**AN0998** **Sept 98**

# Acousto Optic Tuneable Filters

## Basic Theory

## And

## Design Considerations

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## 1. Acousto-optic Basics

All AO devices feature a piezo-electric transducer bonded to one face a transparent crystalline material. When an RF drive signal is applied to the transducer, a travelling acoustic wave is produced in the crystal. This in turn produces a periodic change in the refractive index via the photo-elastic effect. These regions of compression and rarefraction , are similar in effect to the slits in a transmissive diffraction grating. As per a thin diffraction grating, an incident optical beam will be diffracted into many orders if the AO interaction length is small. This is called the Raman-Nath AO diffraction region.

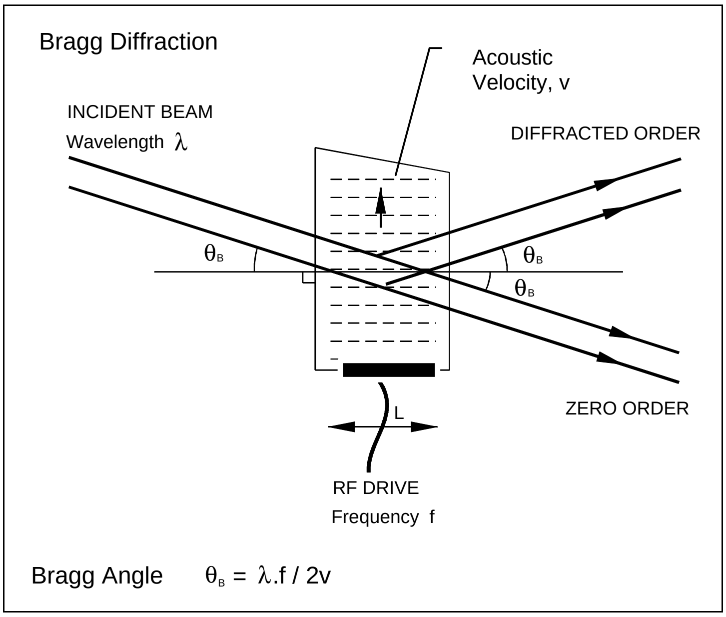


Fig 1.

For practical applications such as modulators and deflectors, AO devices operate in the Bragg regime where the majority of the diffracted light appears in one order. This is achieved by having a long interaction length L, and inputting the incident light at a specific angle, the Bragg angle. The Bragg angle is a function of the optical wavelength, the acoustic frequency and the acoustic velocity in the interaction material. Under these conditions, interaction becomes sensitive to errors in the Bragg angle, in other words, efficiency is a directly related to the divergence of the input beam. As a consequence Bragg devices are generally associated with laser based systems, being very well suited to the pseudo collimated output characteristics of a typical laser. In such systems, the laser beam intensity can be modulated by changing the RF power level to the AO device, scanned by changing the drive frequency



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and as a result of the interaction the output beam is also frequency shifted by the acoustic frequency; useful in heterodyne systems.

## 2.0 Acousto-optic Tuneable Filter

The basic philosophy behind AOTF is to use the inherent wavelength sensitivity of Bragg diffraction to create an electronically controlled optical filter. However compared to the usual modulator and deflector AO devices, the design requirements for the Acousto-optic tuneable filter differ in a number of key areas.

| AO Modulator / Deflector | AO Tuneable Filter |
|---|---|
| Input source – Laser | Input source – Lamp<br>- multiline laser |
| Input wavelength is constant | Input is broadband and variable |
| Incident beam is quasi-collimated | The optical input is divergent & non directional |
| RF drive defines the output characteristic e.g. modulated beam | Optical input defines the output characteristic e.g. spectroscopy |

In summary, the AOTF must offer :

- Low sensitivity to input angle
- High selectivity in wavelength

## 2.1 Basic Theory

Only a brief overview of AOTF theory is given here. For simplicity, the basic principles will be discussed by comparison of momentum matching triangles and angular plots. These graphically illustrate the conditions required for acousto-optic interaction in isotropic and birefringent materials.

## 2.2 Isotropic Interaction

For isotropic diffraction (typical of most modulator materials), $n_i = n_d$ and the relationship between the incident and diffracted beams is constant. I.e. $\theta_I = \theta_d = \theta_{bragg}$.



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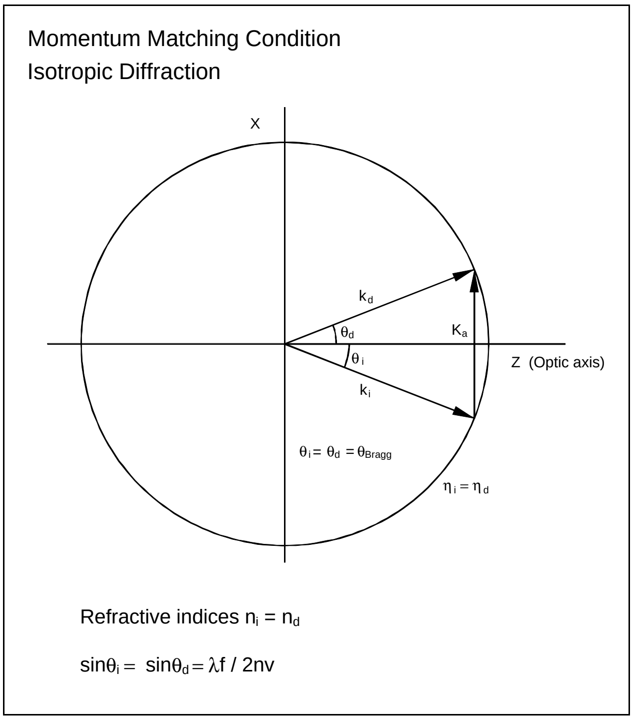



Fig 2.

From the plot of incident and diffracted angles it can be seen that regardless off choice of $\lambda$, frequency. or velocity, isotropic phase matching remains sensitive to incident angle. As a consequence isotropic Bragg diffraction has thus not found any practical filtering applications.

