Numerical definitions

1/*f* noise see *excess noise*.

10Dq see *ligand field splitting parameter*.

1.24 "rule" is the equation that is widely used in converting between the photon energy E in eV and the radiation wavelength λ in microns: $\lambda(\mu\text{m}) = 1.24[E(\text{eV})]^{-1}$. It arises from $E = h\nu = hc/\lambda$.

A

Abbe condenser is a high numerical aperture lens system that normally has two lenses designed to collect and suitably direct light to an object that is to be examined in a microscope.

Abbe diagram see *Abbe number*.

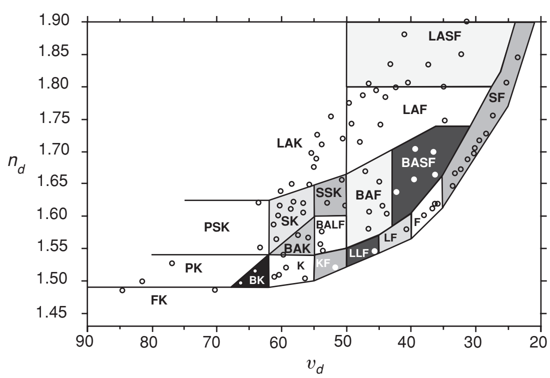
Abbe number or **constringence** of an optical medium is the inverse of its *dispersive power*, that is, it represents the relative importance of refraction and dispersion. There are two common definitions based on using different standard wavelengths. The Abbe number υ_d is defined by

$$\upsilon_d = (n_d - 1)/(n_F - n_C)$$

where n_F, n_d and n_C are the refractive indices of the medium at the Fraunhofer standard wavelengths corresponding to the helium *d*-line ($\lambda_d = 587.6$ nm, yellow), hydrogen *F*-line ($\lambda_F = 486.1$ nm, blue) and hydrogen *C*-line ($\lambda_C = 656.3$ nm, red). The Abbe number υ_e, on the other hand, is defined by

$$\upsilon_e = (n_e - 1)/(n_{F'} - n_{C'})$$

where n_e, $n_{F'}$ and $n_{C'}$ are refractive indices at the *e*-line (546.07 nm), F'-line (479.99 nm) and C'-line (643.85 nm) wavelengths respectively.



Abbe number The *Abbe diagram* is a diagram in which the refractive index n_d of glasses are plotted against their Abbe numbers in a linear n_d vs. υ_d plot and, usually, with the Abbe number decreasing along the *x*-axis, rather than increasing (υ_d values on the the *x*-axis have been reversed). The last letter F or K represents flint or crown glass. Other symbols are as follows: S, dense; L, light; LL, extra light; B, borosilicate; P, phosphate; LA or La, lanthanum; BA or Ba, barium. Examples: BK, dense flint; LF, light flint; LLF, extra light flint; SSK, extra dense crown; PK, phosphate crown; BAK, barium crown; LAF, lanthanum flint, etc. (Adapted from Schott Glass Website.) See *chromatic dispersion*.

Table: Abbe number PC is polycarbonate, PMMA is polymethylmethacrylate, PS is polystyrene.

Optical glass	SF11	F2	BaK1	crown glass	fused silica	PC	PMMA	PS
υ_d	25.76	36.37	57.55	58.55	67.8	34	57	31

[Sources: Melles-Griot and Goodfellow websites]

Abbe-Porro prism is a prism that transmits the image through the prism laterally displaced but fully inverted, that is, flipped vertically and horizontally. It is very similar in its function to the double Porro prism. See *Porro prism*.

Abbe prism is a reflection prism that uses reflections rather than refractions to deflect (deviate) light, invert or rotate an image.

Abbe refractometer see *refractometer*.

