Acousto-Optic Tunable Filters (AOTFs) Optimised for Operation in the 2-4µm region

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Abstract. Acousto-Optic Tunable Filters (AOTFs) are electronically-controlled bandpass optical filters. They are often preferred in applications in spectroscopy where their agility and rapid random-access tuning can be deployed to advantage. When used for spectral imaging a large aperture (typically 10mm or more) is desired in order to permit sufficient optical throughput. However, in the mid IR the λ^2 dependence on RF drive power combined with the large aperture can prove to be a hurdle, often making them impractical for many applications beyond about 2µm.We describe and compare a series of specialised free-space configurations of AOTF made from single crystal tellurium dioxide, that require relatively low RF drive power. We report on AOTFs specifically optimised for operation with a new generation of Supercontinuum source operating in the 2-4µm window and show how these may be used in a spectral imaging system. Finally, we describe an AOTF with an (acoustic) Fabry-Perot cavity operating at acoustic resonance rather than the conventional travelling-wave mode; the acoustic power requirement therefore being reduced. We present an analysis of the predicted performance. In addition, we address the practical issues in deploying such a scheme and outline the design of a prototype "resonant AOTF" operating in the 1-2µm region.

1. Introduction

The principles of acousto-optics have been known for some time, but it is only since the advent of the laser that the science has developed and practical devices found application. Bulk AO devices are used in many forms but principally Q-Switches, Mode-Lockers, Modulators, Deflectors, Frequency-Shifters [refs] and Tunable Filters, together with variations such as Cavity Dumpers and Pulse-Pickers [1].

An Acousto-Optic (AO) device is essentially an optical cell with an ultrasonic transducer (generally in the 10s/100s MHz region) bonded to one of its faces. The acoustic beam creates a sinusoidal perturbation of the refractive index of the medium due to the photoelastic effect which acts as a volume diffraction grating. An optical beam will interact with the induced grating when the angle of incidence and wavelength are matched to the grating periodicity, causing the optical beam to be diffracted at a given angle. The grating periodicity is determined by the acoustic velocity and frequency.

Most AO devices rely upon the "isotropic" AO interaction where the refractive indices of the incident and diffracted beams are the same; the acoustic beam propagates as a longitudinal mode. These devices often referred to as "Bragg Cells" form the basis of modulators and Q-switches etc [1]. However, there is another family of AO devices that utilise the "anisotropic" AO interaction [1]. As the term implies, this interaction requires an optically anisotropic (birefringent) medium, and the incident and diffracted beams have different (ordinary/extraordinary) refractive indices. In addition, the acoustic beam propagates in the slow-shear mode. As a result, the polarisation state of the optical beam is altered at the interaction. To a very good approximation one can say that a linearly polarised input results in a diffracted beam with the plane of polarisation rotated by 90º.

The intensity of the diffracted beam is a function of the power of the acoustic beam. It can be shown that [2]

$$DE = \frac{I_d}{I_0} \approx \sin^2 \sqrt{\frac{\pi^2 L M_2 P}{2H\lambda^2}} \qquad (1)$$

So that maximum diffraction efficiency (*DE*) occurs when

$$P_0 = \frac{H\lambda^2}{2M_2 L} \qquad (2)$$

Where *H* is the height of the acoustic field, *L* is the interaction-length and λ is the light vacuum wavelength. The parameter M_2 is known as the "Acousto-Optic figure of merit", it is material dependent and is a measure of the effectiveness or strength of the AO interaction. It is important to note that the required drive power increases with the square of the wavelength. This becomes very important when designing AOTFs to operate in the infra-red, particularly beyond about 2μm.

2. ACOUSTO OPTIC TUNABLE FILTER

The Acousto Optic Tunable Filter (AOTF) exploits the slow-shear anisotropic interaction to realise a solid-state agile random-access electronically addressable tunable filter, the wavelength being selected by the RF drive frequency. Most AOTFs are made from single crystal tellurium dioxide (TeO_2). TeO_2 is transparent over the range 400nm to 4·5μm and is available with good optical quality. Importantly it has a relatively high value of M_2. The acousto-optic interaction takes place when the phase matching condition between photon-phonon interaction as defined by the K-space diagram [2] is satisfied. The filtered wavelength depends on the RF frequency applied to the ultrasonic transducer.

