Application Note

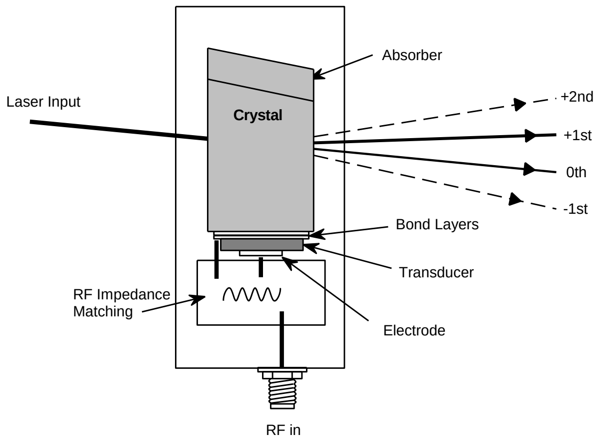
ISOMET

AN0510

Acousto-Optic Modulation

Acousto-optic devices are primarily used for controlling laser beams. This includes Modulators, Deflectors, Tuneable Filters, Frequency Shifters and Q-switches. The basic operating principles apply to all AO types. The performance requirements are optimised by selecting the crystal material and orientation, the acoustic mode and the transducer configuration.

This note will concentrate on Acousto-optic Modulators, although much is in common with the other types of AO device. Emphasis is placed on the practical rather than theoretical principals (For further background, please refer to our application note 'All About Bragg Angle Errors' by Leo Bademian).



All AO devices are based on the photo-elastic effect or the interaction of sound (RF) and light in a crystalline material. An acoustic wave is generated in the crystal by applying a RF drive signal to a piezo-electric transducer. This creates areas of compression and rarefraction in the crystal bulk, causing periodic changes in the refractive index. In very broad terms, this can be likened to the slits in a diffraction grating and light input to the AO device is diffracted into a number of orders at the output.

However unlike a diffraction grating, AO modulators are travelling wave devices. The acoustic wave travels from the transducer to the absorber. The acoustic velocity is determined by the choice of crystal material.

The absorber is shaped to direct the acoustic wave towards an absorbing surface. It is also designed such that any remaining reflections do not create secondary diffraction.

For the majority of applications, AO devices are designed to maximize diffraction of an input laser beam into a single first order position. (see below). The device is then said to be operating in the Bragg regime and requires the AO device to be correctly aligned and the drive power adjusted at or below the RF saturation level.

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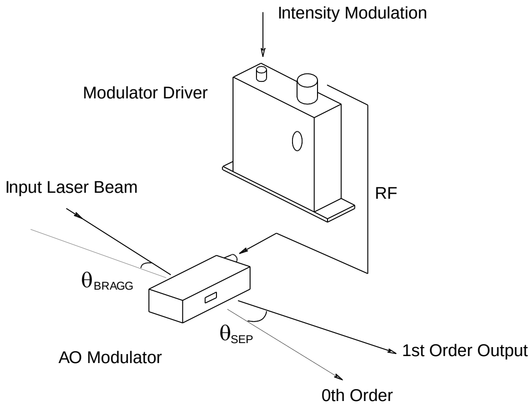
Basic Acousto Optic Modulator and Driver



Key Parameters:

Angles

The input Bragg angle is given by:

$$\theta_{Bragg} = \frac{\lambda . f}{2 . V}$$

This angle is in the plane of deflection and relative to a normal from the input optical surface.
Except for certain AO devices with birefringent crystals, the laser beam can be input into either aperture and at + or - Bragg angle.

