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Optical Elements for Spectroscopy

Chieu D. Tran
Department of Chemistry
Marquette University
Milwaukee, WI 53233

Reprinted from Analytical Chemistry 1992, 64, 971 A–981 A.
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Seventy years ago, Brillouin theorized that light could be diffracted by an acoustic wave (1). This prediction was based on the fact that when an acoustic wave is propagated in a transparent material, it produces a periodic modulation of the index of refraction. The perturbation in the refractive index arises from the change in the number density of the acoustic medium induced by the compression and rarefaction of the traveling sound wave. As a consequence, the propagating acoustic wave produces a moving grating that will diffract portions of an incident light beam.

This sound–light interaction phenomenon, which is called the acousto-optic interaction, was initially observed by Debye and Sears in 1932 (2). Early studies were limited to interactions of low-frequency acoustic waves with incoherent light sources in liquids and gases. As a result, the phenomenon had an impact primarily on the academic community; experimental results provided a basic understanding of the thermal and acoustic properties of liquids and gases.

The first applications of the acousto-optic interaction did not appear until the 1960s. Since then, significant scientific and technological advances have occurred in optics, electronics, and materials chemistry.

Instrumentation

The advent of the laser, the development of new piezoelectric materials with high coupling factors that facilitate high-frequency (GHz) acoustic techniques, and the development of new crystals that have low acoustic loss at high frequencies and require low radio frequency (rf) drive power made it possible to realize practical applications of acousto-optic devices for the deflection, temporal and amplitude modulation, and spectral tuning of light. Today, acousto-optic devices are used in applications ranging from sophisticated scientific instruments such as astronomical spectrophotometers and picosecond laser systems to the commonplace neighborhood supermarket scanner.

Diffraction by acoustic waves may lead to a change in the amplitude, frequency, direction, or wavelength of the incident light. Optical properties of the medium where the acousto-optic interaction occurs usually dictate the type of transformation of the diffracted light. Acousto-optic interactions, when observed in an optical isotropic medium, lead to a change in the frequency, direction, and amplitude of the light. The diffraction in this case can be explained by using the classical Bragg diffraction principle. Acousto-optic devices...
such as light modulators, deflectors, scanners, and mode lockers are based on this type of interaction.

Interesting results are observed when acousto-optic interactions occur in an anisotropic medium. This type of interaction leads to a change not only in the frequency and direction of the incident beam but also in its wavelength. Here the diffraction process cannot be explained by the normal Bragg diffraction principle. This so-called abnormal Bragg diffraction process has been successfully exploited to develop devices such as the acousto-optic tunable filter (AOTF). The AOTF is a compact, solid-state monochromator that can be tuned electronically in a matter of microseconds over a wide spectral range encompassing the UV and IR regions. This device has been called the “new generation monochromator” and provides a unique means for the development of spectroscopic instruments.

In this INSTRUMENTATION article the theory of isotropic and anisotropic acousto-optic diffraction will be described. Emphasis will be placed on the principles and applications of specific devices such as light deflectors, mode lockers, and AOTFs.

**Acousto-optic interactions in an optical isotropic medium**

**Theory.** The diffraction of a light beam by an acoustic wave can be explained in terms of wave interactions or particle collisions. In the former case, the acoustic wave produces a change in the refractive index of the medium and generates a traveling pressure disturbance that includes regions of compression and rarefaction in the crystal. This effect can be considered as generating a diffraction grating that moves at the speed of sound and comprises periodic changes in the optic phase.

The diffraction process can be explained by the optical wavefronts illustrated in Figure 1. Because the velocity of light is about 5 orders of magnitude greater than the velocity of sound, the acoustic wave is considered to be stationary during the time required for the optical beam to travel through the crystal. Suppose that the half-wavelength region labeled \( n + \Delta n \) is under compression, and the region labeled \( n - \Delta n \) is under rarefaction. The portion of the optical wave passing through the compression will be slowed (relative to the undisturbed material of index \( n \)), whereas the portion passing through the rarefaction will be accelerated. The emerging optical wavefront will be “corrupted” and, if the corrugations are joined by a continuous plane, its direction will be tilted relative to that of the incident wavefronts.

Depending on the interaction length \( l \) between the acoustic wave and the light wave, the diffraction process can be divided into two different types: Raman–Nath diffraction (sometimes called Debye–Sears diffraction) and Bragg diffraction. The diffraction is in the Raman–Nath region when the interaction length \( l \) is relatively short or when the Raman–Nath parameter \( Q \), defined as

\[
Q = 4f \lambda / \lambda^2
\]

(where \( \lambda \) and \( \Lambda \) are the wavelength of the optical wave and the sound wave, respectively), is less than one \((3-5)\). The diffraction process (Figure 2a) has multiple orders, because the interaction length is relatively short and can be approximated as a thin grating (i.e., the diffraction spreading of the light between adjacent compression and rarefaction regions overlaps).

When the interaction length \( l \) is large (or when \( Q \gg 1 \)), the diffraction is in the Bragg region \((3-5)\). In this case, only first-order diffraction is observed (Figure 2b). Because the thin grating approximation is no longer valid, higher diffraction orders will undergo complete destructive interference if the incident light beam is normal to the sound beam. For constructive interference to take place, the angle of incidence must be tilted with respect to the acoustic beam direction.

