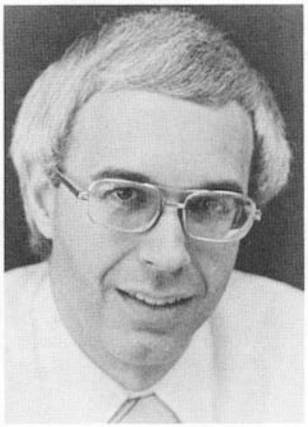

Concepts in Tunable Spectral Filters

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Imaging systems optimized for broad regions of the optical spectrum typically use one or more bandpass filters when closer spectral scrutiny is required. Conventional multilayer interference filters designed for either wide or narrow spectral bands can be arranged on a filter wheel to achieve discrete passbands. However, with multilayer coatings, the passband width ($\delta\lambda$) scales directly with the center wavelength (λ_0) for each filter. Thus it is not possible to vary $\delta\lambda$ independently of λ_0 without physically altering the filter combination.

In many applications, it is sufficient to vary only λ_0. Other applications require that both $\delta\lambda$ and λ_0 be independently variable. The extent of tunability for a tunable spectral filter (TSF) is set by its basic concept and choice of materials. TSF applications can vary from fine tuning within the visible spectrum to tuning through an infrared band that is broader than the whole visible spectrum. To date, TSF research has involved theoretical optics, material studies, and fabrication processes. The area of physics at present identified to be most useful in advancing this field applies acousto-optic, electro-optic, and interference phenomena.

ACOUSTO-OPTIC TUNABLE FILTER

The theoretical foundations for the diffraction of light by elastic waves in liquid and solid media were originally devised by Brillouin in 1922. In principle, the acousto-optic tunable filter (AOTF) exhibits momentum conservation between the diffracted, or filtered, photon-wave vector and the sum of the incident photon and rf-induced phonon-wave vectors within the material bulk.[1] As the acoustic wave propagates through the filter medium, it generates a spatially varying birefringence pattern, which is synchronous with the standing compression wave. When light enters the medium, it observes the spatial pattern as a dielectric grating from which the light scatters into a number of calculable diffraction orders. For an anisotropic medium, the orthogonal vector components of the incident unpolarized light are separated by the acoustic-wave couplings. Placing the AOTF between crossed polarizers reduces light leakage of those optical wavelengths not completing a polarization rotation of $\pi/2$. In the limit, the out-of-band leakage is equivalent to the extinction ratio of the polarizers with a theoretical passband-transmission peak of 50%. Optical tuning is accomplished by changing the electrical frequency input to the acoustic transducer.

Generally, the variations in AOTF design are based on either a collinear or a noncollinear configuration. The collinear AOTF constrains the optical waves to propagate parallel to the acoustic waves, resulting in a long acousto-optic interaction length. As is shown in Fig. 1, however, this configuration requires transducers that are optically transparent. Applications requiring a large tuning range and wide field of view (FOV) incorporate noncollinear designs. The noncollinear AOTF can use multiple acoustic-transducer elements because it allows the optical waves to propagate nearly transversely to the acoustic waves at the expense of the shorter interaction length. By using multiple transducers, as shown in Fig. 2, more than one acoustic wavelength can be launched, thus broadening the effective optical passband. The noncollinear design is complicated in that the acoustic group-velocity vector departs from the phase-velocity vector at a specific walk-off angle. The short interaction length increases the required acoustic driving power. With the acoustic power density proportional to fourth power of the optical FOV, the choice of material becomes important. Historically, material preferences were developed by optimizing the various optical and acoustical parameters that result in a final figure of merit.[2,3]

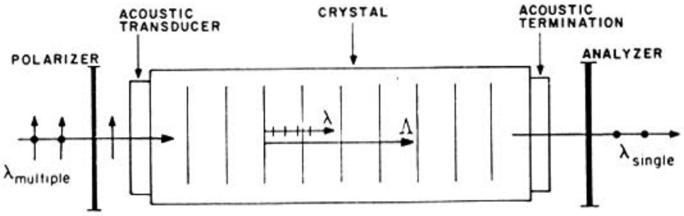

Fig. 1. Collinear AOTF.

