n = k/k_o = k'/k_o.$$

**Complex refractive index,** see **complex propagation constant.**

Compton effect is the **scattering** of a high energy **photon** by a "free" electron. The Compton effect is experimentally observed when an **X-ray** beam is scattered from a target that contains many conduction ("free") electrons such as a metal or graphite. When an X-ray photon interacts with a conduction electron in a metal it becomes deflected just as if it were a "particle" with a certain momentum p. The photon loses some of its energy to the electron and therefore suffers a reduction in the frequency from v to v'. From the Compton experiment, the momentum of the photon has been shown to conform to $p = h/\lambda$ (De Broglie relationship).

Conduction band (CB) is a band of energies for the electron in a **semiconductor** where it can gain energy from an applied field and drift and thereby contribute to electrical conduction. The electron in the conduction band behaves as of were a "free" particle with an effective mass, $m_e{}^*$.

Confining layer is a layer with a wider bandgap than the active layer, and adjacent to it, to confine the injected **minority carriers** to the active layer.

Connector is a mechanical coupling component (frequently at the end of an **optical fiber** cable) that allows two fibers to be easily aligned and coupled together end-to-end as close as possible. A connector can also couple a fiber to an **emitter** or a detector. **Insertion loss** of a connector is usually higher than that of a **splice**.

Consolidation is a process by which the hollow soot rod coming out from the **outside vapor deposition** process is sintered, bypassing through a furnace (1400 -1600 °C), into a clear **glass** preform rod; this **preform** is next used in the fiber **drawing** process. See **outside vapor deposition.**
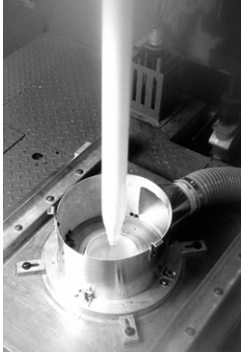
The soot rod is fed into the consolidation furnace for sintering (Courtesy of Corning.)

Constructive interference, see **interference**.

Contacting layer in a heterostructure device is a layer that is grown on a given **semiconductor** for the purpose of making an **ohmic contact**, that is for avoiding a Schottky junction.

Continuous wave (CW) is an untruncated sinusoidal oscillation; untruncated means over the time scale of observation as opposed to a pulsed oscillation that lasts for a short duration of time.

Conversion efficiency gauges the overall efficiency of the conversion from the input of electrical power to the output of **optical power**. Although this is not generally quoted in data sheets, it can be easily determined from the output power at the operating diode current and voltage. In some modern LSD this may be as high as 30-40%.

Core is the central region of an **optical fiber** that has a higher **refractive index** than the outer region. Most of the light propagates through the core region of a fiber.

Cotton-Mouton effect is the inducement of birefringence in a material due to the application of a **magnetic field**, analogous to the electro-optic Kerr effect. For example, when a magnetic field is applied to a liquid, the molecules may become aligned resulting in an optical anisotropy. The induced change in the **refractive index** is proportional to the square of the magnetic field.

Coupled waveguides are two sufficiently closely spaced **optical waveguides**, say *A* and *B*) such that the electric fields associated with the propagation modes in *A* and *B* can overlap so that light can be coupled from one guide to another in a reminiscent way to **frustrated total internal reflection**. We can use qualitative arguments to understand the nature of light coupling between these two guides. Suppose that we launch a light **wave** into the guide *A* operating in single mode. Since the separation *d* of the two guides is small, some of the electric field in the **evanescent wave** of this mode extends into guide *B*, and therefore some electromagnetic energy will be transferred from guide *A* to *B*. This energy transfer will depend on the efficiency of coupling between the two guides and the nature of the modes in *A* and *B*, which in turn depend on the geometries and refractive indices of guides and the **substrate** (acting as a **cladding**). As light in guide *A* travels along *z*, it leaks into *B* and, if the mode in *B* has the right phase, the transferred light waves build up along *z* as a propagating mode in *B*. By the same token, the light now traveling in *B* along *z* can be transferred back into *A* if the mode in *A* has the right phase. The efficient transfer of energy back and forth between the two guides *A* and *B* requires that the two modes be in phase to allow the transferred amplitude to build-up along *z*. If the two modes are out of phase, the waves transferred into a guide do not reinforce each other and the coupling efficiency is poor. Suppose that β_A and β_B are the **propagation constants** of the **fundamental modes** in *A* and *B*, then there is a **phase mismatch** per unit length along *z* that is $\Delta\beta = \beta_A - \beta_B$. The efficiency of energy transfer between the two guides depends on this phase mismatch. If the phase mismatch $\Delta\beta = 0$ then full transfer of power from *A* to *B* will require a coupling distance L_o, called the *transfer distance*. This transfer distance depends on the efficiency of coupling *C* between the two guides *A* and *B*, which in turn depends on the refractive indices and geometries of the two guides. *C* depends on the extent of

overlap of the mode fields E_A and E_B in A and B respectively. The transmission length L_o is inversely proportional to C (in fact, theory shows that $L_o = \pi/C$). In the presence of no mismatch, $\Delta\beta = 0$, full transmission would occur over the distance L_o. However, if there is a mismatch $\Delta\beta$ then the transferred power ratio over the distance L_o becomes a function of $\Delta\beta$. Thus, if $P_A(z)$ and $P_B(z)$ represent the light power in the guides A and B at z, then

$$\frac{P_B(L_o)}{P_A(0)} = f(\Delta\beta)$$

This function has its maximum when $\Delta\beta = 0$ (no mismatch) and then decays to zero at $\Delta\beta = \pi\sqrt{3}/L_o$. If we could induce a phase mismatch of $\Delta\beta = \pi\sqrt{3}/L_o$ by applying an electric field, which modulates the refractive indices of the guides, we could then prevent the transmission of light power from A to B. Light is then *not* transferred to B.
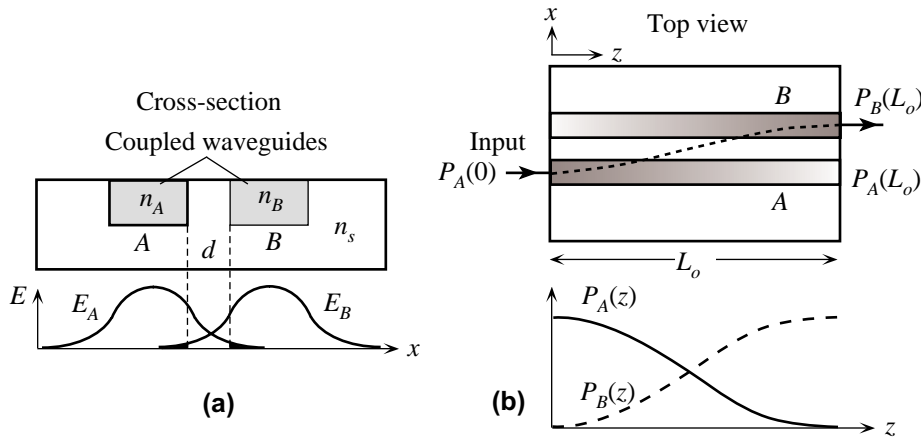
(a) Cross section of two closely spaced waveguides A and B (separated by d) embedded in a substrate. The evanescent field from A extends into B and vice versa. Note: n_A and $n_B > n_s$ (= substrate index).
(b) Top view of the two guides A and B that are coupled along the z-direction. Light is fed into A at $z = 0$, and it is gradually transferred to B along z. At $z = L_o$, all the light has been transferred to B. Beyond this point, light begins to be transferred back to A in the same way.
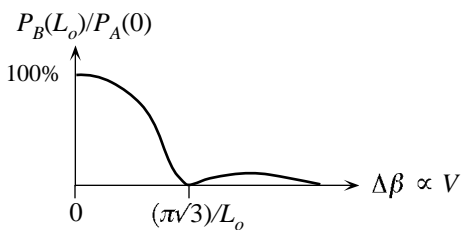
Transmission power ratio from guide A to guide B over the transmission length L_o as a function of mismatch $\Delta\beta$.

Critical angle (θ_c) is the angle of incidence that results in a refracted **wave** at 90° when the incident wave is traveling in a medium of lower **refractive index** and is incident at a boundary with a material with a higher refractive index.

Crystal is a three-dimensional periodic arrangement of atoms or molecules or ions. A characteristic property of the crystal structure is its periodicity and a degree of symmetry. For each atom the number of neighbors and their exact orientations are well defined, otherwise the periodicity will be lost. There is therefore a *long range order* resulting from strict adherence to a well defined bond length and relative bond angle (or exact orientation of neighbors).

Crystal momentum of the electron in a **crystal** is $\hbar k$ where k is the "**wavevector**" of the electron in the crystal, that is $\psi(x) = U(x)\exp(-jkx)$ is a solution of the Scrödinger equation given the periodic potential energy for the particular crystal of interest. Such a solution is a traveling **wave** with a wavevector k and that is spatially modulated by $U(x)$. The rate of change of $\hbar k$ is equal to the sum of all external forces only thus $\hbar k$ represents what we understand as the momentum of a particle. However, in this case the electron is in the crystal and subject to a periodic potential energy; hence the name crystal momentum. In general, $\hbar k$ is not the true momentum of the electron because the rate of change of $\hbar k$ is not equal to the total force, including internal forces. Nonetheless, we can treat $\hbar k$ in most cases as a "momentum".

Crystallization is a process by which **crystals** of a substance are formed from another phase of that substance, for example, from the melt by solidification just below the fusion temperature or by condensation of the molecules from the vapor phase onto a **substrate**. The crystallization process initially requires the formation of small nuclei of the crystal phase which contain a limited number (perhaps 10^3-10^4) of atoms or molecules of the substance. Following nucleation, the nuclei grow by atomic **diffusion** from the melt to the nuclei.

Cut-off wavelength of a mode of an **optical waveguide** is the critical wavelength λ_c below which the guide cannot support the propagation of this particular mode. For example, in a planar slab dielectric waveguide, when the wavelength is such that the **V-number** is less than $\pi/2$, the $m = 1$ (TE_1) mode cannot be supported and the guide can only support the $m = 0$ mode (TE_0); it becomes a **single mode waveguide**.

Dark current of a photodetector is the dc current that flows in the absence of light when it is carrying a **bias** voltage. In a *pn* junction **photodiode**, the bias voltage is a **reverse bias** across the device, and the dark current depends strongly on the temperature. There are two contributions to the dark current which are the **diffusion** of **minority carriers** in the neutral regions and the thermal generation of electron hole pairs (EHPs) in the space charge layer (SCL). Both depend strongly on the temperature and the dark current increases exponentially with increasing temperature, typically as a thermally activated process, *i.e.* $I_{dark} \sim \exp(-E_g/\eta kT)$ where η is 1 if the reverse current is controlled by minority carrier diffusion in the neutral regions and 2 if it is controlled by thermal generation of EHPs in the SCL, E_g is the bandgap of the **semiconductor** material, k is the Boltzmann constant and T is the temperature (K). See **reverese diode current**.

Data rate is the rate at which **bits** are transmitted per unit time according to a well-defined information coding system used, *e.g.* **return-to-zero** (RZ) or **nonreturn-to-zero** (NRZ). NRZ data rate is higher than the RZ data rate.

Debye equations attempt to describe the frequency response of the **complex relative permittivity**, $\varepsilon_r' + j\varepsilon_r''$, of a dipolar medium through the use of a single relaxation time τ to describe the sluggishness of the dipoles driven by the external ac field.

Decibel is a logarithmic unit of *power gain* defined as $dB = 10\log(P_{out}/P_{in})$ where P is the power. It can be used to describe voltage gain as well in which case $dB = 20\log(V_{out}/V_{in})$ where V is the voltage. Similarly it can also describe a current gain by $dB = 20\log(I_{out}/I_{in})$ where I is the current.

Degenerate semiconductor has so many dopants that the electron concentration in the **conduction band** (CB), or hole concentration in the **valence band** (VB), is comparable with the **density of states** in the band. Consequently the carriers interact with each other and **Fermi-Dirac statistics** must be used. The Fermi level is either in the CB for a n^+ type degenerate, or in the VB for a p^+ type degenerate semiconductor. The superscript + indicates a heavily **doped semiconductor**.

Density of states, $g(E)$, is the number of electron **states** (*e.g.* wave functions, $\psi(n,\ell,m_l,m_s)$) per unit energy per unit volume. $g(E)dE$ is thus the number of states in the energy range E to $E+dE$ per unit volume.

Depletion (space charge) layer capacitance is the incremental capacitance (dQ/dV) due to the change in the exposed dopant charges in the **depletion layer** as a result of the change in the voltage across the *pn* junction.

Depletion layer (or space charge layer, SCL**)** is a region around the **metallurgical junction** where **recombination** of electrons and holes has depleted this region of its large number of equilibrium majority carriers.

Destructive interference, see **interference**.

Detectivity is the reciprocal of **noise equivalent power** (NEP).

Dichroism is a phenomenon in which the optical **absorption** in a substance depends on the direction of propagation and the state of **polarization** of the light beam. A dichroic **crystal** is an optically anisotropic crystal in which either the *e*-wave or the *o*-wave is heavily attenuated (absorbed).

Dielectric is a material in which energy can be stored by the polarization of the molecules. It is a material that increases the capacitance or charge storage ability of a capacitor. Ideally it is a non-conductor of electrical charge so that an applied field does not cause a flow of charge but instead relative displacement of opposite bound charges and hence polarization of the medium.

Dielectric loss is the electrical energy lost as heat in the polarization process in the presence of an applied ac field (an alternating electronic field). The energy is absorbed from the ac voltage and converted to heat during the polarizations of the molecules. It should not be confused with conduction loss σE^2 or V^2/R. See **complex relative permittivity.**

Dielectric mirror is made from alternating high and low **refractive index** quarter-wave thick multilayers. Such dielectric mirrors provide a high degree of wavelength selective **reflectance** at the required free space wavelength λ if the thicknesses of alternating layers d_1 and d_2 with refractive indices n_1 and n_2 are such that

$$n_1 d_1 + n_2 d_2 = {}^1\!/_2\lambda$$

which then leads to the **constructive interference** of all partially reflected waves at the interfaces.

Dielectric strength is the maximum field (E_{br}) that can be sustained in a **dielectric** beyond which dielectric breakdown ensues, *i.e.* there is a large conduction current through the dielectric shorting the plates.

Diffraction grating is an optical device with a periodic array of slits for diffracting ("deflecting") an incident light beam through an angle that depends on the wavelength and the periodicity of slits in the grating. In its simplest form it has a periodic series of slits in an opaque screen. An incident beam of light is diffracted in certain well-defined directions that depend on the wavelength λ and the grating properties, that is the slit separation d,

$$d\sin\theta = m\lambda \quad ; m = 0, \pm1, \pm2, \ldots$$

which is the well know *grating equation*, also known as the *Bragg diffraction condition*. The value of *m* defines the **diffraction** order; $m = 0$ being zero-order, $m = 1$ being first order *etc*. Order $m = 0$ corresponds to the fraction of light unperturbed by the grating (transmitted without deviation). This basic geometrical formula does not give the amount of diffracted power in each order.

   In a **transmission grating**, the incident and diffracted beams are on opposite sides of the grating. Typically parallel thin grooves on a **glass** plate would serve as a transmission grating. Among transmission gratings, it is customary to distinguish between **amplitude gratings** (the transmission amplitude is modulated) and so-called **phase gratings** (only the refractive index is modulated, without any losses). A **reflection grating** has the incident beam and the diffracted beams on the same side of the device. The surface of the device has a periodic reflecting structure, easily formed by etching parallel grooves in a metal film *etc*. The reflecting unetched surfaces serve as synchronous secondary sources that interfere along certain directions to give diffracted beams of

zero-order, first-order *etc.* If θ_i is the angle of incidence, then the diffraction angle θ_m for the *m*-th mode is given by,

$$d(\sin\theta_m \pm \sin\theta_i) = m\lambda \; ; \; m = 0, \pm 1, \pm 2, \ldots$$

where the negative (positive) sign applies to a transmission (reflection) grating. Some unintentional defects of periodicity can also lead to spurious diffracted beams known as **ghosts**. A grating is not necessarily plane nor strictly periodic; volumic *holograms* can be considered as a generalised three dimensional diffraction grating.
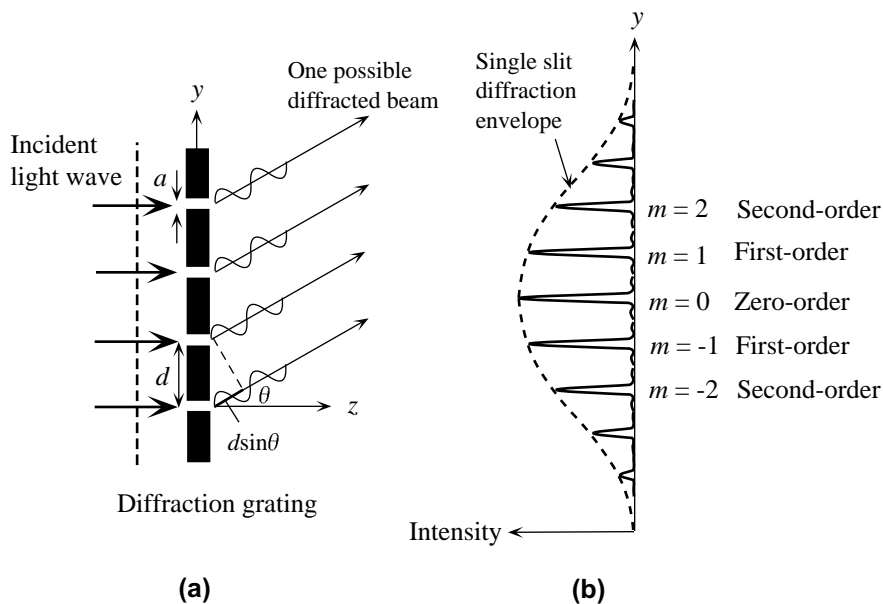
(a) A diffraction grating with *N* slits in an opaque screen. Slit periodicity is *d* and slit width is *a*; *a* << *d*. (b) The diffracted light pattern. There are distinct beams in certain directions (schematic)

William Lawrence Bragg (1890-1971), Australian born British physicist, won the Nobel prize with his father William Henry Bragg for his "famous equation" when he was only 25 years old. (Courtesy of Emilio Segrè Visual Archives, AIP, Weber Collection.)

Diffraction is a spread or bending of a freely propagating wave when it encounters any type of obstacle. For example, sound waves become bent (deflected around) corners. When a light wave passes through an aperture (an opening in an opaque screen) it spreads out from the aperture and the exhibits regions of maximum and minimum intensity as a result of **interference** of **spherical waves** emitted from every point in the aperture in accordance with the **Huygens-Fresnel principle.** The intensity distribution in the diffracted beam as registered by an observer is called the *diffraction pattern*. The light pattern of the diffracted beam does not correspond to the geometric shadow of the aperture. Diffraction phenomena are generally classified into two categories. In *Fraunhofer diffraction*, the incident light beam is a **plane wave** (a collimated light beam) and the

observation or detection of the light intensity pattern (by placing a photographic screen etc.) is done far away from the aperture so that the waves being received also look like plane waves. Inserting a lens between the aperture and the photographic screen enables the screen to be closer to the aperture. In *Fresnel diffraction*, the incident light beam and the received light waves are not plane waves but have significant **wavefront** curvatures. Typically, the light source and the photographic screen are both close to the aperture so that wavefronts are curved. Fraunhofer diffraction is by far the most important.
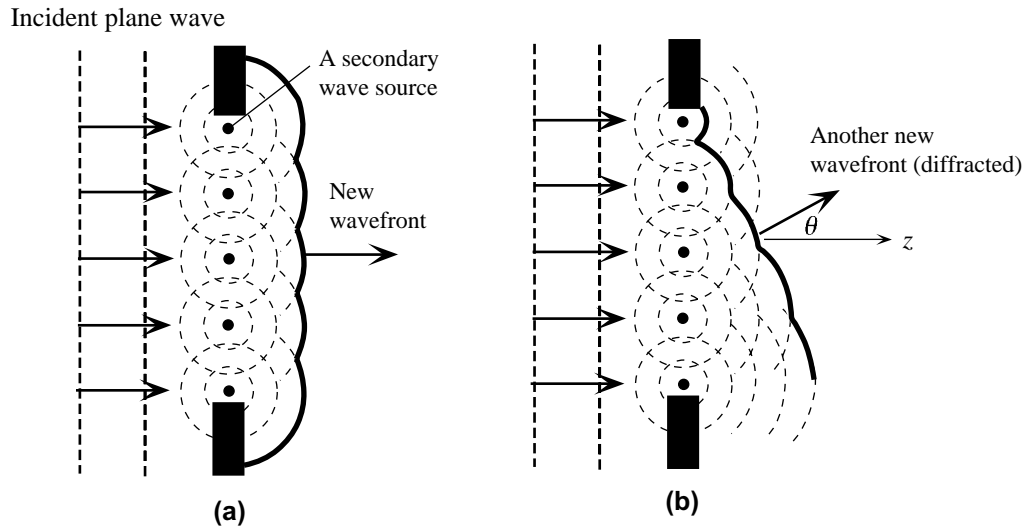
(a) Huygens-Fresnel principles states that each point in the aperture becomes a source of secondary waves (spherical waves). The spherical wavefronts are separated by λ. The new wavefront is the envelope of the all these spherical wavefronts. (b) Another possible wavefront occurs at an angle θ to the *z*-direction which is a diffracted wave.
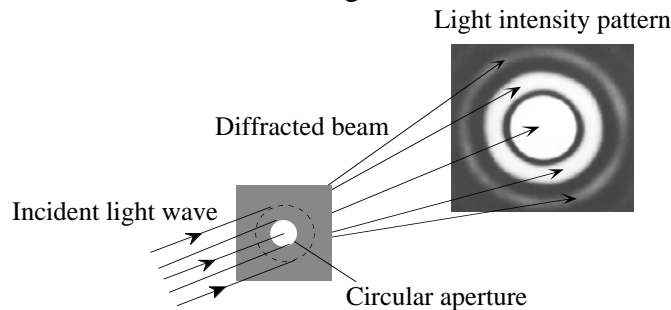
A light beam incident on a small circular aperture becomes diffracted and its light intensity pattern after passing through the aperture is a diffraction pattern with circular bright rings (called Airy rings). If the screen is far away from the aperture, this would be a Fraunhofer diffraction pattern.

Diffraction limited system is an imaging system whose resolution is diffraction limited. Even in the case of perfect *stigmatism* the actual resolution of an imaging instrument is never perfect. For instance, a parabolic telescope, although perfectly stigmatic for the conjugation between an on-axis distant star and the focal point, exhibits a typical Airy diffraction pattern in the focal plane, with a transverse dimension inversely proportional to the diameter of the entrance pupil. From a signal-processing aspect, the Airy pattern is the response function of the apparatus. The only way to enhance the performance is to enlarge the pupil – hence the realization of so-called "very large" telescopes.

Diffuse radiation, see **solar radiation air mass**.

Diffusion coefficient is a measure of the rate at which atoms diffuse. It depends on the nature of the **diffusion** process and typically it is temperature dependent. It is defined as the diffusion flux per unit concentration gradient.

Diffusion is a random process by which particles move from high concentration regions to low concentration regions. There is a flow of particles of a given species from high to low concentration regions by virtue of their random motions. Diffusion is a process by which atoms migrate by virtue of their random thermal motions.

Digital communications is the transmission of information in the form of pulses from one location to another. Typically, an analog signal is sampled at fixed intervals and the value at each interval is put into a binary code containing 1s and 0s and the coded information is then transmitted as pulses (1 corresponding the presence and 0 to the absence of a pulse). Thus the analog signal is digitized and sent by pulses.

Diode (short diode) is a *pn* junction in which the neutral regions are shorter than the **minority carrier diffusion lengths**.

Dipolar (orientational) polarization arises when randomly oriented polar molecules in a **dielectric** are rotated and aligned by the application of a field so as to give rise to a net average dipole moment per molecule. In the absence of the field the dipoles (polar molecules) are randomly oriented and there is no average dipole moment per molecule. In the presence of the field the dipoles are rotated, some partially and some fully, to align with the field and hence give rise to a net dipole moment per molecule.

Dipolar relaxation equation describes the time response of the induced dipole moment per molecule in a dipolar material in the presence of a time dependent applied field. The response of the dipoles depends on their relaxation time which is mean time required to dissipate the stored electrostatic energy in the dipole alignment to heat through **lattice** vibrations or molecular collisions.

Dipole relaxation (dielectric resonance) occurs when the frequency of the applied ac field is such that there is maximum energy transfer from the ac voltage source to heat in the **dielectric** through the alternate polarization and depolarization of the molecules by the ac field. The stored electrostatic energy is dissipated through molecular collisions and **lattice** vibrations (in solids). The peak occurs when the angular frequency of the ac field is the reciprocal of the relaxation time.

Direct radiation, see **solar radiation air mass**.

Direct recombination capture coefficient B is a material constant that characterizes the rate of **recombination** of excess injected carriers in a direct bandgap **semiconductor**. Suppose that excess electrons and holes have been injected, as would be in a *pn*-junction under forward bias, and that Δn_p is the excess electron concentration and Δp_p is the excess hole concentration in the *neutral p*-side of a GaAs *pn* junction. Injected electron and hole concentrations would be the same to maintain charge neutrality, that is, $\Delta n_p = \Delta p_p$. Thus, at any instant,

$$n_p = n_{po} + \Delta n_p = \text{instantaneous } \textit{minority} \text{ carrier concentration,}$$

and $p_p = p_{po} + \Delta n_p = $ instantaneous *majority* carrier concentration.
The instantaneous recombination rate will be proportional to both the electron and hole concentrations at that instant , that is $n_p p_p$. Suppose that the thermal generation rate of electron hole pairs is G_{thermal}. The net rate of *change* of Δn_p is then,

$$\partial \Delta n_p / \partial t = -B n_p p_p + G_{\text{thermal}}$$

where B is a constant called the *direct recombination capture coefficient.* In equilibrium $\partial \Delta n_p / \partial t = 0$ and $n_p = n_{po}$ and $p_p = p_{po}$, where the subscript *o* refers to thermal equilibrium concentrations, so

that $G_{\text{thermal}} = Bn_{po}p_{po}$. Thus, the rate of change in Δn_p is

$$\partial \Delta n_p/\partial t = -B(n_p p_p - n_{po}p_{po})$$

Directional integrated coupler has two implanted symmetrical guides A and B which are coupled over a *transmission length* L_o and also have electrodes placed on them. In the absence of an applied field, the guides are identical and the *phase mismatch*, $\Delta\beta$, is zero (no mismatch) and there is a full transmission from guide A to B. If we apply a voltage between the electrodes, the two guides experiences an applied field E_a in opposite directions and hence experience opposite changes in their refractive indices. If n ($= n_A = n_B$) is the **refractive index** of each guide, and Δn is the induced index change in each guide by **Pockels effect**. The induced index difference Δn_{AB} between the guides is $2\Delta n$. Taking, as a first approximation, $E_a \approx V/d$, and using $\Delta\beta = \pi\sqrt{3}/L_o$ for prevention of transfer, the corresponding switching voltage is V_o is

$$V_o = \frac{\sqrt{3}\lambda d}{2n^3 r L_o}$$

where r is the appropriate Pockels coefficient. Since L_o depends inversely on the coupling efficiency C, for a given wavelength, V_o depends on the refractive indices and the geometry of the guides.
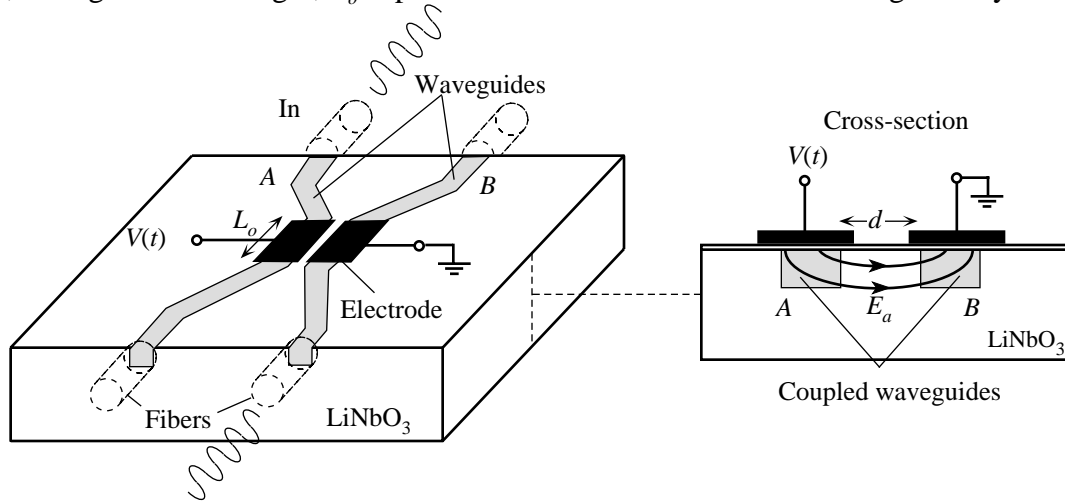
An integrated directional coupler. Applied field E_a alters the refractive indices of the two guides and changes the strength of coupling.

Dislocation is a line imperfection within a **crystal** that extends over many atomic distances.

Dispersion diagram of a waveguide is the angular frequency (ω) vs. **propagation constant** (β) behavior for **electromagnetic waves** propagating in the guide. For example, for an infinite planar dielectric waveguide, the **group velocity** of a mode m can be found from the dispersion diagram $\omega = f(\beta_m)$ inasmuch as

$$V_{gm} = \frac{d\omega}{d\beta_m} = \frac{d\omega}{d[\beta_m(\omega)]} = \text{Function of } \omega$$

ω

Slope = c/n_2

Slope = c/n_1

TE_2

TE_1

$\omega_{\text{cut-off}}$

TE_0

β_m
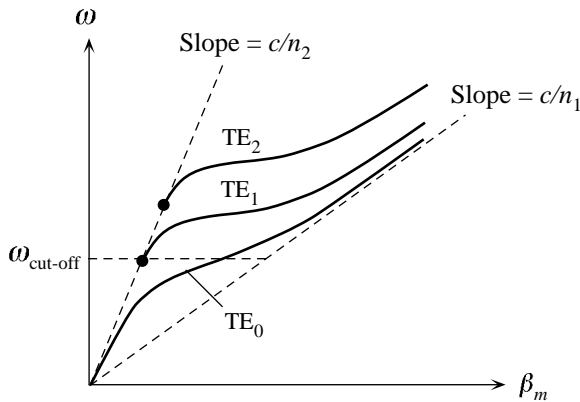
Schematic dispersion diagram, ω vs. β for the slab waveguide for various TE_m. modes. $\omega_{\text{cut-off}}$ corresponds to $V = \pi/2$. The group velocity v_g at any ω is the slope of the ω vs. β curve at that frequency.

Dispersion flattened fiber is an **optical fiber** that has a **refractive index** profile that results in chromatic dispersion being small and flat over a wavelength range. **Waveguide dispersion**, represented by D_w, can be adjusted by changing the waveguide geometry. Waveguide dispersion arises from the **group velocity** v_g dependence on the wavelength λ. As the wavelength increases, the field penetrates more into the **cladding** which changes the proportion of light energy carried by the **core** and the cladding and hence changes v_g. We can thus alter the waveguide geometry , that is the refractive index profile, and thereby control D_w to yield a total chromatic dispersion that is *flattened* between the wavelength λ_1 and λ_2 . The refractive index profile of such a fiber looks like a W in which the cladding is a thin layer with a depressed refractive index; the fiber is called *doubly clad*. The simple **step index fiber** is singly clad. Greater control on waveguide dispersion can be obtained by using multiply clad fibers. Such fibers are more difficult to manufacture but can exhibit excellent chromatic dispersion 1 - 3 ps km^{-1} nm^{-1} over 1.3 - 1.6 μm. Low dispersion over a wavelength range, of course, allows wavelength multiplexing, *e.g.* using a number of wavelengths (*e.g.* 1.3, 1.55 μm) as communication channels.
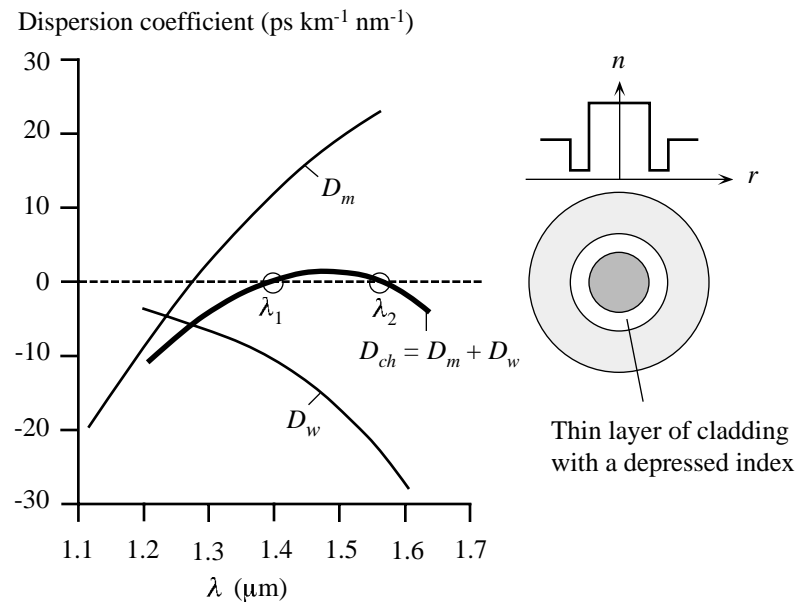
Dispersion flattened fiber example. The material dispersion coefficient (D_m) for the core material and waveguide dispersion coefficient (D_w) for the doubly clad fiber result in a flattened small chromatic dispersion between λ_1 and λ_2.
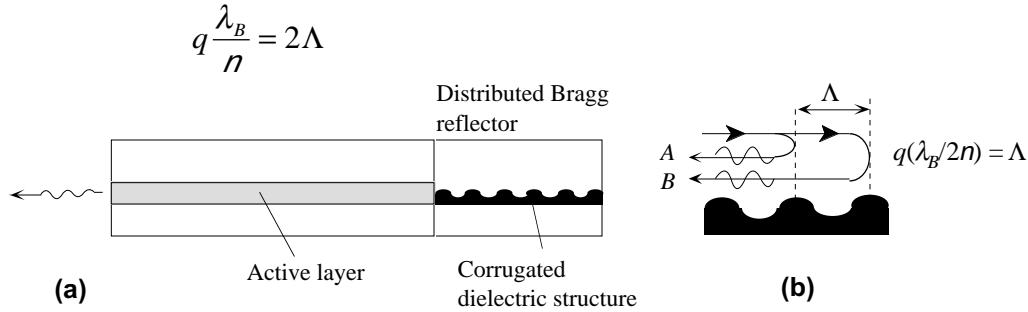
Dispersion in fiber optics is the spread in time, known as temporal broadening, of an infinitesimally thin optical pulse as it propagates along the fiber. The temporal broadening is due to the different propagation characteristics of different wavelength components of light that are coupled into the fiber and propagate along the guide. Due to the dispersion effect there is an upper limit for the rate at which we can transmit light pulses along a fiber.

Dispersion shifted fiber is a fiber in which the chromatic dispersion characteristics (dispersion vs wavelength) has been shifted to longer wavelengths by adjusting the waveguide dispersion by appropriately changing the waveguide geometry or the refractive index profile. Zero dispersion shifted fiber has its chromatic dispersion zero at around 1550 nm. Nonzero dispersion shifted fiber is designed for use with WDM (wavelength division multiplexing) and has its chromatic dispersion outside the Er-doped amplifer band, 1525 - 1620 nm.

Dispersion of a light wave is the separation of light into its various wavelength components, *i.e.* its spectral components.

Dispersive medium has a **refractive index** n that depends on the wavelength, that is n is not a constant. The dispersion relation for the medium is the angular frequency vs. **propagation constant** , *i.e.* ω vs. β behavior in the medium. The slope of this curve at any β-value is the **group velocity** a **wave** with that β.

Distributed Bragg reflector (DBR) laser diode has one of the optical cavity reflectors as a mirror that has been designed like a reflection type **diffraction grating**; it has a periodic corrugated structure. Intuitively, partial reflections of **waves** from the corrugations interfere constructively (that is reinforce each other) to give a reflected wave only when the wavelength corresponds to twice the corrugation periodicity. For example, two partially reflected waves such as *A* and *B* have an optical path difference of 2Λ where Λ is the corrugation period. They can only interfere constructively if 2Λ is a multiple of the wavelength within the medium. Each of these wavelengths is called a **Bragg wavelength** λ_B and given by the condition for in-phase **interference**,

$$q\frac{\lambda_B}{n} = 2\Lambda$$

$q(\lambda_B/2n) = \Lambda$

(a)

Distributed Bragg reflector

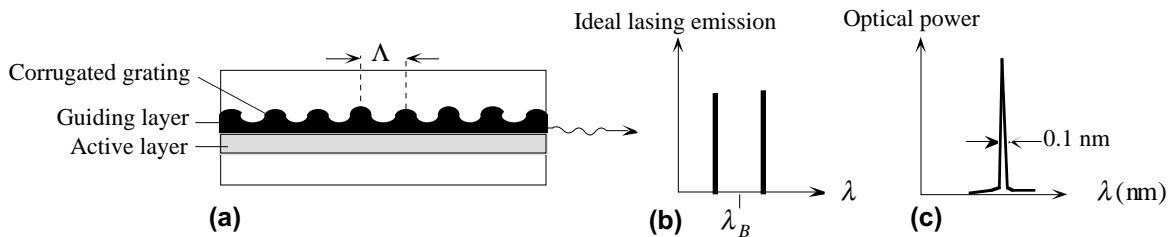Active layer

Corrugated dielectric structure

(b)

(a) Distributed Bragg reflection (DBR) laser principle. (b) Partially reflected waves at the corrugations can only constitute a reflected wave when the wavelength satisfies the Bragg condition. Reflected waves A and B interfere constructive when $q(\lambda_B/2n) = \Lambda$.

Distributed feedback (**DFB**) **laser** has a corrugated layer, called the *guiding layer*, next to the active layer; radiation spreads from the active layer to the guiding layer. These corrugations in the **refractive index** act as optical feedback over the length of the cavity by producing partial reflections. Thus optical feedback is *distributed* over the cavity length. In the DFB structure, traveling **waves** are reflected partially and periodically as they propagate . The left and right traveling waves can only coherently couple to set up a mode if their frequency is related to the corrugation periodicity Λ, taking into account that the medium alters the wave-amplitudes via **optical gain**. The allowed DFB modes are not exactly at **Bragg wavelengths** but are symmetrically placed about λ_B. If λ_m is an allowed DFB lasing mode then

$$\lambda_m = \lambda_B \pm \frac{\lambda_B^2}{2nL}(m+1)$$

where m is a mode integer, 0, 1, 2, …, and L is the effective length of the **diffraction grating** (corrugation length). The relative **threshold gain** for higher modes is so large that only the $m = 0$ mode effectively lases. A perfectly symmetric device has two equally spaced modes placed around λ_B. In reality, either inevitable asymmetry introduced by the fabrication process, or asymmetry introduced in purpose, leads to only one of the modes to appear. Further, typically the corrugation length L is so much larger than the period Λ that the second term in the above equation is very small and the emission is very close to λ_B. There are various commercially available single mode DFB lasers in the market with **spectral widths** of ~0.1 nm at the communications channel of 1.55 μm.

Corrugated grating

Guiding layer

Active layer

Ideal lasing emission

Optical power

0.1 nm

(a)   **(b)** λ_B **(c)** λ (nm)

(a) Distributed feedback (DFB) laser structure. (b) Ideal lasing emission output. (c) Typical output spectrum from a DFB laser.

Diverging waves have **wavevectors**, vectors that are normal to the **wavefront**, that are *not* parallel. The vector that is normal to a wavefront surface at a point such as P represents the direction of wave propagation (**k**) at that point P. Clearly, the propagation vectors everywhere are all parallel and the

plane wave propagates without the wave diverging; *the plane wave has no divergence.* The amplitude of the planar wave does not depend on the distance from a reference point, and it is the same at all points on a given plane perpendicular to k, *i.e.* independent of *x* and *y*. Moreover, as these planes extend to infinity, there is infinite energy in the plane-wave. A plane wave is an idealization that is useful in analyzing many **wave** phenomena. In reality, however, the electric field in a plane at right angles to **k** does not extend to infinity since the light beam would have a finite cross sectional area and finite power. (We would need an infinitely large electromagnetic source with infinite power to generate a perfect plane wave.)

Wave fronts
(constant phase surfaces)

Wave fronts

Wave fronts

A perfect plane wave

A perfect spherical wave

A divergent beam

(a)   **(b)**   **(c)**
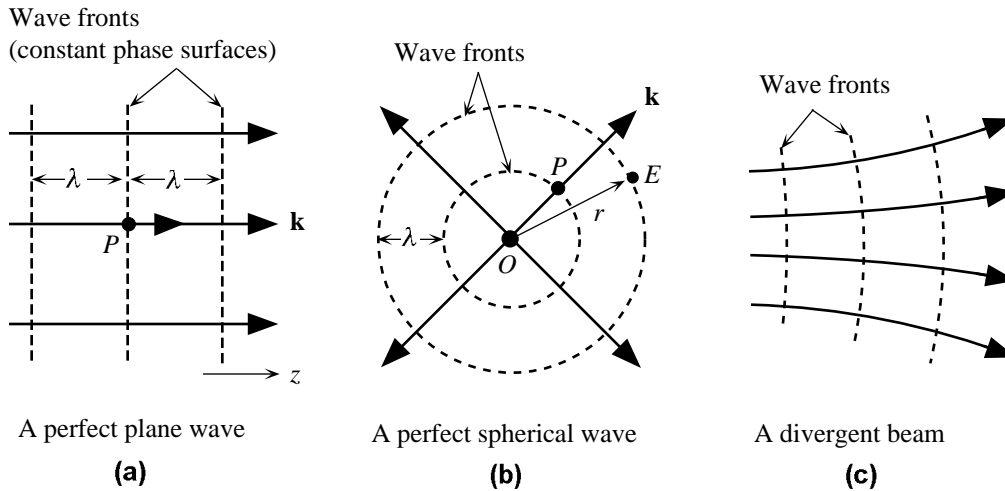
Examples of some possible electromagnetic waves

Donor atoms are dopants in the **semiconductor** that have a valency one more than the host atom. They therefore donate electrons to the **conduction band** (CB) and thereby create electrons in the CB which leads to $n > p$ and hence to an *n*-type semiconductor (*n* is the electron concentration in the CB and *p* is the hole concentration in the VB).

Doped semiconductors, see **extrinsic semiconductors**.

Doping as a general term is used to describe the addition of impurities into a material to modify its properties. For example, phosphorus dopants in a silicon **crystal** act as donor impurities and donate electrons into the **conduction band** and thereby increase the conductivity. When silica (SiO_2) is doped with **germania** (GeO_2), the resulting **glass** (Si-Ge-O) has a higher **refractive index** because the relative permittivity is higher.

Doppler broadened linewidth is the broadening of the emission **spectrum** of a collection of identical sources as a result of their random motions with respect to the observer. Since the atoms of a gas are in random motion then, due to the **Doppler effect**, the observer will detect a range of light frequencies or wavelengths emitted by these atoms. This leads to a Doppler broadened spectrum. When we consider the Maxwell velocity distribution of the gas atoms in the laser tube, we find that the linewidth $\Delta v_{1/2}$ between the half-intensity points (**full width at half maximum** FWHM) in the output intensity vs. frequency spectrum is given by

$$\Delta v_{1/2} = 2 v_o \sqrt{\frac{2 k_B T \ln(2)}{M c^2}}$$
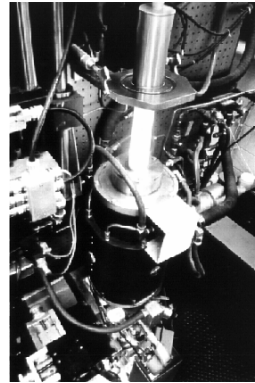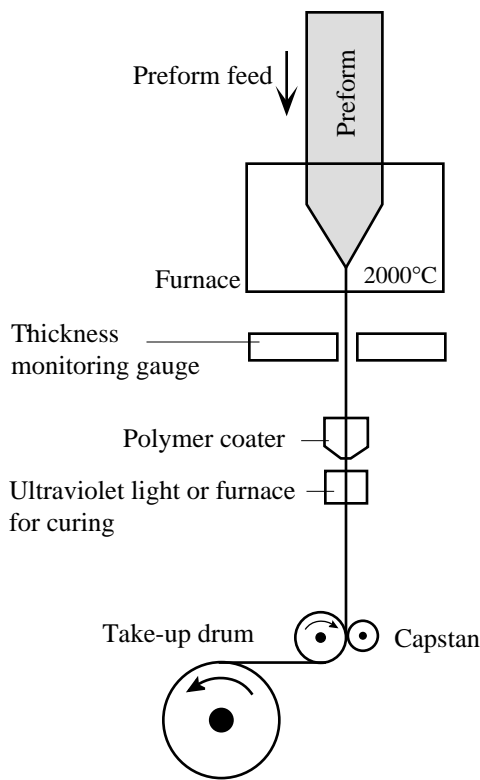
where *M* is the mass of the lasing atom or molecule and v_o is the center frequency of the spectrum (source emission frequency). See also **laser output spectrum**.

Doppler effect is the change in the measured frequency of a **wave** due to the motion of the source relative to the observer. If the source is moving towards the observer the frequency increases (wavelength

decreases), and it decreases when the source is moving away. As a fast train approaches an observer, its whistle becomes higher in pitch (frequency) and as the train moves away from the observer, its pitch becomes lower. The true source frequency remains the same but more waves arrive at the observer per second when the source is moving toward the observer than when it is moving away. In the case of electromagnetic radiation, if v is the relative velocity of the source object toward the observer and v_o is the source frequency, then the measured **electromagnetic wave** frequency v is $v = v_o[1+(v/c)]$, for $(v/c) \ll 1$.

Doubly clad fiber, see **dispersion flattened fiber.**

Drawing in fiber manufacture is a process in which a **glass** preform rod is slowly fed into a hot furnace that has a hot zone around 1900-2000 °C where the glass flows like a viscous melt (resembling honey). As the rod reaches the hot zone and its end begins to flow, its tip is pulled, with just the right tension, to come out as a fiber and is spooled on a rotating take-up drum. The diameter of the fiber must be highly controlled to achieve the required waveguide characteristics. An optical thickness monitor gauge provides information on the changes of the fiber diameter which is used (in an automatic feedback control system) to adjust the speed of the fiber winding mechanism and the speed of the **preform** feeder to maintain a constant fiber diameter, typically better than 0.1%. In some cases, the preform is hollow, that is, it has a thin central hole along the rod axis. The hollow simply collapses during the drawing and does not affect the final drawn fiber. It is essential that, as soon as the fiber is drawn, it is coated with a polymeric layer (*e.g.* urethane acrylate) to mechanically and chemically protect the fiber surface. When a bare fiber glass surface is exposed to ambient conditions it quickly develops various microcracks on the surface and these microcracks dramatically reduce the mechanical strength (fracture strength) of the fiber. The applied polymeric coating is initially a viscous liquid and needs to be cured (hardened) which is done as the coated fiber passes through a curing oven, or ultraviolet lamps if it is UV hardenable. Sometimes two layers of polymeric coating are applied. **Cladding** is typically 125-150 μm and the overall diameter with the polymeric coatings is 250-500 μm. There is a thick polymeric buffer tube, or a buffer jacket, surrounding the fiber and its coating to cushion the fiber against mechanical pressure and microbending (sharp bending). Some fibers are buffered by having the fiber loose within a buffer tube. The tube may then contain a filling compound to increase the buffering ability. Single and multiple fibers are invariably used in cable form and the structure of the cable depends on the application (*e.g.* long-haul communications), the number of fibers carried and the cable environment (*e.g.* underground, underwater, overhead *etc.*).

Preform feed

Preform

Furnace   2000°C

Thickness
monitoring gauge

Polymer coater

Ultraviolet light or furnace
for curing

Take-up drum   Capstan

Glass preform fed into the
fiber drawing furnace.
(Courtesy of Corning.)

Schematic illustration of a fiber drawing tower.

Drift mobility is the **drift velocity** per unit applied field. If μ_d is the drift mobility then the defining equation is $v_d = \mu_d E$ where v_d is the drift velocity and E is the applied electric field.

Drift velocity is the average velocity, over all the conduction electrons in the conductor, in the direction of an applied electrical force ($\mathbf{F} = -e\mathbf{E}$ for electrons). In the absence of an applied field, all the electrons are moving around randomly and the average velocity, over all the electrons, in any direction is zero. With an applied field, E_x, there is a net velocity per electron, v_{dx}, in the opposite direction to the field where v_{dx} depends on E_x via $v_{dx} = \mu_d E_x$ where μ_d is the **drift mobility**.

Edge emitting LEDs (ELED) has the emitted radiation emerging from an area on an edge of the **crystal** *i.e.* from an area on a crystal face perpendicular to the active layer. ELEDs provide a greater intensity light and also a beam that is more collimated than the **surface emitting LEDs**. The light is guided to the edge of the crystal by a *dielectric waveguide* formed by wider bandgap **semiconductors** surrounding a double heterostructure. The **recombination** of injected carriers occurs in the InGaAs **active region** which has a bandgap $E_g \approx 0.83$ eV. Recombination is confined to this layer because the surrounding InGaAsP layers, **confining layers**, have a wider bandgap ($E_g \approx 1$ eV) and the InGaAsP/InGaAs/InGaAsP layers form a double heterostructure. The light emitted in the active region (InGaAs) spreads into the neighboring layers (InGaAsP) which act to contain the light and guide it along the crystal to the edge. InP has a wider bandgap ($E_g \approx 1.35$ eV) and thus a lower **refractive index** than InGaAsP. The two InP layers adjoining the InGaAsP layers therefore act as *cladding layers* and thereby confine the light to the DH structure. Generally some kind of lens system is used to conveniently couple the emitted radiation from an ELED into a fiber. For example, a hemispherical lens attached to the fiber end can be used for collimating the beam into the fiber. **A graded index (GRIN) rod lens** is a glass rod that has a parabolic refractive index profile across

its cross-section with the maximum index on the rod axis. It is like a large diameter short length graded index "fiber" (typical diameters are 0.5 - 2 mm). A **GRIN rod lens** can be used to focus the light from an ELED into a fiber. This coupling is particularly useful for single mode fibers inasmuch as their **core** diameters are typically ~10 μm. The output spectra from surface and edge emitting LEDs using the same semiconductor material is not necessarily the same. The first reason is that the active layers have different **doping** levels. Second is the self-absorption of some of the **photons** guided along the active layer as in ELED. Typically the linewidth of the output **spectrum** from an ELED is less than that from a SLED. In set of experiments, for example, an InGaAsP ELED operating near 1300 nm was observed to have a linewidth of 75 nm whereas the corresponding SLED had a linewidth of 125 nm.
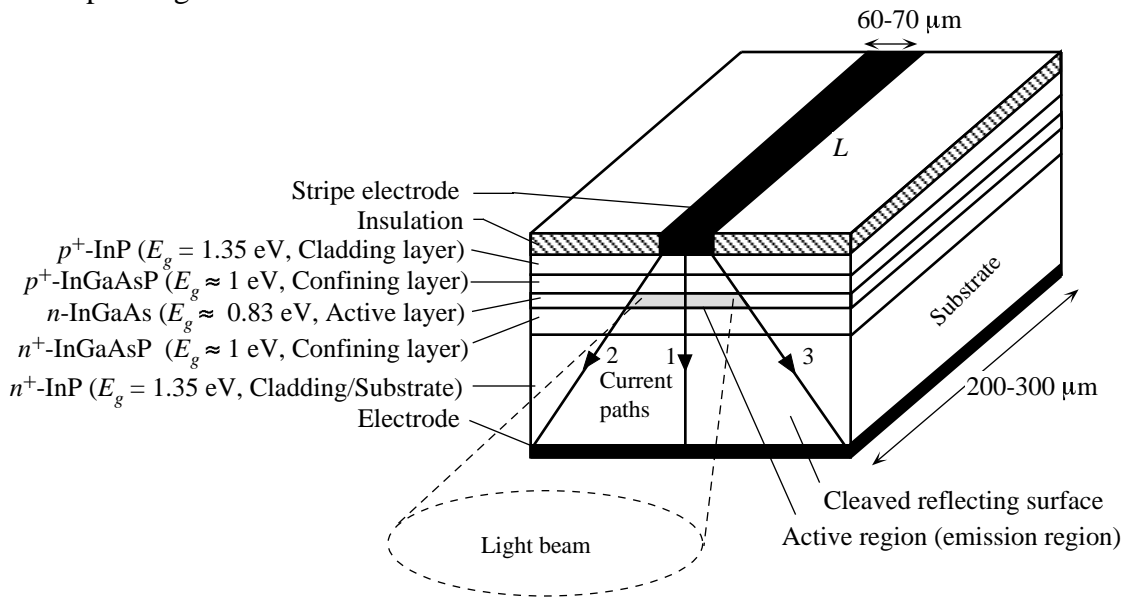
Schematic illustration of the the structure of a double heterojunction stripe contact edge emitting LED
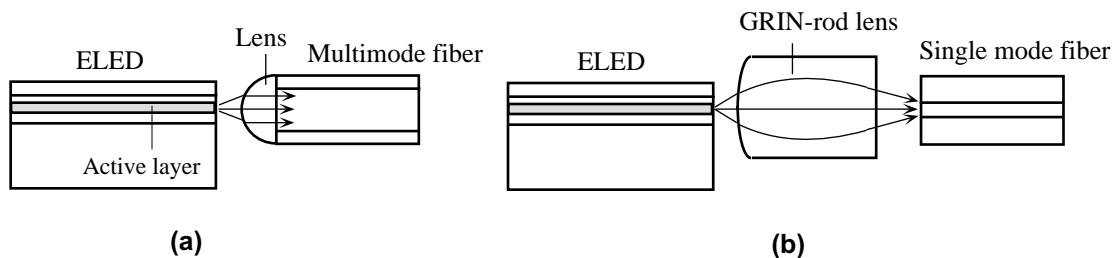
Light from an edge emitting LED is coupled into a fiber typically by using a lens or a GRIN rod lens.

Effective density of states (N_c) at the **conduction band** edge is a quantity that represents all the **states** in the conduction band per unit volume as if they were all at E_c. Similarly N_v which is the effective density of states at the **valence band** edge is a quantity that represents all the states in the valence band per unit volume as if they were all at E_v.

Effective electron mass, $m_e{}^*$, represents the inertial resistance of an electron inside a **crystal** against an acceleration imposed by an external force such as the applied electric field. If $F_{ext} = eE_x$ is the external applied force due to the applied field E_x then the effective mass, $m_e{}^*$, determines the acceleration of the electron by $eE_{x=} m_e{}^* a$. It takes into account the effect of the internal fields on the

motion of the electron. In vacuum where there are no internal fields, m_e^* is obviously the mass in vacuum, m_e. Effective mass of an electron is a quantum mechanical quantity that behaves like the inertial mass in classical mechanics, $F = ma$ in that it measures the objects resistance to acceleration. It relates the acceleration a of an electron in the **conduction band** to the applied external force F_{ext} by $F_{ext} = m_e^* a$. The external force is most commonly the force of an applied electric field, eE_x, and *excludes* all internal forces within the crystal . Similarly the effective mass of a hole in the **valence band** is its inertial mass against acceleration imposed by an external force. We should note that the internal fields depend on the location of the electron and its effect on the motion of the electron can only be determined by solving the **Schrödinger equation** with the appropriate potential energy term V. The effective mass m_e^* depends inversely on the curvature of the E vs. k behavior, *i.e.*

$$m_e^* = \hbar^2 \left[\frac{d^2 E}{dk^2} \right]^{-1}$$

which shows that a high curvature represents a light m_e^* and a broad curvature represents a heavy m_e^*. For example, GaAs E vs. k diagram for the conduction band has a central valley Γ that has a sharp curvature and a satellite valley L that has a small curvature. The electron effective mass is small in Γ but large in L. Consequently the electron **drift mobility**, inversely proportional to the effective mass, is high in Γ and low in L.
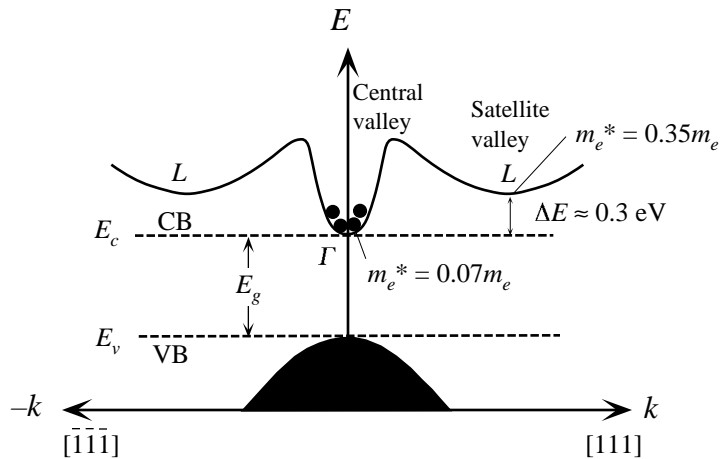
n-type GaAs has the conduction electrons in the central valley at low fields. These have a light effective mass of $0.07m_e$. At sufficiently high fields some of these electrons can be scattered to the satellite valley where they have a heavy effective mass of $0.35m_e$.

Einstein coefficients A_{21}, B_{12} and B_{21} are constants that are used in describing the rates of **spontaneous emission**, **absorption** and **stimulated emission** respectively between two energy levels E_1 and E_2 where $E_2 > E_1$. For example, the rate of spontaneous emission from E_2 and E_1 is proportional to the number of atoms N_2 at E_2 so that spontaneous transition rate is $A_{21}N_2$. The rate of upward transitions from E_1 to E_2 by **photon** absorption is proportional to the number of atoms N_1 at E_1 and also to the number of photons with energy $h\upsilon = E_2 - E_1$ *i.e.* absorption rate is $B_{12}N_1\rho(h\upsilon)$ where B_{12} is the Einstein B_{12} coefficient, and $\rho(h\upsilon)$ is the photon energy density per unit frequency which represents the number of photons per unit volume with an energy $h\upsilon$ ($= E_2 - E_1$). The Einstein coefficients are interrelated. For example, if E_1 and E_2 have the same degeneracy, then $B_{12} = B_{21}$ and $A_{21}/B_{21} = 8\pi h\upsilon^3/c^3$. In the above expressions, h is **Planck's constant**, υ is the radiation frequency, c is the speed of light.

Einstein relation relates the **diffusion coefficient**, D, of a given species of charge carriers to their **drift mobility**, μ, via $D/\mu = kT/q$ where q is the charge of the carrier, k is the Boltzmann constant and T is the temperature (in Kelvin).

Elastic modulus or Young's modulus (*Y*) indicates the ease with which a solid can be elastically deformed. The greater is *Y*, the more difficult it is to elastically deform the solid. When a solid of length *L* is subjected to a tensile **stress**, σ (force per unit area), it will extend elastically by an amount δL. $\delta L / L$ is the **strain**, ε. Stress and strain are related by $\sigma = Y\varepsilon$ so that *Y* is the stress needed per unit elastic strain.

Electric dipole moment exists when a positive charge +*Q* is separated from a negative charge −*Q*. Even though the net charge is zero, there is nonetheless an electric dipole moment, **p**, given by **p** =*Q***x** where **x** is the distance vector from -*Q* to +*Q*. Just as two charges exert a coulomb force on each other, two dipoles also exert a force on each other which depends on the magnitudes of the dipoles, their separation and orientation.

Electric susceptibility (χ_e) is a material quantity that measures the extent of polarization in the material per unit field. It relates the amount of polarization, **P**, at a point in the **dielectric** to the field, **E**, at that point via $\mathbf{P} = \chi_e \varepsilon_o \mathbf{E}$. If ε_r is the relative permittivity then $\chi_e = \varepsilon_r - 1$. Vacuum has no electric susceptibility.

Electrical conductivity (σ) is a property of a material that quantifies the ease with which charges flow inside the material along an applied electric field or a voltage gradient. It is the inverse of electrical resistivity, ρ. Since charge flow is due a voltage gradient, σ is the rate of charge flow through unit area per unit voltage gradient; $J = \sigma E$, where *J* is the current density and *E* is the electric field. The power dissipated as heat per unit volume in a conductor of conductivity σ is given by Joule's law, that is σE^2. In a metal where the conduction electron concentration is *n*, and the electron **drift mobility** is μ, the conductivity is given by $\sigma = en\mu$, where *e* is the electronic charge. In a **semiconductor** there are both electrons in the **conduction band** (CB) and holes in the **valence band** (VB) contributing to electrical conduction and the conductivity is

$$\sigma = en\mu_e, + ep\mu_h,$$

where n is the electron concentration in the CB, p is the hole concentration in the VB, μ_e is the drift mobility of electrons in the CB, and μ_h is the drift mobility of holes in the VB.

Electro-optic effects refer to changes in the **refractive index** of a material induced by the application of an external electric field, which therefore "modulates" the optical properties; the applied field is not the electric field of any light **wave**, but a separate external field. We can apply such an external field by placing electrodes on opposite faces of a crystal and connecting these electrodes to a battery. The presence of such a field distorts the electron motions in the atoms or molecules of the substance, or distorts the crystal structure resulting in changes in the optical properties. For example, an applied external field can cause an optically isotropic crystal such as GaAs to become birefringent. In this case, the field induces **principal axes** and an **optic axis**. Typically changes in the refractive index are small. The frequency of the applied field has to be such that the field appears static over the time scale it takes for the medium to change its properties, that is respond, as well as for any light to cross the substance. The electro-optic effects are classified according to first and second order effects. If we were to take the refractive index *n* to be a function of the applied electric field *E*, that is $n = n(E)$, we can of course expand this as a Taylor series in *E*. The new refractive index *n*′ is

$$n' = n + a_1 E + a_2 E^2 + ...$$

where the coefficients a_1 and a_2 are called the *linear* electro-optic effect and *second* order electro-optic effect coefficients. Although we would expect even higher terms in the expansion of the above equation, these are generally very small and their effects negligible within highest practical fields. The change in *n* due to the first *E* term is called the **Pockels effect.** The change in *n* due to the

second E^2 term is called the **Kerr effect**, and the coefficient a_2 is generally written as λK where K is called the Kerr coefficient. Thus, the two effects are

$$\Delta n = a_1 E$$

$$\Delta n = a_2 E^2 = (\lambda K) E^2$$

All materials exhibit the Kerr effect. It may be thought that we will always find some (non-zero) values for a_1 for all materials but this is not true and only certain crystalline materials exhibit the Pockels effect. If we apply a field **E** in one direction to a crystal and then reverse the field and apply $-$**E** then Δn should change sign. If the refractive index increases for **E**, it must decrease for $-$**E**. Reversing the field should *not* lead to an identical effect (the same Δn). The structure has to respond differently to **E** and $-$**E**. There must therefore be some *asymmetry* in the structure to distinguish between **E** and $-$**E**. In a noncrystalline material, Δn for **E** would be the same as Δn for $-$**E** as all directions are equivalent in terms of **dielectric** properties. Thus $a_1 = 0$ for all noncrystalline materials (such as **glasses** and liquids). Similarly, if the crystal structure has a center of symmetry then reversing the field direction has an identical effect and a_1 is again zero. Only crystals that are **noncentrosymmetric** exhibit the Pockels effect . For example a NaCl crystal (centrosymmetric) exhibits no Pockels effect but a GaAs crystal (noncentrosymmetric) does.

