Basics of Acousto-Optic Devices

Acousto-Optic Beam Modulators and Deflectors Control Laserbeams in Many Applications

by John Lekavich

Acousto-optics, the interaction of sound waves and light in a transparent medium, has proven an effective means of amplitude-modulating, deflecting, or shifting the optical frequency of laser light.

When a transparent medium is subject to a stress, the optical refractive index of the medium changes. High frequency sound waves, launched into a transparent material via a piezoelectric transducer, will produce a periodic change in the refractive index of the material. In effect, the sound waves produce a grating capable of diffracting incident light. The amount of light diffracted is a function of the power in the acoustic wave.

The seminal work on acousto-optic effects dates back to the 1920s and 1930s. The field came into its own in the 1960s, after the development of the laser.

Types of Operation

Two types of acousto-optic interaction can be described; they are differentiated by the light-sound interaction length L. Operation in the Debye-Sears or Raman-Nath regime occurs when the interaction length $L < \Lambda^2/\lambda$, where Λ is the sound wavelength and λ is the light wavelength in the medium. Here, Λ is analogous to the line spacing of a thin diffraction grating, with the incident light diffracted into many orders. Analysis of this type of interaction shows that the amplitudes of the diffracted beams are described by a series of Bessel functions and are separated by angles of approximately λ/Λ. From diffraction theory, $\sin\theta = \lambda/\Lambda$. But since the angles involved typically range from 1 to 100

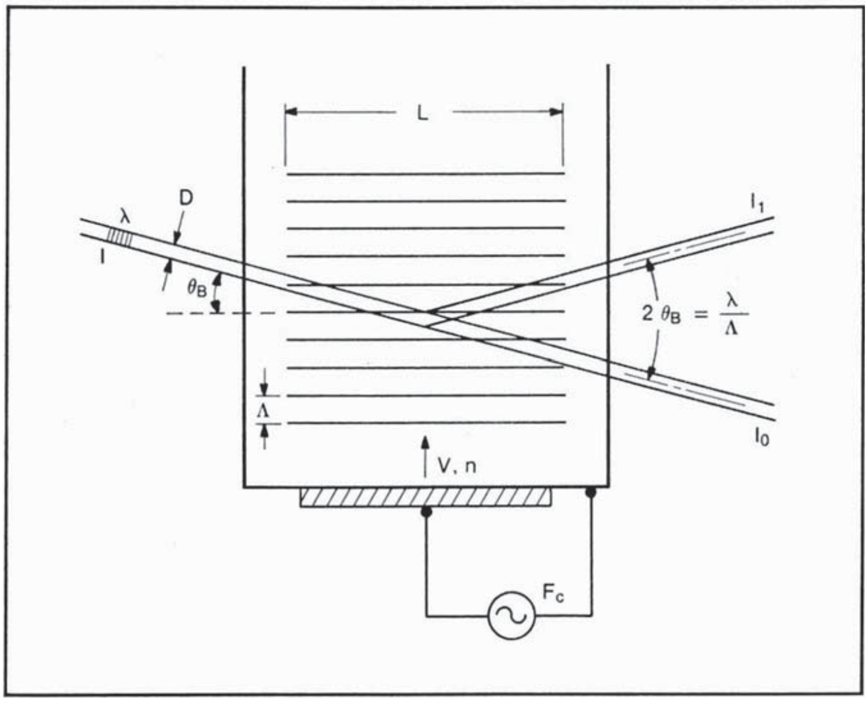

Figure 1. The basic acousto-optic device.

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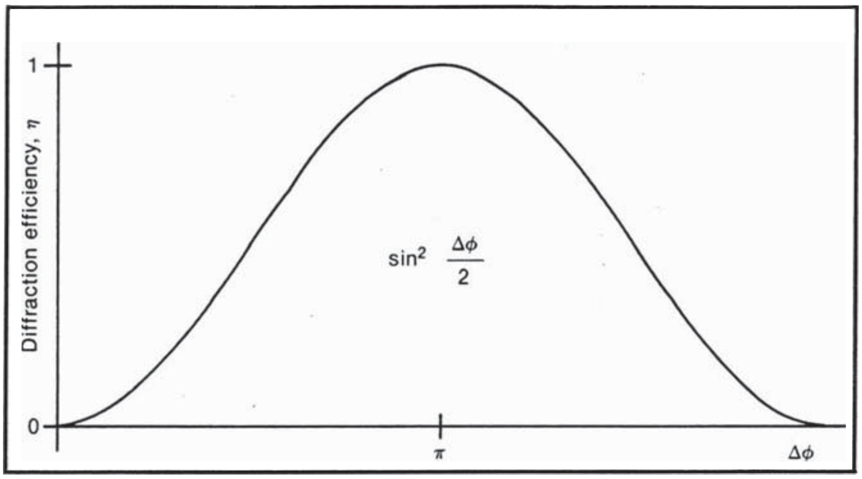


Figure 2. The operating curve for diffraction efficiency, showing that merely increasing acoustic power eventually reduces first-order output and allows light to leak back into the zeroth-order beam.

milliradians, the small angle approximation—$\sin\theta \approx \theta$—is satisfactory for this discussion.