The output separation angle between the Zeroth order and First order is given by:

$$\theta_{sep} = \frac{\lambda . f}{V}$$

where : f = RF frequency
λ = wavelength
V = acoustic velocity,
TeO2: 4.2mm/us
PbMoO4: 3.63mm/us
Quartz: 5.7mm/us
Ge: 5.5mm/us

Efficiency

Diffraction Efficiency (DE) is defined as the ratio of the output zero order beam (RF off) and the first order beam (RF on)

$$DE = \frac{I_{1st}}{I_{0th}}$$

In addition the device exhibits insertion losses (IL) due to absorption in the bulk material and losses at the A/R coated surfaces.

$$IL = 1 - \frac{I_{0th}}{I_{Laser}}$$

Total throughput efficiency is the combination of the above factors, DE x (1-IL) %

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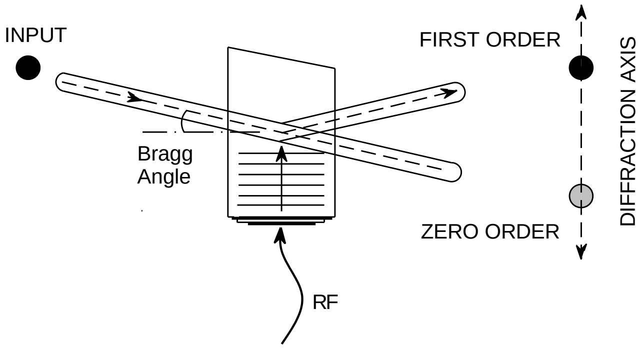
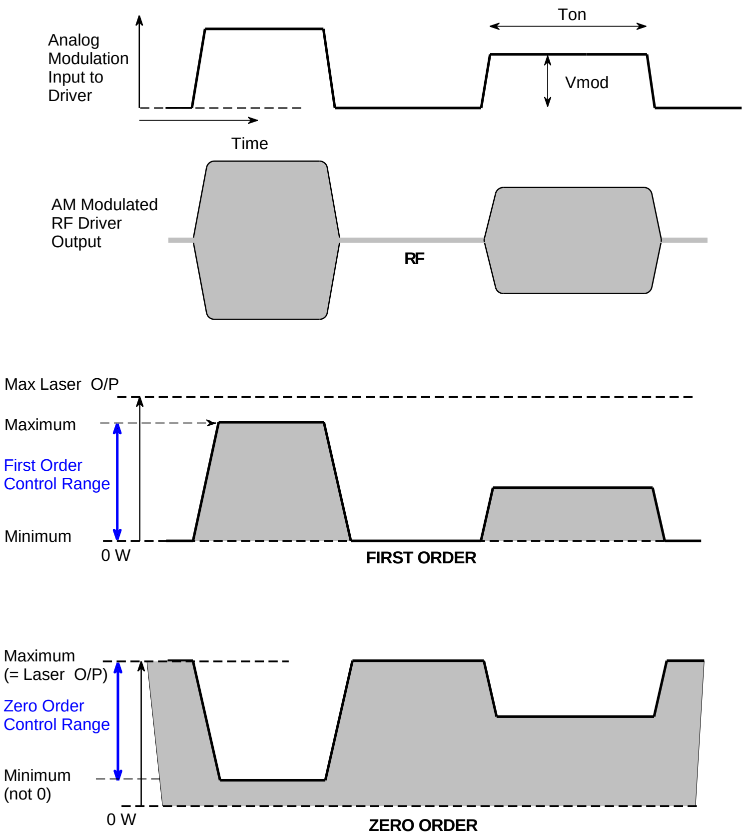
Intensity Modulator

With no RF drive power, the input beam is unaffected and travels straight through the AO device into the zero order position. There will be small transmission losses from the A/R coatings and bulk absorption in the crystal. Together these are termed the “Insertion Loss”. Typical values 3% - 7%.

When the RF power is applied, a significant percentage of the incident beam is directed into the First order.



The relationship between the RF drive, First and Zero order outputs is illustrated below. Up to 90% of the input power can be diffracted into the first order position. The Zero order power is never at zero