Electromagnetic (EM) wave is a traveling **wave** in which the electric field and **magnetic field** oscillations are at perpendicular to each other and also to the direction of propagation. It is a solution of Maxwell's **wave equation** subject to appropriate boundary conditions. One very simple example is a plane polarized electromagnetic wave that has harmonic electric and magnetic field variations with time and space. Such a wave, if of infinite extent, would be a **monochromatic** EM wave. Suppose that **E** (say E_x) is the electric field and **B** (say B_y) is the magnetic field at one instant at one location (at a particular z). If **k** is the **wavevector**, then **E**, **B** and **k** are all perpendicular in a linear **dielectric** medium (optically isotropic).
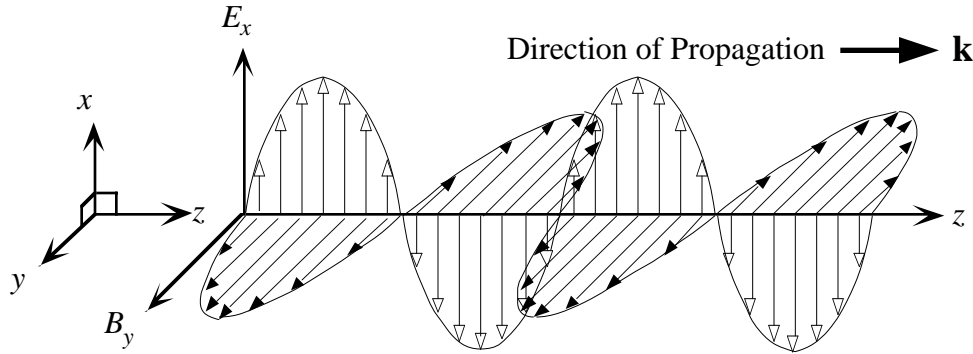
An electromagnetic wave is a travelling wave which has time varying electric and magnetic fields which are perpendicular to each other and the direction of propagation, z.

     The electric and magnetic field components in an EM wave are related. Consider an EM wave propagating along z with electric and magnetic field E_x and E_y. If v is the phase velocity of an EM wave in an isotropic dielectric medium and n is the refractive index, then at all times and anywhere in an EM wave

$$E_x = v B_y = \frac{c}{n} B_y$$

*w*here $v = (\varepsilon_o \varepsilon_r \mu_o)^{-1/2}$ and $n = \sqrt{\varepsilon_r}$. The two fields are simply and intimately related for an EM wave propagating in an isotropic medium. Any process that alters E_x also intimately changes B_y . As the EM wave propagates in the direction of the wavevector **k** as shown in the figure, there is an energy

flow in this direction. The wave brings with it electromagnetic energy. A small region of space in which the electric field is E_x has an energy density, that is, energy per unit volume, given by $(^1/_2)\varepsilon_o\varepsilon_r E_x^2$. Similarly, a region of space where the magnetic field is B_y has an energy density $(^1/_2)B_y^2/\mu_o$. Since the two fields are related, the energy densities in the E_x and B_y fields are the same

$$\frac{1}{2}\varepsilon_o\varepsilon_r E_x^2 = \frac{1}{2\mu_o}B_y^2$$

The total energy density in the wave is therefore $\varepsilon_o\varepsilon_r E_x^2$.

Electromagnetic wave equation is the result of combining **Maxwell's equations** for electromagnetism to obtain a single equation for the space and time dependence of the electric field E or the **magnetic field** in a **dielectric** medium; the solution of this equation is an electromagnetic (EM) wave that propagates with a velocity $v = c/\varepsilon_r^{1/2}$, where ε_r is the relative permittivity. In an isotropic and linear dielectric medium, *i.e.* relative permittivity (ε_r) is the same in all directions and that it is independent of the electric field, the field E must obey *Maxwell's EM wave equation*,

$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + \frac{\partial^2 E}{\partial z^2} = \varepsilon_o\varepsilon_r\mu_o\frac{\partial^2 E}{\partial t^2}$$

where μ_o is the absolute permeability of the medium and ε_o is the absolute permittivity. It is assumed that the conductivity σ is zero. To find the time and space dependence of the field, we must solve Maxwell's equation in conjunction with the initial and boundary conditions.

Electron affinity, χ is the energy required to remove an electron from the bottom of the conduction band E_c to the **vacuum level**.

Electron hole pair (EHP) creation energy gauges the sensitivity of a high energy particle or **X-ray** radiation detector in terms of the energy absorbed from the incident radiation per free electron hole pair that is collected. Stated differently, it is the energy that the material absorbs from the incident beam to generate a free electron and a free hole (or one electron of collected charge in the external circuit). High sensitivity means that the amount of radiation energy required, denoted as W±, to create a single free EHP must be as low as possible because the free (or collectable) charge ΔQ generated from an incident radiation of energy ΔE is simply $e\Delta E/W_\pm$. All experiments on examining the amount of charge generated by high energy particles, including X-rays, have shown that this charge depends on the incident radiation energy, *i.e.* $\Delta Q \propto \Delta E$. This has lead to the introduction of an EHP creation energy ($W_\pm$). The creation of EHPs by an X-ray photon first involves the generation of an energetic primary electron from an inner core shell, for example, the K-shell. As this energetic photoelectron travels in the solid it causes ionizations along its track and hence the creation of many EHPs. For many **semiconductors** the energy $W_\pm$ required to create and electron hole pair has been shown to depend on the energy bandgap E_g via the *Klein rule*

$$W_\pm \approx 2.8E_g + E_{\text{phonon}}.$$

where E_{phonon} is a **phonon** energy term. E_{phonon} is expected to be small (~0.5 eV) so that typically $W_\pm$ is close to $2.8E_g$. Further in many crystalline semiconductors, just like the optical quantum efficiency, $W_\pm$ is field independent and well defined. This $W_\pm$ is so well defined in crystalline semiconductors, such as high purity Ge, ZnCdTe, for example, that they are used in spectrometers to measure the energy of the incident X-rays or high energy charged particles. Que and Rowlands argued that if one relaxes the conservation of **k** rule as required for amorphous semiconductors then the EHP creation energy should be about $2.2E_g + E_{phonon}$ where the latter is again a small phonon energy term.
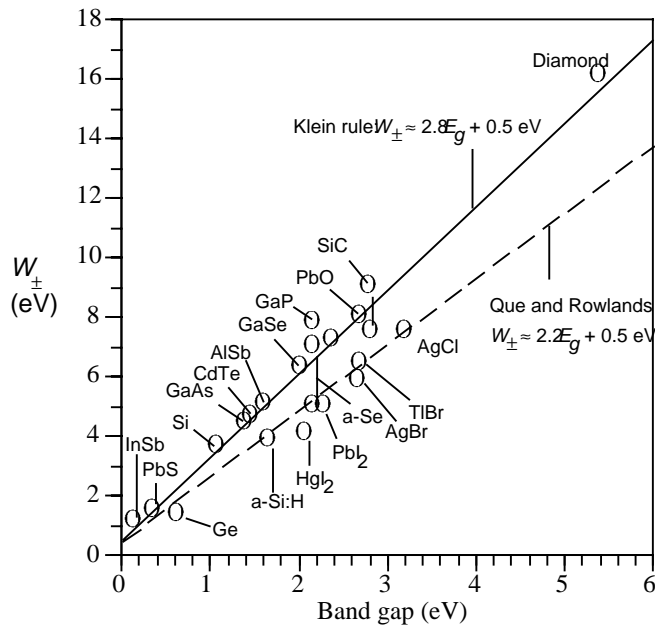
EHP creation energy $W_\pm$ vs energy bandgap for semiconductors (for a-Se $W_\pm$ is field dependent and the value plotted is extrapolated to very large fields so that $W_\pm$ is "intrinsic" or saturated EHP creation energy).

Electronegativity is a relative measure of the ability of an atom to attract electrons to form an anion. **Fluorine** is the most highly electronegative atom as it most easily accepts an electron to become an anion (F⁻). Typically halogens (F, Cl, Br, I) are electronegative elements. In HCl, for example, the Cl atom is more electronegative than the H atom and therefore attracts the electrons more than the H proton. Cl therefore acquires a net negative charge and the hydrogen proton becomes exposed. The molecule therefore has a permanent dipole moment.

Electronic polarization is the displacement of the electron cloud of an atom with respect to the positive nucleus. Its contribution to the relative permittivity of a solid is usually small.

Elliptically polarized, or elliptic light, light has the tip of the **E**-vector trace out an ellipse as the **wave** propagates through a given location in space. As in circular polarization, light can be right and left elliptically polarized depending on clockwise or counterclockwise rotation of the **E**-vector.
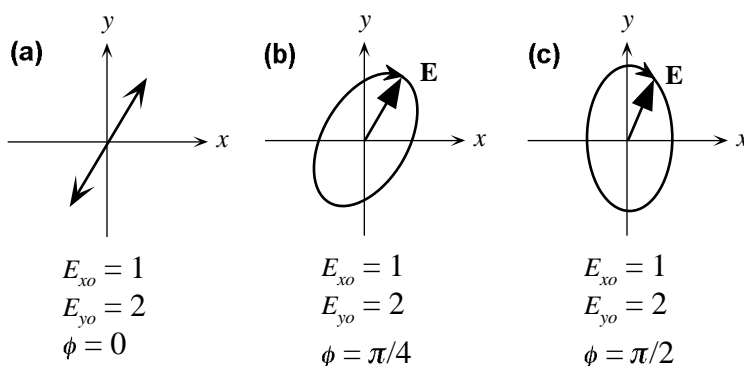
(a) Linearly polarized light with $E_{yo} = 2E_{xo}$ and $\phi = 0$. (b) When $\phi = \pi/4$ (45°), the light is right elliptically polarized with a tilted major axis. (c) When $\phi = \pi/2$ (90°), the light is right elliptically polarized. If E_{xo} and E_{yo} were equal, this would be right circularly polarized light.

Emitter in optoelectronics s a device that emits electromagnetic (EM) radiation, that is **optical power**, such as an LED, **laser diode**, *etc*.

Emitter of a bipolar transistor is one of the two similarly doped (*e.g.* both *n*-type) regions that surrounds the oppositely doped (*p*-type) base and injects **minority carriers** into the base when the emitter-base junction is forward biased.

Energy of the electron in the crystal, whether in the **conduction band** (CB) or **valence band** (VB), depends on its momentum $\hbar k$ through the *E-k* behavior determined by the solutions to **Schrödinger equation** for the particular **crystal** structure (with a particular periodic potential energy). *E-k* behavior is most conveniently represented graphically through *E-k* diagrams. For example, for an electron at the bottom of the CB, *E* increases as $(\hbar k)^2/(2m_e^*)$ where $\hbar k$ is the momentum and m_e^* is the effective mass of the electron which is determined from the *E-k* behavior. The quantity $\hbar k$ is called the **crystal momentum** of the electron because the rate of change of $\hbar k$ is the *external applied force* on the electron, $d(\hbar k)/dt = F_{external}$, and not the actual force which is the sum of external and internal forces. *E-k* diagrams are essentially plots of electron energy vs. crystal momentum of the electron.
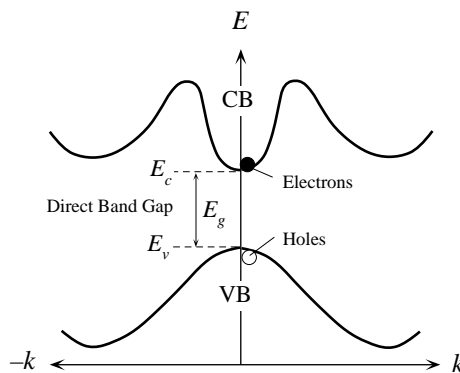
E - k diagram for a direct bandgap semiconductor such as GaAs. The minimum of the CB is directly above the maximum of the VB.

Epitaxial layer is typically a thin layer of near perfect **crystal** grown on a crystalline **substrate** of the same crystal structure (Greek: *epis*-layered and *taxis*-ordered).

Evanescent wave is the **wave** that propagates in a lower **refractive index** medium, along the boundary with a higher refractive index medium, when a wave traveling in the medium of higher refractive index is incident at the boundary at an angle equal to or greater than the **critical angle**. The amplitude of the evanescent wave decreases exponentially with distance from the boundary into the medium with a lower refractive index.

Excess carrier concentration is the excess concentration above the thermal equilibrium value. Excess carriers are generated by an external excitation such as **photogeneration** or applied **bias**.

Excess noise factor (*F*), see **avalanche noise**.

External reflection is the reflection of an **electromagnetic (EM) wave** initially traveling in a medium of lower **refractive index** n_1 at the boundary with a medium of higher refractive index n_2 ($> n_1$); a light **wave** traveling in n_1 is reflected at the boundary n_1-n_2 (some of the energy may however be transmitted). For example, external reflection occurs when a light wave traveling in air is incident on an air-water surface and becomes reflected.

Extinction coefficient *K* represent the attenuation suffered by an electromagnetic wave as it travels along a well-defined propagation direction. It is the imaginary part of the complex refractive index N which is written as $n - jK$. The amplitude of the field in the wave decreases as $E \propto \exp(-k_o K z)$ where k_o is the propagation constant in vacuum.

Extraordinary wave is a **linearly polarized** light wave that propagates in an anisotropic **crystal** without necessarily having the electric field **E** oscillations orthogonal to the **wavevector k**; in ordinary light **E** and **k** are orthogonal. The **E** oscillations do not necessarily lie in the **wavefront** plane. The energy flow direction (the **Poynting vector**) is not along the wavevector direction and this phenomenon is called the Poynting vector "walk-off". The extraordinary and the ordinary waves

have orthogonal **polarizations**.

$\mathbf{S}_e$ = Power flow

$\mathbf{E}_e$ $\mathbf{k}_e$

$\mathbf{k}_e$

Wavefronts (constant phase fronts)
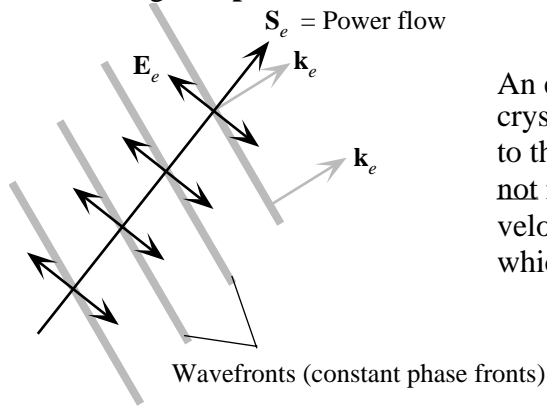
An extraordinary wave in an anisotropic crystal with a wavevector $\mathbf{k}_e$ at an angle to the optic axis. The electric field $\mathbf{E}_e$ is not normal to $\mathbf{k}_e$. The energy flow (group velocity) is along $\mathbf{S}_e$ (the Poynting vector) which is different than $\mathbf{k}_e$.

Extrinsic semiconductor is a **semiconductor** that has been doped so that the concentration of one type of charge carriers far exceeds that of the other. Adding donor impurities releases electrons into the **conduction band** and the concentration of electrons (n) in the conduction band (CB) far exceeds the concentration of holes (p) in the **valence band** (VB) and the semiconductor becomes n-type. When acceptor impurities are added, these acceptors accept electrons from the VB and thereby create holes in the VB so that the hole concentration (p) far exceeds the electron concentration (n); the semiconductor becomes p-type. The **mass action law**, $np = n_i^2$, remains valid in extrinsic semiconductors as long as the semiconductor is in the dark and in thermal equilibrium. Thus, adding donors to increase n concomitantly also decreases p by the same ratio.

CB E_c E_{Fi} E_v VB
(a)

E_c E_{Fn} E_v
(b)

E_c E_{Fp} E_v
(c)
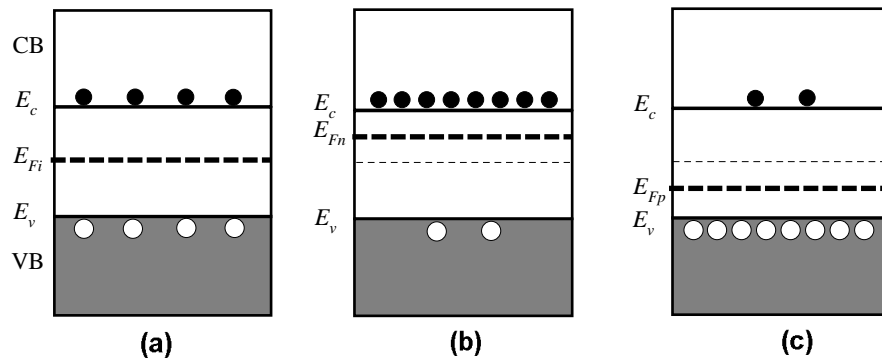
Energy band diagrams for (a) intrinsic (b) n-type and (c) p-type semiconductors. In all cases, $np = n_i^2$. Note that donor and acceptor energy levels are not shown. CB = conduction band, VB = valence band, E_c = CB edge, E_v = VB edge, E_F = Fermi level in intrinsic semiconductor, E_{Fn} = Fermi level in n-type semiconductor, E_{Fp} = Fermi level in p-type semiconductor,

Fabry-Perot laser amplifier, see **optical semiconductor amplifier**.

Fabry-Perot resonator or **etalon,** see **optical resonator.**

Fall time is the time it takes for a pulse (*e.g.* an optical pulse) to fall from its 90% peak value to its 10% peak value.

Far field distribution refers to the field distribution or intensity distribution very far from an aperture or source so that the intensity pattern, by and large, can be examined in terms of its angular dependence (dependence on the distance from the source can be neglected in examining the intensity

distribution).
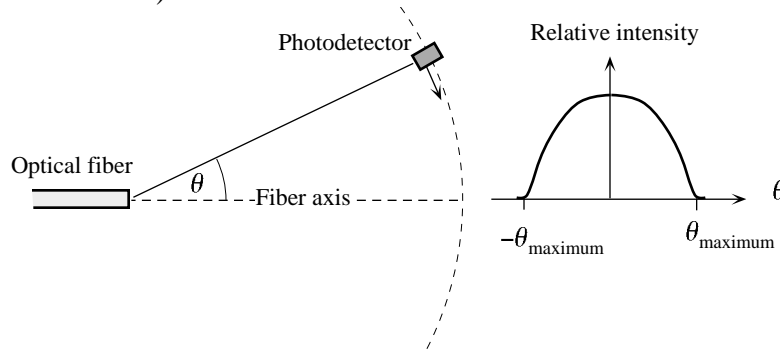
Far field distribuion from an optical fiber

Faraday effect, originally observed by Michael Faraday (1845), is the rotation of the plane of **polarization** of a light **wave** as it propagates through a medium that has been placed in a **magnetic field** that is parallel to the light propagation direction. When an optically inactive material such as **glass** is placed in a strong magnetic field and then a plane polarized light is sent *along* the direction of the magnetic field, it is found that the emerging light's plane of polarization has been rotated. The magnetic field can be applied, for example, by inserting the material into the core of a magnetic coil - a solenoid The induced specific rotatory power (θ/L) has been found to be proportional to the magnitude of applied magnetic field, B. The amount of rotation θ is given by

$$\theta = \vartheta BL$$

where B is the magnetic field (flux density), L is the length of the medium, and ϑ is the so-called *Verdet* constant. It depends on the material and the wavelength. The Faraday effect is typically small. A magnetic field of ~0.1 T causes a rotation of about 1° through a glass rod of length 20 mm. It seems to appear that an "**optical activity**" has been induced by the application of a strong magnetic field to an otherwise optically inactive material. There is however an important distinction between the natural optical activity and the Faraday effect. The sense of rotation θ in the Faraday effect, for a given material (Verdet constant), depends only on the direction of the magnetic field **B**. If ϑ is positive, for light propagating parallel to **B**, the **optical field E** rotates in the same sense as an advancing right-handed screw pointing in the direction of **B**. The direction of light propagation does not change the absolute sense of rotation of θ. If we reflect the wave to pass through the medium again, the rotation increases to 2θ.

Fermi energy (E_F) or level may be defined in several equivalent ways. Fermi level is the energy level corresponding to the energy required to remove an electron from the **semiconductor**; there need not be any actual electrons at this energy level. The energy needed to remove an electron defines the **work function** Φ. We can define the Fermi level to be Φ below the **vacuum level**. E_F can also be defined as that energy value below which all **states** are full and above which all states are empty at absolute zero of temperature. E_F can also be defined through a difference. A difference in the Fermi energy, ΔE_F, in a system is the external electrical work done per electron either on the system or by the system just as electrical work done when a charge e moves through a electrostatic potential energy (PE) difference is $e\Delta V$. It can be viewed as a fundamental material property. In more advanced texts it is referred to as the chemical potential of the semiconductor.

Fermi-Dirac statistics determines the probability of occupancy of a **state** at an energy level E by an electron. It takes into account that when we are considering a collection of electrons, they must obey the **Pauli Exclusion Principle**. The Fermi-Dirac function quantifies this probability via

$$f(E) = \frac{1}{1 + \exp\left(\dfrac{E - E_F}{kT}\right)}$$

where E_F is the **Fermi energy**, k is the **Boltzmann constant** and T is the temperature (Kelvins).
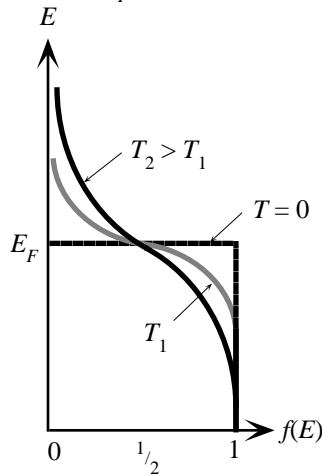
The Fermi-Dirac function. $f(E)$, describes the statistics of electrons in a solid. The electrons interact with each other and the environment so that they obey the Pauili Exclusion Principle.

Field effect transistor (FET) is a transistor whose normal operation is based on controlling the conductance of a channel between two electrodes by the application of an external field. The effect of the applied field is to control the current flow. The current is due to majority carrier drift from the source to the drain and is controlled by the voltage applied to the gate.

Fill factor (FF) is a figure of merit for the **solar cell** that gauges what maximum fraction of the power represented by (short circuit current)×(open circuit voltage), as available as output power deliverable to a load, *i.e.*

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}}$$

where FF is the fill factor, I_m and V_m are the current and voltage corresponding to maximum power transfer to load, and I_{sc} and V_{oc} are the short circuit current and open circuit voltage. It is clearly advantageous to have FF as close to unity as possible but the exponential *pn* junction properties prevent this. Typically FF values are in the range 70-85% and depend on the device material and structure. See **photovoltaic I-V characteristics**.

Filter is a device that allows only certain frequencies (or wavelengths) to pass and others to be blocked. Filters typically have a certain **resonant frequency** υ_o and a **bandwidth** $\Delta\upsilon$ around υ_o such that input (incoming) signals within this $\Delta\upsilon$ are passed.

Finesse of a **Fabry-Perot resonator** is a measure of how fine, *i.e.* narrow, an individual resonant cavity mode is with respect to the separation of two consecutive modes. For a low loss **optical resonator**, it is the ratio of mode separation ($\Delta\upsilon_m$) to **spectral width** ($\delta\upsilon_m$). The narrower the individual mode width and larger the mode separation, the greater is the finesse. Mathematically, the finesse F is defined in terms of the mirror **reflectance** R as

$$F = \frac{\pi R^{1/2}}{1 - R}$$

Finger electrodes, see **photovoltaic devices**

Fluorescence, see **luminescence**.

Fluorine is a gas that is used to dope silica (and thereby introduce F into the SiO_2 glass network) to reduce its **refractive index**.

Fraunhofer diffraction, see **diffraction.**

Free carrier absorption is the attenuation of an electromagnetic (EM) wave as it propagates through a medium in which there are free carriers (*e.g.* electrons). The electric field in the EM wave couples with the free charges in the medium and drifts these carriers, the result of which is a transfer of energy from the EM wave to the medium via the scattering of the free carriers (the so-called σE^2 loss where σ is the conductivity and E is the electric field). Since free carrier absorption represents loss, it contributes to the imaginary part of the relative permittivity ε_r'' by

$$\varepsilon_r'' = \sigma/(\varepsilon_o \omega)$$

where σ is the electrical conductivity and w is the angular frequency of the EM wave. Since the relationship between the attenuation (absorption) coefficient and ε_r'' is $\alpha = (\omega/cn)\varepsilon_r''$, where n is the refractive index, we can represent α in terms of σ as

$$\alpha = \left(\frac{1}{c\varepsilon_o}\right)\frac{\sigma}{n}$$

For example, EM wave absorption in doped semiconductors is more significant than in intrinsic semiconductors.

Frequency division multiplex, see **wavelength division multiplex.**

Fresnel diffraction, see **diffraction.**

Fresnel prism is a prism that converts an incoming unpolarized light into two divergent beams that have opposite circular **polarizations**. Light that enters the right-handed quartz prism (*R*-prism) can be thought as two different circularly polarized **waves**, right circular polarization (*R*-polarization) and left circular polarization (*L*-polarization). These travel with different velocities and experience different refractive indices n_R and n_L, where $n_R < n_L$ so that *R*-polarization propagates faster. In the left-handed quartz prism (*L*-prism) however, the indices are reversed $n_R > n_L$ as *L*-polarization moves faster in *L*-quartz. Thus *R*-polarization wave at the interface experience an increase in n_R and *L*-polarized wave experiences a decreases in n_L. Therefore they have different angles of refraction and hence enter the *L*-prism diverging from each other.
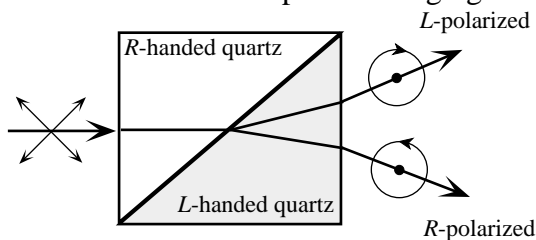
The Fresnel prism for separating unpolarized light into two divergent beams with opposite circular polarizations (*R* = right, *L* = left; divergence is exaggerated)

Fresnel reflection is partial (or full) reflection of an **electromagnetic wave** at a dielectric-dielectric boundary. See **Fresnel's equations**.

Fresnel's equations describe the amplitude and phase relationships between the incident, reflected and transmitted **waves** at a dielectric-dielectric interface in terms of the refractive indices of the two media and the angle of incidence.

(a) $\theta_i < \theta_c$ then some of the wave is transmitted into the less dense medium. Some of the wave is reflected.

(b) $\theta_i > \theta_c$ then the incident wave suffers total internal reflection. However, there is an evanescent wave at the surface of the medium.
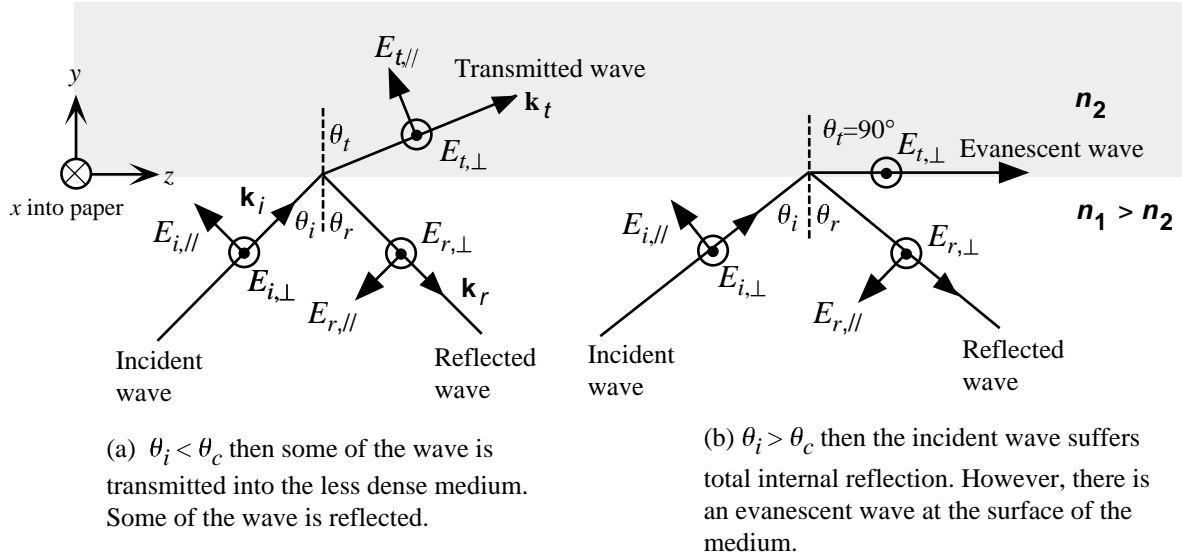
Light wave travelling in a more dense medium strikes a less dense medium. The plane of incidence is the plane of the paper and is perpendicular to the flat interface between the two media. The electric field is normal to the direction of propagation . It can be resolved into perpendicular ($\perp$) and parallel ($//$) components

Consider an electromagnetic (EM)wave going from medium 1 to 2 as illustrated in the figure. The amplitudes of the reflected and transmitted waves can be readily obtained in terms of n_1, n_2 and the incidence angle θ_i alone. If we define $n = n_2/n_1$, as the relative **refractive index** of medium 2 to that of 1, then the **reflection and transmission coefficients** for $E_\perp$ are given by

$$r_\perp = \frac{E_{r0,\perp}}{E_{i0,\perp}} = \frac{\cos\theta_i - \left[n^2 - \sin^2\theta_i\right]^{1/2}}{\cos\theta_i + \left[n^2 - \sin^2\theta_i\right]^{1/2}} \qquad \text{Reflection coefficient}$$

$$t_\perp = \frac{E_{t0,\perp}}{E_{i0,\perp}} = \frac{2\cos\theta_i}{\cos\theta_i + \left[n^2 - \sin^2\theta_i\right]^{1/2}} \qquad \text{Transmission coefficient}$$

There are corresponding coefficients for the $E_{//}$ fields with corresponding **reflection and transmission coefficients**, $r_{//}$ and $t_{//}$,

$$r_{//} = \frac{E_{r0,//}}{E_{i0,//}} = \frac{\left[n^2 - \sin^2\theta_i\right]^{1/2} - n^2\cos\theta_i}{\left[n^2 - \sin^2\theta_i\right]^{1/2} + n^2\cos\theta_i} \qquad \text{Reflection coefficient}$$

$$t_{//} = \frac{E_{t0,//}}{E_{i0,//}} = \frac{2n\cos\theta_i}{n^2\cos\theta_i + \left[n^2 - \sin^2\theta_i\right]^{1/2}} \qquad \text{Transmission coefficient}$$

Further, the above coefficients are related by

$$r_{//} + nt_{//} = 1 \quad \text{and} \quad r_\perp + 1 = t_\perp \qquad \text{Transmission coefficient}$$

Augustin Jean Fresnel (1788 - 1827) was a French physicist, and a civil engineer for the French government, who was one of the principal proponents of the wave theory of light. He made a number of distinct contributions to optics including the well-known Fresnel lens that was used in light houses in the 19th century. He fell out with Napoleon in 1815 and was subsequently put into house-arrest until the end of Napoleon's reign. During his enforced leisure time he formulated his wave ideas of light into a mathematical theory. (Photo: Smithsonian Institution, courtesy of AIP Emilio Segrè Visual Archives.) ("If you cannot saw with a file or file with a saw, then you will be no good as an experimentalist." Augustin Fresnel)

Frustrated total internal reflection (FTIR) occurs when the **optically denser** medium has a finite thickness such that instead of the whole incident beam reflected from the denser medium, some of the incident radiation penetrates this medium and emerges out from the other side. The incident **wave** is partially transmitted through the more dense medium. The intensity of the reflected beam is therefore reduced.

Full width at half maximum (FWHM) is the width on the abscissa between half maximum points of the ordinate. Suppose that y vs. x has a maximum $y = y_{max}$ at $x = x_o$ and then falls to half the maximum value $\frac{1}{2}y_{max}$ at $x = x_2$ and $x = x_1$, where $x_2 > x_o > x_1$. Then FWHM is Δx of y vs. x between the half point $\frac{1}{2}y_{max}$ so that $\Delta x = x_2 - x_1$.

Fundamental mode is the lowest order mode that can exist in a dielectric guide and it is the traveling electric field pattern that has no nodes in the transverse direction to the waveguide axis (nodes are locations where the electric field is zero).

Fusion splicing describes permanently joining two fiber end together by means of heat fusion; melting the fiber ends. The flat ends of the two fibers are aligned and then locally melted (by an electric arc) and fused together to form a continuous fiber.

Gain guided laser is a **laser diode**, such as a **stripe geometry laser diode**, in which the width of the **active region**, or the **optical gain** region, is defined by current density from the smaller electrode to the larger electrode. Optical gain is highest where the current density is greatest. The optical gain width therefore depends on the current density.

Gain is the output signal per unit input signal. For voltages , $G_V = V_{out}/V_{in}$ and for optical signals with power P, usually, $G_{op} = P_{out}/P_{in}$

Gauss's law is a fundamental law of physics (one of **Maxwell's equations**) that relates the surface integral of the electric field over a closed (hypothetical) surface to the sum of all the charges enclosed within the surface. If E_n is the field normal to a small surface area dA and Q_{total} is the enclosed total charge then over the whole closed surface

$$\varepsilon_o \int E_n dA = Q_{total}$$

where the integration is over the whole closed surface. If there is a **dielectric** medium, then we can use

$$\varepsilon_o \varepsilon_r \int E_n dA = Q_{free}$$

where Q_{free} represents the sum of all *free* charges (excluding polarization charges) within the surface. This equation applies to an isotropic medium in which ε_r is independent of the direction of the field.

Gauss's law in point form relates the gradient of the electric field at a point to the charge density ρ at that point, *i.e.* in a one dimensional problem (as through the space charge region of a *pn* junction) the gradient would be *dE/dx*, and

$$\varepsilon_o \varepsilon_r \, dE/dx = \rho_{net}$$

Charges inside the surface

E_n

dA
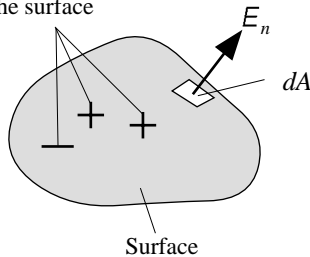
Gauss Law: The surface integral of the electric field normal to the surface is the total charge enclosed. Field is positive if it is coming out, negative if it is going into the surface.

Surface

Gaussian beam is an electromagnetic beam that propagates with a exp$j(\omega t - kz)$ dependence but has an the amplitude that varies spatially away from the beam axis , *i.e. across* the beam, and also *along* the beam axis. The light intensity distribution across the beam cross-section anywhere along *z* is Gaussian. The *beam diameter* 2*w* at any point *z* is defined in such a way that the cross sectional area πw^2 at that point contains 85% of the beam power. Thus the beam diameter 2*w* increases as the beam travels along *z*. A Gaussian beam starts with a finite width $2w_o$ where the **wavefronts** are parallel and then the beam slowly diverges as the wavefronts curve out during propagation along *z*. The finite width $2w_o$ where the wavefronts are parallel is called the *waist* of the beam; w_o is the **waist radius** and $2w_o$ is the **spot size**. Far away from the source, the beam diameter 2*w* increases linearly with distance *z*.
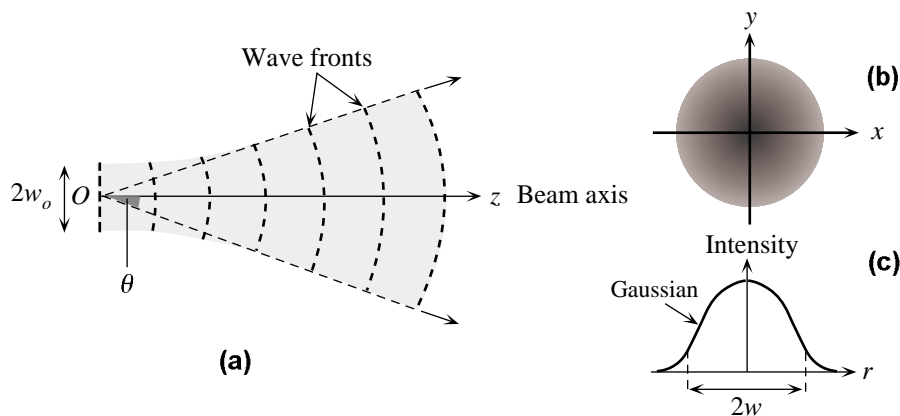
(a) Wavefronts of a Gaussian light beam. (b) Light intensity across beam cross section. (c) Light irradiance (intensity) vs. radial distance *r* from beam axis (*z*).

Germania is germanium dioxide, GeO_2, glass.

Glan-Foucault prism produces a **linearly polarized** light. It is made of two right angle calcite prisms with a prism angle of 38.5°. Both have their optic axes parallel to each other and to the block faces as in the figure. Explain the operation of the prisms and show that the *o*-wave does indeed

experience **total internal reflection**.

Absorber

o-ray

38.5°

e-ray

Calcite

Optic axis

Air-gap
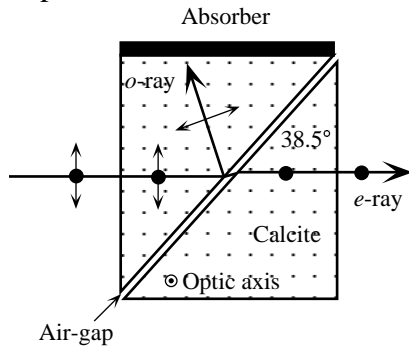
The Glan-Foucault prism provides linearly polarized light

Glass is a term that can be used generically to refer to a *noncrystalline* substance below the glass transition temperature (T_g) or more specifically to a range of inorganic (noncrystalline) materials composed of such oxides as SiO_2, B_2O_3, Na_2O, P_2O_5 *etc*. The glass structure has no long range order of the **crystal**, but exhibits only *short range order*; we can identify the nearest neighbors of an atom because its valency requirements in forming bonds must be satisfied.

● Silicon (or Arsenic) atom   ○ Oxygen (or Selenium) atom

Crystalline and amorphous structures illustrated schematically in two dimensions.

(a) A crystalline solid reminiscent to crystalline SiO_2.(Density = 2.6 g cm^{-3})

(b) An amorphous solid reminiscent to vitreous silica (SiO_2) cooled from the melt (Density = 2.2 g cm^{-3})

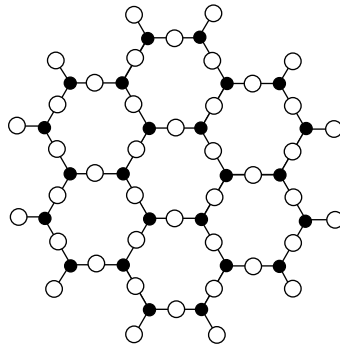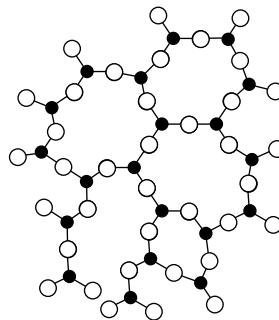**Glass transition (transformation) temperature** T_g is usually a narrow temperature range over which the properties of a material change from solid-like, below T_g, to liquid-like behavior, above T_g. For example, the heat capacity of a **glass** is solid like (small) below T_g and liquid like (high) above T_g. The transition is not always very clear and sometime the distinction between solid-like and liquid-like behavior is made in terms of the **viscosity** of the material. Below the glass transition temperature, the viscosity of the structure is so great that over the time scale of observation there is no significant flow (one may, of course, argue that over thousands of years there may be indeed be a noticeable flow but this will not change our general view of the substance in our lifetime). Any shearing **stress** below T_g results in an elastic response due to the stretching of bonds, and on removal of the stress the glass returns to its original shape. This is a typical solid-like behavior and for all practical purposes we view the structure below T_g as that of a solid. The glass transition temperature is not actually a unique temperature where the liquid on cooling suddenly becomes glass but a temperature range in which the liquid-like behavior gradually changes over to a solid-like behavior as the substance is cooled. It depends not only on the viscosity of the material, which in turn depends on the bonding and structure, but also on the rate of cooling. Clearly, if the cooling is very slow then the atomic arrangements can follow the demands of the cooling rate much more closely and the structure exhibits liquid like behavior to lower temperatures. If the cooling rate is too slow then there may be sufficient time for atomic **diffusions** to form the **crystal**.

Goose-Hänchen shift is the lateral shift of the reflected beam upon being reflected from a boundary with an optically less dense medium. The reflection appears as if it had occurred from a virtual plane

inside the second medium at a distance equal to the **penetration depth** from the interface (Δz in the figure is the Goose-Haenchen shift.)
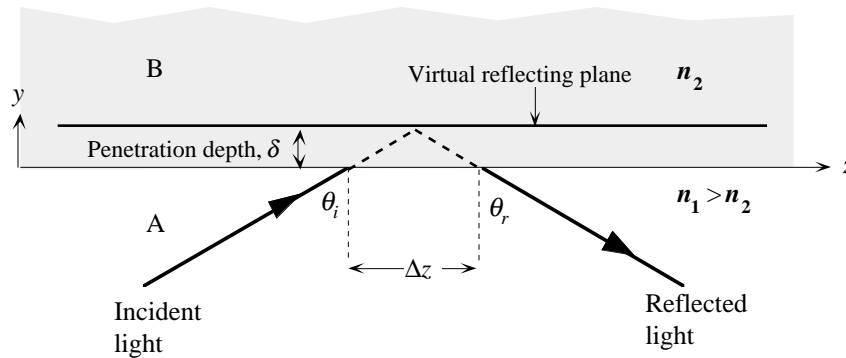
The reflected light beam in total internal reflection appears to have been laterally shifted by an amount Δz at the interface.

Graded index optical fiber has a **core** refractive index that is graded gradually, *i.e.* changes continuously, towards the **cladding**. Typically in a graded index fiber, the **refractive index** profile is approximately parabolic to minimize **modal dispersion** to a virtually inoccuous level . All different mode rays in the graded index fiber arrive at the same time. The intuitive reason for this is that the velocity along the ray path, *c/n*, is not constant and increases as the ray is farther away from the center. A ray such as 2 that has a longer path than ray 1 then experiences a faster velocity during a part of its journey to enable it to catch up with ray 1. Similarly, ray 3, experiences a faster velocity than 2 during part of its propagation to catch up with ray 2 and so on.

(a) Multimode step index fiber. Ray paths are different so that rays arrive at different times.

(b) Graded index fiber. Ray paths are different but so are the velocities along the paths so that all the rays arrive at the same time.
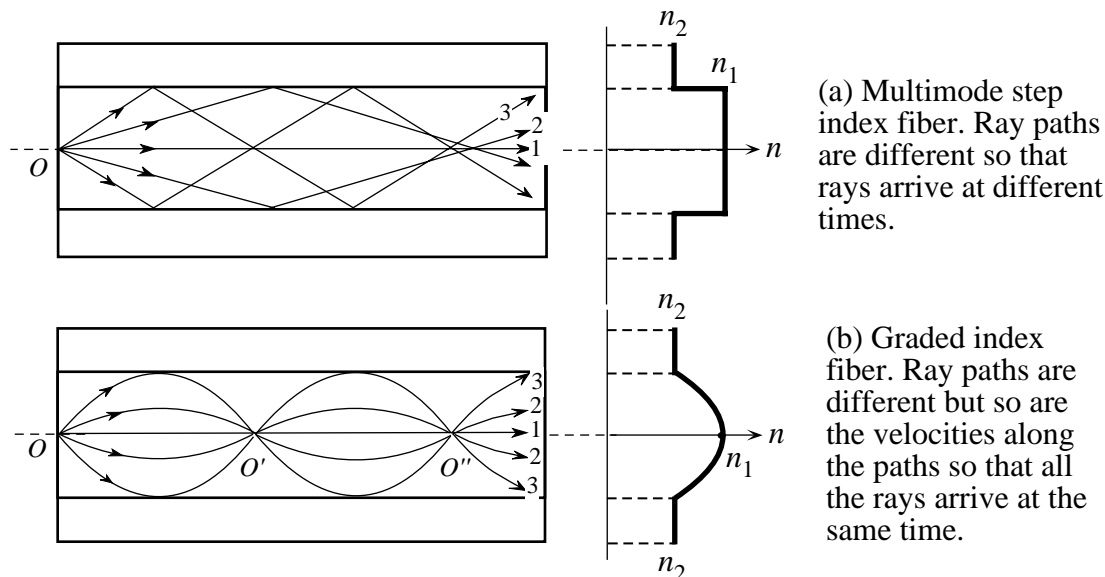
GRIN is an acronym for graded index

GRIN rod lens is a **glass** rod whose **refractive index** is highest at the center, on the rod axis, and then decreases with distance from the rod axis. It is typically used to focus or couple light into a fiber. One pitch (*P*) is a full one period variation in the ray trajectory along the rod axis.

(a)   **(b)**   **(c)**
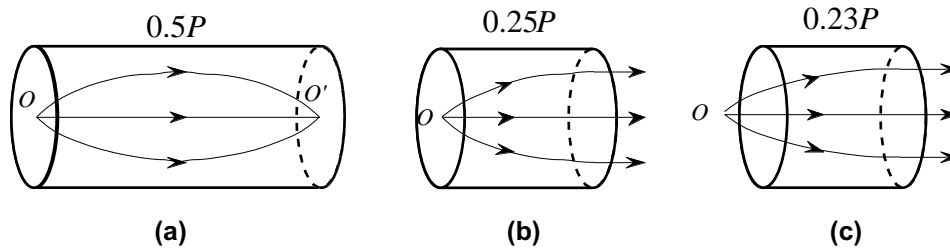
Graded index (GRIN) rod lenses of different pitches. (a) Point O is on the rod face center and the lens focuses the rays onto O' on to the center of the opposite face. (b) The rays from O on the rod face center are collimated out. (c) O is slightly away from the rod face and the rays are collimated out.
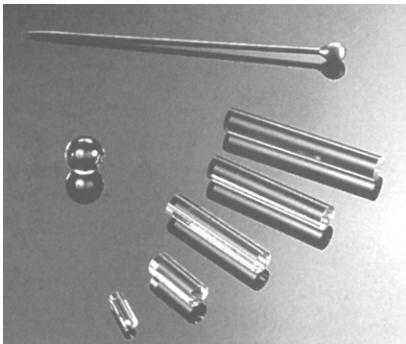
GRIN rod lenses and a spherical lens (a ball lens) used in coupling light into fibers. (Courtesy of Melles Griot.)

Group delay is signal *delay time* per unit distance. The transit time of a light pulse from the input to the output represents a *delay time* in the information being sent. The group delay τ_g is determined by the **group velocity** v_g as it refers to the transit time of signals (energy). If β_{01} is the **propagation constant** of the **fundamental mode** then by definition

$$\tau_g = \frac{1}{v_g} = \frac{d\beta_{01}}{d\omega}$$

Group index (N_g) represent the factor by which the **group velocity** of a group of **waves** in a **dielectric** medium is reduced with respect to propagation in free space, *i.e.* $N_g = v_g/c$ where v_g is the group velocity. The group index can be determined from the ordinary **refractive index** n through

$$N_g = n - \lambda \frac{dn}{d\lambda}$$

Refractive index n and the group index N_g of pure SiO_2 (silica) glass as a function of wavelength.
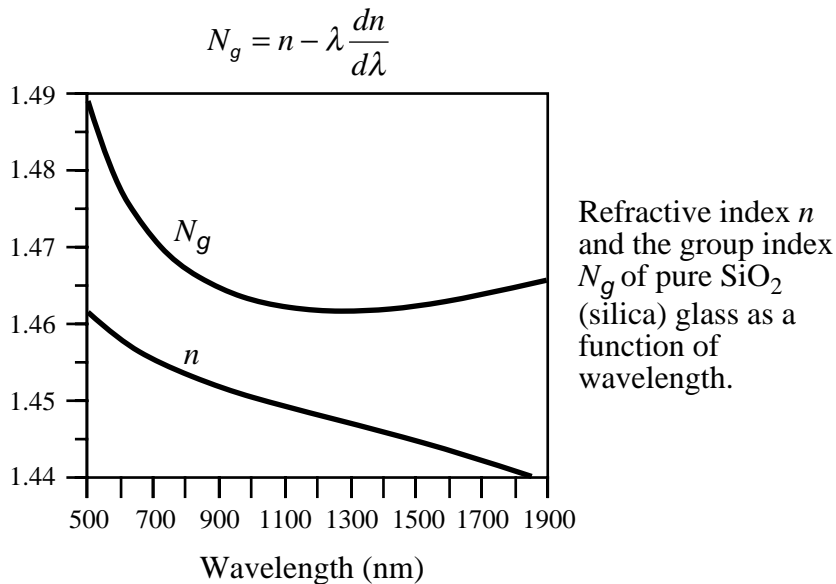
Group velocity (v_g) is the velocity with which a group of **waves** of closely spaced wavelengths (called a wave packet) travel in a medium. It is the velocity with which the energy in the group of waves is propagated in the medium. The group velocity in free space is the same as the velocity of light c in vacuum. Mathematically group velocity is $v_g = d\omega/dk$. Consider the way in which a group of waves differing slightly in wavelength will travel along the z-direction. When two perfectly harmonic waves of frequencies $\omega - \delta\omega$ and $\omega + \delta\omega$ interfere, they generate a *wave packet* which contains an oscillating electric field at the mean frequency ω that is amplitude modulated by a slowly varying field of frequency $\delta\omega$. The maximum amplitude moves with a *group velocity* that is given by

$$v_g = \frac{d\omega}{dk}$$

The group velocity therefore defines the speed with which energy or information is propagated since it defines the speed of the envelope of the amplitude variation. The maximum electric field advances with a velocity v_g whereas the phase variations in the electric field are propagating at the **phase velocity** v.
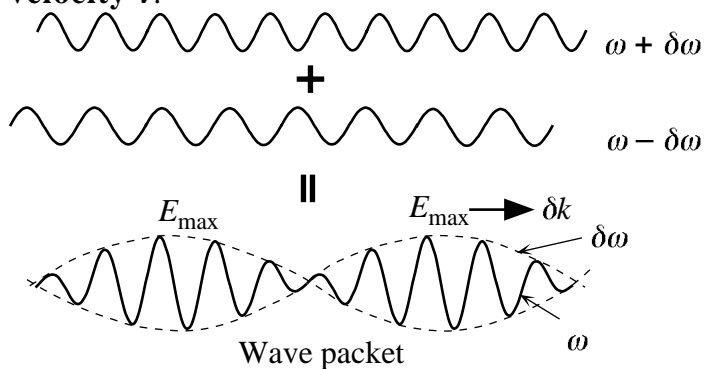
Two slightly different wavelength waves traveling in the same direction result in a wave packet that has an amplitude variation which travels at the group velocity.

Guard ring is an annular region around a *pn* junction to reduce or eliminate undesirable **avalanche breakdown** in the junction periphery; this limits avalanche multiplication to the illuminated region.

Half-wave plate is a retarder plate (made from a birefringent refracting **crystal**) that results in a relative phase change of a half-wave (π) between the **ordinary** and **extraordinary waves** propagating

inside the crystal from entry to exit. A **linearly polarized** light incident with its **E**-field at an angle α to the **optic axis** leaves the crystal with its field rotated by 2α. See **retarding plates.**

He-Ne laser is a gas laser in which he Ne atoms are made to lase by **pumping** them through atomic collisions with He atoms that have been excited by an electrical discharge. The emissions may be in the **infrared** (1523 nm), red (632.8 nm), orange (612 nm), yellow (594.1 nm) or green (543.5 nm). Most popular is the red emitting HeNe laser. Ne is an inert gas whose ground state can be represented in terms of the outer subshell as $(2p^6)$. If one of the electrons from the $2p$ orbital is excited to a $5s$-orbital then the excited configuration $(2p^5 5s^1)$ is a **state** of the Ne atom that has higher energy. Similarly He is also an inert gas which has the ground state configuration of $(1s^2)$. The state of He when one electron is excited to a $2s$-orbital can be represented as $(1s^1 2s^1)$ and has higher energy. The HeNe laser consists of a gaseous mixture of He and Ne atoms in a gas discharge tube. The ends of the tube are mirrored to reflect the stimulated radiation and buildup intensity within the cavity. In other words, an *optical* cavity is formed by the end-mirrors so that reflection of **photons** back into the lasing medium builds up the photon concentration in the cavity; a requirement of an efficient **stimulated emission** process as discussed above. By using dc or RF high voltage, electrical discharge is obtained within the tube which causes the He atoms to become excited by collisions with the drifting electrons. The excitation of the He atom by an electron collision puts the second electron in He into a $2s$ state and changes its spin so that the excited He atom, He*, has the configuration $(1s^1 2s^1)$ with parallel spins which is *metastable* (long lasting) with respect to the $(1s^2)$ state. He* cannot spontaneously emit a photon and decay down to the $(1s^2)$ ground state because the *orbital quantum number l* of the electron must change by ± 1, *i.e.* Δl must be ± 1 for any photon emission or **absorption** process. Further, the emission or absorption of electromagnetic radiation cannot change the electron's spin. If m_s is the *magnetic spin quantum number*, then a radiation emitting transition must have $\Delta m_s = 0$. Thus a large number of He* atoms build up during the electrical discharge because they are not allowed to simply decay back to ground state. When an excited He atom collides with a Ne atom, it transfers its energy to the Ne atom by resonance energy exchange because Ne happens to have an empty energy level, corresponding to the $(2p^5 5s^1)$ configuration, matching that of $(1s^1 2s^1)$ of He*. Thus the collision process excites the Ne atom and de-excites He* down to its ground energy. The excited Ne atom, Ne*, has the $(2p^5 5s^1)$ configuration. With many He*-Ne collisions in the gaseous discharge we end up with a large number of Ne* atoms and a **population inversion** between $(2p^5 5s^1)$ and $(2p^5 3p^1)$ states of the Ne atom. A **spontaneous emission** of a photon from one Ne* atom falling from $5s$ to $3p$ gives rise to an avalanche of stimulated emission processes which leads to a lasing emission with a wavelength 632.8 nm in the red. From the $(2p^5 3p^1)$ energy levels, the Ne atoms decay rapidly to the $(2p^5 3s^1)$ energy levels by spontaneous emission . Most of Ne atoms with the $(2p^5 3s^1)$ configuration, however, cannot simply return to the ground state $2p^6$ by photon emission because the return of the electron in $3s$ requires that its spin is flipped to close the $2p$-subshell. An electromagnetic radiation cannot change the electron spin. Thus the Ne$(2p^5 3s^1)$ energy levels are *metastable* states. The only possible return to the ground state (and for the next repumping act) is by collisions with the walls of the laser tube. We cannot therefore increase the power obtainable from a He-Ne laser by simply increasing the laser tube diameter because that will accumulate more Ne atoms at the metastable $(2p^5 3s^1)$ states.A typical He-Ne laser consist of a narrow **glass** tube which contains the He and Ne gas mixture. The lasing emission intensity (**optical gain**) increases with the tube length since then more Ne atoms are used in stimulated emission. The intensity decreases with increasing tube diameter since Ne atoms in the $(2p^5 3s^1)$ states can only return to the ground state by collisions with the walls of the tube. The ends of the tube are generally sealed with a flat mirror (99.9% reflecting) at one end and, for easy alignment, a concave mirror (99% reflecting) at the other end to obtain an *optical cavity* within the tube. The outer surface of the concave mirror is ground to behave like a convergent lens to compensate for the divergence in the beam arising from reflections from the concave mirror. The output radiation from the tube is typically a beam of diameter 0.5-1 mm and a divergence of 1 milliradians at a power of few milliwatts. In high power He-Ne lasers, the mirrors are external to the tube. In addition, *Brewster windows* are typically used at the ends of the laser

tube to allow only polarized light to be transmitted and amplified within the cavity so that the output radiation is polarized (has electric field oscillations in one plane).Even though we can try to get as parallel a beam as possible by lining up the mirrors perfectly, we will still be faced with **diffraction** effects at the output. When the output laser beam hits the end of the laser tube it becomes diffracted so that the emerging beam is necessarily divergent. Simple diffraction theory can readily predict the divergence angle. Further, typically one or both of the reflecting mirrors in many gas lasers are made concave for a more efficient containment of the stimulated photons within the *active medium* and for easier alignment. The beam within the cavity and hence the emerging radiation is approximately a **Gaussian beam**. Due to their relatively simple construction, He-Ne lasers are widely used in numerous applications such interferometry, for example, accurately measuring distances or flatness of an object, laser printing, **holography**, and various pointing and alignment applications (as in civil engineering).
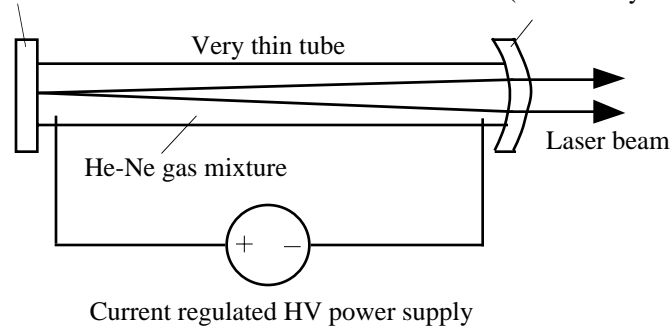
A schematic illustration of the principle of the He-Ne laser. Right: A modern stabilized compact He-Ne laser. (Courtesy of Melles Griot.)
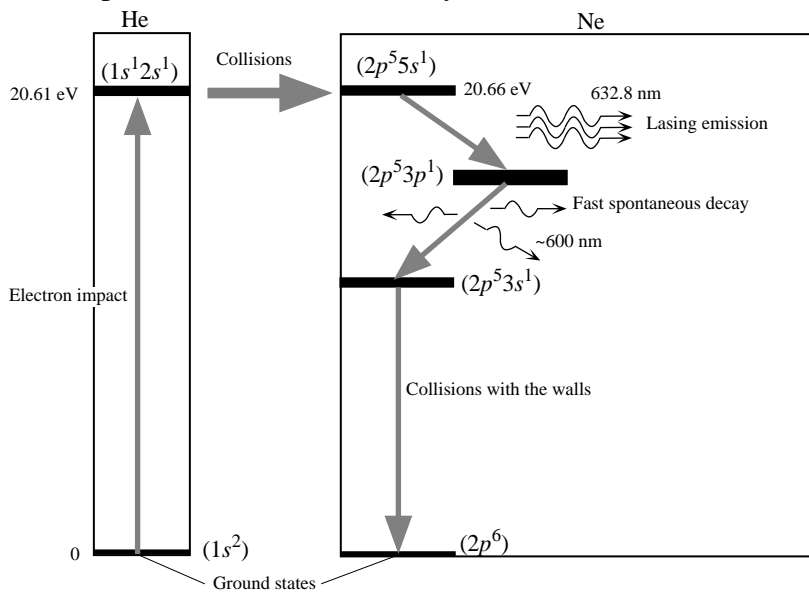
The principle of operation of the He-Ne laser. He-Ne laser energy levels (for 632.8 nm emission).

Hervé-Vandamme relationship, see refractive index

Heterojunction is a **junction** between different **semiconductor** materials, for example between GaAs and AlGaAs **ternary alloy**. There may or may not be a change in the **doping**. The doping in the

wider bandgap semiconductor is denoted with a capital letter *N* or *P*, and that in the narrower bandgap semiconductor with lower case *n* or *p*.

Heterostructure laser diodes have a thin narrower bandgap **semiconductor** layer sandwiched between two wider bandgap semiconductors so that there are two **heterojunctions**. The wider bandgap (E_g) layers provide potential energy steps and hence **carrier confinement** within the narrower E_g layer and also provide a step change in the **refractive index** and hence optical confinement. The sandwiched narrower E_g layer acts as the **active region** in which the electron and hole concentrations are sufficiently high to lead to **stimulated emission**.

Hole (h^+) is a missing electron in an electronic **state** that is in the **valence band**. Intuitively, it is a missing electron in a bond between two neighboring atoms in the semiconductor **crystal**. The region around this "ruptured" bond is a net positive charge of +*e*. It can drift in an applied field because an electron in a neighboring bond can tunnel into this vacant site and thereby cause the positively charge bond-**vacancy** to become displaced, shifted. Thus holes contribute to electrical conduction in **semiconductors** as well. In a full valence band there is no net contribution to the current. There are equal number of electrons (*e.g.* at *b* and *b′*) with opposite momenta. If there is an empty state, *hole*, at *b* at the top of the valence band (VB) then the electron at *b′* contributes to the current. The reason that the presence of a hole makes conduction possible is the fact that the momenta of all the VB electrons are canceled except that at *b′*. Thus, we can consider the net result of the motions of *all* the electrons in the VB just by examining the behavior of the missing electron at *b′* and assigning to it a positive charge +*e* and an effective mass $m_h{}^*$
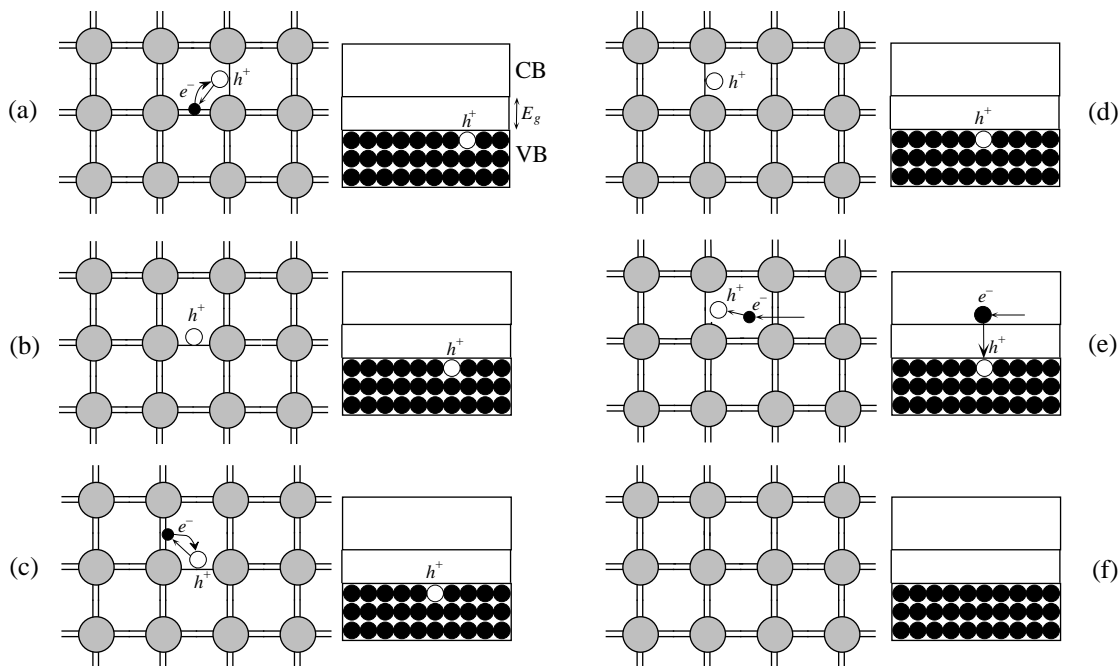
A pictorial illustration of a hole in the valence band wandering around the crystal due to the tunneling of electrons from neighboring bonds.
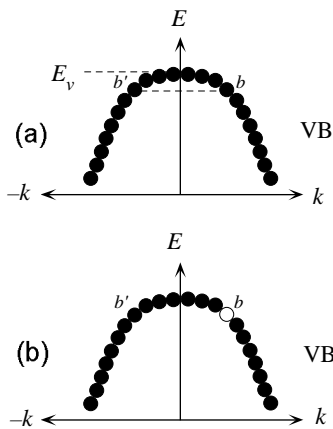
In a full valence band there is no net contribution to the current. There are equal number of electrons (e.g. at b and b') with opposite momenta. (b) If there is an empty state (*hole*) at b at the top of the band then the electron at b' contributes to the current.