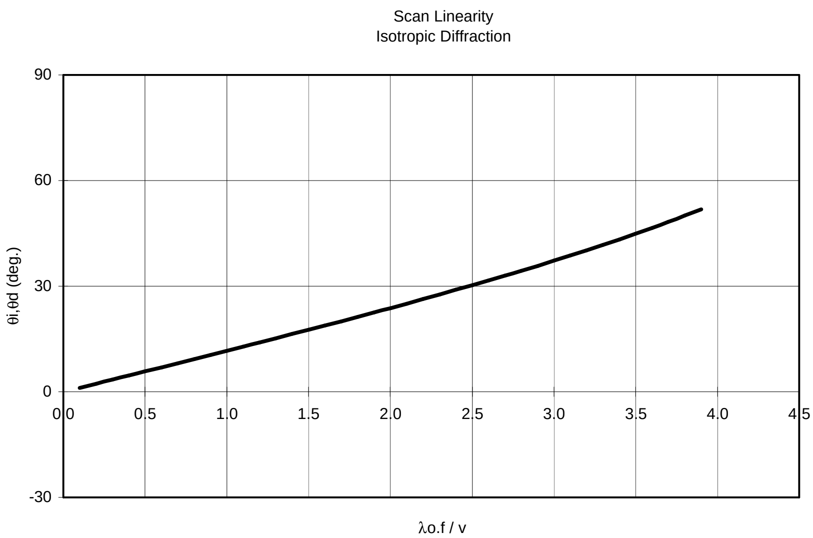
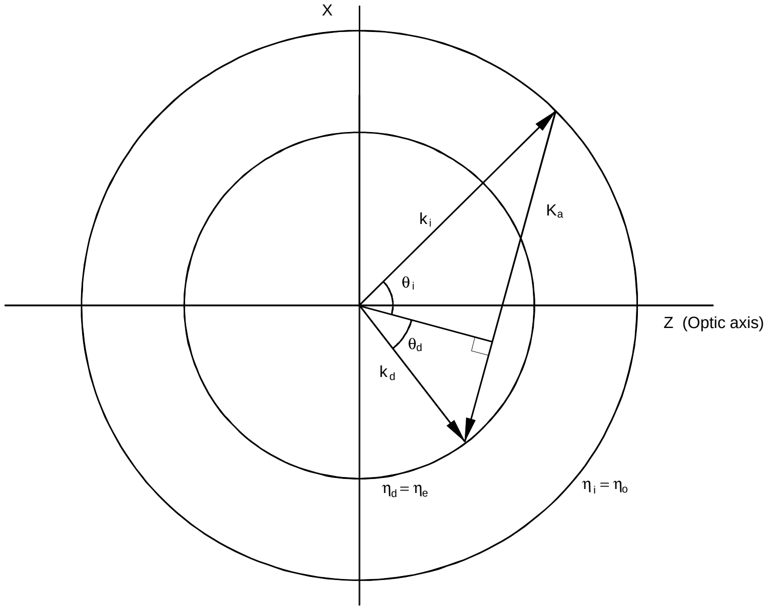



Fig 3

### 2.3 Anisotropic Interaction

This is not the case with anisotropic materials in which the refractive indices for the incident ($n_i$) and diffracted ($n_d$) beam differ due to the birefringence in the material. The 'Dixon' equations describe the Bragg angles of incidence and diffraction for strong interaction in birefringent materials. As shown, the angles of incidence and diffraction required for ideal momentum matching are not equal.

Momentum Matching Condition
Anisotropic Diffraction




$$\sin\theta_i = \frac{\lambda}{2n_i v}\left[f + \frac{v^2}{\lambda^2 f}(n_i^2 - n_d^2)\right] \qquad n_i \neq n_d$$

$$\sin\theta_d = \frac{\lambda}{2n_d v}\left[f - \frac{v^2}{\lambda^2 f}(n_i^2 - n_d^2)\right]$$

Fig 4.

In terms of the angular plot :

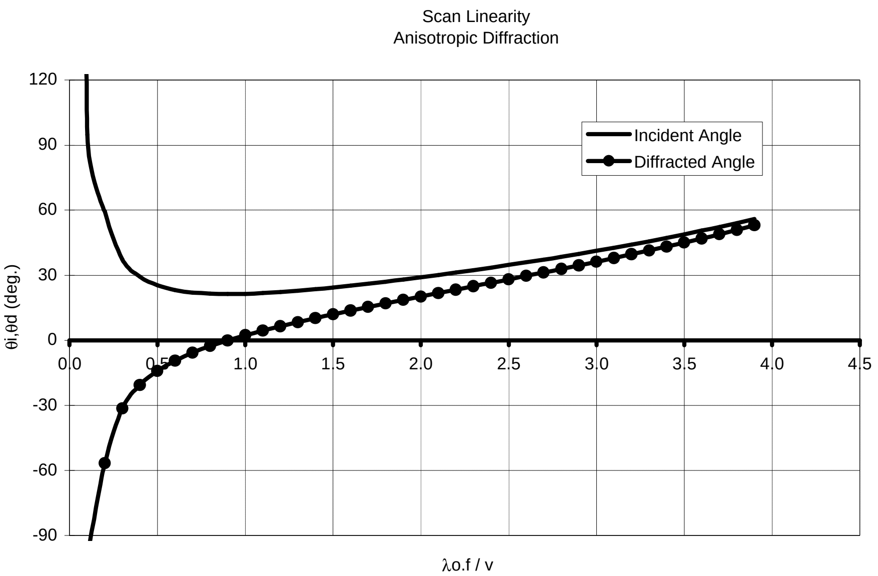



Fig 5.

There are two significant regions of this characteristic:

- The first region is about the turning point of the incidence curve. Here, the characteristics are quite the opposite of that required for an AOTF i.e. a narrow acceptance range of incident angle for a relatively large change in frequency (or $\lambda$). This is ideal characteristic for wide bandwidth AO deflector where large change in frequency results in only a small error in input Bragg angle.

- The significant region for AOTF operation, is the area corresponding to the minimum frequency for which momentum matching can take place i.e. $\sin\theta_I = \sin\theta_d = 1$ and the wave vectors are parallel. It can been seen that there is a large acceptance window of $\theta_i$, for a very narrow change in frequency.