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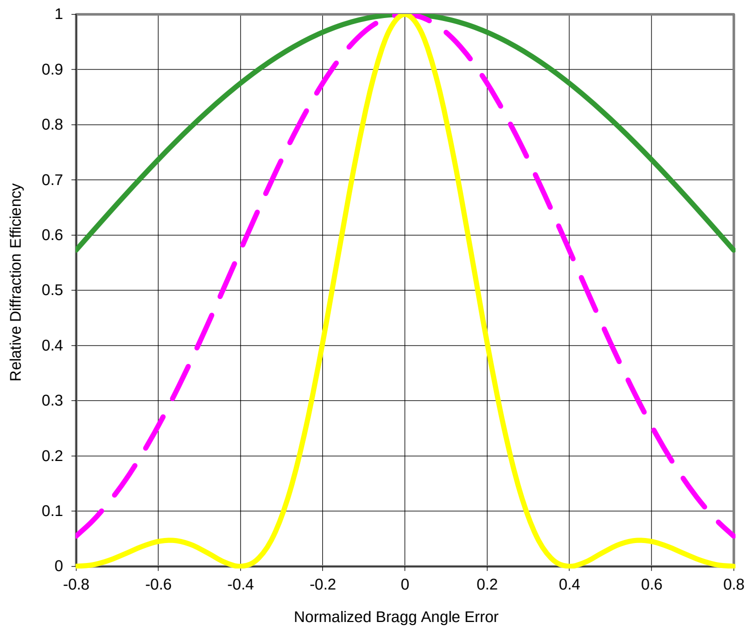
Bragg Angle

Optimum efficiency is achieved when the incident light (laser beam) is input to the AO device at the Bragg angle given by:

$$\theta_{Bragg} = \frac{\lambda . f}{2 . V}$$

Bragg angle errors will reduce efficiency. The sensitivity is shown graphically below.
This shows the response for typical AO devices with low (dark), medium (dashed) and high (pale) "Q" factors (not to be confused with Q-switches. See Design Considertion section below)



RF Driver Power

The optimum RF power for maximum diffraction efficiency is given by:

$$P_{sat} = \frac{k . \lambda^2 . H}{2 . L . M_2}$$

This is termed the saturation power level

where : f = RF frequency
V = acoustic velocity
L = interaction (electrode) length
λ = wavelength
H = electrode height
M_2 = Figure of Merit
k = Transducer Conversion loss (1.12 typ.)

The RF drive power increases with the square of the wavelength.
Often, for devices operating in the NIR, maximum efficiency is restricted because P_{sat} exceeds the device RF power rating for that device. AO Devices requiring high RF drive powers are water cooled.

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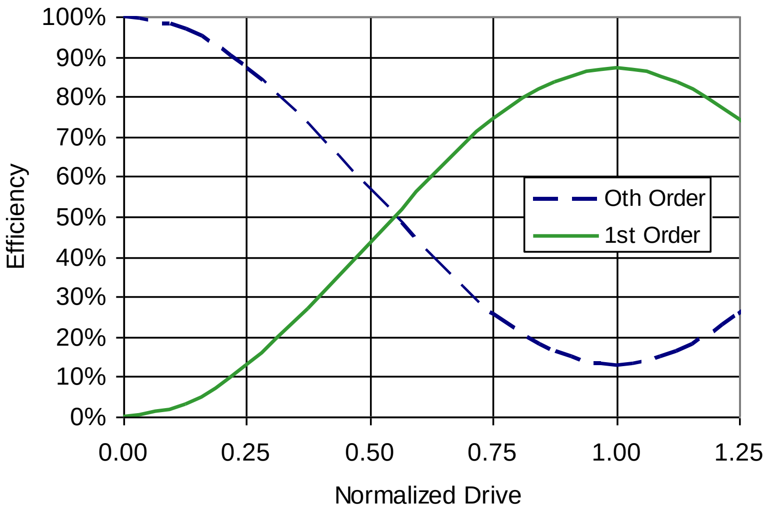
The relationship between the first order diffraction efficiency and RF drive power is a sine squared function. When the device is operated at a power (P) less than Psat, the relative efficiency (ε) can be determined from the formula:

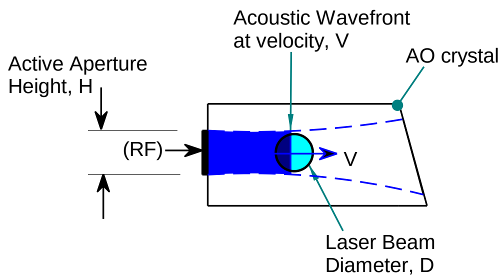
$$\varepsilon = \sin^2 \frac{\pi}{2} . \sqrt{P_{in}/P_{sat}}$$

This is the basis for amplitude modulation of the laser beam
The RF driver can be switched between Zero and Psat for *Digital* (On:Off) modulation or controlled in a proportional fashion for *Analog* modulation of the first order intensity.