Holography is a technique of reproducing three dimensional optical images of an object by using a highly **coherent radiation** from a laser source. The object, *e.g.* a cat, is illuminated by a highly coherent beam as normally would be available from a laser. The laser beam has both *spatial* and **temporal coherence**. Part of the coherent **wave** is reflected from a mirror to form a *reference beam E_{ref}* and travels towards a fine-grained photographic plate. The waves that are reflected from the cat, E_{cat}, will have both amplitude and phase variations that represent the cat's surface (topology). If we were looking at the cat, our eyes would register the **wavefront** of the reflected waves E_{cat}. Moving our head around we would capture different portions of the reflected wave and we would see the cat as a three dimensional object. The reflected waves from the cat (E_{cat}) is made to interfere with the reference wave (E_{ref}) at the photographic plate and give rise to a complicated *interference pattern* that depends on the magnitude and phase variation in E_{cat}. The recorded interference pattern in the photographic film (after processing) is called a *hologram*. It contains all the information necessary to reconstruct the wavefront E_{cat} reflected from the cat and hence produce a three dimensional image. To obtain the three dimensional image, we simply have to illuminate the hologram with the reference beam E_{ref} Most of the beam goes right through but some of it becomes *diffracted* by the interference pattern in the hologram. One diffracted beam is an exact replica of the original wavefront E_{cat} from the cat . The observer sees this wavefront as if the waves were reflected from the original cat and registers a three dimensional image of the cat. This is the *virtual image*. We know that first order

diffraction from a grating has to satisfy the Bragg condition, $d\sin\theta = m\lambda$ ($m = \pm1$) where λ is the wavelength and d is the separation of the slits. We can qualitatively think of a diffracted beam from one locality in the hologram as being determined by the local separation d between interference fringes in this region. Since d changes in the hologram depending on the interference pattern produced by E_{cat}, the whole diffracted beam depends on E_{cat} and the diffracted beam wavefront is an exact scaled replica of E_{cat}. Just as normally there would be another diffracted beam on the other side of the zero-order (through) beam, there is a second image, called the *real image* which is of lower quality. (It may help to imagine what happens if the object consists of black and white stripes. We would then obtain periodic dark and bright interference fringes in the hologram. This periodic variation is just like a **diffraction grating**; the exact analysis is more complicated). Holography is therefore a method of *wavefront reconstruction*.
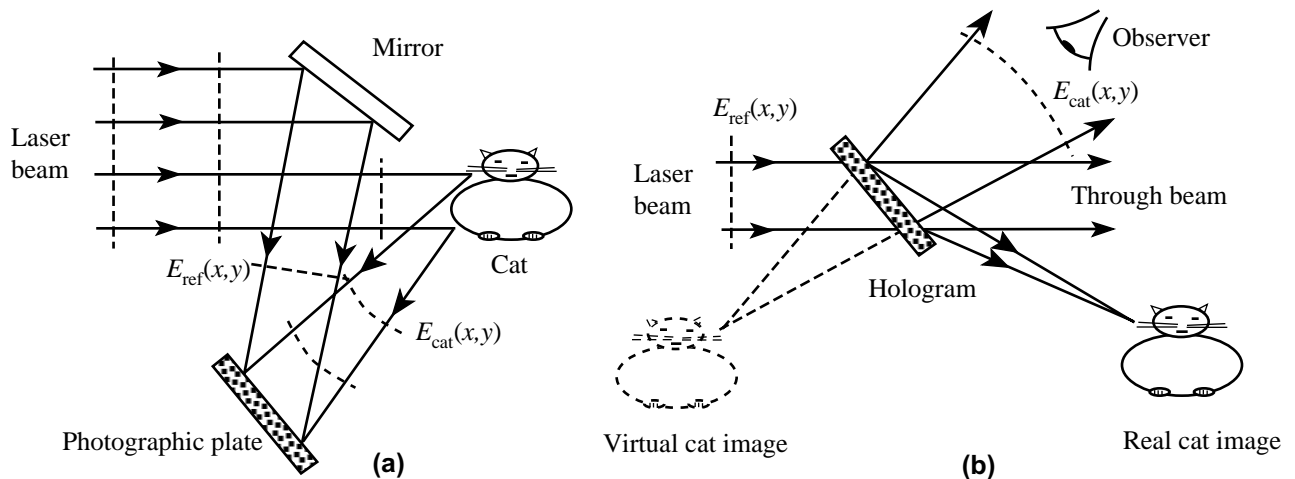
A highly simplified illustration of holography. (a) A laser beam is made to interfere with the diffracted beam from the subject to produce a hologram. (b) Shining the laser beam through the hologram generates a real and a virtual image.

Homojunction is a **junction** between differently doped regions of the same semiconducting material, for example a *pn* junction in the same silicon **crystal**; there is no change in the bandgap energy, E_g.

Hund's rule states that electrons in a given subshell, $n\ell$, try to occupy separate orbitals (different m_ℓ) and keep their spins parallel (same m_s). In doing so they achieve a lower energy than pairing their spins (different m_s) and occupying the same orbital (same m_ℓ). Hund's rule must be consistent with the **Pauli exclusion principle**.

Huygens-Fresnel principle states that every unobstructed point of a **wavefront**, at a given instant in time, serves as a source of spherical secondary waves (with the same frequency as that of the primary wave). The amplitude of the **optical field** at any point beyond is the superposition of all these wavelets (considering their amplitudes and relative phases). See **diffraction.**

Impact ionization is the process by which a high electric field accelerates a free charge carrier (electron in the **conduction band**) which then impacts with a Si-Si bond to generate a free electron hole pair. The impact excites an electron from the **valence band** (E_v) to the conduction band (E_c).

Incandescence is the emission of radiation from a heated object.

Index guided laser diode is a double heterostructure **semiconductor laser** device that has its **active region** defined by a **refractive index** variation to guide the lasing radiation. For example, a *buried double heterostructure diode* has its active region surrounded by high refractive index semiconductor materials so that the **photons** are confined to the active region which acts as an **optical waveguide** or confines the radiation to this region.

Infrared (IR) is radiation with wavelengths that are longer than 700 nm but shorter than 1 mm. Infrared radiation was discovered by *William Herschel* (1738 - 1822) in 1800 in the **spectrum** of the Sun.

ordinary **glass** absorb infrared wavelengths greater than ~2 μm.

Injection (electrode) limited current through a solid occurs when the current flow is limited by the rate at which the electrical contacts can inject carriers into the sample. As the applied field increases, the potential energy barrier against the injection of carriers from the electrode into the sample is lowered by the Schottky effect .

Injection electroluminescence, see **light emitting diode**.

Injection laser diode, see **laser diode**.

Injection pumping is the achievement of **population inversion** in a region of a **semiconductor laser** device by injecting sufficiently large number electrons (in the **conduction band**) and holes (in the **valence band**) by virtue of passing a sufficiently large current.

Insertion loss is an **attenuation** caused by the insertion of a component into a optical transmission system.

Instantaneous irradiance is the instantaneous flow of energy per unit time per unit area and is given by the instantaneous value of the **Poynting vector**, $\mathbf{S} = v^2 \varepsilon_o \varepsilon_r \mathbf{E} \times \mathbf{B}$, where v is the velocity of the **electromagnetic wave** in the medium ($v^2 = c^2/\varepsilon_r$), ε_r is the relative permittivity, $\mathbf{E}$ is the electric field and $\mathbf{B}$ is the **magnetic field**.

Integrated optics refers to the integration of various optical devices and components on a single common **substrate**, for example, lithium niobate, just as in integrated electronics all the necessary devices for a given function are integrated in the same semiconductor **crystal** substrate (**chip**). There is a distinct advantage to implementing various optically communicated devices, *e.g.* **laser diodes**, waveguides, splitters, modulators, photodetectors and so on, on the same substrate as it leads to miniaturization and also to an overall enhancement in performance and usability (typically).

Interband absorption in a direct bandgap semiconductors such as III-V semiconductors (*e.g.* GaAs, InAs, InP, GaP) and in many of their alloys (*e.g.* InGaAs, GaAsSb) is a photon **absorption** process in which there is no assistance from **lattice** vibrations. The **photon** is absorbed and the electron is excited directly from the **valence band** to the **conduction band** without a change in its k-vector (or its **crystal momentum** $\hbar k$) inasmuch as the photon momentum is very small. The change in the electron momentum from the valence band (VB) to the conduction band (CB) is

$$\hbar k_{CB} - \hbar k_{VB} = \text{photon momentum} \approx 0.$$

This process corresponds to a vertical transition on the *E-k* diagram, that is electron energy (E) vs. electron momentum ($\hbar k$) in the **crystal**). The **absorption coefficient** of these **semiconductors** rises sharply with decreasing wavelength from λ_g as for GaAs and InP. *Interband absorption in indirect bandgap* semiconductors such as Si and Ge, is a photon absorption process for photon energies near and above the bandgap (E_g) energy and requires the absorption and emission of lattice vibrations, that is **phonons**, during the absorption process. If K is the **wavevector** of a lattice wave (lattice vibrations travel in the crystal), then $\hbar K$ represents the momentum associated with such a lattice vibration, that $\hbar K$ is a *phonon momentum*. When an electron in the valence band is excited to the conduction band there is a change in its momentum in the crystal and this change in the momentum cannot be supplied by the momentum of the incident photon which is very small. Thus, the momentum difference must be balanced by a phonon momentum:

$$\hbar k_{CB} - \hbar k_{VB} = \text{phonon momentum} = \hbar K.$$

The absorption process is said to be *indirect* as it depends on lattice vibrations which in turn depend on the temperature. Since the interaction of a photon with a valence electron needs a third body, a lattice vibration, the probability of photon absorption is not as high as in a direct transition. Furthermore, the **cut-off wavelength** is not as sharp as for direct bandgap semiconductors.

During the absorption process, a phonon may be absorbed or emitted. If ϑ is the frequency of the lattice vibrations then the phonon energy is $h\vartheta$. The photon energy is hv where v is the photon frequency. Conservation of energy requires that the

$$hv = E_g \pm h\vartheta$$

Thus, the onset of absorption does not exactly coincide with E_g, but typically it is very close to E_g inasmuch as $h\vartheta$ is small (< 0.1 eV). The absorption coefficient initially rises slowly with decreasing wavelength from about λ_g

(a) GaAs (Direct bandgap)　　　　(b) Si (Indirect bandgap)
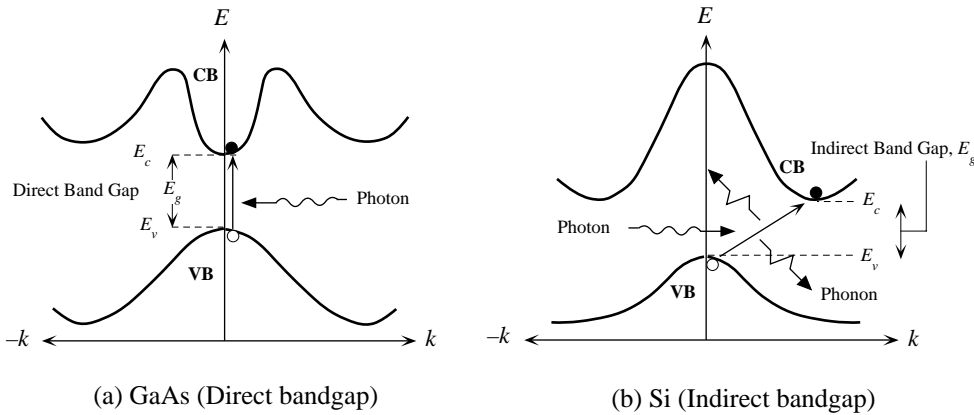
(a) Photon absorption in a direct bandgap semiconductor. (b) Photon absorption in an indirect bandgap semiconductor (VB, valence band; CB, conduction band)

Interference is the interaction of two or more **waves** of the same type (*e.g.* all waves are oscillations of the electric field) that are at the same location. Consider the interference of two **electromagnetic waves** in terms of their electric field oscillations. When the two waves are at the same location, they will interact and the result of the interaction is an instantaneous net electric field $\mathbf{E}$ that is the vector sum of the individual electric fields $\mathbf{E}_1$ and $\mathbf{E}_2$: $\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2$. *Constructive interference* occurs when the two individual waves reinforce each other and the resultant is greater than the individual amplitudes. *Destructive interference* occurs when the two waves have opposite instantaneous vector fields (*i.e.* oppositely directed fields) so that the net resultant is zero if the individual waves have the same amplitude.

Interferometer is an optical instrument that uses the wave-interference phenomena to produce interference fringes (*e.g.* bands, rings) which can be used to measure the wavelength of light, surface flatness or small distance *etc.*, In the *Fabry-Perot interferometer*, a broad monochromatic source is incident on a Fabry-Perot etalon and the transmitted **waves** are focused onto a screen using a lens. The interference fringes consist of bright and dark rings. The ring diameter depends on the wavelength and the optical separation (**refractive index** × distance) of the plates of the etalon. If θ is the angle that a bright ring makes with the axis of the etalon-lens system passing through the center of the rings, then the interferometer bright rings are determined by **constructive interference** as determined by

$$2nL\cos(\theta) = m\lambda,$$

where L is the separation of the faces of the etalon, n is the refractive index of the material within the

etalon, λ is the frefe-space wavelength, (**wavevector** $k = 2\pi/\lambda$) and m is the integer, 1,2,….
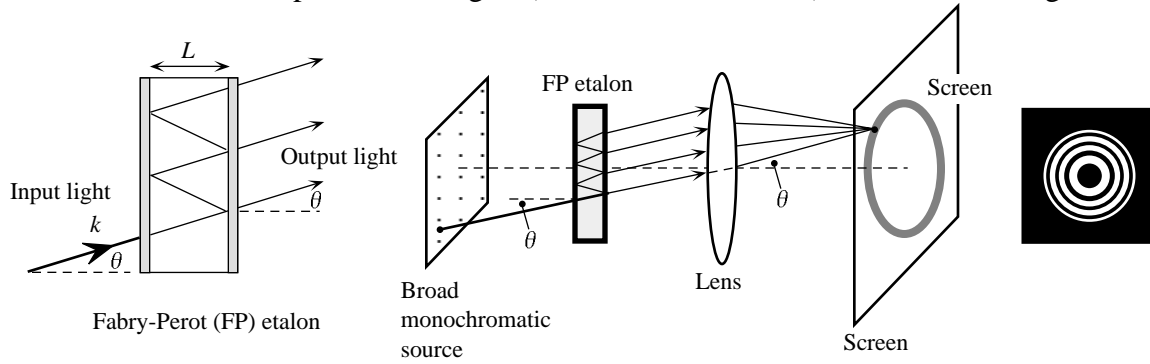
Fabry-Perot optical resonator and the Fabry-Perot interferometer (schematic)

Internal quantum efficiency (η_{int}) **of a light emitting diode** gauges what fraction of electron hole **recombinations** in the forward biased *pn* junction are radiative and therefore lead to **photon** emission. **Nonradiative transitions** are those in which and electron and a hole recombine through a **recombination center** such as a **crystal** defect or an impurity and emit **phonons** (**lattice** vibrations). By definition,

$$\eta_{\text{int}} = \frac{\text{Rate of radiative recombination}}{\text{Total rate of recombination (radiative and nonradiative)}}$$

or
$$\eta_{\text{int}} = \frac{\dfrac{1}{\tau_r}}{\dfrac{1}{\tau_r} + \dfrac{1}{\tau_{nr}}}$$

where τ_r is the mean lifetime of a **minority carrier** before it recombines radiatively and τ_{nr} is the mean lifetime before it recombines via a recombination center without emitting a photon. The total current I is determined by the total rate of recombinations whereas the number of photons emitted per second (Φ_{ph}) is determined by the rate of radiative recombinations. Thus,

$$\eta_{\text{int}} = \frac{\text{Photons emitted per second}}{\text{Total carriers lost per second}} = \frac{\Phi_{ph}}{I/e} = \frac{P_{op(\text{int})}/h\upsilon}{I/e}$$

where $P_{op(\text{int})}$ is the **optical power** generated internally (not yet extracted), e is the electronic charge, and $h\upsilon$ is the photon energy.

Internal quantum efficiency of a photodetector is the number of free electron hole pairs photogenerated per *absorbed photon* ; this is not per incident photon on the device. Inasmuch as internal quantum efficiency is defined in terms of per absorbed photon, it is greater than external quantum efficiency which is defined in terms of per incident photon; not all incident photons are absorbed.

Internal reflection is the reflection of an **electromagnetic (EM) wave** initially traveling in a medium of high **refractive index** n_1 at the boundary with a medium of lower refractive index n_2 $(< n_1)$; a light **wave** traveling in n_1 is reflected at the boundary n_1-n_2 (some of the energy may however be transmitted). For example, internal reflection occurs when a light wave traveling in water is incident on the water-air surface and becomes reflected.

Intramodal or intramode dispersion describes the temporal spread of a propagating optical pulse in a fiber when the propagation is through a single mode (and hence intramode) and the dispersion arises because the guide properties force different frequencies present in the optical pulse to travel with different group velocities. Put differently, the input signal into an optical guide has a range of

frequencies or wavelengths and these propagate with different group velocities and arrive at different times at the destination. The cause is the nonlinear ω vs. β **dispersion diagram** of the guide. Intramode dispersion can be broken into **material dispersion**, **waveguide dispersion** and **profile dispersion**.

Intrinsic carrier concentration (n_i) is the electron concentration in the **conduction band** of an **intrinsic semiconductor** (an ideal perfect **crystal** that has not been doped). The hole concentration in the **valence band** is equal to the electron concentration. The intrinsic concentration is a material property that depends on the energy bandgap E_g and the temperature and can be written as

$$n_i^2 = N_c N_v \exp(-E_g/kT)$$

where N_c and N_v are the effective densities of states at the conduction and valence band edges, E_g is the bandgap, k is the **Boltzmann constant** and T is the absolute temperature.

Intrinsic semiconductor has equal number of electrons and holes due to thermal generation across the bandgap, E_g. It corresponds to a pure semiconductor **crystal** in which there are no impurities and crystal defects to cause an effective **doping** of the crystal.

Inversion layer is a region in the **semiconductor laser** device in which there is a **population inversion** (more **stimulated emission** than **absorption**) due to the presence of sufficiently large number of injected electrons and holes brought in by the **diode** current. Holes represent empty electron **states** in the **valence band** and electrons occupy states in the **conduction band**.

Ionization is a process that either removes an electron or adds an electron to an atom or a molecule which results in the creation of an ion (an atom or a molecule with a net charge). Ionization of an atom or a molecule can occur by a collision with a projectile particle (*e.g.* a projectile electron) with a sufficient energy, by an **absorption** of a **photon** with the right energy, or by an application of a very large electric field.

Irradiance (average) is the average flow of energy per unit time per unit area where averaging is typically carried out by the light detector (over many oscillation periods). Average irradiance can also be defined mathematically by the average value of the **Poynting vector** $\mathbf{S} = v^2 \varepsilon_o \varepsilon_r \mathbf{E} \times \mathbf{B}$ over one period; $S_{\text{average}} = \frac{1}{2} c \varepsilon_o n E_o^2$ where E_o is the amplitude of the electric field, c is the speed of light, ε_r is the relative permittivity, n is the **refractive index** ($\varepsilon_r^{1/2}$), $\mathbf{E}$ is the electric field and $\mathbf{B}$ is the **magnetic field**. The **instantaneous irradiance** can only be measured if the power meter can respond more quickly than the oscillations of the electric field, and since this is in the optical frequencies range, all practical measurements invariably yield the average irradiance because all detectors have a response rate much slower than the frequency of the **wave**.

Jones Matrices represent the state of **polarization** of a light **wave**. Various operations on the polarization state correspond to multiplying this matrix with another matrix that represents the optical operation. Consider a light wave traveling along z with field components E_x and E_y along x and y. These components are orthogonal and, in general, would be of different magnitude and have a phase difference ϕ between them . If we use the exponential notation then

$$E_x = E_{xo} \exp[j(\omega t - kz + \phi_x)] \quad \text{and} \quad E_y = E_{yo} \exp[j(\omega t - kz + \phi_y)]$$

Jones matrix is a column matrix whose elements are E_x and E_y without the common $\exp j(\omega t - kz)$ factor

$$\mathbf{E} = \begin{bmatrix} E_x \\ E_x \end{bmatrix} = \begin{bmatrix} E_{xo} \exp(j\phi_x) \\ E_{yo} \exp(j\phi_y) \end{bmatrix}$$

Usually this equation is normalized by dividing the total amplitude $E_o = (E_{xo}^2 + E_{yo}^2)^{1/2}$. We can further factor out $\exp(j\phi_x)$ to further simplify to obtain the Jones matrix

$$\mathbf{J} = \frac{1}{E_o} \begin{bmatrix} E_{xo} \\ E_{yo} \exp(j\phi) \end{bmatrix}$$

where $\phi = \phi_y - \phi_x$. For example a **linearly polarized** light that is 45° to the x-axis is

$$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

Passing a wave of given Jones vector $\mathbf{J}_{in}$ through an optical device is represented by multiplying $\mathbf{J}_{in}$ by the *transmission matrix* $\mathbf{T}$ of the device. If $\mathbf{J}_{out}$ is the Jones vector for the output light through the device, then $\mathbf{J}_{out} = \mathbf{T} \, \mathbf{J}_{in}$.

Junction is a plane in a **crystal** which has differently doped materials, such as *p*-type and *n*-type **semiconductors**) on opposite sides.

Kerr effect is a second order electro-optic effect in which an applied strong electric field modifies the **refractive index** in such a way that the refractive index change is proportional to the square of the applied field. For example, when a strong field is applied to an otherwise optically isotropic material such as **glass** (or liquid), the change in the refractive index will be due only to the Kerr effect, since such materials exhibit no **Pockels effect**. If E_a is the applied field, then the change in the refractive index for **polarization** parallel to the applied field is given by

$$\Delta n = \lambda K E_a^{\,2}$$

where K is the Kerr coefficient. Suppose that we arbitrarily set the *z*-axis of a Cartesian coordinate system along the applied field. The applied field distorts the electron motions (orbits) in the constituent atoms and molecules, including those valence electrons in covalent bonds, in such a way that it becomes "more" difficult for the electric field in the light **wave** to displace electrons parallel to the applied field direction. Thus a light wave with a polarization parallel to the *z*-axis will experience a smaller refractive index, reduced from its original value n_o to n_e. A light waves with polarizations orthogonal to the *z*-axis will experience the same refractive index n_o. The applied field thus induces birefringence with an **optic axis** parallel to the applied field direction. The material becomes birefringent for waves traveling off the *z*-axis. The polarization modulator and intensity modulator concepts based on the Pockels cell can be extended to the Kerr effect. In the Kerr case, the applied field again induces birefringence. The Kerr phase modulator uses the fact that the applied field along *z* induces a refractive index n_e parallel to the *z*-axis whereas that along the *x*-axis will still be n_o. The light components $\mathbf{E}_z$ and $\mathbf{E}_z$ then travel along the material with different velocities and emerge with a phase difference $\Delta\phi$ resulting in an **elliptically polarized** light. However, the Kerr effect is small as it is a second order effect, and therefore only accessible for modulation use at high fields. The advantage, however, is that, all materials, including glasses and liquids, exhibit the Kerr effect and the **response time** in solids is very short, much less than nanoseconds leading to high modulation frequencies (greater than GHz). See also **electro-optic effects**.
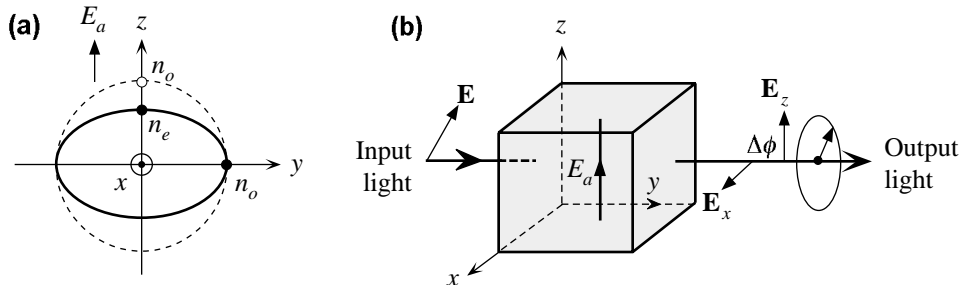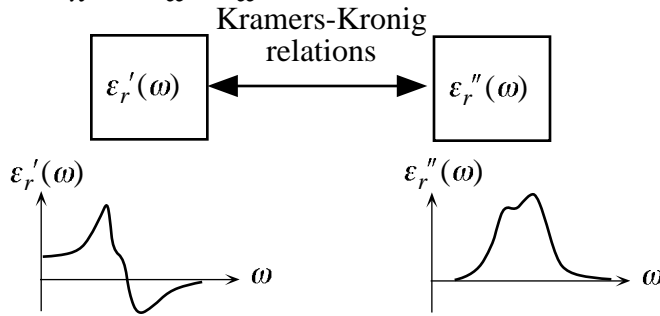

(a) An applied electric field, via the Kerr effect, induces birefringences in an otherwise optically istropic material. n_o and n_e are the ordinary and extraordinary refractive indices (b) A Kerr cell phase modulator.

Kramers-Kronig relations relate the frequency dependence of the real part of the relative permittivity $\varepsilon_r'(\omega)$ to the frequency dependence of the imaginary part. $\varepsilon_r''(\omega)$. If we know the frequency dependence of the real part ε_r' of the relative permittivity of a material, we can also determine the frequency dependence of the imaginary part ε_r''; and vice versa. This may seem remarkable but it is true provided that we know the frequency dependence of either the real or imaginary part over as wide a range of frequencies as practically possible (ideally from dc to infinity) and the material is *linear*, *i.e.* it has a relative permittivity that is independent of the applied field; the polarization response must be linearly proportional to the applied field. Similarly one can relate the real and imaginary parts of the polarization, $\alpha'(\omega)$ and $\alpha''(\omega)$, and the real and imaginary parts of the complex refractive index, $n(\omega)$ and $K(\omega)$. For example, Kramers-Kronig relations for the relative permittivity are

$$\varepsilon_r'(\omega) = 1 + \frac{2}{\pi} P \int_0^\infty \frac{\omega' \varepsilon_r''(\omega')}{\omega'^2 - \omega^2} d\omega' \qquad \text{and} \qquad \varepsilon_r''(\omega) = -\frac{2\omega}{\pi} P \int_0^\infty \frac{\varepsilon_r'(\omega')}{\omega'^2 - \omega^2} d\omega'$$

where P represents the Cauchy principal value of the integral and the singularity at $\omega = \omega'$ is avoided. For $\alpha'(\omega)$ and $\alpha''(\omega)$,

$$\alpha'(\omega) = \frac{2}{\pi} P \int_0^\infty \frac{\omega' \alpha''(\omega')}{\omega'^2 - \omega^2} d\omega' \qquad \text{and} \qquad \alpha''(\omega') = -\frac{2\omega}{\pi} P \int_0^\infty \frac{\alpha'(\omega')}{\omega'^2 - \omega^2} d\omega'$$

Kramers-Kronig relations allow frequency dependences of the real and imaginary parts of the relative permittivity to be related to each other. The material must be a linear system.

Laser diode equation relates the output **optical power** P_o to the diode current density J (or current I) above the **threshold current** density J_{th}. In simple terms,

$$P_o = \left[\frac{hc^2 \tau_{ph} W(1-R)}{2en\lambda} \right] (J - J_{th})$$

where R is the **reflectance** of the optical cavity reflectors, n is the **refractive index**, λ is the wavelength, W is the width of the **active region** and τ_{ph} is the **photon** decay time in the cavity; the power in a light **wave**, in the absence of amplification, decreases as $\exp(-\alpha_t x)$ which is equivalent to a decay in time as $\exp(-t/\tau_{ph})$ where $\tau_{ph} = n/(c\alpha_t)$ and α_t is the total **attenuation** coefficient

representing all these loss mechanisms.
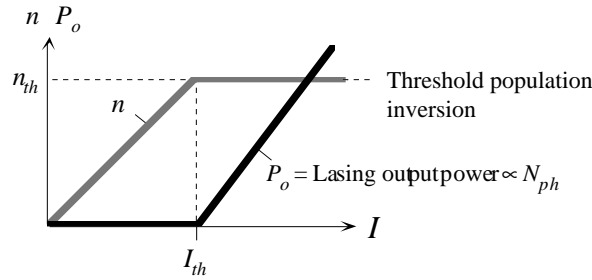
Simplified and idealized description of a semiconductor laser
diode based on rate equations. Injected electron concentration
n and coherent radiation output power P_o vs. diode current I.

Laser diode external differential quantum efficiency η_{EDQE}, of a **laser diode** is defined as

$$\eta_{EDQE} = \frac{\text{Increase in number of output photons from diode (per unit second)}}{\text{Increase in number of injected electrons into diode (per unit second)}} = \left(\frac{e}{E_g}\right)\frac{dP_o}{dI}$$

where P_o is the emitted **optical power**, E_g is the bandgap of the **active region** semiconductor and I is the diode current.

Laser diode external power efficiency η_{EPE}, of the **laser diode** is defined by

$$\eta_{EPE} = \frac{\text{Optical output power}}{\text{Electical input power}} = \eta_{EQE}\left(\frac{E_g}{eV}\right)$$

where η_{EQE} is the laser diode external quantum efficiency , E_g is the bandgap of the **active region** semiconductor and V is the diode voltage.

Laser diode external quantum efficiency η_{EQE}, is defined as

$$\eta_{EQE} = \frac{\text{Number of output photons from the diode (per unit second)}}{\text{Number of injected electrons into diode (per unit second)}} = \frac{eP_o}{E_g I}$$

where P_o is the emitted **optical power**, E_g is the bandgap of the **active region** semiconductor and I is the diode current.

Laser diode is a semiconductor diode which emits **coherent radiation** in contrast to an LED (**light emitting diode**) which emits incoherent radiation. Laser diodes operate on the principle of **stimulated emission** resulting from electron hole pair injection and **photon** induced direct **recombination** under forward bias.

Laser diode output vs current characteristics typically refer to the lasing output power vs. diode current characteristics at various temperatures. Above the **threshold current** (I_{th}), the **optical power** in the lasing emission increases sharply with the diode current and, to a first order, the optical power is proportional to the diode current above the threshold value ($I - I_{th}$).

P_o (mW)
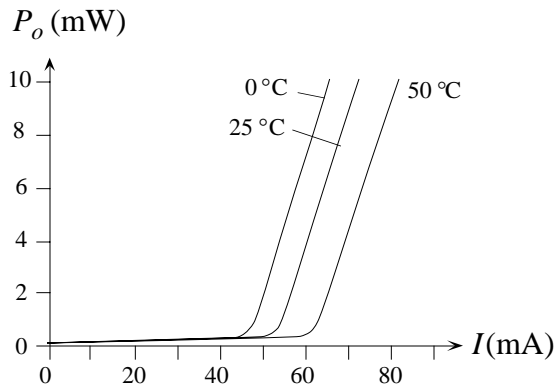
Output optical power vs. diode current as three different temperatures. The threshold current shifts to higher temperatures.

Laser modes are distinct electric field patterns that are allowed by the active **optical resonator** structure of a **laser diode**. The output **spectrum** from a laser diode (LD) depends on two factors: the nature of the optical resonator used to build the **laser oscillations** and the **optical gain** curve (lineshape) of the active medium. The optical resonator is essentially a Fabry-Perot cavity which can be assigned a length (L), width (W) and height (H). The length L determines the *longitudinal mode* separation whereas the width W and height H determine the transverse modes, or *lateral modes* in LD nomenclature. If the transverse dimensions (W and H) are sufficiently small, only the lowest transverse mode, TEM_{00} mode, will exit. This TEM_{00} mode however will have longitudinal modes whose separation depends on L.
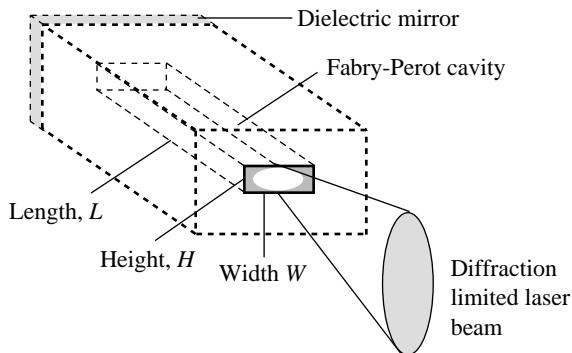
The laser cavity definitions and the output laser beam characteristics.

Laser oscillations occur in a laser device when the it has achieved lasing emission, that is, there are sustainable electromagnetic oscillations in the laser optical cavity as a result of **optical gain** (from **stimulated emissions**) which overcomes the cavity losses.

Laser output spectrum refers to the **spectral intensity** vs. wavelength characteristics of the laser beam. The output **spectrum** is the result of the broadening of the **optical gain** curve of the lasing medium and the requirement that the optical cavity can only sustain certain wavelengths. For simplicity, consider a gas laser. The frequency of the emitted radiation from the gas atoms is broadened around the stimulated emission transition frequency υ_o due to the **Doppler effect**. Consequently, the optical gain of the medium vs. frequency characteristic is also broadened. We recall from the kinetic molecular theory that gas atoms are in random motion with an average kinetic energy of $^3/_2 k_B T$ (k is the **Boltzmann constant** and T is temperature). Suppose that these gas atoms emit radiation of frequency υ_o which we label as the source frequency. Then, due to the Doppler effect, when a gas atom is moving *away* from or *towards* an observer, the latter detects a

lower or higher frequency υ_1 or υ_2 respectively given by

$$\upsilon_1 = \upsilon_o\left(1 - \frac{V_x}{c}\right) \qquad \text{and} \qquad \upsilon_2 = \upsilon_o\left(1 + \frac{V_x}{c}\right)$$

where V_x is the relative velocity of the atom along the laser tube (x-axis) with respect to the observer and c is the speed of light. Since the atoms are in random motion the observer will detect a range of frequencies due to this Doppler effect. As a result, the frequency or wavelength of the output radiation from a gas laser will have a "linewidth" $\Delta\upsilon = \upsilon_2 - \upsilon_1$. This is what we mean by a *Doppler broadened linewidth* of a laser radiation. There are other mechanisms which also broaden the output spectrum but we will ignore these in the present case of gas lasers. From the kinetic molecular theory we know that the velocities of gas atoms obey the Maxwell distribution. Consequently, the stimulated emission wavelengths in the lasing medium must exhibit a distribution about a central wavelength $\lambda_o = c/\upsilon_o$. Stated differently, the lasing medium therefore has an **optical gain** (or a **photon** gain) that has a distribution around $\lambda_o = c/\upsilon_o$). The variation in the optical gain with the wavelength is called the **optical gain lineshape**. For the Doppler broadening case, this lineshape turns out to be a Gaussian function. For many gas lasers, this spread in the frequencies from υ_1 to υ_2 is 2 -5 GHz (for the **He-Ne laser** the corresponding wavelength spread of ~0.02 Å). When we consider the Maxwell velocity distribution of the gas atoms in the laser tube, we find that the linewidth $\Delta\upsilon_{1/2}$ between the half-intensity points (**full width at half maximum** FWHM) in the output intensity vs. frequency spectrum is given by,

$$\Delta\upsilon_{1/2} = 2\,\upsilon_o\sqrt{\frac{2k_BT\ln(2)}{Mc^2}}$$

where M is the mass of the lasing atom or molecule. This width $\Delta\upsilon_{1/2}$ above can be taken to be the FWHM of the optical gain curve of nearly all gas lasers. It does not apply to solid state lasers in which other broadening mechanisms operate. Suppose that for simplicity we consider an optical cavity of length L with parallel end mirrors. Such an optical cavity is called a **Fabry-Perot optical resonator or etalon**. The reflections from the end mirrors of a laser give rise to traveling **waves** in opposite directions within the cavity. These oppositely traveling waves interfere constructively to set up a standing wave, that is stationary electromagnetic (EM) oscillations. Some of the energy in these oscillations is tapped out by the 99% reflecting mirror to get an output just like the way we tap out the energy from an oscillating field in an *LC* circuit by attaching an antenna to it. Only standing waves with certain wavelengths however can be maintained within the optical cavity just as only certain acoustic wavelengths can be obtained from musical instruments. Any standing wave in the cavity must have an integer number of half-wavelengths $\lambda/2$ that fit into the cavity length L,

$$m\left(\frac{\lambda}{2}\right) = L$$

where m is an integer that is called the **mode number** of the standing wave. The wavelength λ in this equation is that within the cavity medium but for gas lasers the **refractive index** is nearly unity and λ is the same as the free space wavelength. Each possible standing wave within the laser tube (cavity) satisfying this standing **wave equation** is called a *cavity mode*. Further, each allowed wavelength is a mode wavelength and is labeled λ_m. Modes that exist along the cavity axis are called **axial** (or **longitudinal**) **modes**. Other types of modes, that is stationary EM oscillations, are possible when the end mirrors are not flat. The laser output thus has a broad spectrum with peaks at certain wavelengths corresponding to various cavity modes existing within the Doppler broadened optical gain curve. At wavelengths satisfying the mode wavelength λ_m, that is representing certain cavity modes, we have spikes of intensity in the output. The net envelope of the output radiation is a Gaussian distribution which is essentially due to the Doppler broadened linewidth. Notice that there

is a finite width to the individual intensity spikes within the spectrum which is primarily due to nonidealities of the optical cavity such as acoustic and thermal fluctuations of the cavity length L and nonideal end mirrors (less than 100% reflection). Typically, the frequency width of an individual spike in a He-Ne gas laser is ~1 MHz, though in highly stabilized gas lasers widths as low as ~1 kHz have been reported. It is important to realize that even if the laser medium has an optical gain, the optical cavity will always have some losses inasmuch as some radiation will be transmitted through the mirrors, and there will be various losses such as **scattering** within the cavity. Only those modes that have an optical gain that can make up for the radiation losses from the cavity can exist.
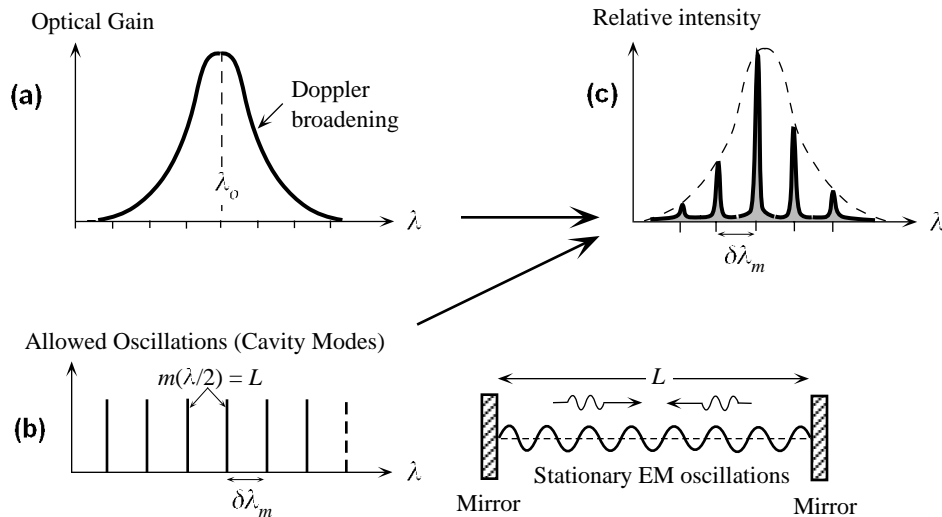
(a) Optical gain vs. wavelength characteristics (called the optical gain curve) of the lasing medium λ_o is the source wavelength corresponding to υ_o. (b) Allowed modes and their wavelengths due to stationary EM waves within the optical cavity. (c) The output spectrum (relative intensity vs. wavelength) is determined by satisfying (a) and (b) simultaneously, assuming no cavity losses.

Lasing conditions are the conditions for obtaining **continuous wave** lasing emissions from a laser device consisting of a pumped medium with an **optical gain** within an **optical resonator** structure, that is within an optical cavity with end reflectors. The optical gain of the medium is must just overcome the losses in the medium and also the losses from the end reflectors (*i.e.* radiation escaping from the cavity). The net round-trip gain must be unity and the phase change must be a multiple of 2π, otherwise the **electromagnetic wave** cannot replicate itself. The corresponding optical gain of the medium is the threshold optical gain g_{th}.

Lateral laser diode mode is a distinct electric field pattern within the **semiconductor laser** cavity that is determined by the lateral dimension of the cavity. Each lateral mode has many longitudinal modes.

Lattice is a regular array of points in space with a periodicity. There are fourteen distinct lattices in the three dimensional space. When an atom or molecule is placed at each lattice point the resulting regular structure is the **crystal** structure.

Lattice parameters are the lengths of the sides of the unit cell and the angles between the sides.

Lattice scattering limited mobility is the mobility of the electrons when their motion is limited by **scattering** from thermal vibrations of the **lattice** atoms. Generally lattice scattering limited drift mobility decreases with increasing temperature.

Law of the junction relates the injected **minority carrier** concentration just outside the **depletion layer** to the applied voltage. For holes in the n-side, that is for minority carriers, it is, $p_n(0) =$

$p_{no}\exp(eV/kT)$ where $p_n(0)$ is the hole concentration just outside the depletion layer, p_{no} is the equilibrium hole concentration (both in the *n*-side), V is the external applied voltage, k is the **Boltzmann constant** and T is the temperature. Law of the junction states that the injected minority carrier concentration depends exponentially on the voltage across the *pn* junction device.

Laydown is the first stage in the **outside vapor deposition** process by which soot **glass** products (from the chemical burning of silicon tetrachloride and germanium tetrachloride vapors with a fuel) are deposited onto a target rod (a fused **silica glass** rod, or a ceramic rod such as alumina). This target rod acts as a mandrel and is rotated during the deposition. The required glass material for the **preform** with the right composition is grown on the outside surface of this target rod by depositing glass soot particle.

LED characteristics typically refer to the emitted light spectral characteristics in terms of **spectral intensity** vs. wavelength, output light intensity vs. diode current, current-voltage characteristics and the angular variation of the emitted light intensity. There may be other additional associated characteristics as well such as changes in the light output characteristics with temperature *etc.* The width of the output light spectrum depends not only on the temperature but also on LED material, whether direct or indirect bandgap **semiconductor** is used. Typically the output spectral with corresponds to a few k_BT in the energy distribution of the emitted **photons**. Typical current-voltage characteristics exhibit a *turn-on* or the *cut-in voltage* from which point the current increases sharply with voltage. The turn-on voltage depends on the semiconductor and generally increases with the energy bandgap E_g. For example, typically, for a blue LED it is about 3.5 - 4.5 V, for a yellow LED, it is about 2 V, and for a GaAs **infrared** LED it is around 1 V.
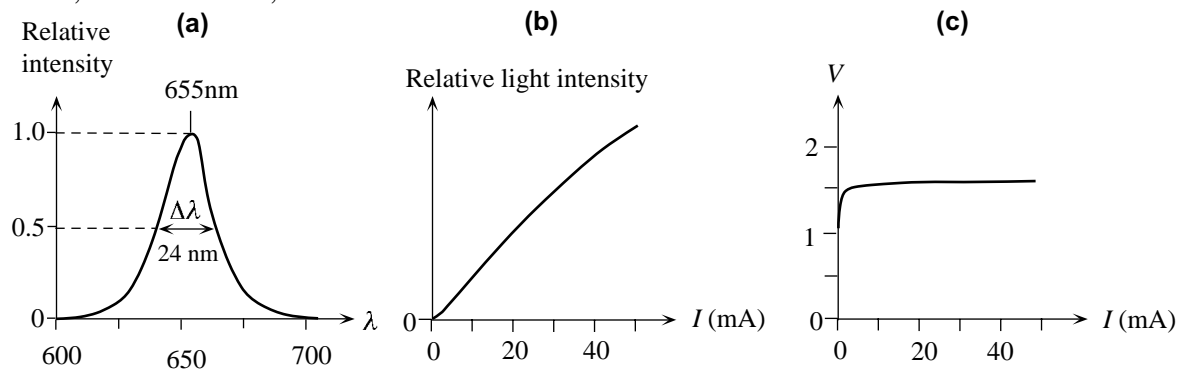
(a) A typical output spectrum (relative intensity vs. wavelength) from a red GaAsP LED. (b) Typical output light power vs. forward current. (c) Typical I-V characteristics of a red LED. The turn-on voltage is around 1.5V.

LEDs for optical fiber communications are used as **emitter** in short haul applications, *e.g.* local networks because they are simpler to drive, more economic, have a longer lifetime and provide the necessary output power even though their output **spectrum** is much wider than that of a **laser diode**. LEDs are frequently used with graded index fibers inasmuch as typically **dispersion** in a graded index fiber is primarily due to **modal dispersion** rather than **intramodal dispersion**. For long-haul and wide **bandwidth** communications invariably laser diodes are used because of their narrow linewidth, high output power and higher signal bandwidth capability. There are essentially two types of LED devices. If the emitted radiation emerges from an area in the plane of the recombination layer then the device is a **surface emitting LED** (SLED). If the emitted radiation emerges from an area on an edge of the **crystal** *i.e.* from an area on a crystal face perpendicular to the active layer, then the LED is an **edge emitting LED** (ELED).
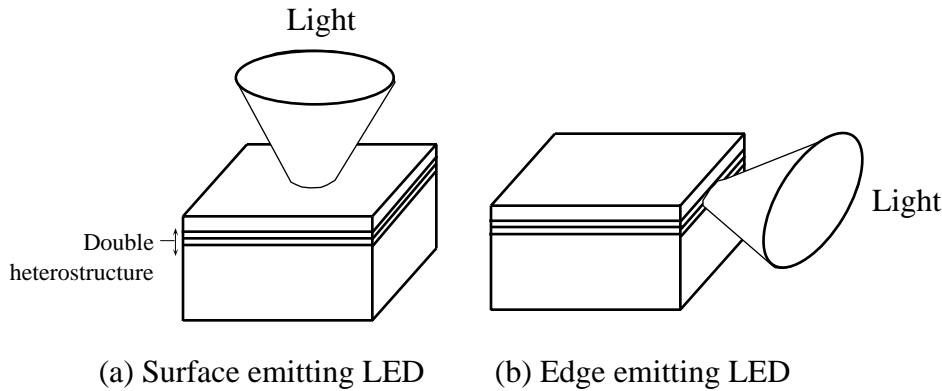
(a) Surface emitting LED   (b) Edge emitting LED

Light emitting diode (LED) is a semiconductor diode which emits incoherent radiation. LEDs operate on the principle of **spontaneous emission** resulting from electron hole pair injection and *direct recombination* under forward bias. Consider what happens when a p-n^+ junction is forward biased. As soon as a forward bias V is applied across this **junction**, this voltage drops across the depletion region since this is the most resistive part of the device. Consequently, the built-in potential V_o is reduced to $V_o - V$ which then allows the electrons from the n^+ side to diffuse, or become injected, into the p-side. The hole injection component from p into the n^+ side is much smaller than the electron injection component from the n^+ to p-side. The recombination of injected electrons in the depletion region as well as in the neutral p-side results in the spontaneous emission of **photons**. Recombination primarily occurs within the depletion region and within a volume extending over the diffusion length L_e of the electrons in the p-side. This recombination zone is frequently called the **active region**. The phenomenon of light emission from electron-hole pair (EHP) recombination as a result of **minority carrier injection** as in this case is called *injection electroluminescence*. Because of the statistical nature of the recombination process between electrons and holes, the emitted photons are in random directions; they result from spontaneous emission processes in contrast to **stimulated emission**. The LED structure has to be such that the emitted photons can escape the device without being reabsorbed by the **semiconductor** material. This means the p-side has to be sufficiently narrow or we have to use *heterostructure* devices as discussed below,

● Electron in CB
○ Hole in VB
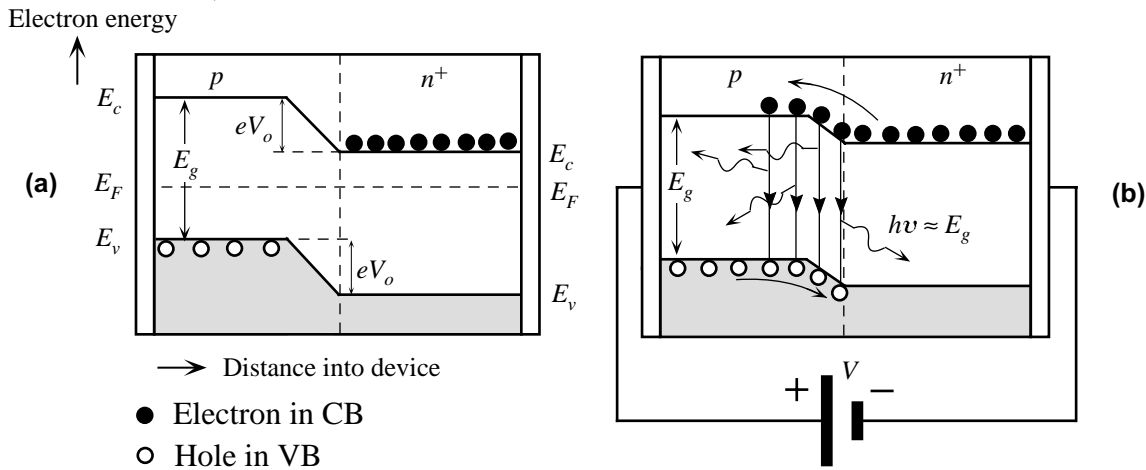
(a) The energy band diagram of a p-n^+ (heavily n-type doped) junction without any bias. Built-in potential V_o prevents electrons from diffusing from n^+ to p side. (b) The applied bias reduces V_o and thereby allows electrons to diffuse, be injected, into the p-side. Recombination around the junction and within the diffusion length of the electrons in the p-side leads to photon emission.

Light emitting diode (LED) materials are typically various direct bandgap **semiconductor** materials that can be readily doped to make commercial *pn* junction LEDs which emit radiation in the visible range of wavelengths.

(a) $GaAs_{1-x}P_x$ (b) N doped GaP   (c) Al doped SiC
$x < 0.45$
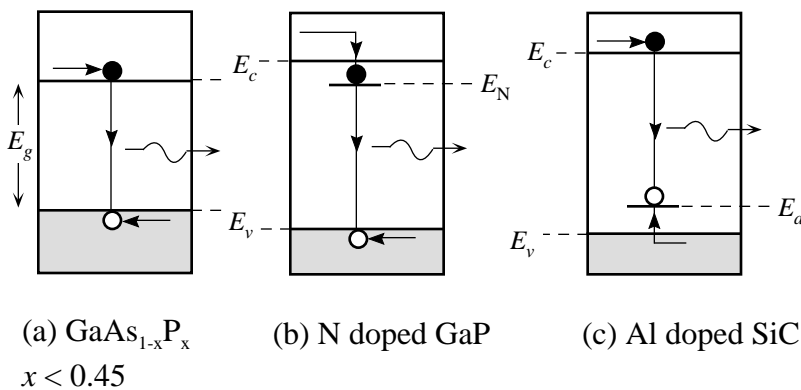
(a) Photon emission in a direct bandgap semiconductor. (b). GaP is an indirect bandgap semiconductor. When doped with nitrogen there is an electron trap at E_N. Direct recombination between a trapped electron at E_N and a hole emits a photon. (c) In Al doped SiC, EHP recombination is through an acceptor level like E_a.

An important class of commercial semiconductor materials which cover the visible **spectrum** is the *III-V ternary alloys* based on alloying GaAs and GaP which are denoted as $GaAs_{1-y}P_y$. In this compound, As and P atoms from group V are distributed randomly at normal As sites in the GaAs **crystal** structure. When $y < 0.45$, the alloy $GaAs_{1-y}P_y$ is a direct bandgap semiconductor and hence the electron hole pair (EHP) **recombination** process is direct . The rate of recombination is directly proportional to the product of electron and hole concentrations. The emitted wavelengths range from about 630 nm, red, for $y = 0.45$ ($GaAs_{0.55}P_{0.45}$) to 870 nm for $y = 0$, GaAs.
$GaAs_{1-y}P_y$ alloys (which includes GaP) with $y > 0.45$ are indirect bandgap semiconductors. The EHP recombination processes occur through **recombination centers** and involve **lattice** vibrations rather than **photon** emission. However, if we add *isoelectronic impurities* such as nitrogen (in the same group V as P) into the semiconductor crystal then some of these N atoms substitute for P atoms. Since N and P have the same valency, N atoms substituting for P atoms form the same number of bonds and do not act as donors or acceptors. The electronic cores of N and P are, however, different. The positive nucleus of N is less shielded by electrons compared with that of the P atom. This means that a conduction electron in the neighborhood of a N atom will be attracted and may become trapped at this site. N atoms therefore introduce localized energy levels, or electron traps, E_N, near the **conduction band** edge. When a conduction electron is captured at E_N, it can attract a hole (in the **valence band**) in its vicinity by Coulombic attraction and eventually recombine with it directly and emit a photon. The emitted photon energy is only slightly less than E_g as E_N is typically close to E_c. As the recombination process depends on N **doping**, it is not as efficient as direct recombination. Thus, the efficiency of LEDs from N doped indirect bandgap $GaAs_{1-y}P_y$ semiconductors is less than those from direct bandgap semiconductors. Nitrogen doped indirect bandgap $GaAs_{1-y}P_y$ alloys are widely used in inexpensive green, yellow and orange LEDs. There are two types of blue LED materials. GaN is a direct bandgap semiconductor with an E_g of 3.4 eV. The blue GaN LEDs actually use the GaN alloy InGaN which has a bandgap of about 2.7 eV which corresponds to blue emission. The less efficient type is the Al doped *silicon carbide* (SiC), which is an indirect bandgap semiconductor. The acceptor type localized energy level captures a hole from the valence band and a conduction electron then recombines with this hole to emit a photon. As the recombination process is not direct and therefore not as efficient, the brightness of blue SiC LEDs is limited. Recently there has been considerable progress made towards more efficient blue LEDs using direct bandgap compound semiconductors such as II-VI semiconductors, for example ZnSe (Zn and Se are in groups II and VI in the Periodic Table). The main problem in using II-VI compounds is the current technological difficulty in appropriately doping these semiconductors to fabricate efficient *pn* junctions.
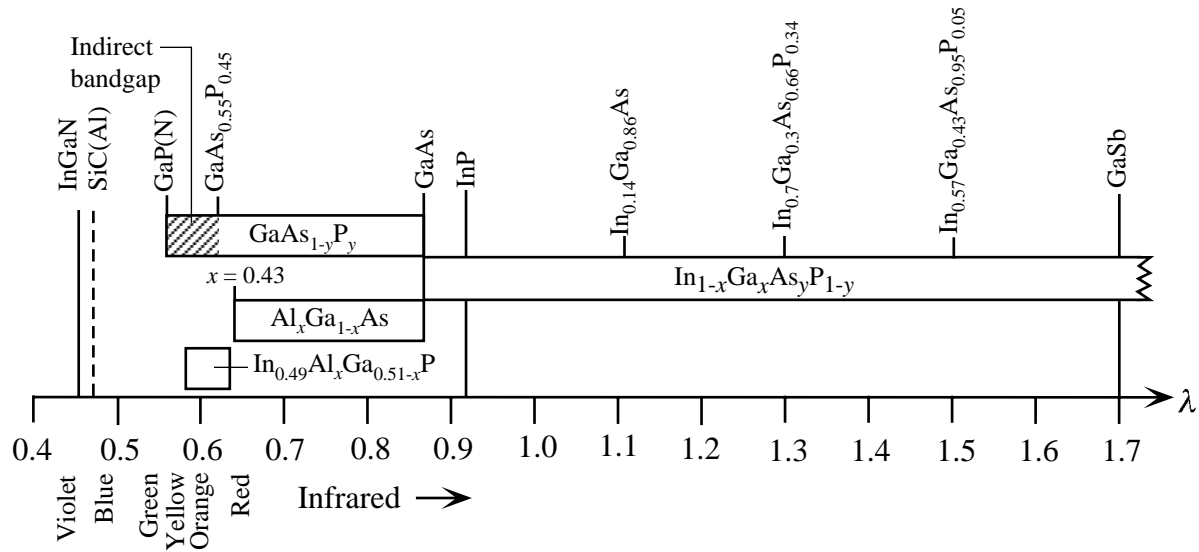
Free space wavelength coverage by different LED materials from the visible spectrum to the infrared including wavelengths used in optical communications. Hatched region and dashed lines are indirect E_g materials.

There are various commercially important direct bandgap semiconductor materials that emit in the red and **infrared** wavelengths which are typically **ternary** (containing three elements) and **quarternary** (four elements) alloys based on III and V elements, so called **III-V alloys**. For example, GaAs with a bandgap of about 1.43 eV emits radiation at around 870 nm in the infrared.

But ternary alloys based on $Al_{1-x}Ga_xAs$ where $x < 0.43$ are direct bandgap semiconductors. The composition can be varied to adjust the bandgap and hence the emitted radiation from about 640 - 870 nm, from deep red light to infrared. In-Ga-Al-P is a quarternary III-V alloy (In, Ga, Al from III and P from V) that has a direct bandgap variation with composition over the visible range. It can be **lattice** matched to GaAs **substrates** when in the composition range $In_{0.49}Al_{0.17}Ga_{0.34}P$ to $In_{0.49}Al_{0.058}Ga_{0.452}P$. Recent high intensity LEDs have been based on this material which is likely to eventually dominate the high-intensity visible LED range. The bandgap of **quarternary alloys** $In_{1-x}Ga_xAs_{1-y}P_y$ can be varied with composition (x and y) to span wavelengths from 870 nm (GaAs) to 3.5 μm (InAs) which includes the optical communication wavelengths of 1.3 and 1.55 μm

TABLES OF SELECTED PROPERTIES

Selected LED semiconductor materials. Optical communication channels are at 850 nm (local network) and at 1.3 and 1.55 μm (long distance). D = direct, I = Indirect bandgap. DH = Double heterostructure. $\eta_{external}$ is typical and may vary substantially depending on the device structure.
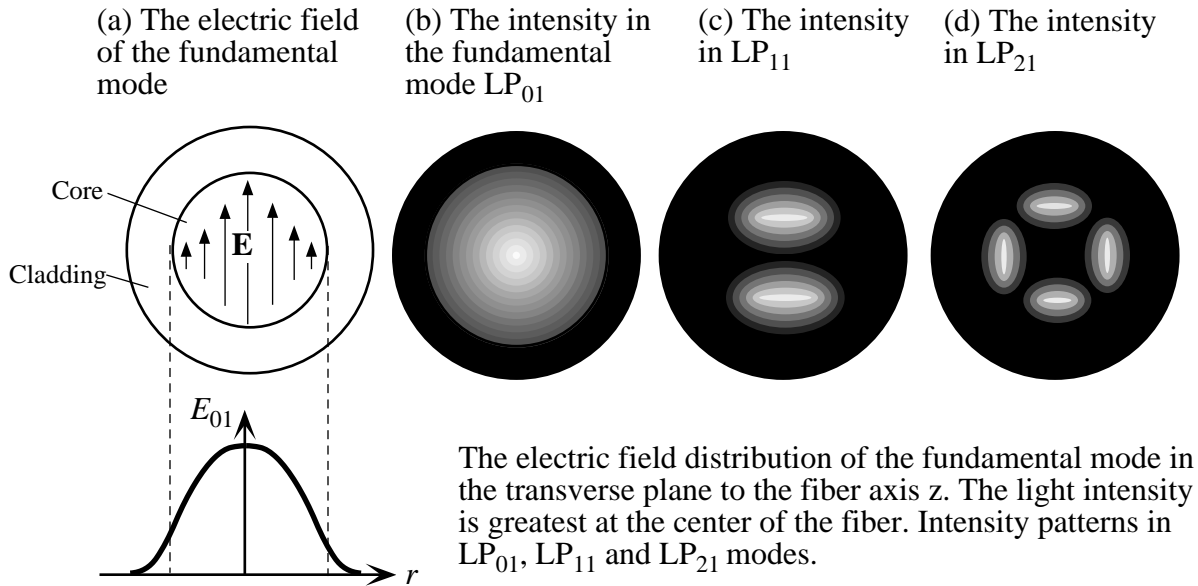
Semiconductor	Substrate	D or I	λ (nm)	η_{external} (%)	Comment
GaAs	GaAs	D	870 - 900	10	Infrared LEDs
Al_xGa_{1-x} As (0< x < 0.4)	GaAs	D	640 - 870	5 - 20	Red to IR LEDs. DH
$In_{1-x}Ga_xAs_yP_{1-y}$ ($y \approx 2.20x$, 0 < x < 0.47)	InP	D	1 - 1.6 μm	> 10	LEDs in communications
InGaN alloys	GaN or SiC Saphire	D	430 - 460	2	Blue LED
			500 - 530	3	Green LED
SiC	Si; SiC	I	460 - 470	0.02	Blue LED. Low efficiency
$In_{0.49}Al_x Ga_{0.51-x}$ P	GaAs	D	590 - 630	1 - 10	Amber, green red LEDs
$GaAs_{1-y}P_y$ (y < 0.45)	GaAs	D	630 - 870	< 1	Red - IR
$GaAs_{1-y}P_y$ (y > 0.45) (N or Zn, O doping)	GaP	I	560 - 700	< 1	Red, orange, yellow LEDs
GaP (Zn-O)	GaP	I	700	2 - 3	Red LED
GaP (N)	GaP	I	565	< 1	Green LED

Linear polarizer will only allow electric field oscillations along some preferred direction, called the **transmission axis**, to pass through the device. A *polaroid sheet* is a good example of a commercially available linear polarizer. Dichroic **crystals** such as tourmaline crystals are good polarizers because they are optically anisotropic and attenuate electromagnetic (EM) waves with fields that are *not* oscillating along the optical axis (hence the transmission axis) of the crystal. The emerging beam from the polarizer has its field oscillations along the transmission axis and hence it is **linearly polarized**.

Linearly polarized (LP) modes are allowed nearly plane polarized, transverse electric and magnetic (TEM) propagating modes in a weakly guiding step optical fiber, that is a fiber with a small **refractive index** difference ($\Delta \ll 1$). The field magnitudes in a LP mode, however, are not constant in a plane. A guided LP mode along the fiber can be represented by the propagation of an electric field distribution $E(r,\varphi)$ along z where r, φ and z represent cylindrical coordinates in which z is along the fiber axis. This field distribution, or pattern, is in the plane normal to the fiber axis and hence depends on r and φ but not on z. A guided LP mode along the fiber can be represented by the propagation of an electric field distribution $E(r,\varphi)$ along z. This field distribution, or pattern, is in the plane normal to the fiber axis and hence depends on r and φ but not on z. Further, because of the presence of two boundaries it is characterized by two integers, l and m. The propagating field distribution in an LP mode is therefore given by $E_{lm}(r, \varphi)$ and we represent the mode as LP_{lm}. Thus an LP_{lm} mode can be described by a traveling **wave** along z of the form,

$$E_{LP} = E_{lm}(r,\varphi) \exp j(\omega t - \beta_{lm}z)$$

where E_{LP} is the field of the LP mode and β_{lm} is its **propagation constant** (**wave number**) along z. It is apparent that for a given l and m, $E_{lm}(r,\varphi)$ represents a particular field pattern at a position z that is propagated along the fiber with an effective **wavevector** β_{lm}.

(a) The electric field of the fundamental mode

(b) The intensity in the fundamental mode LP_{01}

(c) The intensity in LP_{11}

(d) The intensity in LP_{21}

Core

Cladding

E

E_{01}

r

The electric field distribution of the fundamental mode in the transverse plane to the fiber axis z. The light intensity is greatest at the center of the fiber. Intensity patterns in LP_{01}, LP_{11} and LP_{21} modes.

The electric field pattern (E_{01}) in the **fundamental mode**, which corresponds to $l = 0$ and $m = 1$, the LP_{01} mode, has maximum intensity in the center of the **core** (or fiber axis) and penetrates somewhat into the **cladding** due to the accompanying **evanescent wave**. The extent of penetration depends on the **V-number** of the fiber (and hence on the wavelength). The light intensity in a mode is proportional to E^2 which means that the intensity distribution in the LP_{01} mode has a maximum along the fiber axis. The integers l and m are related to the intensity pattern in a LP_{lm} mode. There are m number of maxima along r starting from the core center and $2l$ number of maxima around a circle around the fiber axis. l is called the **azimuthal mode number**.

Linearly polarized light has its the electric field oscillations contained within a well defined plane.