Consider the collisions of photons and phonons, as shown by Yariv \((5)\). From a quantum theoretical point of view, the interaction of sound and light can be treated as a collision of photons and phonons. The incident light beam with a wave vector \( \mathbf{k} \), and the frequency \( \omega_0 \), can be considered as consisting of a stream of particles (photons) with momentum \( h\mathbf{k} \), and energy \( h\omega_0 \). Similarly, the sound wave can be thought of as particles (phonons) with momentum \( h\mathbf{k}_a \) and energy \( h\omega_0 \).

As illustrated in Figures 2b and 2c, the diffraction of light by the acoustic beam involves a series of collisions, each consisting of the annihilation of one incident photon at frequency \( \omega_0 \) and one phonon \( (\omega_0) \) as well as the simultaneous creation of a new (diffracted) photon at a frequency \( \omega_0 \). For these collisions to occur, conservation of energy and momentum must be observed. Conservation of momentum requires that the momentum \( h(\mathbf{k} + \mathbf{k}_a) \) of the colliding particles be equal to the momentum \( h\mathbf{k}_d \) of the diffracted photon. Therefore

\[
\mathbf{k}_d = \mathbf{k} + \mathbf{k}_a
\]  

Conservation of energy dictates that

\[
\omega_0 = \omega_d \pm \omega_a
\]

It is evident from Equation 3 that the diffracted beam is shifted in frequency by an amount equal to the sound frequency. These relationships facilitate the use of propagation of the applied acoustic wave to either increase or decrease the frequency of the diffracted beam by an amount equal to \( \omega_0 \). Figure 2b illustrates the upshift case in which the conservation of energy requires addition of the phonon energy to that of the annihilated (incident) photon to form a new (diffracted) photon. As a consequence, \( \omega_0 = \omega_d + \omega_a \). If the direction of the sound wave in Figure 2b is reversed (as shown in Figure 2c), the diffraction process is the one in which a new (diffracted) photon and a new phonon are generated while the incident photon is annihilated. In this case, conservation of energy yields

\[
\omega_d = \omega_a - \omega_0
\]

This process is generally known as downshift Bragg diffraction. Because the energy of the acoustic waves is much smaller than that of the photons, \( \mathbf{k}_a = \mathbf{k}_a \) may be assumed. The momentum-matching triangle is isosceles; thus, the incident and diffracted angles are the same \((\theta = \theta_0)\) and are related to the wavelength of

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**Figure 1.** Diffraction of optical wavefronts by an acoustic wave.
the light \( \lambda \) and of the sound \( \Lambda \) by the well-known Bragg equation

\[
\sin \theta = k_\lambda / 2k_d = \lambda / 2\Lambda
\]

\[\text{(5)}\]

**Applications**

**Deflectors.** Acousto-optic deflectors are based on the deflection of light by a propagating acoustic wave in an optical isotropic medium. Incident light is deflected in one or more directions by periodic variations in the refractive index produced by the propagating ultrasound wave. A change in the deflection angle (defined as the angle between the transmitted and the diffracted beam) is achieved by changing the applied acoustic frequency. This change can be accomplished only if the operation is near the Bragg diffraction condition (i.e., the laser beam is oriented at the Bragg angle of incidence \( \theta \) in relation to the acoustic beam of frequency \( \omega_0 \)). Because the Bragg condition is satisfied, diffraction is optimized and the momentum vector diagram shown in Figure 3 is closed. After being diffracted by the sound wave, all light rays emerge in phase at an angle \( \theta \) and interfere constructively.

The sound frequency is then varied from \( f_0 \) to \( f_0 + \Delta f_0 \) while the incident angle is kept constant at \( \theta \). Because \( k_\lambda = 2\pi f_0/v_e \) (where \( v_e \) is the acoustic velocity), this frequency variation causes a change \( \Delta k_\lambda = 2\pi \Delta f_0/v_e \) in the magnitude of the sound wave vector, as shown in Figure 3. To satisfy the conservation of momentum, all diffracted wave vectors must lie on the circle through \( A \) and \( B \), with \( O \) as the center. Because the incident angle \( \theta \) and the magnitude of the diffracted wave vector remain unchanged, the tip of the diffracted wave vector, as previously explained, must lie on the circle. The momentum diagram cannot be closed, and the momentum therefore is not strictly conserved. The beam will diffract in the direction that gives the least violation (i.e., along the direction \( OB \)), causing a change of \( \Delta \theta \) in the diffraction angle. The value of \( \Delta \theta \) is calculated from the figure as

\[
\Delta \theta = \Delta k_\lambda/k_\lambda = \lambda \Delta f_0/v_e
\]

\[\text{(6)}\]

Thus the deflection angle is proportional to the change of the sound frequency.

Another important parameter is the number of resolvable spots \( N \) or the factor by which \( \Delta \theta \) exceeds the beam divergence angle. If the deflection angle \( \theta_{def} \) is assumed to be \( \lambda/N D \) where \( D \) is the beam diameter, the number of resolvable spots is

\[
N = \theta_{def} = (\lambda/v_e) \Delta f_0/(\lambda/D) = \Delta f_0 (D/v_e) = \Delta f_0 \tau
\]

\[\text{(7)}\]

where \( \tau = D/v_e \) is the time it takes the sound to cross the optical beam diameter.