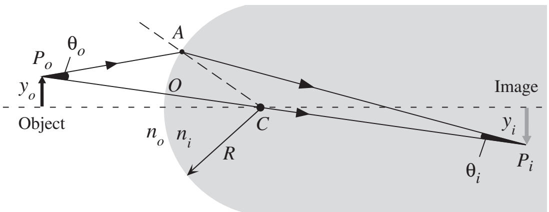
Abbe's sine condition, discovered by Abbe and Helmholtz (1873) and also simply called the *sine condition*, specifies the condition under which arbitrary rays leaving a particular point P_o on the object are able to arrive at the same (and unique) image point P_i that is an image (or conjugate point) of P_o. Consider an image formed by a spherical surface. A point P_o on the object at a height y_o in the object space of refractive index n_o gives rise to a point P_i of height y_i in the image space of index n_i; the two media are separated by a spherical boundary with its center of curvature at C. An arbitrary ray from P_o that is incident on the spherical surface at A (an arbitrary point) is refracted, and can only pass through the required unique image point P_i if *Abbe's sine* condition is satisfied, i.e.

$$n_o y_o \sin\theta_o = n_i y_i \sin\theta_i$$

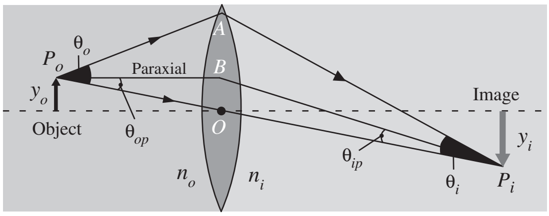
where θ_o is the angle the object ray P_oA makes with the principal ray P_oCP_i (that ray passing through the center C without refraction) and θ_i is the angle that the image ray AP_i makes with the principal ray P_oCP_i. There are no assumptions in this condition, and if an optical system is such that it satisfies the sine condition, then spherical and coma (off-axis) aberrations are eliminated since all arbitrary rays from P_o arrive at P_i. Consider a simple lens imaging system in which the object and the image are in the same refractive index media, $n_o = n_i$. The magnification is y_o/y_i, so that $y_i/y_o = \sin\theta_o/\sin\theta_i$. Both marginal and paraxial rays will produce the same magnification, that is the same P_i for a given P_o, if

$$y_i/y_o = \sin\theta_o/\sin\theta_i = \theta_{op}/\theta_{ip} = \text{constant}$$

which will then result in no spherical or coma aberration; $\sin\theta_o/\sin\theta_i = \theta_{op}/\theta_{ip}$ is sometimes stated as the *sine condition* for the absence of spherical and coma aberration. It has been stated that "Abbe's sine condition requires that all rays emanating from the axial object point within the incident cone must emerge in image space, where they form a converging cone toward the axial image point, at the same height at which they entered the system" (M. Born and E. Wolf, *Principles of Optics*, Cambridge University Press, 1999). The height *OA* must be the same for both the object rays and the image rays. See *aplanaticlens, aplanatic optical system, aplanatic points*.

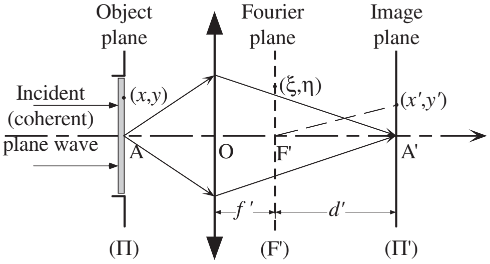


Abbe's sine condition for refraction at a curved surface. *C* is the center of curvature. Subscripts *o* and *i* refer to object and image.

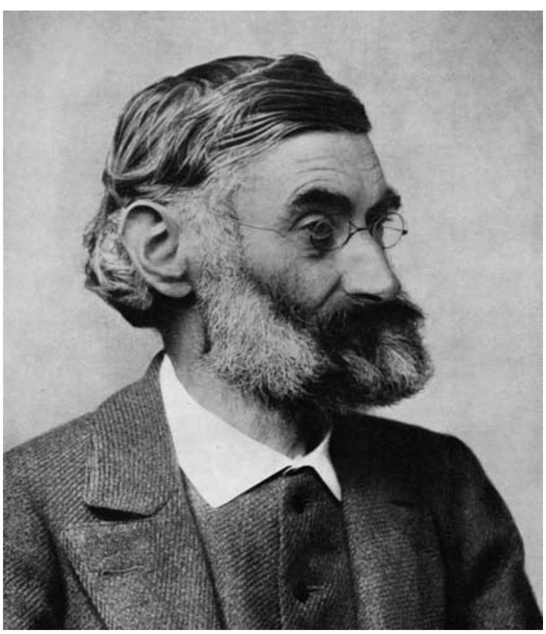


Abbe's sine condition for a lens; an arbitrary ray from P_o generates P_i.

