

Applications of acousto-optic devices for spectral imaging systems

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Abstract. The acousto-optic tunable filter (AOTF) is an example of a small number of commercially available optical filter technologies that lend themselves to imaging applications. AOTFs can cover an octave of optical frequency with access times of 10-25 μ s being typical. Diffraction efficiencies of 90% are not uncommon, and RF drive powers of substantially >1W are possible in the visible region of the spectrum. Recently, there has been much interest in AOTF technology for various applications related to hyperspectral imaging, including fluorescence microscopy, endoscopy, and various military topics. The recent trend towards large aperture devices suitable for imaging applications has put pressure on the paratellurite (TeO₂) crystal growers and the component manufacturers, and has resulted in an upsurge in research activity in these areas. The majority of commercial AOTFs use TeO₂, which is transparent from approximately 0.36 μ m to 4.5 μ m. Many of the important AOTF design considerations are common to all these wavelength ranges, i.e. are device independent. Image quality, side-lobe level, and spectral purity are inter-related in an interesting way in an AOTF and using careful design, -30dB side-lobe levels and diffraction-limited images can be achieved. We discuss the issues effecting the performance and design of an AOTF and describe our recent and current work on AOTFs suitable for inclusion in high quality hyperspectral imaging systems.

There is an increasing interest in spectral imaging systems for application to a number of areas. These include aerial observation, medical microscopy, endoscopy as well as art conservation. The fastest growing area is that of medical imaging. Typical filter requirements for such an application are:

- The filter must be tunable across the visible spectrum (at least 450nm < λ < 700nm)
- The pass-band must be narrow to discriminate between wavelengths of interest, but at the same time, broad enough to allow sufficient energy to pass to the detector array
- The aperture size and field of view should be matched to the optical system
- There should be little or no image distortion

An acousto-optic tunable filter (AOTF) with careful design can fulfil all of these requirements.

1. How does an AOTF work?

An AOTF is essentially a solid-state agile random-access tunable filter, the wavelength being selected by the RF drive frequency^[1]. Most AOTFs use tellurium dioxide (TeO₂) as the interaction medium. This discussion is limited to TeO₂. Figure 1 explains the fundamental principles of operation for a non-collinear AOTF in TeO₂.

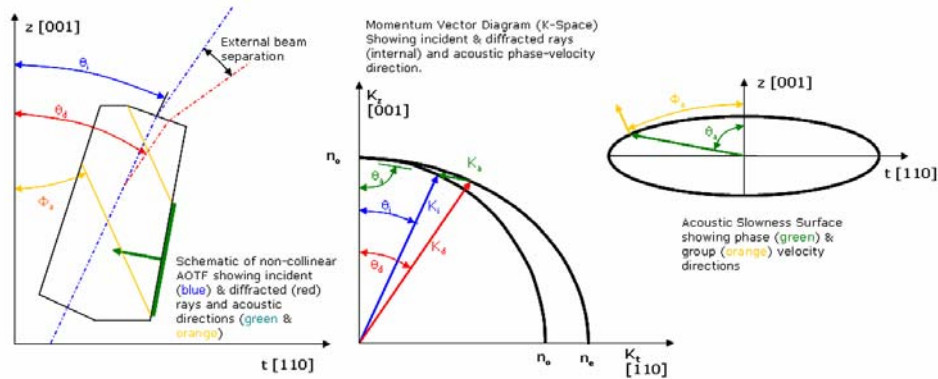


Figure 1: Geometry of non-collinear, parallel-tangents AOTF relative to refractive-index and acoustic-slowness surfaces.

The diagram shows a slice of TeO_2 in the t - z plane, an orientation that is a 45° rotation about the z -axis. The t -axis is along the $[110]$ direction and the z -axis is the $[001]$. This orientation is chosen as it gives the most efficient acousto-optic interaction. The left-hand diagram depicts the AOTF cell relative to the crystal axes, in the centre the K -space momentum vector-diagram and to the right the acoustic slowness surface.