It is evident from Equations 6 and 7 that materials with low acoustic velocity \( v_e \) will provide a large angle of deflection and a large number of resolvable spots. However, such materials cannot be used in high-speed operation and in the high-frequency region because they have high acoustic attenuation. Usually, a compromise must be made in designing such devices. This type of acousto-optic device has been used not only as a deflector but also as an optical scanner, an intracavity Q switch, and a cavity dumper (6–8).
Modulators and mode lockers. In addition to modulating direction and frequency as in the deflector, an acousto-optic device can be used to modulate the diffracted beam amplitude. Two types of modulators are possible, depending on whether the applied acoustic wave is a propagating wave or a standing wave.

When the applied acoustic wave is a propagating wave, the modulator consists of a combination of an acousto-optic deflector and a spatial filter, a device with a lens and a pinhole. The filter is aligned so that it will reject the deflected beam and pass the undeflected beam. The deflected beam will be turned on and off as the wave propagates across the crystal, and the amplitude of the beam emerging from the spatial filter will be modulated (3, 4).

The second type of modulator is different from other acousto-optic devices in that it has no dampers to absorb the propagating acoustic wave. Thus the acoustic wave generated by the transducer will be reflected by the opposite face of the crystal. Interference between the propagating and the reflected waves produces standing waves inside the crystal. The diffraction of light by standing waves produces some interesting phenomena, notably the locking of the longitudinal modes of the laser or mode locking (5).

A mode locker is an acousto-optic modulator placed inside a laser cavity. An acousto standing wave is produced inside the modulator when an rf signal is applied to the transducer through the transducer. According to Bragg diffraction, the modulator will introduce a periodic loss into the laser cavity at twice the frequency of the acoustic standing wave. As a consequence of the loss, the energy inside the cavity decreases. If all the losses are in standing pulses, these compressed pulses must travel at the same frequency and in phase (i.e., the longitudinal modes have to be locked together) to produce a very short output pulse.

To mode lock a laser, the frequency of the modulator must be in synchronization with the traveling time of the compressed pulse inside the cavity. To make a round trip in the laser cavity, a pulse requires a time of 2L/c (where L is the cavity length and c is the speed of light). Thus the frequency of the standing wave inside the modulator must be c/2L if mode locking is to be achieved. This condition enables the modulator (the mode locker) to act as a very fast shutter that is in synchronization with the pulse. It will open only once per round-trip transit time to allow passage of the pulse; the shutter is closed at all other times, and the only light that can circulate between the output coupler and the high reflector is the mode-locked pulse. Because this pulse experiences minimum loss and maximum gain, it will be amplified. Light traveling in the cavity when the mode locker is closed will be attenuated and cannot reach threshold.

The output of a mode-locked laser is, therefore, a train of very short pulses. The time separation between pulses is the time it takes for each pulse to make one round trip inside the cavity, 2L/c, and the frequency of the mode-locked pulses is therefore c/2L. For example, a laser that has a distance of 30 cm between the high reflector and the output coupler will produce a mode-locked pulse train at 500 MHz.

Acousto-optic interactions in an optical anisotropic medium

Theory. For acousto-optic diffraction to occur in an isotropic medium, the phonon vector is normal to the bisector of k₀ and k₁ and

$$[kₐ] = [k₁] \quad (8)$$

Because [kₐ] = 2πn₀/λ and [k₁] = 2πn₁/λ, Equation 8 is valid only when the refractive index for the incident and diffracted waves is identical (i.e., n₁ = nₐ). However, this is not true when the light is diffracted by shear acoustic waves in an optical anisotropic medium. In a shear acoustic wave, the displacement of matter is perpendicular to the direction of its propagation. A light beam propagating as an extraordinary ray (e-ray) is converted into an ordinary ray (o-ray) by interaction with and diffraction from the shear acoustic wave propagating in the same medium. This 90° rotation of the polarization stems from the fact that the disturbance caused by the shear wave induces a birefringence that acts on the incident light as a birefringent plate (3, 4, 9, 10). Thus the plane of polarization of light is rotated. Because the crystal is birefringent, the rotation of the plane of polarization results in a significant change in refractive index (n₁ ≠ nₐ), and a change in momentum and wavelength must occur.

The associated momentum vector diagram is no longer symmetric as it was in Figures 2b and 2c. Instead, it appears as shown in Figures 4a and 4b, where θₐ may be significantly different from θ. The same effect also occurs in isotropic crystals. However, in isotropic materials, the wavevector for the incident and diffracted beams is the same (because n₁ = nₐ); thus, there is no effect on the diffraction processes (3, 4, 9, 10).

