Acousto-optic tunable filters are powerful tools for spectroscopy, imaging, and WDM. Gupta traces the development of these devices and discusses current and future applications.

Optical technologies (optoelectronics, fiber optics, and acousto-optics) are playing an increasingly important role in our daily lives. Lasers and optics are widely used in such diverse settings as supermarkets, homes, offices, and hospitals. A recent development in acousto-optics (AO) is an electronically tunable optical filter with no moving parts. This filter fulfills an essential requirement for next-generation spectroscopic instruments, wavelength division multiplexing (WDM) switches, and multispectral imaging systems. Acousto-optic tunable filter
(AOTF) technology offers the potential for rapid, frequency agile tuning from the ultraviolet (UV) to the long infrared (IR) wavelength range. An AOTF is an electronically tunable phase grating set up in an anisotropic crystal by the propagation of an ultrasonic wave in the crystal. Such filters, containing no moving parts, offer high-speed wavelength tuning that can be done sequentially or randomly, depending upon the programmed instructions for the applied radio frequency (rf). AOTFs are finally beginning to replace conventional grating-technology-based optical instruments in a wide range of filtering, sensing, and imaging applications that can benefit from the size, speed, ruggedness, reproducibility, and accuracy of AOTFs.

Among the attractive features of AOTFs are their small size, light weight, computer-controlled operation, and large optical wavelength range of operation, as well as the feasibility of making their operation ultrasensitive by the use of advanced signal processing algorithms. These filters are being used in such applications as the design of new spectroscopic instruments, remote detection and monitoring of chemicals, switching in optical communication networks, and tuning of laser cavities. In recent years, AOTF-based near IR spectrometers have gained increasing acceptance as powerful diagnostic tools for real-time monitoring for process control and quality assurance in pharmaceutical manufacturing, the chemical and petroleum industries, paper manufacturing, food processing, and optics and semiconductor manufacturing. AOTF filters have also been developed for multispectral imaging applications by NASA scientists to study the planetary atmosphere of outer planets. An AOTF-based instrument was also flown aboard a Soviet satellite.

This article will discuss the historical development of AOTF technology, give a brief introduction to concepts underlying the operation of these devices, introduce the two types of AOTF cells, explain the important factors involved in the design of such cells, and discuss the main applications of this technology. The measurements setup and results for Raman spectra of chemicals at the Army Research Laboratory (ARL) are discussed and recent results from multispectral imaging work for the detection of mines done at the Jet Propulsion Laboratory (JPL) are provided.

**Developments of AOTF technology**

AO deals with the interaction of sound and light in a dielectric material. Such an interaction in crystals was first theoretically predicted by Brillouin in 1922 and was experimentally verified a decade later. AO interaction is due to the photoelastic properties of such a crystal where an applied strain changes the optical properties, i.e., the refractive index of the material. In such an
interaction, a transmission grating is set up in the crys-
tal by the alternating planes of compression and rarefa-
tion created by a traveling ultrasonic wave, and the in-
cident light is diffracted similarly to the diffraction of
x-rays in crystals. The grating constant is equal to the
wavelength of the sound wave in the crystal and can eas-
ily be changed by a change in the frequency of the
acoustic wave. The fundamental operation of an AO
device is as follows: a high-frequency electrical signal is
converted into an ultrasonic wave by a piezoelectric
oscillator (transducer) bonded to an AO medium; the
sound wave travels through the medium and diffracts
light in a certain direction. AO technology has now
reached sufficient maturity that AO modulators and
beam deflectors are widely used in laser printers and
scanners.