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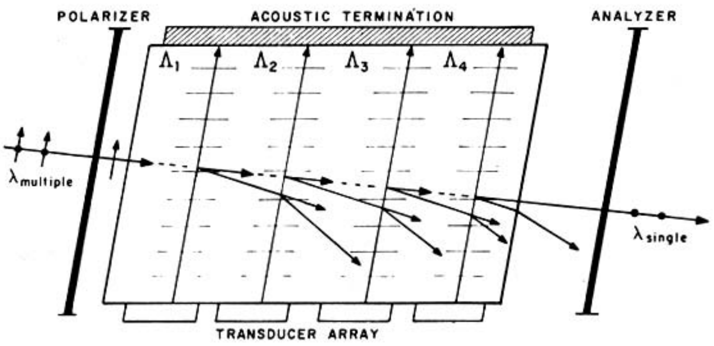

Fig. 2. Noncollinear AOTF.

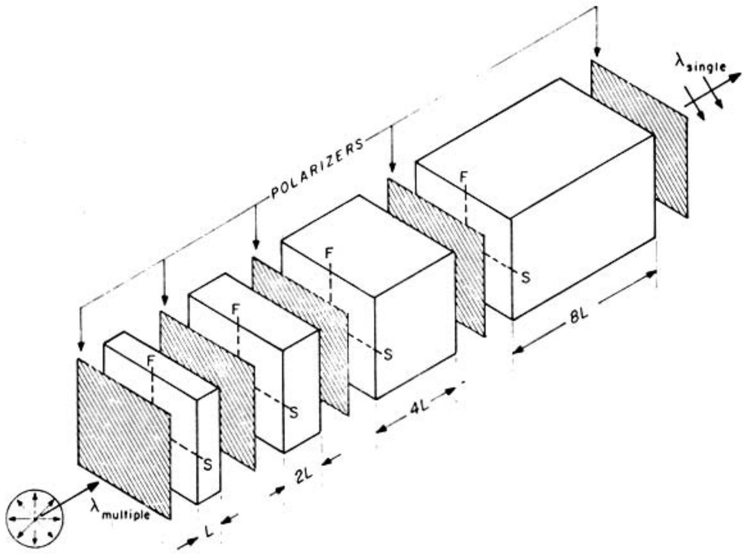

Fig. 3. Lyot filter.

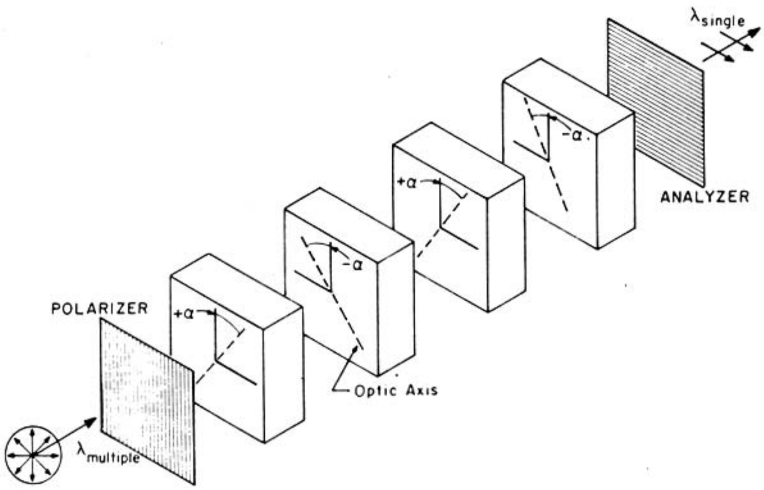

Fig. 4. Solc folded filter.

Combining the figure of merit with the required acoustic power density and normalized interaction length leads to a total optical-transmission coefficient for an AOTF.

