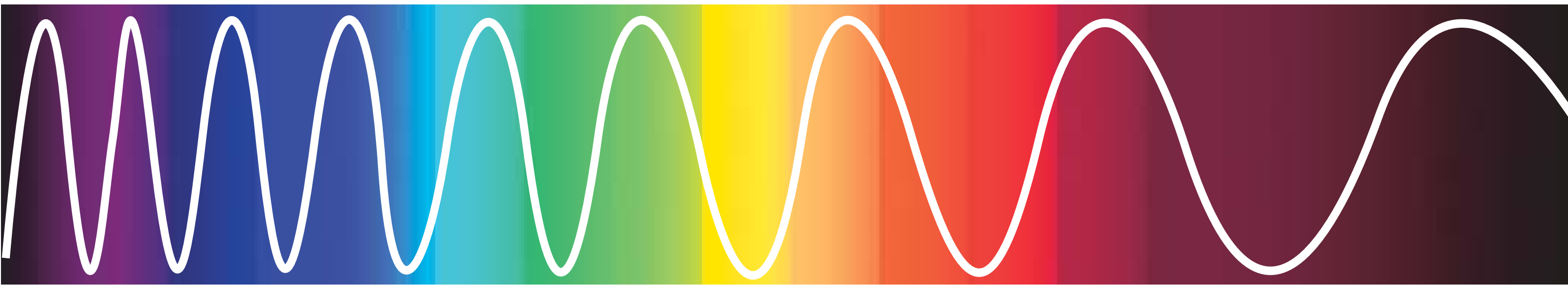
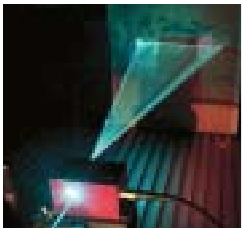
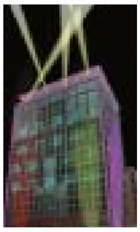
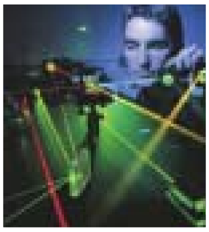
Do you know Acousto-optics ?









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Application Notes

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OPTO-ELECTRONIC

Acousto-Optics - Radio Frequency - Microwaves

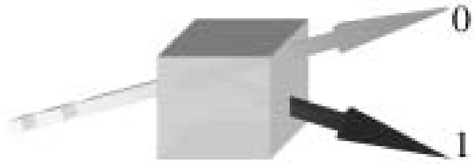
AO HISTORY

Brillouin predicted the light diffraction by an acoustic wave, being propagated in a medium of interaction, in 1922.
In 1932, Debye and Sears, Lucas and Biquard carried out the first experimentations to check the phenomena.
The particular case of diffraction on the first order, under a certain angle of incidence, (also predicted by Brillouin), has been observed by Rytow in 1935.
Raman and Nath (1937) have designed a general ideal model of interaction taking into account several orders. This model was developed by Phariseau (1956) for diffraction including only one diffraction order.
At this date, the acousto-optic interaction was only a pleasant laboratory experimentation. The only application was the measurement of constants and acoustic coefficients.
The laser invention has led the development of acousto-optics and its applications, mainly for deflection , modulation and signal processing. Technical progresses in both crystal growth and high frequency piezoelectric transducers have brought valuable benefits to acousto-optic components ‘ improvements.

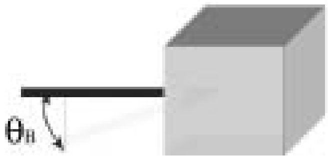
GLOSSARY

Bragg cell:
A device using a bulk acousto-optic interaction (eg. deflectors, modulators, etc...).

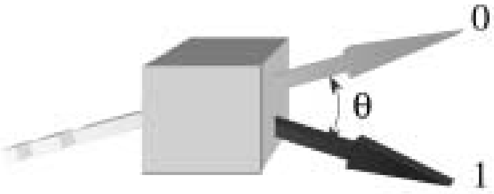
“Zero” order,”1st” order:
The zero order is the beam directly transmitted through the cell. The first order is the diffracted beam generated when the laser beam interacts with the acoustic wave.



