

Acousto-Optic Tunable Filters Spectrally Modulate Light

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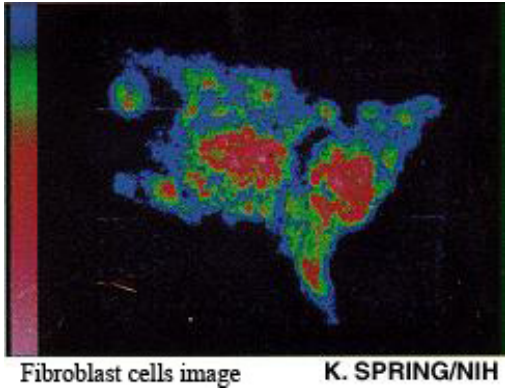
The development of opt electronic technology in the past two decades has intensified research on devices that control and manipulate optical radiation. Acousto-optic devices are based on acousto-optic effects in which the optical medium is altered by the presence of ultrasound. Examples of acousto-optic devices include optical modulators, deflectors, scanners, Q-switches, isolators, and frequency shifters. These devices have many applications in high-speed laser printers, laser lithography, optical communications and computing, large-screen laser projectors, frequency shifting, particle inspection, optical spectrum analysis, signal processing, and radar, range finder, and target designation.

Progress in acousto-optics has been stimulated by the development of growth methods for acousto-optic crystals and by new methods for fabricating piezoelectric transducers that can efficiently convert electrical energy into acoustic energy at frequencies ranging from a few tens of megahertz up to several gigahertz. One promising development in acousto-optic devices is the recent commercial availability of acousto-optic tunable filters (AOTFs). In these filters, the interaction between an ultrasonic wave and light in an acousto-optic crystal is used to spectrally filter the light. In operation, tunable filters resemble interference filters and can be used in applications that require a filter wheel, grating, or prism.

Principle of Operation

The AOTF is based on acoustic diffractions of light in an anisotropic medium. The device consists of a piezoelectric transducer bonded to a birefringent crystal. When the transducer is excited by an applied RF signal, acoustic waves are generated in the medium. The propagating acoustic wave produces a periodic modulation of the index of refraction. This provides a moving phase grating that, under proper conditions, will diffract portions of an incident beam. For a fixed acoustic frequency, only a limited band of optical frequencies can satisfy the phase-matching condition and be cumulatively diffracted. As the RF frequency is changed, the center of optical pass band is changed accordingly so that the phase-matching condition is maintained.

In principle, both isotropic and anisotropic Bragg diffraction can be used for the spectral-filtering mechanism. However, a filter based on isotropic diffraction is impractical, because its optical pass band is dependent upon the angular aperture of the incident beam and is only usable with well collimated light (on the order of milliradians). The angular aperture limitation arises because a change of the angle of incident light will introduce a momentum mismatch. For an incident light beam of finite divergence, the width of the pass band is greatly increased. In addition, the diffracted beam is deflected to a different angle for each wavelength.



False-color image of two fibroblast cells stained with fluorescent dye reveals detail when illuminated with 514-nm line of argon laser selected by a TeO_2 acousto-optic tunable filter. The cells are about 40 micrometers across in the largest dimension.

The design of an AOTF is based on anisotropic Bragg diffraction in a birefringent crystal. Anisotropic diffraction necessarily involves rotation of the polarization plane of the diffracted wave. Because the refractive indices for ordinary and extraordinary light in a birefringent crystal are not the same, it is possible to choose the direction of acoustic-wave propagation so that the group velocity for both the incident and diffracted light is collinear. This process is referred to as noncritical phase matching (NPM). Under the NPM condition, maximum compensation of the momentum mismatch due to angular deviation of the incident light beam is achieved by the angular change of birefringence. Hence, the NPM is maintained to the first order over a large angular change of the incident light beam. the field of view angle for a noncollinear AOTF can be as high as $\pm 20^\circ$