Lithium niobate polarization modulator is an integrated optic device in which the phase of a light **wave** propagating through a waveguide channel is modulated by an external applied voltage. The modulator has an embedded waveguide is fabricated by implanting a $LiNbO_3$ **substrate** with Ti atoms which increase the **refractive index**. Two coplanar strip electrodes run along the waveguide and enable the application of a transverse field E_a to light propagation direction z. The external modulating voltage $V(t)$ is applied between the coplanar drive electrodes and, by virtue of the

Pockels effect, induces a change Δn in the refractive index and hence a voltage dependent phase shift through the device. We can represent light propagation along the guide in terms of two orthogonal modes, E_x along x and E_y along y. These two modes experience symmetrically opposite phase changes. The applied (or induced) field is not uniform between the electrodes and, further, not all applied field lines lie inside the waveguide. The **electro-optic effect** takes place over the spatial overlap region between the applied field and the **optical fields**. This spatial overlap efficiency is lumped into a coefficient Γ and the phase shift $\Delta\phi$ is written as

$$\Delta\phi = \Gamma \frac{2\pi}{\lambda} n_o^3 r_{22} \frac{L}{d} V$$

where typically $\Gamma \approx 0.5 - 0.7$ for various integrated polarization modulators of this type. Since the phase shift depends on the product of V and L, a comparative device parameter would be the $V \times L$ product for a phase shift of π (half-wavelength), *i.e.* $V_{\lambda/2}L$. At $\lambda = 1.5$ μm for an x-cut $LiNbO_3$ modulator, with $d \approx 10$ μm, $V_{\lambda/2}L \approx 35$ V-cm. For example, a modulator with $L = 2$ cm has a half-wave voltage $V_{\lambda/2} = 17.5$ V. By comparison, for a z-cut $LiNbO_3$ plate, that is for light propagation along the y-direction and E_a along z, the relevant Pockels coefficients (r_{13} and r_{33}) are much greater

than r_{22} which leads to $V_{\lambda/2}L \approx 5$ V-cm.
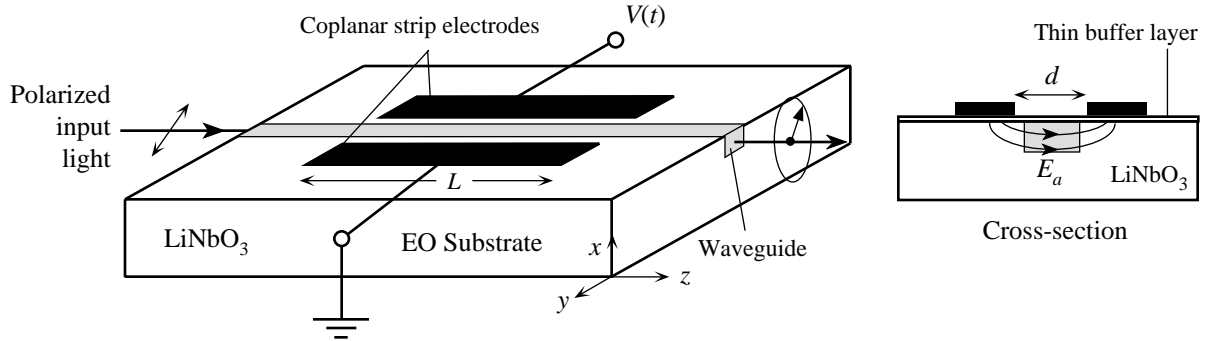
Integrated tranverse Pockels cell phase modulator in which a waveguide is diffused into an electro-optic (EO) substrate. Coplanar strip electrodes apply a transverse field E_a through the waveguide. The substrate is an x-cut LiNbO$_3$ and typically there is a thin dielectric buffer layer (*e.g.* ~200 nm thick SiO$_2$) between the surface electrodes and the substrate to separate the electrodes away from the waveguide.

Lithography is a process by which a pattern is defined on the surface of the wafer which identifies the **crystal** regions to be doped.

Longitudinal Pockels cell has the applied field is along the direction of light propagation, both parallel to z-axis (**optic axis**). Suggest schemes that would allow light to enter the **crystal** along the applied field direction. Suppose that a KDP crystal is used. KDP is uniaxial and $n_1 = n_2 = n_o$ (**polarizations** parallel to x and y) and $n_3 = n_e$ (polarization parallel to z). The **principal axes** x and y are rotated by 45° to become x' and y' and

$$n_1' \approx n_o - \tfrac{1}{2}n_o^3 r_{63}E_a \qquad n_2' \approx n_o + \tfrac{1}{2}n_o^3 r_{63}E_a \qquad \text{and} \qquad n_3' = n_3 = n_e$$

Calculate the half-wave voltage required induce a retardation of π between the emerging components of the electric field, for free space wavelength of 633 nm if for KDP at 633 nm, $n_o \approx 1.51$, $r_{63} \approx 10.5 \times 10^{-12}$ m/V. Light propagates along z with polarizations parallel to x' and y' axes and these orthogonal **waves** propagate with different refractive indices n_1' and n_2'. The applied field $E_a = V/L$ along z so that, the relative phase change $\Delta\phi$ between E_x' and E_y' is

$$\Delta\phi = \frac{2\pi}{\lambda} L(n_2' - n_1') = \frac{2\pi}{\lambda} n_o^3 r_{63} V$$

and for $\Delta\phi = \pi$ we have

$$V_\pi = \frac{\lambda}{2n_o^3 r_{63}} = \frac{(633 \times 10^{-9})}{2(1.51)^3(10.5 \times 10^{-12})} = 8.75 \text{ kV.}$$
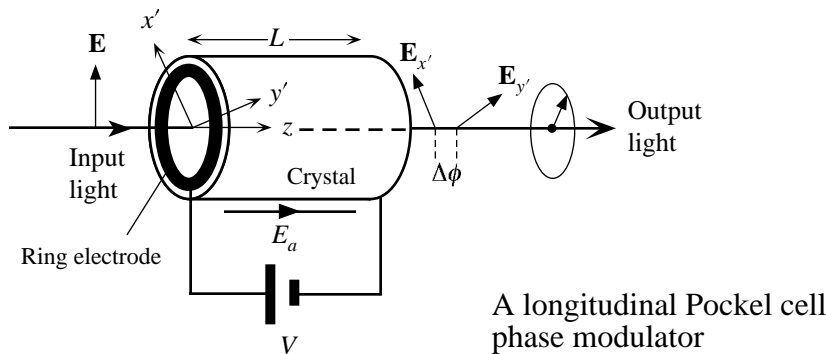
A longitudinal Pockel cell phase modulator

Luminescence, in general terms, is the emission of light as a result of an excited electron transiting down to the ground energy level. In a **semiconductor**, this would correspond to the **recombination** of an electron and a hole; the excited electron is the **conduction band** (CB) electron and its ground state corresponds to a hole in the **valence band** (VB) . In contrast, light emitted from an ordinary light bulb is due to the heating of the metal filament. The emission of radiation from a heated object is called **incandescence**. In luminescence, emission of radiation requires the initial excitation of electrons. If the electron excitation is due to photon **absorption**, then the process is identified as *photoluminescence*. The direct electron–hole recombination mechanism generally occurs very quickly. For example, typical **minority carrier lifetimes** are in the range of nanoseconds so that light emission from a semiconductor stops within nanoseconds after the removal of excitation. Such luminescence processes are normally identified as *fluorescence*. The emission of light from a fluorescent tube is actually a fluorescence process. The tube contains a gas mixture of argon and mercury. The Ar and Hg gas atoms become excited by the electrical discharge process and emit light mainly in ultraviolet region which is absorbed by the fluorescent coating on the tube. The excited electrons in the fluorescent coating material then recombine emitting light in the visible spectrum. There are also materials, called *phosphors*, from which light emission may continue for milliseconds to hours after the cessation of excitation. These slow luminescence processes are normally referred to as *phosphorescence*.
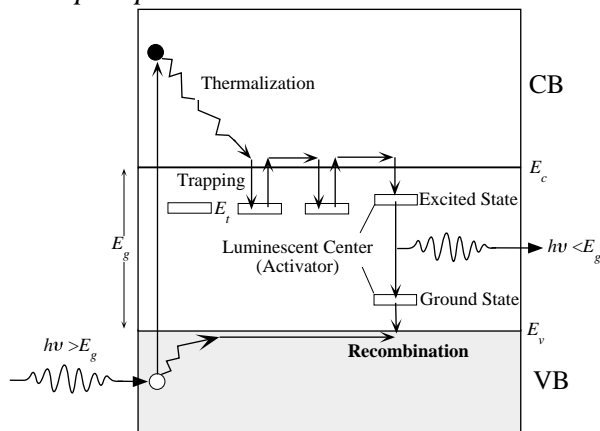
Optical absorption generates an EHP. The electron thermalizes and then becomes trapped at a local center and thereby removed from the CB. Later it becomes detrapped and wanders in the CB again. Eventually it is captured by a luminescent center where it recombines with a hole emitting a photon. Traps therefore delay recombination.

Consider a semiconductor that has localized **states** that are electron traps and temporarily capture an electron from the conduction band and thereby immobilizes it. After a while a strong **lattice** vibration returns the electron back into the conduction band (by thermal excitation). The traps may be due to **crystal** defects or they may be added impurities. The time the electron spends trapped at E_t depends on the energy depth of the trap from the conduction band, $E_c–E_t$. Initially the incident **photon** excites a valence band electron to the conduction band. The electron then thermalizes, *i.e.* loses the excess energy as it is collides with lattice vibrations, and falls close to E_c. As the electron wanders in the conduction band it becomes captured by a trap at E_t. It remains captured until a strong lattice vibration excites it back into the conduction band. The electron wanders around again in the conduction band and eventually it becomes trapped in an excited state of a luminescent center or an activator. Typically, luminescent centers are intentionally added impurities or crystal defects such as interstitials or vacancies. The electron then falls down in energy to the ground state of the activator releasing a photon. Later the electron at the ground state recombines with a wandering hole in the valence band band. Thus the activator acts as a radiative **recombination center**. With some impurities the energy that is released when the electron falls down to the ground state is in the form of lattice vibrations so that the impurity acts as a nonradiative recombination center. The time interval between **photogeneration** and recombination can be quite long if the electron remains captured at E_t for a considerable length of time. In fact, the electron may become trapped and detrapped many times before it finally recombines so that the emission of light can persist for a relatively long time after the cessation of excitation. There are many examples of phosphors with various activators. For example, ZnS is a typical phosphor material. Small amounts of Cu in the

ZnS phosphor acts as an activator with luminescence occurring in the green region. Mn, on the other hand, is an activator which gives luminescence in the red region. It is also possible to excite electrons into the CB by bombarding the material with a high energy electron beam. If these electrons recombine with holes and emit light then the process is called cathodoluminescence. This is the mechanism which allows us to view the electron beam trace on the screen of a CRT (cathode ray tube). The electron beam excites EHPs in the phosphor coating on the CRT screen. In the case of color CRT displays, typically the screen is coated uniformly with three sets of phosphor dots which exhibit *cathodoluminescence* in the blue, red and green wavelengths. In *electroluminescence* an electric current, either ac or dc, is used to excite electrons into the CB which then recombine with holes and emit light. For example passing a current through certain semiconducting phosphors such as ZnS doped with Mn causes light emission by electroluminescence. The emission of light from an **light emitting diode** (LED) is an example of **injection electroluminescence** in which the applied voltage causes charge carrier injection and recombination in a device (**diode**) that has a **junction** between a *p*-type and an *n*-type semiconductor.

Mach-Zehnder modulator is a lithium niobate based electro-optic device whose light **transmittance** is controlled by an applied external voltage. It uses the **Pockels effect** of liNbO$_3$ and the intereference of two **waves** which have a relative phase difference, induced by an applied external voltage. It converts induced phase shift by an applied voltage to an amplitude variation by using an **interferometer**, a device that interferes two waves of the same frequency but different phase. As shown below in the figure, the device has implanted single-mode waveguides in a LiNbO$_3$ (or other electro-optic) **substrate** in the geometry shown. The waveguide at the input that branches out at *C* to two arms *A* and *B* and these arms are later combined at *D* to constitute the output. The splitting at *C* and combining at *D* involve simple Y-junction waveguides. In the ideal case, the power is equally split at *C* so that the field is scaled by a factor $\sqrt{2}$ going into each arm. The structure acts as an interferometer because the two waves traveling through the arms *A* and *B* interfere at the output port *D* and the output amplitude depends on the phase difference (optical path difference) between the *A* and *B*-branches. Two back-to-back identical **phase modulators** enable the phase changes in *A* and *B* to be modulated. Notice that the applied field in branch *A* is in the opposite direction to that in branch *B*. The **refractive index** changes are therefore opposite which means the phase changes in arms *A* and *B* are also opposite. For example, if the applied voltage induces a phase change of $\pi/2$ in arm *A*, this will be $-\pi/2$ in arm *B* so that *A* and *B* would be out of phase by π. These two waves will then interfere destructively and cancel each other at *D*. The output intensity would then be zero. Since the applied voltage controls the phase difference between the two interfering waves *A* and *B* at the output, this voltages also controls the output light intensity, though the relationship is not linear. It is apparent that the relative phase difference between the two waves *A* and *B* is therefore doubled with respect to a phase change ϕ in a single arm. We can predict the output intensity by adding waves *A* and *B* at *D*:

$$\frac{P_{\text{out}}(\phi)}{P_{\text{out}}(0)} = \cos^2 \phi$$

The power transfer is zero when $\phi = \pi/2$ as expected. In practice, the Y-junction losses and uneven splitting results in less than ideal performance; *A* and *B* do not totally cancel out when $\phi = \pi/2$.
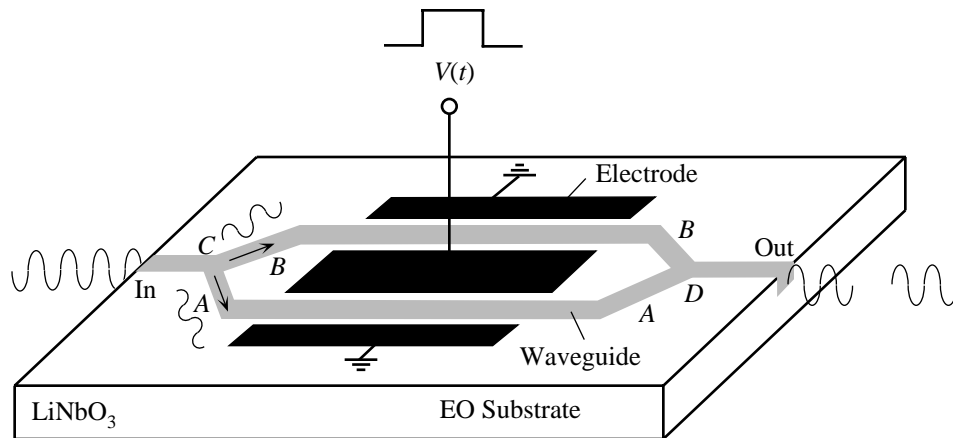
An integrated Mach-Zender optical intensity modulator. The input light is split into two coherent waves *A* and *B*, which are phase shifted by the applied voltage, and then the two are combined again at the output.
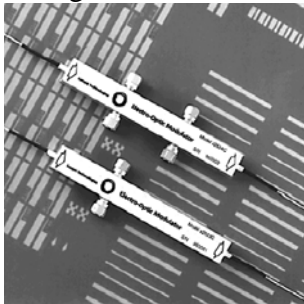
Ti diffused lithium niobate electro-optic (Pockels effect) modulators for use in high-speed optical fiber communications up to 16 GHz. Operates at 1550 nm. Maximum modulation voltage is ±20V. (Courtesy of Lucent Technologies.)

Macrobending loss is due to small changes in the **refractive index** of the fiber due to induced **strains** when it is bent during its use, *e.g.* when it is cabled and laid. Induced strains change n_1 and n_2, and hence affect the **mode field diameter**, that is the field penetration into the **cladding**. Some of this increased cladding field will reach the cladding boundary to become lost into the outer medium (radiation, **absorption** *etc.*). Typically macrobending loss crosses over into **microbending loss** when the radius of curvature becomes less than a few centimeters.

Magnetic field of a propagating electromagnetic radiation is related to its electric field *E*. In an isotropic medium of **refractive index** *n*, ($n = \sqrt{}$(relative permittivity)), the magnetic field $B = E/v$ where $v = c/n = c/\sqrt{(\varepsilon_r)}$ is the **phase velocity** in the medium which is assumed to be nonmagnetic.

Magneto-optic effects are changes in the optical properties due to the application of an external **magnetic field**.

Malus's law relates the output light intensity to the input light intensity when a **linearly polarized** light is pass through two polarizers that have their transmission axes aligned at different orientations. There are various optical devices that operate on the **polarization** state of a **wave** passing through it and thereby modify the polarization state. Consider light passing through two polarizers with their transmission axes making an angle θ. The field in the radiation passing through the first polarizer will have the E-field aligned with the **transmission axis** of this first polarizer. However, only the component $E\cos\theta$ of the field will be allowed to pass through the second polarizer. The **irradiance** (intensity) of light passing through the second polarizer is proportional to the square of the electric

field which means that the detected intensity varies as $(E\cos\theta)^2$. Since all the electric field will pass when $\theta = 0$, this is the maximum irradiance condition. The irradiance $\mathcal{I}$ at any other angle θ is then given by Malus's law, $\mathcal{I}(\theta) = \mathcal{I}(0)\cos^2\theta$.
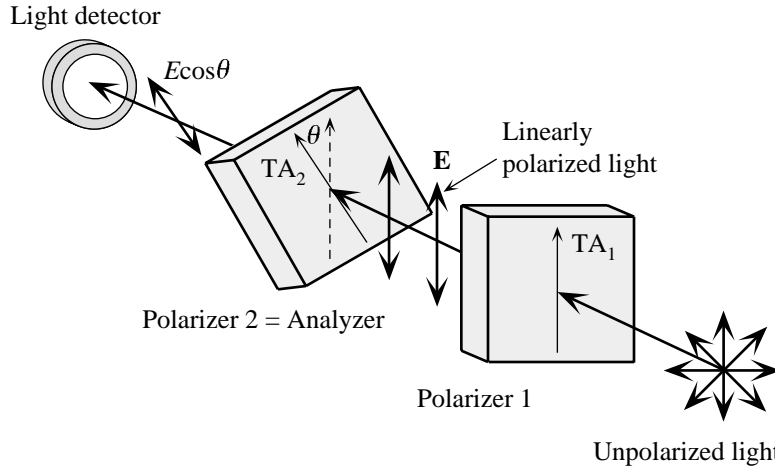
Randomly polarized light is incident on a Polarizer 1 with a transmission axis TA_1. Light emerging from Polarizer 1 is linearly polarized with **E** along TA_1, and becomes incident on Polarizer 2 (called "analyzer") with a transmission axis TA_2 at an angle θ to TA_1. A detector measures the intensity of the incident light. TA_1 and TA_2 are normal to the light direction.

Mass action law in **semiconductor** science refers to the law $np = n_i^2$ (where n and p are electron and hole concentrations and n_i is the intrinsic concentration) which is valid under thermal equilibrium conditions and in the absence of external **biases** and illumination.

Material dispersion coefficient D_m is the time spread of a propagating optical pulse in an optical guide per unit length and per unit spectral wavelength width due to the wavelength dependence of the medium. If $\delta\lambda$ is the spread of the excitation wavelengths coupled into the fiber, $\delta\tau$ is the spread in propagation times of these different wavelengths due to **material dispersion**, L is the fiber length then,

$$D_m = \frac{1}{L}\frac{\delta\tau}{\delta\lambda}$$

D_m can be determined from the n vs. λ relationship via,

$$D_m \approx -\frac{\lambda}{c}\left(\frac{d^2n}{d\lambda^2}\right)$$

Material dispersion is the spread in the velocities of different wavelength **waves** in a **dielectric** medium due to the wavelength dependence of the **refractive index** of the medium. As long as the propagating EM (electromagnetic) wave is not monochromatic (single wavelength), and the medium has a **group index** that changes with the wavelength, there will always be material dispersion.

Matrix emitter, see **vertical cavity surface emitting lasers.**

Maxwell's equations are a set of equations that describe the space and time dependence of the electric and **magnetic fields** in a medium through partial derivatives. In an isotropic **dielectric** material with a relative permittivity ε_r, Maxwell's equations lead to a **wave equation** for the electric field E.

$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + \frac{\partial^2 E}{\partial z^2} = \varepsilon_o\varepsilon_r\mu_o\frac{\partial^2 E}{\partial t^2}$$

where ε_o and μ_o are the permittivity and permeability of free space. It is assumed that the dielectric material is nonmagnetic, *i.e* $\mu_r = 1$. The solution of this equation is an electromagnetic wave that is

traveling with a velocity v given by

$$v = \frac{1}{\sqrt{\varepsilon_o \varepsilon_r \mu_o}}$$

James Clerk Maxwell (1831 - 1879) was a Scottish physicist born in Edinburgh. He held professorships at Aberdeen (1856 - 1860), London (1860 - 1865) and Cambridge (from 1871) Universities; at Cambridge he set up the Cavendish Laboratory (1856). He is renowned for his mathematical formulation for describing light in terms of the behavior of time varying electric and magnetic fields . He also made distinct contributions to the kinetic molecular theory. [(*Source:* Physics World, March 1999, p.43.)
See **electromagnetic wave.**

Mean free path is the mean distance traversed by an electron between scattering events. If τ is the mean free time between scattering events, and u is the mean speed of the electron, then the mean free path, $\lambda = u\tau$.

Mean free time is the average time it takes to scatter a conduction electron. If t_i is the free time between collisions (between scattering events) for an electron labeled as i, then $\tau = \overline{t_i}$ averaged over all the electrons. The **drift mobility** is related to the mean free time by $\mu_d = e\tau / m_e$. The reciprocal of the mean free time is the mean probability per unit time that a conduction electron will be scattered, or, put differently, the mean frequency of scattering events.

Meridional ray is a light ray that enters an **optical fiber** through the fiber axis and hence also crosses the fiber axis on each reflection as it zigzags down the fiber. It travels in a plane that contains the fiber axis. Guided modes resulting from meridional rays are either TE or TM type.

A meridional ray always crosses the fiber axis.
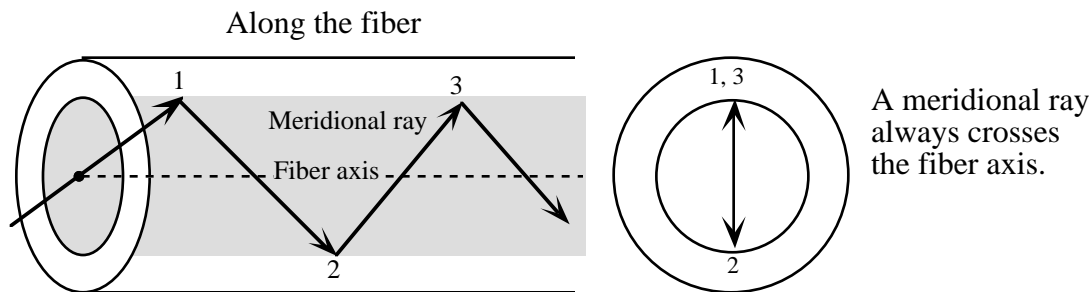
Metallurgical junction is where there is an effective **junction** between the *p*-type and *n*-type doped regions in the **crystal**. It is where the donor and acceptor concentrations are equal or where there is a transition from *n*- to *p*-type **doping**.

Microbending loss is the **attenuation** of light in a fiber due to the local (sharp) bending of the fiber; typically for fiber bending with radius of curvature less than ~10 mm. Microbending loss is due to a "sharp" local bending of the fiber which changes the guide geometry and **refractive index** profile locally which leads to some of the light energy being radiating away from the guiding direction. A sharp bend will change the local waveguide geometry in such a way that a zigzagging ray suddenly finds itself with an incidence angle θ', narrower than its normal angle θ ($\theta' < \theta$) which gives rise to

either a transmitted **wave** (a refracted wave into the **cladding**), or to a greater cladding penetration. If $\theta' < \theta_c$, the **critical angle**, then there will be no **total internal reflection** and substantial light power will be radiated into the cladding and eventually to the outside medium (polymer coating *etc.*). Greater penetration can lead to the **optical field** reaching the cladding-outer boundary and hence to some of the light being lost away into the outer coating. Attenuation increases sharply with the extent of bending; as θ' gets narrow and TIR is lost, substantially more energy is transferred into the cladding. Further, highest modes propagate with incidence angles θ close to θ_c which means that these modes are most severely affected. **Multimode fibers** therefore suffer more from **bending losses** then single mode fibers. Microbending loss α_B increases rapidly with increasing bend "sharpness" *i.e.* with decreasing radius of bend curvature, R . The microbending loss α_B increases exponentially with R which depends on the wavelength and the fiber characteristics (*e.g.* **V-number**). Typically, bend radii less than ~10 mm can lead to appreciable microbending loss. Microbending loss α_B depends on the fiber characteristics and wavelength and can be calculated approximately given various fiber parameters using the single mode fiber microbending loss equation (D. Marcuse, *J. Op. Soc. Am.*, Vol. 66, pp. 216-220, 1976)

$$\alpha_B \approx \frac{\pi^{1/2}\kappa^2}{2\gamma^{3/2}V^2[K_1(\gamma a)]^2} R^{-1/2} \exp(-\frac{2\gamma^3}{3\beta^2}R)$$

where R is the **bend radius** of curvature, a = fiber radius, β is the **propagation constant**, determined by b, **normalized propagation constant**, which is related to V, $\beta = n_2k[1 + b\Delta]$; $k = 2\pi/\lambda$ is the free-space **wavevector**; $\gamma = \sqrt{[\beta^2 - n_2^2k^2]}$; $\kappa = \sqrt{[n_1^2k^2 - \beta]}$, and $K_1(x)$ is a first-order modified **Bessel function**, available in math software packages. Note that $b \approx (1.1428 - 0.996V^{-1})^2$ for a single mode fiber with $1.5 < V < 2.5$.(See A.J. Harris and P.F. Castle, *IEEE J. Light Wave Technol.,* Vol. LT4, 34-41, 1986.)

Field distribution   Microbending
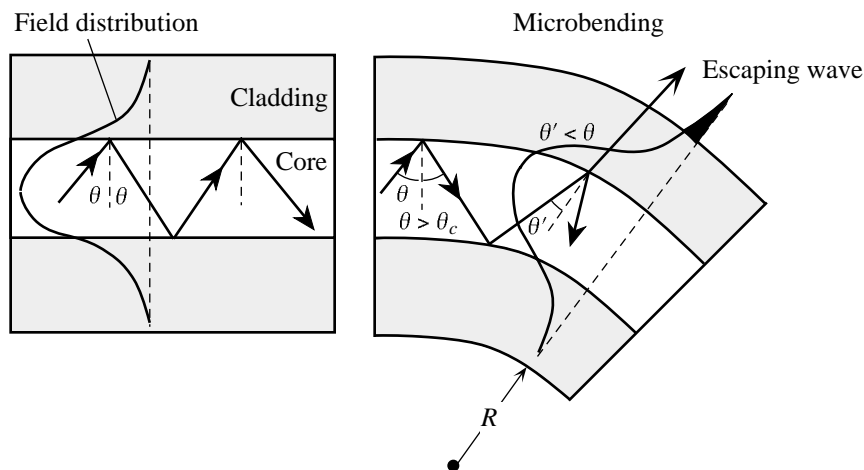
Sharp bends change the local waveguide geometry that can lead to waves escaping. The zigzagging ray suddenly finds itself with an incidence angle θ' that gives rise to either a transmitted wave, or to a greater cladding penetration; the field reaches the outside medium and some light energy is lost.

α_B (m^{-1}) for 10 cm of bend
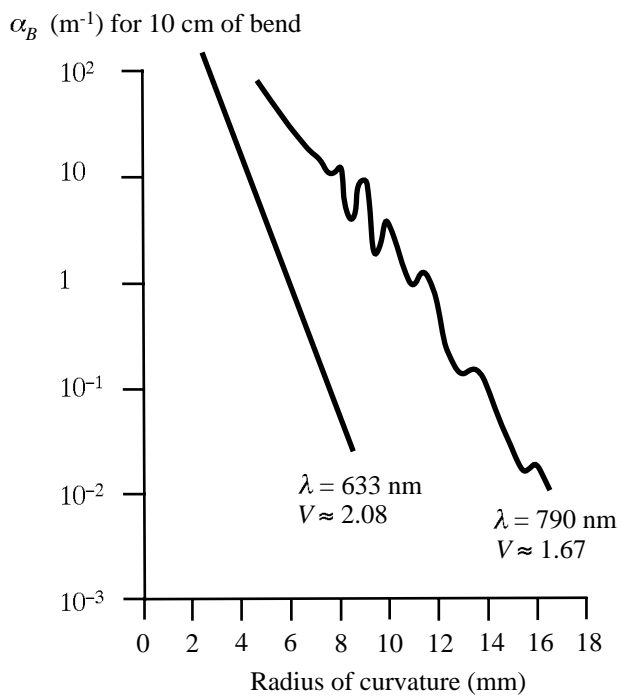
Measured microbending loss for a 10 cm fiber bent by different amounts of radius of curvature *R*. Single mode fiber with a core diameter of 3.9 μm, cladding radius 48 μm, Δ = 0.00275, *NA* ≈ 0.10, *V* ≈ 1.67 and 2.08 (Data extracted and replotted from A.J. Harris and P.F. Castle, *IEEE J. Light Wave Technology*, Vol. LT14, pp. 34-40, 1986; see original article for discussion of peaks in α_B vs. *R* at 790 nm).

$\lambda = 633$ nm
$V \approx 2.08$

$\lambda = 790$ nm
$V \approx 1.67$

Radius of curvature (mm)

Microlaser, see **vertical cavity surface emitting lasers.**

Minority carrier diffusion length (*L*) is the mean distance a **minority carrier** diffuses before **recombination**, $L = \sqrt{[D\tau]}$ where *D* is the **diffusion coefficient** and τ is the **minority carrier lifetime**.

Minority carrier injection is the flow of electrons into the *p*-side and holes into the *n*-side of a *pn* junction when a voltage is applied to reduce the **built-in voltage** across the **junction**. It can also refer to an increase in the **minority carrier** concentration due to **photogeneration**.

Minority carrier lifetime (τ) is the mean time for a **minority carrier** to disappear by **recombination**. $1/\tau$ is the mean probability per unit time that a minority carrier recombines with a majority carrier. Suppose that excess electrons and holes have been injected, as would be in a *pn*-junction under forward bias, and that Δn_p is the excess electron, minority carrier, concentration and Δp_p is the excess hole, majority carrier, concentration in the *neutral p*-side of a GaAs *pn* junction. Injected electron and hole concentrations would be the same to maintain charge neutrality, that is, $\Delta n_p = \Delta p_p$. In many instances the rate of change $\partial \Delta n_p / \partial t$ is proportional to Δn_p and an *excess minority carrier recombination time (lifetime)* τ_e is defined by

$$\frac{\partial \Delta n_p}{\partial t} = -\frac{\Delta n_p}{\tau_e}$$

In practice, the injected excess minority carrier concentration Δn_p is much greater than the actual equilibrium minority carrier concentration n_{po}. There are two conditions on Δn_p corresponding to weak and **strong injection** based on Δn_p compared with the majority carrier concentration p_{po}. In **weak injection**, $\Delta n_p << p_{po}$, where p_{po} is the majority carrier concentration. Then $n_p \approx \Delta n_p$ and $p_p \approx p_{po} + \Delta p_p \approx p_{po} \approx N_a$ = acceptor concentration. The rate of recombination in this case is given by,

$$\partial \Delta n_p / \partial t = -B(n_p p_p - n_{po} p_{po}) \approx -B_o N_a \Delta n_p$$

where B is the direct recombination capture coefficient.. Thus, under weak injection, the lifetime is constant and given by,

$$\tau_e = 1/BN_a$$

In strong injection, $\Delta n_p >> p_{po}$. Then the rate of recombination becomes,

$$\partial \Delta n_p / \partial t = -B_o \Delta p_p \Delta n_p = B(\Delta n_p)^2$$

so that under high level injection conditions the lifetime τ_e is inversely proportional to the injected carrier concentration. When a **light emitting diode** (LED) is modulated under high injection levels for example, the lifetime of the minority carriers is therefore not constant, which in turn leads to distortion of the modulated light output. See **direct recombination capture coefficient.**

Minority carriers are electrons in a *p*-type and holes in an *n*-type **semiconductor**.

Modal noise, or **speckle noise,** in an optical system is random fluctuations in the transmitted power due to the **optical power** carried by various modes experiencing random phase changes which result in random "**mode mixing**" *and* the fact that **attenuation** losses being mode dependent; single fiber has no modal noise.

Modal or intermodal dispersion is due to the spread in time of an infinitesimally thin light pulse of single wavelength as it propagates along a fiber through various modes. Each mode has a different **propagation constant** so that at the end of the fiber the modes arrive at different times and constitute an output pulse that is broadened in time. Modal dispersion zero in a single mode fiber that allows only one mode, the **fundamental mode**, to propagate. In a **multimode fiber**, modal dispersion in terms of full spread $\Delta \tau$ is approximately given by,

$$\frac{\Delta \tau}{L} \approx \frac{n_1 - n_2}{c}$$

where L is the guide length, n_1 and n_2 are the refractive indices of the **core** and the **cladding** and c is the velocity of light in free space.
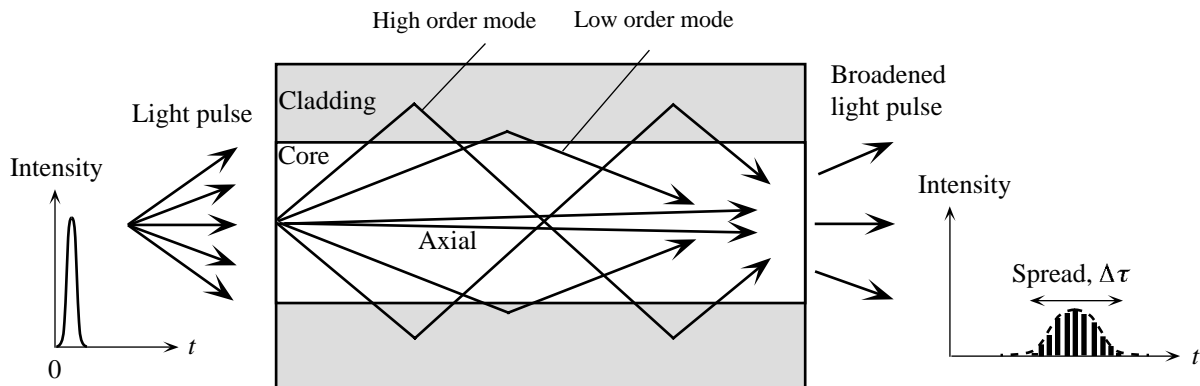
Schematic illustration of light propagation in a slab dielectric waveguide. Light pulse entering the waveguide breaks up into various modes which then propagate at different group velocities down the guide. At the end of the guide, the modes combine to constitute the output light pulse which is broader than the input light pulse.

Mode field diameter MFD ($2w_o$) is the extent of the field distribution across the optical guide in the **fundamental mode**. The field penetrates the **cladding** so that the mode field diameter is not simply the diameter of the **core**. The MFD depends on the *V*-number. If $2a$ is the core region

thickness, then approximately,

$$2w_o \approx 2a\frac{(V+1)}{V}$$

Mode hop is a sudden change in the mode appearing in the lasing output **spectrum** from a laser as a result of temperature change or an increase in the **pumping** (*e.g.* increase in the diode current).
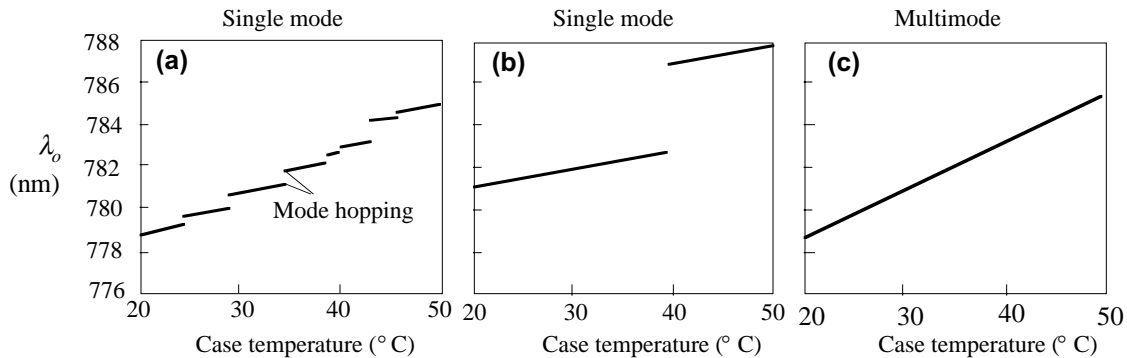
Peak wavelength vs. case temperature characteristics. (a) Mode hops in the output spectrum of a single mode laser diode. (b) Restricted mode hops and none over the temperature range of interest (20 - 40 °C). (c) Output spectrum from a multimode laser diode.

Mode locked laser is a laser that has been constructed to have one transverse mode and many longitudinal modes that have the same phase so that the longitudinal modes reinforce each other to generate an intense pulse of lasing emission at fixed time intervals which depends on the laser cavity length and the speed of light in the lasing medium. Normally the longitudinal modes of a laser tube would be "independent" with random relative phases. In such a case, the output intensity from the laser would simply be the sum of these many individual modes. If, on the other hand, the modes have the same phase then they would reinforce each other in such a way that they generate an intense optical pulse that repeats itself every $T_{\text{round-trip}} = 2L/c$ seconds where L is the **optical resonator** length, c is the velocity of light in the medium and $T_{\text{round-trip}} = 2L/c$ is the round-trip time of a light pulse in the optical resonator. The situation is analogous to taking a fixed number of sine **waves** with multiple frequencies, adjusting their phases so that one can obtain the maximum amplitude from their summation. The achievement of such an intense light pulse at every $T_{\text{round-trip}}$ seconds requires that the "modes are locked", that is their relative phases have been correctly adjusted and fixed, to yield the required maximum output intensity. When modes have been locked, there must be an optical pulse in the resonator that is traveling between the mirrors with a round-trip time of $T_{\text{round-trip}}$ = $2L/c$. The width Δt of an individual pulse depends on the frequency width $\Delta \upsilon$ of the **optical gain** curve between points where the gain just exceeds cavity losses (threshold condition). Of course, $\Delta \upsilon$ also determines how many modes M there are in the output. Thus, $\Delta t \sim 1/\Delta \upsilon \sim T_{\text{round-trip}}/M$. In practice, it is not very difficult to obtain mode locking since the required output must correspond to an intense pulse train of repetition rate $T_{\text{round-trip}}$. This output itself corresponds to a single optical pulse in the resonator bouncing back and forward between the mirrors with a round trip time $T_{\text{round-trip}}$. Each time this pulse impinges on a partially reflecting mirror, a portion of it is transmitted as an output pulse. Suppose that we insert an electro-optic switch that is switched to be made transparent at every $T_{\text{round-trip}}$ seconds. The switch is on to be transparent only when the pulse is there and only for the duration of the pulse. Then the only possible situation is where a single optical pulse can bounce back and forward in the resonator and this corresponds to locking the modes. This is an example of *active* mode locking. Another possibility is *passive* mode locking where a saturable absorber is used in the optical cavity. A saturable absorber's **absorption** decreases with increasing light intensity so that it becomes transparent only at high intensities. This

means the optical cavity is lossy for low light intensities. Such an absorber would only allow a high intensity light pulse to exist in the cavity which would correspond to various modes having the right phases; mode locking. The output pulses are spatially separated by $2L$ because this is the effective distance the pulse in the resonator travels at every $T_{\text{round-trip}}$ seconds to come back to the output mirror and generate another output pulse. A mode-locked **He-Ne laser** typically has a pulse width of about 600 ps where as a mode locked Nd:glass laser pulse width is around 400 fs.


Electro-optic switch turned on transparent every
$2L/c$ seconds.
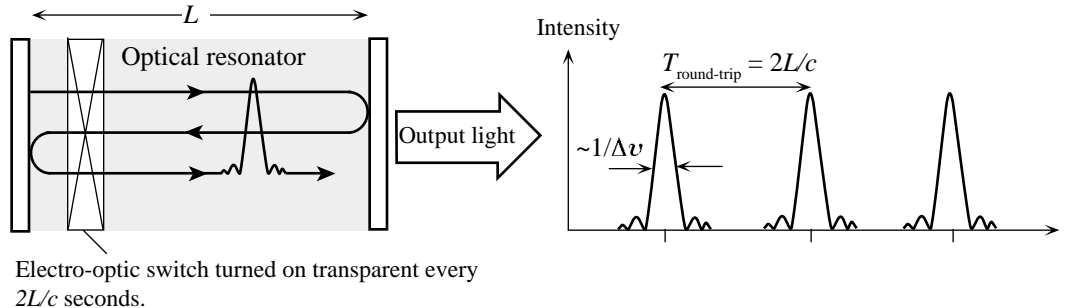
Output light intensity from a mode locked laser is a periodic series of short intense optical pulses that are separated in time by $2L/c$, the round trip time for the pulse in the resonator. Each time the pulse in the resonator impinges on the right mirror, every $2L/c$ seconds, a portion of it is transmitted which constitutes the output .

Mode mixing is the exchange of radiation energy between various modes as light propagates along an **optical fiber**. Due to small variations in the sample geometry and the **refractive index** profile along the fiber, there is a small but finite energy exchange between the propagating modes. One propagating mode gradually excites and transfers energy to another mode and so on leading to *mode mixing*. Consequently, the **bandwidth** of a long **multimode fiber** is generally wider than the expected bandwidth obtained by simple extrapolation from a short fiber. Thus, bandwidth-distance (BL) product is strictly not a constant and is expressed as $BL^{-\gamma}$ = constant where γ is an index between 0.5 to 1 depending on the extent of mode mixing. The index γ is 1 for a short fiber but approaches 0.5 for a long fiber.

Mode number is an integer quantity, analogous to a quantum number, that identifies and distinguishes various allowed modes in an **optical waveguide**.

Mode of a laser is a distinct field pattern at a reflector that can propagate to the other reflector and back again and return the same field pattern. If a particular field pattern can travel from one reflector to the other and back again, experience the right phase change and experience the right amplitude changes to replicate itself, then it is an allowed field pattern and hence a mode of the laser device (the active optical resonator). All such **laser modes**, can be represented by fields (**E** and **B**) that are nearly normal to the cavity axis; they are referred to as *transverse modes* or *transverse electric and magnetic (TEM) modes*. Each allowed mode corresponds to a distinct spatial field distribution at a reflector. These modal field patterns at a reflector can be described by three integers p, q, m and designated by TEM_{pqm}. The integers p, q represent the number of nodes in the field distribution along the transverse directions y and z to the cavity axis x (put differently across the beam cross section). The integer m is the number of nodes along the cavity axis x and is the usual longitudinal **mode number**. Each transverse mode with a given p, q has a set of longitudinal modes (m values) but usually m is very large (~10^6 in gas lasers) and is not written, though understood. Thus, transverse modes are written as TEM_{pq} and each has a set of longitudinal modes ($m = 1, 2, \ldots$). Moreover, two different transverse modes may not necessarily have the same longitudinal frequencies. (For example, the **refractive index** may be not be spatially uniform and different TEM modes have different spatial field distributions.)
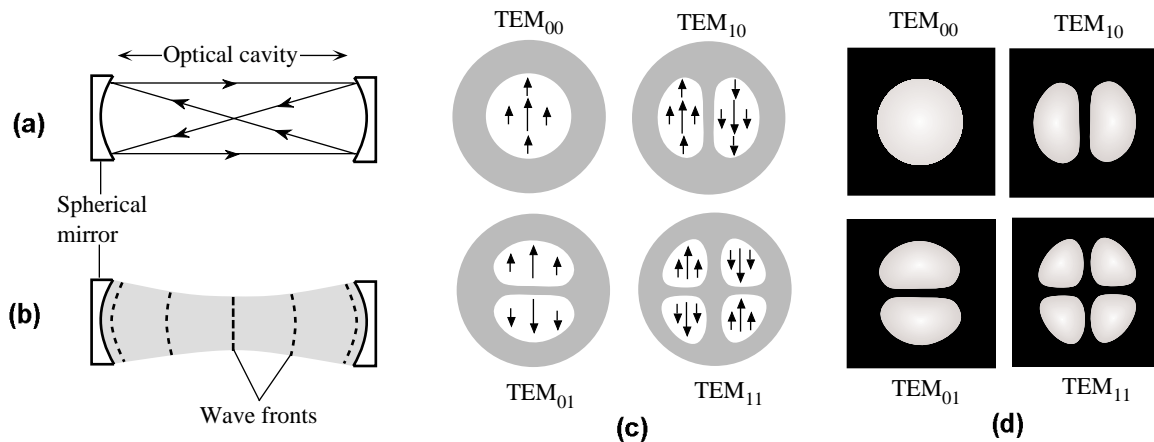
Laser Modes (a) An off-axis transverse mode is able to self-replicate after one round trip. (b) Wavefronts in a self-replicating wave (c) Four low order transverse cavity modes and their fields. (d) Intensity patterns in the modes of (c).

Mode of an optical fiber is a distinct transverse (to the waveguide axis) electric field pattern that can propagate and hence be guided along the waveguide.

Molecular beam epitaxy (MBE) is one of the most advanced epitaxial techniques available today, offering arguably the most flexibility during growth and highest quality material. MBE is a refined form of vacuum evaporation. The refinement comes from the nature of the sources used and the vacuum system itself. The vacuum levels typical for this technique are on the order of 10^{-11} **Torr** permitting molecular flow (*i.e.*, molecules from the source arrive at the **substrate** without suffering collisions with other molecules). These conditions are commonly referred to as *Ultra High Vacuum* (UHV) conditions. MBE sources provide beams of material used for deposition. These beams result in very slow growth rates (about 1 to 3 Å/second for GaAs). Source beams originate from *Knudsen* or **effusion cells**, which are essentially heated crucibles with a defined aperture at their open end. The cells are filled with high purity charges of appropriate elements or compounds and are heated to provide a flux of pure vapor of the appropriate constituent. By blocking the aperture with a shutter the beams can be turned on and off. Given the extremely slow growth rates, this enables atomically engineered device structures to be fabricated (so-called *nanostructures*). Growth is usually performed at relatively low temperatures (from about 580 to 630 ^{o}C for GaAs). **Doping** is achieved by adding appropriate additional Knudsen cells. In general, complex materials structures can be programmed; this is done in practice by adding appropriate Knudsen cells, and by adjusting the flux of atoms from the given cell by adjusting its temperature, while applying appropriate shuttering. Because of the extremely slow growth rates, film quality is excellent, as is the capability to vary structures (*e.g.*, thickness, composition and doping) on the nanoscale. Moreover, layer purity is also excellent as source purity is always strictly controlled and the environment itself is conducive to strict purity standards. Another key feature of the MBE UHV environment is that it is ideally suited for incorporating *in situ* characterization tools including, for example, techniques for real-time layer-by-layer thickness monitoring.

Monochromatic wave is an untruncated sinusoidal **wave** of the form $\sin(\omega t - kz + \phi_o)$ that has a well-defined frequency ω and **wavevector** k (or wavelength λ); it is of infinite space and time extent and hence an idealization. The quantity ϕ_o is a phase constant (independent of z and t) that simply accounts for the fact that the wave may not be zero when $t = 0$ and $z = 0$. The period T of the wave represents the periodicity on the time domain and is $2\pi/\omega$. The wavelength λ of the wave represents the periodicity of the spatial variations and is $2\pi/k$.
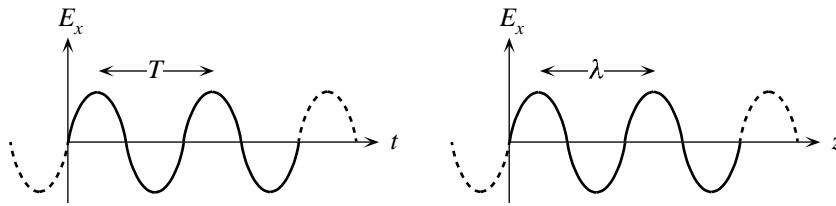
A plane monochromatic wave is a wave in which a property or a quantity such as the electric field (E_x, field along the *x*-direction) is varying with time and space in a sinusoidal fashion over an infinite time scale and for all space

Monomode optical fiber is a single mode optical fiber. See **single mode fiber.**

Moss's rule   see refractive index

Multimode fiber allows the propagation of light via many guides EM (electromagnetic) waves called guided modes along the fiber. Typically it has a **core** diameter that is much larger than the wavelength of light which leads to a **V-number** greater 2.405 and hence to many guided modes.

Multiple quantum well (MQW) lasers have the structure of alternating ultrathin layers of wide and narrow bandgap **semiconductors**. The smaller bandgap layers are the active layers where electron confinement and lasing transition take place whereas the wider bandgap layers are the barrier layers.

A multiple quantum well (MQW) structure. Electrons are injected by the forward current into active layers which are quantum wells.
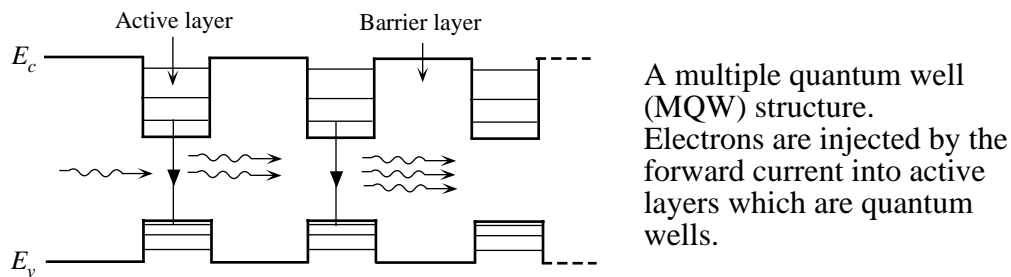
Although the optical gain curve is narrower than the corresponding bulk device, the output **spectrum** from a **quantum well device** is not necessarily a single mode. The number of modes depends on the indiviual widths of the quantum wells. It is, of course possible, to combine a MQW design with a distributed feedback structure to obtain a single mode operation. Many commercially available LDs are currently MQW devices.
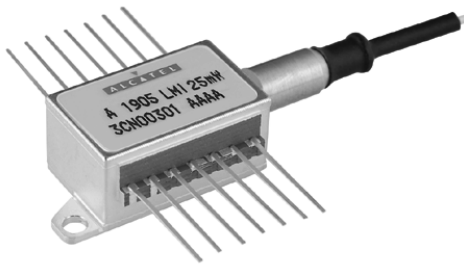
Multiple quantum well device is a **semiconductor** structure that has more than one quantum well and that the quantum wells form a period structure.

Multiplied photocurrent, see avalanche multiplication.

Mutual temporal coherence between two **waves** is time duration over which there is a correlation between two waves. Suppose that two finite length (truncated) identical frequency sine waves coincide only over the time interval Δt. Thus, they can only give rise to **interference** phenomena

over this time interval. They therefore have *mutual temporal coherence* over the time interval Δ*t*.
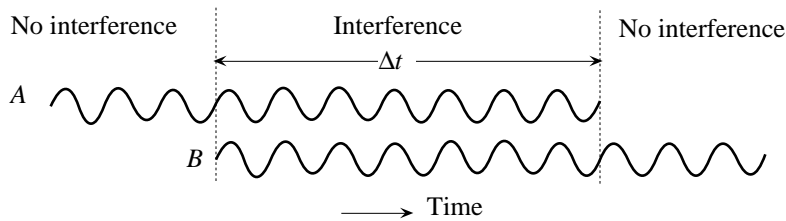
Two waves can only interfere over the time interval Δ*t* which defines
their mutual temporal coherence.

Nanoelectronics refers to the technology for fabricating electronic devices with feature sizes ranging from a few **nanometers** to the sub-**micron** range. The general motivation for implementing this technology is to achieve enhanced functionality of electronic devices; this includes (i) operating speed, (ii) memory capacity, and (iii) novel devices based on quantum-confinement effects. Ultimately, this can lead to a "superchip", which would consist of a three-dimensional network of trillions of switching elements operating at terahertz switching speeds. This will be made possible by reducing feature sizes to the level of several nanometers. Since on this scale, the quantum-mechanical nature of electrons determines their behavior, novel structures, devices and circuits are possible. In such cases, electron **tunneling** and energy quantization are of paramount importance and novel types of nanoelectronic devices have been developed including, for example, *quantum dot and quantum wire based devices, resonant tunneling devices* and *single electron devices*. **Nanofabrication** refers to the **nanometer**-scale fabrication of semiconductor structures and devices and nanometer-scale modification of surfaces. This field is rapidly developing to realise the benefits of **nanoelectronic** devices. We can distinguish between several types of nanofabrication methods: (i) *conventional lithography* and patterning using electron beams, **X-rays**, and **ions**, (ii) methods employing **self-assembly**, and (iii) nanometer-scale fabrication of semiconductor structures and modification of surfaces using *scanning probe microscopy* (SPM) techniques, such as *scanning tunneling microscopy* (STM) and *atomic force microscopy* (AFM).

Nanometer (nm) is the unit of linear measurement equal to 1/1,000,000,000 (one billionth) of a meter. It is equivalent to 10 angstroms or typically to several atom diameters. It is also used in the measurement of the wavelength of light.

Nanotechnology refers to a multidisciplinary field (or set of technologies) for designing, fabricating, and applying **nanometer**-scale materials, structures and devices.

Near field distribution refers to the field distribution or intensity distribution very near an aperture or source so that the intensity pattern differs from the far-field pattern. The near field distribution normally has a distance dependence. In the case of an **optical fiber**, the near field distribution normally refers to the intensity distribution over the cross sectional area of the fiber.
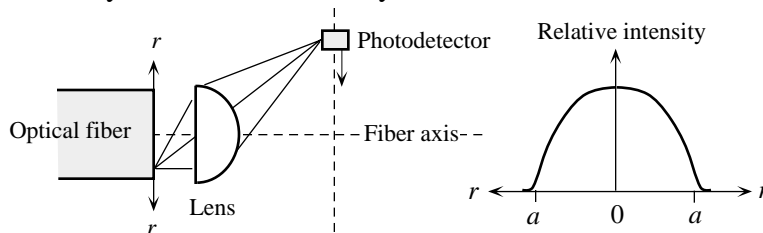
Near-field distribuion from an optical fiber

Noise equivalent power (NEP) is an important property of a photodetector that is defined as the optical signal power required to generate a photocurrent signal that is equal to the total noise current in the

photodetector at a given wavelength and within a **bandwidth** of 1Hz. It is numerically equal to the **optical power** necessary to give a photocurrent equal to the noise current in the detector when the detector bandwidth is 1Hz. NEP represents the required optical power to achieve a signal-to-noise (SNR) of 1 within a bandwidth of 1 Hz. The **detectivity** D is the reciprocal of NEP, $D = 1/\text{NEP}$.

Non-linear optics is the utilization of the fact that the when the electric field of the light **wave** is sufficiently high, the induced **polarization** in a medium is not linearly proportional to the electric field but depends on its higher power as well. The application of an electric field E to a **dielectric** material causes the constituent atoms and molecules to become polarized. The medium responds to the field E by developing a polarization P which represents the net induced dipole moment per unit volume. In a linear dielectric medium the induced polarization P is proportional to the electric field E at that point and the two are related by $P = \varepsilon_o \chi E$ where χ is the **electric susceptibility**. However, the linearity breakdown at high fields and the P vs. E behavior deviates from the linear relationship. P becomes a function of E which means we can expand it in terms of increasing powers of E. It is customary to represent the induced polarization as

$$P = \varepsilon_o \chi_1 E + \varepsilon_o \chi_2 E^2 + \varepsilon_o \chi_3 E^3$$

where χ_1, χ_2 and χ_3 are the linear, second-order and third-order susceptibilities. The coefficients decrease rapidly for higher terms and are not shown in the above equation. The importances of the second and third terms, *i.e.* nonlinear effects, depend on the field strength E. Non-linear effects begin to become observable when fields are very large, *e.g.* ~10^7 V m^{-1}. Such high fields require light intensities (~1000 kW cm^{-2}) that invariably require lasers. All materials, whether crystalline or noncrystalline, possess a finite χ_3 coefficient. However, only certain classes of **crystals** have a finite χ_2, and the reason is the same as for the observation of the **Pockels effect**. Only those crystals, such as quartz, that have no center of symmetry have non-zero χ_2 coefficient; these crystals are also piezoelectric.

Nonradiative transitions, see **radiationless recombination**.

Nonreturn-to-zero, see **return-to-zero**.

Normalized frequency is another name for the *V*-number.

Normalized index difference Δ for a step index optical fiber is defined by $\Delta = (n_1 - n_2)/n_1$ where n_1 and n_2 are the **core** and **cladding** refractive indices respectively.

Normalized propagation constant b is a dimensionless **propagation constant** that is used for mathematical convenience to represent a waveguide mode with a propagation constant β through a definition

$$b = \frac{(\beta/k) - n_2}{n_1 - n_2} \qquad i.e \qquad \beta = n_2 k [1 + b\Delta]$$

where n_1 and n_2 are the **core** and **cladding** refractive indices, k is the free-space **wavevector** and Δ is the normalized **refractive index** difference. The b vs. *V*-number characteristics for various **linearly polarized modes** are then universal for weakly guiding **step index fibers**.
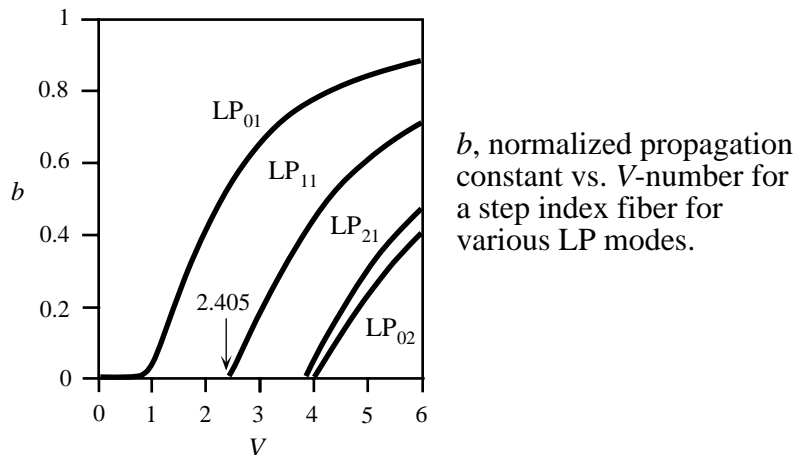
b, normalized propagation constant vs. *V*-number for a step index fiber for various LP modes.

Normalized thickness is another name for the *V*-number.

Numerical aperture is a characteristic of an **optical fiber** that depends on the refractive indices of the **core** and the **cladding** and measures light gathering ability of the core. It is the sine of the maximum **acceptance angle** at which a ray of light can enter the fiber core and propagate along the core. If n_1 and n_2 are the core and cladding refractive indices of a step index optical fiber, the numerical aperture *NA* is defined by

$$NA = \left(n_1^2 - n_2^2\right)^{1/2}$$

Ohmic conduction refers to electrical conduction that is governed by $J = \sigma E$ where σ is the conductivity of the material. The current flow is limited by the rate of transport of intrinsic charge carriers (e.g electrons and holes) in the material and their **drift mobility** and not by the rate of carrier injection from the electrical contacts. The contacts ideally simply replenish the electrons and holes in the material reaching the electrodes and exiting the sample.

Ohmic contact is a contact that can supply charge carriers to a **semiconductor** at a rate determined by charge transport through the semiconductor and not by the contact properties itself. Thus the current is limited by the conductivity of the semiconductor and not be the contact.

Optic axis of an anisotropic **crystal** is a direction in the crystal along which all **waves** have the same **phase velocity** whatever their **polarization**. For example the **ordinary** and the **extraordinary waves** traveling along the optic axis have the same phase velocity and experience the same **refractive index**.

Optical activity refers to the rotation of the electric field **E**-vector of a **linearly polarized** light **wave** as it passes through certain **crystals**, such as a quartz, along the **optic axis**. This rotation increases continuously with the distance traveled through the crystal (about 21.7° per mm of quartz). The rotation of the plane of polarization by a substance is called *optical activity*. In very simply intuitive terms, optical activity occurs in materials in which the electron motions induced by the external electromagnetic field follows spiraling or helical paths (orbits)[1]. Electrons flowing in helical paths resemble a current flowing in a coil and thus possess a magnetic moment. The **optical field** in light therefore induces oscillating magnetic moments which can be either parallel or antiparallel to the induced oscillating electric dipoles. Wavelets emitted from these oscillating induced magnetic and electric dipoles interfere to constitute a forward wave that has its optical field rotated either clockwise or counterclockwise. If θ is the angle of rotation, then θ is proportional to the distance *L* propagated

---

[1] The explanation of optical activity involves examining both induced magnetic and electric dipole moments which will not be described here in detail. There are very readable qualitative explanations as mentioned under Further Reading.

in the optically active medium. For an observer receiving the wave through quartz , the rotation of the plane of polarization may be *clockwise* (to the right) or *counterclock*wise (to the left) which are called *dextrorotatory* and *levorotatory* forms of optical activity. The structure of quartz is such that atomic arrangements spiral around the **optic axis** either in clockwise or counterclockwise sense. Quartz thus occurs in two distinct crystalline forms, right-handed and left-handed, which exhibit dextrorotatory and levorotatory types of optical activity respectively. Although we used quartz as an example, there are many substances that are optically active, including various biological substances and even some liquid solutions (*e.g.* corn syrup) that contain various organic molecules with a rotatory power. The *specific rotatory power* is defined as the extent of rotation per unit length. (θ/L) of distance traveled in the optically active substance. Specific rotatory power depends on the wavelength. For example, for quartz this is 49° at 400 nm but 17° at 650 nm.
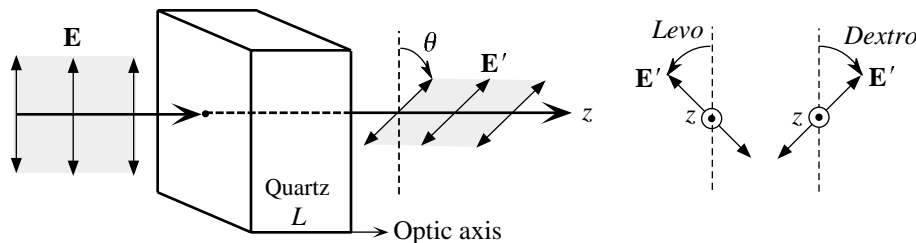
An optically active material such as quartz rotates the plane of polarization of the incident wave: The optical field **E** rotated to **E**′. If we reflect the wave back into the material, **E**′ rotates back to **E**.

Optical amplifier is an amplifier that amplifies an optical signal, that is light. A common type of an optical amplifier is an *erbium ion doped optical fiber amplifier* (EDFA) in which erbium ions are pumped to an excited state by using a **laser diode** (or an LED) at 980 nm. This **pumping** leads to a **population inversion** of Er-ions that corresponds to a narrow wavelength range around 1550 nm which is long-haul communications wavelength.

Optical divergence refers to the angular separation of **wavevectors** on a given **wavefront**. Put differently, it describes how a propagating **wave** spreads out as it travels. A **spherical wave** has a 360° of divergence. A perfect **plane wave** has a 0° of divergence. Plane and spherical waves represent two extremes of wave propagation behavior from perfectly parallel to fully diverging wavevectors. They are produced by two extremes sizes of electromagnetic (EM) wave source; an infinitely large for the plane wave and a point source for the spherical wave. In reality, an EM source is neither of infinite extent nor in point form, but would have a finite size and finite power. See **diverging waves**.

Optical fiber amplifier is an **optical amplifier** consisting of a **glass** fiber doped with certain rare-earth ions such as Er^{3+} ions, operating on the principle of **stimulated emission**. Typically it is a glass **optical fiber** whose **core** is doped with rare earth ions which are optically excited from an external light source to achieve **population inversion** and hence optical amplification.

Optical fiber is a thin cylindrical glass fiber, perhaps 100 microns or so in total thickness (as thin as hair), that acts as a dielectric waveguide, that is guiding light (**electromagnetic waves**) from one end to the other. An optical fiber has a **core** region of higher **refractive index** and a surrounding region, **cladding**, of lower refractive index which "clads" the core. In the case of a **step index fiber**, the change in the refractive index from the core to the cladding occurs as a step and typically this change is very small (less than 1%). The core region must have as low optical **attenuation** as possible to allow the transmission of light through the optical fiber. Light entering the fiber can only propagate along the fiber as certain distinct electric field patterns across the fiber, each of which is a distinct

mode of the fiber. If the wavelength of the light is longer than the **cut-off wavelength** of the waveguide, then only the **fundamental mode** can propagate and there in no intermode **dispersion.**
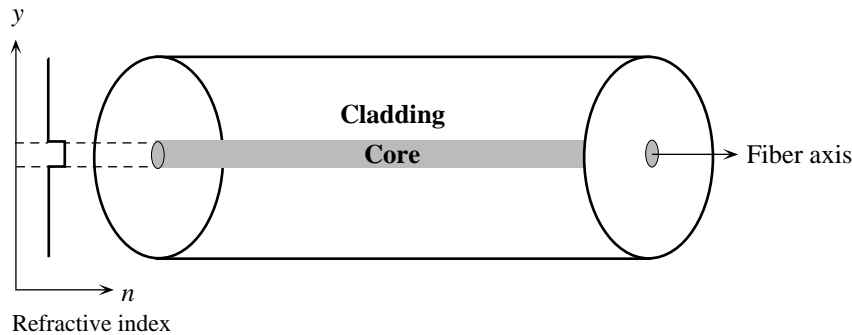
A step index optical fiber

Professor Charles Kao who has been recognized as the inventor of fiber optics is receiving an IEE prize from Professor John Midwinter (1998 at IEE Savoy Place, London, UK; courtesy of IEE)
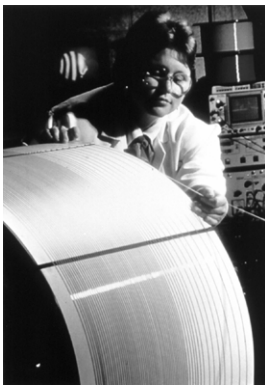
Reeled optical fibers on a drum. (Courtesy of Corning.)