Consider Figure 4, where the incident light is an e-ray and the diffracted light is an o-ray. The associated wavevectors are

$$k₁ = (2πn₁/λ)$$ and $$kₐ = (2πnₐ/λ)$$

As expected, θ₁ = θₐ. The angles θ₁ and θₐ are related (10) to the acoustic frequency fₐ, the refractive indices for the incident and diffracted light polarizations n₁ and nₐ, and the acoustic velocity vₐ by

$$\sin θ₁ = \left( \frac{1}{2n₁} \right) \left( \frac{λₐ}{λₐ} \right) \times \left[ 1 + \left( \frac{vₐ}{λₐ} \right)^2 \left( n₁^2 - nₐ^2 \right) \right]$$

(10)

and

$$\sin θₐ = \left( \frac{1}{2nₐ} \right) \left( \frac{λₐ}{λₐ} \right) \times \left[ 1 + \left( \frac{vₐ}{λₐ} \right)^2 \left( n₁^2 - nₐ^2 \right) \right]$$

(11)

In Figure 5, θ₁ and θₐ are plotted against the acoustic frequency for paratellurite (TeO₂) at λ = 632.8 nm, n₁ = 2.45, nₐ = 2.26, and vₐ = 6.17 × 10⁴ cm/s. The minimum frequency at which an interaction may occur corresponds to θ₁ = 90° and θₐ = -90°. At
these angles, the three wavevectors $k_i$, $k_o$, and $k_d$ are collinear, as shown in Figure 4a, and the conservation of momentum can be written as

$$|k_i| + |k_o| = |k_d|$$  \hspace{1cm} (12)

The frequency for which collinear diffraction takes place is

$$f_a = \left[ v_s (n_i - n_d) / \lambda_o \right]$$  \hspace{1cm} (13)

Because of this collinearity, the interaction between the incident and acoustic waves is relatively long and the bandwidth of the diffracted light is narrow (high resolution). The acceptance angle is relatively large: When the incident wavevector changes from $k_i$ to $k_i'$, the diffracted wavevector becomes $k_o'$ and the momentum matching condition is still approximately maintained ($k_d' = k_o' + k_i'$; see Figure 4a).

If the incident light were an o-ray rather than an e-ray, the direction of the acoustic wave in Figure 4a would be reversed. In fact, the roles of the two curves in Figure 5 would be reversed by interchanging $n_i$ and $n_d$.

Collinear acoustic diffraction can only be achieved in a uniaxial crystal where the incident and diffracted light are normal to the optical axis of the crystal. Because of the symmetry of crystals, it is sometimes not possible to have this type of interaction. The common type of interaction is noncollinear, as shown in Figure 4b, where the incident and diffracted wavevectors and the acoustic wavevector are not collinear. To satisfy the momentum-matching condition, it is necessary to select the acoustic wavevector so that the tangents to the incident and diffracted wavevector loci are parallel. Figure 4b shows the incident e-beam (whose wavevector is $k_i'$) diffracted by the acoustic wave (the acoustic wave vector $k_o'$) to a diffracted o-beam (whose wavevector is $k_d'$). The two optical beams do not separate until they exit the crystal, at which time the diffracted beam is separated from the transmitted beam (i.e., the zero-order diffracted beam). This separation facilitates isolation of the diffracted beam by an aperture (9, 10).

The relationship between the acoustic frequency $f_a$ and the incident angle $\theta$ is given by

$$f_a = \left[ v_s (n_i - n_d) \right] (1/\lambda_o) (\sin^2 \theta_1 + \sin^2 2\theta_0)$$  \hspace{1cm} (14)

When $\theta_1 = 90^\circ$, Equation 14 reduces to Equation 13, the collinear case.

In an anisotropic crystal in which the phase-matching requirement is satisfied, diffraction occurs only under optimal conditions. These conditions are defined by the frequency of the acoustic waves and the type of crystal. For a particular crystal and a particular acoustic frequency $f_a$, only light whose wavelength satisfies either Equation 13 or 14 is diffracted from the crystal. The crystal can, therefore, be spectrally tuned by changing the frequency of the acoustic wave.

The acousto-optic interaction in an anisotropic medium has led to the development of AOTFs (9, 11–19). As indicated previously, an AOTF is an electronically driven optical dispersion device capable of performing spectral analysis of optical signals. It is constructed from a birefringent crystal, such as quartz or TeO$_2$, onto which an array of piezoelectric transducers (e.g., LiNbO$_3$, LiTaO$_3$, LiIO$_3$) is bonded. When an rf signal is applied to the transducer, acoustic waves are generated in the crystal. The propagating acoustic waves produce a periodic moving grating that will diffract a portion of the incident beam. For a fixed acoustic frequency and sufficiently long interaction length, only a very narrow band of optical frequencies can approximately satisfy the phase-matching conditions necessary for diffraction.

The narrow spectral bandwidth of the filter can thus be tuned over large optical regions simply by changing the frequency of the applied rf signal.

Based on the configuration of the optical and acoustic wavevectors, the AOTFs can be divided into two different types: collinear and noncollinear (9, 11–19). In collinear AOTFs, the acoustic wave is brought in as a longitudinal wave, which is then converted to a shear wave upon reflection at the input face of the crystal (Figure 6a). The acoustic wave and the input optical beam then propagate collinearly down the crystal, along which the acousto-optic interaction occurs. The diffracted wave, whose polarization is orthogonal to that of the incident beam, also propagates down the crystal collinearly with the incident beam and the acoustic wave. The transmitted (or zero-order diffraction) and diffracted beams also emerge collinearly from the AOTF. Because polarization of the diffracted beam is orthogonal to that of the transmitted beam, it is separated from the latter not by a pinhole but rather by a polarizer (Figure 6a). The interaction length between the incident wave and the acoustic wave is relatively long in this type of filter. AOTFs fabricated from birefringent crystals that have relatively small acoustic figures of merit (e.g., quartz and MgF$_2$) are often of the collinear type.