The corresponding vector diagram for the momentum matching condition is shown below with the incident, diffracted and acoustic waves all propagating along the same direction



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**2.4 <u>Collinear AOTF</u>**

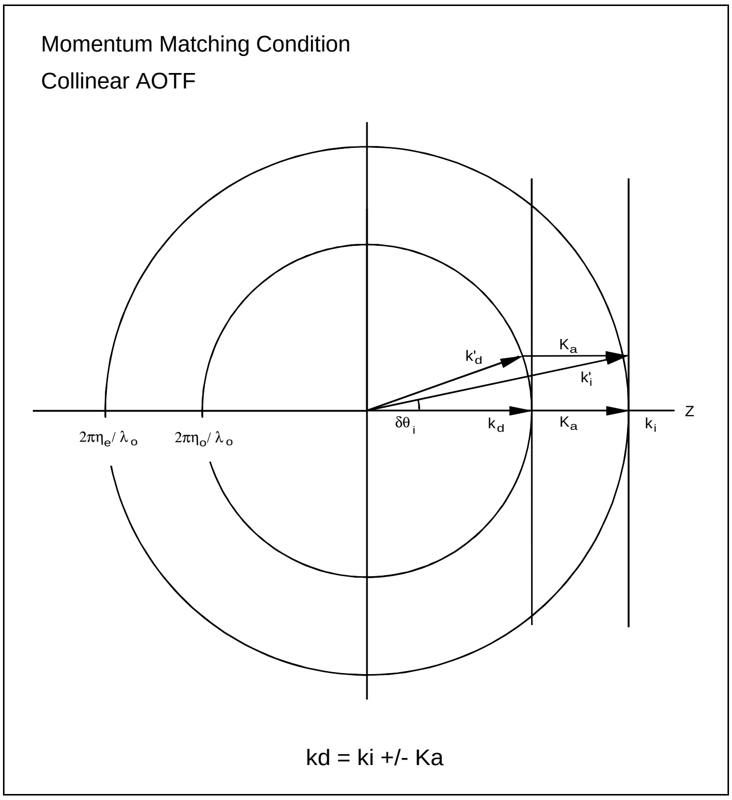


Fig 6.

This diagram highlights an important feature of AOTF's ; the tangents to the wave vector surfaces at the end of the incident vector $k_i$ and diffracted vector $k_d$ are parallel. As shown, for a reasonable change in incident angle $\delta\theta_i$, the momentum matching condition ($k_d = k_i \pm Ka$) remains satisfied to a first approximation for the same $k_i$ ($\lambda$) and Ka (freq). As a result, wavelength selectivity is retained and angular sensitivity ($\delta\theta_i$ ) is minimised.

The AOTF above is described as the collinear AOTF. Isomet offered commercial devices fabricated form $CaMoO4$ back in the late 70's. These devices are complex and thus costly to manufacture. As the <u>vector diagram</u> shows, the acoustic and optical beams are collinear. There is no spatial separation between the incident and diffracted beams and thus complex arrangements for launching the acoustic wave into the crystals and separating the optical output beams is required.



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One such arrangements is illustrated here.

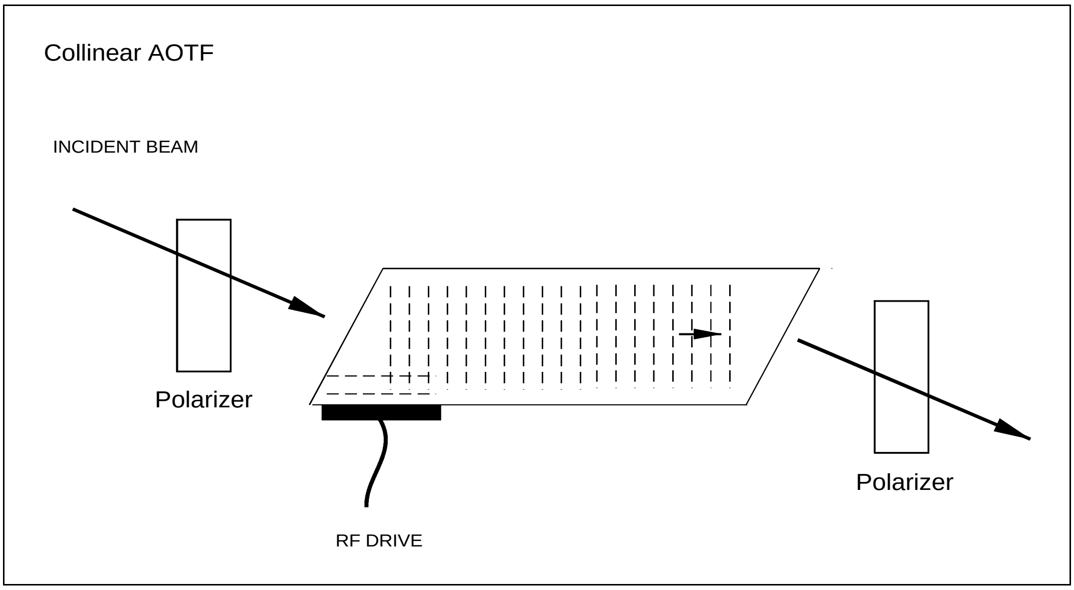


Fig 7.

An additional draw back of this type of AOTF is a limitation in choice of materials which exhibit collinear interaction. As a result of these drawbacks, collinear AOTF devices are not favoured.

## 2.5 Non-collinear AOTF

Today the vast majority of AOTF finding commercial/industrial applications are non-collinear devices. The development of this class of AOTF devices (by Chang and others) followed the discovery of the highly efficient AO material $TeO_2$ in the early 70's

The theory behind non-collinear interaction is well documented. In brief, the basic concept capitalises on the change in birefringence as a function of incident angle. This in effect is used to compensate for the momentum mismatch that occurs between the incident light and acoustic waves across a large input acceptance angle.