Optical field is the electric field in a light **wave**.

Optical gain lineshape describes the **optical gain** g vs. wavelength λ (or frequency υ) behavior of a medium. Normally the medium is pumped to achieve an optical gain. The lineshape function is the function $g = g(\upsilon)$ that represents the optical gain g vs. frequency (υ) behavior. See **laser output spectrum**.

Optical gain occurs whenever the **irradiance** of an electromagnetic radiation is amplified as the radiation propagates through a medium. The amplification is usually described by an *optical gain coefficient g* which is the fractional increase in the **optical power** per unit distance along the direction of

propagation. The amplification generally involves the rate of **stimulated emissions** exceeding **absorption** and **spontaneous emission**.

Optical indicatrix (Fresnel's ellipsoid) is a **refractive index** surface placed in the center of the **principal axes** x, y and z of a **crystal**; axis intercepts are n_1, n_2, and n_3. We can represent the optical properties of a crystal in terms of three refractive indices along three orthogonal axes, the principal axes of the crystal, x, y and z . These are special axes along which the **polarization vector** and the electric field are parallel. (Put differently, the electric displacement **D** and the electric field **E** vectors are parallel). The refractive indices along these x, y and z axes are the principal indices n_1, n_2 and n_3 respectively for electric field oscillations along these directions (not to be confused with the **wave** propagation direction). For example, for a wave with a polarization parallel to the x-axes, the refractive index is n_1. The refractive index associated with a particular electromagnetic (EM) wave in a crystal can be determined by using this optical indicatrix, that is Fresnel's *refractive index ellipsoid*. If all three indices were the same, $n_1 = n_2 = n_3 = n_o$ we would have a spherical surface and all electric field polarization directions would experience the same refractive index, n_o. Such a spherical surface would represent an optically isotropic crystal. For positive **uniaxial crystals** such as quartz, $n_1 = n_2 < n_3$. Suppose that we wish to find the refractive indices experienced by a wave traveling with an arbitrary wave vector **k**, which represents the direction of phase propagation. Suppose that this phase propagation direction is OP and is at an angle θ to the z-axis. We place a plane perpendicular to OP and passing through the center O of the indicatrix. This plane intersects the ellipsoid surface in a curve $ABA'B'$ which is an *ellipse*. The major (BOB') and minor (AOA') axes of this ellipse determine the field oscillation directions and the refractive indices associated with this wave. Put differently, the original wave is now represented by two orthogonally **polarized EM waves**. The line AOA', the *minor axis*, corresponds to the polarization of the ordinary wave and its semiaxis AA' is the refractive index $n_o = n_2$ of this o-wave. The electric displacement and the electric field are in the same direction and parallel to AOA'. If we were to change the direction of OP we would always find the same minor axis, *i.e.* n_o is either n_1 or n_2 whatever the orientation of OP (try orientating OP to be along y and along x). This means that the o-wave always experiences the same refractive index in all directions. (The o-wave behaves just like an ordinary wave (hence the name). The line BOB', the *major axis*, corresponds to the electric displacement field (**D**) oscillations in the **extraordinary wave** and its semiaxis OB is the refractive index $n_e(\theta)$ of this e-wave. This refractive index is smaller than n_3 but greater than n_2 ($= n_o$). The e-wave therefore travels more slowly than the o-wave in this particular direction and in this crystal. If we change the direction of OP, we find that the length of the major axis changes with the OP direction. Thus, $n_e(\theta)$ depends on the wave direction, θ. As apparent, $n_e = n_o$ when OP is along the z-axis, that is, when the wave is traveling along z. This direction is the **optic axis** and all waves traveling along the optic axis have the same **phase velocity** whatever their polarization. When the e-wave is traveling along the y-axis, or along the x-axis, $n_e(\theta) = n_3 = n_e$ and the e-wave has its slowest phase velocity. Along any OP direction that is at an angle θ to the optic axis, the e-wave has a refractive index $n_e(\theta)$ given by

$$\frac{1}{n_e(\theta)^2} = \frac{\cos^2 \theta}{n_o^2} + \frac{\sin^2 \theta}{n_e^2}$$

Clearly, for $\theta = 0°$, $n_e(0°) = n_o$ and for $\theta = 90°$, $n_e(90°) = n_e$. The major axis BOB' determines the e-wave polarization by defining the direction of the displacement vector **D** and not **E**. Although **D** is perpendicular to **k**, this is not true for **E**. The electric field of the e-wave is orthogonal to that of the o-wave, and it is in the plane determined by **k** and the optic axis, as discussed below. **E** is

orthogonal to **k** when the *e*-wave propagates along one of the principal axes.
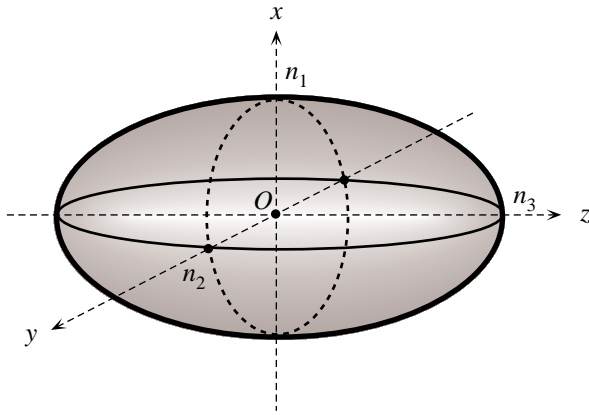
(a) Fresnel's ellipsoid
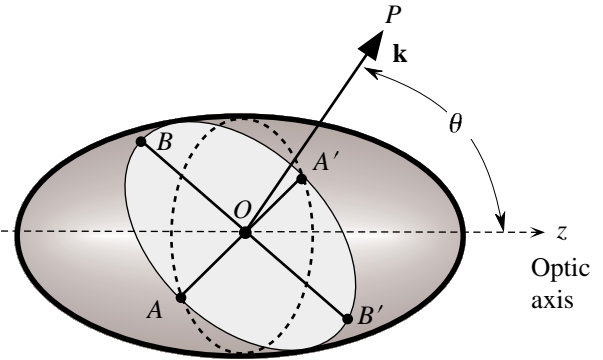
(b) An EM wave propagating along *OP* at an angle θ to optic axis.

Optical isolator allows light to pass in one direction and not in the opposite direction. For example, the light source can be isolated from various reflections by placing a polarizer and a Faraday rotator that rotates the field by 45°. The reflected light will have a $2\theta = 90°$ rotation and will not pass through the polarizer back to the source. The **magnetic field** is typically applied by enclosing the Faraday medium in a rare-earth magnet ring.
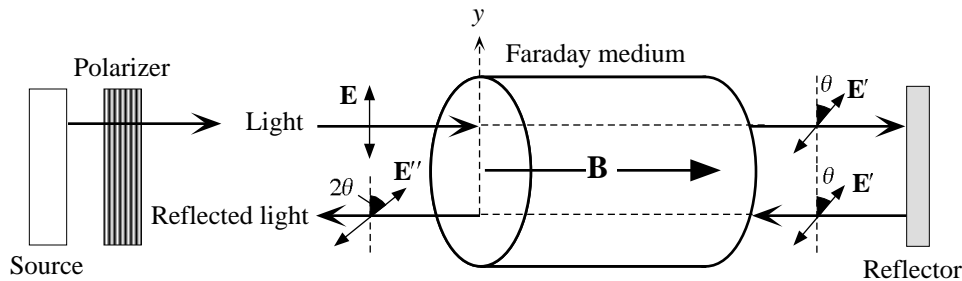
The sense of rotation of the optical field **E** depends only on the direction of the magnetic field for a given medium (given Verdet constant). If light is reflected back into the Faraday medium, the field rotates a further θ in the same sense to come out as **E″** with a 2θ rotation with respect to **E**.

Faraday effect optical isolators: Air-path isolators (top) and laser diode-to-fiber isolator (below). The cylindrical case contains a rare-earth magnet. (Courtesy of OFR.)

Optical Kerr effect is the change in the **refractive index** of an optically isotropic medium when the intensity of a propagating light **wave** is sufficiently high. Consider a material in which the **polarization** *P* does not have the second order term

$$P = \varepsilon_o \chi_1 E + \varepsilon_o \chi_3 E^3 \quad \text{or} \quad P/(\varepsilon_o E) = \chi_1 + \chi_3 E^2$$

The first term with the **electric susceptibility** χ_1 corresponds to the relative permittivity ε_r and hence to the refractive index n_o of the medium in the absence of the third order term, *i.e.* under low fields. The E^2 term represents the **irradiance** $\mathcal{I}$ of the beam. Thus, the refractive index depends on the intensity of the light beam, a phenomenon called the optical Kerr effect

$$n = n_o + n_2 \mathcal{I} \quad \text{and} \quad n_2 = \frac{3\eta\chi_3}{4n_o^2}$$

The phase ϕ of an **electromagnetic wave** at a point z is given by

$$\phi = \omega_o t - \frac{2\pi n}{\lambda} z = \omega_o t - \frac{2\pi[n_o + n_2 \mathcal{I}]}{\lambda} z$$

It is clear that the phase depends on the light intensity and the change in the phase along Δz due to light intensity alone is

$$\Delta\phi = \frac{2\pi n_2 \mathcal{I}}{\lambda} \Delta z$$

As the light intensity modulates the phase, this is called **self-phase modulation**. Obviously light is controlling light. Consider the phase at time t and point z:

$$\phi = \omega_o t - \frac{2\pi n}{\lambda} z = \omega_o t - \frac{2\pi[n_o + n_2 \mathcal{I}]}{\lambda} z$$

When the light intensity is small $n_2 \mathcal{I} \ll n_o$, obviously $\omega = \partial\phi/\partial t = \omega_o$. However, suppose we have an intense beam and the intensity $\mathcal{I}$ is time dependent $\mathcal{I} = \mathcal{I}(t)$. Consider a pulse of light traveling along the z-direction and the light intensity vs. t shape is a "Gaussian" (this is approximately so when a light pulse propagates in an **optical fiber**, for example). Then the instantaneous frequency is

$$\omega = \frac{\partial\phi}{\partial t} = \omega_o - \frac{2\pi n_2 z}{\lambda} \frac{\partial \mathcal{I}}{\partial t}$$

so that the frequency changes with "time", or across the light pulse. Since $\partial \mathcal{I}/\partial t$ is rising at the leading edge and falling in the trailing edge, the two ends of the pulse contain different frequencies! The change in the frequency over the pulse is called *chirping*. Self-phase modulation therefore changes the frequency **spectrum** of the light pulse during propagation. The second term above results in the broadening of the frequency spectrum and hence leads to more **dispersion** for a Gaussian pulse propagating in an optical fiber. A **Gaussian beam** passing through a plate of nonlinear medium can become *self-focused* by the optical Kerr effect.

The intensity variation across the beam cross section leads to a similar refractive index variation in the nonlinear medium. Thus, the medium resembles a graded index guide or a GRIN rod and can focus the beam.

Intensity across beam cross section
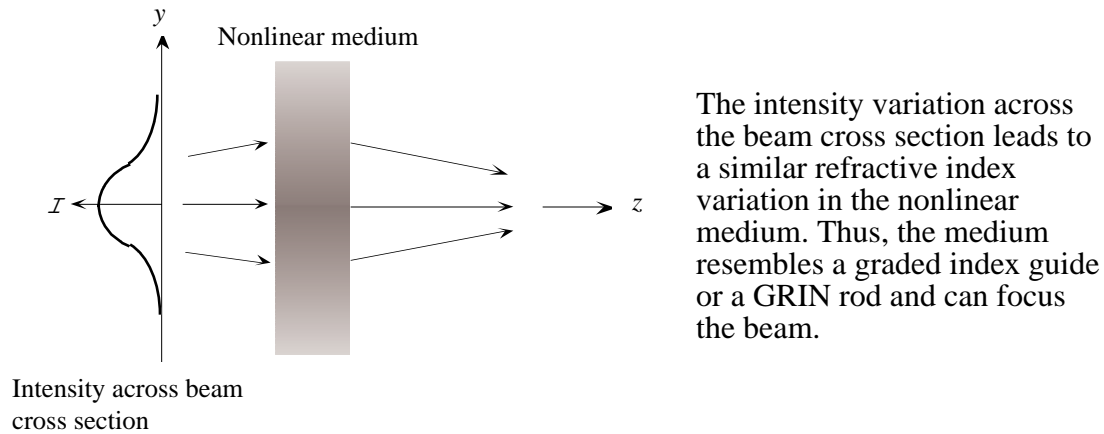
Optical power is the **electromagnetic wave** (light) energy flowing per unit time through an area of interest. It is also called the radiant flux. Light intensity, also known as **irradiance** or radiant flux density, is the optical power flowing per unit area.

Optical rectification is the generation of a dc voltage, or **polarization** (*P*), in a nonlinear medium from an **electromagnetic wave** (light). The electromagnetic oscillations at the light frequency are "rectified" by the medium to result in a constant (dc) polarization.

Optical resonator is an *optical cavity* defined by two reflectors such that only certain light frequencies are allowed to exist within the cavity just as only certain frequencies are allowed in an electrical *LC* circuit. The cavity may contain an optical medium with a refractive index. If the reflectors are flat and parallel mirrors then the resonator is called a *Fabry-Perot resonator or etalon*. Only certain frequencies υ_m are allowed within the cavity, or to pass through the resonator. For example, if υ_m is an allowed frequency, a *mode of the resonator*, then $\upsilon_m = mc/(2L)$ where *L* is the cavity length and *m* is an integer 1,2,….The width of each mode depends on the cavity losses including mirror **reflectances**.

Fabry-Perot etalon

Transmitted light through a Fabry-Perot optical cavity.
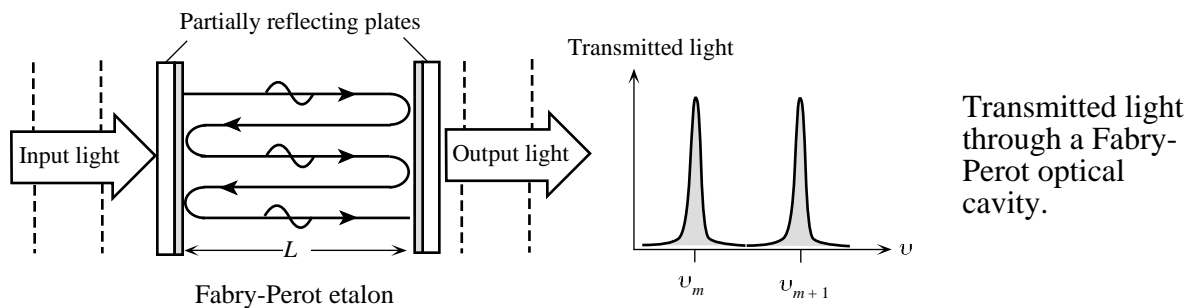
Optical semiconductor amplifier is a **semiconductor laser** structure that can be used as an **optical amplifier** that amplifies light **waves** passing through its **active region**. Light to be amplified is made to enter the active region of the laser semiconductor diode and the active region is pumped by a sufficiently large diode current just as in a normal **laser diode**. The wavelength of radiation to be amplified must be within the optical gain **bandwidth** of the laser. Such a device would not be laser oscillator, emitting lasing emission without an input, but an optical amplifier with input and output ports for light entry and exit. In the *traveling wave semiconductor laser* amplifier the ends of the optical cavity have antireflection (AR) coatings so that the optical cavity does not act as an efficient **optical resonator**, a condition for laser-oscillations. Light, for example, from an **optical fiber**, is coupled into the active region of the laser structure. As the radiation propagates through the active layer, optically guided by this layer, it becomes amplified by the induced **stimulated emissions**, and leaves the optical cavity with a higher intensity. The *Fabry-Perot laser amplifier* is similar to the conventional laser oscillator, but is operated below the **threshold current** for lasing oscillations; the active region has an **optical gain** but not sufficient to sustain a self-lasing output. Light passing through such an active region will be amplified by stimulated emissions but, because of the presence of an optical resonator, there will be internal multiple reflections. These multiple reflections lead to the gain being highest at the resonant frequencies of the cavity within the optical gain bandwidth. Optical frequencies around the cavity resonant frequencies will experience higher gain than those away from resonant frequencies. Although the Fabry-Perot laser amplifier can have a higher gain than the traveling wave amplifier, it is less stable.

(a) Traveling wave amplifier   (b) Fabry-Perot amplifier
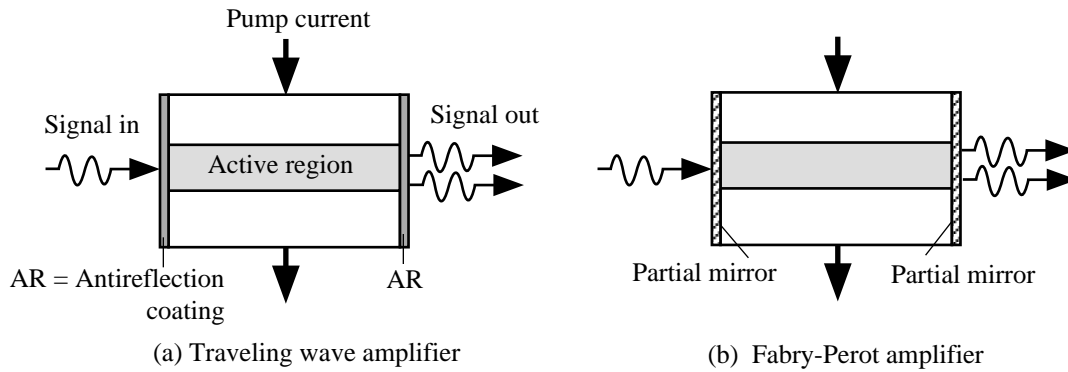
Simplified schematic illustrations of two types of laser amplifiers
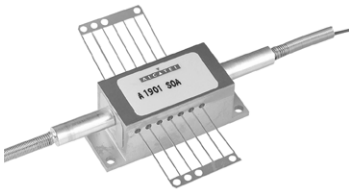
A 1550 nm semiconductor optical amplifier using an InGaAsP chip. (Courtesy of Alcatel)

Optical time domain reflectometry (OTDR) is a technique in which light **attenuation** along an **optical fiber** is determined as a function of distance along the fiber by measuring the backscattered light power . A very short light pulse is launched at the front end of a fiber. As this pulse propagates, portions of it become scattered (Rayleigh **scattering**). A further portion of these scattered **waves** in the backward direction will enter a guided mode of the fiber and become guided back; this is the *backscattered wave*. When the backscattered waves reach the front end, they are directed towards a detector where the backscattered power P_{BS} is measured as a function of time t from the launch instant. The time t of observation represents a "round trip" time from the fiber front end to the scattering point x and back to the front end. Thus, time t corresponds to a distance $2x = t \times$(velocity in **core**) which means that $x = ct/2n_1$, where n_1 is the core **refractive index**. The detected backscattered signal is analyzed and displayed as backscattered power (usually in dB) vs. distance, x. As x (*i.e.* time) increases, representing further propagation along the fiber, P_{BS} decreases as a result of attenuation along the fiber. A **splice** typically leads to a drop in P_{BS} due to a degree of attenuation at the splice. An end-to-end fiber connection may exhibit a spike due to a **Fresnel reflection** (dielectric-dielectric reflection). When the pulse reaches the far-end, it experiences a Fresnel reflection which occurs as a final spike in the OTDR signal. The P_{BS}, the power in the backscattered wave, is a fraction of the forward traveling wave but attenuated by $\exp(-\alpha x)$, where α is the attenuation coefficient. This is because the backscattered wave travels a distance x back to the front end. Since the forward wave at x is $\exp(-\alpha x)$ of the launch power,

$$P_{BS} \propto \exp(-2\alpha x),$$

and $d\ln(P_{BS})/dx = -2\alpha$

Clearly, the slope of P_{PB} (dB) vs x provides an indication of the local attenuation α at x.
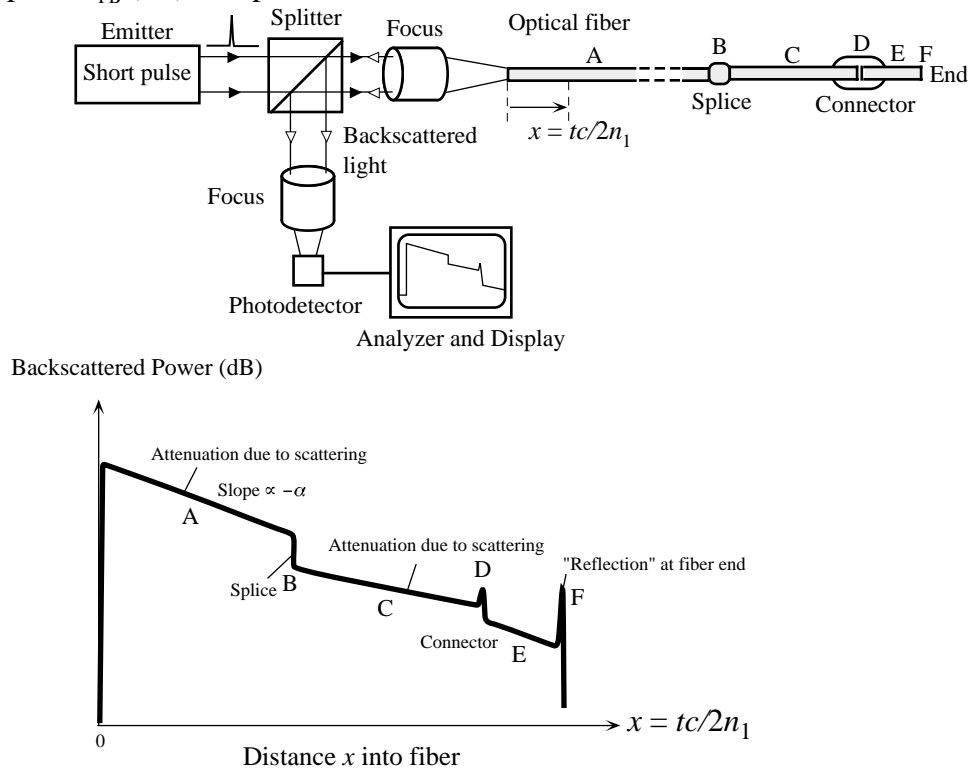
Optical time domain reflectometer (schematic) and a typical result on a fiber that has a splice and a connector (the curve is idealized.)

Optical tunneling is a phenomenon in which light is able to tunnel through a thin optical barrier and appear on the other side. The intensity of the transmitted light through the barrier depends on the thickness of the barrier; and decreases exponentially with this thickness.
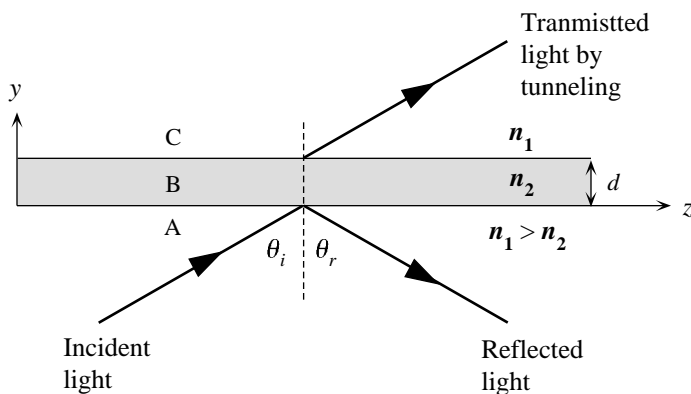
When medium B is thin (thickness d is small), the field penetrates to the BC interface and gives rise to an attenuated wave in medium C. The effect is the tunneling of the incident beam in A through B to C.

Optical waveguide is a dielectric waveguide which has a **core** region of higher **refractive index** surrounded by a region of lower refractive index called the **cladding**. **Electromagnetic waves** with wavelengths in the optical region propagate in the core region of guide by **total internal reflection**.

Optically denser medium has a higher **refractive index**.

Optimal profile index ($\gamma_{optimal}$) is the value of the **profile index** that results in a minimum of intermodal dispersion; typically $\gamma \approx 2$.

Outside vapor deposition (OVD) is one of the vapor deposition techniques used to produce the rod **preform** used in fiber **drawing**. The OVD process has two stages. The first **laydown** stage involves using a fused **silica glass** rod (or a ceramic rod such as alumina) as a target rod. This acts as a mandrel and is rotated. The required glass material for the preform with the right composition is grown on the outside surface of this target rod by depositing glass soot particles. The deposition is achieved by burning various gases in an oxyhydrogen burner (torch) flame where glass soot is produced as reaction products.
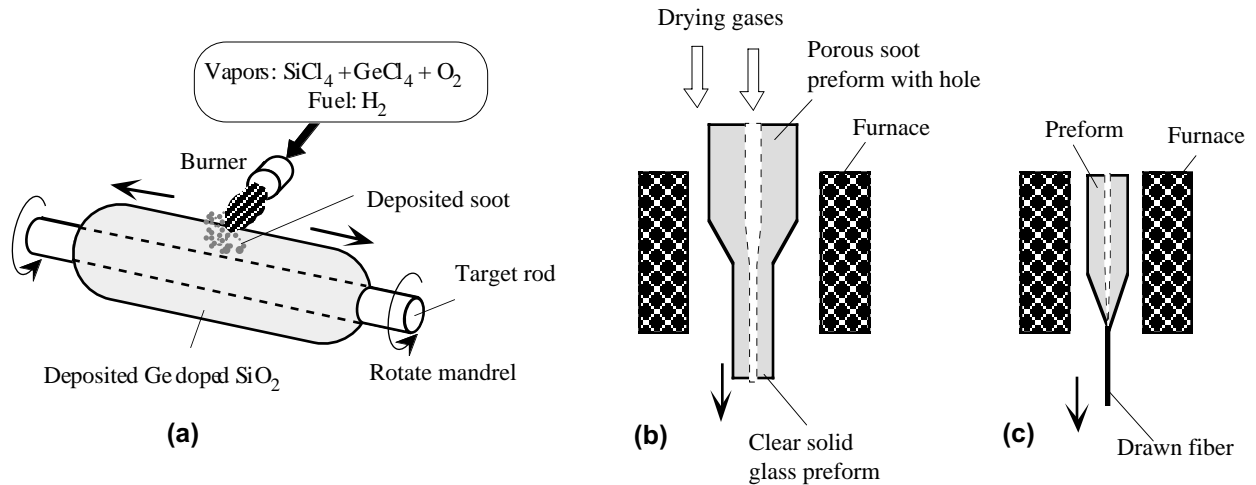
Schematic illustration of OVD and the preform preparation for fiber drawing. (a) Reaction of gases in the burner flame produces glass soot that deposits on to the outside surface of the mandrel. (b) The mandrel is removed and the hollow porous soot preform is consolidated; the soot particles are sintered, fused, together to form a clear glass rod. (c) The consolidated glass rod is used as a preform in fiber drawing.

Pauli exclusion principle excludes any two electrons from having the same set of quantum numbers, n, ℓ, m_ℓ, m_s in a given system of confined electrons, where n is the **principal quantum number**, ℓ is the orbital angular momentum quantum number, m_ℓ is the magnetic quantum number and m_s is the magnetic spin quantum number. There can be no two electrons occupying a given **state** $\psi(n, \ell, m_\ell, m_s)$, where ψ is the electron **wavefunction** including spin. Equivalently, up to two electrons with opposite spins can occupy a given orbital, $\psi(n, \ell, m_\ell)$.

Penetration depth of an **electromagnetic wave** into a medium is the distance over which the electric field drops by a factor of e^{-1}. Penetration depth δ is the reciprocal of the **attenuation** coefficient α in the medium; $\delta = 1/\alpha$. See **absorption coefficient.**

Phase mismatch between two propagating **waves** to the difference between their propagation constants β, that is $\Delta\beta$.

Phase modulator is a **Pockels effect** modulator in which the an applied voltage, and hence the applied electric field, modulates the **refractive index** and hence the phase of a light **wave** propagating through the **crystal**. For example, in the transverse phase modulator, the applied electric field, $E_a = V/d$, is applied in a transverse direction to the propagation of the light wave. Suppose that E_a is parallel to the y-direction, normal to the direction of light propagation along z. Suppose that the incident beam is **linearly polarized** with **E** say at 45° to the y axes. We can represent the incident

light in terms of **polarizations** ($\mathbf{E}_x$ and $\mathbf{E}_y$) along the x and y axes. These components $\mathbf{E}_x$ and $\mathbf{E}_y$ experience refractive indices n'_1 and n'_2 respectively. Thus when $\mathbf{E}_x$ traverses the distance L, its phase change is by ϕ_1,

$$\phi_1 = \frac{2\pi n'_1}{\lambda} L = \frac{2\pi L}{\lambda}(n_o + \tfrac{1}{2}n_o^3 r_{22}\frac{V}{d})$$

When the component $\mathbf{E}_y$ traverses the distance L, its phase change is by ϕ_2, given by a similar expression except that r_{22} changes sign. Thus the phase change $\Delta\phi$ between the two field components is

$$\Delta\phi = \phi_1 - \phi_2 = \frac{2\pi}{\lambda} n_o^3 r_{22}\frac{L}{d}V$$

The applied voltage thus inserts an adjustable phase difference $\Delta\phi$ between the two field components. The polarization state of output wave can therefore be controlled by the applied voltage and the Pockels cell is a *polarization modulator*. We can change the medium from a quarter-wavelength to a **half-wave plate** by simply adjusting V. The voltage $V = V_{\lambda/2}$, the *half-wave voltage*, corresponds to $\Delta\phi = \pi$ and generates a half-wave plate. The advantage of the transverse **Pockels effect** is that we can independently reduce d, and thereby increases the field, and increase the crystal length L, to build-up more phase change; $\Delta\phi$ is proportional to L/d. This is not the case in the longitudinal Pockels effect. If L and d were the same, typically $V_{\lambda/2}$ would be a few kilovolts but tailoring d/L to be much smaller than unity would bring $V_{\lambda/2}$ down to desirable practical values.
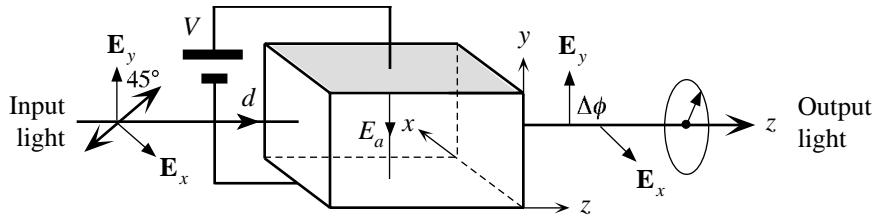
Tranverse Pockels cell phase modulator. A linearly polarized input light into an electro-optic crystal emerges as a circularly polarized light.

Phase of a traveling **wave** is the quantity $(kx - \omega t)$ which determines the amplitude of the wave at position x and at time t given $k(=2\pi/\lambda)$ and ω. In three dimensions it is the quantity $(\mathbf{k}\cdot\mathbf{r} - \omega t)$ where $\mathbf{k}$ is the **wavevector** and $\mathbf{r}$ is the position vector; the amplitude is measured at time t.

Phase velocity is the rate at which a given phase on a traveling **wave** advances. It represents the velocity of a given phase rather than the velocity at which information is carried by the wave. Two consecutive peaks of a wave are separated by a wavelength λ and it takes a time period $1/\upsilon$ for one peak to reach the next (or time -separation of two consecutive peaks at one location), then the phase velocity is defined as $v = \lambda/(1/\upsilon) = \lambda\upsilon$.

Phonon is a quantum of energy associated with the vibrations of the atoms in the **crystal**, analogous to the **photon**. A phonon has an energy of $\hbar\Omega$ where Ω is the angular frequency of the **lattice** vibration, and $\hbar = 2\pi/h$, $h = $ **Planck's constant**. If K is the **wavevector** of a lattice vibration wave, a phonon, then the momentum of the phonon is $\hbar K$.

Phosphorescence, see **luminescence**.

Phosphors, see **luminescence**.

Photocarrier is a charge carrier in a **semiconductor** (or any device) that has been generated by the **absorption** of light.

Photoconductive detectors have the simple metal-semiconductor-metal structures, that is two electrodes are attached to a **semiconductor** that has the desired **absorption coefficient** and quantum efficiency over the wavelengths of interest. Incident **photons** become absorbed in the semiconductor and photogenerate electron hole pairs (EHPs). The result is an increase in the conductivity of the semiconductor and hence an increase in the external current which constitutes the photocurrent I_{ph}. The actual response of the detector depends whether the contacts to the semiconductor are ohmic or blocking (for example Schottky junctions that do not inject carriers) and on the nature of carrier **recombination** kinetics.
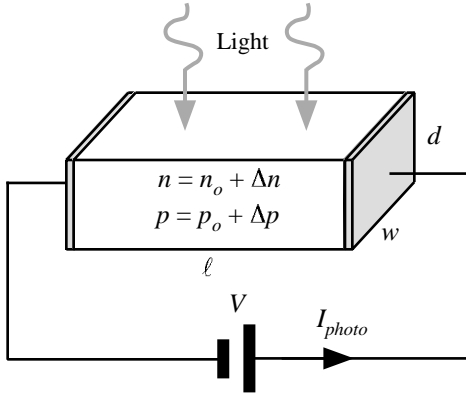
A semiconductor slab of length ℓ, width w and depth d is illuminated with light of wavelength λ and intensity is I. Equilibrium carrier concentrations are n_o and p_o. Under steady state illumination these become $n = n_o + \Delta n$ and $p = p_o + \Delta p$. The change in the conductivity $\Delta\sigma$ is the photoconductivity of the sample.

The **photoconductivity** of the sample $\Delta\sigma$ under uniform illumination is given by

$$\Delta\sigma = \frac{e\eta I \lambda \tau (\mu_e + \mu_h)}{hcd}$$

where e is the electronic charge, η is the quantum efficiency, μ_e and μ_h are the electron and hole drift mobilities, τ is the mean recombination time (lifetime), h is **Planck's constant**, c is the speed of light and d is the thickness of the photoconductive slab. It is assumed that all the incident radiation is absorbed; otherwise this expression must be multiplied by $[1 - \exp(-\alpha d)]$, where α is the absorption coefficient at the wavelength of interest.

Photoconductive gain is occurs in a photoconductor when the *external* photocurrent is due to more than one electron flow per absorbed **photon**. The photoconductor must have **ohmic contacts** to allow carriers to enter the **semiconductor**. The photoconductive gain is then simply

$$G = \frac{\text{Rate of electron flow in external circuit}}{\text{Rate of electron generation by light absorption}}$$

which can be shown to be

$$G = \frac{\tau}{t_e}\left(1 + \frac{\mu_h}{\mu_e}\right)$$

where μ_e and μ_h, are the drift mobilities of the electrons and holes respectively, t_e is the electron *transit time*, $t_e = \ell/(\mu_e E)$ where ℓ is the photoconductor length and E is the electric field and τ is the mean recombination time. The photoconductive gain can be quite high if τ/t_e is kept large which means a long recombination time and a short transit time. The transit time can be made shorter by applying a greater field but this will also lead to an increase in the **dark current** and more noise. The speed of response of the device is limited by the recombination time of the injected carriers. A

long τ means a slow device.
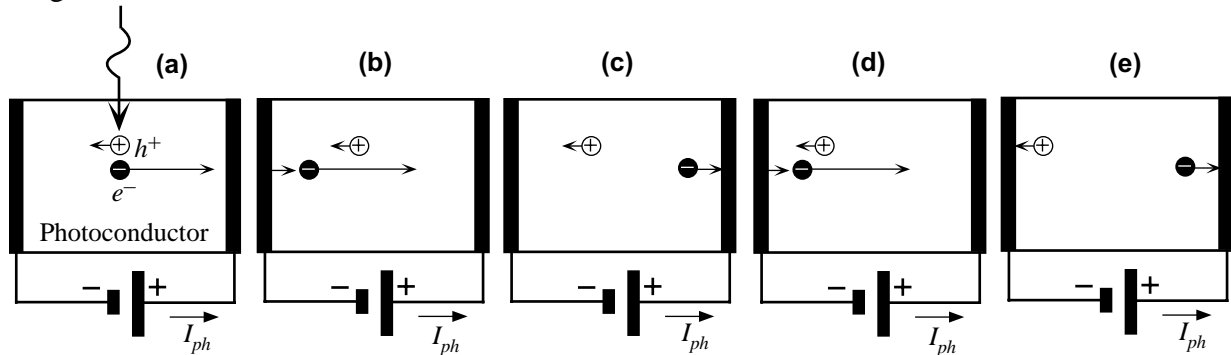
A photoconductor with ohmic contacts (contacts not limiting carrier entry) can exhibit gain. As the slow hole drifts through the photoconductors, many fast electrons enter and drift through the photoconductor because, at any instant, the photoconductor must be neutral. Electrons drift faster which means as one leaves, another must enter.

Photoconductivity is the change in the conductivity from dark to light, $\sigma_{light} - \sigma_{dark}$.

Photodetector is a device that converts a light signal to an electrical signal such as a voltage or current. In many photodetectors such as photoconductors and photodiodes this conversion is typically achieved by the creation of free electron hole pairs by the absorption of photons, that is, the creation of electrons in the conduction band and holes in the valence band. In some devices such as **pyroelectric detectors** the energy conversion involves the generation of heat which increases the temperature of the device which changes its polarization and hence its relative permittivity.

Photodiode is a semiconductor diode (a *pn* junction) that generates a photocurrent upon illumination with a suitable range of wavelengths. *pn* junction based photodiodes are small and have high speed and good sensitivity for use in various optoelectronics applications, the most important of which is in optical communications.

Photoelastic effect is the phenomenon in which the induced **strain** (*S)* in a **crystal** changes its **refractive index** *n*. The strain changes the density of the crystal and distorts the bonds (and hence the electron orbits) which lead to a change in the refractive index *n*. If we were to examine the change in $1/n^2$ instead of *n*, then we would find that this is proportional to the induced strain *S* and the proportionality constant is the photoelastic coefficient *p*, *i.e.*

$$\Delta\left(\frac{1}{n^2}\right) = pS$$

The relationship is not as simple as stated above since we must consider the effect of a strain *S* along one direction in the crystal on the induced change in *n* for a particular light propagation direction and some specific **polarization**. The above equation in reality is a tensor relationship.

Photogeneration in a **semiconductor** is the excitation of an electron from the **valence band** (VB) into the **conduction band** (CB) by the **absorption** of a **photon**. Thus, an electron hole pair is generated.

Photogeneration is the excitation of an electron into the **conduction band** by the **absorption** of a **photon**. If the photon is absorbed by an electron in the **valence band** then its excitation to the conduction band will generate an EHP.

Photoinjection is the **photogeneration** of carriers in the **semiconductor** by illumination. Photogeneration may involve the excitation of an electron from the **valence band** to the **conduction band** in which case electrons and holes are generated in pairs.

Photolithography uses light in the lithographic process to define a pattern on the surface of wafer.

Photoluminescence, see **luminescence**.

Photon is a quantum of electromagnetic radiation whose energy is $h\upsilon$, where h is the Planck constant and υ the frequency of the electromagnetic radiation. It also has a zero rest mass and a momentum p given by the De Broglie relationship, $p = h/\lambda$ where λ is the wavelength.

3×10^3 photons 1.2×10^4 photons

9.3×10^4 photons 7.6×10^5 photons

3.6×10^6 photons 2.8×10^7 photons
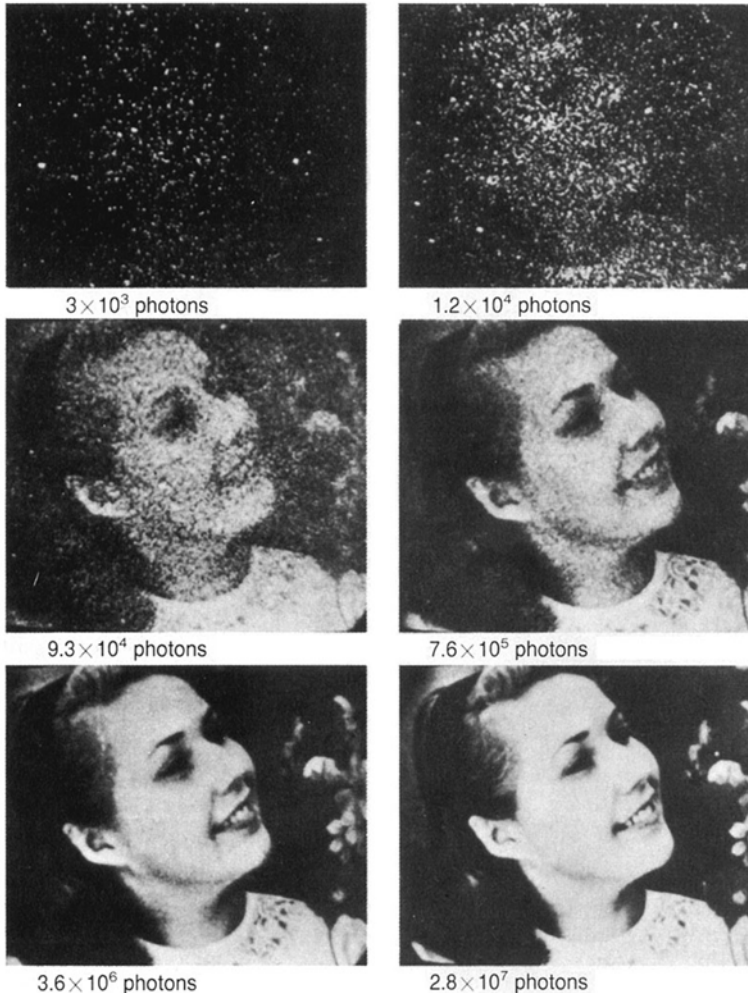
These electronic images were made with the number of photons indicated. The discrete nature of photons means that a large number of photons are needed to constitute an image with satisfactorily discernable details. [A. Rose, "Quantum and noise limitations of the visual process" *J. Opt. Soc. of America*, Vol. 43, 715, 1953 (Courtesy of OSA)]

Photon or optical confinement is the restriction of **optical power**, **photons**, to certain region of a device by virtue of **refractive index** profiling; for example, by constructing a waveguide structure.

Phototransistor is a **bipolar junction transistor** (BJT) that operates as a photodetector with a photocurrent gain. Typically the base terminal is normally open and there is a voltage applied between the collector and **emitter** terminals just as in the normal operation of a common emitter BJT. An incident **photon** is absorbed in the space charge layer (SCL) between the base and collector to generate an electron hole pair (EHP). The electric field E in the SCL separates the electron hole pair and drifts them in opposite direction. This is the **primary photocurrent** and effectively constitutes a base current even though the base terminal is open circuit (current is flowing into the base from the collector). Since the photon generated primary photocurrent I_{pho} is amplified as if it were a base current (I_B), the photocurrent flowing in the external circuit is

$$I_{ph} \approx \beta I_{pho}$$

where β is the current gain (or h_{FE}) of the transistor. The **phototransistor** construction is such that incident radiation is absorbed in the base-collector junction SCL. It is possible to construct a *heterojunction phototransistor* that has different bandgap materials for the emitter, base and collector. For example, if the emitter is InP (E_g = 1.35 eV) and the base is an InGaAsP alloy (for example, E_g ≈ 0.85 eV) then photons with energies less than 1.35 eV but more than 0.85 will pass through the emitter and become absorbed in the base. This means the device can be illuminated through the emitter.

Photovoltaic devices or **solar cells** convert the incident solar radiation energy into electrical energy. Incident **photons** are absorbed to photogenerate charge carriers that pass through an external load to do electrical work. Photovoltaic devices may be metal/semiconductor Schottky junctions , *pn* junction or *pin* devices . For example, a crystalline Si *pn* junction solar cell may have a thin *n*-type **semiconductor** layer on a thick *p*-type **substrate**. The electrodes attached to the *n*-side must allow illumination to enter the device and at the same time result in a small series resistance. They are deposited on to *n*-side to form an array of *finger electrodes* on the surface. The *n*-side is very narrow to allow most of the photons to be absorbed within the depletion region and within the neutral *p*-side. These photons photogenerate electron hole pairs (EHPs) in these regions. EHPs photogenerated in the depletion region are immediately separated by the built-in field E_o which drifts them apart. The electron drifts and reaches the neutral n^+ side whereupon it makes this region negative by an amount of charge $-e$. Similarly the hole drifts and reaches the neutral *p*-side and thereby makes this side positive. Consequently an open circuit voltage develops between the terminals of the device with the *p*-side positive with respect to the *n*-side. If an external load is connected then the excess electron in the *n*-side can travel around the external circuit, do work, and reach the *p*-side to recombine with the excess hole there. There will be an external photocurrent. It is important to realize that without the internal field E_o it is not possible to drift apart the photogenerated EHPs and accumulate excess electrons on the *n*-side and excess holes on the *p*-side. A thin **antireflection coating** on the surface reduces reflections and allows more light to enter the device.

Finger electrodes on the surface of a solar cell reduce the series resistance

The principle of operation of the solar cell.
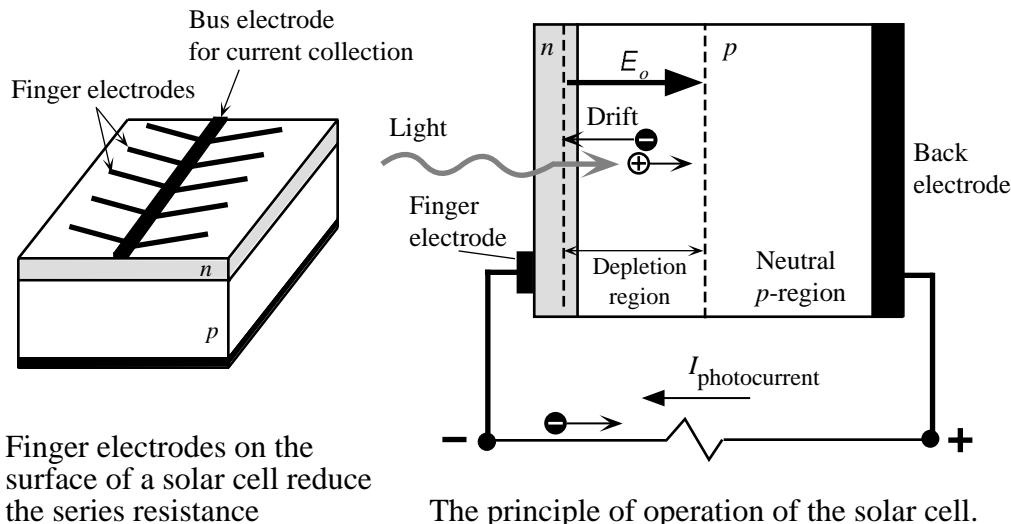
Honda's two seated Dream car is powered by photovoltaics. The Honda Dream was first to finish 3,010 km in four days in the 1996 World Solar Challenge. (Courtesy of Photovoltaics Special Research Centre, University of New South Wales, Sydney, Australia)

Photovoltaic effect is the generation of an emf (electromotive force) as a result of illumination. See **photovoltaic devices**.

Photovoltaic or solar cell *I-V* characteristics are the current vs. voltage characteristics of the device under different intensities of illumination within the spectral response curve of the device. Under illumination, the dark *I-V* characteristics become shifted so that there is a short circuit current I_{sc} and an open circuit voltage V_{oc}; that is, a photocurrent I_{sc} when the solar cell is shorted and a voltage V_{oc} when it is in open circuit. I_{sc} represents the conventional current that would normally flow in a forward biased **diode**. However, the actual photocurrent I_{ph} is in the opposite direction to I_{sc}, thus $I_{sc} = -I_{ph}$.
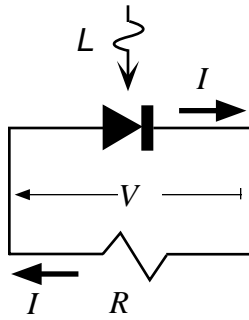
When a solar cell drives a load *R*, *R* has the same voltage as the solar cell but the current through it is in the opposite direction to the convention that current flows from high to low potential.
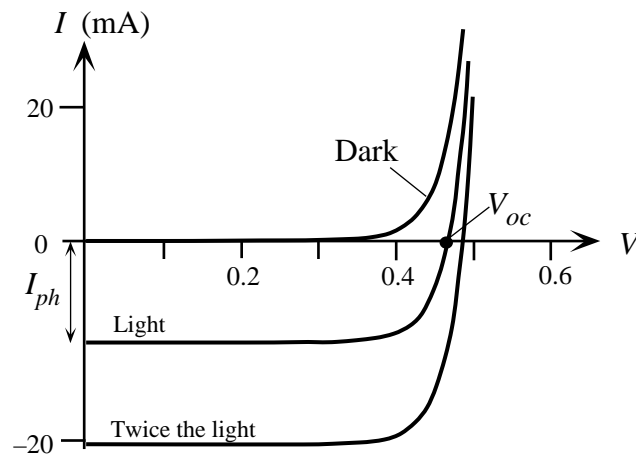
Typical *I-V* characteristics of a Si solar cell. The short circuit current is $-I_{ph}$ and the open circuit voltage is V_{oc}. The *I-V* curves for positive current requires an external bias voltage. Photovoltaic operation is always in the negative current region.

The total current *I* through a *pn* junction solar cell can normally be written as,

$$I = -I_{ph} + I_o \left[\exp\left(\frac{eV}{nkT} \right) - 1 \right]$$

where *V* is the voltage across the solar cell, I_{ph} is the short circuit photocurrent, *k* is the **Boltzmann constant**, *T* is temperature (K) and *n* is the ideality factor (1 to 2) for the *pn* junction. The open circuit output voltage, V_{oc}, of the solar cell is given by the point where the *I-V* curve cuts the *V*-axis ($I = 0$). It is apparent that although it depends on the light intensity, its value for Si solar cells

typically lies in the range 0.4-0.6 V. When the solar cell is connected to a load R, the load has the same voltage as the solar cell and carries the same current. But the current I through R is now in the opposite direction to the convention that current flows from high to low potential. Thus,

$$I = -\frac{V}{R}$$

The actual current I' and voltage V' in the circuit must satisfy both the *I-V* characteristics of the solar cell and that of the load. We can find I' and V' by solving these two equations through a graphical solution; called a load line construction. The *I-V* characteristics of the load is a straight line with a negative slope $-1/R$. This is called the *load line*. The load line cuts the solar cell characteristic at a point P called the *operating point*. At P, the load and the solar cell have the same current and voltage I' and V'. The current I' and voltage V' in the circuit are hence given by point P. The power delivered to the load is $P_{out} = I'V'$, which is the area of the rectangle bound by I- and V- axes and the dashed lines in the figure. Maximum power is delivered to the load when this rectangular area is maximized (by changing R or the intensity of illumination), when $I' = I_m$ and $V' = V_m$. Since the maximum possible current is I_{ph} and the maximum possible voltage is V_{oc}, $I_{ph}V_{oc}$, represents the desirable goal in power delivery for a given solar cell. It is therefore useful to compare the maximum power output, I_mV_m, with $I_{sc}V_{oc}$. The **fill factor** FF, which is a figure of merit for the solar cell, is defined as

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}}$$

FF is a measure of the closeness of the solar cell *I-V* curve to the rectangular shape (the ideal shape). It is clearly advantageous to have FF as close to unity as possible but the exponential *pn* junction properties prevent this. Typically FF values are in the range 70-85% and depend on the device material and structure.
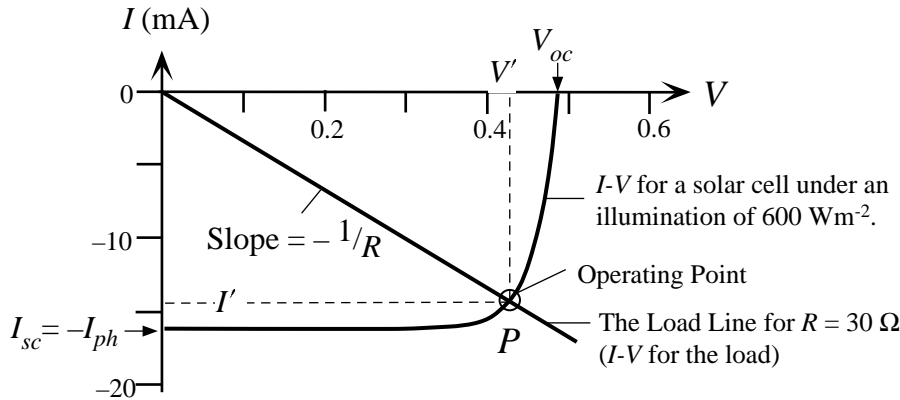
The current I' and voltage V' in the circuit of (a) can be found from a load line construction. Point P is the operating point (I', V'). The load line is for $R = 30\ \Omega$.

Piezoelectric material has a non-centrosymmetric **crystal** structure which leads to the generation of a **polarization vector** P, or charges on the crystal surfaces, upon the application of a mechanical **stress**, T. When strained, a piezoelectric crystal develops an internal field and therefore exhibits a voltage difference between two of its faces. Equivalently, a piezoelectric crystal when strained develops an internal field and therefore exhibits a voltage difference between two of its faces. The mechanical stress, T_i, in one direction (along i) can generate polarization, P_j, along a different direction (along j) and are related by $P_i = d_{ij} T_j$ where d_{ij} is the piezoelectric coefficient.

Pigtail is a short **optical fiber** that is directly coupled to an optical component, for example, an LED. A pigtailed **emitter**, for example, comes with this short fiber already attached to it so that one can

simply use this short fiber to couple the emitter to another component (*e.g.* a long-haul fiber by splicing *etc.*).

A 1550 nm MQW-DFB InGaAsP laser diode pigtail-coupled to a fiber. (Courtesy of Alcatel.)

***pin* diode** is semiconductor diode that has the structure, p^+/ intrinsic /n^+ with a relatively thick intrinsic region that is depleted of free carriers. The intrinsic layer has a much smaller doping than both p^+ and n^+ regions and it is much wider than these regions, typically 5-50 μm depending on the particular application. In the idealized *pin* photodiode, the *i*-Si region is simply taken to be truly intrinsic whereas in practice it is slightly doped. When the structure is first formed, holes diffuse from the p^+-side and electrons from n^+-side into the *i*-Si layer where they recombine and disappear. This leaves behind a thin layer of exposed negatively charged acceptor ions in the p^+-side and a thin layer of exposed positively charged donor ions in the n^+-side. The two charges are separated by the *i*-Si layer of thickness *W*. The depletion layer widths of the thin sheets of acceptor and donor charges in the p^+ and n^+ sides are negligible compared with *W*. There is a uniform built-in field E_o in *i*-Si layer from the exposed positive donor ions to exposed acceptor negative ions. In contrast, the built-in field in the depletion layer of a *pn* junction is not uniform. With no applied bias, equilibrium is maintained by the built-in field E_o which prevents further diffusion of majority carriers into the *i*-Si layer. The separation of two very thin layers of negative and positive charges by a fixed distance, width *W* of the *i*-Si, is the same as that in a parallel plate capacitor. The junction capacitance tends to be very small, in the picofarad range, and independent of the bias voltagve. The *pin* is normally reverse biased with a voltage V_r which drops almost entirely across the width of *i*-Si layer. The field E in the *i*-Si layer is still uniform and increases to $E \approx V_r/W$. The *pin* structure is designed so that photon absorption occurs over the *i*-Si layer. The photogenerated EHPs in the *i*-Si layer are then separated by the field E and drifted towards the n^+ and p^+ sides respectively. The drift of the photogenerated carriers through the *i*-Si layer they gives rise to an external photocurrent which is detected as a voltage across a small sampling resistor *R*. The **response time** of the *pin* photodiode is determined by the transit times of the photogenerated carriers across the width *W* of the *i*-Si layer. Increasing *W* allows more photons to be absorbed which increases the quantum efficiency but it slows down the speed of response inasmuch as carrier transit times become longer. The intrinsic response time of the *pin* is normally determined by the drift time of the slowest carriers across the depletion region. This response time can be shortened by increasing the drift velocity of the carrier, that is, by increasing the field (*i.e.* V_r) but eventually the carrier drift velocity saturates and the drift time cannot be shortened further. For an *i*-Si layer of width 10 μm, with carriers drifting as saturation velocities, the drift time is about 0.1 ns which is longer than typical RC_{dep} time constants. The speed of *pin* photodiodes are invariably limited by the transit time of photogenerated carriers

across the *i*-Si layer.
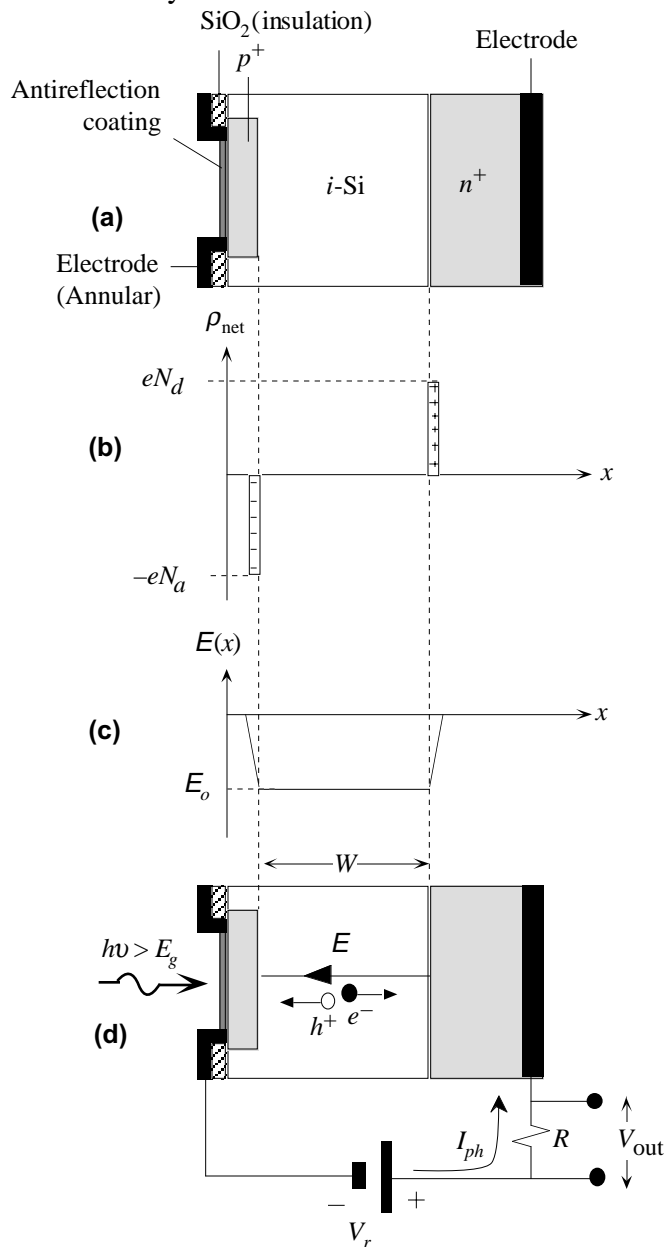
(a) The schematic structure of an idealized *pin* photodiode (b) The net space charge density across the photodiode. (c) The built-in field across the diode. (d) The *pin* photodiode in photodetection is reverse biased.

Planck's black body radiation law, see **black body radiation.**

Planck's constant h is a universal constant that is defined as the smallest quantum of radiation energy (at one frequency) per unit radiation frequency; $h = 6.626 \times 10^{-34}$ J s. The quantity $h/2\pi$ is denoted as $\hbar$.

Plane electromagnetic wave is a traveling **wave** with time varying electric and **magnetic fields**, that is E_x and B_y respectively, which are propagating through space in such a way that they are always perpendicular to each other and the direction of propagation z. The simplest traveling wave is a sinusoidal wave which, for propagation along z, has the general mathematical form,

$$E_x = E_o \cos(\omega t - kz + \phi_o)$$

where E_x is the electric field at position z at time t, k is the **propagation constant**, or **wave number**, given by $2\pi/\lambda$, where λ is the wavelength, ω is the angular frequency, E_o is the amplitude of the wave and ϕ_o is a phase constant which accounts for the fact that at $t = 0$ and $z = 0$, E_x may or may not necessarily be zero depending on the choice of origin. The argument $(\omega t - kz + \phi_o)$ is called the **phase** of the wave and denoted by ϕ. In any plane perpendicular to the direction of propagation (along z), the phase of the wave is constant which means that the field in this plane is also constant. A surface over which the phase of a wave is constant is referred to as a **wavefront**. A wavefront of a **plane wave** is obviously a plane perpendicular to the direction of propagation.
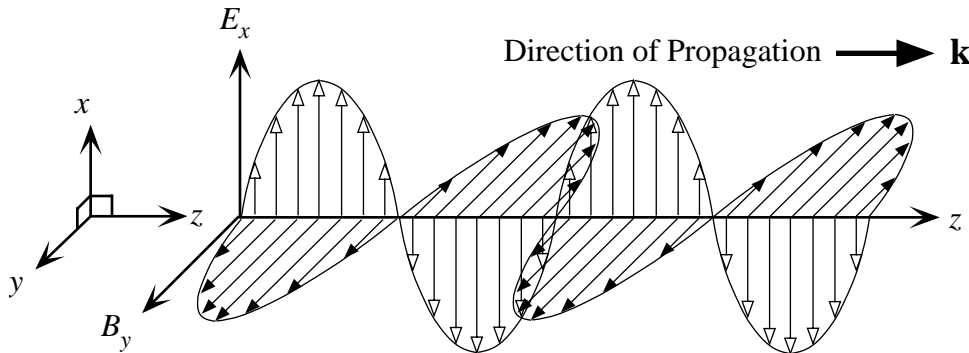
An electromagnetic wave is a travelling wave which has time varying electric and magnetic fields which are perpendicular to each other and the direction of propagation, z.

Plane wave is a **wave** that has a constant electric field and a constant **magnetic field** in any given infinite plane perpendicular to the direction of propagation, **k**. The field in successive planes, however, oscillates with time. The field is said to have a constant phase anywhere on a given plane perpendicular to **k**.

Pockels cell intensity modulator is a Pockels phase modulator with a polarizer P and an analyzer A before and after the phase modulator such that they are cross-polarized, *i.e.* P and A have their transmission axes at 90° to each other. The **transmission axis** of P as at 45° to the y-axis (hence A also has its transmission axis at 45° to y) so that the light entering the **crystal** has equal $\mathbf{E}_x$ and $\mathbf{E}_y$ components. In the absence of an applied voltage, the two components travel with the same **refractive index** and **polarization** output from the crystal is the same as its input. There is no light detected at the detector as A and P are at right angles ($\theta = 90°$ in **Malus's law**). An applied voltage inserts a phase difference $\Delta\phi$ between the two electric field components. The light leaving the crystal now has an elliptical polarization and hence a field components along the transmission axis of A. A portion of this light will therefore pass through A to the detector. The transmitted intensity now depends on the applied voltage V. The field components at the analyzer will be out of phase by an amount $\Delta\phi$. Only the component of the field along the transmission axis of A can pass through. The intensity $\mathcal{I}$ of the detected beam (output beam) is then

$$\mathcal{I} = \mathcal{I}_o \sin^2(\frac{\pi}{2} \cdot \frac{V}{V_{\lambda/2}})$$

where $\mathcal{I}_o$ is the light intensity under full transmission, and an applied voltage of $V_{\lambda/2}$ is needed to allow full transmission. In digital electronics, we would switch a light pulse on and off so that the non-linear dependence of transmission intensity on V would not be a problem. However, if we wish

to obtain a linear modulation between the intensity $\mathcal{I}$ and V we need to **bias** this structure about the apparent "linear region" of the curve at half-height . This is done by inserting a **quarter-wave plate** after the polarizer P which provides a **circularly polarized light** as input. That means $\Delta\phi$ is already shifted by $\pi/4$ before any applied voltage. The applied voltage then, depending on the sign, increases or decreases $\Delta\phi$. The new transmission characteristic is shown as a dashed curve. We have, effectively, optically biased the modulator at point Q on this new characteristics .
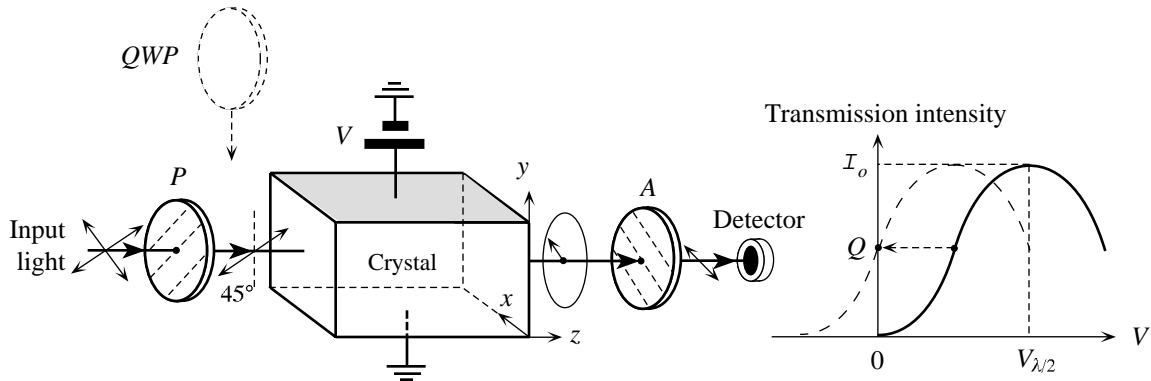
Left: A tranverse Pockels cell intensity modulator. The polarizer P and analyzer A have their transmission axis at right angles and P polarizes at an angle $45°$ to y-axis. Right: Transmission intensity vs. applied voltage characteristics. If a quarter-wave plate (QWP) is inserted after P, the characteristic is shifted to the dashed curve.