As explained in the previous section, it is sometimes impossible to construct collinear AOTFs because of crystal structure. Noncollinear AOTFs have been reported. Figures 6b and 6c illustrate the case where

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**Figure 5.** Angles of (extraordinary) incident ($\theta_1$) and (ordinary) diffraction ($\theta_d$) as a function of acoustic frequency for diffraction of 532.8-nm light by an acoustic wave in an anisotropic crystal (TeO$_2$) with $n_i = 2.45$, $n_d = 2.26$ and acoustic velocity of $6.17 \times 10^4$ cm/s.
the incident, diffracted, and acoustic waves are noncollinear. In Figure 6b, the acoustic wave diffracts the vertically polarized incident beam into a horizontally polarized beam. Because the transmitted and diffracted beams are well separated, the latter can be readily isolated by an aperture. Because of the birefringence of the crystal and the noncollinearity of the transmitted and diffracted beams, an incident horizontal polarized light beam will be diffracted into a vertical polarized light beam, and an incident unpolarized light beam will be diffracted into two beams that have orthogonal (vertical and horizontal) polarization propagated in different directions (see, e.g., Figure 6c). AOTFs of this type are often reserved for crystals that have relatively high acoustooptic figures of merit, such as TeO$_2$ (9, 11–19).

A typical spectral profile of diffracted light as a function of the applied rf for a nonlinear TeO$_2$ AOTF is shown in Figure 7 (12). The incident light in this case is a multiline argon ion laser beam that was a mixture of six different wavelengths: 514.5, 501.7, 496.5, 488.0, 476.5, and 457.9 nm. As indicated in Equation 14, the wavelength of the diffracted light depends on the frequency of the applied rf signal. Light with relatively shorter wavelengths will be diffracted from the AOTF when the filter is applied with a higher rf signal. For example, 514.5-nm light is diffracted when a 64.3115-MHz rf signal is applied to the AOTF. Increasing the frequency to 75.8522 MHz changes its wavelength to 457.9 nm.

As illustrated, the intensity of the diffracted light is very sensitive to the frequency of the applied rf signal. A very small change in the frequency may result in a large change in the intensity of the diffracted light (12). The power of the applied rf signal also affects the intensity of the diffracted light, $I$, because it is a function of the acoustic power density $P_a$, and $I$ is given by (9, 10)

$$I = I_0 \sin^2 \left( \Delta k l / 2 \right)$$

where $\Delta k$ is the wavevector mismatch, $l$ is the interaction length between the acoustic and the optical beams; and $I_0$ is defined as $I_0 = \sin^2 (\pi \Delta \omega / \Delta \omega_0)$. $I_0$ is a function of an acoustic power density $P_a$, the acoustooptic figure of merit $M_a$, and the interaction length $l$, and is given by

$$I_0 = \sin^2 (\pi M_a P_a l^2 / 2 \Delta \omega^2)$$

Figure 8 shows the intensity of the light diffracted by the TeO$_2$ AOTF plotted in three dimensions against the frequency and the acoustic power of the applied rf signal (20). The intensity of the diffracted light can be controlled by controlling either the frequency or the power of the applied rf signal.

Other characteristics of the AOTF include its resolution, spectral tuning range, and response time. The filter resolution, defined as the full width at half maximum, is given by

$$\Delta \lambda = \lambda_0^2 / 2 \Delta \lambda_0 \sin^2 \theta_1$$

where $\Delta \lambda = \lambda_2 - \lambda_0$ and $\lambda_0$ is the wavelength of observation (9). The resolution of a nonlinear TeO$_2$ AOTF with $l = 1$ cm and $\Delta \lambda = 2.45 - 2.26 = 0.19$ is calculated as 3$\Delta \lambda$ at 632.8 nm (3). It is evident from Equation 17 that the AOTF resolution is dependent on the wavelength. The resolution is higher at shorter wavelengths and becomes degraded as the wavelength increases. Other factors such as increasing the interaction length $l$ can also be exploited to enhance the resolution. For a particular AOTF, $l$ can be increased by increasing the number of acoustic waves in the optical aperture of the crystal. To achieve good performance, the acoustic frequency should be high and the aperture should be large. Finite aperture and attenuation of the acoustic waves at high frequencies (through absorption by the AOTF) determine the final resolution. AOTFs with resolutions of a few angstroms are commercially available from Brimrose Corp. (Baltimore, MD) and Matsushita Electronic Components (Kodama, Osaka, Japan).

Important criteria for selecting birefringent materials for AOTFs include the acoustooptic figure of merit $M_a$ and the high-frequency acoustic loss. According to Equation 16, materials with high $M_a$ values will provide diffracted light with higher intensity. Higher resolution AOTFs will be achieved when the filter is constructed from material that can tolerate acoustic waves with higher frequency (i.e., low absorption loss). A relatively large number of materials with the required transmission range and optical quality are available.