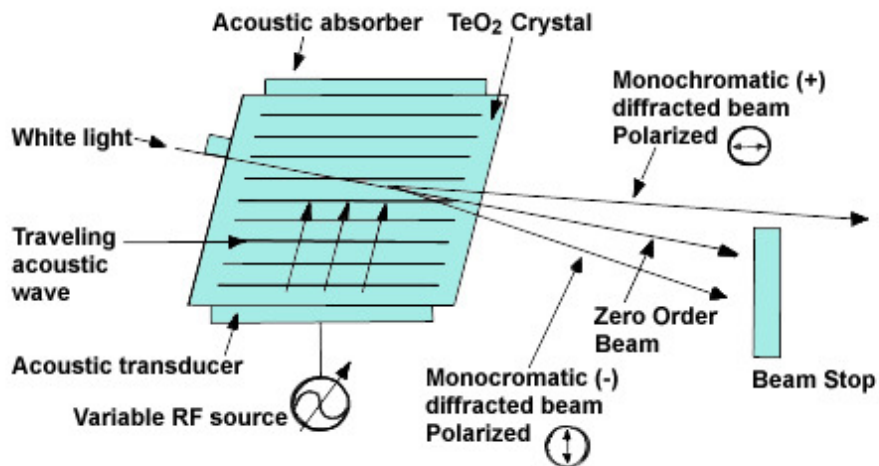


Figure 1. Crystalline quartz collinear AOTF produces beam that must be separated from input with polarizer (top). Tellurium dioxide (TeO_2) noncollinear AOTF separates zero-order and diffracted beams without a polarizer.

AOTF devices fall into two categories in terms of configurations (see Fig. 1). In quartz collinear AOTF, the incident light, the diffracted filtered light and the acoustic wave all interact collinearly in a birefringent crystal. As a result of the acousto-optic interaction, part of the incident light beam within the filter spectral pass band is coupled to the diffracted light beam. The polarization of the incident light beam is orthogonal to that of the diffracted light beam. Because of the zero-order beam and the diffracted beam are collinear, polarizers must be used to separate them.

In a tellurium dioxide (TeO_2) noncollinear AOTF, the acoustic and optical waves propagate at quite different angles through the crystal. In this configuration, the zero-order and diffracted beam are physically separated, so that the filter can be operated without polarizers. Also, the two orthogonally-polarized beams do not separate until they exit from the crystal, and the angle of diffracted beam is absent for the change in the first order with a change of wavelength. This implies that only a single fixed detector is necessary during a spectral scan.

Most AOTF devices are designed with two types of birefringent crystals depending upon operational wavelength. TeO_2 is preferred AOTF material because of its high acousto-optic figure of merit. The crystal, although useful in the visible and infrared region up to 4.5 micrometers, is not suitable for ultraviolet applications due to its short-wavelength transmission cutoff at 350 nm. For ultraviolet spectroscopy, crystalline quartz is used.

Fast Tunable Light Source

The AOTF can be incorporated with an incoherent light source or multiline white-light laser to produce a fast tunable light source. It can be switched between any randomly selected wavelength in microseconds, with resolution from several nanometers up to 0.1 nm. One of the applications for this source is fluorescence spectroscopy.⁴ Fluorescent probes can indicate diverse properties as ion concentration, pH, and electronic potential in live cells and tissues. In acquiring kinetic data from fluorescent probes, it is often necessary to monitor the ratio of two (or several) excitation or emission wavelengths to cancel out the intensity of excitation and dye concentration, giving an accurate estimation of target ion concentration. It is also essential to alternate wavelengths as rapidly as possible. Conventionally, a spinning filter is used, but it is slow, hard to synchronize with opt electronic data collection, and also causes mechanical vibration that can be troublesome in a microscopy setup.