Pockels effect is a change in the **refractive index** of a **crystal** due to an application of an external electric field, other than the field of the light **wave**. Suppose that x,y and z are the **principal axes** of a crystal with refractive indices n_1, n_2 and n_3 along these directions. For an optically isotropic crystals, these would be the same whereas for a **uniaxial crystal** $n_1 = n_2 \neq n_3$. Suppose that we suitably apply a voltage across a crystal an thereby apply an external dc field E_a along the z-axis. In Pockels effect, the field will modify the **optical indicatrix**. The exact effect depends on the crystal structure. For example, a crystal like GaAs, optically isotropic with a spherical indicatrix, becomes birefringent, and a crystal like KDP (KH_2PO_4 - potassium dihydrogen phosphate) that is uniaxial becomes biaxial. In the case of KDP, the field E_a along z rotates the principal axes by $45°$ about z, and changes the principal indices. The new principal indices are now n'_1 and n'_2 which means that the cross section is now an ellipse. Propagation along the z-axis under an applied field now occurs with different refractive indices n'_1 and n'_2. The applied field induces new principal axes x', y' and z' for this crystal (though in this special case $z' = z$). In the case of $LiNbO_3$ (lithium niobate), an optoelectronically important uniaxial crystal, a field E_a along the y-direction does not significantly rotate the principal axes but rather changes the **principal refractive indices** n_1 and n_2 (both equal to n_o) to n'_1 and n'_2 . As an example consider a wave propagating along the z-direction (**optic axis**) in a $LiNbO_3$ crystal. This wave will experience the same refractive index ($n_1 = n_2 = n_o$) whatever the **polarization**. However, in the presence of an applied field E_a parallel to the principal y axis, the light propagates as two orthogonally polarized waves (parallel to x and y) experiencing different refractive indices n'_1 and n'_2. The applied field thus *induces a birefringence* for light traveling along the z-axis. The field induced rotation of the principal axes in this case, though present, is small and can be neglected. Before the field E_a is applied, the refractive indices n_1 and n_2 are both equal to n_o. The Pockels effect then gives the new refractive indices n'_1 and n'_2 in the presence of E_a as

$$n_1' \approx n_1 + \tfrac{1}{2} n_1^3 r_{22} E_a \qquad \text{and} \qquad n_2' \approx n_2 - \tfrac{1}{2} n_2^3 r_{22} E_a$$

where r_{22} is a constant, called a Pockels coefficient, that depends on the crystal structure and the material. The reason for the seemingly unusual subscript notation is that there are more than one constant and these are elements of a tensor that represents the optical response of the crystal to an applied field along a particular direction with respect to the principal axes (the exact theory is more mathematical than intuitive). We therefore have to use the correct Pockels coefficients for the refractive index changes for a given crystal and a given field direction. If the field were along z, the Pockels coefficient above would be r_{13}. It is clear that the control of the refractive index by an external applied field (and hence a voltage) is a distinct advantage which enables the phase change through a Pockels crystal to be controlled or modulated; such a **phase modulator** is called a *Pockels cell*. In the *longitudinal Pockels cell phase modulator* the applied field is in the direction of light propagation whereas in the *transverse phase modulator*, the applied field is transverse to the direction of light propagation. see **electro-optic effects**.

(a)   **(b)**   **(c)**
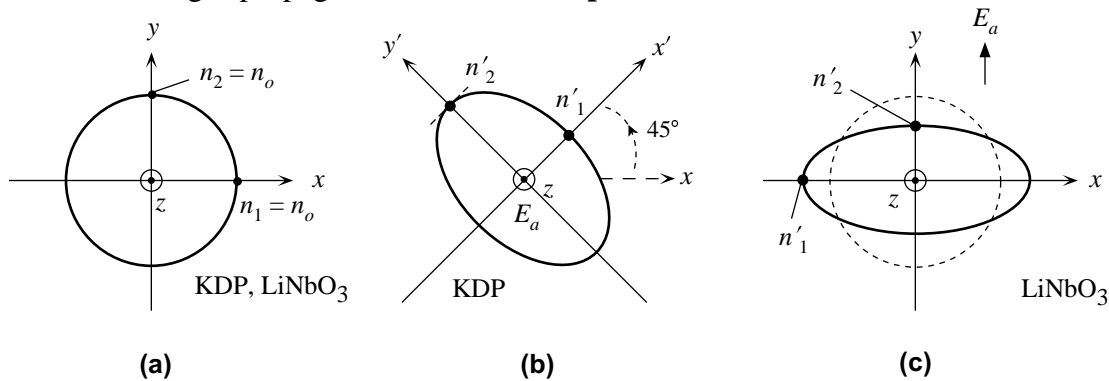
(a) Cross section of the optical indicatrix with no applied field, $n_1 = n_2 = n_o$ (b) The applied external field modifies the optical indicatrix. In a KDP crystal, it rotates the principal axes by 45° to x' and y' and n_1 and n_2 change to n_1' and n_2'. (c) Applied field along y in LiNbO$_2$ modifies the indicatrix and changes n_1 and n_2 change to n_1' and n_2'.

Friedrich Carl Alwin Pockels (1865 - 1913) son of Captain Theodore Pockels and Alwine Becker, was born in Vincenza (Italy). He obtained his doctorate from Göttingen University in 1888. From 1900 until 1913, he was a professor of theoretical physics in the Faculty of Sciences and Mathematics at the University of Heidelberg where he carried out extensive studies on electro-optic properties of crystals - the Pockels effect is basis of many practical electro-optic modulators (Courtesy of the Department of Physics and Astronomy, University of Heidelberg, Germany.)

Polarization angle, see **Brewster's angle.**

Polarization by anisotropic scattering is a phenomenon in which the **polarization** of the scattered light **wave** depends on the direction of **scattering** and the polarization of the incoming light wave. An oscillating electric dipole emits electromagnetic radiation which has a non-spherical the electric field (E) pattern around it as shown in the figure for an oscillating **electric dipole moment** $p(t)$

parallel to the *y*-axis. There is no field radiation along the dipole axis *y*. The **irradiance** $\mathcal{I}$ of the radiation along a direction at an angle θ to the perpendicular to the dipole axis, is proportional to $\cos^2\theta$. The electric field in an incoming **electromagnetic wave** will induce dipole oscillations in a molecule of the medium. The scattering of an incident unpolarized electromagnetic wave by this molecule leads to waves with different polarizations along the *x* and *y* axes as in the figure.

Oscillating molecular dipole

Oscillating dipole along *y*

(a)

(b)

(a) A snap shot of the field pattern around an oscillating dipole moment in the *y*-direction. Maximum electromagnetic radiation is perpendicular to the dipole axis and there is no radiation along the dipole axis. (b) Scattering of electromagnetic waves from induced molecular dipole oscillations is anisotropic.

Polarization dispersion arises when the fiber is not perfectly symmetric and homogeneous, that is, the **refractive index** is *not isotropic*. When the refractive index depends on the direction of the electric field, the **propagation constant** of a given mode depends on its **polarization**. Due to various variations in the fabrication process such as small changes in the **glass** composition, geometry and induced local **strains** (either during fiber **drawing** or cabling), the refractive indices n_1 and n_2 may not be isotropic. Suppose that n_1 has the values n_{1x} and n_{1y} when the electric field is parallel to the *x* and *y* axes respectively. Then the propagation constant for fields along *x* and *y* would be different, $\beta_x(01)$ and $\beta_y(01)$, leading to different **group delays** and hence **dispersion** even if the source wavelength is monochromatic. The situation in reality is more complicated because n_{1x} and n_{1y} would vary along the fiber length and there will be interchange of energy between these modes as well. The final dispersion nonetheless depends on the extent of anisotropy, $n_{1x} - n_{1y}$, which is kept minimum by various manufactures procedures (such as rotating the fiber during drawing *etc.*). Typically polarization dispersion is less than a fraction of a picosecond per kilometer of fiber; dispersion does not scale linearly with fiber length *L* (in fact, it scales roughly as L^2).
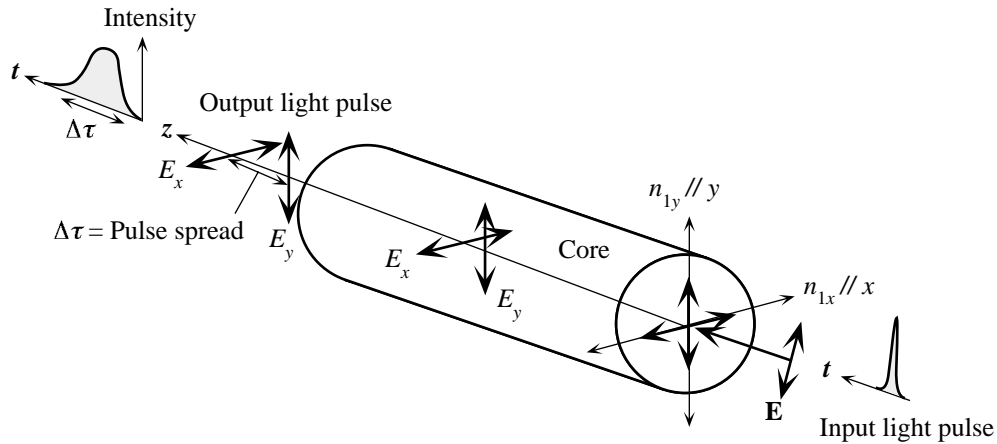
The core refractive index has different values along two orthogonal directions corresponding to two orthogonal electric field oscillation directions (polarizations). Take x and y axes along these directions. An input light will travel along the fiber with E_x and E_y polarizations having different group velocities and hence arrive at the output at different times which leads to the dispersion of the light pulse.

Polarization of an electromagnetic (EM) wave describes the behavior of the electric field vector in the EM wave as it propagates through a medium. If the oscillations of the electric field at all times are contained within a well-defined line then the EM wave is said to be **linearly polarized**. The field vibrations and the direction of propagation, *e.g.* z-direction, define a plane of polarization (plane of vibration) so that linear polarization implies a **wave** that is **plane-polarized**. By contrast, if a beam of light has waves with the E-field in each in a random perpendicular direction to z, then this light beam is *unpolarized*. A light beam can be linearly polarized by passing the beam through a *polarizer*, such as a polaroid sheet, a device that only passes electric field oscillations lying on a well defined plane at right angles to the direction of propagation.

(a)　　　　　　**(b)**　　　　　　**(c)**
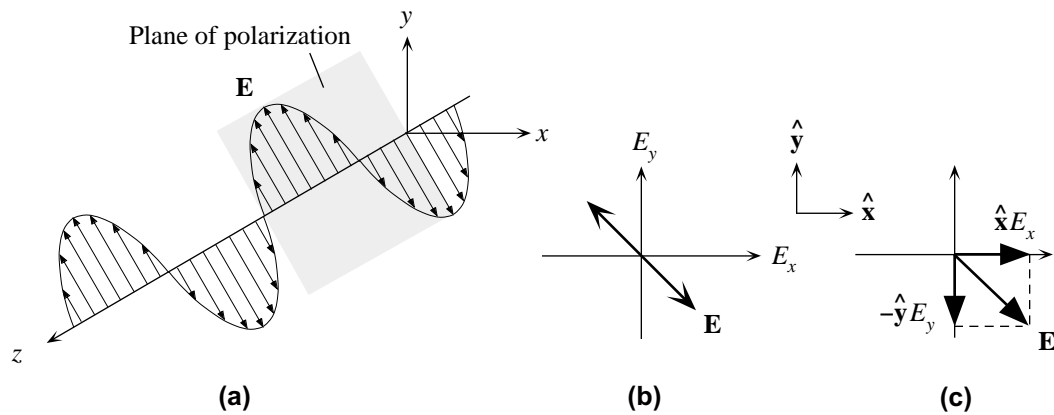
(a) A linearly polarized wave has its electric field oscillations defined along a line perpendicular to the direction of propagation, z. The field vector $\mathbf{E}$ and z define a *plane of polarization*. (b) The E-field oscillations are contained in the plane of polarization. (c) A linearly polarized light at any instant can be represented by the superposition of two fields E_x and E_y with the right magnitude and phase.

Polarization vector ($\mathbf{P}$) measures the extent of **polarization** in a unit volume of dielectric matter. It is the vector sum of dielectric dipoles per unit volume. If $\mathbf{p}$ is the average dipole moment per molecule

and n is the number of molecules per unit volume then $\mathbf{P} = n\mathbf{p}$. In a polarized dielectric matter (*e.g.* in an electric field), the bound surface charge density, σ_p, due to polarization is equal to the normal component of $\mathbf{P}$ at that point, $\sigma_p = P_{\text{normal}}$.

Polarized EM wave (polarized light) is an EM (electromagnetic) wave which has the oscillations of the electric field in a well defined direction (but still at right angles to the direction of propagation). In unpolarized light the field oscillations are in random directions but once polarized the field oscillations are along a well defined direction. If this direction does not change as the **wave** propagates it is said to be plane polarized.

Population inversion is the phenomenon of having more atoms occupy an excited energy level E, than a lower energy level E, so that the normal equilibrium distribution is reversed, *i.e.* $N(E_2) > N(E_1)$. Population inversion occurs temporarily as a result of the excitation of a medium (**pumping**). If left on its own, the medium will eventually, however long, will return to its equilibrium population distribution with more atoms at E_1 than at E_2. For gas atoms, this means $N(E_2)/N(E_1) = \exp[-(E_2-E_1)/kT]$, where k is the **Boltzmann constant** and T is the temperature (Kelvins).

Poynting vector S represents the energy flow per unit time per unit area in a direction determined by $\mathbf{E} \times \mathbf{B}$ (direction of propagation), $\mathbf{S} = v^2 \varepsilon_o \varepsilon_r \mathbf{E} \times \mathbf{B}.$ Its magnitude, power flow per unit area, is called the **irradiance.**

Preform is a **glass** rod which has an appropriate **core** and **cladding** from which an **optical fiber** is drawn by a fiber **drawing** process at an elevated temperature.

Primary or unmultiplied photocurrent is normally the photocurrent in an **avalanche photodiode** just below the onset of avalanche multiplication, *i.e.* when the **reverse bias** is sufficient to cause reach through (the depletion region reaches through the device) but not sufficiently high to cause **avalanche breakdown**.

Principal axes of a **crystal** are three appropriate orthogonal directions, say x, y and z , corresponding to the three **principal refractive indices** n_1, n_2 and n_3.

Principal quantum number, n, is a quantum number with integer values 1,2,3,... which characterizes the total energy of the electron. The energy increases with n. It determines, with the other quantum numbers ℓ and m_ℓ, the orbital of the electron in an atom, $\psi_{n,\ell,m\ell,ms}(\rho,\theta,\phi)$. $n = 1,2,3,4,...$ are labeled as $K,L,M,N,...$ shells within each of which there may be subshells based on $\ell = 0,1,2,..(n-1)$ and corresponding to $s,p,d,...$ **states**.

Principal refractive indices of a **crystal**, according all experiments and theories, are a set of three refractive indices n_1, n_2 and n_3 (along three mutually orthogonal directions in the crystal, say x, y and z called **principal axes**) which are necessary to characterize light propagation even in the most anisotropic crystal. These indices correspond to the **polarization** state of the **wave** along these axes. Crystals that have three distinct principal indices also have *two* optic axes and are called **biaxial crystals**. On the other hand, **uniaxial crystals** have two of their principal indices the same ($n_1 = n_2$) and only have *one* **optic axis**. Uniaxial crystals, such as quartz, that have $n_3 > n_1$ and are called **positive**, and those such as calcite that have $n_3 < n_1$ are called **negative** uniaxial crystals.

Profile dispersion is the broadening of a propagating optical pulse in a fiber as a result of the **group velocity** $v_g(01)$ of the **fundamental mode** also depending on the **refractive index** difference Δ, *i.e.* $\Delta = \Delta(\lambda)$. If Δ changes with wavelength, then different wavelengths from the source would have different group velocities and experience different **group delays** leading to pulse broadening. It is part of chromatic dispersion because it depends on the input **spectrum** $\Delta\lambda$. Profile dispersion coefficient D_p is the time spread of a propagating optical pulse in an optical guide per unit length and

per unit spectral wavelength width due to the wavelength dependence of the refractive index difference Typically, D_p is less than 1 ps nm^{-1}km^{-1} .

Profile index or index grading coefficient (γ) is a parameter that describes the variation of the refractive n with radial distance r from the fiber axis assuming that for $r < a$, the **refractive index** decreases with r as $n = n_1[1 - 2\Delta(r/a)^\gamma]^{1/2}$, where a is the fiber **core** region radius, Δ is the normalized refractive index difference and n1 is the maximum refractive index at the fiber axis. At $r = a$, $n = n_2$ and is a constant.

Propagation constant β is a property of a **wave** that, for a given frequency and at a given time, represents the change in the phase per unit distance. Since this phase change is 2π over a wavelength λ, $\beta = 2\pi/\lambda$. The propagation constant β and **wavevector k** represent essentially the same property except that **k** has a direction associated with it. See **complex propagation constant**.

Pumping in lasers involves exciting atoms from their ground states to **states** at higher energies.

Q-factor or quality factor of an impedance is the ratio of its reactance to its resistance. The Q-factor of a capacitor is X_c / R_p where $X_c = 1/\omega C$ and R_p is the equivalent parallel resistance that represents the dielectric and conduction losses. The Q-factor of a resonant circuit measures the circuit's peak response at the **resonant frequency** and also its **bandwidth**. Greater is Q, higher is the peak response and narrower is the bandwidth. For a series RLC resonant circuit, $Q = \omega_o L/R = 1/(\omega_o CR)$ where ω_o is the resonant angular frequency, $\omega_o = 1/\sqrt{(LC)}$. The width of the resonant response curve between half-power points is $\Delta\omega = \omega_o Q$.

Q-switched laser is a laser whose optical cavity is switched from a low Q to a high Q to generate an intense laser pulse. While the optical cavity has low Q, lasing is suppressed and the active medium can be pumped to high energies to achieve a large **population inversion**. When the Q of the optical cavity is switched to a high value, then an intense lasing emission is generated. While the Q is low, the pumped lasing medium is effectively a very high gain **photon** amplifier. There is too much loss in the **optical resonator** (*i.e.* no optical feedback) to achieve a lasing oscillation. As soon as the Q is switched to a high value, the low loss in the optical resonator allows lasing oscillations to occur which depletes the population inversion and decreases the gain until the population inversion falls below the threshold value and lasing oscillation cease. The Q-switching can be conveniently, for example, implemented by using an electro-optic switch.

Pump energy

(a)   (b)

Mirror

Lasing medium

Mirror

High population inversion

Lasing pulse

Optical cavity has low Q Optical cavity has high Q
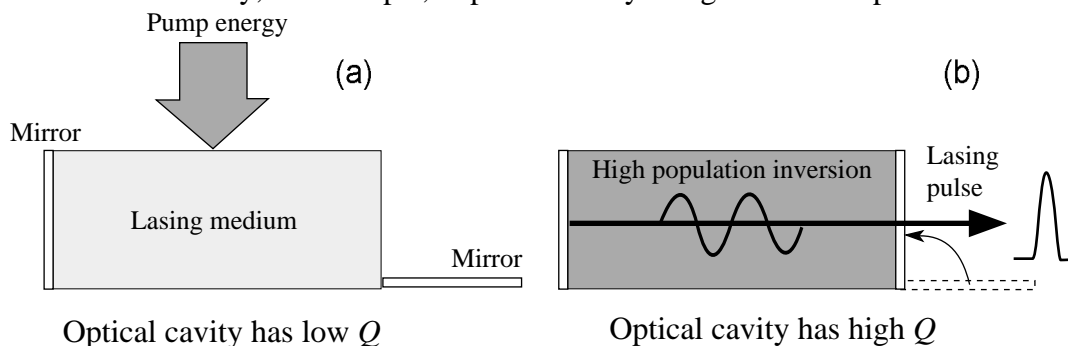
(a) The optical cavity has a low Q so that pumping takes the atoms to a very high degree of population inversion; lasing is prevented by not having a right hand mirror. (b) The right mirror is flung to make an optical resonator, Q is switched to a high value which immediately encourages lasing emissions. There is an intense pulse of lasing emission which brings down the excess population inversion.

Quantum efficiency (QE) η of the detector, or external quantum efficiency, is defined as

$$\eta = \frac{\text{Number of free electron - hole pairs generated and collected}}{\text{Number of incident photons}}$$

Not all the incident **photons** are absorbed to create *free* electron-hole pairs (EHPs) that can be collected and give rise to a photocurrent. The efficiency of the conversion process of received photons to free EHPs is measured by the above quantum efficiency definition. The measured photocurrent I_{ph} in the external circuit is due to the flow of electrons per second to the terminals of the **photodiode**. Number of electrons collected per second is I_{ph}/e. If P_o is the incident **optical power** then the number of photons arriving per second is $P_o/h\upsilon$. Then the QE η can also be defined by

$$\eta = \frac{I_{ph}/e}{P_o/h\upsilon}$$

where h is the Planck constant, e is the electronic charge and υ is the frequency of light. Not all of the absorbed photons may photogenerate free EHPs that can be collected. Some EHPs may disappear by **recombination** without contributing to the photocurrent or become immediately trapped. Further if the **semiconductor** length is comparable with the **penetration depth** $(1/\alpha)$ then not all the photons will be absorbed. The device QE is therefore always less than unity. It depends on the **absorption coefficient** α of the semiconductor at the wavelength of interest and on the structure of the device. QE can be increased by reducing the reflections at the semiconductor surface, increasing **absorption** within the **depletion layer** and preventing the recombination or trapping of carriers before they are collected. The above QE is for the whole device. More specifically, it is known as the *external quantum efficiency*. *Internal quantum efficiency* is the number of free EHPs photogenerated per *absorbed photon* and is typically quite high for may devices (see also **internal quantum efficiency**). The external quantum efficiency incorporates internal quantum efficiency because it applies to the whole device.

Quantum noise or photon noise is the fluctuations in the photocurrent due to the quantum or discrete (*i.e.* **photon**) nature of light. Incident light on a photodetector is a flux of photons, discrete entities, which means that the **photogeneration** process is *not* a smooth continuous process without fluctuations; photons arrive like discrete particles.

Quantum well device is a *heterostructure devic* that has an ultra thin, typically less than 50 nm, narrow bandgap **semiconductor**, such as GaAs, sandwiched between two wider bandgap semiconductors, such as AlGaAs. We assume that the two semiconductors are **lattice** matched in the sense that they have the same **lattice parameter** a. This means that interface defects due to mismatch of **crystal** dimensions between the two semiconductor crystals are minimal. Since the bandgap, E_g, changes at the interface, there are discontinuities in E_c and E_v at the interfaces. These discontinuities, ΔE_c and ΔE_V, depend on the semiconductor materials and their **doping**. In the case of GaAs/AlGaAs heterostructure shown in the figure, ΔE_c is greater than ΔE_v. Very approximately, the change from the wider E_{g2} to narrower E_{g1} is proportioned 60% to ΔE_c and 40% to ΔE_v. Because of the potential energy barrier, ΔE_c, conduction electrons in the thin GaAs layer are confined in the x-direction. This confinement length d is so small that we can treat the electron as in a one-dimensional potential energy (PE) well in the x-direction but as if it were free in the yz plane.
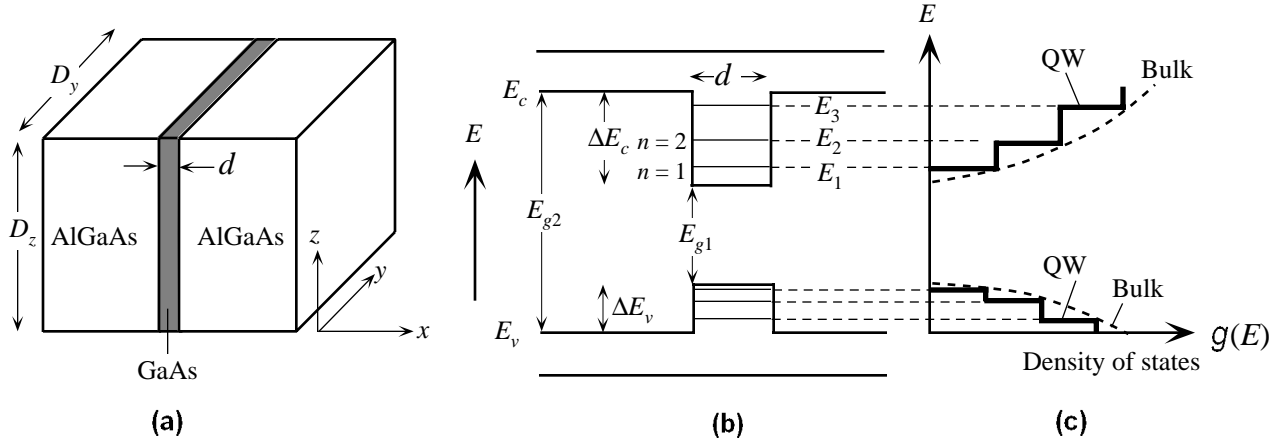
A quantum well (QW) device. (a) Schematic illustration of a quantum well (QW) structure in which a thin layer of GaAs is sandwiched between two wider bandgap semiconductors (AlGaAs). (b) The conduction electrons in the GaAs layer are confined (by ΔE_c) in the x-direction to a small length d so that their energy is quantized. (c) The density of states of a two-dimensional QW. The density of states is constant at each quantized energy level.

We can appreciate the confinement effect by considering the energy of the conduction electron that is bound by the size of the GaAs layer which is d along x and D_y and D_z along y and z. The energy of the conduction electron will be the same as that in a three dimensional PE well of size d, D_y and D_z and given by

$$E = E_c + \frac{h^2 n^2}{8 m_e^* d^2} + \frac{h^2 n_y^2}{8 m_e^* D_y^2} + \frac{h^2 n_z^2}{8 m_e^* D_z^2}$$

where n, n_y and n_z are quantum numbers having the values 1,2,3,…. The reason for the E_c in this equation is that the potential energy (PE) barriers are defined with respect to E_c. These PE barriers are ΔE_c along x and **electron affinity** (energy required to take the electron from E_c to vacuum) along y and z. But D_y and D_z are orders of magnitude greater than d so that the minimum energy, denoted as E_1, is determined by the term with n and d, the energy associated with motion along x. The minimum energy E_1 corresponds to $n = 1$ and is above E_c of GaAs. The separation between the energy levels identified by n_y and n_z and associated with motion in the yz plane is so small that the electron is free to move in the yz plane as if it were in the bulk semiconductor. We therefore have a two-dimensional electron gas which is confined in the x-direction. The holes in the **valence band** are confined by the potential energy barrier ΔE_v (hole energy is in the opposite direction to electron energy) and behave similarly. The density of electronic states for the two dimensional electron system is not the same as that for the bulk semiconductor. For a given electron concentration n, the **density of states** $g(E)$ number of quantum states per unit energy per unit volume, is constant and does not depend on the energy. The density of states for the confined electron and that in the bulk semiconductor are shown schematically below. $g(E)$ is constant at E_1 until E_2 where it increases as a step and remains constant until E_3 where again it increases as a step by the same amount and at every value of E_n. Density of states in the valence band behaves similarly.
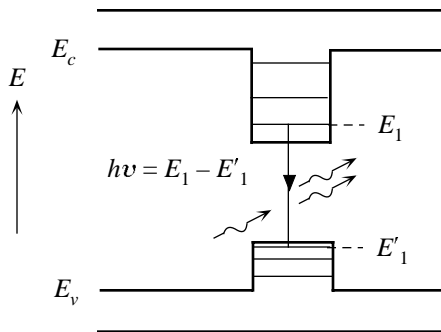
In single quantum well (SQW) lasers electrons are injected by the forward current into the thin GaAs layer which serves as the active layer. Population inversion between E_1 and E'_1 is reached even with a small forward current which results in stimulated emissions.

Since at E_1 there is a finite and substantial density of states, the electrons in the **conduction band** do not have to spread far in energy to find states. In the bulk semiconductor, on the other hand, the density of states at E_c is zero and increases slowly with energy (as $E^{1/2}$) which means that the electrons are spread more deeply into the conduction band in search for states. A large concentration of electrons can easily occur at E_1 whereas this is not the case in the bulk semiconductor. Similarly, the majority of holes in the valence band will be around E'_1 since there are sufficient states at this energy. Under a forward bias electrons are injected into the conduction band of the GaAs layer which serves as the active layer. The injected electrons readily populate the ample number of states at E_1 which means that the electron concentration at E_1 increases rapidly with the current and hence **population inversion** occurs quickly without the need for a large current to bring in a great number of electrons. Stimulated transitions of electrons from E_1 to E'_1 leads to a lasing emission. The **threshold current** for population inversion and hence lasing emission is markedly reduced with respect to that for bulk semiconductor devices. For example in a *single quantum well* (SQW) laser this is typically in the range $0.5 - 1$ mA whereas in a double heterostructure laser the threshold current is in the range $10 - 50$ mA.

Quarter-wave plate is a retarder plate (made from a birefringent refracting **crystal**) that results in a relative phase change of a quarter of a **wave** ($\pi/4$) between the **ordinary** and **extraordinary waves** propagating inside the crystal from entry to exit. A **linearly polarized** light incident with its **E**-field at an angle α to the **optic axis** leaves the crystal either as **elliptically polarized** light or as a **circularly polarized light** ($\alpha = 45°$).

Quarternary (III-V) alloys have four different elements from the III and V groups. For example $In_{1-x}Ga_xAs_{1-y}P_y$. is a quaternary alloy having Ga and In from group III and As and P from group V. There are as many group III elements as there are group V elements and formula reflects this requirement.

Radiant sensitivity, see **responsivity**.

Radiationless recombination, a nonradiative transition, is that in which an electron and a hole recombine through a **recombination center** such as a **crystal** defect or an impurity and emit **phonons** (**lattice** vibrations).

Raman scattering is the **scattering** of light due to its interactions with the vibrations of the molecules of the material system, or the vibrations of the **crystal** lattice, in such a way that the scattered light has been shifted in wavelength; the **photon** energy has been changed by the scattering process by an amount that corresponds to a change in the vibrational energy of the molecule or the **lattice** vibrations. Suppose that $h\vartheta$ is the **phonon** energy associated with molecular or lattice vibrations of frequency ϑ, $h\upsilon$ is the incident **photon** energy that has a frequency υ, then the scattered photon energy is

$$h\upsilon' = h\upsilon - h\vartheta.$$

Normally Raman scattering is weak. The scattered photon has less energy because it generates a phonon, or excites a molecular vibration, therefore it has a lower frequency but a longer wavelength.

The shift $\upsilon' - \upsilon$ (or its corresponding shift in wavelength) is called *Stokes shift*. If the incident photon interacts with a molecule that is already excited so that the photon absorbs energy is absorbed from the molecular vibration, the scattered photon has a higher energy, higher frequency and therefore a shorter wavelength. This is called *anti-Stokes shift*. The latter process is in the **crystal** is the **absorption** of a phonon by a photon.

Ramo's theorem relates the external photocurrent $i(t)$ due to a charge q being drifted with a velocity $v_d(t)$ by a field between two **biased** electrodes separated by L, that is

$$i(t) = \frac{q v_d(t)}{L} \; ; t < t_{\text{transit}}$$

Consider a **semiconductor** material with a negligible dark conductivity that is electroded and biased to generate a field E in the sample that is uniform and is given by V/L. This situation is almost identical to the intrinsic region of a **reverse biased** *pin* **photodiode**. Suppose that a single **photon** is absorbed at a position $x = l$ from the left electrode and instantly creates an electron hole pair. The electron and the hole drift in opposite directions with respective drift velocities $v_e = \mu_e E$ and $v_h = \mu_h E$, where μ_e and μ_h are the electron and hole drift mobilities respectively. The *transit time* of a carrier is the time it takes for a carrier to drift from its generation point to the collecting electrode. The electron and hole transit times t_e and t_h are

$$t_e = \frac{L - l}{v_e} \qquad \text{and} \qquad t_h = \frac{l}{v_h}$$

Consider first only the drifting electron. Suppose that the external photocurrent due to the motion of this electron is $i_e(t)$. The electron is acted on by the force eE of the electric field. When it moves a distance dx, work must be done by the external circuit. In time dt, the electron drifts a distance dx and does an amount of work $eEdx$ which is provided by the battery in time dt as $Vi_e(t)dt$. Thus,

$$\text{Work done} = eEdx = Vi_e(t)dt$$

Using $E = V/L$ and $v_e = dx/dt$ we find the electron photocurrent

$$i_e(t) = \frac{e v_e}{L} \; ; t < t_e$$

It is apparent that this current continues to flow as long as the electron is drifting (has a velocity v_e) in the sample. It lasts for a duration t_e at the end of which the electron reaches the battery. Thus, although the electron has been photogenerated instantaneously, the external photocurrent is *not* instantaneous and has a *time spread*. We can apply similar arguments to the drifting hole as well which will generate a hole photocurrent $i_h(t)$ in the external circuit given by

$$i_h(t) = \frac{e v_h}{L} \; ; t < t_h$$

The total external current will be the sum of $i_e(t)$ and $i_h(t)$. If we integrate the external current $i_{ph}(t)$ to evaluate the collected charge $Q_{\text{collected}}$ we would find,

$$Q_{\text{collected}} \int_0^{t_e} i_e(t) + \int_0^{t_h} i_h(t) = e$$

Thus, the collected charge is not $2e$ but just one electron.
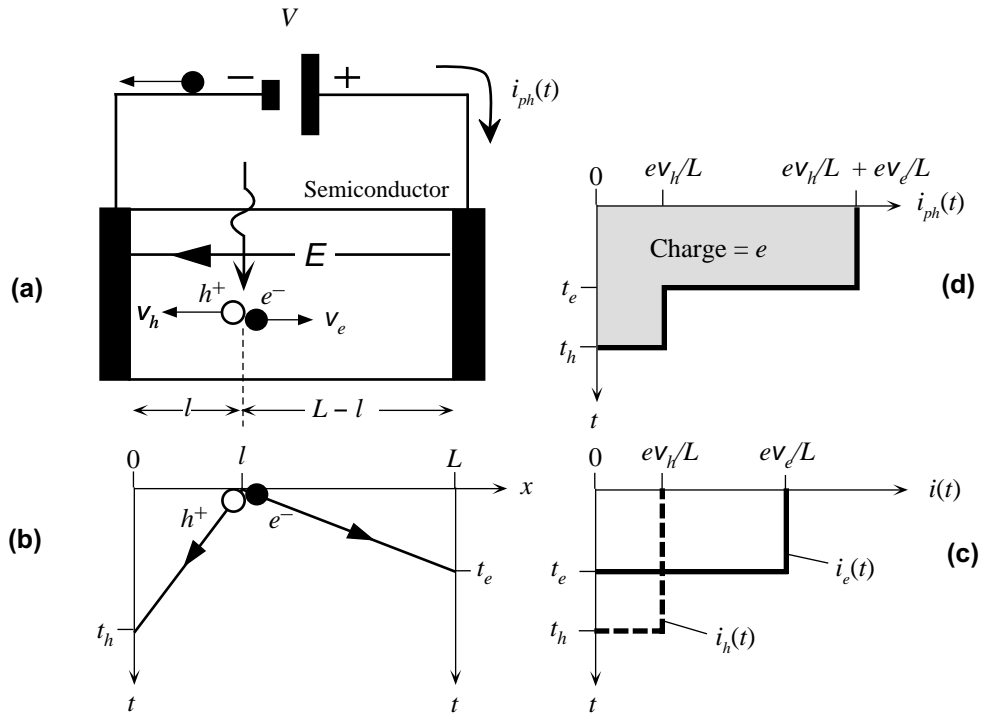
(a) An EHP is photogenerated at $x = l$. The electron and the hole drift in opposite directions with drift velocities v_h and v_e. (b) The electron arrives at time $t_e = (L - l)/v_e$ and the hole arrives at time $t_h = l/v_h$. (c) As the electron and hole drift, each generates an external photocurrent shown as $i_e(t)$ and $i_h(t)$. (d) The total photocurrent is the sum of hole and electron photocurrents each lasting a duration t_h and t_e respectively.

Rayleigh criterion determines the minimum angular resolution of an imaging system by specifying that the an imaging system can just resolve two neighboring points when their **diffraction** patterns are such that the maximum intensity of one coincides with the first zero intensity of the other. If the two point sources have an angular separation $\Delta\theta$ and are observed through an aperture of diameter D, and if λ is the wavelength in the observer's medium, then the minimum angular separation $\Delta\theta_{min}$ is given by

$$\sin(\Delta\theta_{min}) = 1.22\frac{\lambda}{D}$$
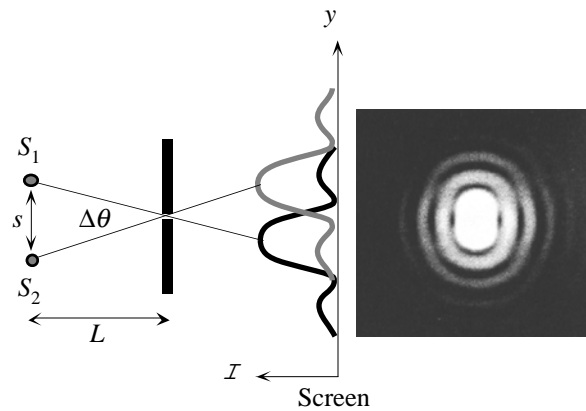
Resolution of imaging systems is limited by diffraction effects. As points S_1 and S_2 get closer, eventually the Airy disks overlap so much that the resolution is lost.

Reach-through avalanche photodiode (APD) is an avalanche photodiode device with a structure n^+ - p - π - p^+, where π represents very slight p-type **doping**. The n^+ side is thin and it is the side that is illuminated through a window. There are three p-type layers of different doping levels next to the n^+ layer to suitably modify the field distribution across the diode. The first is a thin p-type layer and the second is a thick lightly p-type doped (almost intrinsic) π-layer and the third is a heavily doped p^+ layer. The diode is **reverse biased** to increase the fields in the depletion regions. Under zero bias the **depletion layer** in the p-region (between n^+p) does not normally extend across this layer. But when a sufficient reverse bias is applied the depletion region in the p-layer widens to *reach-through* to the π-layer (and hence the name *reach-through*). The field extends from the exposed positively charged donors in the thin depletion layer in n^+ side, all the way to the exposed negatively charged acceptors in the thin depletion layer in p^+-side. The electric field is given by the integration of the net space charge density ρ_{net} across the diode subject to an applied voltage V_r across the device. The variation in the field across the diode is such that the field lines start at positive ions and end at negative ions which exist through the p, π and p^+ layers. This means that E is maximum at the n^+p junction, then decreases slowly through the p-layer. Through the π-layer it decreases only slightly as the net space charge density here is small. The field vanishes at the end of the narrow depletion layer in the p^+ side. The **absorption** of **photons** and hence **photogeneration** takes place mainly in the long π-layer. The nearly uniform field here separates the electron-hole pairs (EHPs) and drifts them at velocities near saturation towards the n^+ and p^+ sides respectively. When the drifting electrons reach the p-layer, they experience even greater fields and therefore acquire sufficient kinetic energy (greater than the bandgap E_g) to *impact-ionize* some of the Si covalent bonds and release EHPs. These generated EHPs themselves can also be accelerated by the high fields in this region to sufficiently large kinetic energies to further cause **impact ionization** and release more EHPs which leads to an *avalanche of impact ionization processes*. Thus from a single electron entering the p-layer one can generate a large number of EHPs all of which contribute to the observed photocurrent. The **photodiode** possesses an *internal gain mechanism* in that a single photon absorption leads to a large number of EHPs generated. The photocurrent in the APD in the presence of avalanche multiplication therefore corresponds to an effective quantum efficiency in excess of unity. The reason for keeping the photogeneration within the π-region and reasonably separate from the avalanche p-region is that avalanche multiplication is a statistical process and hence leads to carrier generation fluctuations which leads to *excess noise* in the avalanche **multiplied photocurrent**. This is minimized if impact ionization is restricted to the carrier with the highest impact ionization efficiency which in Si is the electron.
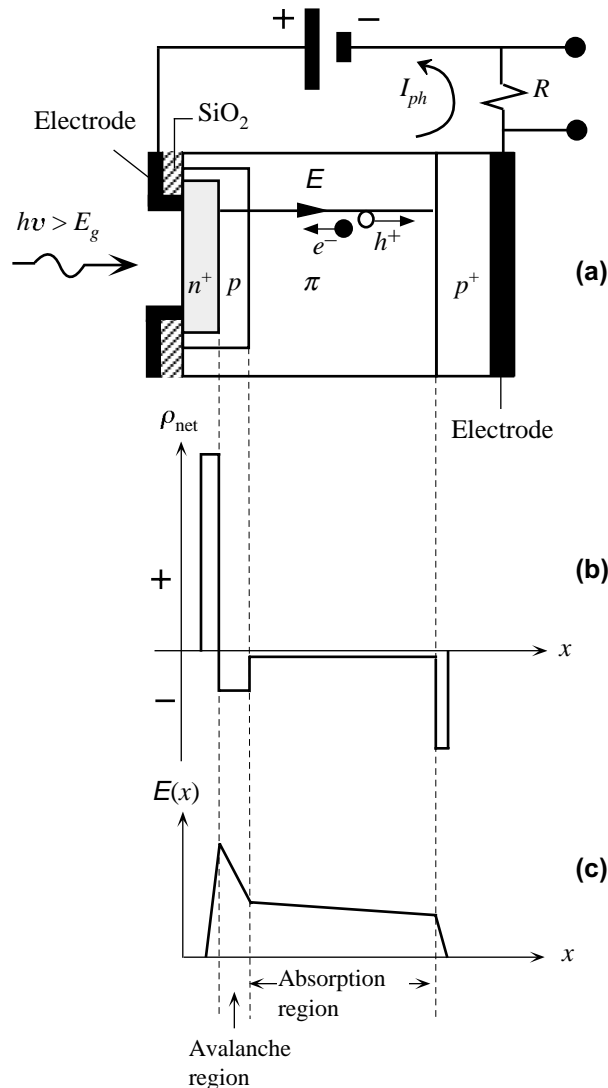
(a) A schematic illustration of the structure of an avalanche photodiode (APD) biased for avalanche gain. (b) The net space charge density across the photodiode. (c) The field across the diode and the identification of absorption and multiplication regions.

Recombination centers are defects or impurities in a **crystal** that facilitate the **recombination** of electrons and holes, usually (but not always) via **phonon** emissions, that is, without **photon** emission.

Recombination current flows under forward bias to replenish the carriers recombining in the space charge (depletion) layer (SCL). Typically the recombination current is described by $I = I_{ro}[\exp(eV/2kT)-1]$, where I_{ro} is a constant, e is the electronic charge, k is the **Boltzmann constant** and T is the temperature (Kelvins). The constant I_{ro} contains the details of the carrier **recombination** process in the space charge layer, for example, the mean recombination times in the SCL in the p and n-sides.

Recombination of an electron hole pair involves an electron in the **conduction band** (CB) falling in energy down into an empty **state** (hole) in the **valence band** (VB) to occupy it. The result is the annihilation of the electron hole pair. Recombination is direct when the electron falls directly down

into an empty state in the VB as in GaAs. Recombination is indirect if the electron is first captured locally by a defect or an impurity, called a **recombination center**, and from there it falls down into an empty state (hole) in the VB as in Si and Ge.

Reflectance is the fraction of power in the reflected **electromagnetic wave** with respect to the incident power.

Reflection coefficient is the ratio of the amplitude of the reflected EM (electromagnetic) wave to that of the incident **wave**. It can be positive, negative or a complex number which then represents a phase change.

Refraction is a change in the direction of **wave** when it enters a medium with a different **refractive index**. A wave that is incident at a boundary between two media with different refractive indices experiences refraction and changes direction in passing from one to the other medium. The angles of incidence and refraction obey **Snell's law**. If light is traveling in a medium with index n_1 is incident on a medium of index n_2, and if the angles of incidence and refraction (transmission) are θ_i and θ_t, then according to Snell's law:

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{n_2}{n_1}$$
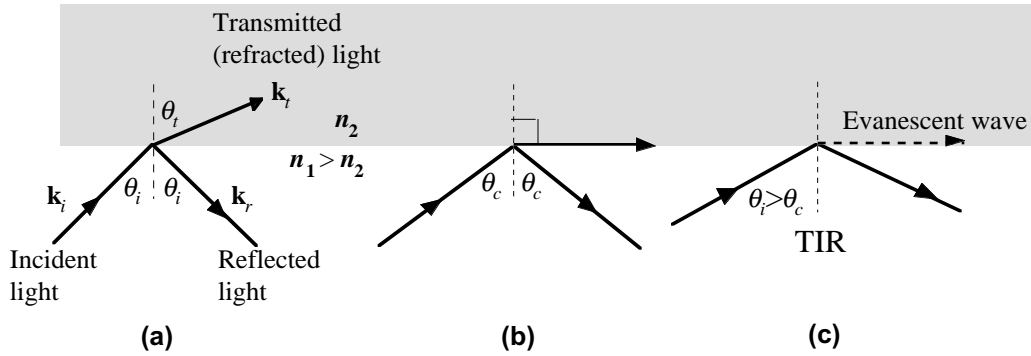
Light wave travelling in a more dense medium strikes a less dense medium. Depending on the incidence angle with respect to θ_c, which is determined by the ratio of the refractive indices, the wave may be transmitted (refracted) or reflected. (a) $\theta_i < \theta_c$ (b) $\theta_i = \theta_c$ (c) $\theta_i > \theta_c$ and total internal reflection (TIR).

Refractive index n of an optical or dielectric medium is the ratio of the velocity of light c in vacuum to its velocity v in the medium; $n = c/v$. If ε_r is the relative permittivity at the frequency of interest, the electromagnetic wave frequency at which n is of interest, then $n = (\varepsilon_r)^{1/2}$. The refractive index depends on the wavelength of light; for example, in glasses n decreases with increasing λ. The refractive index of a semiconductor material typically decreases with increasing energy bandgap E_g. There are various empirical and semi-empirical rules and expressions that relate n to E_g. In **Moss's rule**, n and E_g are related by $n^4 E_g = K = $ constant (roughly ~100 eV). In the Hervé-Vandamme relationship,

$$n^2 = 1 + \left(\frac{A}{E_g + B}\right)^2$$

where A and B are constants ($A \approx 13.6$ eV and $B \approx 3.4$ eV and $dB/dT \approx 2.5\times10^{-5}$ eV K^{-1}). The refractive index typically increases with increasing temperature. The **temperature coefficient of refractive index** TCRI of semiconductors can be found from the Hervé-Vandamme relationship

$$\text{TCRI} = \frac{1}{n} \cdot \frac{dn}{dT} = \frac{(n^2 - 1)^{3/2}}{13.6n^2} \left[\frac{dE_g}{dT} + \frac{dB}{dT} \right]$$

TCRI is typically in the range 10^{-6} to 10^{-4}. The dependence of the refractive index on the wavelength can generally be described by the **Sellmeier equation**, which, for diamond, takes the form

$$n^2 = 1 + \frac{A\lambda^2}{\lambda^2 - \lambda_1^2} + \frac{B\lambda^2}{\lambda^2 - \lambda_2^2}$$

where $A = 0.3306$ and $B = 4.3356$, $\lambda_1 = 175$ nm and $\lambda_2 = 106$ nm.

Repeater, optical repeater, is a device or an electronic circuit restores the received optical signal back to its original shape with amplification so that it can be sent again along a transmission line.

Resonance, in general, is a "state" of a system in which the smallest driving oscillations can most easily build up into large amplitude oscillations of the system. For example, a parallel inductor-capacitor circuit is in resonance when the driving oscillator frequency, $f = 1/[2\pi(LC)^{1/2}]$ at which the circuit oscillates naturally and consumes the minimum energy from the driving oscillator.

Resonant frequency, in general, is the frequency of an allowed **wave** or oscillation within a given structure; a natural frequency of the structure. A *resonant frequency of an optical cavity* is a frequency of an allowed mode of electromagnetic oscillations within the optical cavity. The resonant frequency depends on the cavity properties; the cavity size, **reflectances** and the **refractive index**

Response time is the duration of time it takes for a device to produce the required output in response to a step input.

Responsivity is the photocurrent generated by a **photodiode** per unit incident **optical power**. It depends on the quantum efficiency and the wavelength of the incident radiation. The responsivity R of a photodiode characterizes its performance in terms of the photocurrent generated (I_{ph}) per incident optical power (P_o) at a given wavelength by

$$R = \frac{\text{Photocurrent (A)}}{\text{Incident Optical Power (W)}} = \frac{I_{ph}}{P_o}$$

From the definition of *quantum efficiency* (QE)

$$R = \eta \frac{e}{h\upsilon} = \eta \frac{e\lambda}{hc}$$

where η is the quantum efficiency which depends on the light wavelength λ, h is **Planck's constant**, υ is the light frequency and e is the electronic charge. The responsivity therefore clearly depends on the wavelength. R is also called the *spectral responsivity* or *radiant sensitivity*. The R vs. λ characteristics represents the spectral response of the photodiode and is generally provided by the manufacturer. Ideally with a quantum efficiency of 100% ($\eta = 1$), R should increase with λ up to λ_g. In practice, QE limits the responsivity to lie below the ideal photodiode line with upper and lower wavelength limits as shown for a typical Si photodiode in the same figure. The QE of a well designed Si photodiode in the wavelength range 700 - 900 nm can be close to 90-95%

Responsivity (A/W)

Ideal Photodiode
QE = 100% ($\eta = 1$)

λ_g

Si Photodiode
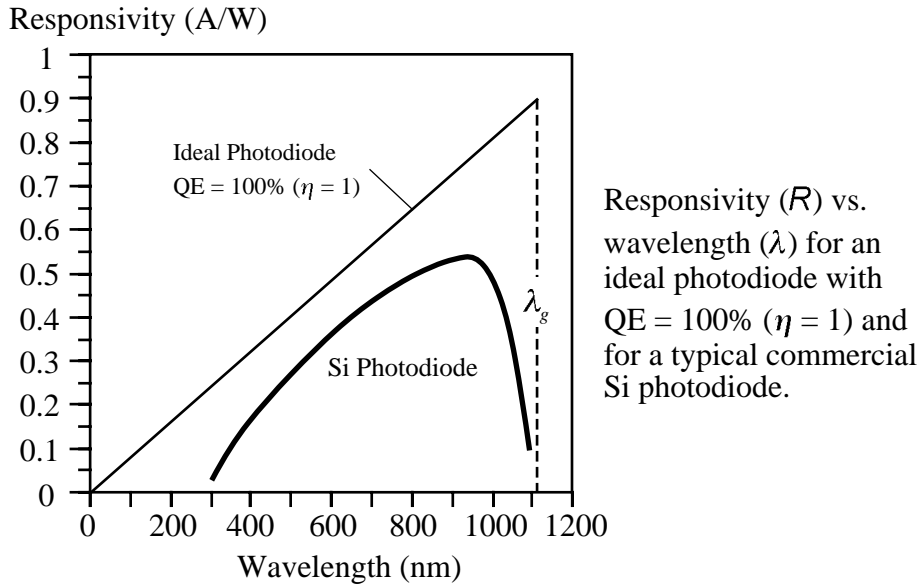
Wavelength (nm)

Responsivity (R) vs. wavelength (λ) for an ideal photodiode with QE = 100% ($\eta = 1$) and for a typical commercial Si photodiode.

Retarding plates are optical devices that change the state of **polarization** of an incident light beam. For example, consider a positive **uniaxial crystal** such as quartz ($n_e > n_o$) plate that has the **optic axis** (taken along z) parallel to the plate faces. Suppose that a *linearly polarized* wave is incident at normal incidence on a plate face. If the field **E** is parallel to the optic axis ($E_{//}$), then this **wave** will travel through the crystal as an *e*-wave with a velocity c/n_e slower than the *o*-wave since $n_e > n_o$. Thus, optic axis is the "slow axis" for waves polarized parallel to it. If **E** is right angles to the optic axis ($E_\perp$) then this wave will travel with a velocity c/n_o, which will be the fastest velocity in the crystal. Thus, the axis perpendicular to the optic axis (say x) will be the "fast axis" for polarization along this direction. When a light ray enters a crystal at normal incidence to the optic axis and plate surface, then the *o*- and *e*-waves travel along the same direction. We can resolve a linear polarization at an angle α to z into $E_\perp$ and $E_{//}$. When the light comes out at the opposite face these two components would have been phase shifted by ϕ (one component retarded relative to the other). Depending on the initial angle α of E and the length of the crystal, which determines the total phase shift ϕ through the plate, the emerging beam can have its initial linear polarization rotated, or changed into an elliptically or **circularly polarized light**. If *L* is the thickness of the plate then the *o*-wave experiences a phase change $k_{o\text{-wave}}L$ through the plate where $k_{o\text{-wave}}$ is the **wavevector** of the o-wave: $k_{o\text{-wave}} = (2\pi/\lambda)n_o$, where λ is the free space wavelength. Similarly, the *e*-wave experiences a phase change $(2\pi/\lambda)n_oL$ through the plate. Thus, the phase difference ϕ between the orthogonal components $E_\perp$ and $E_{//}$ of the emerging beam is

$$\phi = \frac{2\pi}{\lambda}(n_e - n_o)L$$

The phase difference ϕ expressed in terms of full wavelengths is called the *retardation* of the plate. For example, a phase difference ϕ of 180° is a half-wavelength retardation. The polarization of the through beam depends on the crystal-type , $(n_e - n_o)$, and the plate thickness *L*. We know that depending on the phase difference ϕ between the orthogonal components of the field, the EM wave can be linearly, circularly or **elliptically polarized**. A **half-wave plate** retarder has a thickness *L* such that the phase difference ϕ is π or 180°, corresponding to a half of wavelength ($\lambda/2$) of retardation. The result is that, $E_\perp$ is delayed by 180° If we add the emerging $E_\perp$ and $E_{//}$ with this shift

ϕ, E would be at an angle $-\alpha$ to the optic axis and still **linearly polarized**. E has been rotated counterclockwise through 2α. A **quarter-wave plate** retarder has a thickness L such that the phase difference ϕ is $\pi/2$ or 90°, corresponding to a quarter of wavelength. If we add the emerging $E_\perp$ and $E_{//}$ with this shift ϕ, the emerging light will be elliptically polarized if $0 < \alpha < 45°$ and circularly polarized if $\alpha = 45°$.
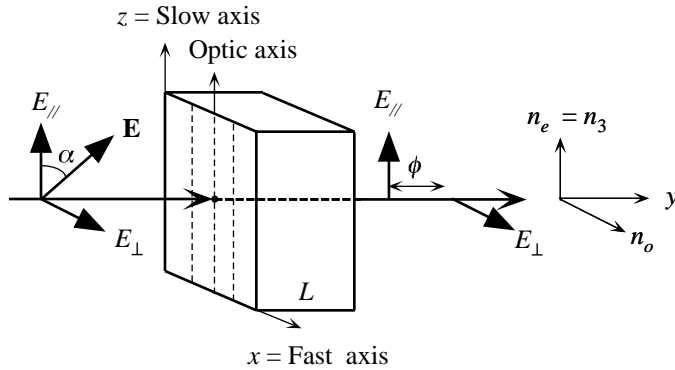
A retarder plate. The optic axis is parallel to the plate face. The *o*- and *e*-waves travel in the same direction but at different speeds.
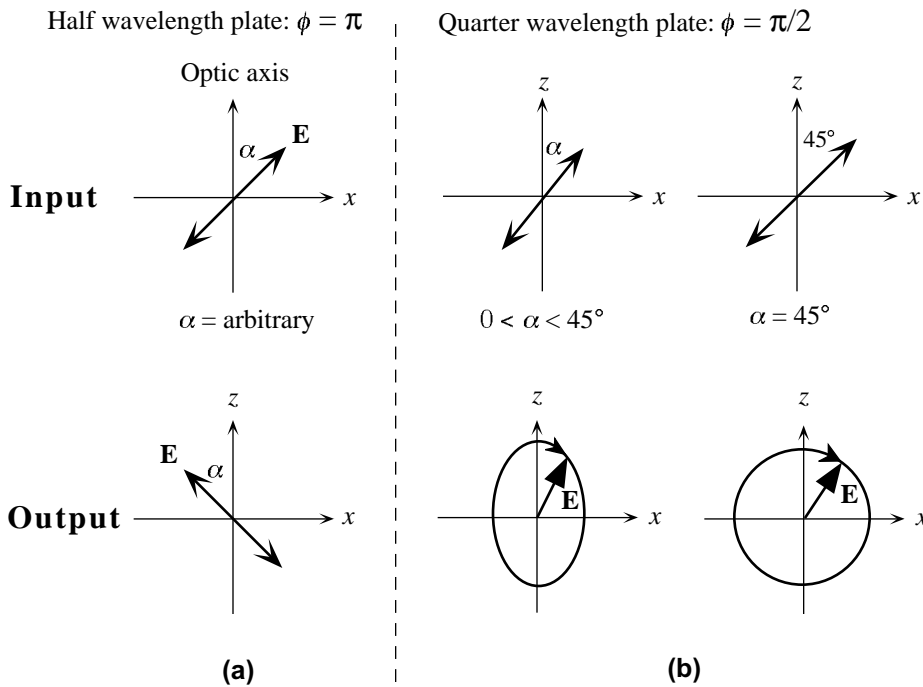
Input and output polarizations of light through (a) a half-wavelength plate and (b) through a quarter-wavelength plate.

Return-to-zero (RZ) is a digital coding system in which information in binary form is represented by pulses that return to zero, for a duration equal to the pulse width, before the next **bit** of information. Suppose that T is the information bit period, that is information is sent every T seconds. In RZ coding, the pulse width for information is $T/2$ and is zero for the next half period $T/2$. In *nonreturn to zero (NRZ)* the information is represented by pulses that do not have to return to zero. The pulse

width is the same as the information period *T*.
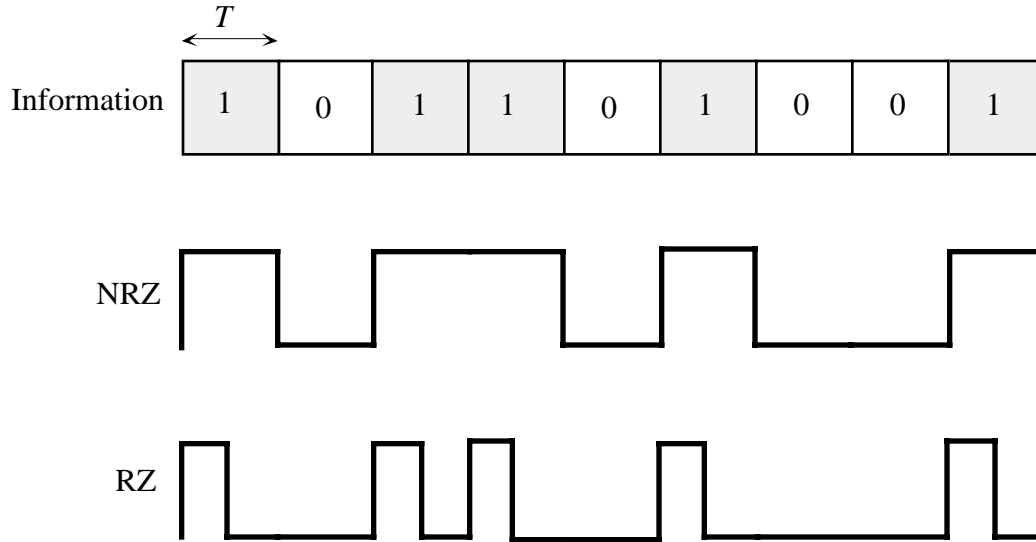
Reverse bias is the application of an external voltage to a *pn* junction such that the positive terminal is connected to the *n*-side and negative to the *p*-side. The applied voltage increases the built-in potential and hence the internal field in the space charge layer.

Reverse diode current is the **diode** current in the dark when the diode is reverse biased. Under reverse bias, the hole concentration in the *n*-side just outside the space charge layer (SCL) is nearly zero by the **law of the junction**, whereas the hole concentration in the bulk (or near the negative terminal) is the equilibrium concentration p_{no}, which is small. There is therefore a small concentration gradient and hence a small hole **diffusion** current towards the SCL.
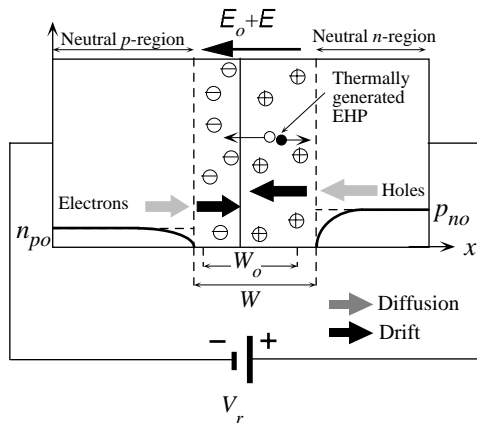
Reverse biased *pn* junction. Minority carrier profiles and the origin of the reverse current.

Similarly, there is a small electron diffusion current from bulk *p*-side to the SCL. Within the SCL, these carriers are drifted by the field. This reverse current is basically the Shockley equation under **reverse bias** and is called the **reverse saturation current**, I_{so}. This saturation current depends on the square of the intrinsic concentration, that is n_i^2, but not on the voltage. The thermal generation of electron hole pairs (EHPs) in the space charge region can also contribute to the observed reverse current since the internal field in this layer will separate the electron and hole and drift them towards the neutral regions. This drift will result in an external current $I_{generation}$ due to EHP generation in the SCL. $I_{generation}$ increases slightly with the reverse bias V_r because SCL width increases with V_r. $I_{generation}$ is proportional to n_i. The total *reverse current* I_{rev} is the sum of the diffusion and generation components. Their relative importance of these terms depends not only on the semiconductor

properties but also on the temperature since $n_i \sim \exp(-E_g/2kT)$, where E_g is the **semiconductor** bandgap, k is the **Boltzmann constant** and T is the temperature. For example, the reverse **dark current** $I_{reverse}$ in a Ge *pn* junction (a photodiode) when plotted as $\ln(I_{reverse})$ vs. $1/T$ as in the figure shows two regions. Above 238 K, $I_{reverse}$ is controlled by n_i^2 because the slope of $\ln(I_{reverse})$ vs. $1/T$ yields an E_g of approximately 0.63 eV, close to the expected E_g of about 0.66 eV in Ge. In this range, the reverse current is due to minority carrier **diffusion** in neutral regions. Below 238 K, $I_{reverse}$ is controlled by n_i because the slope of $\ln(I_{reverse})$ vs. $1/T$ is equivalent to an $E_g/2$ of approximately 0.33 eV. In this range, the reverse current is due to EHP generation in the SCL via defects and impurities (**recombination centers**).