Abbe's theory of microscope imaging refers to the case where the (thin) *phase object* is under coherent illumination, either by a laser or by light emitted from a sufficiently small source via a condenser of low aperture. The object in the Π plane acts as a diffraction phase grating, forming its



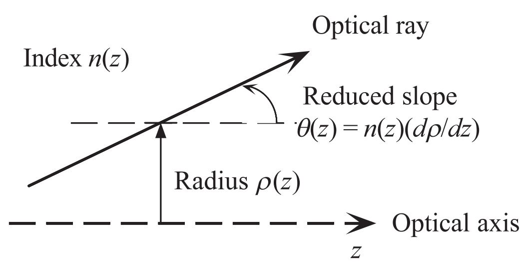
Abbe's theory of image formation. A filter conveniently located in the F′ plane enables one to select, or suppress, any given spatial frequency. (x,y) represent the coordinates of a point on the object plane, (ξ,η) the coordinates of a point on the Fourier transform plane, and (x',y') the coordinates of a point on the image plane. See also *spatial filtering*.

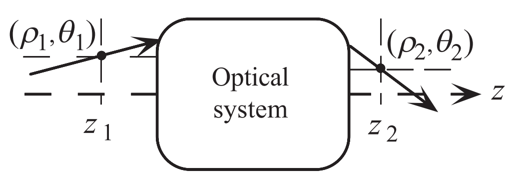


Ernst Abbe (1840–1905, Germany). Ernst Abbe was appointed a professor of physics and mathematics at Jena in 1870. As a result of his innovative works on optics with Carl Zeiss, Abbe became quite wealthy. (Jena Review, 1965, Zeiss Archive, courtesy AIP Emilio Segre Visual Archives, E. Scott Barr Collection.)

Fourier transform in the image focal plane F′ of the objective, where each point acts as a secondary source. The final image in the image plane Π′ is the result of the interference of all these sources. The whole theory has been summarized as follows: "The microscope image is the interference effect of diffraction phenomena."

ABCD matrix or **ray-transfer matrix** is a matrix that conveniently describes an optical operation on a ray of light; it is a direct result of the linearity of the paraxial equations. At any abscissa z along the main axis, any given optical ray propagating in a medium of refractive index n is completely determined by two numbers: the distance $\rho(z)$ to the axis and the reduced slope $\theta(z) = n(z)d\rho(z)/dz$ as illustrated in the figure.



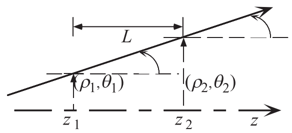


The couple $\{\rho_1,\theta_1\}$ at abscissa z_1 is transformed at abscissa z_2 into $\{\rho_2,\theta_2\}$ such that

$$\begin{pmatrix}\rho_2\\ \theta_2\end{pmatrix} = \begin{pmatrix}A & B\\ C & D\end{pmatrix}\begin{pmatrix}\rho_1\\ \theta_1\end{pmatrix},$$

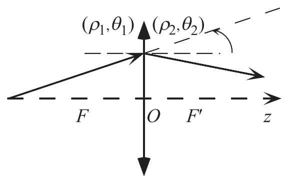
with $AD-BC=1$. Some examples are reported in the following table.

Propagation in free space (length L, index n_0)



$$\begin{pmatrix}\rho_2\\ \theta_2\end{pmatrix} = \begin{pmatrix}1 & L/n_0\\ 0 & 1\end{pmatrix}\begin{pmatrix}\rho_1\\ \theta_1\end{pmatrix}$$

Thin lens (focal f)



$$\begin{pmatrix}\rho_2\\ \theta_2\end{pmatrix} = \begin{pmatrix}1 & 0\\ -1/f & 1\end{pmatrix}\begin{pmatrix}\rho_1\\ \theta_1\end{pmatrix}$$