Operation in the Bragg regime occurs if $L > \Lambda^2/\lambda$ *and* the incident laserbeam enters the sound field at an angle of $\lambda/2\Lambda$. In the Bragg regime, most of the light will be diffracted into the first order and will be separated from the small amount of undiffracted or zeroth-order light by an angle of λ/Λ. This occurs when the incident and diffracted laserbeam angles are symmetrical with respect to the acoustic wavefronts. This condition is analogous to Bragg reflection of x-rays by parallel crystal lattice planes; hence, this type of device is known as an acousto-optic Bragg cell. Bragg diffraction is the more useful of the two types of a-o operation and will be treated in detail in the following discussion.

Amplitude Modulation

Figure 1 shows the characteristics of an a-o device. A signal source generates a sinusoidal voltage of frequency F_c across the piezoelectric transducer. The transducer, in turn, produces sound waves of wavelength Λ that travel upward with velocity V in the transparent medium of refractive index n. The acoustic waves produce a three-dimensional phase corrugation in the medium. An incident laserbeam of intensity I, wavelength λ, and diameter D enters the sound field at the Bragg angle, $\theta_B = \lambda/2\Lambda$ and undergoes a cumulative phase excursion $\Delta\phi = kL\Delta n$, where k is the vacuum propagation constant of light, $2\pi/\lambda$, and Δn is the change in refractive index, which is proportional to the sound amplitude. The amount of light I_1 in the first order, separated from the zeroth-order beam I_0 by twice the Bragg angle is given by

$$\eta = I_1/I = \sin^2(\Delta\phi/2). \qquad (1)$$

In Figure 2, we see that the diffraction efficiency, η, is a maximum when $\Delta\phi = \pi$. The phase excursion $\Delta\phi$ is determined by the acoustic power level, material properties, and the geometry of the sound field. For a given light wavelength

$$\Delta\phi = (\pi/\lambda)[2(L/H)M_2P]^{1/2}, \qquad (2)$$

where L/H is the aspect ratio (length to height) of the sound field, M_2 is the material's acousto-optic figure of merit, and P is the acoustic power. Increasing P beyond $\Delta\phi = \pi$ will decrease light in the first order, causing zeroth-order light to reappear.

M_2, determined by the physical constants of the interaction medium, is given by

$$M_2 = n^6p^2/V^2\varrho, \qquad (3)$$

where p is the material's photoelastic constant and ϱ is the material's density. M_2 is a commonly used figure of merit for choosing materials used in modulation applications. Clearly, it is advantageous to choose a material with a high refractive index and low sound velocity. The photoelastic constant, p, is less of a factor because it does not vary significantly for most materials ($0.15 < p < 0.3$). Table 1 gives a comparison of selected materials often found in acousto-optic devices.

Rise time, T_r, is the time interval for light amplitude to go from 10% to 90% of maximum value in response to an acoustic step function. Rise time, for a Gaussian input beam, is given by

$$T_r = 0.64\ D/V = 0.64\ \tau, \qquad (4)$$

where τ is the transit time of the acoustic wave across the laserbeam. To reduce T_r, a material with a high sound velocity should be chosen. However, the choice is limited by previous material considerations and, in practical situations, by existing product design. For a given material and optical wavelength, the simplest means of shortening T_r is reducing the optical beam diameter. This, however, will increase optical divergence:

$$\alpha_d = 4\lambda/\pi D. \qquad (5)$$

A detailed analysis shows that diffraction efficiency, η, for a well-collimated beam is a function of