Photodiode reverse current (A) at $V_r = 5$ V
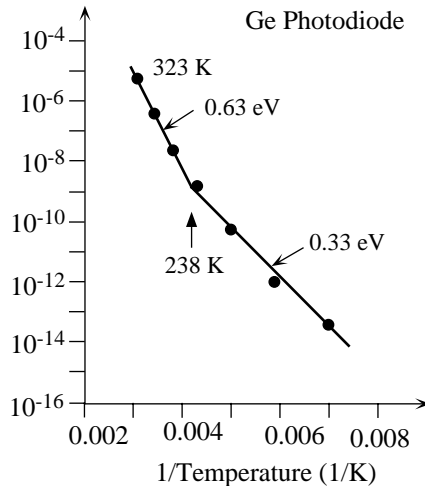
Dark current, *i.e.* reverse diode current, in a Ge *pn* junction as a function of temperature in a $\ln(I_{reverse})$ vs $1/T$ plot.

Above 238 K, $I_{reverse}$ is controlled by n_i^2 and below 238 K it is controlled by n_i.

The vertical axis is a logarithmic scale with actual current values. (From D. Scansen and S.O. Kasap, *Cnd. J. Physics.* **70**, 1070-1075, 1992.)

Reverse saturation current is the reverse current that would flow in a reversed biased ideal *pn* junction obeying the Shockley equation.

Rise time is the time it takes for the photocurrent to rise from the 10% to the 90% of the steady state value when the photodetector is suddenly illuminated as a step function.

Scattering is a process by which the energy from a propagating EM (electromagnetic) wave is redirected as secondary EM waves in various directions away from the original direction of propagation. There are a number of scattering process. In Rayleigh scattering, fluctuations in the **refractive index**, inhomogeneities etc. lead to the scattering of light that decreases with the wavelength as λ^4. For an EM (electromagnetic) wave propagating along an **optical fiber**, scattering is a cause of **attenuation** along the fiber (direction of propagation). Rayleigh scattering is responsible for the blue color of the sky as blue wavelengths are scattered more in the atmosphere.

A dielectric particle smaller than wavelength

Incident wave

Through wave

Scattered waves
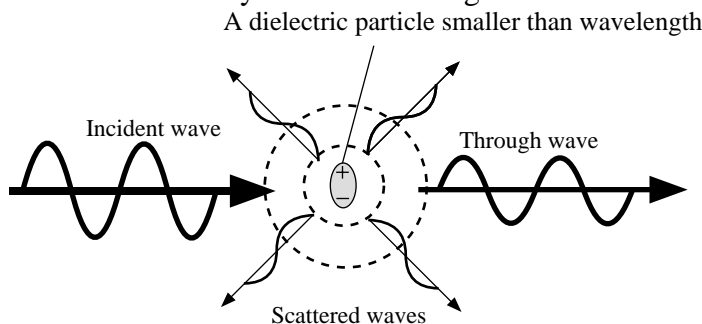
Rayleigh scattering involves the polarization of a small dielectric particle or a region that is much smaller than the light wavelength. The field forces dipole oscillations in the particle (by polarizing it) which leads to the emission of EM waves in "many" directions so that a portion of the light energy is directed away from the incident beam.

Lord Rayleigh (John William Strutt) was an English physicist (1877 - 1919) and a Nobel Laureate (1904) who made a number of contributions to wave physics of sound and optics. (Courtesy of AIP Emilio Segrè Visual Archives, Physics Today Collection)

Schrödinger equation is a fundamental equation in nature whose solution describes the wave-like behavior of a particle. The equation cannot be derived from a more fundamental law. Its validity is based on its ability to predict any known natural phenomena. The solution requires as input, the potential energy function, $V(x,y,z,t)$, of the electron and the boundary and initial conditions. The *PE* function, $V(x,y,z,t)$ describes the interaction of the particle with its environment. Time independent Schrödinger equation describes the wave behavior of a particle under steady state conditions, *i.e.* when the *PE* is time independent, $V(x,y,z)$. If E is the total energy, $\nabla^2 = (d^2/dx^2 + d^2/dx^2 + d^2/dx^2)$, m_e is the electron mass and ψ is the **wavefunction** of the electron then $\nabla^2\psi + (2m_e/\hbar^2)(E - V)\psi = 0$. The solution of the time independent Schrödinger equation, gives the wavefunction $\psi(x,y,z)$ of the electron and its energy E. The wavefunction, $\psi(x,y,z)$ has the interpretation that $|\psi(x,y,z)|^2$ is the probability of finding the electron per unit volume at point x,y,z.

Second harmonic generation (SHG) and photonic interpretation involves two **fundamental mode** photons that interact with the dipoles moments to produce a single second harmonic **photon**.

The photon momentum is $\hbar\mathbf{k}$ and energy is $\hbar\omega$. Suppose that subscripts 1 and 2 refer to fundamental and second harmonic photons. In general terms, we can write the following two equations. Conservation of momentum requires that

$$\hbar\mathbf{k}_1 + \hbar\mathbf{k}_1 = \hbar\mathbf{k}_2$$

The conservation of energy requires that

$$\hbar\omega_1 + \hbar\omega_1 = \hbar\omega_2$$

We tacitly assumed that the interaction does not result in **phonon** (**lattice** vibration) generation or **absorption**. We can satisfy the second equation by taking $\omega_2 = 2\omega_1$, so that the frequency of the second harmonic is indeed twice the fundamental. To satisfy the first equation we need $\mathbf{k}_2 = 2\mathbf{k}_1$. The **phase velocity** v_2 of the second harmonic **waves** is

$$v_2 = \frac{\omega_2}{k_2} = \frac{2\omega_1}{2k_1} = \frac{\omega_1}{k_1} = v_1$$

Thus, the fundamental and the second harmonic photons are required to have the same phase velocity which is tantamount to a phase matching criterion in terms of pure waves. If $\mathbf{k}_2$ is not exactly $2\mathbf{k}_1$, *i.e.* $\Delta k = k_2 - 2k_1$ is not zero, *i.e.* there is a mismatch, then SHG is only effective over a limited length l_c which can be shown to be given by $l_c = \pi/\Delta k$. This length l_c is essentially the **coherence length** of the second harmonic (depending on the index difference, this may be quite short, *e.g.* $l_c \approx 1 - 100$ μm). If the **crystal** size is longer than this, the second harmonics will interfere randomly with each other and the SHG efficiency will be very poor, if not zero. Phase matching is therefore an essential requirement for SHG. The **conversion efficiency** depends on the intensity of exciting laser beam, the materials χ_2 coefficient and the extent of phase matching and can be substantial (as high as 70-80%) if well-engineered by, for example, placing the converting crystal into the cavity of the laser itself.

Second harmonic
photon, $\mathbf{k}_2$

Fundamental photon, $\mathbf{k}_1$

$\hbar\omega_1$

$\hbar\omega_1$

Fundamental photon, $\mathbf{k}$

$\hbar\omega_2$

Dipole moment-photon
interaction region

Photonic interpretation of second
harmonic generation (SHG)
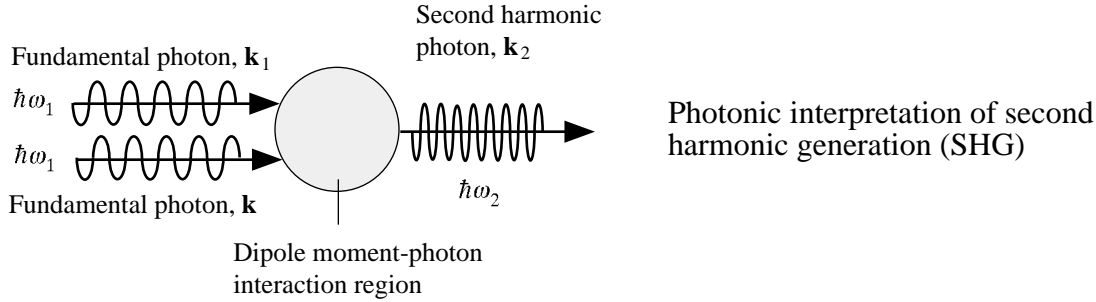
Second harmonic generation (SHG) occurs an intense light beam of angular frequency ω passing through an appropriate **crystal** (*e.g.* quartz) generates a light beam of double the frequency, 2ω. If E is the electric field in the light **wave**, then the induced **polarization** P becomes a function of E and can be written as

$$P = \varepsilon_o\chi_1 E + \varepsilon_o\chi_2 E^2 + \varepsilon_o\chi_3 E^3$$

where χ_1, χ_2 and χ_3 are the linear, second-order and third-order susceptibilities. SHG is based on a finite χ_2 coefficient in which the effect of χ_3 is negligible. Consider a beam of monochromatic light, with a well-defined angular frequency ω, passing through a medium. The **optical field** E at any point in the medium will polarize the medium at the same point in synchronization with the optical field oscillations. An oscillating dipole moment is well known as an electromagnetic emission source (just like an antenna). These secondary electromagnetic emissions from the dipoles in the medium interfere and constitute the actual wave traveling through the medium (Huygen's construction from secondary waves). Suppose that the optical field is oscillating sinusoidally between $\pm E_o$ as shown in the figure. In the linear regime (E_o is "small"), P oscillations will also be sinusoidal with a frequency ω. If the field strength is sufficiently large, the induced polarization will not be linear and will not oscillate in a simple sinusoidal fashion. The polarization now oscillates between P_+ and P_- and is not symmetrical. The oscillations of the dipole moment P now emit waves not only at the frequency[2] ω but also at 2ω. In addition there is a dc component (light is "rectified", *i.e.* gives rise to a small permanent polarization). The *fundamental* ω and the *second harmonic,* 2ω, components, along with the dc, are shown in shown in the figure below. If we write the optical field as $E = E_o\sin(\omega t)$ and substitute into the expression for P we would find the induced P as

$$P = \varepsilon_o\chi_1 E_o\sin(\omega t) - \tfrac{1}{2}\varepsilon_o\chi_2 E_o\cos(2\omega t) + \tfrac{1}{2}\varepsilon_o\chi_2 E_o$$

The first term is the fundamental, second is the second harmonic and third is the dc term. The second harmonic (2ω) oscillation of local dipole moments generates secondary second harmonic (2ω-) waves in the crystal. It may be though that these secondary waves will interfere constructively and result in a second harmonic beam just as the fundamental (ω-) secondary waves interfere and give rise to the propagating light beam. However, the crystal will normally possess different refractive indices $n(\omega)$ and $n(2\omega)$ for frequencies ω and 2ω which means that the ω- and 2ω- waves propagate with different phase velocities v_1 and v_2 respectively. As the ω-wave propagates in the crystal it generates secondary 2ω waves along its path, S_1, S_2, S_3, ... When wave S_2 is generated, S_1 must arrive there in phase which means S_2 must travel with the same velocity as the fundamental

---

[2] In this section, the adjective *angular* is dropped from the frequency though implied.

wave; and so on. It is apparent that only if these 2ω waves are in phase, that is they propagate with the same velocity as the ω-wave, that they can interfere constructively and constitute a second harmonic beam. Otherwise, the S_1, S_2 and S_3.. will eventually fall out of phase and destroy each other and there will be either no or very little second harmonic beam. The condition that the second harmonic waves must travel with the same **phase velocity** as the fundamental wave to constitute a second harmonic beam is called *phase matching* and requires $n(\omega) = n(2\omega)$. For most crystals this is not possible as n is dispersive; depends on the wavelength. SHG efficiency depends on the extent of phase matching, $n(\omega) = n(2\omega)$. One method is to use a **birefringent crystal** as these have two refractive indices: ordinary index n_o and extraordinary index n_e. Suppose that along a certain crystal direction at an angle θ to the **optic axis**, $n_e(2\omega)$ at the second harmonic is the same as $n_o(\omega)$ at the fundamental frequency: $n_e(2\omega) = n_o(\omega)$. This is called *index matching* and the angle θ is the *phase matching angle*. Thus, the fundamental would propagate as an ordinary wave and the second harmonic as an **extraordinary wave** and both would be in phase. This would maximize the **conversion efficiency**, though this would still be limited by the magnitude of second order term with respect to the first. To separate the second harmonic beam from the fundamental beam, something like a **diffraction grating**, a prism or an optical filter will have to be used at the output as. The phase matching angle θ depends on the wavelength (or ω) and is sensitive to temperature.

(a) Induced polarization vs. optical field for a nonlinear medium. (b) Sinusoidal optical field oscillations between $\pm E_o$ result in polarization oscillations between P_+ and P_-. (c) The polarization oscillation can be represented by sinusoidal oscillations at angular frequencies ω (fundamental), 2ω (second harmonic) and a small DC component.
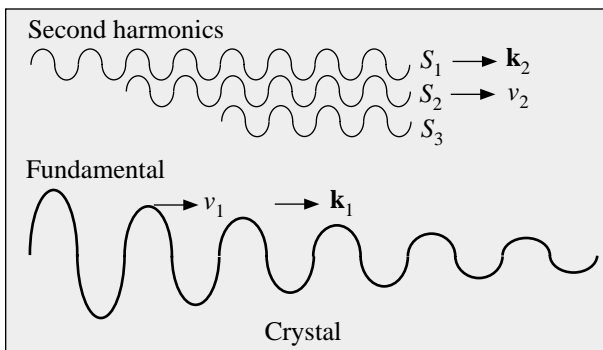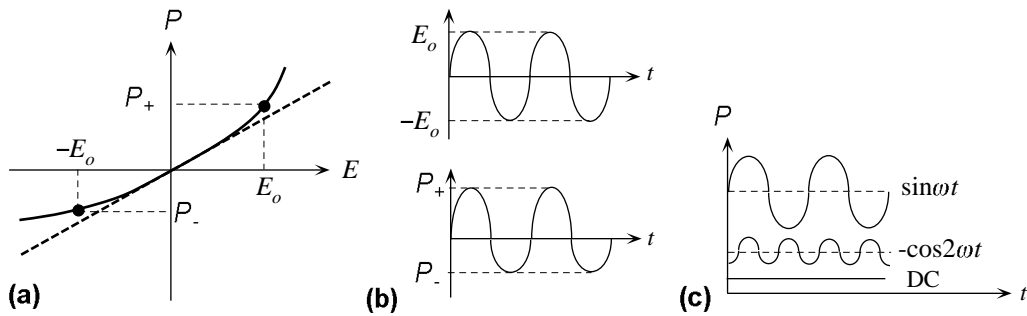
As the fundamental wave propagates, it periodically generates second harmonic waves (S_1, S_2, S_3, ...) and if these are in phase then the amplitude of the second harmonic light builds up.
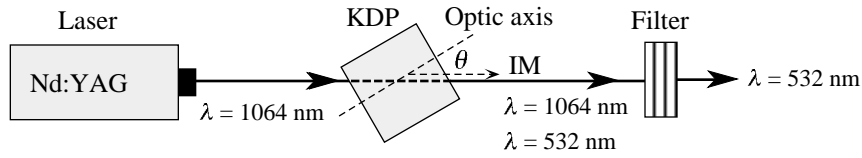
A simplified schematic illustration of optical frequency doubling using a KDP (potassium dihydrogen phosphate) crystal. IM is the index matched direction at an angle θ (about 35°) to the optic axis along which $n_e(2\omega) = n_o(\omega)$. The focusing of the laser beam onto the KDP crystal and the collimation of the light emerging from the crystal are not shown.

Selection rules determine what values of ℓ and m_ℓ are allowed for transitions involving the emission and **absorption** of electromagnetic radiation, *i.e.* **photons**. In summary, $\Delta\ell = \pm 1$ and $\Delta m_\ell = 0, \pm 1$. The spin of the electron, m_s, remains unchanged. The transition of the electron within an atom from one **state**, $\psi(n, \ell, m_\ell, m_s)$, to another, $\psi(n', \ell', m_\ell', m_s')$, due to collisions with other atoms or electrons does not necessarily obey the selection rules.

Self-focused light see **optical Kerr effect**.

Self-phase modulation dispersion is the modulation of the phase of a **wave** by its own magnitude. At sufficiently high light intensities, the **refractive index** of **glass** n' can be written as $n' = n + C\mathcal{I}$ where C is a constant and $\mathcal{I}$ is the light intensity. The intensity of light modulates its own phase.

Self-phase modulation is the modulation of the phase of a **wave** as a result of time-dependent changes in the **refractive index** of the medium due to the instantaneous intensity of the wave; see **optical Kerr effect**.

Sellmeier equation relates the refractive index of a substance to the wavelength of light through an empirical dispersion relation of the form,

$$n^2 - 1 = \frac{G_1 \lambda^2}{\lambda^2 - \lambda_1^2} + \frac{G_2 \lambda^2}{\lambda^2 - \lambda_2^2} + \frac{G_3 \lambda^2}{\lambda^2 - \lambda_3^2}$$

where G_1, G_2, G_3 and λ_1, λ_2 and λ_3 are constants (called Sellmeier coefficients) that are determined by fitting this expression to the experimental data. The actual Sellmeier formula has more terms in the right hand summation of the same type *e.g.* $G_i \lambda^2 / (\lambda^2 - \lambda_i^2)$ where $i = 4, 5,...$ but these can generally be neglected in representing n vs. λ behavior over typical wavelengths of interest and ensuring that three terms included in the Sellmeier equation correspond to the most important or relevant terms in the summation. Sellmeier coefficients for pure Silica (SiO_2) and SiO_2-13.5 mol.% GeO_2 are given in the table below.

The $\lambda_1, \lambda_2, \lambda_3$ are in μm.

	G_1	G_2	G_3	λ_1	λ_2	λ_3
SiO_2	0.696749	0.408218	0.890815	0.0690660	0.115662	9.900559
SiO_2-13.5%GeO_2	0.711040	0.451885	0.704048	0.0642700	0.129408	9.425478

Semiconductor is a nonmetallic element (*e.g.* Si or Ge) that contains both electrons and holes as charge carriers in contrast to an enormous number of electrons only as in metals. A hole is essentially a "half-broken" covalent bond which has a missing electron and therefore behaves effectively as if positively charged. Under the action of an applied field the hole can move by accepting an electron

from a neighboring bond thereby passing on the "hole". Electron and hole concentrations in a semiconductor are generally many orders of magnitude less than those in metals thus leading to much smaller conductivities.

Semiconductor laser is a solid state laser device that may have various structures to form an **optical resonator** and to provide a lasing output at a particular wavelength under forward bias.

A semiconductor laser (Courtesy of SDL, San Jose, California)

Separate absorption and multiplication (SAM) avalanche photodiode (APD) is typically a heterostructure, *e.g.* InGaAs-InP, with different bandgap materials to separate absorption and multiplication (SAM). InP has a wider bandgap than InGaAs and the *p* and *n* type **doping** of InP is indicated by capital letters, *P* and *N*. The main depletion layer is between P^+-InP and *N*-InP layers and it is within the *N*-InP. This is where the field is greatest and therefore it is in this *N*-InP layer where avalanche multiplication takes place. With sufficient **reverse bias** the depletion layer in the *n*-InGaAs reaches through to the *N*-InP layer. The field in the depletion layer in *n*-InGaAs is not as great as that in *N*-InP. Although the long wavelength **photons** are incident onto the InP side, they are not absorbed by InP since the photon energy is less than the bandgap energy of InP ($E_g = 1.35$ eV). Photons pass through the InP layer and become absorbed in the *n*-InGaAs layers. The field in the *n*-InGaAs layer drifts the holes to the multiplication region where **impact ionization** multiplies the carriers. The real device is more complicated than this simple description. Photogenerated holes drifting from *n*-InGaAs to *N*-InP become trapped at the interface because there is a sharp increase in the bandgap and a sharp change ΔE_v in E_v (**valence band** edge) between the two

semiconductors and holes cannot easily surmount the potential energy barrier ΔE_v. This problem is overcome by using thin layers of *n*-type InGaAsP with intermediate bandgaps to provide a graded transition from InGaAs to InP. Effectively ΔE_v has been broken up into two steps. The hole has sufficient energy to overcome the first step and enter the InGaAsP layer. It drifts and accelerates in the InGaAsP layer to gain sufficient energy to surmount the second step. These devices are called *separate absorption, grading and multiplication* (SAGM) APDs. Both the InP layers are grown epitaxially on an InP **substrate**. The substrate itself is not used directly to make the *P-N* junction to prevent **crystal** defects (for example, **dislocations**) in the substrate appearing in the multiplication region and hence deteriorating the device performance.
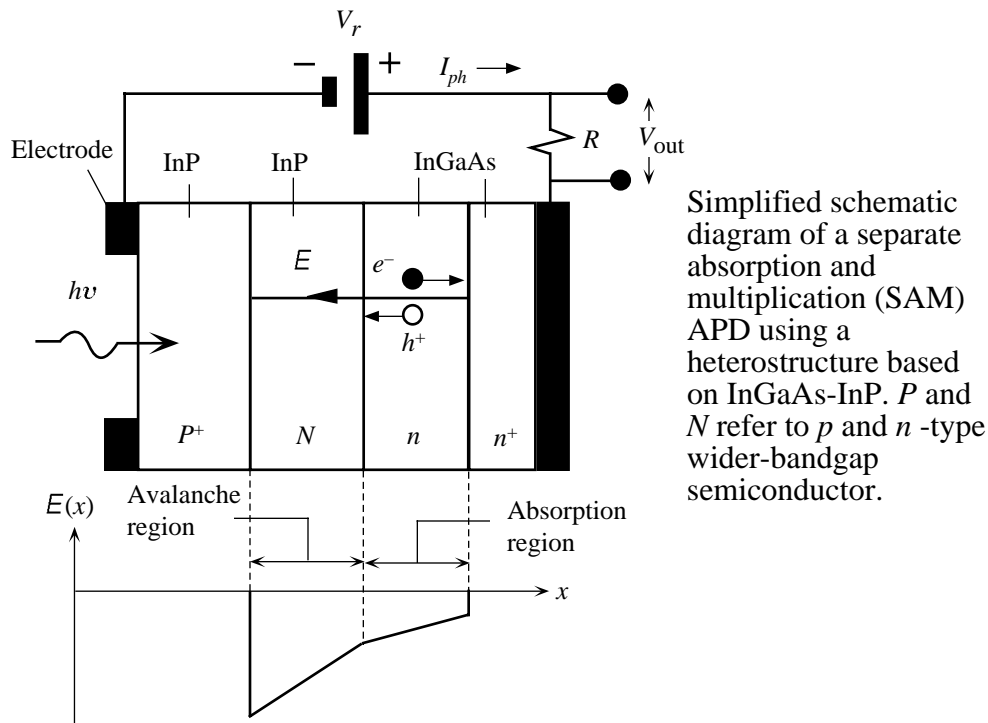
Simplified schematic diagram of a separate absorption and multiplication (SAM) APD using a heterostructure based on InGaAs-InP. *P* and *N* refer to *p* and *n* -type wider-bandgap semiconductor.

Short diode is a *pn* junction in which the neutral regions are shorter than the **minority carrier diffusion lengths**.

Shot noise is the fluctuations in the current due to the discrete nature of charge. Electrons in a current flow as discrete charges, as particles with each one carrying a charge of –*e*. If the current were a continuous flow of "gaseous charge" without any fluctuations then the shot noise would be zero. Each time an electron arrives at an electrode, there is a discrete charge of -*e* in the collected charge. It is analogous to randomly dropping ball bearings on a drum. The balls are discrete (each the same mass) but they arrive at random times, like shots, and the sound they make is called shot noise. If the current were a continuous flow of "gaseous charge" without any fluctuations then the shot noise would be zero.

Signal to noise ratio (SNR, *S/N*) in the photodetector is defined as the ratio of the power in the photogenerated current to the noise power (power in the random fluctuations) in the detector. When the photodetector is connected to a receiving circuit, the noise power must include that generated in the circuit as a whole:

$$\text{SNR} = \frac{\text{Signal Power}}{\text{Noise Power}}$$

Silica glass or fused silica glass is the non-crystalline, or amorphous, form of SiO_2. It is similar to melt silica but, due to a very high **viscosity** at room temperature, behaves like a solid (**glass**). The crystalline form is called quartz.

Single mode step index fiber is a **step index fiber** that allows only the **fundamental mode** to propagate at the wavelength of interest. To allow the fundamental mode to propagate, the fiber normally has a thin **core** (*e.g.* ≈ 5-10 μm in diameter) and a very small **refractive index** different between the core and **cladding** (0.2-0.3%). The *V*-**number** of the fiber must be less than 2.405.

Buffer tube: $d = 1$mm

Protective polymeric coating
Cladding: $d = 125 - 150$ μm

Core: $d = 8 - 10$ μm

The cross section of a typical single-mode fiber with a tight buffer tube. ($d =$ tube diameter)
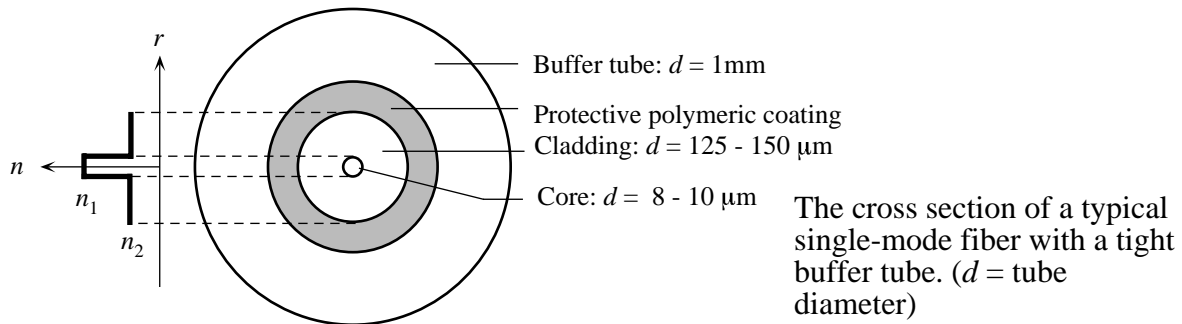
Single mode waveguide is a waveguide that can only carry the *fundamental mode* (lowest mode) of radiation within the wavelength range of interest, that is wavelengths longer than the critical cut-off wavelength. See **cut-off wavelength**.

Skew ray is a light ray that enters the fiber off the fiber axis and zigzags down the fiber without crossing the axis and when viewed looking down the fiber (its projection in a plane normal to the fiber axis) it traces out a polygon around the fiber axis. A skew ray therefore has a *helical path* around the fiber axis. In a **step index fiber** both meridional and skew rays give rise to guided modes (propagating **waves**) along the fiber each with a **propagation constant** β along *z*. as in the case of the planar waveguide. Skew rays give rise to modes that have both E_z and B_z (or H_z) components along the guide axis *z* and they are therefore not TE or TM waves.

Along the fiber

Skew ray

Fiber axis

A skew ray does not have to cross the fiber axis. It zigzags around the fiber axis.

Ray path along the fiber

Ray path projected on to a plane normal to fiber axis
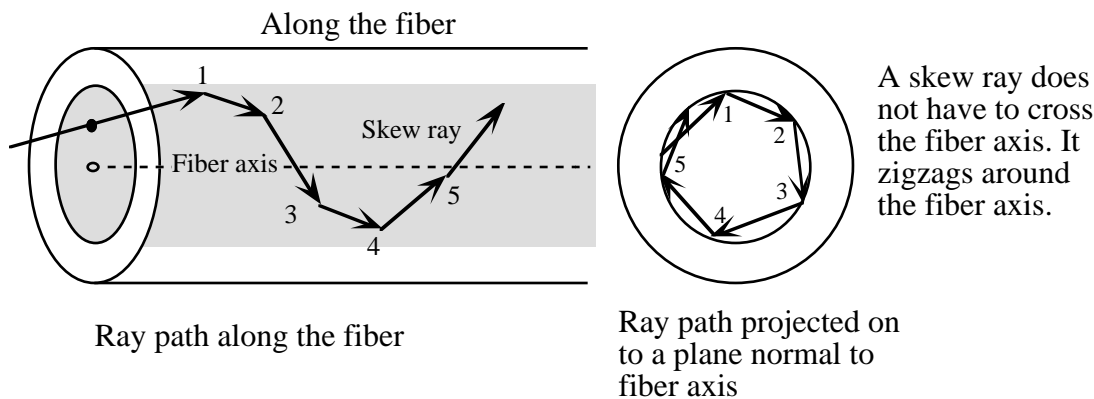
Slope efficiency determines the **optical power** P_o in the lasing emission in terms of the diode current above the **threshold current** I_{th}. If *I* is the diode current, the slope efficiency η_{slope} (in watts per ampere) is defined by

$$\eta_{\text{slope}} = \frac{P_o}{I - I_{th}}$$

Snell's Law describes the motion of **electromagnetic waves** through a medium with different refractive indices (*e.g.* traveling from air to **glass**). Suppose that light is traveling in a medium with index n_1 is incident on a medium of index n_2, and if the angles of incidence and refraction (transmission) are θ_i and θ_t, then according to Snell's law, $n_1 \sin\theta_i = n_2 \sin\theta_t$. See **refraction.**

Softening point of **glass** is the temperature at which the **viscosity** of a glass is about 10^3 -10^4 Pa s.

For example, for fused **silica glass** this is about 1600 - 1730 °C. Viscosity of glass is strongly temperature dependent and decreases steeply as the temperature increases. At the softening point, the viscosity is sufficiently low to allow the glass the flow under its own weight. Very roughly, the softening point is the glass transformation point where the rigid glass (solid) "transforms" to a supercooled liquid that can flow under a small shear **stress** (just like "honey").

Solar cell, see **photovoltaic devices**.

Solar constant is the integrated intensity above Earth's atmosphere, that is, the total power flow through a unit area perpendicular to the direction of the sun. This quantity is called the *solar constant* or *air-mass zero* (AM0) radiation and it is approximately constant at a value of 1.353 kW m^{-2}.

Solar radiation air mass m (Amm) is defined as the ratio of the actual sun radiation path h to the shortest path h_0, that is $m = h/h_0$. Since $h = h_0\sec\theta$, AMm is AM$\sec\theta$. This **spectrum** refers to incident energy on a unit area *normal* to sun rays (which have to travel the atmospheric length h.) The actual intensity spectrum on Earth's surface depends on the **absorption** and **scattering** effects of the atmosphere and hence on the atmospheric composition and the radiation path length through the atmosphere. These atmospheric effects depend on the wavelength. Clouds increase the absorption and scattering of sun light and hence substantially reduce the incident intensity. On a clear sunny day, the light intensity arriving on Earth's surface is roughly 70% of the intensity above the atmosphere. Absorption and scattering effects increase with the sun beam's path through the atmosphere. The shortest path through the atmosphere is when the sun is directly above that location and the received spectrum is called air mass one (AM1). All other angles of incidence increase the optical path through the atmosphere, and hence the atmospheric losses. In addition, atmospheric molecules and dust particles scatter the sun light. Scattering not only reduces the intensity in the direction towards the Earth but also gives rise to the sun's rays arriving at random angles. Consequently, the terrestrial light has a *diffuse* component in addition to the *direct* component. The diffuse component increases with cloudiness and sun's position, and has a spectrum shifted toward the blue light . The scattering of light increases with decreasing wavelength so that shorter wavelengths in the original sun beam experience more scattering than longer wavelengths. On a clear day, the diffuse component can be roughly 20% of the total radiation, and significantly higher on cloudy days.
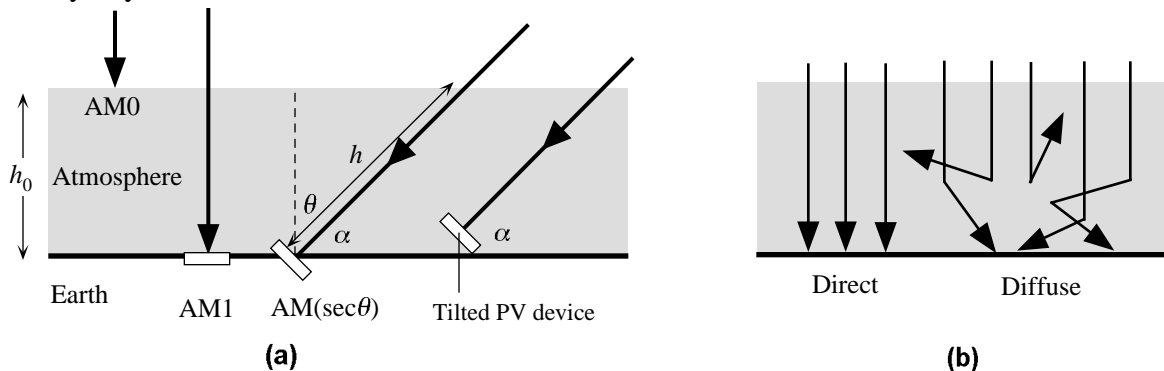
(a) Illustration of the effect of the angle of incidence θ on the ray path length and the definitions of AM0, AM1 and AM($\sec\theta$). The angle α between the sun beam and the horizon is the solar latitude (b) Scattering reduces the intensity and gives rise to a diffused radiation

Soleil-Babinet compensator is an optical compensator is a device that allows one to control the retardation (*i.e.* the phase change) of a **wave** passing through it. In a wave plate retarder such as the **half-wave plate**, the relative phase change ϕ between the **ordinary** and **extraordinary waves** depends on the plate thickness and cannot be changed. In compensators, ϕ is adjustable. The Soleil-Babinet compensator has two quartz wedges touching over their large faces to form a "block" of adjustable height d. Sliding one wedge over the other wedge alters the "thickness" d of this block. The two-wedge block is placed on a parallel plate quartz slab with a fixed thickness D. The slab has its **optic axis** parallel to its surface face. The optical axes in the wedges are parallel but perpendicular to the optic axis of the slab. Suppose that a **linearly polarized** light is incident on this compensator at normal incidence. We can represent this light by field oscillations parallel and

perpendicular to the optic axis of the two-wedge block; these fields are E_1 and E_2 respectively. The **polarization** E_1 travels through the wedges (d) experiencing a **refractive index** n_e (E_1 is along the optic axis) and travels through the plate (D) experiencing an index n_o (E_1 perpendicular to the optic axis). Its phase change is

$$\phi_1 = \frac{2\pi}{\lambda}(n_e d + n_o D)$$

But the E_2 polarization wave first experiences n_o through the wedges (d) and then n_e through the plate (D) so that its phase change is

$$\phi_2 = \frac{2\pi}{\lambda}(n_o d + n_e D)$$

The phase difference ϕ ($= \phi_2 - \phi_1$) between the two polarizations is

$$\phi = \frac{2\pi}{\lambda}(n_e - n_o)(D - d)$$

It is apparent that as we can change d continuously by sliding the wedges (by using a micrometer screw), we can continuously alter the phase difference ϕ from 0 to 2π. We can therefore produce a quarter-wave of half-wave plates by simply adjusting this compensator. It should be emphasized that this control occurs over the surface region that corresponds to both the wedges and in practice this is a narrow region.

Soleil-Babinet Compensator
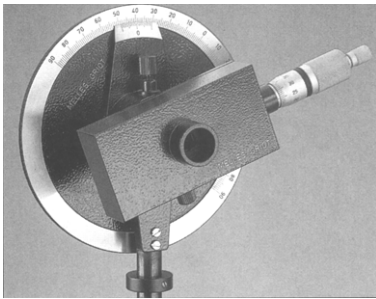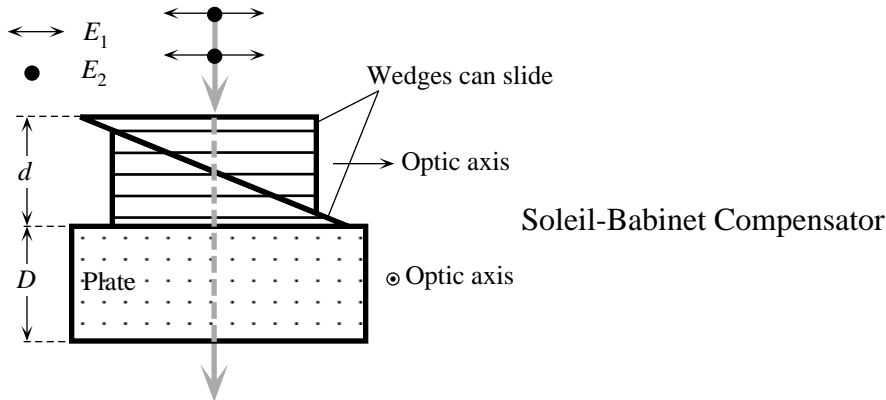
A Soleil-Babinet compensator (Courtesy of Melles-Griot.)

Soliton is an isolated **wave** (a solitary wave), in the form of a "pulse of vibration" with a certain shape and intensity profile, in a non-linear medium that is able to propagate without suffering **dispersion**. A soliton can propagate without experiencing a net dispersion because the dispersive effect, due to the **refractive index** depending on the wavelength, is balanced by the non-linearity of the medium in which the refractive index depends on the intensity. The overall result is as if the wave were propagating in a non-dispersive linear medium. Such solitons have interesting properties. For example, two solitons do not interfere as normal waves do. They pass right through each other without changing their shapes as if they were independent entities; only a phase shift is induced as a result of the interaction. If ψ is the disturbance or perturbation that is propagating, such as displacement, one possible soliton shape (wave envelope) that is propagating along the z-direction is

a sech function,

$$\psi = A\,\text{sech}^2[(vt - z)/l]$$

where v is the local signal velocity and A and l are constants; l is a constant that represents the spatial extent of the soliton. The above is only one possible soliton from a family of solitons that can exist in a given non-linear medium. Solitons satisfy a special equation called the nonlinear **Schrödinger equation**. A soliton pulse can only be excited and propagated if the input pulse has the right shape and the amplitude×width product; otherwise an ordinary optical pulse will be excited A *spatial soliton* is an intense beam that can propagate without diverging because the **diffraction** effects (that lead to divergence) have been balanced by the non-linear effects of the medium. One can intuitively appreciate this as follows. All propagating beams of finite cross sectional area are known to diverge. If the intensity is sufficiently large, the intensity profile of the beam will modify the refractive index of the medium due to the non-linear response of the medium (**polarization** is not a linearly related to the field). If the beam has the right intensity profile such that the altered index variation results in an induced waveguide, and the beam is a mode of this waveguide, then the beam becomes *self-guided*; it no longer diverges.
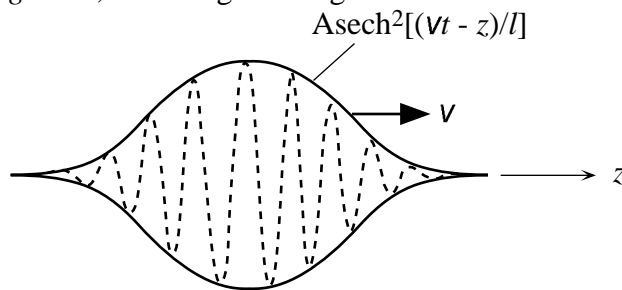
A visualization of a soliton wave packet

Spatial coherence describes the extent of coherence between **waves** radiated from different locations on a light source. If the waves emitted from two locations P and Q on the source are in phase then P and Q are spatially coherent. A spatially coherent source emits waves that are in phase over its entire emission surface. These waves however may have partial **temporal coherence**. A light beam emerging from a spatially coherent light source will hence exhibit spatial coherence across the beam cross section. A mostly incoherent beam will contain waves that have very little correlation with each other.
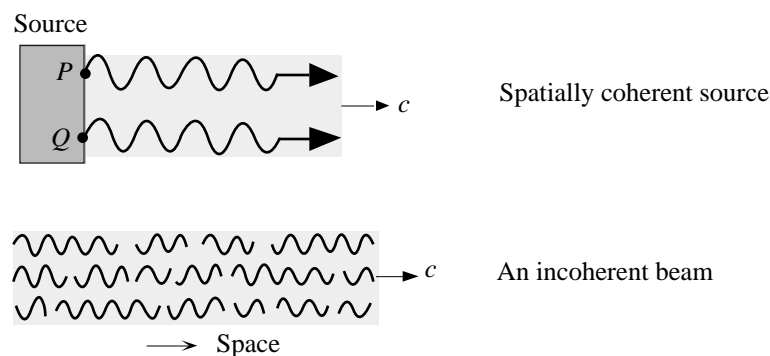
Spatial coherence involves comparing the coherence of waves emitted from different locations on the source

Speckle noise, see **modal noise**.

Spectra is a general term used to describe the emitted or absorbed radiation at various wavelengths. Spectra of gases have discrete wavelengths because they correspond to electronic transitions between various quantized energy levels. In an absorption process, an atom with an energy E_1 is

excited to a higher energy level E_2 by absorbing a photon of energy $h\upsilon = E_2 - E_1$. The absorption spectrum is observed when white light, light with all the wavelengths, is passed through the medium. Those wavelengths that are missing represent the photons that have been absorbed from white light in exciting the gas atoms. The emission process is the reverse of the absorption process, except that there must be atoms at the energy level E_2 that can become de-excited to E_1 by emitting photons of energy $h\upsilon = E_2 - E_1$. Emission spectra can be obtained by first exciting the atoms in the gas, for example, by an electric discharge. The excited atom with an energy E_2 can become de-excited to a lower energy level E_1 by emitting a photon that has an energy $h\upsilon = E_2 - E_1$, provided that the transition obeys the quantum mechanical *selection rules*. Typically the excitation of gas atoms involves accelerating electrons (or gas ions) in the discharge colliding with the gas atoms.
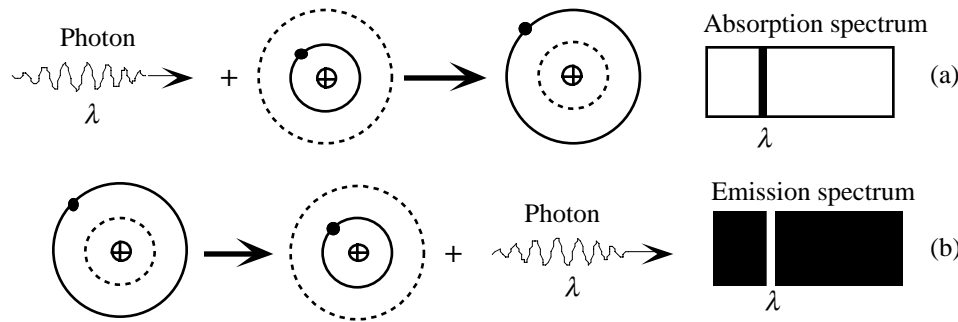
The physical origin of (a) absorption spectra and (b) emission spectra.
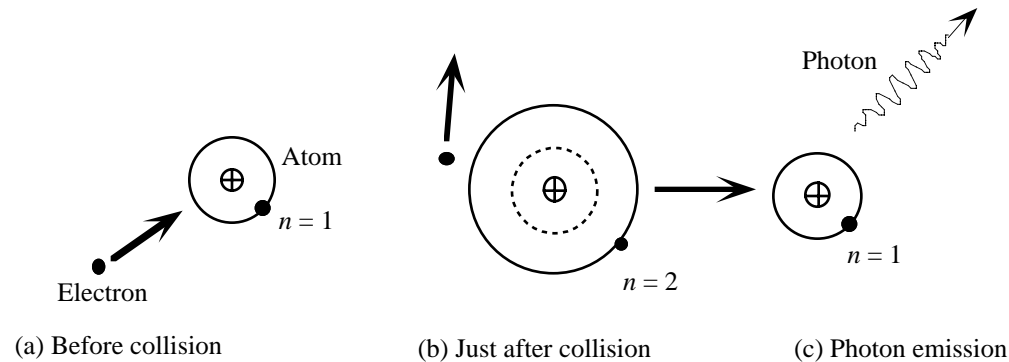
(a) Before collision   (b) Just after collision   (c) Photon emission

An atom in a gas discharge tube can become excited by a projectile electron colliding with it.

Spectral intensity I_λ is intensity per unit wavelength so that $I_\lambda \delta\lambda$ is the intensity in a small interval $\delta\lambda$. Integration of I_λ over the whole **spectrum** gives the integrated or *total intensity*, I.
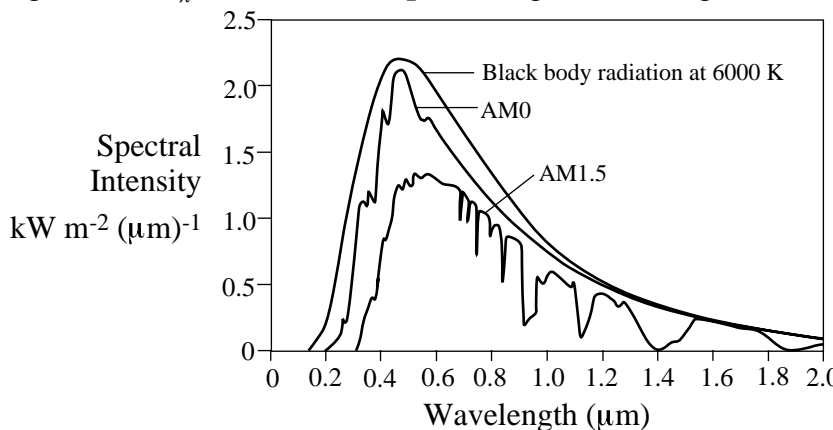
The spectrum of the solar energy represented as spectral intensity (I_λ) vs wavelength above the earth's atmosphere (AM0 radiation) and at the earth's surface (AM1.5 radiation). Black body radiation at 6000 K is shown for comparison.

Spectral responsivity, see **responsivity**.

Spectral width $\delta\upsilon_m$ of the Fabry-Perot etalon is the **full width at half maximum** (FWHM) of an individual mode intensity and depends on the **finesse** factor of the cavity. The greater the finesse, the narrower the width of an individual mode. See **optical resonator**.

Spectral width is the frequency (or wavelength) width of the **spectrum** of a signal that contains majority of the power.

Spectrum of a laser diode output is the **optical power** density vs. wavelength behavior of the lasing emission from the diode. This spectrum may be multimode or single mode depending on the **optical resonator** structure and the **pumping** current level.

Relative optical power

$P_o = 5$ mW

$P_o = 3$ mW

$P_o = 1$ mW

λ (nm)

778   780   782

Output spectra of lasing emission from an index guided LD. At sufficiently high diode currents corresponding to high optical power, the operation becomes single mode. (Note: Relative power scale applies to each spectrum individually and not between spectra)
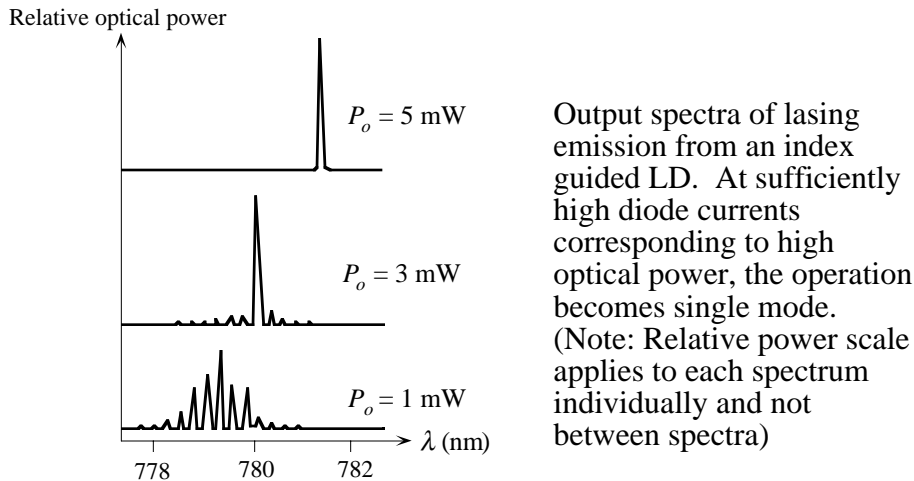
Spectrum of an optical signal is generally understood to be the "relative optical power" vs. frequency distribution that constitutes the optical light signal. It represents all the necessary frequencies each with the correct **optical power** level that is needed to constitute the signal. The relative optical power vs. frequency spectrum is represented in such a way that its integration over all the frequencies represents the total **optical power** of the signal. Thus, "relative optical power" means optical power per unit frequency. The spectrum can also be represented in terms of wavelength. The necessary phase information is typically not included in spectrum discussions.

Spherical wave is described by a traveling field that emerges out from a point electromagnetic source (EM) source and whose amplitude decays with distance r from the source. At any point r from the source, the field at time t is given by

$$E = \frac{A}{r}\cos(\omega t - kr)$$

where A is a constant, ω is the angular frequency and k is the **propagation constant**.

Spin of an electron, S, is its intrinsic angular momentum (analogous to the spin of Earth around its own axis) which is space quantized to have two possibilities. The magnitude of the electron's spin is constant, $\hbar\sqrt{3}/2$, but its component along a **magnetic field** in the z-direction is $m_s\hbar$, where m_s is the spin magnetic quantum number, $+\frac{1}{2}$ or $-\frac{1}{2}$. The quantity $\hbar$ is **Planck's constant** divided by 2π.

Splice is a permanent joint between two fibers usually achieved by heat fusion of the end of the fiber.

Spontaneous emission is the phenomenon by which a **photon** is emitted when an electron in a high energy **state**, $\psi(n,\ell,m_\ell,m_s)$ with an energy E_2, spontaneously oscillates down to a lower energy state, $\psi(n',\ell',m_\ell',m_s')$ with energy E_1 that is not occupied. The photon energy, $h\upsilon = (E_2-E_1)$, where

h is **Planck's constant**. Since the emitted photon has an angular momentum, the orbital quantum number, ℓ, of the electron must change, *i.e.* $\Delta \ell = \ell' - \ell = \pm 1$.

Absorption, spontaneous (random photon) emission and stimulated emission.

(a) Absorption   (b) Spontaneous emission   (c) Stimulated emission
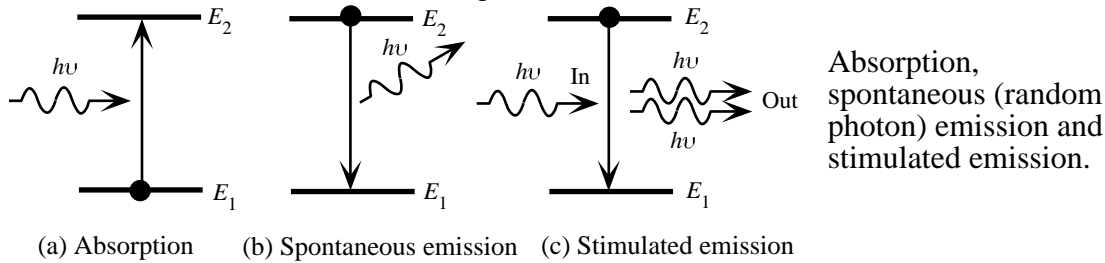
Spot size, see **Gaussian beam**.

State is a possible **wavefunction** for the electron that defines its spatial (orbital) and spin properties *e.g.* $\psi(n,\ell,m_\ell,m_s)$ is a state of the electron. From the **Schrödinger equation**, each state corresponds to a certain electron energy E. We thus speak of a state with energy E as state of energy E, or even an *energy state*. Generally there may be more than one state ψ, with the same energy E.

Stefan's Law is a phenomenological description of the energy radiated per unit second from a surface. When a surface is heated to a temperature T then it radiates net energy at a rate given by $P_{radiated} = \varepsilon \sigma A(T^4 - T_o^4)$ where σ is Stefan's constant ($= 5.6 \times 10^{-8}$ W m^{-2} K^{-4}), ε is the emissivity of the surface, A is the surface area and T_o is the ambient temperature.

Step index fiber has a central **core** of constant **refractive index** and a surrounding layer of **cladding** of smaller refractive index. There is a step decrease in the refractive index from the core to the cladding.

Stimulated emission is the phenomenon by which an incoming **photon** of energy $h\upsilon = E_2 - E_1$ interacts with an electron in a high energy **state**, $\psi(n,\ell,m_\ell,m_s)$, at E_2, and induces it to transit down to a lower energy state, $\psi(n',\ell',m_\ell',m_s')$, at E_1, that is not occupied. (Note: *h* is **Planck's constant** and υ is the frequency of light.) The photon that is emitted by stimulation has the same energy and phase as the incoming photon and, further, it is in the same direction. Consequently, stimulated emission results in two coherent photons, with the same energy, traveling in the same direction. The stimulated emission process must obey the selection rule just as **spontaneous emission**; $\Delta \ell = \ell' - \ell = \pm 1$.

Stimulated Raman scattering is a **Raman scattering** of **electromagnetic waves** in a such a way the the scattered **waves** are in phase and reinforce each other to generate a strong scattered radiation. This can be achived by "**pumping**" the system with an intense radiation at the right frequency, for example, at the frequency that excites the required molecular vibrations.

Strain is a measure of the deformation a material exhibits under an applied **stress**. It is expressed in normalized units. Under an applied tensile stress, strain (ε) is the change in the length per unit original length, $\Delta L / L_o$. When a shear stress is applied, the resulting deformation involves a shear angle. *Shear strain* is defined as the tangent of the shear angle that is developed by the application of the shearing force.

Strain point of **glass** is the temperature at which the **viscosity** of a glass is about 10^{13} Pa s. For example, for fused **silica glass** this is about 1050 °C. Viscosity of glass is strongly temperature dependent and decreases steeply as the temperature increases. Below the strain point , the glass can be cooled rapidly without introducing unwanted internal stresses.

Stress is force per unit area, F / A. When the applied force is perpendicular to the area it leads either to a tensile or compressive stress, $\sigma = F / A$. If the applied force is tangential to the area then it leads to a shear stress, $\tau = F / A$.

Stripe geometry laser diode is a double heterostructure laser device in which one of the electrodes has a stripe geometry, narrow width, to increase the current density in the **active region**, and which results in a lower **threshold current** for lasing emissions.

Cleaved reflecting surface

W

Stripe electrode

L

Oxide insulator
p-GaAs (Contacting layer)
p-Al$_x$Ga$_{1-x}$As (Confining layer)
p-GaAs (Active layer)
n-Al$_x$Ga$_{1-x}$As (Confining layer)
n-GaAs (Substrate)

2 1 3
Current
paths

Substrate

Electrode

Elliptical
laser
beam

Cleaved reflecting surface

Active region where $J > J_{th}$.
(Emission region)
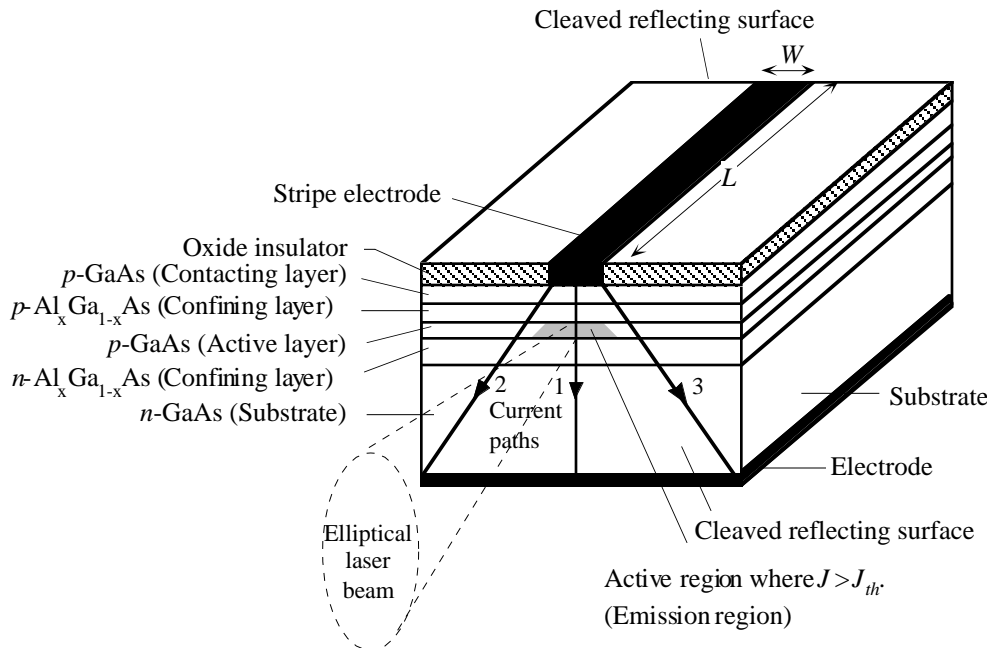
Schematic illustration of the the structure of a double heterojunction stripe contact laser diode

Strong injection is usually a condition in **semiconductor** device in which the injected **minority carrier** concentration is much greater than the equilibrium majority carrier concentration in the same region; injection may be due to **photogeneration** or voltage application to forward bias a *pn* junction. See **minority carrier lifetime.**

Substrate is a single mechanical support which carries active and passive devices. For example in the integrated circuit technology, typically, many integrated circuits are fabricated on a single silicon **crystal** wafer which serves as the substrate.

Superlattice avalanche photodiode (APDs) is a **photodiode** that minimized excess noise in the photocurrent by limiting avalanche multiplication to a single type of carried by the use of a superlattice structure which is formed by alternating thin layers of different bandgap **semiconductors**, as in multiple quantum well (MQW) devices. The multilayered structure consisting of many alternating layers of different bandgap semiconductors is called a *superlattice*. Typically, the bandgap in each layer changes from a minimum E_{g1} to a maximum E_{g2} which is more than twice E_{g1}. There is a step change ΔE_c in the **conduction band** edge between two neighboring graded layers that is greater than E_{g1}. In very simple terms, the photogenerated electron initially drifts in the graded layer conduction band. When the electron drifts into the neighboring layer, it now has a kinetic energy ΔE_c above E_c in this layer. It therefore enters the neighboring layer as a highly energetic electron and loses the excess energy ΔE_c by **impact ionization**. The process repeats itself from layer to layer leading to an avalanche multiplication of the photogenerated

electron. Since the impact ionization is primarily achieved as a result of transition over ΔE_c, the device does not need the high fields typical of avalanche multiplication in bulk semiconductor; it can operate at lower fields. Further, the impact ionized holes experience only a small ΔE_v which is insufficient to lead to multiplication. Thus, effectively, only electrons are multiplied and the device is a solid state photomultiplier. Such staircase superlattice APDs are difficult to fabricate and involve varying the composition of a quaternary semiconducting alloy (such as AlGaAsSb) to obtain the necessary bandgap grading. Superlattice structures that are simply alternating layers of low and high bandgap semiconductor layers, that is layers do not have a graded bandgap, are easier to fabricate and constitute multiple quantum well (MQW) detectors. Typically *molecular beam epitaxy* (MBE) is used to fabricate such multilayer structures.
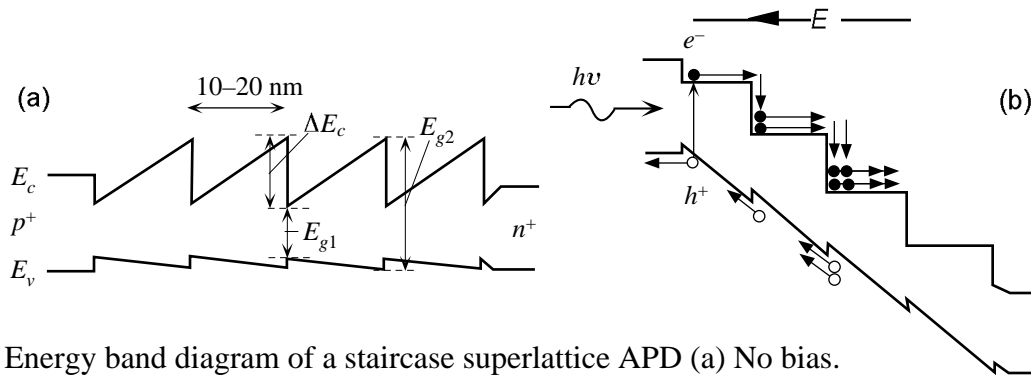
Energy band diagram of a staircase superlattice APD (a) No bias.
(b) With an applied bias.

Surface acoustic wave, see **acousto-optic modulator**

Surface emitting LEDs (SLED) has its emitted radiation emerging from an area in the plane of the recombination layer .The simplest method of coupling the radiation from a surface emitting LED into an **optical fiber** is to etch a well in the planar LED structure and lower the fiber into the well as close as possible to the **active region** where emission occurs. This type of structure is called a *Burrus* type device (after its originator). An epoxy resin is used to bond the fiber and provide **refractive index** matching between the **glass** fiber and the LED material to capture as much of the light rays as possible. Note that in the double heterostructure LED used in this way, the **photons** emitted from the active region (*e.g. p*-GaAs) do not get absorbed by the neighboring layer (AlGaAs) which has a wider bandgap. Another method is to use a truncated *spherical lens* (a microlens) with a high refractive index ($n = 1.9 - 2$) to focus the light into the fiber. The lens is bonded to the LED with a refractive index matching cement and, in addition, the fiber can be bonded to the lens with a

similar cement.
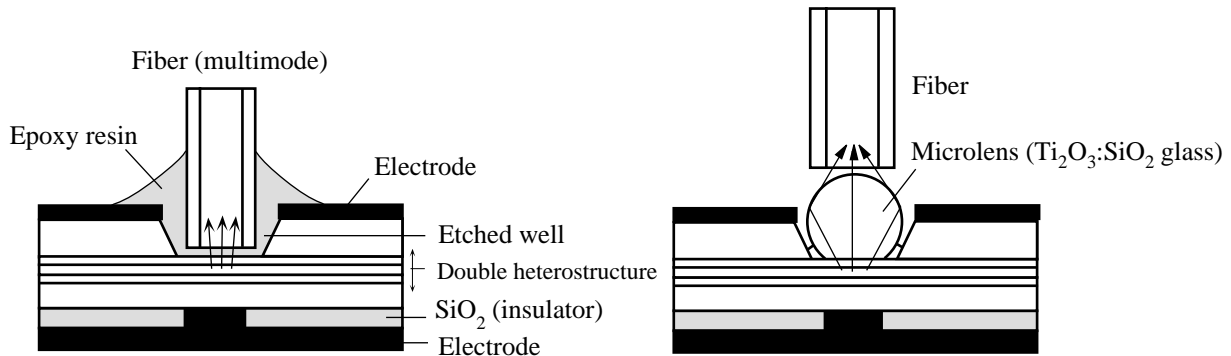
(a)

Light is coupled from a surface emitting LED into a multimode fiber using an index matching epoxy. The fiber is bonded to the LED structure.

(b)

A microlens focuses diverging light from a surface emitting LED into a multimode optical fiber.

Surface states are electronic states originating from surface-related phenomena - these include, surface relaxation and reconstruction processes, as well as states formed as a result of chemical processes on surfaces. The latter includes surface **oxidation**, and the interaction of surfaces with adsorbed species. The surface state related energy bands would not exist in the absence of these phenomena, resulting in the only a bulk band structure. It should be noted that a so-called ideal surface, in which atoms assume their bulk relationships, can still result in a surface band structure owing to the severing of bonds at the surface resulting in a redistribution of charge, distinct from that of the bulk. The occupation of surface bands is responsible for a surface charge, and this, in turn, results in a near surface field. The insensitivity of Schottky barrier heights to the metal **work function**, for certain combinations of metals deposited on semiconductor surfaces, has been attributed to a pinning of the **Fermi energy** within such surface states.

Temporal coherence measures the extent to which two points P and Q on a given waveform separated in time at a given location in space can be correlated, that is one can be reliably predicted from the other. For a pure sine wave, at any given location, any two points P and Q separated by any time interval are always correlated because we can predict the phase of one (*Q)* from the phase of the other (*P*) for any temporal separation.

Ternary III-V alloys alloys have three different elements from the III and V groups. For example GaAs and InAs are III-V compounds individually but they can me alloyed to produce a ternary alloy, $In_{1-x}Ga_xAs$. There are as many group III elements as there are group V elements.