With an AOTF, these problems can be circumvented, because it is a solid-state device with no moving parts. Also, a single AOTF can be used as a multiwavelength modulator. By coupling the AOTF to a broadband light source (or a multiline white laser) and driving the AOTF with two RF frequencies, two excitation wavelengths can be generated simultaneously. Furthermore, each wavelength can be modulated electronically at different frequencies, and lock-in amplifiers can demodulate the fluorescent emission into its two components.

As an example, an AOTF can be coupled with an argon-krypton white laser that simultaneously emits 12 wavelengths. By simultaneously adding several RF frequencies with properly adjusted power levels, artificial composite laser color can be generated that may find applications in confocal microscopy, holograph, and laser entertainment.

Scientists at the National Institutes of Health (Bethesda, MD) are pioneering innovative biomedical and chemical applications of AOTFs. In one experiment, an argon laser equipped with an AOTF is used as a light source for fluorescent microscopy.⁵ The narrow bandwidth, rapid wavelength selection (microseconds), and the intensity control enable a variety of measurements to be made in an extremely short time. Recently, this system was used to bleach a small region of a sample periodically at 514 nm to determine rates of flow and diffusion in two fibroblast cells stained with a fluorescent dye (see first graphic at the top of the page). The sharp details and high signal-to-noise ratio result from the narrow bandwidth of the exciting light produced by the laser-AOTF combination.

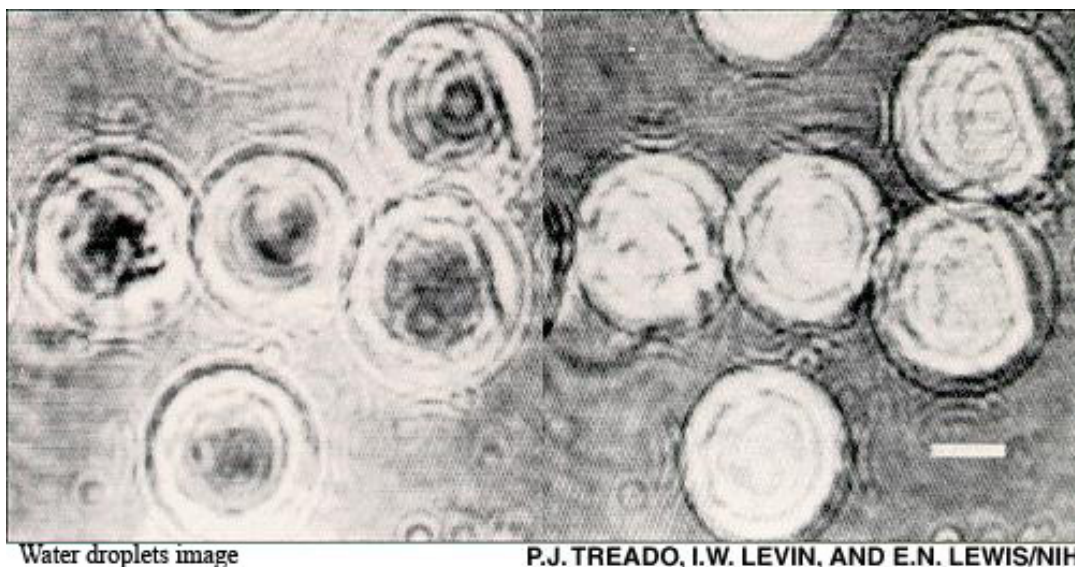


Figure 2. Near-IR light source illuminates water droplets at 960 nm (left) and 850 nm (right); wavelengths are selected by AOTF. Darkening of spots results from water absorption; reference bar corresponds to 7 micrometers.

In another experiment, an AOTF coupled with a tungsten lamp provided a fast-tuning near-infrared (NIR) light source for spectroscopic imaging of water (see Fig. 2).⁶ The microscope images of water were collected at 960 nm and 850 nm; the darkening of the droplets at 960 nm corresponds to the vibrational absorption of water (specifically, the second overtone O-H stretch). For presentation, the images are corrected for instrument response and background contributions.