Despite this progress, the effect that allowed the
development of an AOTF was not discovered until
much later; the delay occurred because until 1967, the
discussion of AO interaction was confined to isotropi-
crystals. The AO interaction in anisotropic crystals (in
which the speed of light is different in different direc-
tions) was first discovered by Dixon in 1967. Two years
later, Harris and Wallace exploited this effect in a pro-
duced design for a collinear AOTF in lithium niobate
(LiNbO₃); in the latter part of 1969, the first collinear
AOTF in LiNbO₃ was demonstrated. In a collinear
AOTF, the incident light, acoustic wave, and diffracted
beam all travel in the same direction. A number of dif-
f erent crystals (e.g., quartz, LiNbO₃) with different crys-
tal orientations allow collinear diffraction of light with
either longitudinal or shear acoustic waves. Chang gener-
alyzed the design of an AOTF by introducing the con-
cept of a noncollinear AOTF in tellurium dioxide
(TeO₂), a crystal that is birefringent (having two refrac-
tive indices) and that cannot exhibit collinear interac-
tion because of its crystal symmetry. In such a cell, the
incident and diffracted light, and the acoustic wave do
not travel in the same direction.

At present, a number of AOTF cells and spectrome-
ters are available commercially and as research instru-
ments (see Fig. 1). The U.S., Russia, and Japan are the
leading players in this technology. Since the first com-
mercial offering of an AOTF by the Isomat Corp. in
1975, this technology has made much progress. At pre-
sent, a number of companies fabricate and sell AOTF
cells and systems that are starting to play a key role in
industrial settings.

In the former Soviet Union, a spectropolarimeter
called “Traser” was flown aboard the Soviet satellite
“Okean,” which was launched in 1989 for remote sens-
ing of sea surfaces from space and collected data for two
years. At present, an AOTF spectrometer is remotely
operated from Moscow to detect concentrations of vari-
ous gases absorbed in water, as well as radon gas under
depth water (30–50 m) in Kamchatka, Russia, for earth-
quake prediction. AOTFs are under consideration for
future space missions, in particular for real-time water
quality monitoring aboard the U.S. space station, for a
comet lander, and possibly for use on a Mars rover.

**AOTF concepts**

An AOTF is essentially a real-time programmable filter.
When white light is incident on the filter, it passes only a
selected number of narrow bands corresponding to the
applied rf frequencies, as shown in Figure 2a. In other
words, the filter can be used to pass light with either a
single wavelength or multiple wavelengths, depending
upon the applied rf signal. Either a collinear or a non-
collinear geometry can be used in designing an AOTF
cell, based on the symmetry properties of the anisotropic
crystal under consideration. A collinear AOTF cell is a
special case of the general noncollinear type. Figure 2b
shows the propagation of light and sound in a collinear
AOTF cell: the wave vectors for the incident and diffracted
light are \( \mathbf{k}_{\text{in}} \) and \( \mathbf{k}_{\text{diff}} \), respectively; for the sound
wave the wave vector is \( \mathbf{q}_{\text{sound}} \). The incident light is lin-
early polarized by a polarizer in front of the crystal. As
this polarized light passes through the crystal perpen-
dicular to the optic axis, it is diffracted in the same
direction by a diffraction grating set up by the collinear-
ly traveling sound wave. Since the polarization of the
diffracted beam is perpendicular to the incident light
beam, it can be separated from the incident beam by
another polarizer. Owing to conservation of energy, the
frequency of the diffracted light is Doppler shifted, but
this frequency shift is insignificant and can be ignored
(the frequency of the incident light is \( 10^6 \) times greater
than the frequency of the ultrasonic beam). Based on
the conservation of momentum, a tuning relationship
between the center wavelength of the filter and the
applied rf frequency can be established:

\[
\lambda = (n_e - n_o) v / \Omega,
\]

where \( \lambda \) is the center wavelength of the filter, \( n_e \) and \( n_o \)
are the refractive indices of the birefringent crystal cor-
responding to the propagation of light along the ordi-
nary and extraordinary axes, respectively, and \( v \) and \( \Omega \)
are the speed and frequency of the acoustic wave,
respectively. The bandwidth \( \Delta \lambda \) of the AOTF is equal to
\( \lambda^2 / \Delta n L \), where \( L \) is the length of the AO interaction, and
\( \Delta n \) is the difference of the two refractive indices. For
example, we can calculate the rf frequency range and the
respective filter bandwidth for a quartz collinear
AOTF operating in the 400–800 nm spectral wavelength
region. If we take \( \Delta n = 0.009 \), \( v = 5.75 \times 10^5 \) cm/sec,
and \( L = 15 \) cm, the rf frequency range is 130–65 MHz,
and \( \Delta \lambda \) is 0.12 nm at 400 nm. Neglecting the spectral
dependence of the refractive indices, we find that the
wavenumber resolution \( \Delta \lambda \) has a value of 7.4 cm⁻¹ in
the entire spectral region of interest.