The K -space diagram is a representation of the phonon-photon interaction at a single wavelength. The circle and ellipse are the refractive-index surfaces for all directions between the t and z . Since the material is symmetric, only the first quadrant - ignoring optical activity - is shown. The vectors \mathbf{k}_i and \mathbf{k}_d respectively are representations of the incident and diffracted beams idealised as plane waves. \mathbf{K}_a represents the acoustic beam. The directions of the three vectors (θ_i , θ_d and θ_a as measured from the $[001]$) are the directions of the phase velocities in all three cases. The magnitude of \mathbf{K}_a is a measure of the acoustic wavelength (Λ) and hence the acoustic frequency (f). The vector triangle $\mathbf{k}_i - \mathbf{K}_a - \mathbf{k}_d$ represents the condition for phase-matching when diffraction will occur.

AOTFs use the slow-shear acousto-optic interaction. This is polarisation sensitive. For an optical input along the z -axis ($\theta_i=0$) the polarisation should be circular for 100% (relative) efficiency, or along the t -axis ($\theta_i=90^\circ$) linearly polarised. For directions in-between, the input should be some elliptical state for maximum diffraction efficiency. In practice, this will approximate to a linear state for $\theta_i > 10^\circ$ i.e. far enough away from the optic axis to ignore optical activity. The diffracted beam will be polarisation rotated by 90° .

Most AOTFs are designed to operate in the “parallel tangents” condition. This simply means that the tangents to the index surfaces at \mathbf{k}_i and \mathbf{k}_d are parallel. Therefore, for small changes in θ_i phase-matching will still occur for the same \mathbf{K}_a . The limit for which this is valid represents the available internal field of view of the AOTF.

For a given wavelength range, there will be an infinite number of separate diagrams with differing index surface profiles, one per wavelength. In practice, the vector \mathbf{K}_a will not be perfectly defined, but will have a spread or “fuzziness” associated with it because of the necessarily finite size of the acoustic transducer. This produces acoustic divergence and it is this divergence that defines the width of the pass-band in the wavelength domain. The acoustic divergence is primarily determined by the length of the acoustic transducer. The shape of the acoustic intensity distribution also defines the acoustic side-lobes. These in turn define the side-lobes in the wavelength domain.

TeO₂ is acoustically anisotropic, the direction of energy propagation being in the direction of the group velocity (Φ_a). The acoustic slowness surface (inverse velocity) is the analogue of the refractive index surface of the K-Vector diagram. The direction of Φ_a is the normal to the slowness surface at θ_a .

2. Design of an imaging AOTF

In imaging applications, side-lobes, scene-shift and acoustic blur are important aspects of the filter design as well as key areas in the optimisation of an imaging system. We here discuss these issues and present some recent results of an AOTF optimised to minimise them.

2.1 Side-lobes

Side-lobes result from the angular plane wave distribution of the acoustic field produced by the transducer. In the low efficiency limit, the optical band-shape function is related to the Fourier Transform of the acoustic amplitude distribution. For example, a rectangular acoustic profile as produced by a uniform acoustic transducer will give the “traditional” sinc² distribution (figure 2).

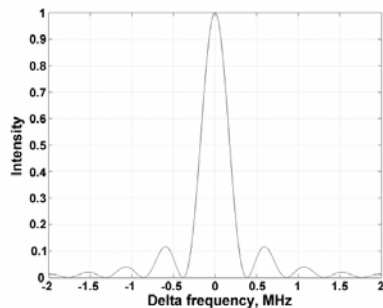


Figure 2: Conventional AOTF pass-band showing side-lobes.

Control of the acoustic intensity profile will also control the side-lobes. Conventionally, this is done by shaping the transducer. Typically this can reduce the side-lobe intensity to a few percent or about 10-15dB suppression. Another technique is to segment the transducer along its length into discrete zones, and to vary the drive power in a controlled manner to these zones. By distributing the power along the effective transducer length so as to produce a stepwise approximation to a Gaussian function, the Fourier Transform will also be substantially Gaussian. Within the Gooch & Housego group this has been achieved, and side-lobe suppression of <-20dB has been demonstrated (figure 3).

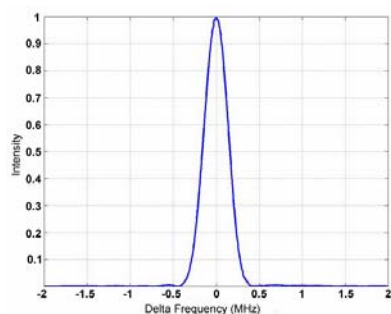


Figure 3: AOTF Multi-transducer pass-band demonstrating side-lobe suppression.

The transducer has 15 segments, each connected independently to a special RF drive system. The AOTF in question is shown in figure 4.