Any succession of optical elements, all aligned along a single axis, can therefore be associated a single ray-transfer matrix, obtained by a matrix product (in the right order) of each subcomponent. This can be successfully generalized to a linear medium exhibiting a refractive index decreasing quadratically with ρ, such as $n(\rho) = n_0(1-\gamma^2\rho^2/2)$. In this case,

$$\begin{pmatrix}\rho_2\\ \theta_2\end{pmatrix} = \begin{pmatrix}\cos(\gamma z) & \sin(\gamma z)/(n_0\gamma)\\ -(n_0\gamma)\sin(\gamma z) & \cos(\gamma z)\end{pmatrix}\begin{pmatrix}\rho_1\\ \theta_1\end{pmatrix},$$

and the optical ray is "trapped" along the axis, forced to propagate in a curved way. Graded-index quadratic fibers are based on this principle (GRIN fibers).

Two other applications of ABCD matrices should be mentioned: the stability analysis of laser cavities and the propagation of Gaussian beams generated by such a laser.

Aberrations generally refer to unwanted deviations in the optical imaging characteristics of a lens or a mirror from the ideal, based on *paraxial ray imaging*. Aberrations are usually divided into two categories. *Chromatic aberration* is due to the wavelength dependence of the refractive index and hence the focal length f, which now depends on the color of light. *Monochromatic* (or near monochromatic) *aberrations* are also called *third-order aberrations* (originally analyzed by Seidel in 1857) and are primarily *spherical*, *coma*, *astigmatism*, *field curvature*, and *distortion*, and arise as a result of the departure from the paraxial approximation when the angles of the rays in the imaging system are not sufficiently small. Aberrations typically result in the distortions of the image and in the unwanted blurring in the image quality (loss of resolution). When a light ray traveling in air is incident on a lens, it is refracted at the lens surface. It obeys Snell's law, i.e.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

where n_1 and n_2 are the air and glass (lens) refractive indices and θ_1 and θ_2 are the angles of incidence and refraction with respect to the normal on the lens surface at the point of incidence. There is a similar expression for the ray leaving the lens. The whole paraxial lens theory and the usual lens equations are based on assuming small angles so that $\sin\theta_1 \approx \theta_1$, and $\sin\theta_2 \approx \theta_2$, and $n_1\theta_1 \approx n_2\theta_2$. Thus, in

$$\sin\theta = \theta - \frac{\theta^3}{3!} + \frac{5^3}{5!} - \ldots$$

we normally neglect the third-order and higher terms, which is the paraxial approximation; small angles. The third-order term $(\theta^3/3!)$ is the cause of third-order aberrations, which are sometimes called *Seidel aberrations*. Unless $\theta = 0$ (normal incidence), there will always be a third term in the above expansion (small but finite), and hence always some aberration. In practice, aberrations occur in combination which makes it difficult to cancel them exactly. Nonetheless, either by suitable lens shaping, or using two or more lenses with stops,

Table: Aberrations in optics (Summarized from various sources including J. R. Meyer-Arendt, *Introduction to Modern Optics*, Fourth Edition, Prentice Hall, 1994.)

Aberration	Cause and character	Correction
Chromatic aberration	Focal point F depends on λ (n depends on λ). Image blur	Doublet
Monochromatic aberration types		
Spherical	On-axis and off-axis blur	Lens bending; aspherical lenses; gradient index; doublet
Coma	Off-axis blur	Lens bending; spaced doublet with central stop
Astigmatism	Off-axis blur	Spaced doublet with stop
Curvature of field	Off-axis objects imaged onto a curved surface instead of a plane	Spaced doublet. Field flattener
Distortion	Off-axis distortion due to varying magnification with distance from axis	Spaced doublet with stop

it is possible to reduce aberrations to an insignificant level.

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.

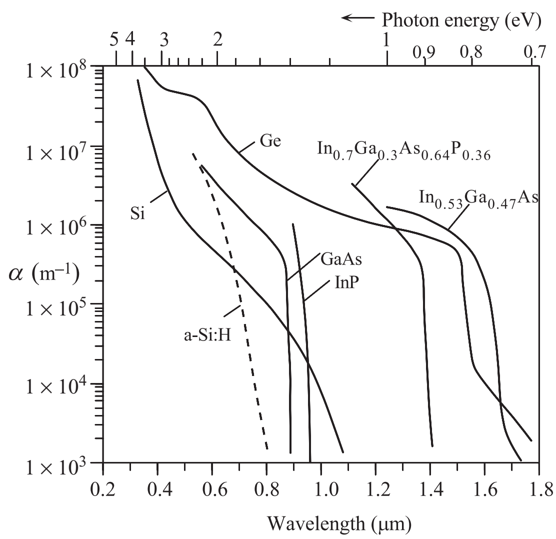
Absorption broadening see *photon reabsorption broadening*.