Figure 2c shows the schematic layout of a non-
collinear AOTF cell. Here the diffracted beam is spatially
separated from the undiffracted beam. This may look
like a regular Bragg cell, but because of the anisotropic
nature of the AO interaction involved, the polarizations
of the two diffracted beams are orthogonal to each oth-
er, and each of these beams travels with a different speed
in the crystal. Many excellent review articles on AOTF
technology and applications are available.
AOTF design

One can create an AOTF cell by bonding a transducer (made of LiNbO$_3$) on an anisotropic crystal that has been cut with a specific orientation and polished. The acoustic waves are generated in this crystal by the application of an rf signal to the transducer. The tuning range for a single transducer is about one octave in acoustic (and optical) frequency. An AOTF cell can be designed with multiple transducers to cover a wider frequency range of operation.

The key elements in an AOTF cell design are material selection, choice of crystal geometry, transducer design and bonding, design of AOTF cell architecture, electronics for the operation and control of the AOTF, computer interface, signal processing algorithms, and software.

The performance of AOTFs is primarily limited by the availability of superior materials. To qualify as a candidate for use as an interaction medium for an AOTF, a material must be optically birefringent and transparent in the operating wavelength range of interest. Also, it must have a low acoustic attenuation in the acoustic frequency range of operation, and it must have a large AO figure of merit. Table 1 lists a number of important crystal materials used to design AOTF cells and their spectral ranges of coverage. A number of TeO$_2$ AOTFs are now commercially available.

AOTF applications

AOTFs are powerful tools for spectroscopic and imaging applications, as well as being useful in other applications, i.e., communication and laser cavity tuning. This section will concentrate on two major applications, spectroscopy and imaging, and present some results.

Spectroscopy

AOTFs are increasingly being used in research areas requiring fast spectroscopic measurements based on absorption, emission, fluorescence, and Raman characterization techniques. Such filters can be used as replacements for filter wheels and diffraction gratings. Because they are lightweight, compact, and insensitive to vibrations, they are very useful in designs for field-portable spectrometers. A compact, no-moving-part, fully automated spectrometer can be designed that uses an AOTF cell with a suitable detection system, such as a photomultiplier tube (PMT). Because AOTF spectrometers do not suffer from one of the main drawbacks of traditional spectrometers (the need for mechanical moving parts for the dispersive elements), AOTF spectrometers are much easier to maintain and operate. They are used more and more for process and quality control in various manufacturing settings in the pharmaceutical and chemical industries.

At ARL, a quartz collinear AOTF spectrometer (see Fig. 1) designed by the Laboratory of Acousto-Optics and Optoelectronics (VNIFIRI), Mendeleevo, Russia, has been used to perform both fluorescence and Raman spectroscopy. These spectrometers operate in two optical bands: UV to visible (255–430 nm) and visible to near-IR (400–800 nm). The Raman setup used in the laboratory is shown in Figure 2. A bifurcated fiber bundle delivers the light from an argon ion laser (514.5 nm) and collects the scattered light from the sample. A single holographic notch filter passes the frequency-shifted Raman signal to the visible AOTF spectrometer. The measured Raman spectrum of naphthalene (commonly used for mothballs) is shown in the inset of Figure 3. In general, Raman signals are narrow spectral lines with extremely weak intensities ($10^{-8}$ to $10^{-10}$ of the incident light), and their detection requires high resolution and high sensitivity. Reference 8 shows that the results obtained by this compact spectrometer with 7.4 cm$^{-1}$ resolution compare favorably with those obtained with traditional Fourier transform (FT) Raman spectrometers and take less time.