Quartz is used to construct collinear AOTFs that operate over the 240–400-nm wavelength region (13), MgF$_2$ is used for nonlinear AOTFs for the 200–700-nm region (21), CaMoO$_4$ for collinear AOTFs for the 510–670-nm region (22), TeO$_2$ for nonlinear AOTFs for the visible range from 370 nm to the IR region of 4.5 $\mu$m (12, 14–20, 23), and Tl$_3$AsS$_6$ for nonlinear AOTFs for 1.23–17 $\mu$m (9). TeO$_2$ is perhaps the most widely used material because, in addition to its high $M_a$ value, low acoustic attenuation, and good transmission range, it is available in large quantities and has good optical quality. The spectral tuning range for an AOTF is limited not by the transmission of the crystal but by the bandwidth of the acoustic transducer. A piezoelectric crystal (LiNbO$_3$) is bonded to the AOTF crystal on a specific crystal face to inject an acoustic wave in the required direction. A single transducer provides one or two octaves of scan range. Multiple
transducers have been bonded to AOTFs to enhance the scan range and/or to increase the interaction length. For example, two arrays of transducers are employed to provide the MgF$_2$ AOTF with a spectral tuning range of 200–700 nm (13).

In selecting a material for an AOTF, one must remember that a polarizer is needed to separate the diffracted light from the transmitted light for the collinear AOTF. Noncollinear AOTFs should be used in the short-wavelength region of the UV and in the IR region, where no suitable polarizers are available.

The scanning speed of an AOTF is controlled by the transit time of an acoustic wave across an optical beam. In the case of the TeO$_2$ AOTF, because the acoustic velocity in the crystal is known to be $6.17 \times 10^4$ m/s (15), it takes an acoustic wave 1.6 $\mu$s to travel across an optical beam of 1 mm diameter. It is thus evident that the tuning speed of the filter can be as fast as a few microseconds. Of course, rapid scanning of the filter may lead to degradation of the filter resolution.

The demand for rapid scanning and the requirement for materials with high optical and acoustic homogeneity often limit the aperture of AOTFs to a few millimeters (e.g., 5 mm $\times$ 5 mm). However, an AOTF as large as 25 mm $\times$ 25 mm has been constructed (24). Such a large AOTF is quite expensive because not only does it employ a large crystal and a large number of transducers, but it also requires an extensive scheme to dissipate the heat generated. The required acoustic power density (or the power of the applied rf signal) increases as the aperture and as the square of the wavelength increase (24). Thus long-wavelength and large-aperture AOTFs generate a considerable amount of heat that must be dissipated quickly for the filter to remain in operation. However, small-aperture AOTFs are suitable for almost all applications because they have acceptance angles as large as 20°.

Collectively, when compared with other dispersive devices (such as a grating or a prism), the advantages of the AOTF include the following: a compact, solid-state design that is rugged and contains no moving parts, a wide angular field (i.e., wide acceptance angle), a wide tuning range (from the UV through the visible to the IR regions), high spectral resolution (bandwidth of light diffracted by the filter is about 1–6 Å), rapid scanning ability (on the order of a few microseconds), high-speed random or sequential wavelength access, and imaging ability.

**Applications**

The advantages of the AOTF allow development of novel instruments that could not otherwise be easily accomplished. In initial applications, AOTFs were used mainly as rapid-scanning dispersive devices. Examples of novel AOTF-based instruments include rapid-scanning UV–vis (22), near-IR (18), and mid-IR (25) spectrophotometers; a circular dichroism spectropolarimeter (19); a fluorescence spectrophotometer (11); a near-IR microscope (14); and an astronomical photometer (26) and polarimeter (24).

In addition to dispersive and scanning capabilities, AOTFs can serve as electronic shutters for amplitude modulation of the diffracted beam (12, 23). This function is possible because the wavelength of the diffracted light is dependent on the frequency of the applied rf signal: No light will be diffracted from the AOTF when the applied frequency does not correspond to any wavelengths in the input beam. Therefore, by controlling the frequency duration and the scanning speed of the applied rf signal, spectral scanning and amplitude modulation of the diffracted light can be readily achieved.

This feature makes the AOTF particularly suited for the development of multiwavelength photothermal and photoacoustic spectrophotometers that require a dark period following each excitation period for a sample to relax to its original state. In fact, an AOTF-based multiwavelength thermal lens spectrophotometer has been developed (23).

The intensity of the diffracted light is dependent on the frequency and the power of the acoustic wave. Thus the AOTF provides a unique way to maintain the intensity of light of different wavelengths at a constant level. By incorporating a feedback system into the driver, either the frequency (12) or the power (20) of the rf signal can be controlled. Two systems based on controlling one of these elements have been reported (12, 20). The capability of the AOTF to stabilize the amplitude of the diffracted light is important in optical spectroscopic techniques—particularly in the IR region. Even though other devices can stabilize the amplitude of the light (e.g., an electro-optical modulator or a Pockels cell driven by a feedback driver (27)), they can only be used in the UV–vis region. These devices lack a suitable

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**Figure 8.** Plot of the intensity of light diffracted from a noncollinear TeO$_2$ acousto-optic tunable filter as a function of the power and frequency of the applied rf signal.

Powers of the applied rf are A: 122.5 mW, B: 90.0 mW, C: 62.5 mW, D: 40.0 mW, E: 22.5 mW, and F: 8.1 mW. (Adapted with permission from Reference 20.)
electrooptic crystal for the IR region, a compact, low-extinction IR polarizer, and a compact, sensitive IR detector. The AOTF, which can be used in the UV–vis and the IR regions, is not limited by restrictions such as stabilizers based on Pockels cells.