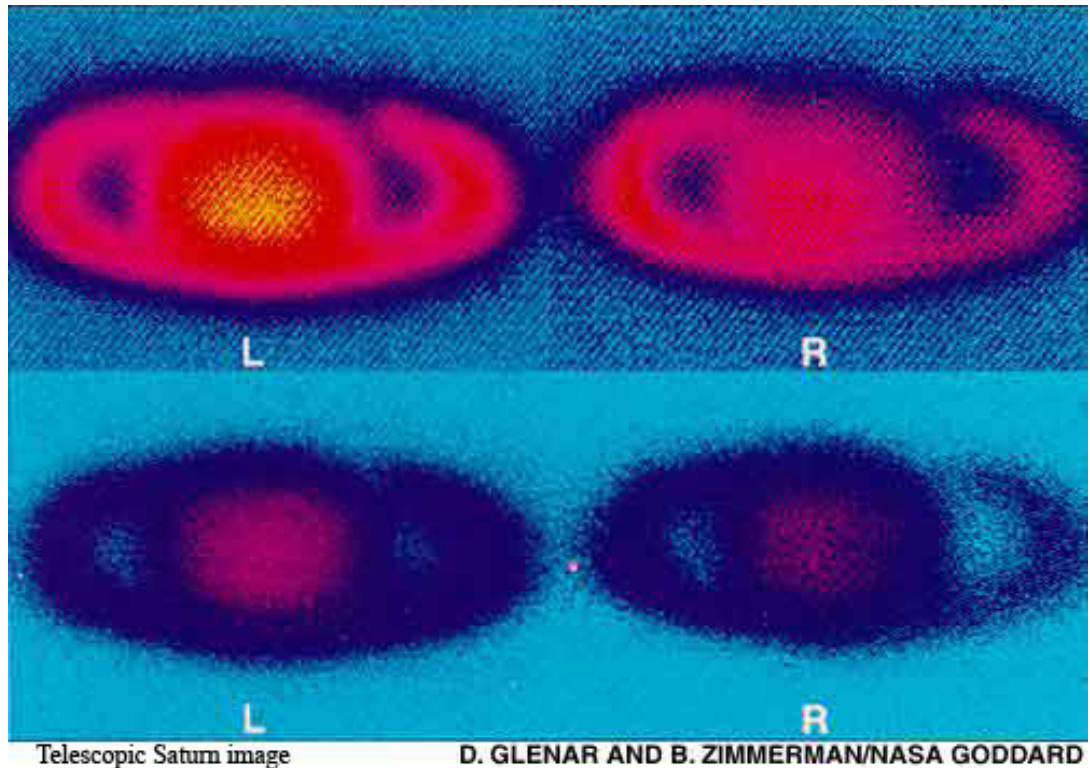


Figure 3. AOTF telescopic polarized images of Saturn reveal methane absorption in rings at 727 nm (top); interband space is evident by lack of absorption at 753 nm (bottom).

Spectral Imaging

Because of its large field-of-view angle and high spatial resolution (>100 lines/mm), an AOTF can also be used for spectral imaging applications. It can be used for acquiring spatial, spectral, and polarization information from fluorescent probes in biological cells, space and terrestrial observation, and image sensing. Spectral imaging at orthogonal polarizations can give the spectral properties and size distribution of gases and aerosols, in addition to revealing the nature of solid surfaces from their reflectance spectra. Figure 3 shows an orthogonally polarized image of Saturn at 727 and 753 nm recorded by scientists at the NASA/Goddard Space Flight Center (Greenbelt, MD). The used a TeO₂ AOTF coupled into an imaging telescope system to produce these images. At the methane- absorption wavelength, the polarization contrast is enhanced.