Ternary semiconducting alloy has three different elements in its composition, for example, $Al_xGa_{1-x}As$ has three elements Al, Ga, As. This $Al_xGa_{1-x}As$ alloy is composed of III (Al and Ga) and V (As) groups only and the molar amounts from each group is the same; and hence it is a **III-V ternary alloy**. The bandgap E_g of the ternary alloys $Al_xGa_{1-x}As$ follows the empirical expression,
$$E_g(eV) = 1.424 + 1.266x + 0.266x^2.$$
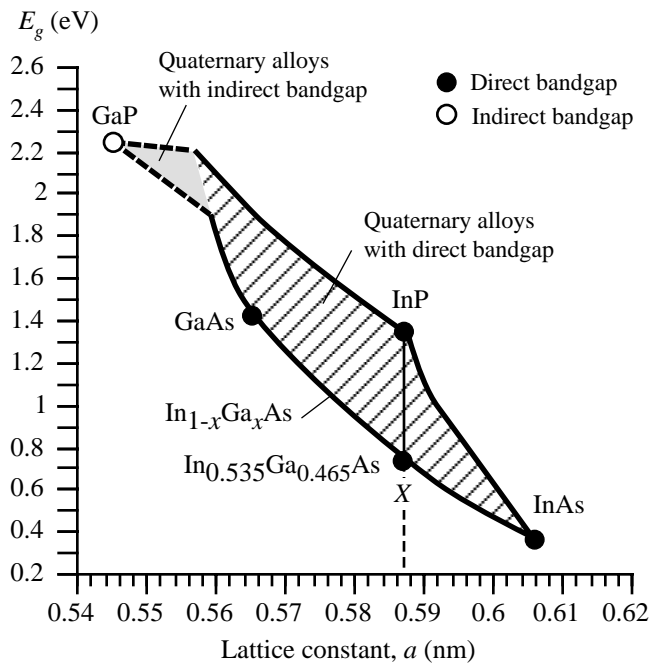
Bandgap energy E_g and lattice constant a for various III-V alloys of GaP, GaAs, InP and InAs. A line represents a ternary alloy formed with compounds from the end points of the line. Solid lines are for direct bandgap alloys whereas dashed lines for indirect bandgap alloys. Regions between lines represent quaternary alloys. The line from X to InP represents quaternary alloys $In_{1-x}Ga_xAs_{1-y}P_y$ made from $In_{0.535}Ga_{0.465}As$ and InP which are lattice matched to InP.

Thermal equilibrium carrier concentrations are those electron and hole concentrations that are solely determined by the statistics of the carriers and the **density of states** in the band. Thermal equilibrium concentration obey the **mass action law**, $np = n_i^2$.

Thermal generation current is the current that flows in a **reverse biased** pn junction as a result of the thermal generation of electron hole pairs in the **depletion layer** which become separated and swept across by the built-in field.

Thermalization is a process in which an excited electron in the **conduction band** (CB) loses the excess energy as it is collides with **lattice** vibrations, and falls close to E_c, that is, until its average energy is $(3/2)kT$ above E_c.
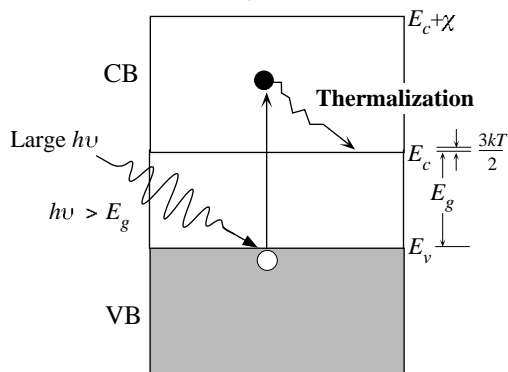
Optical absorption generates electron hole pairs. Energetic electrons must loose their excess energy to lattice vibrations until their average energy is $^3/_2 kT$ in the CB. (CB = Conduction Band, VB = Valence Band, E_g = Bandgap energy)

Thermionic emission is the emission of electrons from the surface of a heated metal. When a metal is

heated, the proportion of electrons having grater energy than the **work function** (Φ) plus **Fermi energy** (E_F) increase due to the tailing of the Fermi-Dirac function to higher energies. Consequently, some of the electrons can be emitted over this potential barrier into vacuum and become free. The emission probability depends exponentially on the temperature. If the emitted electrons are collected and the metal replenished with electrons, as in the vacuum tube, then the thermionic current density is described by the Richardson-Dushman equation.

Thin film optics involves multiple reflections of light entering a thin film **dielectric** (typically on a **substrate**) so that the reflection and **transmission coefficients** are determined by multiple wave **interference** phenomena.
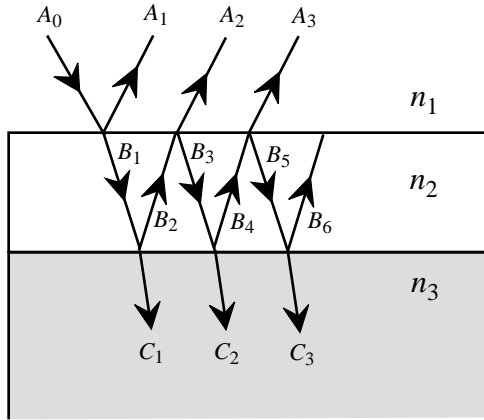
Thin film coating ona substrate and
multiple reflections.

Consider a thin film coating on an object. Suppose that the incident wave has an amplitude of A_0, then there are various transmitted and reflected waves as shown in the figure. We then have the following amplitudes based on the definitions of the reflection and transmission coefficients,

$$A_1 = A_0 r_{12} \qquad\qquad B_1 = A_0 t_{12} \qquad\qquad B_2 = A_0 t_{12} r_{23} \qquad\qquad C_1 = A_0 t_{12} t_{23}$$
$$A_2 = B_3 = A_0 t_{12} r_{23} r_{21} \qquad\qquad\qquad B_4 = A_0 t_{12} r_{23} r_{21} r_{23} \qquad C_2 = A_0 t_{12} r_{23} r_{21} t_{23}$$
$$A_3 = A_0 t_{12} r_{23} r_{21} r_{23} t_{21} \quad B_5 = A_0 t_{12} r_{23} r_{21} r_{23} r_{21} \quad B_6 = A_0 t_{12} r_{23} r_{21} r_{23} r_{21} r_{23} \qquad C_3 = A_0 t_{12} r_{23} r_{21} r_{23} r_{21} t_{23}$$

and so on, where r_{12} is the reflection coefficient of a wave in medium 1 incident on medium 2, and t_{12} is the transmission coefficient from medium 1 into 2. Suppose that $n_1 < n_2 < n_3$ and that the thickness of the coating is d. For simplicity, we will assume normal incidence. The phase change in traversing the coating thickness d is $\phi = (2\pi/\lambda)n_2 d$ where λ is the free space wavelength. The wave has to be multiplied by $\exp(-j\phi)$ to account for this phase difference. The reflection r and transmission t coefficients are then given by,

$$r_1 = r_{12} = \frac{n_1 - n_2}{n_1 + n_2} = -r_{21}, \qquad r_2 = r_{23} = \frac{n_2 - n_3}{n_2 + n_3}$$

and
$$t_1 = t_{12} = \frac{2n_1}{n_1 + n_2}, \qquad\qquad t_2 = t_{21} = \frac{2n_2}{n_1 + n_2},$$

where
$$1 - t_1 t_2 = r_1^2$$

The reflection coefficient is then
$$r = \frac{A_{\text{reflected}}}{A_0} = r_1 - \frac{t_1 t_2}{r_1} \sum_{k=1}^{\infty} \left(-r_1 r_2 e^{-j2\phi} \right)^k$$

which can be summed to
$$r = \frac{r_1 + r_2 e^{-j2\phi}}{1 + r_1 r_2 e^{-j2\phi}}$$

The transmission coefficient is
$$t = \frac{C_{\text{transmitted}}}{A_0} = -\frac{t_1 t_2 e^{j\phi}}{r_1 r_2} \sum_{k=1}^{\infty} \left(-r_1 r_2 e^{-j2\phi} \right)^k = \left(\frac{t_1 t_2 e^{j\phi}}{r_1 r_2} \right) \frac{r_1 r_2 e^{-j2\phi}}{1 + r_1 r_2 e^{-j2\phi}}$$

which can be summed to

$$t = \frac{t_1 t_2 e^{-j\phi}}{1 + r_1 r_2 e^{-j2\phi}}$$

Threshold current I_{th} of a **laser diode** is the minimum current that is needed for achieving a lasing emission from the device. At this current value, the **optical gain** in the **active region** is the **threshold gain**. Lasing radiation is only obtained when the optical gain in the medium can overcome the **photon** losses from the cavity, which requires the diode current I to exceed a *threshold value* I_{th}. Below I_{th}, the light from the device is due to **spontaneous emission** and not **stimulated emission**. The light output is then composed of incoherent photons that are emitted randomly and the device behaves like an LED. Threshold current is strongly temperature dependent.
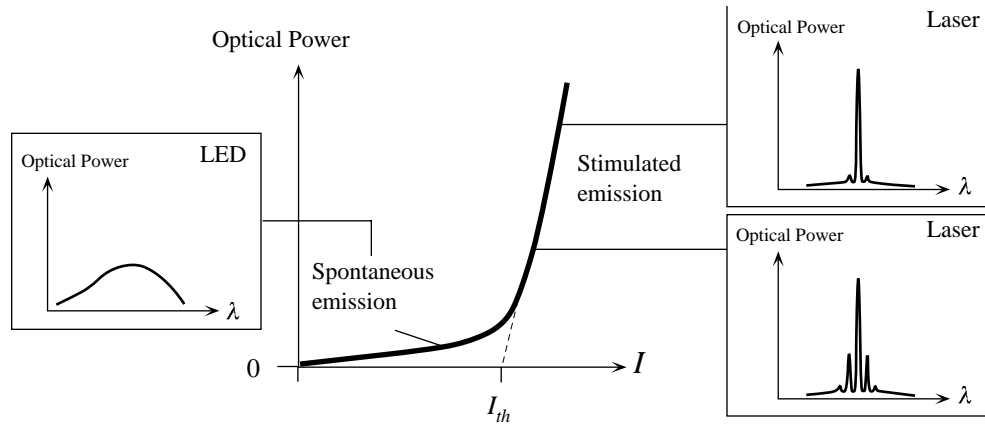
Typical output optical power vs. diode current (I) characteristics and the corresponding output spectrum of a laser diode.

Threshold gain is the critical **optical gain** g_{th} that an active medium in an **optical resonator** must have to achieve steady state (self-sustained) lasing radiation as output from this resonator; this threshold gain just overcomes the losses in the active medium and also the losses from the optical cavity and the reflectors. When the optical gain of the medium is equal to the threshold gain g_{th} the device becomes a self-sustained *laser oscillator*. If γ is the loss coefficient of the medium, L is the length of the optical cavity, R_1 and R_2 are the **reflectances** of the end-reflectors of the cavity, then the optical gain of the medium for lasing oscillations (*i.e.* for **continuous wave** lasing emission from the device),

$$g_{th} = \gamma + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2} \right)$$

Threshold population inversion is the **population inversion** $N_2 - N_1$ that corresponds to the threshold **optical gain** (g_{th}).
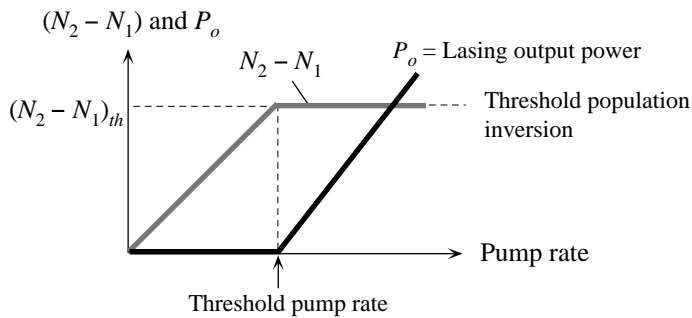
Simplified description of a laser oscillator. $(N_2 - N_1)$ and coherent output power (P_o) vs. pump rate under continuous wave steady state operation.

Total internal reflection (TIR) is the total reflection of a wave traveling in a medium when it is incident at a boundary with another medium of lower **refractive index**. The angle of incidence must be greater than the **critical angle** θ_c which depends on the refractive indices $\sin\theta_c > n_2/n_1$.

Transmission axis of a polarizer identifies the electric field direction that is allowed to pass through the polarizer.

Transmission coefficient is the ratio of the amplitude of the transmitted **wave** to that of the incident wave when the incident wave traveling in a medium meets a boundary with a different medium (different **refractive index**).

Transmittance is the fraction of transmitted intensity when a **wave** traveling in a medium is incident at boundary with a different medium (different **refractive index**).

Transparency current I_{trans} is the diode current that provides just sufficient injection to lead to **stimulated emissions** just balancing **absorption** there is then no net **photon** absorption and the medium is transparent. Above I_{trans} there is a net **optical gain** in the medium though the optical output is not yet a continuous wave **coherent radiation**.

Transverse electric field (TE) mode has the electric field oscillations at right angles to the direction of propagation of the mode along the waveguide axis. *Transverse magnetic field* (TM) mode has the **magnetic field** oscillations at right angles to the direction of propagation of the mode along the waveguide axis. *Transverse electric and magnetic field modes* (TEM) have both the electric and magnetic field at right angles to the direction of propagation.

(a) TE mode   (b) TM mode

Possible modes can be classified in terms of (a) transelectric field (TE) and (b) transmagnetic field (TM). Plane of incidence is the paper.
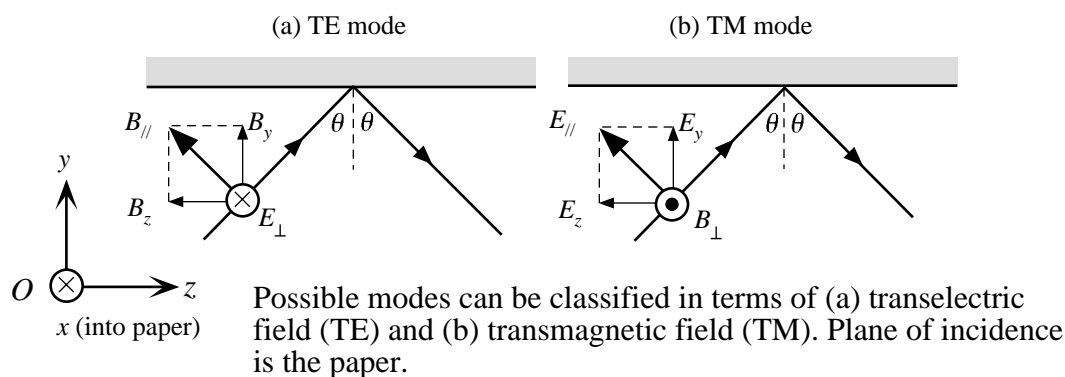
Traveling wave semiconductor laser, see **optical semiconductor amplifier**.

Ultraviolet (UV) radiation is an **electromagnetic wave** with a wavelength typically in the range 400 nm-4 nm, shorter than violet light but longer than **x-rays**. When the wavelength is in the 400-300 nm range it is called near uv and in the 300-200 nm range it called far UV. Ultraviolet radiation with a wavelength shorter than 200 nm is known as extreme or vacuum uv.

Uncertainty principle states that the uncertainty, Δx, in the position of a particle and the uncertainty, Δp_x, in its momentum in the x-direction obey $(\Delta x)(\Delta p_x) > \hbar$. This is a consequence of the **wave** nature of matter and has nothing to do with the precision of measurement. If ΔE is the uncertainty in the energy of a particle during a time, Δt, then according to the uncertainty principle, $(\Delta E)(\Delta t) > \hbar$. To measure the energy of a particle without any uncertainty means that we will need an infinitely long time, $\Delta t \rightarrow \infty$.

Uniaxial crystals, see **anisotropy.**

V-number or **normalized frequency** is a dimensionless quantity that is a characteristic of a dielectric waveguide which determines the nature of propagation of EM (electromagnetic) waves along the guide. For a **step index fiber** it is defined by $V = (2\pi a/\lambda)[n_1^2 - n_2^2]^{1/2}$ where a is the **core** radius, λ is the free space wavelength of the radiation to be guided and n_1 and n_2 are the refractive indices of the core and **cladding** respectively.

Vacancy is a point defect in a **crystal** where a normally occupied **lattice** site has a missing atom .

Vacuum level is the energy level where the potential energy of the electron and the kinetic energy of the electron are both zero. It defines the energy level where the electron is just free from the solid. Typically at distance of ~100 nm, the electron would be considered free from a solid.

Valence band (VB) is a band of energies for the electrons in bonds in a **semiconductor**. The valence band is made of all those **states** (**wavefunctions**) that constitute the bonding between the atoms in the **crystal**. At absolute zero of temperature the valence band is full of all the bonding electrons of the atoms. When an electron is excited to the **conduction band**, then this leaves behind an empty state which is called a hole. It carries positive charge and behaves as it were a "free" positively charged entity with an effective mass of m_h^*. It moves around the VB by having a neighboring electron tunnel into the unoccupied state.

Varshni equation describes the change in the energy bandgap E_g of a semiconductor with temperature T in terms of

$$E_g = E_{go} + \frac{AT^2}{B+T}$$

where E_{go} is the bandgap at $T = 0$ K, and A and B are material-specific constants . For example, for GaAs, $E_{go} = 1.519$ eV, $A = 5.405 \times 10^{-4}$ eV K^{-1}, $B = 204$ K, so that at $T = 300$ K, $E_g = 1.42$ eV. We can find the temperature coefficient of bandgap E_g' by differentiating the Varshni equation,

$$E_g' = \frac{dE_g}{dT} = -\frac{AT(T+2B)}{(B+T)^2}$$

which for GaAs, using the values above, gives $E_g' = -0.45$ meV K^{-1}.

Vertical cavity surface emitting lasers (VCSELs) has the optical cavity axis along the direction of current flow rather than perpendicular to the current flow as in conventional **laser diodes**. The **active region** length is very short compared with the lateral dimensions so that the radiation emerges from the "surface" of the cavity rather than from its edge. The reflectors at the ends of the cavity are **dielectric mirrors** made from alternating high and low **refractive index** quarter-wave thick multilayers. Such dielectric mirrors provide a high degree of wavelength selective **reflectance** at the required free surface wavelength λ if the thicknesses of alternating layers d_1 and d_2 with refractive indices n_1 and n_2 are such that

$$n_1 d_1 + n_2 d_2 = \tfrac{1}{2}\lambda$$

which then leads to the **constructive interference** of all partially reflected **waves** at the interfaces. Since the wave is reflected because of a periodic variation in the refractive index as in a grating, the dielectric mirror is essentially a **distributed Bragg reflector** (DBR). High

reflectance end mirrors are needed because the short cavity length *L* reduces the **optical gain** of the active layer inasmuch as the optical gain is proportional to exp(gL) where g is the optical gain coefficient. There may be 20 - 30 or so layers in the dielectric mirrors to obtain the required reflectance (~99%). The whole optical cavity looks "vertical" if we keep the current flow the same as

in a conventional laser diode cavity. The active layer is generally very thin (< 0.1 μm) and is likely to be a multiple quantum well (MQW) for improved **threshold current**. The required **semiconductor** layers are grown by epitaxial growth on a suitable **substrate** which is transparent in the emission wavelength. For example, a 980 nm emitting VCSEL device has InGaAs as the active layer to provide the 980 nm emission, and a GaAs **crystal** is used as substrate which is transparent at 980 nm. The dielectric mirrors are then alternating layers of AlGaAs with different compositions and hence different bandgaps and refractive indices. The top dielectric mirror is etched after all the layers have been epitaxially grown on the GaAs substrate. In practice, the current flowing through the dielectric mirrors give rise to an undesirable voltage drop and methods are used to feed the current into the active region more directly, for example, by depositing "peripheral" contacts close to the active region. There are presently various sophisticated VCSEL structures. The vertical cavity is generally circular in its cross section so that the emitted beam has a circular cross-section, which is an advantage. The height of the vertical cavity may be as small as several microns. Therefore the longitudinal mode separation is sufficiently large to allow only one longitudinal mode to operate. However, there may be one or more lateral (transverse) modes depending on the lateral size of the cavity. In practice there is only one single lateral mode (and hence one mode) in the

output **spectrum** for cavity diameters less than ~8 μm. Various VCSELs in the market have several lateral modes but the **spectral width** is still only ~0.5 nm, substantially less than a conventional longitudinal multimode **laser diode**. With cavity dimensions in the microns range, such a laser is referred to as a **microlaser**. One of the most significant advantages of microlasers is that they can be arrayed to construct a **matrix emitter** that is a broad area surface emitting laser source. Such laser arrays have important potential applications in optical interconnect and optical computing technologies. Further, such laser arrays can provide a higher **optical power** than that available from a single conventional laser diode. Powers reaching a few watts have been demonstrated using such matrix lasers.
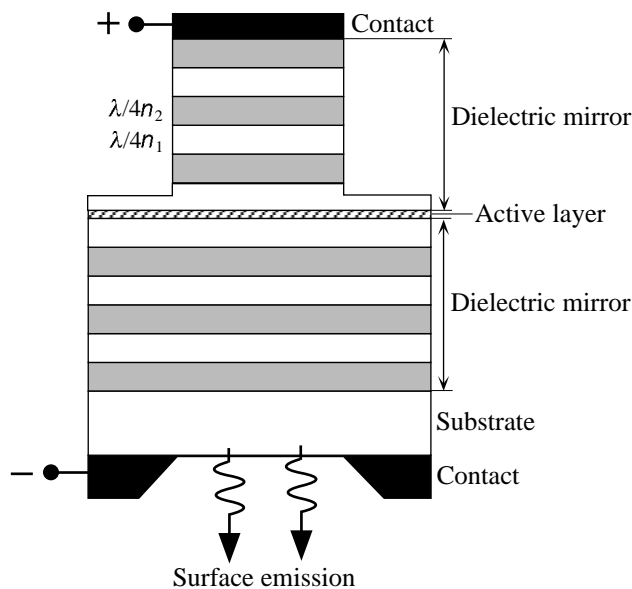
A simplified schematic illustration of a vertical cavity surface emitting laser (VCSEL).
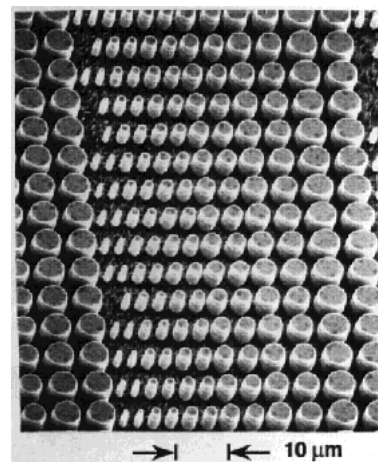
SEM (scanning electron microscope) of the first low-threshold VCSELs developed at Bell Laboratories in 1989. The largest device area is 5 μm in diameter (Courtesy of Alex Scherer, CalTech)

Very large scale integration (VLSI) is the integration of 10^6-10^7 devices into a single Si **chip** to implement very complex circuits (for example, microprocessor chips, memories etc.)

Viscosity is a measure of the resistance of a material against flow under an applied shear **stress**. It is the reciprocal of the *fluidity* of a material. If under an applied shear stress, the substance tends to flow easily, then it is said to be fluid, or exhibit little viscosity. When a shear stress $\tau = F/A$ is applied to a liquid-like material, atomic layers flow with respect to each other resulting in permanent deformation which we call *viscous flow*. Within the material, the atomic layers move with different velocities with respect to the bottom layer, which we take as reference. There is therefore a velocity gradient in the material. In time Δt, the permanent displacement is $\Delta x = v\Delta t$ where v is the flow velocity. Viscosity is then defined as shear stress required to generate a unity velocity gradient, *i.e.*

$$\tau = \eta \frac{dv}{dy}$$

Viscosity is measured in Pa s (Pascal × second). If an applied shear stress generates a uniform flow velocity gradient, the fluid is called Newtonian; otherwise it is called non-Newtonian. Viscosity of **glasses** exhibits a strong temperature dependence, typically following an *Arrhenius behavior*, $\eta \propto \exp(\Delta H_\eta/RT)$ where ΔH_η is the **activation energy** (in J mol^{-1}), R is the gas constant and T is the temperature.

Material	Water	Olive oil	Borosilicate glass
Viscosity (Pa s)	10^{-3}	10^{-1}	10^3 at 1245 °C, 10^7 at 820 °C, 10^{13} at 435 °C.
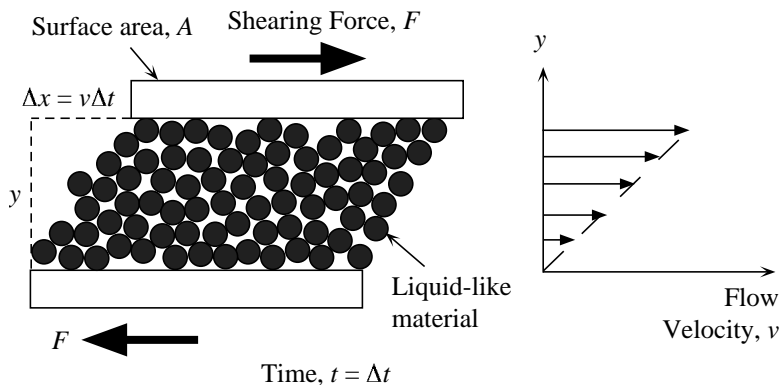
Under a shear stress F/A, the atomic layers move with different velocities with respect to the bottom layer. There is therefore a velocity gradient in the material.

In time Δt, the permanent displacement is $\Delta x = v\Delta t$ where v is the flow velocity.

Waist radius, see **Gaussian beam**.

Wave equation is a general partial differential equation in classical physics, of the form $v^2 d^2u/dx^2 - d^2u/dt^2$ whose solution describes the space and time dependence of the displacement, $u(x,t)$ from equilibrium or zero, given the boundary conditions. The parameter v in the wave equation is the propagation velocity of the **wave**. In the case of **electromagnetic waves** in vacuum, the wave equation describes the variation of the electric (or magnetic) field $E(x,t)$ with space and time, $c^2 d^2E/dx^2 - d^2E/dt^2 = 0$ where c is the speed of light.

Wave is a periodically occurring disturbance, such as the displacements of atoms from equilibrium positions in a solid carrying sound waves, or a periodic variation in a measurable quantity, such as the electric field $E(x,t)$ in a medium or space. In a traveling wave, energy is transferred from one location to another by the oscillations. For example, $E_y(x,t) = E_{yo}\sin(kx-\omega t)$, where $k = 2\pi / \lambda$ and $w = 2\pi\upsilon$, is a traveling wave in the x direction. The electric field in the y-direction varies periodically along the x with a period λ called the wavelength and with time with a period $1 / \upsilon$ where υ is the frequency. The wave propagates along the x - direction with a velocity of propagation, c. In a

longitudinal wave, the displacement is in the direction of propagation as in the propagation of a sound wave, whereas in a transverse wave, the displacement is at right angles to the direction of propagation as in an **electromagnetic wave**. Electromagnetic waves are transverse waves in which the electric and **magnetic fields** $E_y(x,t)$ and $H_z(x,t)$ are at right angles to each other and also the direction of propagation, x. A traveling wave in the electric field must be accompanied by a similar traveling wave in the magnetic field $H_z(x,t) = H_{zo}\sin(kx - \omega t)$. Typical wave-like properties are **interference** and **diffraction**.

Wave number or **propagation constant** is defined as $2\pi/\lambda$. It is the phase shift in the **wave** over a distance of unit length.

Wavefront is a surface where all the point have the same phase. A wavefront on a **plane wave** is an infinite plane perpendicular to the direction of propagation.

E and B have constant phase in this xy plane; a wavefront

$E_x = E_o\sin(\omega t - kz)$

A plane electromagnetic wave travelling along z, has the same E_x (or B_y) at any point in a given xy plane. All electric field vectors in a given xy plane are therefore in phase. The xy planes are of infinite extent in the x and y directions.
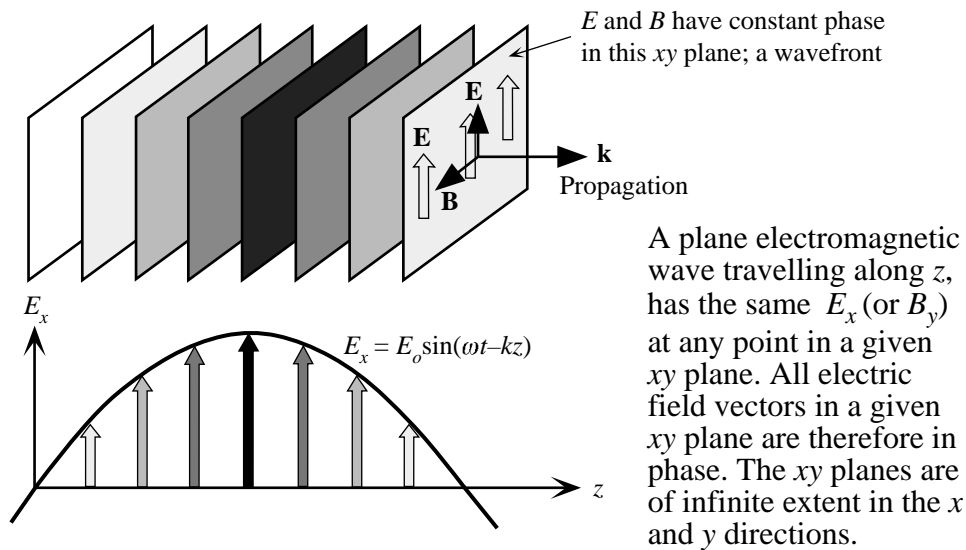
Wavefront reconstruction, see **holography.**

Wavefunction, $\Psi(x,y,z,t)$, is a probability based function that is used to describe the **wave**-like properties of a particle. It is obtained by solving the **Schrödinger equation** which in turn requires the knowledge of the *PE* of the particle and the boundary and initial conditions. $|\Psi(x,y,z,t)|^2$ is the probability per unit volume of finding the electron at (x,y,z) at time t. Put differently, $|\Psi(x,y,z,t)|^2 dxdydz$ is the probability of finding the electron in the small volume $dxdydz$ at (x,y,z) at time t. Under steady state conditions, the **wavefunction** can be separated into space dependent, $\psi(x,y,z)$, and time dependent components as $\Psi(x,y,z,t) = \psi(x,y,z)\exp(-jEt/\hbar)$ where E is the energy of the particle and $\hbar = h/(2\pi.)$ The spatial part, $\psi(x,y,z)$ satisfies the time independent Schrödinger equation.

Waveguide condition specifies the condition which an **EM (electromagnetic) wave** must satisfy to be propagated and hence be guided through a waveguide given the *V-number* of the waveguide. Each EM (electromagnetic) wave satisfying the waveguide condition is a *mode* of the waveguide as it can be propagated. Waveguide condition is a mathematical relationship for determining the allowed modes, particular EM radiation patterns, that can propagate in a waveguide from the waveguide properties (thickness, refractive indices *etc.*)

Waveguide dispersion coefficient D_w is the time spread of a propagating optical pulse in an optical guide per unit length and per unit spectral wavelength width due to the wavelength dependence of

the **V-number**, a waveguide property. If $\delta\lambda$ is the spread of the excitation wavelengths coupled into the fiber, $\delta\tau$ is the spread in propagation times of these different wavelengths due to waveguide dispersion, L is the fiber length then,

$$D_w = \frac{1}{L}\frac{\delta\tau}{\delta\lambda}$$

If the *V*-number is in the range $1.5 < V < 2.4$, then

$$D_w \approx -\frac{1.984 N_{g2}}{(2\pi a)^2 2cn_2^2}$$

where N_{g2} and n_2 are the group and refractive indices of the **cladding** (medium 2) and a is the **core** radius.

Waveguide dispersion, as separate from materials dispersion, is dispersion that arises because of the wavelength dependence of the **V-number** which determines the **propagation constant** inside the guide. As the radiation fed into the **core** has a finite range of wavelengths, $\Delta\lambda \neq 0$, the *V*-number is not constant which leads to **fundamental modes** with different wavelengths which propagate at different velocities. Waveguide dispersion results from the guiding properties of the dielectric structure and it has nothing to do with the frequency (or wavelength) dependence of the **refractive index**. Since increasing the wavelength, decreases the *V*-number, a characteristic property of the guide, the dispersion can also be stated as due to the wavelength dependence of the *V*-number.

The electric field of TE$_0$ mode extends more into the cladding as the wavelength increases. As more of the field is carried by the cladding, the group velocity increases.
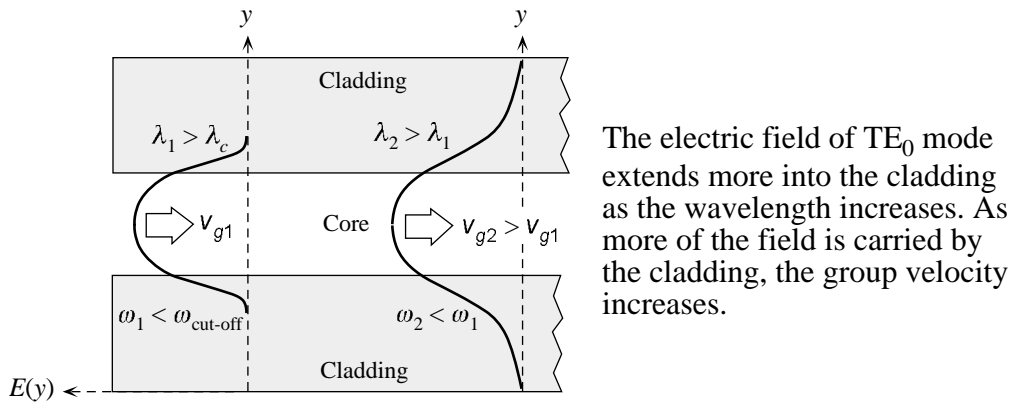
Wavelength division multiplexing (WDM) is a method of transmitting information by breaking it into a sets of information and then transmitting the sets at different wavelengths through the transmission medium; it is the same as *frequency division multiplex*. Thus, the communication systems operates at more than one wavelength.

Wavepacket is a group of **waves** with slightly different frequencies traveling together and forming a "group". This wavepacket travels with a **group velocity** v_g that depends on the slope of ω vs. k characteristics of the wavepacket, *i.e.* $v_g = d\omega/dk$.

Wavevector is a vector denoted as **k** that describes the direction of propagation of a **wave** and has the magnitude of the **wave number**, $k = 2\pi/\lambda$.

Weak injection is usually a condition in **semiconductor** device in which the injected **minority carrier** concentration is much less than the equilibrium majority carrier concentration in the same region; injection may be due to **photogeneration** or voltage application to forward bias a *pn* junction. See **minority carrier lifetime.**

Wire-grid polarizer consists of closely spaced parallel thin conducting wires. The light beam passing through the wire-grid becomes **linearly polarized** at right angles to the wires. E_x is along the wires and drives the conduction electrons along the length of the wires and thereby generates a

current. The collisions of these driven electrons with **lattice** vibrations leads to Joule loss, *i.e.* I^2R. Thus energy is absorbed from the E_x field and the wires heat up a little (negligible amount) just as energy would be absorbed from a battery driving a current through a wire. As the wires are very thin, E_y field cannot drive the electrons too far.

The wire grid-acts as a polarizer

Wire-grid polarizer
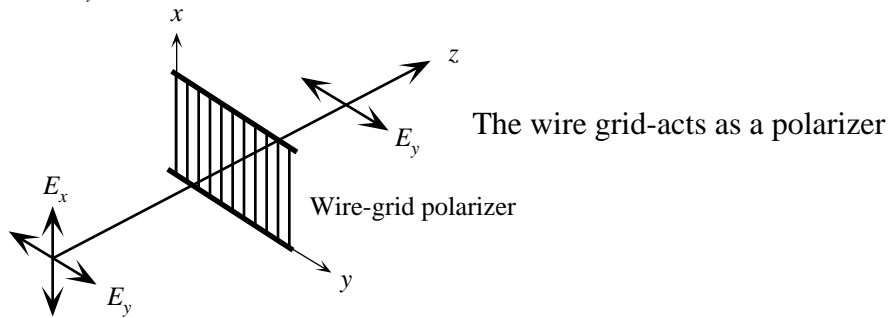
Work function, Φ_{metal} is the minimum energy needed to free an electron from the metal at absolute zero of temperature. It is the energy separation of the Fermi level from the vacuum level. Work function, in general, is the energy required to remove an electron from the solid to the vacuum level. The energy involved in freeing an electron from a metal surface depends on the crystal surface because different surfaces have different surface concentrations and arrangements of positive metal ions. Two examples are shown in the table below for an FCC and a BCC crystal. Vacuum level defines the energy where the electron is free from that particular solid (typically ~ 10 nm away from the surface) and where the electron has zero kinetic energy. The semiconductor work function $\Phi_{semiconductor}$ still represents the energy difference between the vacuum level and the semiconductor's Fermi energy E_F, even though there are normally no electrons at E_F. It may be thought the minimum energy required to remove an electron from the semiconductor is simply the *electron affinity χ* but this is not so. Thermal equilibrium requires that only a certain fraction of all the electrons in the semiconductor should be in the conduction band at a given temperature. When an electron is removed from the conduction band, then thermal equilibrium is upset and some additional energy has to be supplied to maintain the thermal equilibrium. The effective energy required to remove an electron, as for metals, is energy from E_F to the vacuum level, $\Phi_{semiconductor}$.

Crystal Plane	(100)	(110)	(111)	Typical
FCC relative planar concentration, atoms /nm² (1 is maximum)	0.87	0.61	1	
Nickel Φ_B (eV)	5.22	5.04	5.35	5.09
BCC relative planar concentration, atoms /nm² (1 is maximum)	0.71	1	0.41	
Tungsten, Φ_B (eV)	4.63	5.25	4.47	4.57
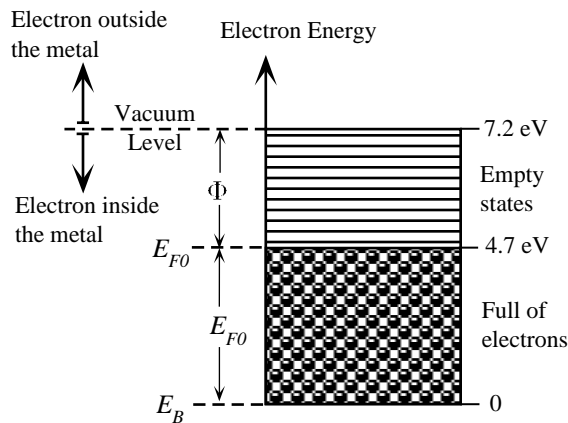
Typical electron energy band diagram for a metal (Li). All the valence electrons are in an energy band which they only partially fill. The top of the band is the vacuum level where the electron is free from the solid (potential energy = 0). E_{F0} is the Fermi energy at 0 K. E_B is the bottom of the conduction band. Φ is the work function.

Working point of **glass** is the temperature at which the **viscosity** of a glass is about 10^7 Pa s. Viscosity of glass is strongly temperature dependent and decreases steeply as the temperature increases. At the working point, the viscosity is sufficiently low to allow the glass to be easily worked in various glass fabrication processes such as **drawing**, pressing *etc.*

X-rays are electromagnetic radiation of wavelength typically in the range 10 pm - 1 nm. X-ray **photons** have high energies.

Zener breakdown is the enormous increase in the reverse current in a *pn* junction when the applied voltage is sufficient to cause the tunneling of electrons from the **valence band** in the *p*-side to the **conduction band** in the *n*-side. Zener breakdown occurs in *pn* junctions that are heavily doped on both sides so that the **depletion layer** width is narrow.

Physical Constants

c	Speed of light in vacuum	2.9979×10^8 m s^{-1}
h	Planck's constant	6.6261×10^{-34} J s
$\hbar$	$\hbar = h/2$	1.0546×10^{-34} J s
e	Electronic charge	1.60218×10^{-19} C
ε_o	Absolute permittivity	8.8542×10^{-12} F m^{-1}
k_B	Boltzmann constant ($k_B = R/N_A$)	1.3807×10^{-23} J K^{-1}
$k_B T/e$	Thermal voltage at 300 K	0.02585 V
m_e	Mass of the electron in free space	9.10939×10^{-31} kg
μ_o	Absolute permeability	$4\pi \times 10^{-7}$ H m^{-1}
N_A	Avogadro's number	6.0221×10^{23} mol^{-1}
R	Gas constant ($N_a k$)	8.31457 J mol^{-1} K^{-1}

Useful Information

Wavelength ranges and colors as usually specified for LEDs

Color	Blue	Emerald green	Green	Yellow	Amber	Orange	Red-Orange	Red	Deep red	Infrared
λ (nm)	$\lambda < 500$	530-564	565-579	580-587	588-594	595-606	607-615	616 - 632	632-700	$\lambda > 700$

1 eV = 1.60218×10^{-19} J

1 Å = 10^{-10} m = 0.1 nm

Some Useful Formulae

Complex Numbers

$j = (-1)^{1/2} \qquad j^2 = -1$

$\exp(j\theta) = \cos\theta + j\sin\theta$

$Z = a + jb = re^{j\theta} \qquad\qquad r = (a^2 + b^2)^{1/2} \qquad\qquad \tan\theta = b/a$

$Z^* = a - jb = re^{-j\theta}$

$\text{Re}(Z) = a$ $\text{Im}(Z) = b$

$\text{Magnitude}^2 = |Z|^2 = ZZ^* = a^2 + b^2$ $\text{Argument} = \theta = \arctan(b/a)$

$\cos\theta = \dfrac{1}{2}\left[e^{j\theta} + e^{-j\theta}\right]$ $\sin\theta = \dfrac{1}{2j}\left[e^{j\theta} - e^{-j\theta}\right]$

Trigonometry

$\sin(\pi/2 \pm \theta) = \cos\theta$ $\sin^2\theta + \cos^2\theta = 1$

$\sin2\theta = 2\sin\theta\cos\theta$ $\cos2\theta = 1 - 2\sin^2\theta = 2\cos^2\theta - 1$

$\sin(A + B) = \sin A\cos B + \cos A\sin B$ $\cos(A + B) = \cos A\cos B - \sin A\sin B$

$\sin A + \sin B = 2\sin[\tfrac{1}{2}(A + B)]\cos[\tfrac{1}{2}(A - B)]$

$\cos A + \cos B = 2\cos[\tfrac{1}{2}(A + B)]\cos[\tfrac{1}{2}(A - B)]$

Expansions

$e^x = 1 + x + \dfrac{1}{2!}x^2 + \dfrac{1}{3!}x^3 + \ldots$

$(1 + x)^n = 1 + nx + \dfrac{n(n-1)}{2!}x^2 + \dfrac{n(n-1)(n-3)}{3!}x^3 + \ldots$

Small x $(1 + x)^n \approx 1 + nx$ $\sin x \approx x$ $\tan x \approx x$ $\cos x \approx 1$

Small Δx in $x = x_o + \Delta x$, $f(x) \approx f(x_o) + \Delta x\left[\dfrac{df}{dx}\right]_{x_o}$

Materials Data

See Web-Materials for extensive data

http://Materials.Usask.Ca

Properties of Selected Semiconductors at 300 K

$\varepsilon_r(0)$ and $\varepsilon_r(\infty)$ represent the relative permittivity at dc (low frequency) and at optical (high) frequencies. $\varepsilon_r(\infty)$ excludes ionic polarization but includes electronic polarization. Effective mass related to conductivity (a) is different than that related to the density of states (b).

Property	Ge	Si	GaAs	In$_{0.53}$Ga$_{0.47}$As	InP
Density g cm^{-3}	5.33	2.33	5.32	6.15	4.81
E_g (eV)	0.66	1.12	1.42	0.75	1.35
n_i (cm^{-3})	2.4×10^{13}	1.45×10^{10}	1.8×10^6		1.2×10^7
N_c (cm^{-3})	1.04×10^{19}	2.8×10^{19}	4.7×10^{17}		5.4×10^{17}

N_v (cm^{-3})	6×10^{18}	1.02×10^{19}	7×10^{18}		1.2×10^{19}
$\varepsilon_r(0)$; $\varepsilon_r(\infty)$	16	11.9	13.1; 10.6	12.5; 9.61	12.5; 9.61
m_e^*/m_e	0.12a 0.56b	0.26a 1.08b	0.07a,b		
m_h^*/m_e	0.23a 0.40b	0.38a 0.56b	0.40a 0.50b		
μ_e (cm^2 V^{-1} s^{-1})	3900	1350	8500	13800	4600
μ_h (cm^2 V^{-1} s^{-1})	1900	450	400	400	150

Selected Semiconductors

Crystal structure, lattice parameter a, bandgap energy E_g at 300 K, type of bandgap (D = Direct and I = Indirect), change in E_g per unit temperature change (dE_g/dT), bandgap wavelength λ_g and refractive index n close to λ_g. (A = Amorphous, D = Diamond, W= Wurtzite, ZB = Zinc blende)

Semiconductors	Crystal	a nm	E_g eV	Type	dE_g/dT meV K^{-1}	λ_g (µm)	n around λ_g
Group IV							
Ge	D	0.5658	0.66	I	−0.37	1.87	4
Si	D	0.5431	1.12	I	−0.23	1.11	3.45
a-Si:H	A		1.7-1.8			0.73	
SiC			2.9	I		0.42	3.1
III-V Compounds							
AlAs	ZB	0.5661	2.16	I	−0.5	0.57	3.2
AlP	ZB	0.5451	2.45	I	−0.35	0.52	3
AlSb	ZB	0.6135	1.58	I	−0.3	0.75	3.7
GaAs	ZB	0.5653	1.42	D	−0.45	0.87	3.6
GaAs$_{0.88}$Sb$_{0.12}$	ZB		1.15	D		1.08	
GaN	W	0.3190 a 0.5190 c	3.44	D	−0.45	0.36	
GaP	ZB	0.5451	2.24	I	−0.54	0.55	3.4
GaSb	ZB	0.6096	0.73	D	−0.35	1.7	4
In$_{0.53}$Ga$_{0.47}$As on InP	ZB	0.5869	0.75	D		1.65	
In$_{0.58}$Ga$_{0.42}$As$_{0.9}$P$_{0.1}$ on InP	ZB	0.5870	0.80	D		1.55	
In$_{0.72}$Ga$_{0.28}$As$_{0.62}$P$_{0.38}$ on InP	ZB	0.5870	0.95	D		1.3	
InP	ZB	0.5869	1.35	D	−0.46	0.91	3.4-3.5
InAs	ZB	0.6058	0.35	D	−0.28	3.5	3.8
InSb	ZB	0.6479	0.18	D	−0.3	7	4.2
II-VI Compounds							
ZnSe	ZB	0.5668	2.7	D	−0.72	0.46	2.3
ZnTe	ZB	0.6101	2.25	D		0.55	2.7

Selection of Typical Notation and Abbreviations in Semiconductor Science and Optoelectronics

A	area; cross sectional area
a	half dimension of the core region of an optical waveguide; fiber core radius; lattice parameter of a crystal, side of a cubic crystal
a (subscript)	acceptor, *e.g.* N_a = acceptor concentration
A_{21}	Einstein coefficient for spontaneous emission
ac	alternating current
AM	air mass, describes the integrated solar intensity and depends on location
APD	avalanche photodiode
AR	antireflection coating
B	maximum bit-rate; frequency bandwidth; direct recombination capture coefficient
$\mathbf{B}$, B	magnetic field vector (T), magnetic field, magnetic flux density
b	normalized propagation constant
B_{12} B_{21}	Einstein absorption and stimulated emission coefficients for the rate transitions between energy levels 1 and 2
BJT	bipolar junction transistor
BL	bit-rate × distance product (Gb s^{-1})×km
C	capacitance
c	speed of light in free-space (3×10^8 m s^{-1})
C^3	cleaved coupled cavity
CB	conduction band
C_{dep}	depletion region capacitance of a *pn* junction; junction capacitance of *pin*
CVD	chemical vapor deposition
CW	continuous wave
D	diameter of a circular aperture; diffusion coefficient (m^2 s^{-1}); detectivity; thickness
$\mathbf{D}$, D	displacement vector (C m^{-2})
D	direct (bandgap)
d	differential in mathematics; distance; diameter
d (subscript)	donor, *e.g.* N_d = donor concentration
DBR	distributed Bragg reflector
dc	direct current
D_{ch}	chromatic dispersion coefficient
DFB	distributed feedback
DH	double-heterostructure
D_m	material dispersion coefficient

DOS	density of states, number of electronic states per unit energy per unit volume in a given energy band
D_p	polarization dispersion coefficient
D_w	waveguide dispersion coefficient
E	electric field; energy
E (arial)	electric field
e	electronic charge (1.60218×10^{-19} C)
e	Napierian base, 2.71828...
e (subscript)	electron, *e.g.* μ_e = electron drift mobility
E_a	applied external field (non optical field) in an electro-optic crystal
E_a, E_d	acceptor and donor energy levels
E_c, E_v	conduction band edge energy, valence band edge energy
EDFA	erbium doped fiber amplifier
E_F	Fermi energy with respect to the bottom of the valence band.
E_{Fi}	Fermi energy in the intrinsic semiconductor
E_{Fn}	Fermi energy in the *n*-side of a *pn* junction
E_{Fp}	Fermi energy in the *p*-side of a *pn* junction
E_g	bandgap energy
EHP	electron hole pair
ELED	edge light emitting diode
EM	electromagnetic
EMF, emf	electromagnetic force (V)
E_n	energy corresponding to quantum number *n*
EO	electro-optic
E_{ph}	photon energy, $h\upsilon$ (usually stated in eV)
eV	electron volt
exp(*x*)	exponential function of *x*
F	Finesse of a Fabry-Perot cavity; excess noise factor
f(E)	Fermi-Dirac function
FF	fill factor of a solar cell
f_{op}	optical bandwidth , optical bandwidth and fiber length product
FTIR	frustrated total internal reflection
FWHP	full width at half power
G	gain; rate of generation (m^{-3} s^{-1}); photoconductive gain
g	optical gain coefficient due to stimulated emissions exceeding absorption between the same two energy levels (m^{-1})
g(E)	density of states, number of electronic states (possible electron wavefunctions) per unit volume per unit energy

$g(\upsilon)$	optical gain lineshape; optical gain vs. frequency curve shape
G_{op}	net optical gain
g_{ph}	photogeneration rate per unit volume
G_{ph}	rate of photogeneration ($\text{m}^{-3}\,\text{s}^{-1}$)
GRIN	graded index
g_{th}	threshold optical gain coefficient for achieving a lasing emission from a laser device (for laser oscillations)
G_{thermal}	thermal generation rate of electron hole pairs ($\text{m}^{-3}\,\text{s}^{-1}$)
H	height of the optical cavity in a laser diode
$\mathbf{H}$, H	magnetic field intensity (strength) or magnetizing field (A m^{-1})
h	Planck's constant (6.6261×10^{-34} J s)
h (subscript)	hole, *e.g.* μ_h = hole drift mobility
$\hbar$	Planck's constant divided by 2π (1.0546×10^{-34} J s), $\hbar = h/2$.
HF	high frequency
I	electric current (A)
I (courier)	irradiance or intensity of light (W m^{-2})
I	indirect (bandgap)
i (subscript)	initial; intrinsic, *e.g.* n_i = intrinsic concentration
IC	integrated circuit
I_d	dark current
I_{diff}	forward diffusion (Shockley) current of a *pn* junction
I_{ph}	photocurrent; multiplied APD photocurrent
I_{pho}	unmultiplied APD photocurrent
I_{recomb}	forward recombination current of a *pn* junction
I_{ro}	reverse recombination current of a *pn* junction
I_{sc}	short circuit current in light (solar cells)
I_{so}	reverse Shockley saturation current of a *pn* junction
I_{th}	threshold current
i_n	noise current, rms fluctuati*ons in the photodetector current*
i_{ph}	photocurrent
J	current density
j	imaginary constant: $\sqrt{-1}$
J_{gen}	reverse current in a *pn* junction due to thermal generation of EHPs in the SCL
J_{rev}	total reverse current in a *pn* junction
J_{th}	threshold current density value
K	Kerr coefficient
$\mathbf{K}$, K	phonon wavevector

k, k	wavevector, wavenumber, free-space wavevector : $k = 2\pi/\lambda$
k_B	Boltzmann constant ($k_B = R/N_A = 1.3807 \times 10^{23}$ J K^{-1})
KDP	potassium dihydrogen phosphate
KE	kinetic energy
L	distance, length; optical cavity length; inductance
ℓ	length
ℓ_n, ℓ_p	lengths of the neutral n and p regions outside depletion region in a *pn* junction
l	orbital angular momentum quantum number of an electron, 0, ±1, ±2, ... $n - 1$; n is the principal quantum number
LASER	light amplification by stimulated emission of radiation
LD	laser diode
L_e, L_h	electron and hole diffusion lengths: $L_e = \sqrt{(D_h\tau_h)}$ and $L_h = \sqrt{(D_h\tau_h)}$
LED	light emitting diode
LF	low frequency
ln (x)	natural logarithm of x
L_o	transfer distance for full light transfer from one to another coupled optical guide
LP	linearly polarized
M	number of modes; multiplication in avalanche effect; mass
m	integer; mode number; mass
m (arial)	numerical constant characterizing the photon energy width of the LED output spectrum
MBE	molecular beam epitaxy
m_e	mass of the electron in free space (9.10939 × 10^{-31} kg)
m_e^*, m_h^*	electron and hole effective masses in a crystal
MFD	mode field diameter, $2w_o$
	effective mass of a hole in a crystal (in the valence band)
m_l	magnetic quantum number for an electron, $-l,\ldots, -1, 0, +1, \ldots +l$
MMF	miltimode fiber
MQW	multiple quantum well
m_s	spin magnetic quantum number (±1/2)
N	number of molecules per unit volume; n-type semiconductor with a wider bandgap
n	electron concentration in the conduction band; principal quantum number (0, 1, 2 …); refractive index.
n (arial)	refractive index
N_A	Avagodro's number (6.022×10^{23} mol^{-1})
NA	numerical aperture
N_a, N_d	acceptor and donor dopant concentrations in a semiconductor
N_c, N_v	effective density of states at the conduction and valence band edges respectively (m^{-3})

	donor concentration (m^{-3})
n_e, n_o	refractive index for the extraordinary and ordinary waves in a birefringent crystal
NEP	noise equivalent power, 1/Detectivity
N_g	group index, $N_g = c / v_g$
n_i	intrinsic concentration
n_L, n_R	refractive index experienced by left handed circularly polarized and right handed circularly polarized waves in a crystal
n_n, p_p	instantaneous majority carrier concentrations (*e.g.* electrons in an *n*-type semiconductor)
n_{no}, p_{po}	equilibrium majority carrier concentrations (*e.g.* electrons in an *n*-type semiconductor)
n_p, p_n	instantaneous minority carrier concentrations (*e.g.* electrons in an *p*-type semiconductor)
n_{po}, p_{no}	equilibrium minority carrier concentrations (*e.g.* electrons in an *p*-type semiconductor)
$n_p(0)$	electron concentration just outside the depletion region in the *p*-side of a *pn* junction
N_{ph}	photon concentration in the optical cavity
NRZ	nonreturn to zero (pulses)
OVD	outside vapor deposition
P (arial)	polarization vector, polarization per unit volume in a dielectric
P	power, energy flow per unit time ; *p*-type doping in a larger bandgap material.
p	hole concentration in the valence band; photoelastic coefficient
PD	photodiode, photodetector
PE	potential energy
pin	*p*-type/intrinsic/*n*-type semiconductor photodiode
$p_n(0)$	hole concentration just outside the depletion region in the *n*-side of a *pn* junction
Q	charge
q	an integer; diffraction order; charge
QE	quantum efficiency
R (arial)	reflectance (fractional reflected light intensity at a dielectric-dielectric interface); spectral responsivity or radiant sensitivity of a photodetector
R, R_L	resistance
R_L	load resistance (external to device)
R_p, R_s	parallel and series resistances of a solar cell
r, r_{22}	Pockels coefficient
r	radial distance
r	position vector
r (arial)	EM wave reflection coefficient
R (arial)	responsivity
Re	real part
RZ	return to zero (pulses)

rms	root mean square
S	strain
$\mathbf{S}$, S	Poynting vector that quantifies the rate of electromagnetic energy flow
s, p, f	atomic subshells
SAGM	separate absorption, grading and multiplication
SAM	separate absorption and multiplication
SCL	space charge layer, depletion region, of a pn junction
SHG	second harmonic generation
SLED	surface emitting LED
SMF	single mode fiber
SNR, S/N	signal to noise ratio
SQW	single quantum well
T	temperature in Kelvin
T (arial)	transmittance, fractional intensity transmitted through a dielectric-dielectric interface
t	time; thickness
t (arial)	transmission coefficient
t_h	transit time of holes
TA	transmission axis of a polarizer
t_{drift}	drift time of a carrier
TE	transverse electric field modes
TEM	transverse electric and magnetic (TEM) modes
T_f	fictive temperature, softening temperature of glass (K)
TIR	total internal reflection
TM	transverse magnetic field modes
t_r	rise time of a signal (usually from 10% to 90%)
UV	ultraviolet
V	V-number, V-parameter, normalized thickness
V	applied voltage , potential energy in the Schrödinger equation
v	velocity
V_{br}	avalanche breakdown voltage
$V_{\lambda/2}$	applied voltage in a Pockels cell that introduces a relative phase change $\Delta\phi$ of π
V_o	built-in voltage, potential
V_{oc}	open circuit voltage of a solar cell
V_r	reverse bias voltage
VB	valance band
VCSEL	vertical cavity surface emitting laser

v_d	drift velocity
v_e, v_h	electron and hole drift velocities
v_g	group velocity
v_{th}	thermal velocity of an electron in the conduction band and a hole in the valence band
w	width
W	width; thickness; width of depletion region in a *pn* junction
W_n, W_p	widths of depletion region on the *n*-side and on the *p*-side of the *pn* junction
w_o	half-waiste of a Gaussian beammode field radius (MFD÷2)
W_o	width of depletion region of a *pn* junction with no applied voltage
x	distance; excess avalanche noise index for APDs
⊥ (subscript)	perpendicular
// (subscript)	parallel

α	optical attenuation; attenuation coefficient for the electric field in medium 2; absorption coefficient of a semiconductor; dielectric polarizability per molecule
α_{dB}	attenuation in dB
α_R	Rayleigh scattering attenuation
α_t	total attenuation coefficient in the optical cavity of a semiconductor laser
α_{max}	maximum acceptance angle for an optical fiber
β	propagation constant; base-to-collector bipolar transistor current gain
β_m	propagation constant along a planar dielectric waveguide for mode *m*
β_T	isothermal compressibility (m^2/N)
Γ, Γ_{ph}	flux (m^{-2} s^{-1}), photon flux (photons m^{-2} s^{-1})
γ	loss coefficient in a laser optical cavity
Δ	difference, change; normalized index difference, $\Delta = (n_1 - n_2)/n_1$
$\Delta\tau$	propagation time difference along an optical guide
$\Delta\tau_{1/2}$	time width of the output light pulse between half intensity points
Δv_{rms}	the width between rms points of the intensity vs. frequency spectrum
$\Delta\beta$	phase mismatch per unit length between two propagating waves
$\Delta\phi$	phase change
$\Delta\lambda$	spectral width of the output spectrum (intensity vs. wavelength) of a light source. This can be between half-intensity points ($\Delta\lambda_{1/2}$) or between rms points.
$\Delta\lambda_m$	wavelength separation of allowed modes in an optical cavity
$\Delta n = n - n_o$	excess electron concentration (above equilibrium)
ΔN_{th}	$(N_2 - N_1)_{th}$: threshold population for threshold gain (lasing emission)
$\Delta\theta$	divergence angle due to diffraction effects
δ	small change; penetration depth of an EM wave from one medium to another

$\delta\lambda_m$	spectral wavelength width of an allowed mode in an optical cavity; wavelength separation between two consecutive optical cavity modes
$\varepsilon = \varepsilon_o\varepsilon_r$	permittivity of a medium where ε_o = permittivity of free space or absolute permittivity, ε_r = relative permittivity or dielectric constant
ε_n	energy in a quantum well with respect to the bottom of the conduction band, n is a quantum number 1, 2,…
η	efficiency; quantum efficiency; ideality factor of a diode
η_{external}	external efficiency
η_{slope}	slope efficiency of a laser diode
θ	angle ; angular spherical coordinate
θ_c	critical angle for total internal reflection
θ_i	angle of incidence
θ_p	Brewster's polarization angle
κ	propagation constant along the transverse direction of a planar dielectric waveguide
Λ	periodicity of a corrugated Bragg grating; acoustic wavelength
λ	free space wavelength
λ_B	Bragg wavelength of a grating type structure that satisfies the Bragg condition
λ_c	critical or cut-off wavelength
λ_g	threshold wavelength for photoexcitation; bandgap wavelength
$\mu = \mu_o\mu_r$	magnetic permeability (H m^{-1}); μ_o = absolute permeability, μ_r = relative permeability
μ_d	drift mobility (m^2 V^{-1} s^{-1})
μ_h , μ_e	hole drift mobility, electron drift mobility (m^2 V^{-1} s^{-1})
μm	micron, micrometer
π	pi, 3.14159...
ρ	resistivity; charge density (C m^{-3})
ρ_{net}	net space change density
$\rho(h\upsilon)$	photon energy density per unit frequency
$\rho_{eq}(h\upsilon)$	Planck's black body equilibrium radiation distribution as a function of frequency
σ	conductivity; rms deviation of dispersion of a light pulse going through a fiber
τ	group delay time in a fiber; recombination time of a charge carrier; lifetime (τ_e for electrons, τ_h for holes); time constant
τ_g	group delay time per unit length, $\tau_g = 1/v_g$; mean time to thermally generate an electron-hole pair in a semiconductor
τ_{ph}	photon decay time in the optical cavity, time it takes for the photon to be lost from the cavity
τ_{sp}	average time for an electron-hole pair recombination by spontaneous emission
ϑ	phonon frequency; lattice vibration frequency;Verdet constant
υ	frequency
Φ	phase change; work function

φ	an angular spherical coordinate
ϕ	phase ($\phi = \omega t - kz + \phi_o$); phase change
ϕ_o	phase constant
χ	electron affinity; electric susceptibility
χ_1, χ_2, χ_3	linear, second-order and third-order electric susceptibilities
$\psi(x)$	spatial dependence of the electron wavefunction under steady state conditions satisfying the Schrödinger equation
$\psi_k(x)$	Bloch wavefunction, electron wavefunction in a crystal with a wavevector k.
Ω	phonon angular freqeuncy
ω	angular frequency $2\pi\upsilon$ (of light)

Safa Kasap is currently a Professor of Electronic Materials and Devices in the Electrical Engineering Department at the University of Saskatchewan, Canada. He obtained his PhD (1983) degree from Imperial College of Science, Technology and Medicine, University of London, specializing in amorphous semiconductors and optoelectronics. In 1996 he was awarded the DSc (Engineering) degree from London University for his research contributions to materials science in electrical engineering. He is a Fellow of the Institution of Electrical Engineers, the Institute of Physics and the Institute of Materials. His research interests are in amorphous semiconductors, noise in electronic devices, photoconductors, photodetectors, X-ray image detectors, laser induced transient photoconductivity and related topics, with more than one hundred refereed journal publications in these areas. He is the author of McGraw-Hill's *Principles of Electrical Engineering Materials and Devices*, which is now used as a standard textbook in electronic materials in many major universities world wide. His second textbook, *Optoelectronics and Photonics: Principles and Practices* has been just published by Prentice Hall (http://Photonics.Usask.Ca)

Harry Ruda received the Ph.D. degree from Massachusetts Institute of Technology, Cambridge, Massachusets, USA, in 1982, for work on growth and characterization of HgCdTe for infrared detectors. Following these studies, he accepted an IBM postdoctoral fellowship to work on defect calculations in GaAs and transport in low dimensional GaAlAs-based quantum heterostructures. In 1984 he joined 3M where his work focused on theoretical optical and transport properties of wide bandgap II-VI semiconductors, principally ZnSe-based. In 1989, Dr. Ruda joined the University of Toronto and now holds the position of Full Professor. He currently is also the Energenius Advanced Nanotechnology chair holder, and Director of the Energenius Centre for Advanced Nanotechnology as well as the Photonics Materials Research Cemtre at the University of Toronto.

Dr Yann Boucher (born in Paris, 1964) received his Ingénieur degree in optics from the École Supérieure d'Optique, Orsay, France (1988), Diplôme d'Études Approfondies (DEA) in nonlinear optics and lasers from Orsay, France, and his PhD from Institut d'Optique Théorique et Appliquée, Orsay, France (1993). His doctoral work was on the theoretical and experimental study of optically pumped VCSELs. He joined RESO Laboratory, École Nationale d'Ingénieurs de Brest in 1994. His research interests include multilayer and periodic semiconductor structures such as VCSELs, distributed feedback or SSG. Dr. Boucher is a member of the Société Française d'Optique.

"Al Asuli writing in Bukhara some 900 years ago divided his pharmacopoeia into two parts, 'Diseases of the rich' and 'Diseases of the the poor'."

Abdus Salam   (1926-1997; Nobel Laureate, 1979)

Email the author to report your corrections: Kasap@Engr.Usask.Ca

Version 1.3.1 (3 February 2000)