Table 1 — Comparison of Materials

Material	**Optical Transmission Range** (μm)	**Index of Refraction** (n)	**Density** (ϱ, gm/cm³)	**Velocity** (v, mm/μs)	**M2** (× 10⁻¹⁵ m²/W)
Fused quartz	0.2-4.5	1.46	2.20	5.96	1.56
Dense flint glass	0.4-2.3	1.69	4.20	3.90	9.00
Gallium phosphide	0.6-10	3.31	4.13	6.32	44.60
Germanium	2-20	4.00	5.33	5.50	815.00
Lithium niobate	0.4-4.5	2.20	4.70	6.57	7.00
Lead molybdate	0.42-5.5	2.26	6.95	3.63	50.00
Tellurium dioxide (shear)	0.35-5	2.26	6.00	0.62	793.00
Tellurium dioxide (long.)	0.35-5	2.26	6.00	4.20	34.50

the incident angle θ, is inversely proportional to L, and varies as the far-field diffraction pattern of the acoustic energy inside the interaction medium:

$$\eta\theta = (\sin^2 [\pi L\theta/\Lambda])/[\pi L\theta/\Lambda]^2. \quad (6)$$

Efficient interaction occurs only over a limited range of acceptance angle. ~~To maintain a reasonable peak diffraction efficiency (say, $\eta >$ 70%), the ratio of optical divergence to acoustic divergence ($\alpha_a = \Lambda/L$) should be $\alpha_d/\alpha_a > 2$, as shown in Figure 3.~~ For a given interaction length L, reducing D considerably will decrease diffraction efficiency, because rays on the edge of the optical beam will not interact efficiently with the sound field.

The center or carrier frequency F_c should be high enough to achieve two purposes. First, the fractional transducer bandwidth or total radio-frequency bandwidth ΔF should pass the Fourier spectrum of the applied modulation signal, f_m. For sinusoidal modulation, $\Delta F > 2f_m$. For squarewave modulation, $\Delta F > 2(3/T_p)$, where T_p is the pulse duration. Transducer material coupling factors for lead zirconate-lead titanate and lithium niobate typically produce 50% to 60% fractional bandwidths.

Second, the separation of the zeroth- and first-order diffracted beams must maintain a high dc contrast ratio, where CR is defined as I_{max}/I_{min}. The separation should be greater than twice the beam diffraction spread:

$$(\lambda/V)F_c > 2\ (4\lambda/\pi D) \quad (7)$$

$$F_c > 8/\pi\tau. \quad (8)$$

The frequency response of an a-o modulator can be described by the modulation index or depth of modulation, as

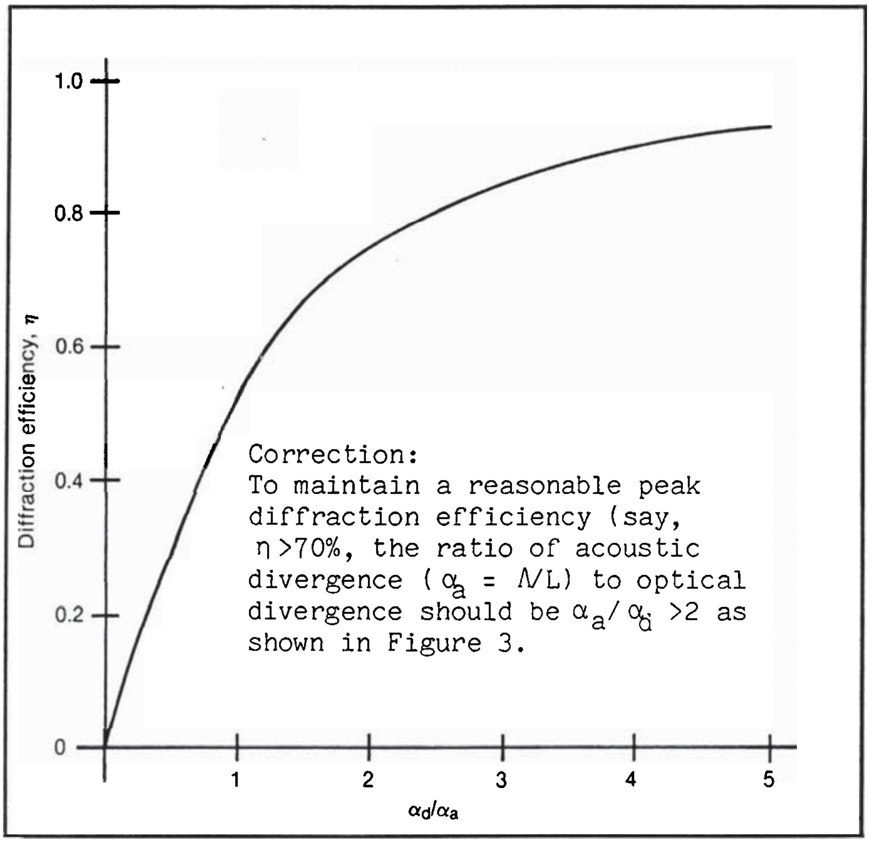
$$M = (I_{max} - I_{min})/(I_{max} + I_{min}). \quad (9)$$

which can be calculated for sinusoidal inputs from the following equation:

$$M = \exp(-\pi^2 f_m{}^2 \tau^2/8). \quad (10)$$

I_{max} and I_{min} are the maximum and minimum light intensity levels in the first-order beam in response to total (100%) modulation of the acoustic carrier.