Similar to the collinear AOTF, the design is optimised when the tangents to the wave vector surfaces at the end of the incident vector $k_i$ and diffracted vector $k_d$ are parallel. The wave vector diagram for the non-collinear AOTF illustrates this parallel tangent condition and is shown with the input light extraordinary polarised

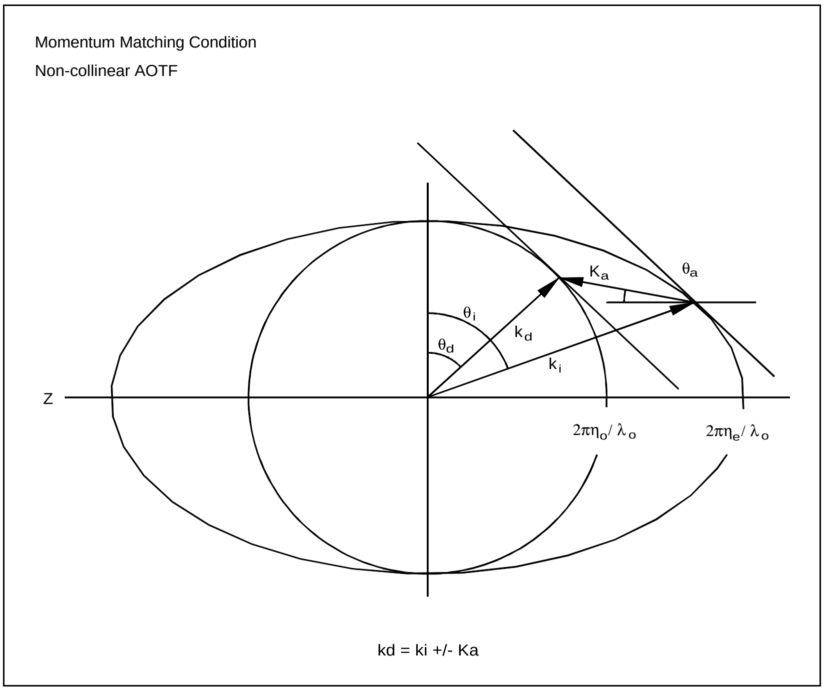


Fig 8.

By selecting an appropriate angle ($\theta_a$ ) and magnitude for the acoustic vector, the parallel tangent condition can be satisfied for any incident angle ($\theta_i$). The relationship between these angles is dependent only on the incident angle and is thus independent of material properties.

$$\theta_a = \theta_i + \operatorname{atan}( 2.\cot \theta_a)$$

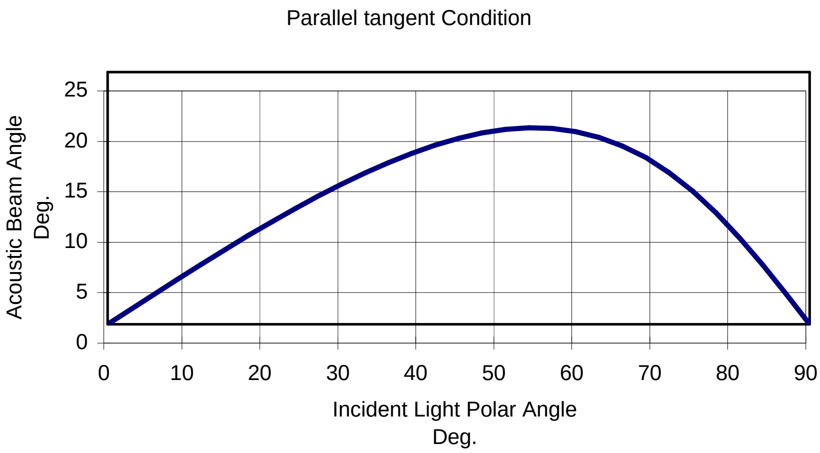


Fig 9.



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An incident angle of 0° represents vanishing birefringence and an angle of 90° is equivalent to the collinear AOTF. For practical considerations, incident angles are chosen in the range below the peak at 55°.

Because of the fixed relationship between the incident and acoustic angles, the choice of $\theta_I$ and the interaction length L effect all the key design parameters of the AO filter, namely:

| AOTF Performance Parameters |
|---|
| Resolution |
| Angular Aperture (FOV) |
| Tuning Relationship |
| Output Separation Angles |
| Figure of Merit (RF drive power) |
| Acoustic Velocity (Tuning rate) |

It therefore informative to display these characteristics in relation to the incident angle

By way of example, Tellurium Dioxide, $TeO_2$ is used to illustrate the filter performance characteristics. This material has a very high figure of merit, has useful anisotropic diffraction, is transmissive from the visible to the IR, and is relatively easy to grow and fabricate.

## 3.0 Design Parameters

Non-collinear AOTF

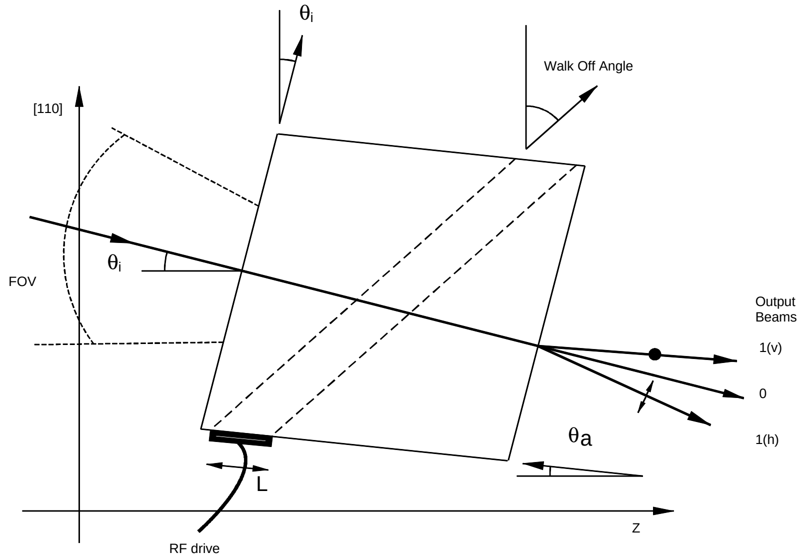


Fig 10.