Absorption coefficient, α, characterizes the absorption 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,

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

where I is the intensity of the radiation. $1/\alpha$ is also the mean probability per unit distance that a photon is absorbed. The absorption coefficient depends on the photon energy or wavelength λ. The 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. The absorption coefficient depends on the radiation absorbing processes. If K is the extinction coefficient (imaginary part of the complex refractive index, $N = n - jK$), and λ is the free space wavelength, ω is the angular frequency ($2\pi\nu$), then

$$\alpha = 2(2\pi/\lambda)K = (2\omega/c)K.$$



Absorption coefficient (α) vs. wavelength (λ) for various semiconductors. (Data selectively collected and combined from various sources.)

If we know the real and imaginary parts of the relative permittivity, $\varepsilon_r = \varepsilon_{r1} - j\varepsilon_{r2}$, of a medium, we can calculate its α by

$$\alpha = \frac{4\pi}{\lambda}\left[\frac{\left(\varepsilon_{r1}^2 + \varepsilon_{r2}^2\right)^{1/2} - \varepsilon_{r1}}{2}\right]^{1/2}.$$

See *cross-section, sum rules*.

Absorption cross section see *cross-section*.

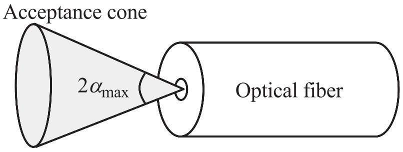
Absorptivity see *emissivity*.

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_0, then the maximum acceptance angle $\alpha_{\max}$ is given by

$$\sin\alpha_{\max} = \frac{\mathrm{NA}}{n_0} = \frac{\left(n_1^2 - n_2^2\right)^{1/2}}{n_0}$$

where n_1 and n_2 are the refractive indices of the core and cladding of the fiber. The 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. See *acceptance angle*.

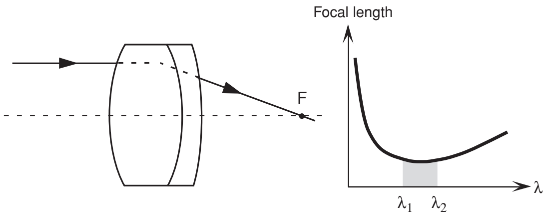


Acceptance cone.

Acceptor atoms are dopants that have one or more 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 a greater hole than electron concentration, $p > n$, and hence to a p-type semiconductor.

Achromatic doublet see *chromatic dispersion*.

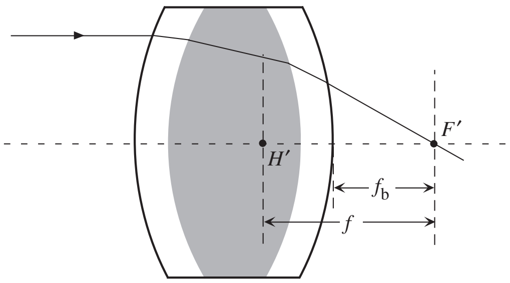
Achromatic lens is a composite lens (made up of two or more closely fitted lenses) so that the combination has its chromatic aberration corrected at least at two different wavelengths. Stated differently, the achromatic lens has the same focal length f at two wavelengths λ_1 and λ_2 ($>\lambda_1$) and its focal length does not vary significantly with the wavelength from λ_1 to λ_2. For example, a positive achromatic lens usually has a positive (convex) low index lens (e.g. crown glass) and a negative (concave) high index lens (e.g. flint glass) cemented together. The combination is a weaker convex lens.



Left: **Achromatic lens** from two lenses. Right: The focal length vs. wavelength behavior.

Achromatic light, see *color*.

Achromatic triplet is a triplet lens that has three lenses to reduce chromatic dispersion. A Steinheim achromatic triplet has a symmetric convex lens of lower refractive index (crown glass) that has higher refractive index (flint) meniscus lenses cemented to its surfaces.