Figure 4 shows M as a function of normalized frequency, $f_m\tau$. The 50% depth of modulation or −3 decibel bandwidth occurs when $f_m\tau = 0.75$.



Correction:
To maintain a reasonable peak diffraction efficiency (say, $\eta >$70%, the ratio of acoustic divergence ($\alpha_a = \Lambda/L$) to optical divergence should be $\alpha_a/\alpha_d >2$ as shown in Figure 3.

Figure 3. Diffraction efficiency as a function of optical and acoustic divergence.

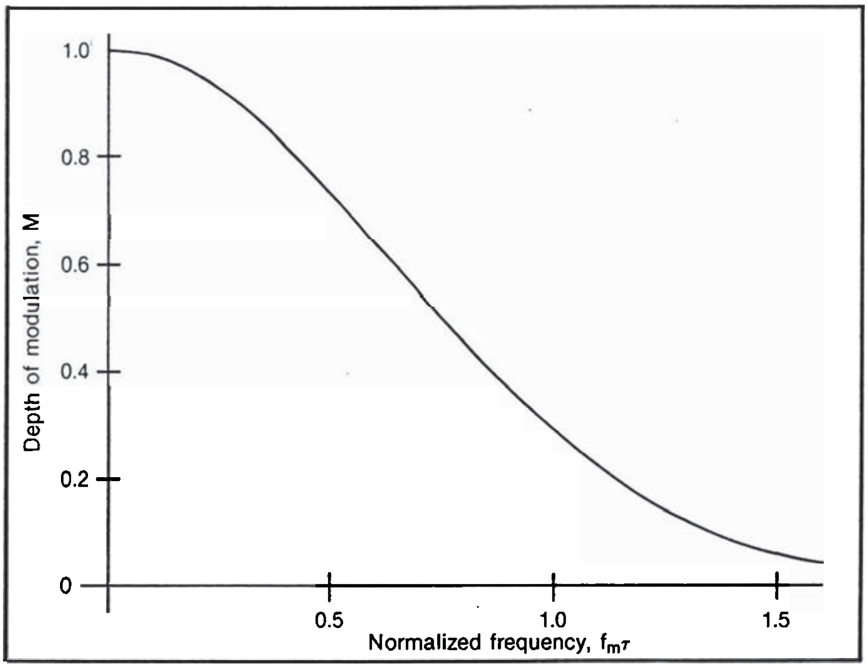


Figure 4. Modulation index as a function of normalized frequency.

The first-order beam is typically used in most modulation applications; at low modulation frequencies, the contrast ratio can exceed 1,000:1. A static optical insertion loss of 0.25% to 4%, values common to devices operating in the visible and near-infrared, is caused by surface reflections and optical absorption. Drive powers in the range of 0.75 to 3 watts are typical for devices working with a helium-neon laser at 632.8 nanometers. First-order diffraction efficiencies up to 90% are easily achieveable. For most modulators, carrier frequencies range from 40 to 500 megahertz, rise times vary from 300 to 4 nanoseconds, and −3 dB modulation bandwidths range from 1.5 to 125 MHz.