Modulation Speed

The optical switching time is defined by the transit time of the acoustic wave across the beam waist in the AO crystal.



For a Gaussian beam the optical rise time can be approximated by the formula

$$\tau_r = 0.65 . \frac{d}{V}$$

where : d = 1/e^2 beam diameter
V = acoustic velocity

Acoustic velocities are in the range of 0.6mm/usec to 5.9mm/usec
The desired optical rise/fall time will define the required AOM RF bandwidth and centre frequency

RF Frequency considerations

Modulation bandwidth is approximated by: $\boldsymbol{BW_{mod} = 0.35/\tau_r}$

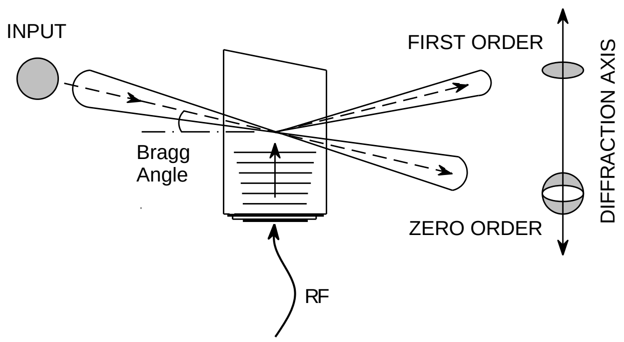
The required AO transducer bandwidth is twice this modulation bandwidth. (Consider the AOM as a double sideband modulator), Thus the full device RF bandwidth $\boldsymbol{BW_{full} = 2.BW_{mod}}$

AO devices inputs are RF matched to 50 ohm impedance and limited to an octave bandwidth in order to reduce 2nd order effects. The minimum centre frequency is therefore 2x BW

Beam Waist Considerations

To increase the modulation rate, it is necessary to focus the beam into the AO device.

As the beam is increasingly focussed, the efficiency and output beam circularity will degrade due to Bragg angle errors. As illustrated in the diagram below, the outer rays of the input cone of light are no longer at the same angle its core. The entire beam is not at the optimum Bragg angle and the extremities will not be diffracted as efficiently as the centre. This effect only occurs in the one axis along the plane of diffraction.



Hint:
The resultant dark line through the centre of the Zero order can be used as an aid to Bragg angle adjustment. Maximum efficiency is achieved when this line is near centre of the zero order

The *Beta* factor is a measure of modulator performance and output beam characteristics under focussed beam conditions. This is given by the ratio of the optical and acoustic divergences in the AO crystal.

$$\boldsymbol{\beta = \frac{\lambda . L . f}{n . \omega_o . V}}$$

where:
- V = acoustic velocity
- L = interaction length
- f = RF frequency
- n = refractive index
- λ = wavelength
- $\boldsymbol{\omega_o}$ = beam waist

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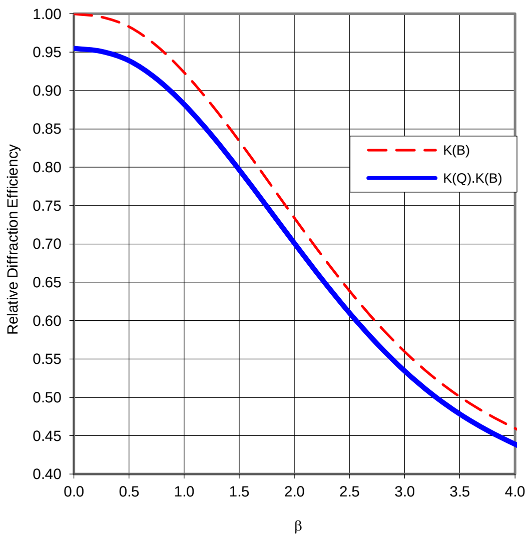
As illustrated below, the diffraction efficiency reduces as the beam becomes increasing focussed See K(B) trace ≈ β. [K(Q) is a function of the Q-factor, explained further below]



Design Considerations

The operating wavelength, modulation frequency and optical power density dictate the AO design parameters. These must also satisfy the Bragg criteria.