Figure 4: Multi-channel AOTF end-view.

2.2 Scene-shift or chromatic aberration

As the AOTF is tuned, K_a will change in length and thus θ_d will change causing the diffracted beam to scan with drive frequency. Since the wavelength associated with k_d is also changing, the dispersion inherent in TeO_2 can be and is used to compensate for the scanning effect. With first-order correction of this type, pointing stability of the order of 0.1mrad is achievable – and so scene-shift need not be a problem.

2.3 Acousto-optic blur

Acousto-optic blur results from very small uncertainties in the diffraction angle brought about by acoustic spread. It manifests itself as a distortion of the image in the Bragg plane. It may be reduced by minimising the acoustic divergence. This is generally achieved by maximising the interaction length. Figure 5 gives an indication of acousto-optic blur in the multi-segmented AOTF described above.

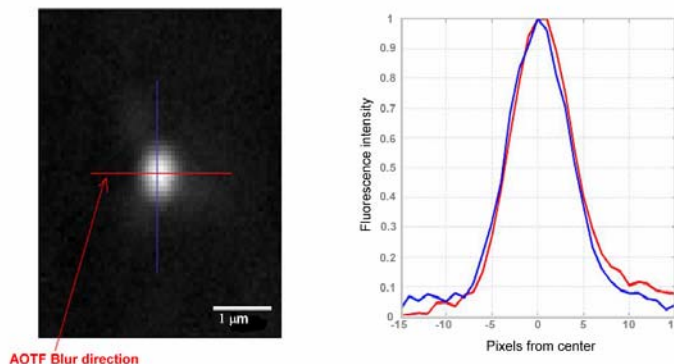


Figure 5: Acousto-optic blur.

A 0.1 μm diameter fluorescence bead is shown imaged through the AOTF module. Acousto-optic blur only occurs in the horizontal (red) direction (left figure). The size of the bead in the vertical direction (blue) therefore gives a measure of the native, nominally diffracted-limited resolution of the microscope. Blur is negligible in this case and diffraction-limited imaging is being achieved.

Aside from the specific design parameters discussed above, other more general features affect the overall system design. An imaging system based on an AOTF can exploit its unique performance potential.

2.3 Spectral range

TeO_2 is transparent in the range 450nm-4 μm . At the UV end of the spectrum the usable range may be extended further to beyond 430nm provided high optical powers are not used. This gives the AOTF a performance advantage when compared to some other technologies.

2.4 Pass-band resolution

As discussed in 1 above, the pass-band resolution of the AOTF ($\Delta\lambda$) is set by the acoustic divergence. In order to minimise blur, the divergence is set to be low giving narrow resolution. In some applications however it is desirable to have broader resolution in order to increase the net throughput of light.

Pass-band broadening of an AOTF can be achieved by driving the transducer with multiple frequencies. The spacing of these frequencies (together with $\Delta\lambda$) will define the resultant pass-band shape. Similarly, by driving the AOTF at multiple widely-spaced frequencies will result in multiple widely-spaced pass-bands. Thus multiple colours may be selected simultaneously.

2.5 Aperture/Field of view

Ultimately, the aperture size of an AOTF is limited by the availability of imaging-quality TeO_2 . Other factors influencing the performance are acoustic adsorption which leads to a variation in diffraction efficiency across the aperture and RF drive power which increases in direct proportion to the aperture height.

The acceptance angle or field of view is defined by the acoustic divergence and hence the transducer length. There is often a trade-off between acceptance angle and pass-band resolution. Some users mistakenly confuse beam-separation with acceptance angle. Generally the acceptance angle is less than the separation between diffracted and zero-order beams. Overfilling the acceptance field of view will result in an effective broadening of the pass-band resolution.

AOTFs with aperture sizes in excess of 12mm x 12mm with a field of view in excess of 4° may be realised. Figure 6 shows an example of a large aperture AOTF.

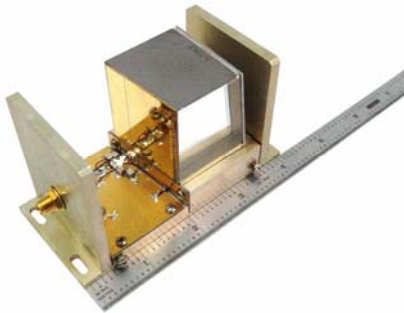


Figure 6: Large aperture imaging AOTF.