Achromatic triplet f_b is the back focal length measured from the back focal point F' on the lens axis to the lens.

Acoustic velocity see *sound velocity*.

Acoustooptic (AO) 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 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. 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. Depending on the wavelength of the optical (λ) and acoustic waves (Λ), and the length of interaction, there may be a single or multiple diffracted beams. If there are multiple diffracted beams then the AO effect is called *Raman–Nath* diffraction and if there is only the first order, it is referred to as the AO *Bragg diffraction*; the latter is easier to quantify. (See *Raman–Nath diffraction*.) Bragg diffraction occurs at high acoustic frequencies where the acoustic wavelength is short. 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, and 2θ is the diffraction (deflection) angle inside the AO diffraction medium, within the device. The intensity of the diffracted beam depends on the power of the acoustic wave that induces the diffraction grating, and hence on the modulating voltage, a convenient way to modulate the intensity of a light beam. If the AO modulator has an essentially first-order diffracted beam, the first-order diffracted intensity I_1 is usually given by

$$\frac{I_1}{I_0} = \sin^2\left[\frac{\pi}{\lambda}\left(\frac{L}{2H}M_2 P_{\text{acoustic}}\right)^{1/2}\right] \approx \frac{\pi^2 M_2 P_{\text{acoustic}} L}{2\lambda^2 H}$$

where I_0 is the zero-order beam, P_{acoustic} is the power in the acoustic wave, M_2 is a figure of merit for the AO medium (given below), L is the acoustic beam length and H the acoustic beam height or width in a plane parallel to the propagation of incident light.

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

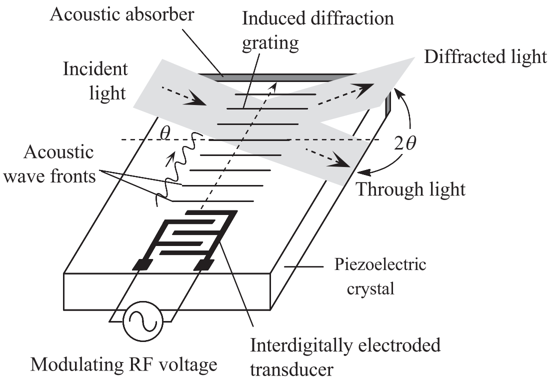
$$\omega' = \omega \pm \Omega.$$

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 acoustic waves. (The diffraction angle is then also changed.)

$LiNbO_3$ is a piezoelectric crystal and hence allows the convenient generation of acoustic waves by the simple placement of interdigital electrodes;

Table: Acoustooptic modulator Figures of merit for various acoustooptic materials. *N* is the refractive index *v* is the acoustic velocity. (From the Brimstone website and others.)

Material	$LiNbO_5$	TeO_2	Ge	InP	GaAs	GaP	Fused quartz	$PbMoO_4$	Flint glass	Chalcogenide glass
λ (μm)	0.6–4.5	0.4–5	2–12	1–1.6	1–11	0.59–10	0.2–4.5	0.4–1.2	0.45–2	1.0–2.2
n	2.2	2.26	4	3.3	3.37	3.31	1.46	2.26	1.8	2.7
(at μm)	(0.633)	(0.633)	(10.6)		(1.15)	(1.15)	(6.3)	(0.633)		
v km s^{-1}	6.6	4.2	5.5	5.1	5.34	6.3	5.96	3.63	3.51	2.52
M_2	7	35	180	80	104	44	1.6	50	8	164



Acoustooptic modulator 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.