A measure of the Bragg condition is given by the 'Q-factor'.

$$Q = 2.\pi.\frac{\lambda.L.f^2}{n.V^2}$$

where:
- V = acoustic velocity
- L = interaction length
- f = RF frequency
- n = refractive index
- λ = wavelength

Ideally Q should be > 10 for strong Bragg diffraction. However if the Q-factor is too high, the device will be very sensitive to angular alignment and intolerant of input beam divergence (or convergence).

Conversely, Q-factors of less than 5 will result a significant percentage of the zero order beam diffracted into higher orders (Output beams at multiple angles).

The majority of devices are designed to operate in the Bragg regime. Exceptions include low frequency Q-switches and some loss modulators, where the zero order beam is the active output.

Summary

The design of a high speed modulator is a compromise between increasing the acoustic divergence to "compensate" for the optical convergence (low *Beta* factor), keeping the "Q "factor in the Bragg regime (9 < Q < 15) and limiting the RF power to a safe operating region.

In addition the wavelength and optical power density will dictate the choice of suitable AO crystal material(s) for any given application.

Modulator Techniques

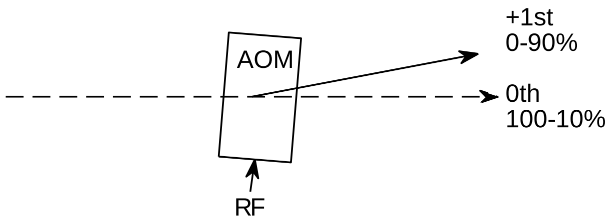
Multi-spot Modulators

There are several methods to generate a number of independently controllable spots from one AOM. These use the deflection properties of the AO device by changing the drive frequency and/or phase.

Schematic of Single and Dual beam modulation methods:

A: Basic Modulator Configuration

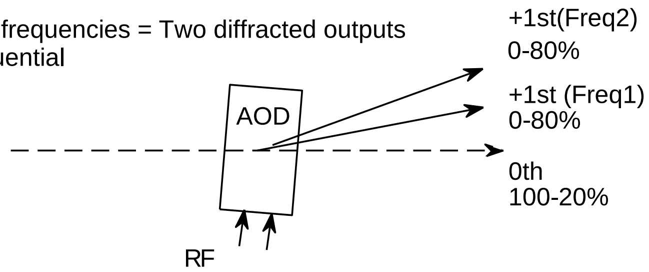
One frequency = One diffracted output
0th order cannot be 0%



0th order + 1st order always = 100%

B: Multispot / Deflector Configuration

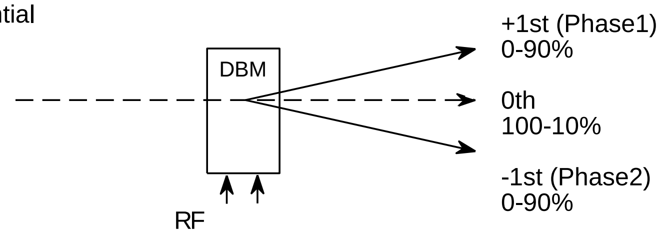
Two frequencies = Two diffracted outputs
Sequential



+1st (Freq1) and +1st (Freq2) powers independent

C: Dual Beam Modulator Configuration

One phase reversal = Two diffracted outputs
Sequential



+1st order and -1st order powers independent

Configurations B and C allow for multiple beam generation from a single laser input.

Config B is the classical approach using a change in RF drive frequency to create two or more spots.

Config C is a novel method that uses a change in phase across an transducer array to create two spots, each one either side of the zero order.