The major components of a drive-

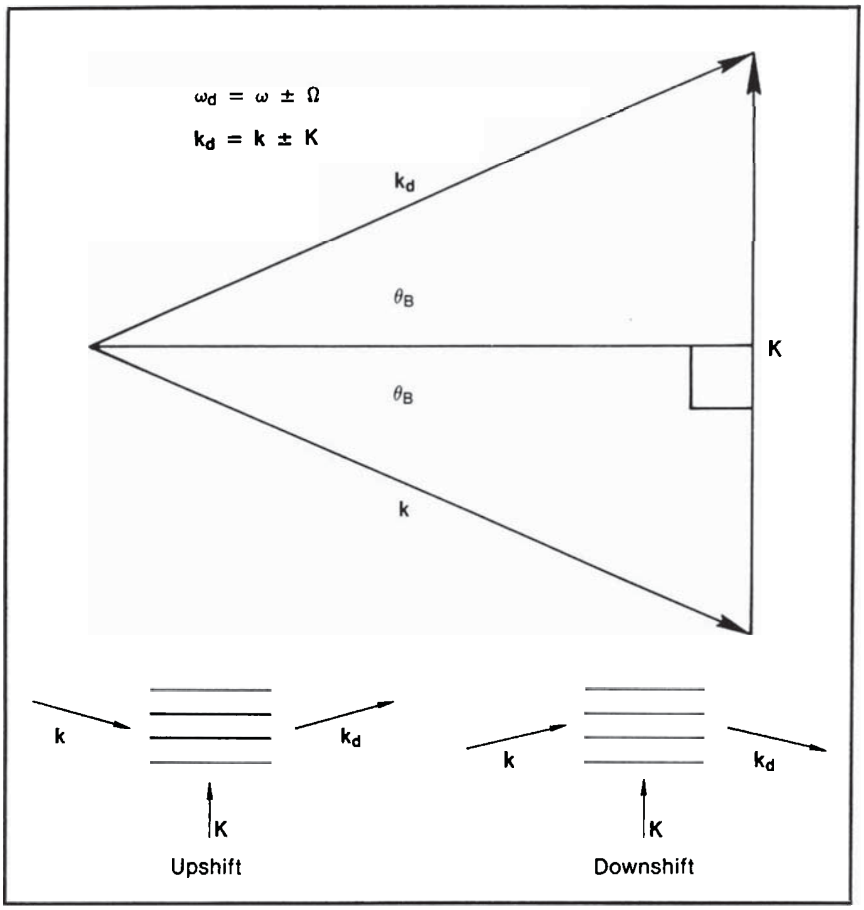


Figure 5. Frequency shifting sums the optical and acoustic wave vectors.

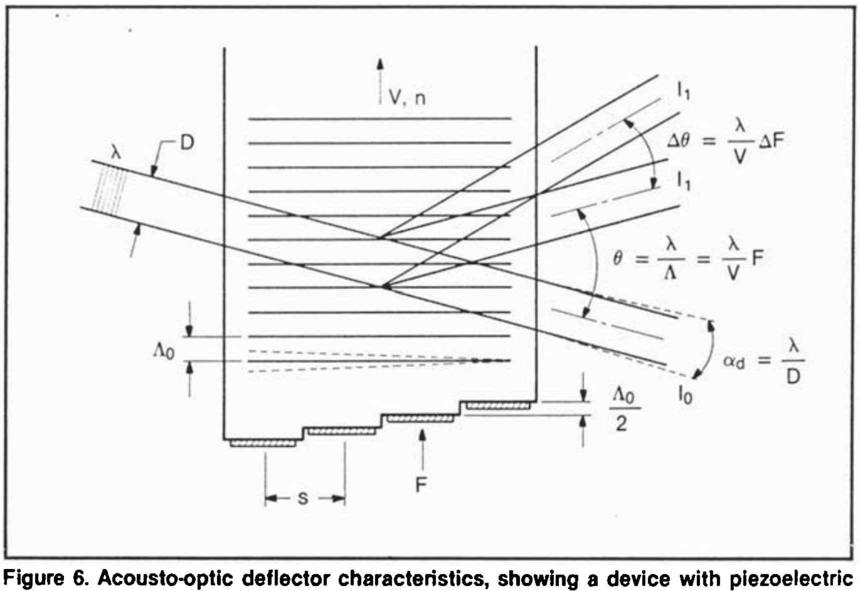


Figure 6. Acousto-optic deflector characteristics, showing a device with piezoelectric transducers sequentially stepped into the mass of the interaction medium to rotate the acoustic wavefronts to maintain diffraction efficiency.

electronics package for an a-o modulator are a low-power oscillator, modulation circuit, and broadband rf power amplifier. Efficient power transfer occurs between the power amplifier and a-o cell when both are designed to work into a 50-ohm system.

Optical Frequency Shifting

Because the acoustic wave travels across the optical beam, the optical frequency undergoes a Doppler shift by an amount equal to the acoustic frequency. The diffraction process or acoustic scattering of light is essentially lossless and can be described by energy-momentum principles. The optical and acoustic waves can be denoted by the wave vectors $\mathbf{k} = \omega/v$ and $\mathbf{K} = \Omega/V$, where ω and Ω are the optical and acoustic angular frequencies and v and V are optical and acoustic velocities in the interaction medium.