MECHANICALLY TUNABLE BIREFRINGENT FILTER

The simplest mechanically tunable birefringent filter (MTBF) design uses a single birefringent element positioned between a crossed polarizer-analyzer combination. The basic phenomenon describing the MTBF can be referenced to early optical phase-compensation techniques using birefringent materials and polarizer-analyzer combinations.[4] The principle of operation is based on a phase shift in the polarization state of the transmitted light. In practice, the desired phase shift can be induced through the use of optically active materials. The slightly different refractive index along each optical axis supports differing phase velocities of the fundamental propagation frequency, resulting in a phase shift of the transmitted light. By definition, a given material thickness would then allow only a single frequency (and its integer multiples) to be transmitted. In order to narrow the bandpass, this Lyot[5] filter can be modified to incorporate the continuously doubling thickness ratio shown in Fig. 3. However, continuous spectral tuning of the simple birefringent filter is ideally possible only if the desired 2*N*th thickness ratio is maintained throughout the tuning range. This requires a continuous change of each birefringent element's thickness as different wavelengths are passed. By introducing variable phase plates in the form of Polaroid sheets, or by rotating or wedge-shaping the birefringent elements, one can make various filter designs mechanically tunable. Recently, a temperature-compensated MTBF with a 0.1-Å bandwidth and a 12-Å free spectral range was constructed[6] for operation in the visible spectrum.

ELECTRO-OPTIC TUNABLE FILTER

The desired phase shift in polarization can also be generated by materials that readily respond to an external electric field. Under an applied field, a material such as crystalline ammonium dihydrogen phosphate (ADP) will increase its birefringence. Obtaining fractional wavelength shifts with electrically controlled birefringent plates arranged in series has the advantage of inducing continuous wavelength variation without the adjustment discontinuities and slower tuning speed of the MTBF. In addition to developing the birefringent series filter shown in Fig. 4 with ADP, Solc[7] also initiated the practical use of tuned series filters in a converging beam of light and reported on the assemblage of an 80-plate electro-optic tunable filter (EOTF) device. In more recent work,[8] an EOTF was described with a $LiTaO_3$ platelet configuration operating with a transverse electric field between crossed polarizers and tuning over a very broad band from 4700 Å to 4.5 μm. As with the AOTF and MTBF, the EOTF out-of-band light leakage is also limited by the extinction ratio of the polarizers.

DUAL-TUNABLE FABRY-PEROT FILTER

Classically, the Fabry-Perot interferometer has always been considered a spectral filter with its operating principle based on the self-interference of light within a transmissive optical cavity. Traditional applications use a long cavity to achieve narrow but multiple bandwidths. Inserting a Fabry-Perot cavity or étalon inside a laser resonator is known to improve the spectral purity of the emitted wavelength(s). For such a cavity, the longitudinal mode separation for a specific optical wavelength is an inverse function of the cavity length.

To increase the bandwidth for broadband applications, the cavity length may be reduced. Since the determination of the spectral bandwidth does not depend on the polarization state of the incident light, the maximum achievable transmission approaching 100% is limited only by reflection lossses at the surface interfaces of the Fabry-Perot device. However, the associated out-of-band light leakage is typically greater than that exhibited by other TSF devices using crossed polarizers.

Although they are generally designed for parallel light transmission, Fabry-Perot devices have been adapted to converging beams. Recent work with short cavity lengths has resulted in a dual-tunable Fabry-Perot (DTFP) filter.[9] By translating multiple cavities that are optically decoupled, the DTFP filter can tune over broad spectral ranges. However, it is the selection of cavity substrate and coating materials that is crucial to the final design.

SUMMARY

Tunable spectral filters have been identified as an area of increased research activity in optics. With new applications anticipated in both industry and government, this research area will benefit directly from the exchange of ideas with members of the optical community currently involved in related fields. The Tunable Spectral Filter Workshop scheduled for the Optical Society of America's 1981 Annual Meeting will provide an opportunity for this interaction.

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