Both these methods produce spots that are sequential in time

Pulsed laser systems

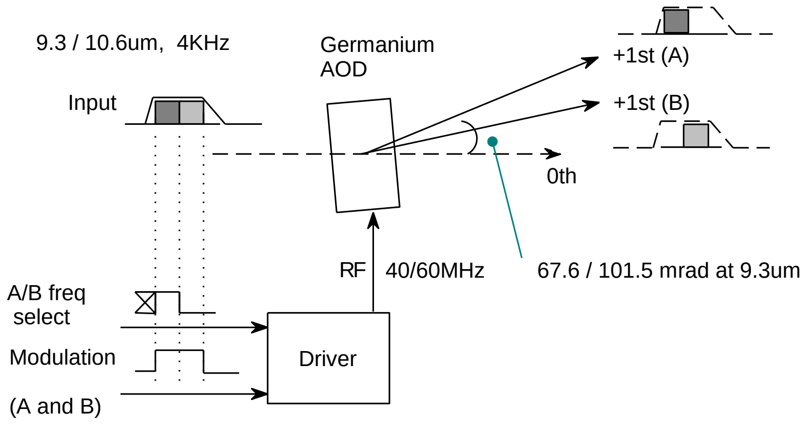
AO Deflectors can be used for pulse shaping, modulation and multiple beam generation. The method will depend on the laser pulse width.

Long laser pulses can be divided as shown in ‘Pulse Division’. This requires the laser pulse width to be longer than the transit time of the acoustic wave across the laser beam.

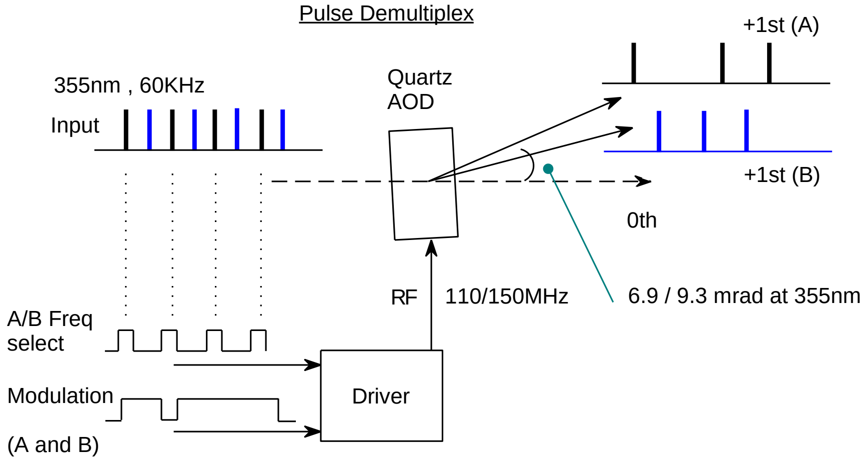
Short laser pulses can be demultiplexed as shown in ‘Pulse Demultiplex’
This creates two beams at half the input repetition rate

Multispot / Deflector Configurations

Pulse Division



Pulse Demultiplex



The above techniques also apply to the phase controlled Dual Beam Modulators

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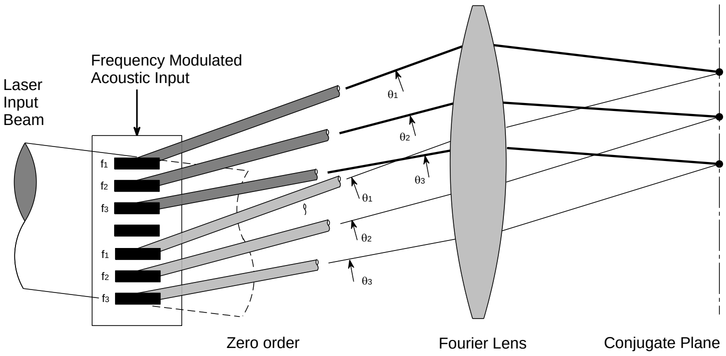
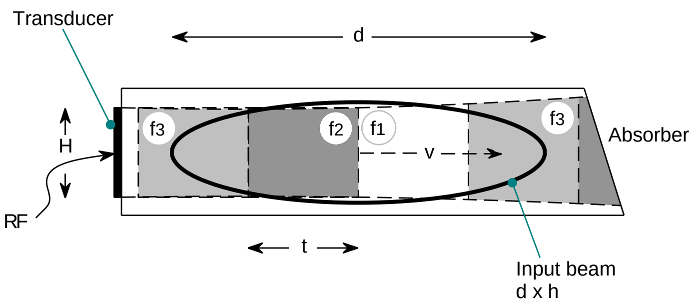
Sequential frequency, multi-beam generation.