The addition of the optic and acoustic wave vectors yields the diffracted light vector. The optical frequency is either upshifted or downshifted by the acoustic frequency, depending on the optical beam propagation direction relative to the sound field propagation direction (Figure 5). All characteristics for efficient Bragg interaction apply. Optical frequency shifting is useful in applications such as optical heterodyning and laser Doppler anemometry.

Q Switching

A Q switch is a laser intracavity loss modulator which controls the gain in the cavity. Acousto-optic Q switches use the undiffracted order; when rf power is turned on, light is diffracted from the zeroth-order beam. This introduces a loss in the cavity, thereby quenching laser oscillation. During this time, energy is stored in the lasing medium; when rf power is turned off, the stored energy is released in a short, high-peak-power pulse.

Q-switch applications require a modulator that can handle the high intracavity circulating power. This requires the use of high-quality, strain-free fused quartz, which has very low optical absorption. In some lower power applications, a glass interaction medium can be used. A quartz Q switch with antireflection coatings can have an optical transmission > 99.5%. Single-pass dynamic losses—when rf power is turned on and diffraction occurs—can be on the order of 40% or more.

Two basic types of a-o Q switches can be constructed; one uses longitudinal-mode sound waves while the other uses shear-mode sound waves. Longitudinal sound velocity is approximately 60% greater than the shear-mode velocity in most materials. Thus, where shorter transit times are needed, longitudinal-mode devices are usually chosen.

Optimum longitudinal-mode diffraction efficiency occurs for optical polarization perpendicular to the direction of sound-wave propagation, requiring 7 dB less drive power than when polarization is parallel to the sound-wave direction. Shear-mode Q switch diffraction efficiency is polarization-insensitive.

With an unpolarized laserbeam,

diffraction efficiencies for both types of Q switches are similar. For a polarized beam, however, optimum longitudinal-mode operation requires approximately 6 dB less drive power than shear-mode operation. Typical drive power required to produce a 40% dynamic loss for a shear-mode Q switch with a 5-millimeter-high sound field is approximately 50 W. Loss modulation specifications are typically given for extracavity operation, because the operating characteristics of intracavity Q switches depend on the specific laser design.

Acousto-optic Q switches are generally used in continuouswave-pumped or low-gain pulsed lasers. The high optical transmission and relatively low dynamic loss of a-o Q switches may be insufficient to quench lasing in high-gain pulse-pumped lasers.

A basic drive-electronics package contains a crystal-controlled oscillator, modulator circuit, power amplifier, and power supply with optional pulse-forming circuitry. Several operating frequencies between 24 and 50 MHz are used. Power amplifiers with output capabilities up to 75 W are available. Most designs are keyed to 50-ohm loads, so efficient power transfer is generally assured. Water cooling is typical, to dissipate the heat generated in the Q switch, although devices operating in the optimum longitudinal mode might not require water cooling.

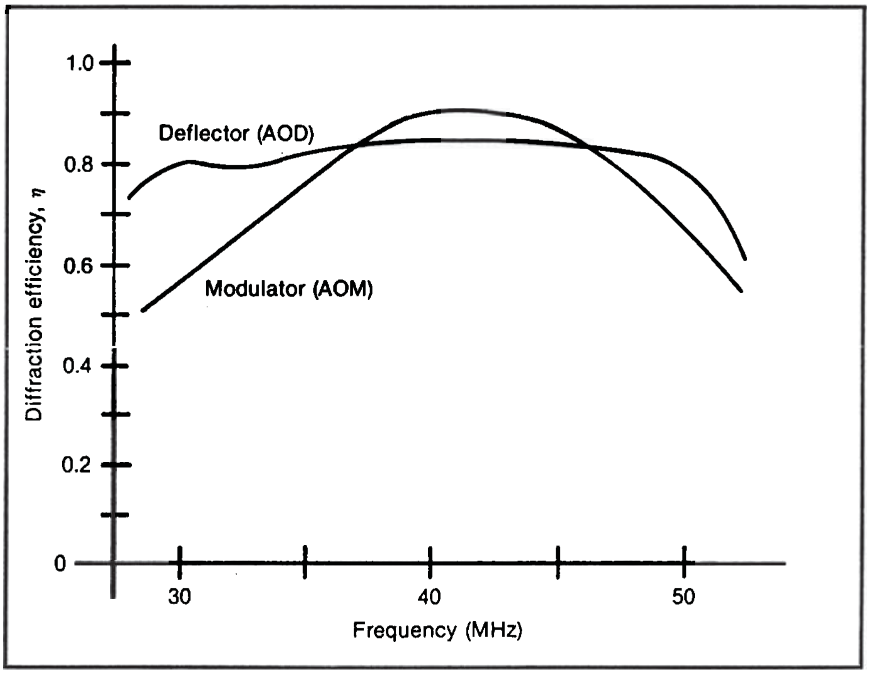


Figure 7. Flat array (acousto-optic modulator) and phased array (acousto-optic deflector) deflection response.