Imaging

AOTFs are powerful tools for multispectral and hyperspectral imaging applications because they can acquire spatial, spectral, and polarization information. Such instruments are useful on board satellites and for exploration of space. Scientists at JPL have performed research in multispectral imaging exploiting the polarization dependence of AOTF outputs using a non-collinear TeO$_2$ visible (480–750 nm) AOTF cell with suitable beam forming optics. Their AOTF imagery is shown in Figure 4, which demonstrates how the difference in the two polarization images at a particular wavelength can be used for the remote detection (at a distance of 40 m) of a variety of metallic and plastic mines covered with foliage in an iceplant field in Los Angeles on a sunny day in June.

IR polarization imaging using AOTF is expected to be a very powerful tool in object recognition for automatic navigation and related man-made object recognition due to the possibility of exploiting the elliptical polarization characteristics exhibited by regular surfaces in this spectral region.

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**Table 1.** AOTF materials and their spectral range.

<table>
<thead>
<tr>
<th>Material</th>
<th>Spectral band (µm)</th>
<th>Cell Type</th>
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<tbody>
<tr>
<td>LiNbO$_3$</td>
<td>0.4 – 4.5</td>
<td>Collinear</td>
</tr>
<tr>
<td>Crystal quartz (SiO$_2$)</td>
<td>0.25 – 0.8</td>
<td>Both</td>
</tr>
<tr>
<td>MgF$_2$</td>
<td>0.2 – 0.7</td>
<td>Noncollinear</td>
</tr>
<tr>
<td>CaMg$_3$O$_7$</td>
<td>0.4 – 4.5</td>
<td>Collinear</td>
</tr>
<tr>
<td>TeO$_2$</td>
<td>0.35 – 4.5</td>
<td>Noncollinear</td>
</tr>
<tr>
<td>Ti$_3$AsSe$_5$</td>
<td>1.1 – 17.0</td>
<td>Both</td>
</tr>
<tr>
<td>Hg$_2$Cl$_2$</td>
<td>0.35 – 20.0</td>
<td>Noncollinear</td>
</tr>
</tbody>
</table>
Other applications
AOTFs can be used for generating an arbitrary spectral signal that can transmit through an obscured environment and be used for polarization-sensitive scattering applications. This is possible because an AOTF can be operated at multiple frequencies simultaneously with different rf powers. For laser wavelength tuning, an AOTF cell can be used either inside or outside the laser cavity. AOTFs are now becoming valuable system components in WDM communication networks because of their broad continuous electronic wavelength tuning capability and narrow filter bandwidth. Multiwavelength filtering capability adds another dimension of flexibility to network design that cannot be achieved by any other filter, and AOTFs are also being used in active gain equalization of optically amplified networks, as well as in the design of erbium-doped fiber ring lasers. The possibility of such applications has contributed greatly to the research and development taking place in the integrated-optic LiNbO$_3$, AOTFs.

At present, both the spectroscopic and imaging applications of AOTFs are limited to mainly visible and near-IR spectral regions. AOTF cells are not commonly available at longer wavelengths where they will be more useful for remote sensing of the environment, as well as for medical applications, due to the fact that this is where various hydrocarbons and other compounds exhibit their molecular absorption spectra. More research needs to be carried out in growing newer and better quality anisotropic crystals to be used to design AOTF cells at longer IR wavelengths.

Outlook for the future
AOTF technology has evolved significantly since its inception 30 years ago. The advantages in size, time of measurement, cost, programmability, and sensitivity offered by AOTF devices make them suitable for chemical sensing, frequency tuning, WDM switching, and imaging applications that require portability, robustness, and compact size, both in laboratory and field testing setups. This promising technology can become more widely used if the fabrication is made more automated and the cost per unit is lowered. More research is needed to develop new materials and to improve the quality of existing materials to expand the wavelength range of operation to shorter UV and longer IR regions.

References

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