2.6 Speed

Calculation of the access time of an AOTF is not straightforward because of the complex geometry of the device. In essence, it is determined by the acoustic velocity which is of the order of 0.6 mm/ μs . Typical access time for a large aperture device will be $<25\mu\text{s}$.

3. AOTF: Performance with a future

The AOTF is one of the few mature technologies capable of yielding fast, real time tunable filters for optical imaging applications. However, it needs care with the design and integration into the optical system. Given this, diffraction-limited performance can be achieved, fast colour measurement is possible, and the AOTF will give partial polarisation information too. We believe the AOTF is the fastest currently available option $\sim 20\mu\text{s}/\text{frame}$ typical. It can be used in colour matching applications and in hyperspectral microscopy provided side-lobes are controlled.

The wavelength range for an individual device is typically limited to an octave of frequency, although there are schemes to extend this range. The transparency range of TeO_2 is nominally 450nm-4 μm , although this is extendable at either end. State-of-the-art AOTFs achieve this level of performance and work. Work is in progress to refine AOTFs still further. This includes enhanced side-lobe suppression (>35dB), a simpler, more user-friendly embodiment of the driver topology and interface. Also the use of other materials is under consideration for extending the range into the UV or IR. A hyperspectral imaging system designed in conjunction with an AOTF can fully exploit these features.

Finally, AOTFs are finding their way into real systems and are attracting commercial interest. Figure 7^[2] shows results from an AOTF-based system designed for mineral analysis in the field.

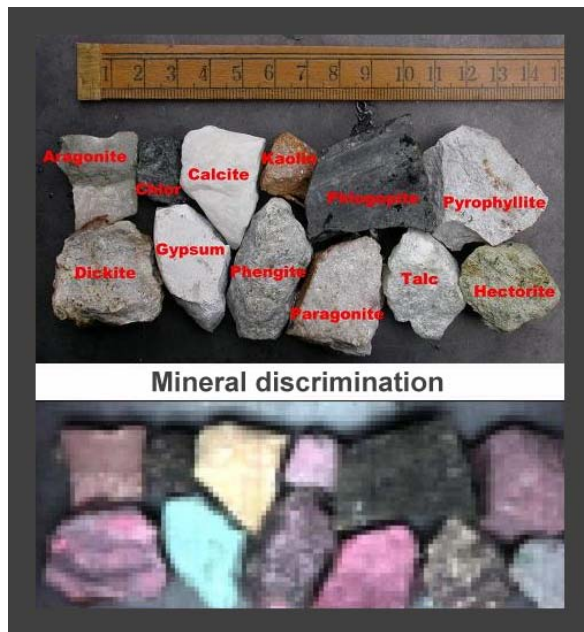


Figure 7: White-light image of mineral samples and false-colour infra-red image.

Figure 8^[3] shows a multi-colour image of a plastic ruler and a snapshot taken through an AOTF at a single wavelength in the green region of the spectrum.



Figure 8: White-light image of plastic ruler and as viewed through green filter.

A series of such snapshots can be taken to build-up a data-cube. Figure 9 displays a typical data-cube from an AOTF hyperspectral imager currently under commercial development in the Gooch & Housego group.

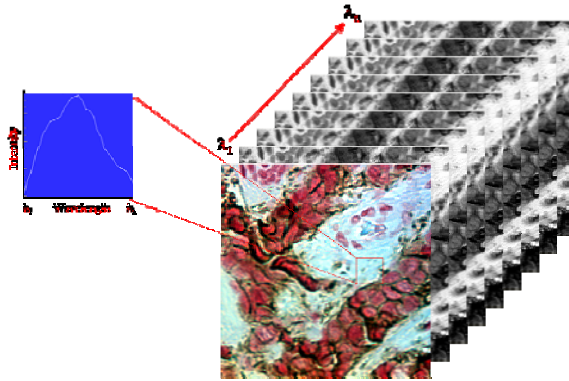


Figure 9: Data-cube constructed from series of monochromatic images.

Reference list:

- [1] There are many texts e.g. Acousto-Optic Devices, Xu & Stroud, Wiley Interscience
- [2] Courtesy of Spectra-Map - www.spectra-map.co.uk
- [3] Courtesy of Think Spectrally - www.thinkspectrally.com