The AOTF can also be used to generate images of a sample. The AOTF-based imaging spectrometer usually has one of two possible configurations. In the first, the AOTF is placed in front of a broadband light source to select the wavelength. Normally, the filter sweeps through hundreds of nanometers at predetermined wavelength intervals, recording one frame with the focal plane array detector at each wavelength interval. Hundreds or even thousands of frames may be collected to generate images of the sample. This method of imaging is particularly suited for transmission measurements, and an AOTF-based near-IR imaging microscope has been described (14).

Alternatively, the AOTF can be placed in front of the imaging detector, and the sample directly excited by a broadband light source. This configuration is often used for techniques such as fluorescence and Raman scattering. An AOTF-based fluorescence imaging spectrometer that employs this configuration has been developed (11).

The IR region is perhaps the most scientifically and industrially important region for spectral and/or chemical imaging, and IR imaging sensors based on the use of the AOTF have been reported. Difficulties such as the requirement of operating the filter at cryogenic temperature, the mismatch in the thermal expansion of the crystal and the transducer material, and problems associated with heat dissipation impede progress in this field. However, a cryogenic AOTF device that can operate in the 2.3–5.2-μm range has been reported by Tracy (28).

Applications of the AOTF are not limited to rapid-scanning electronic gratings. In conventional systems, at any given time only a single rf signal is applied to the filter to deflect out a single wavelength beam. It is possible to apply several rf signals simultaneously into the filter. This capability was investigated recently in a study in which a TeO₂ AOTF was used (29).

Previously it was determined that this filter provided diffracted light at 514.5 or 488.0 nm when an rf signal of 64.310 or 69.200 MHz was applied individually. When these two rf signals are simultaneously applied, the filter diffracts light that has two different wavelengths: 514.5 and 488.0 nm. The total number of wavelengths in the diffracted light is determined by the total power of the applied rf signals that the AOTF can tolerate and the relationship (for each wavelength) between the applied rf signal and diffraction efficiency. Thus it is dependent on the type of crystal and the construction of the filter. Specifically, it is known that the maximum rf power that an AOTF can tolerate is dependent on its construction. This is normally on the order of a few watts. For a given wavelength, the relationship between the applied rf power and the diffraction efficiency is a parabolic curve.

For crystals such as TeO₂, which have high acoustic figures of merit, 20-mW rf power can provide diffraction efficiency as high as 90% (3, 9). Therefore up to 100 different wavelengths of light can be selected simultaneously from a TeO₂ AOTF filter. The AOTF can be used not only as a monochromator but also as a polychromator. Compared with a conventional grating polychromator, the AOTF polychromator can provide an output beam that has unique features such as being well collimated (all wavelengths will be diffracted from the filter at approximately the same angle) and being individually and differentially amplitude-modulated.

The latter feature is accomplished by modulating the amplitude of each applied rf signal at the desired frequency. For the TeO₂ AOTF described above, when the applied 64.310- and 69.200-MHz signals were individually and sinusoidally modulated at 100 and 66 Hz, respectively, the diffracted light was a mixture of the 514.5-nm light modulated at 100 Hz and the 488.0-nm light modulated at 66 Hz. There was no cross talk (there was neither a modulated component at 66 Hz in the 514.5-nm light nor a 100-Hz-modulated component in the 488.0-nm light). This feature should allow the use of an AOTF to develop a multidimensional fluorometer (29).

Conventional multidimensional fluorometers are those based on the (grating) polychromator and multichannel detector (e.g., diode array, vidicon, charge-coupled device, or charge-injection device) use the ability of the polychromator to spatially focus different wavelengths of light. For instance, in the first videofluorometer, the polychromator was set on its side to provide excitation wavelengths in the vertical plane (30). Two-dimensional spectra can be acquired because the emission is detected by use of a diode array detector in the horizontal plane.

Because the AOTF-based polychromator diffracts all wavelengths of light to approximately the same point, the same principle could not be used to develop an AOTF-based multidimensional fluorometer. In such an instrument, each excitation (and emission) wavelength is differentiated from another wavelength not by spatial resolution but by the frequency of the amplitude modulation. In the example above, if the sample is excited by the light diffracted from the TeO₂ AOTF, the fluorescence signal detected at 100 Hz is attributable only to the 515.4-nm excitation, whereas the 488.0-nm excitation leads to the fluorescence component modulated at 66 Hz (29). This AOTF-based multidimensional fluorometer has been used successfully to simultaneously analyze two-component samples (29). In the AOTF-based multidimensional fluorometer, the AOTF is used as a polychromator to disperse excitation and emission. Only a single-channel detector such as a photomultiplier is needed; thus, the sensitivity of the instrument is increased and the cost is lowered.

Descriptions of the AOTF applications have thus far been limited to the (laser) extracavity use of this device. The extracavity use may, in some cases, lead to a waste of laser power and the need to operate the laser at high current. For instance, because the 457.9-nm line is a weak output line of an argon ion laser, when the AOTF is used as an extracavity device and this line is selected from the multiline output, the laser must be operated at a higher current to achieve adequate power for this line. Stronger lines such as 514.5, 488.0, and 476.5 nm transmit through the filter and are wasted. This can be eliminated by inserting the AOTF into the laser cavity. In fact, when used inside the cavity of a standing wave dye laser, a TeO₂ AOTF can provide scanning from 560 to 610 nm in as little as 50 μs. The output beam has a power output as high as 130 mW and a bandwidth of 0.3 nm (31). In another example, the AOTF constructed from Te₅AsSe₃ and inserted in the cavity of a pulsed CO₂ laser provided rapid scanning from 9 to 11 μm (32). An intracavity AOTF tuning device for solid-state lasers such as Ti:sapphire was recently reported (33).