Near-Infrared Spectroscopy

Near-infrared spectroscopy is a powerful diagnostic tool for identifying and analyzing the concentrations of components in samples. For example, the starch, protein, liquid, and fiber concentrations of grains, octane numbers of gasoline, moisture content of chemicals or food, or the lignin content of pulp and paper can be determined through NIR analysis. However, for industrial on-line monitoring, samples, which are usually moving, may be inhomogeneous and their compositions and optical characteristics may suddenly change.

Measurements need to be performed rapidly to derive accurate compositional or quality parameters. A large number of measurements may need to be averaged to correct errors. Also, data may need to be recorded at multiple wavelengths in real time, preferably simultaneously. For

this application, the spectrometer must be able to be tuned repeatedly to precise wavelengths reliably over long periods of time. In addition, the spectrometer must be rugged, compact, flexible, and simple to operate. Problems in meeting these requirements with classical spectroscopic technologies have limited the deployment of NIR spectroscopy in industrial and commercial applications.

Although instruments using other technologies have been successfully used, AOTF technology is unique in its ability to satisfy all the criteria for hands-off real-time NIR spectroscopy in the industrial environment. With the advent of rugged, compact, fast spectrometers based on AOTF technology, NIR spectroscopy is set to fulfill its promise as an important on-line diagnostic tool.⁷

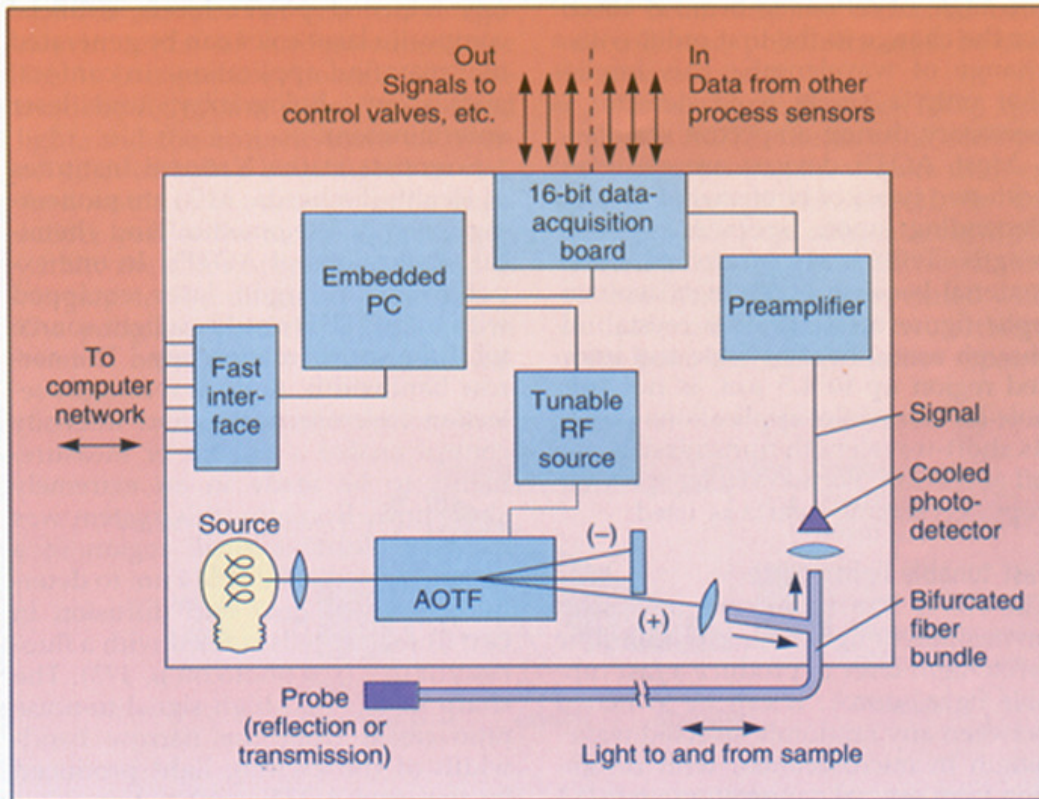


Figure 4. For industrial on-line analysis, an AOTF selects wavelengths for NIR spectrometer; sampling is via a fiber bundle.