## 3.1 Resolution

The FWHM spectral bandwidth is a function of incident angle, $\theta_i$ and the interaction length,L given by:

$$\Delta\lambda_0 = \frac{1.8\,\pi\,\lambda_0^2}{b\,L\,\sin^2\theta_i}$$

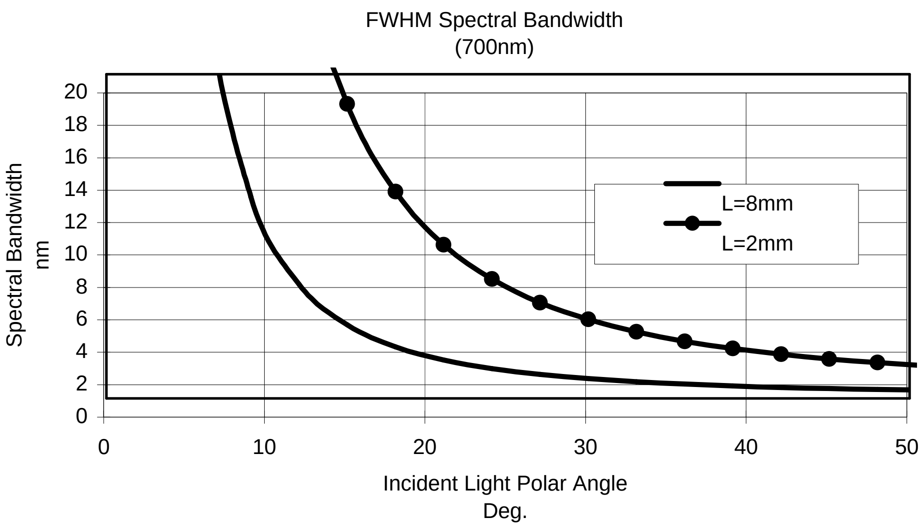


Fig 11.



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Narrow spectral bandwidths are achieved through increasing the interaction length. However too high a value will result in a large transducer electrode area and an inherent low impedance. Without the use of complex multi-electrode designs, efficient wideband tuning of such large electrodes can be problematical. Conversely wider spectral bandwidths are achieved with lower interaction length.

Since the RF drive power requirement is inversely proportional to the length, a low value of L may lead to an excessive RF power requirement for optimum diffraction efficiency particularly at longer wavelengths. (see 6.5)

### 3.2 Transmission

The transmission function of the AOTF is basically a $sinc^2$ function for a rectangular electrode, with the first sidelobes at -13dB from the peak.

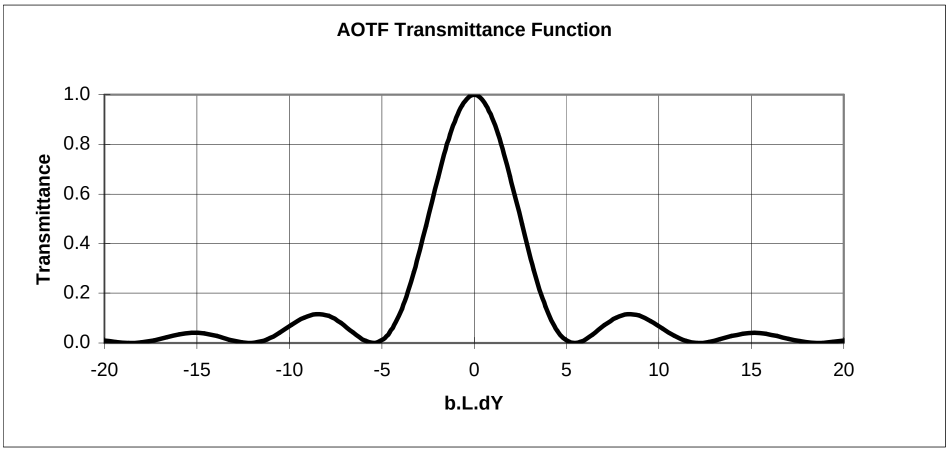


Fig 12.

The sidelobes can be reduced (usually at the expense of some broadening of the passband) by modifying the profile of the acoustic field. Several techniques exist. The first involves shaping the electrode to produce the desired apodization. The second applies weighted electrical drive signals to adjacent elements of a multi element rectangular electrode.

An alternative solution, with user controllability, is to operate two AOTF devices in series and at slightly different frequencies. The frequency offset is adjusted to match the spacing between the maxima and minima. The drawback is that overall throughput is reduced to a half.



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**3.3 Input Field of View**

The input field of view is also dependent on the incident angle and interaction length.

$$\Delta\theta_i = \frac{2n}{\sin\theta_i} \cdot \sqrt{\frac{0.9\,\lambda}{\Delta n L(2.\cot^2\theta_i - 1)}}$$

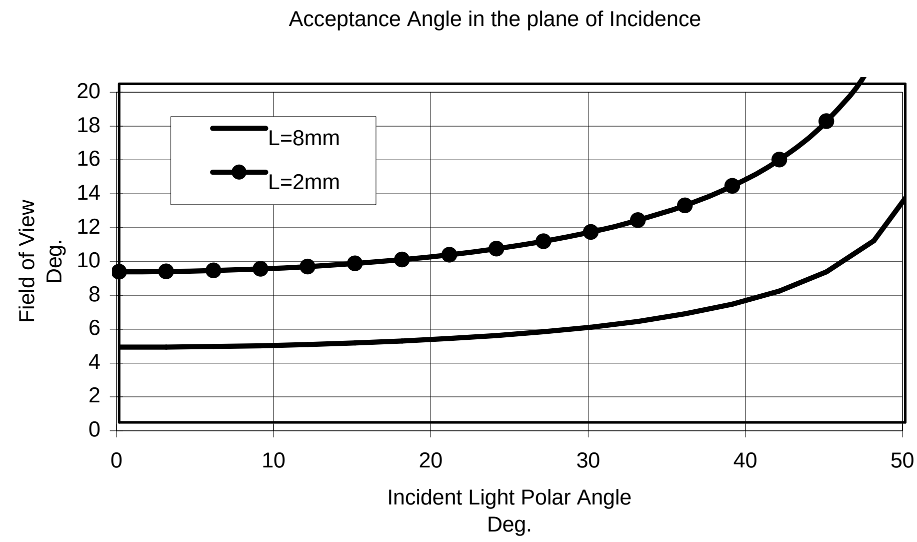


Fig 13.

In general, a large field of view corresponds to a short interaction length (L). A low value of L will degrade resolution and may again lead to an excessive RF power requirement for optimum diffraction efficiency. The orthogonal acceptance angle is generally larger
(The approximations used are not valid below 5deg.)