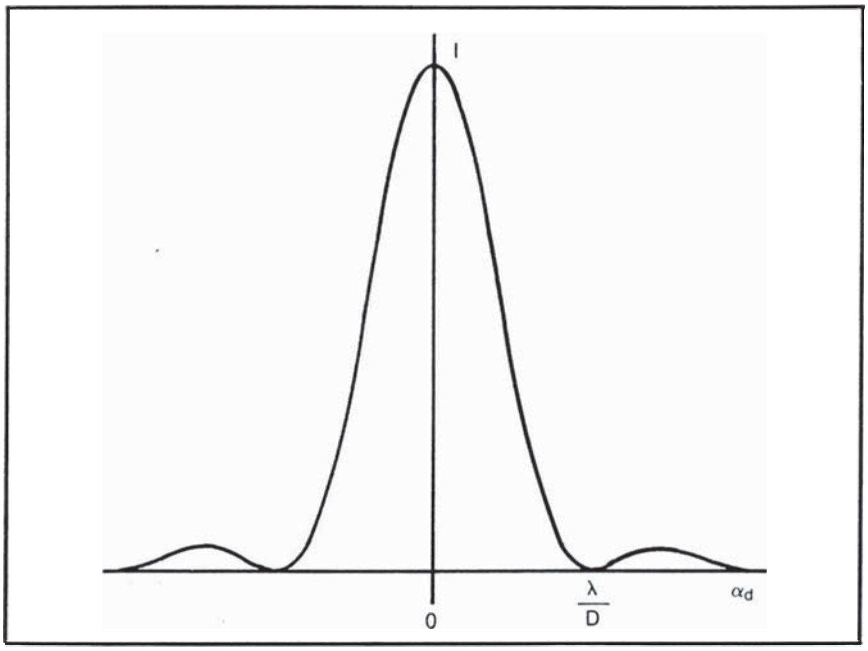


Figure 8. Far-field light intensity pattern. Per the Rayleigh criterion, adjacent intensity patterns are just resolvable if the peak of one falls atop the first minimum of the other.

Deflection

Random deflection or scanning applications require that the light intensity remain constant while a change in the direction of the diffracted beam occurs. Because the angular separation between I_0 and I_1 is proportional to acoustic frequency F, the first-order diffracted beam is deflected through an angle $\Delta\theta = \lambda\Delta F/V$, where ΔF is the incremental change of acoustic frequency (Figure 6). As the angle of I_1 changes, so do the conditions for efficient diffraction; the incident and diffracted beams are no longer symmetrical with respect to the acoustic wavefronts. If the direction of I_1 changes by $\Delta\theta$, then the direction of I should be changed by $\Delta\theta/2$. That would be rather difficult to do in high-speed scanning applications.

A simpler means of maintaining efficient diffraction is available. Incorporating a 180° phase delay between adjacent transducers spaced a distance s ($= \Lambda_0^2 n/\lambda$) apart will produce phased-array acoustic beam steering. This will effectively rotate the acoustic wavefronts to compensate for the change in direction of I_1. The phase delays can be introduced in one of two ways. Mechanically, cutting steps into the interaction medium, each $\Lambda_0/2$ in size (where Λ_0 is the acoustic wavelength at the design center frequency) and driving them in phase will rotate the acoustic wavefronts. Electronically, introducing 180° phase delays to a series of transducers constructed in a flat array will accomplish the same result. Figure 6 depicts the mechanical approach. Figure 7 compares the diffraction efficiency for a nonphased-array a-o modulator and a phased-array a-o deflector as a function of the applied drive frequency.

Deflector resolution N, the number of resolvable elements across the total scan angle, is defined as the maximum deflection angle divided by the diffraction spread of the light beam. This condition occurs when the separation of two adjacent beams is such that the first minimum of the diffraction pattern of one beam coincides with the maximum of the diffraction pattern of the adjacent beam. The first diffraction pattern null for a uniformly illuminated beam occurs at an angle of $\alpha_d = \lambda/D$ (Figure 8).