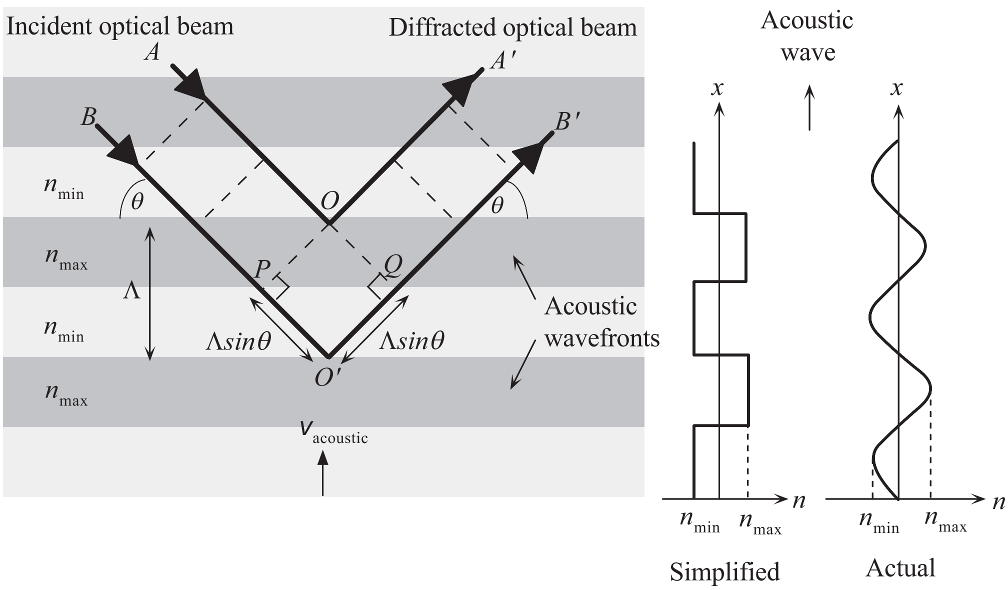
it is used in high-speed IR AO modulators. AO gratings can also be generated in nonpiezoelectric materials because the basic principle is the induction of a diffraction grating by an acoustic wave, which can be coupled into the material from an (external) ultrasonic transducer. The rarefactions and compressions associated with the acoustic wave generates a phase grating by virtue of the photoeleastic effect. For example, germanium is commonly used in various commercially available infrared (2–11 μm) AO devices that deflect light, modulate the light intensity, and shift the optical frequency. AO devices based on other crystals, e.g. TeO_2 (400–1000 nm), GaP (600–1000 nm), $PbMoO_4$ (400–1200 nm) and glasses, e.g. fused silica (240–450 nm), dense flint glass (440–770 nm), chalcogenide glasses (1.2–3 μm), are also available and cover a wide spectral range from UV to IR and implement various AO modulation functions. (Wavelengths in parentheses cover typical useful ranges, and not necessarily the wavelength range of optical transparency.)

The deflection efficiency of an AO modulator depends not only on the material properties such as the efficiency of the optolelastic effect but also on the power in the acoustic wave. One very simple and useful figure of merit M_2 is

$$M_2 = \frac{n^6 p^2}{\rho v^3}$$

where *n* is the refractive index, *p* is the photoelastic constant, ρ is the density and v is the acoustic velocity. The n^6 in the numerator implies that the changes in *n* have the largest effect on the AO modulation efficiency. The modulation speed and hence the bandwidth of an AO is determined by the transit time of the acoustic waves across the light beam waist. If the optical beam has a waist (diameter) *d* in the modulator, then the rise time (in digital modulation) depends on d/v, which is called the transit time across the beam diameter. Reducing v to increase the speed however results in the reduction of diffraction efficiency so there is a compromise between the speed and diffraction efficiency.

(D. Pinnow, *IEEE Journal of Quantum Electronics*, **6**, 223, 1970.)



Acoustooptic modulator 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 one 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 be able to form the product. The probability that a system has an energy equal to the activation energy is proportional to the Boltzmann factor: $\exp(-E_A/k_B T)$, where E_A is the activation energy, k_B is the Boltzmann constant and T is the temperature (Kelvins), or it can be expressed as $\exp(\Delta H/RT)$ where ΔH would be in J mole^{-1}, and R is the gas constant.

Activator see *luminescence*.

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

Active matrix array (AMA) is a two-dimensional array of pixels in which each pixel has a TFT that can be externally addressed to drive a device such as an LED or a liquid crystal cell located at the pixel; or to read a signal from a sensor located at the pixel. Depending on the application, an AMA can have a few pixels or millions of pixels. The TFT AMA technology was pioneered by Peter Brody using CdSe TFTs in the early 1970s. As shown in the figure, each pixel is identical with its TFT gate