Because of the relationship between the applied rf and the dif-
fracted wavelength, the AOTF can, in principle, be exploited in both directions. Thus far, only one facet of applications has been described: the application of different rf signals into the AOTF to disperse and/or analyze optical signals. The AOTF can also be used to analyze the frequency distribution of rf signals (34). In this case rf signals collected through an antenna and processed by an amplifier are fed into the filter (34). A stable, well-characterized light source is then introduced into the AOTF. Because of the applied rf signals, the filter will diffract the incident light beam into different wavelengths. The frequency distribution of rf signals is then calculated from the rf optical wavelength relationship and from wavelengths of the diffracted light. An rf spectrum analyzer based on this principle has been recently constructed and reportedly can measure rf signals with bandwidths as large as 5 GHz (34).

Future prospects

It would be misleading to conclude this discussion with the idea that acousto-optic devices have reached technological maturity and that they do not have disadvantages and defects. In fact, the field has not been fully developed. Disadvantages and defects do exist, and much fundamental as well as technological research needs to be performed. Furthermore, some improvements have been proposed in theory but have not been experimentally realized. Some of these are discussed below.

TeO$_2$ remains the best material for devices operated in the visible and near-IR regions (up to 5 μm). In the UV region, where the absorption of many compounds of interest occurs, there are very few birefringent crystals suitable for acoustic devices. Those currently available (quartz, MgF$_2$) have low acoustic figures of merit and small photoelastic tensors. AOTFs fabricated from these materials are usually collinear or noncollinear, but with very small deflection angles. A polarizer is needed to isolate the diffracted light. Because polarizers in this region are currently unavailable, it is essential to find new materials with better acousto-optic properties for the UV region. The situation is better for AOTFs in the mid-IR region. Several new birefringent materials that have relatively good acousto-optic properties and are transparent up to 17 μm were recently described (9).

As mentioned earlier, acousto-optic materials must have low acousto-optic attenuation. It is possible to reduce the acoustic attenuation of a given crystal by cooling it, as demonstrated in a recent report of the acoustic attenuation of a TeO$_2$ crystal, which was reduced sixfold when the crystal was cooled to 4 K (35).

As shown in Equation 15, the intensity of the diffracted light is a sinc$^2$ function. It is, therefore, similar to that of the diffraction grating. That is, for each specific diffracted wavelength, there are several side bands in addition to the main band.

An example of this was shown in Figure 7. Because the incident beam was a multiline output from an argon ion laser, side bands and the main band have the same spectral purity (i.e., they have exactly the same wavelength). Therefore, their presence does not degrade the filter resolution.

The same cannot be said when an incoherent continuous light source such as an incandescent or a xenon arc lamp is used. In this case, side bands of one wavelength may overlap with those of another wavelength and hence degrade the filter resolution. Several methods may be used to depress these side bands. For example, appropriate adjustment of the power of the applied rf signal may substantially reduce the side bands (36). As an example, it was found that the diffraction efficiency (and hence the intensity of the diffracted light) of a nonlinear TeO$_2$ AOTF is proportional to the power of the applied rf signal (36). The proportional-ity constants are, however, different for the main band and the side bands.

Appropriate selection of the power will lead to a substantial reduction of the side bands. For 488.0-nm light at a 10-mW applied rf signal, the ratio of the main band to the first side band is 9.0. An increase in rf power to 35 mW, which is the optimal power for maximum diffraction efficiency (for the main band), will increase the main band and will also increase the side bands (36). Because the side bands increase more than the main band in this region, the ratio of the main band to the first side band decreases to 4.5 (36). Alternatively, the side bands can also be reduced by apodizing the acoustic profile. It has been reported that by using the apodization method based on the Hamming window, the first side bands were reduced 30 dB below the main band (37).

The resolution of an AOTF filter can, in principle, be improved substantially by using the filter in the
wavelength region close to the absorption edge of the crystal. This prediction is based on the fact that, according to Equation 17, the resolution of the AOTF is inversely proportional to the dispersive constant \( \Delta \), and \( \Delta \) is known to be wavelength dependent. It becomes very large near the absorption band edge of the crystal.

The resolution of the AOTF, as shown in Equation 17, also depends on the wavelength. This dependency makes it somewhat difficult to use the AOTF to develop a spectrophotometer based on a continuous white light source. Efforts are being made to develop an AOTF that has constant resolution and spectral bandwidth (38).

This article is limited to the subject of acousto-optic interactions in bulk materials and their applications in optical spectrometry. Other areas of acousto-optic interactions, including integrated optics and surface acoustics, are also important—particularly in the fields of electronics, communications signal processing, and sensing (39), where intense investigations are under way.

I am grateful to my co-workers, whose work is cited in the references, and also to acknowledge the National Institutes of Health, National Center for Research Resources, Biomedical Research Technology Program for financial support of some of the work reported here.

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