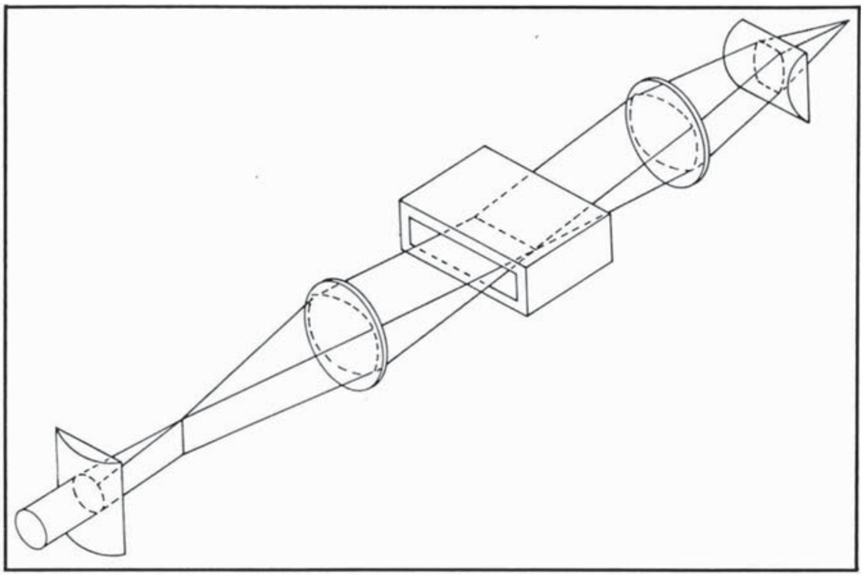


Figure 9. The cylindrical lensing effect in an acousto-optic beam deflector can be compensated with another cylindrical lens downstream of the deflector.

The maximum deflection angle $\Delta\theta_{max} = \theta_T$ is determined by the transducer fractional bandwidth. Resolution is given by

$$\begin{aligned} N &= \theta_T/\alpha_d \\ &= (D/V)\Delta F \\ &= \tau\Delta F. \end{aligned} \qquad (11)$$

Resolution for a nonuniformly illuminated beam is $N = k\tau\Delta F$, where k depends on the optical beam truncation ratio and is approximately 0.85 for a Gaussian laserbeam.

Note that resolution is independent of light wavelength; it is a function of the transit time of the acoustic waves across the laserbeam and the transducer bandwidth. Because rf bandwidth is limited by transducer coupling factors and fabrication techniques, it appears that D should be made as large as possible. However, acoustic attenuation, optics size constraints, and scanning speed requirements limit τ to a practical value of about 10 microseconds and D to approximately 35 to 55 mm. Note that τ is the time taken to fill or clear the optical aperture of sound. Therefore, τ limits the spot position access time in a random-access application or the retrace time in a linear repetitive scanning application.

The transit time for tellurium dioxide (Table 1) working in the slow shear-wave mode can be relatively long compared to other materials, thereby producing a correspondingly higher resolution. The slow velocity can limit random access or scanning time but can be useful for optical signal processing applications that require a large time-bandwidth product ($\tau\Delta F$).

In linear scanning applications, a frequency gradient of θ_T/T is produced across the optical aperture. The gradient acts like a cylindrical lens of fixed focal length ($fl = VT/\theta_T$), either converging or diverging the diffracted light beam, depending on the sweep direction. If total scan time T is short, the cylindrical lens effect will preclude bidirectional scanning. The effect can be compensated in a unidirectional scanning system by adjusting the cylinder optics in the anamorphic optical system used to expand the light beam to diameter D (Figure 9). In a linear scanning application for a television or video display system where λ is 633 nm and T is 54 μs, an a-o deflector with $V = 4$ kilometers per second and $\Delta F = 100$ MHz would produce a cylinder lens with an effective focal length of 13.6 meters. If $T < \tau$, a frequency chirp signal travels across the optical aperture, producing a scanning beam focused at a moderate distance. Chirp deflectors can be used in signal correlation applications.

A deflector drive-electronics package contains a low-power voltage-controlled oscillator (VCO) and a broadband rf power amplifier. Because beam position is a function of frequency, deflection linearity is a function of the VCO linearity. As with other types of a-o devices, most designs are keyed to 50-ohm loads.

Summary

Acousto-optic modulators, Q switches, and deflectors have found wide use in laser applications as diverse as reprographics and spectroscopy. The operating characteristics of competitive products can be compared readily, giving system architects design flexibility. □