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### 3.4 Tuning range

The tuning range of the AOTF is fraction of the full optical transmission range of the AO material.

$$f_T = \frac{\Delta n.V}{\lambda_o} \left[ \sin^2 2\theta_i + \sin^4 \theta_i \right]^{½}$$

Tuning Frequency

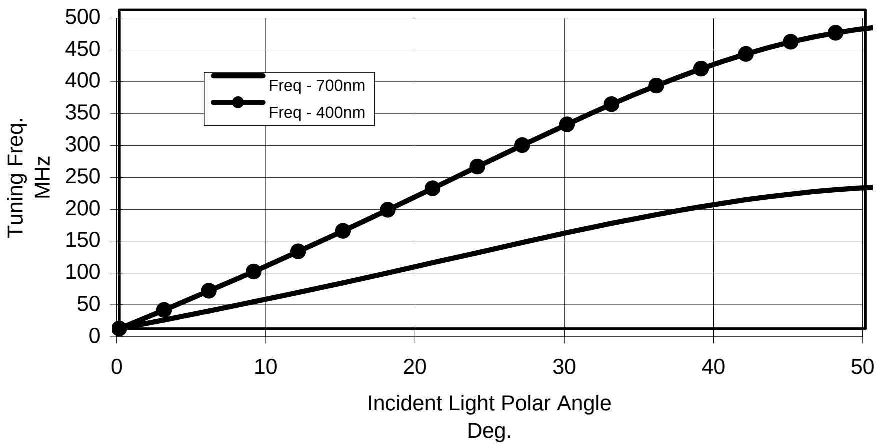


Fig 14.

The main limiting factor is the electrical bandwidth of the transducers, which are typically less than one octave. Multi-transducer designs are feasible but at a price, increased complexity and size. A further consideration of broadband designs is undesired diffraction by the harmonics of the RF drive. Spurious output will result if the light source contains a corresponding wavelength component.

High frequency devices may need to be RF power limited due to the thinness of the transducer.



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**3.5 Clear Aperture**

The optical aperture is limited to the height of the electrode and width of clear aperture from transducer to absorber.

In general, the aperture height is limited by drive power and RF matching considerations. The optimum drive power (Psat) is proportional to the electrode height H. The electrode area will determine the transducer impedance.

$$\text{Psat} = \frac{\lambda^2 H}{2.L.M_2}$$

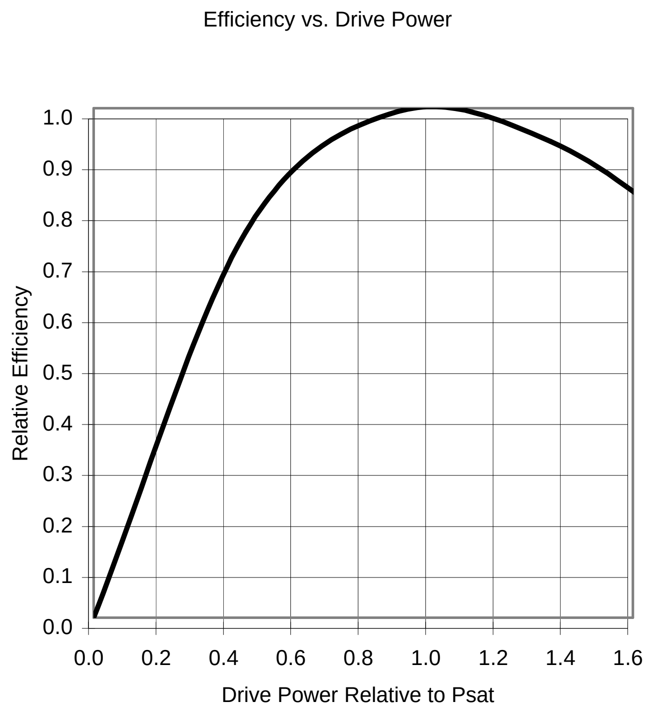


Fig 15.

Along the acoustic axis, the aperture width is limited to the size of crystal that can be produced with good optical uniformity, and the amount of acoustic attenuation that can be tolerated. For $TeO_2$, the acoustic attenuation is in the order of 29dB/mm/GHz$^2$.



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### 3.6 Walk Off Angle

A further determining factor on crystal size is the acoustic walk off angle or energy flow direction. (See Fig 10).

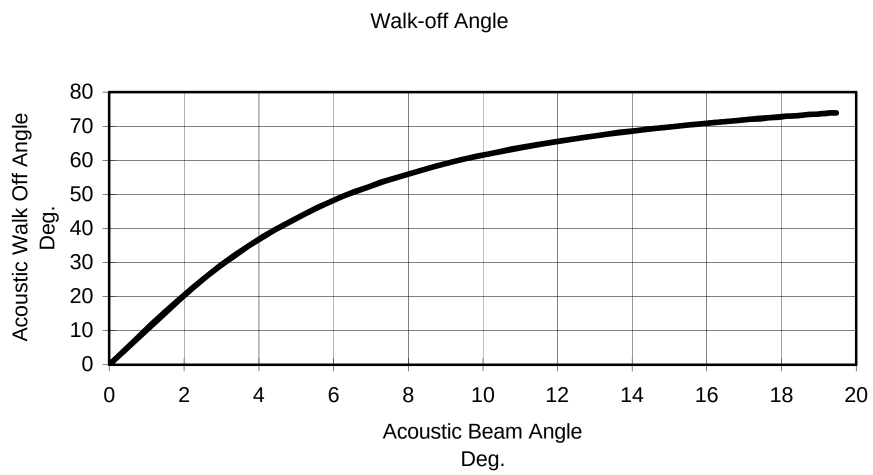


Fig 16.

For highly anisotropic materials such as $TeO_2$ the walk off angle can be significant for high values of acoustic angle and as can be seen from Fig 10, this leads to a rather inefficient use of the crystal volume.

### 3.7 Tuning Rates

The time for the acoustic wave to traverse the aperture defines the tuning rate. The faster the acoustic velocity and lower the aperture width, the faster the AOTF can be tuned without degrading resolution. Tuning at too high a rate will lead to a chirp of frequencies across the aperture and consequential broadening of the diffracted output and degrade resolution.