The drawing below illustrates a sequence of three frequency packets scrolling through an AO device. Each frequency will produce a spot at a different diffraction angle. The angular displacements are then transposed to linear spacing at the Fourier plane using a single lens.



The optical beam width defines the exposure time. The period of each RF frequency defines the effective rise time of each diffracted spot i.e. the time taken for the RF packet to move into the optical beam. This can be much lower than the exposure time.



Sequential Frequency Mode

where : v = acoustic velocity
d = optical beam width
h = optical beam height
t = frequency period
H = active aperture height (H > h)

The amplitude of each RF packet will control the exposure level at each spot position.

Exposure time per spot = d/v   Rise time per spot = t   Diffracted spot size = h x v.t

Each RF packet can be considered as an aperture for the diffracted beam. Hence the output beam width is given by the product of the acoustic velocity and RF period. The output beam height is given by the lesser of the input beam height or active aperture height.

The angular spacing is restricted by the RF bandwidth of the AO device. The resolution of the device is given by the divergence of the input laser beam and the full scan angle of the AO modulator

$$N = \frac{\text{optical divergence through RF packet}}{\text{Full AO bandwidth Scan angle}}$$

This technique is used in plotters for graphic arts market. These are typically drum systems using an 8 or 10 spot system. The AO device axis is tilted to negate the spot shift due to the time taken to output spot 1 to spot 8 as the drum rotates.

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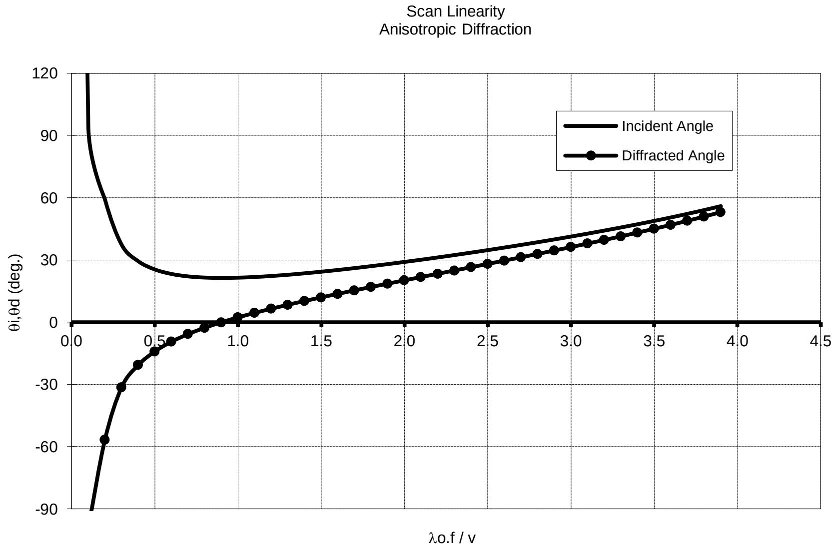
Shear-mode Devices

These are a class of AO devices which exploit birefringent properties of anisotropic AO crystals. The main crystal type is slow shear TeO_2 with an acoustic velocity of 0.6mm/usec to 0.7mm/usec .

Anisotropic materials are those with different refractive indices for the incident (n_i) and diffracted (n_d) beams. The 'Dixon' equations describe the angles of incidence and diffraction for interaction in these AO devices and are illustrated in the simplified plot below:



There are two significant regions:

- The first region is about the turning point of the 'Incident' curve (0.5 – 1.5 on the x-axis). This is the ideal operating point for AO deflector (and AOM), i.e. a small change in incident (Bragg) angle over a relatively large change in drive frequency (or wavelength λo). This is ideal characteristic for wide bandwidth AO deflector where large scan angles require large changes in drive frequency. The very low errors in input Bragg angle result in a flat efficiency response.