2.1. Non Collinear AOTF

In theory an infinite number of configurations of incident and acoustic angle are possible; so long as the phase-matching condition in K-space is satisfied. However, in practice it is useful to introduce some constraint. Most AOTFs are designed to operate in the "parallel tangents" condition [3], which yields devices (figure 1-a) with the widest field of view and is generally preferred for this reason.

2.2. Quasi Collinear AOTF

It will be noted that the direction of energy propagation or group-velocity of the acoustic beam (ie walk-off) is in general different to the phase velocity. This is a consequence of TeO_2 being acoustically anisotropic. The effect is significant, so when designing a "parallel-tangents" AOTF care needs to be taken to manage the acoustic energy. An alternative constraint may be introduced such that the acoustic group-velocity direction is parallel with the input beam [4]. One way of achieving this is to reflect the acoustic beam at an optical interface (figure 1-b). In this case there will be excellent overlap between the acoustic and optical beams and the interaction-length may be made to be relatively long. This results in AOTFs with low drive power and narrow resolution [5]. By choosing the appropriate cut/orientation of TeO_2 the AOTF may be optimised to minimise drive power or to achieve narrower linewidth. A downside is that the field of view is restricted, so much so that in

general the optical input needs to be at or very close to the diffraction-limit. Such AOTFs are known as Quasi-Collinear or sometimes Collinear Beam AOTFs.
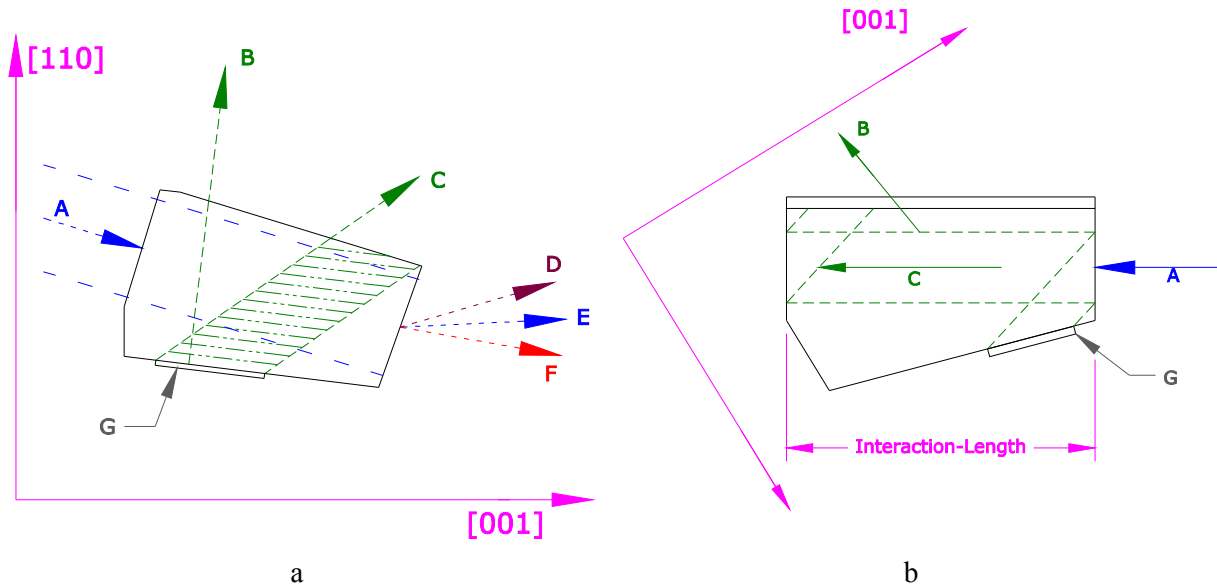