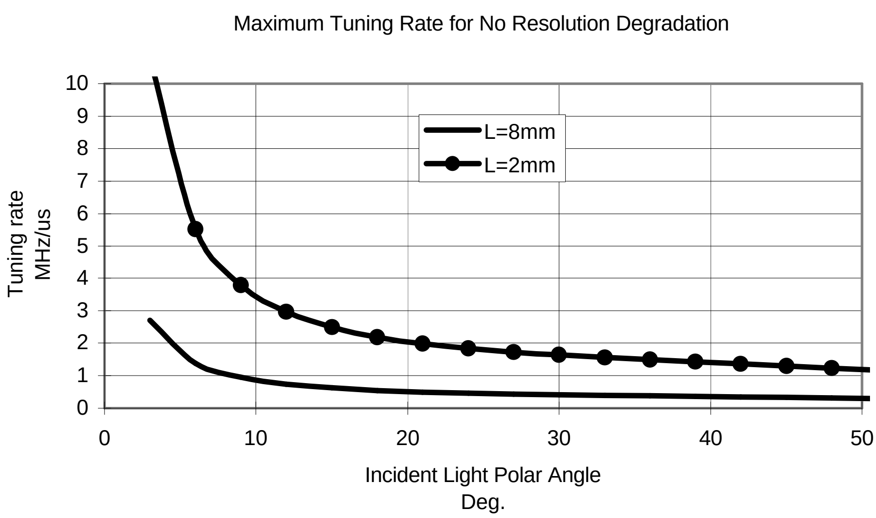


Fig 17.

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A further consideration is the settling time of drive electronics. PLL design may have settling times in excess of the access time of the AOTF. In contrast, the settling time of a DDS based frequency source can be in the order of tens of nsec.

**3.8 Beam Separation**

In general, the non-collinear AOTF does not require a polarizer to separate the output beams. The incident, undiffracted and diffracted beams are at different angles.

$$\theta_{sep} = \Delta n.\sin 2\theta_i$$

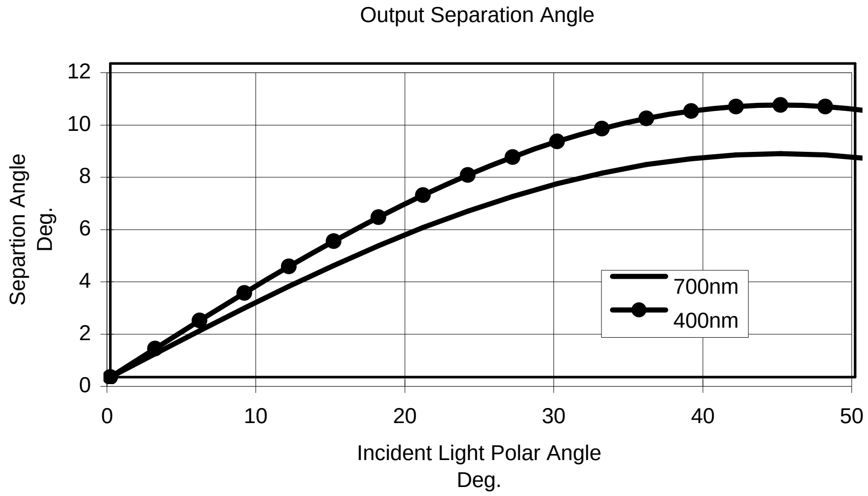


Fig 18.

For an unpolarized input, the beam is split into two orthogonally polarised output beams at equal but opposite angles to the undiffracted output. (see Fig 10.)

The change in output angle with wavelength can be partially corrected by polishing a wedge on the output face of the AOTF.



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## 4.0 Practical devices

The design of an AOTF is a balance of compromises. For practical commercial devices, incident angles are typically in the range of 10 – 40 degrees and interaction lengths range from 5 – 25mm

In order to place some real values for the various parameters discussed above, the following table lists the performance characteristics for two standard $TeO_2$ AOTF types offered by Isomet based on 6° acoustic off axis device for the visible and 9° off axis device for the IR.

| Model | AOTF614-08 | | | | | | |
|---|---|---|---|---|---|---|---|
| Aperture | 5mm x 5mm | | | | | | |
| Incidence Angle (deg) | 15 | | | | | | |
| Wavelength (nm) | 400 | 500 | 600 | 700 | 800 | 1000 | 1200 |
| Frequency (MHz) | 140 | 95 | 75 | 65 | 50 | 40 | 35 |
| Bandwidth (nm) | 1.0 | 2.3 | 4.0 | 6.0 | 8.0 | 14.0 | 22.0 |
| Acceptance Angle (deg) | 3.5 | 3.8 | 4.2 | 4.5 | 5.0 | 5.5 | 6.0 |
| Separation Angle (deg) | 4.4 | 4.0 | 3.75 | 2.8 | 2.65 | 2.5 | 2.5 |
| RF Drive Power (mW) | 100 | 150 | 200 | 270 | 350 | 570 | 800 |


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| Model | AOTF920-24 | | | | | | |
|---|---|---|---|---|---|---|---|
| Aperture | 5mm x 5mm | | | | | | |
| Incidence Angle (deg) | 30 | | | | | | |
| Wavelength (nm) | 700 | 800 | 1200 | 1500 | 1700 | 1800 | 2400 |
| Frequency (MHz) | 95 | 80 | 52 | 42 | 37 | 35 | 26 |
| Bandwidth (nm) | 1.0 | 1.5 | 4.0 | 6.2 | 8.0 | 9.0 | 15.5 |
| Acceptance Angle (deg) | 3.0 | 3.2 | 3.8 | 4.3 | 4.5 | 4.7 | 5.5 |
| Separation Angle (deg) | 5.25 | 5.1 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| RF Drive Power (mW) | 120 | 150 | 320 | 500 | 650 | 700 | 1200 |

## 5.0 Crystal Materials for AOTF devices

The ideal characteristics are summarised in the following list :

- High optical transmission across the wavelength range of interest
- Low acoustic attenuation
- High figure of Merit and thus low RF drive requirements
- Good optical uniformity in large crystal sizes
- Low optical scattering
- Good physical properties to aid fabrication:

  Cutting,

  Polishing,

  A/R coating,

  Transducer bonding,

  Robust in use



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### 5.1 Material Comparison

| Crystal | Transmission Range (um) | AOTF type |
|---|---|---|
| **α-quartz** | **0.12 - 4.5** | **Collinear Non-collinear** |
| **$CaMoO_4$** | **0.4 - 4.5** | **Collinear** |
| **$LiNbO_3$** | **0.4 - 4.5** | **Collinear** |
| **$TeO_2$** | **0.36 - 4.5** | **Non-collinear** |
| **$Tl_3AsSe_3$** | **1.25 - 17** | **Collinear Non-collinear** |
| **$Hg_2Cl_2$** | **0.4 - 20** | **Non-collinear** |

The only practical material for use in the UV is α-quartz. It is rather prone to scattering centres and has a rather low figure of Merit. The low figure of Merit and the wavelength dependence of drive power restricts its use the lower wavelengths, even though α-quartz transmits well into the NIR. Nevertheless it is inexpensive, available in large sizes and has good AO properties.

For the visible to NIR wavelengths, there are a number of materials including $TeO_2$ for non-collinear AOTF's , $CaMoO_4$ and $LiNbO_3$ for collinear devices. By far the most popular is the $TeO_2$ AOTF. This material has a very high figure of merit, has useful anisotropic diffraction, transmits from the visible to the IR, and is relatively easy to grow and fabricate.

Materials for use into the Far - IR are available but from limited sources. These include Thallium Arsenic Selenide ($Tl_3AsSe_3$) and Mercurous chloride ($Hg_2Cl_2$). Both materials exhibit a wide transmission range for visible up to 20um but are comparatively fragile and have poor thermal characteristics. The latter point is important for devices to designed operate in the Far IR necessitating high RF drive powers


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## 6.0 Operational Benefits of AOTFs'

- Inherent agility.

An AOTF is electronically controlled solid state device that can be driven in random, sequential step, ramp or multi frequency modes. With access times as low as 10us, tuning rates are considerably faster than mechanical filtering techniques.

- Modulation capability.

Modulating or switching the RF drive amplitude can directly control the intensity of the diffracted output from the AOTF.

- Pass band control

The spectral pass band of the AOTF can be rapidly dithered by FM modulation of the Drive signal.

- Wavelength mixing

Due to the highly selective frequency-wavelength relationship, AOTFs' can operate in a simultaneous mode with multiple drive frequencies. This offers the capability of colour mixing the diffracted output.

## 7.0 Typical applications list

A sample of applications includes:

- Spectral imaging system - placing a large aperture AOTF at the input of a CCD camera
- Absorption Spectroscopy -
- Fluorescence Spectroscopy
- Laser Tuning i.e. Line selection
- Wavelength Multiplexing

(The wide FOV makes for efficiently coupling to the divergent output of F/O).



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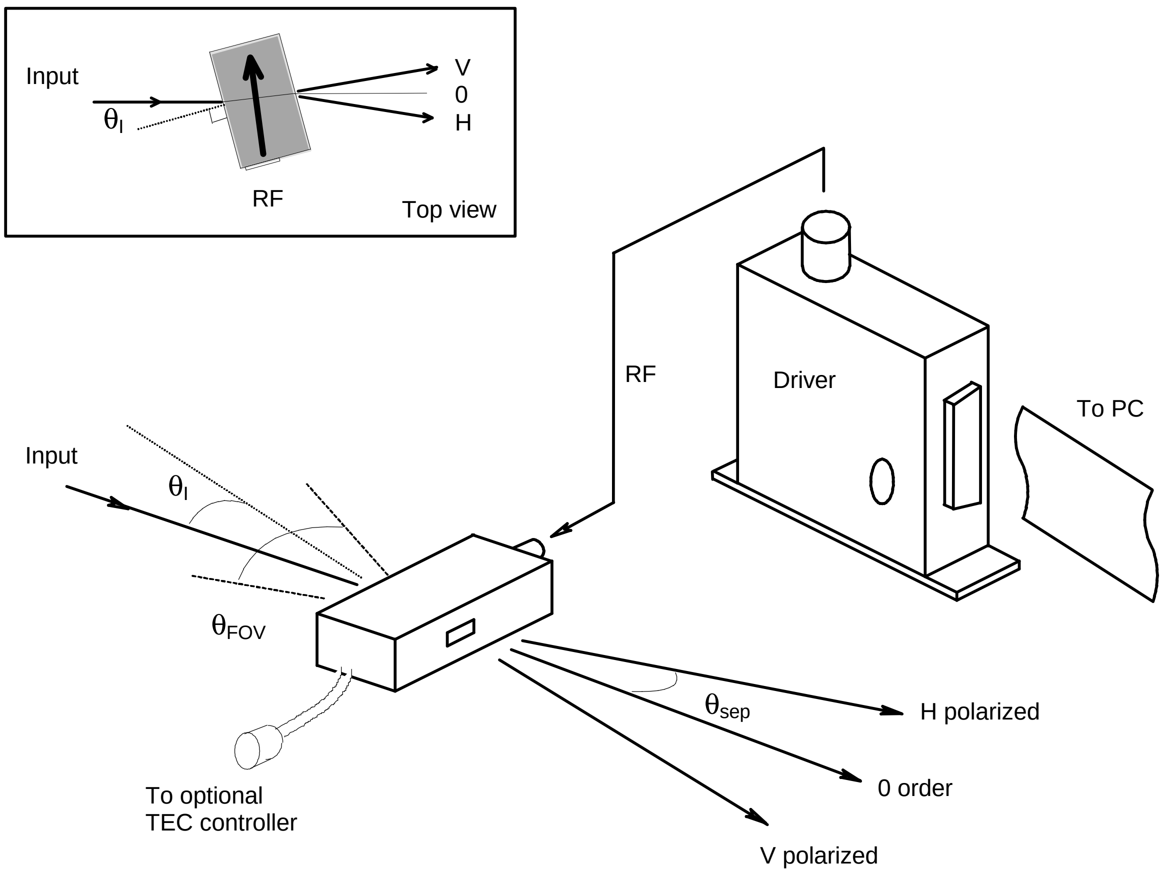
## 8.0 Schematic of the AOTF and driver



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