- The second significant region applies to AOTF operation (< 0.1 on the x axis). This area corresponds to high sensitivity where diffraction only exists over a very narrow frequency bandwidth (or wavelength range). It is also an area with large input acceptance, (θ_i) .
  e.g. in the region where $\sin\theta_I = \sin\theta_d = 1$

In all shear mode devices the diffracted output polarization is rotated by 90deg

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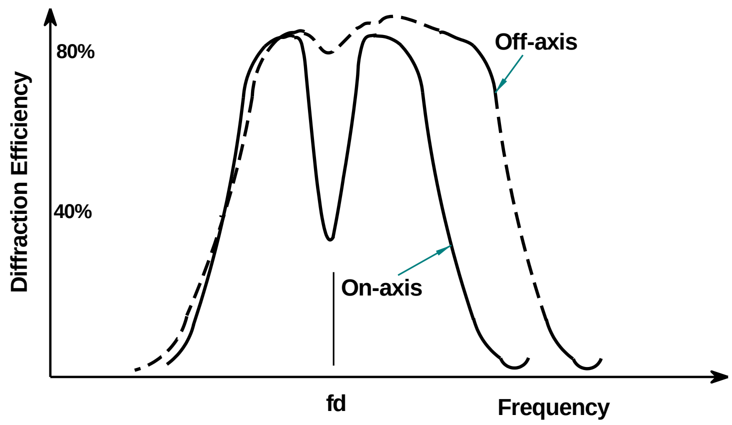
On-axis and Off axis diffraction in Slow Shear Birefringent AO devices



Typical frequency response for On and Off-axis AO device

ON-Axis: e.g. Acoustic wave travels down the 110 crystal axis (orthogonal to transducer)

Due to the nature of diffraction in birefringent crystal materials such as slow shear TeO_2, re-diffraction will occur over a narrow range of acoustic frequencies. This creates a dip in the 1st order diffraction response, as illustrated by the solid curve above and a very strong 2nd second order output.

The dip (at f_d) is often termed 'mid-band degeneracy' and the frequency at which this occurs will depend on the optical wavelength. Consequently the majority of On-axis devices are designed to operate above or below f_d

Wavelength	f_d
442nm	83MHz
532nm	54MHz
633nm	39MHz
800nm	25MHz
1064nm	16MHz

Maximum efficiency for On-axis devices is achieved for circular polarized input light.

Off-Axis: Acoustic wave is launched at an angle to the 110 crystal axis

The effects of the mid-band degeneracy can be alleviated using an Off-axis design (dotted curve). The Off-axis angle determines the efficiency flatness, the diffraction bandwidth and the crystal volume. An optimal design is wavelength specific.

Maximum efficiency for Off-axis devices is achieved for horizontally polarized input light.

The volume of crystal required for Off-axis devices is far larger than an On-axis equivalent. This generally makes Off-axis devices more expensive.

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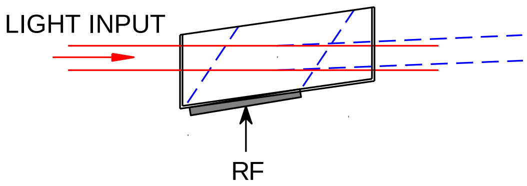
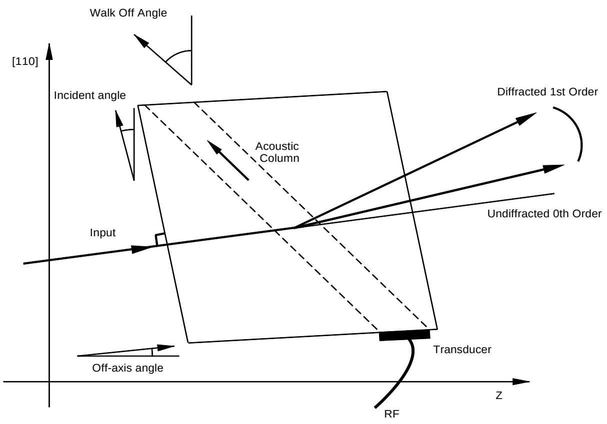
Typical Off-axis devices and orientations

Case 1: AO Tuneable Filter orientation



Case 2: Off-axis deflector schematic, orientation A



Case 3: Off-axis modulator/deflector, orientation B