Figure 1. Configuration of (a) non-collinear AOTF & (b) Quasi-Collinear AOTF
A – unpolarised input optical beam, B - acoustic phase-velocity direction, C - acoustic group-velocity direction, D – vertically polarised diffracted order, E – 0-order, F - horizontally polarised diffracted order, G – acoustic transducer

3. OPERATION IN THE INFRA-RED

Tellurium dioxide is transparent to beyond 4µm. However, from equation 2 it is apparent that the drive power required increases with λ^2. This effect becomes noticeable at about 1µm and is compounded by the fact that the figure of merit (M_2) also decreases with increasing wavelength. The drive power becomes a major if not the overriding factor in the realisation of AOTFs at wavelengths beyond about 2µm.

3.1. Quasi-Collinear

For the reasons stated above, AOTF designs that inherently use lower power are of interest. In particular, the ongoing developments in ZBLAN based Supercontinuum sources operating beyond 2µm [6] have focussed attention on Quasi-Collinear AOTF designs since the Supercontinuum source has a single spatial mode output that aligns well with the angular aperture limitation of the Quasi-Collinear configuration. In addition, there was a desire to deliver an output with an unusually narrow spectral linewidth [7].

We have built a Quasi-Collinear AOTF that tunes from 2 to 4·5µm. The interaction-length at 40mm is longer than is normal resulting in a narrow passband; initial evaluation figures indicating δλ<1nm @ 2µm with modest drive power for an AOTF at this wavelength <0·25W @ 2µm giving excellent agreement with the design predictions. In addition to this AOTF, manufacture of a "cut-down" version with an interaction length of 20mm is well under way. This will have a passband approximately twice as broad and a slightly larger acceptance angle. Thus, it will be easier to align and allow a greater throughput making it more practical for a number of applications. When used in conjunction with the Supercontinuum this combination makes for an interesting illumination source for hyperspectral imaging. It is particularly appropriate for use on microscope based systems and dispenses with the

need for a filter in front of the detector [7]. True hyperspectral operation is achievable since the AOTF is continuously tunable across the range; the system not being restricted to a fixed number of wavelength bands. In addition, the AOTF is truly random access and fast, characterized by a switching time of less than 100μs to tune between wavelengths. In actual fact, the long interaction length makes this AOTF relatively slow in comparison to other AOTFs.

3.2. Resonant Acoustic AOTF
An AOTF with a wider field of view and low drive power is also desirable. Returning to equation 2 it can be seen that the drive power requirement is inversely dependent upon the interaction length, thus one option would be to design a "long" AOTF. Eventually however practical limitations, not least the availability of good quality single crystal TeO_2 of sufficient dimensions restrict the ultimate size that is achievable. An alternative approach is to make better use of the acoustic energy, and rather than just "throw it away" at an acoustic dump to re-use it. To this end we have designed an acoustically resonant AOTF, where the opposite face to the transducer face is polished to be parallel. In this way we can create an acoustic resonant cavity and fill it with a standing acoustic wave, as near-perfect acoustic reflection will take place at the TeO_2/air boundary. Thus, when modelling the cavity the parameters of interest will principally be acoustic attenuation and divergence.

We have demonstrated the concept [8] by adapting a travelling-wave AOTF into a standing-wave AOTF, tuning across the 1-2μm region. Optical and pulse-echo acoustic measurements have indicated a gain of at least a factor of 4. This is in-line with our predictions based on acoustic attenuation and divergence. Resonance may be detected by monitoring the reflected RF signal from the transducer. The stability of the device was reasonable given that there is no active temperature control; experiments are in-hand to further investigate this point. Overall, the results were sufficiently encouraging for us to design a carefully optimised resonant AOTF to tune across the 2-4μm region. In addition, a specialised RF driver prototype to accompany the new device is also under design. This will continuously monitor the reflected RF signal and lock on to the resonance.

4. CONCLUSION
Despite the inherently high RF drive-power requirement at longer wavelengths, practical AOTFs may be built operating to the transmission window limit of 4·5μm. Further improvements are possible using carefully optimised resonant designs.

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