In an AOTF spectrometer, the output of a tungsten lamp is collimated and directed into a TeO_2 AOTF (see Fig. 4). The monochromatic output beam from the AOTF is coupled into a bifurcated fiber bundle. The fiber exits the spectrometer and terminates in a probe designed for reflection or finite-path-length absorption measurements. Light from the sample passes back along the fiber where it is focused onto a photo detector. The normalized signal intensity at each wavelength is digitized by a high-speed 16-bit analog-to-digital converter before being stored and/or analyzed by the central processing unit.

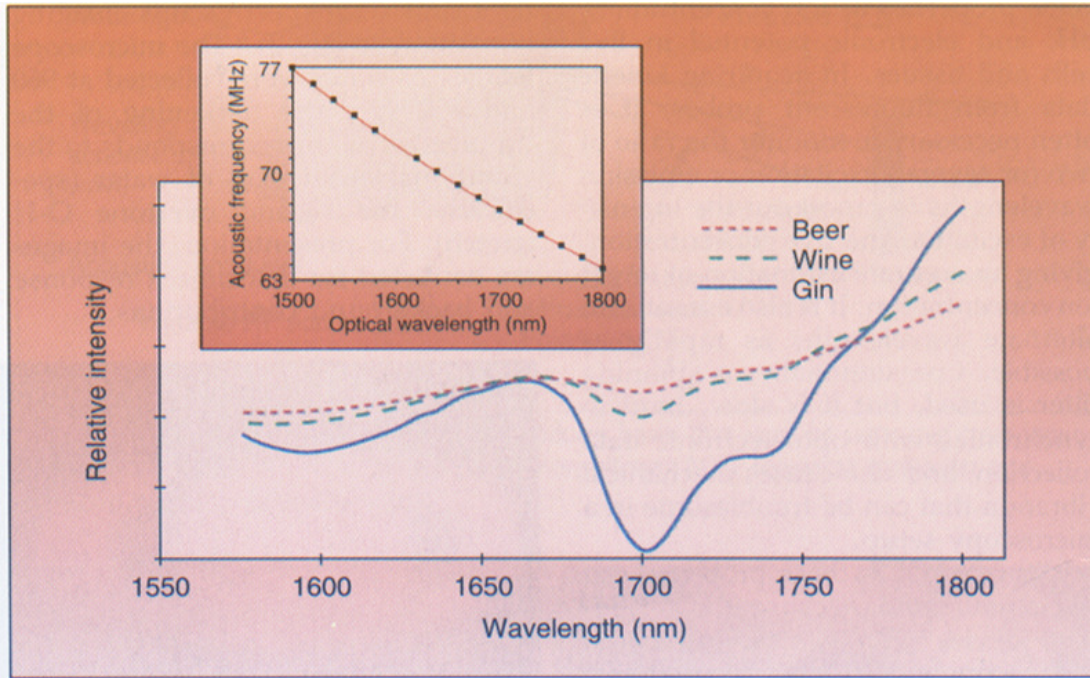


Figure 5. Transmission spectra of three beverages obtained with a TeO_2 AOTF NIR spectrometer show increase in absorption around 1700 nm as alcohol content increases. Inset shows calibration of applied acoustic frequency versus optical wavelength produced by AOTF.

Beverage monitoring is one application for AOTF spectrometers (see Fig. 5). The transmission spectra of several alcoholic beverages were recorded using a Brimrose Luminar 2000 NIR AOTF spectrometer. Notice the increased intensity of the methyl and methylene bands at approximately 1700 nm as the alcohol content increases. A system such as this could be used for quality assurance in the beverage industry.

References

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