Bragg angle (θ_B):
The particular angle of incidence (between the incident beam and the acoustic wave) which gives efficient diffraction into a single diffracted order. This angle will depend on the wavelength and the RF frequency.

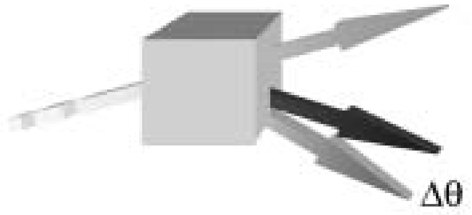


Separation angle (Θ):
The angle between the zero order and the first order.



RF Bandwidth (ΔF):
For a given orientation and optical wavelength there is a particular RF frequency which matches the Bragg criteria. However, there will be a range of frequencies for which the situation is still close enough to optimum for diffraction still to be efficient. This RF bandwidth determines, for instance, the scan angle of a deflector or the tuning range of an AOTF.

Maximum deflection angle ($\Delta\theta$):
The angle through which the first order beam will scan when the RF frequency is varied across the full RF bandwidth.



Rise time (T_R):
Proportional to the time the acoustic wave takes to cross the laser beam and, therefore, the time it takes the beam to respond to a change in the RF signal. The rise time can be reduced by reducing the beam’s width.

Modulation bandwidth (ΔF_{mod}):
The maximum frequency at which the light beam can be amplitude modulated. It is related to the rise time - and can be increased by reducing the diameter of the laser beam.

Efficiency (η):
The fraction of the zero order beam which can be diffracted into the “1st” order beam.

Extinction ratio:
The ratio between maximum and minimum light intensity in the “1st” order beam, when the acoustic wave is “on” and “off” respectively.

Frequency shift (F):
The difference in frequency between the diffracted and incident light beams. This shift is equal to the acoustic frequency and can be a shift up or down depending on orientation.

Resolution (N):
The number of resolvable points, which a deflector can generate - corresponding to the maximum number of separate positions of the diffracted light beam - as defined by the Rayleigh criterion.

RF Power (P_{RF}):
The electrical power delivered by the driver.

Acoustic power (P_a):
The acoustic power generated in the crystal by the piezoelectric transducer. This will be lower than the RF power as the electro-mechanical conversion ratio is lower than 1.

PHYSICAL PRINCIPLES
MAIN EQUATIONS

An RF signal applied to a piezo-electric transducer, bonded to a suitable crystal, will generate an acoustic wave. This acts like a “phase grating”, traveling through the crystal at the acoustic velocity of the material and with an acoustic wavelength dependent on the frequency of the RF signal. Any incident laser beam will be diffracted by this grating, generally giving a number of diffracted beams.

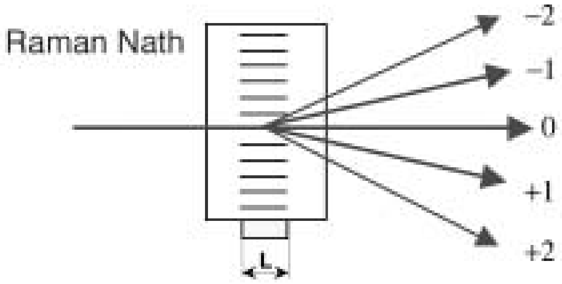
Interaction conditions

A parameter called the “quality factor, Q”, determines the interaction regime. Q is given by:

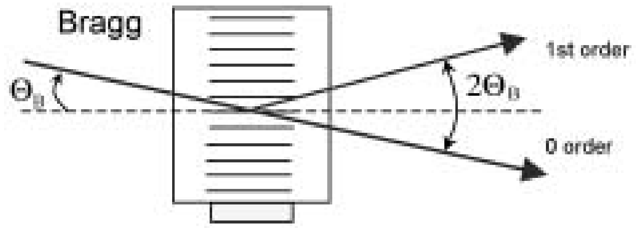
$$Q = \frac{2\pi\lambda_0 L}{n\Lambda^2}$$

where l_0 is the wavelength of the laser beam, n is the refractive index of the crystal, L is the distance the laser beam travels through the acoustic wave and L is the acoustic wavelength.

Q<<1 : This is the Raman-Nath regime. The laser beam is incident roughly normal to the acoustic beam and there are several diffraction orders (...-2 -1 0 1 2 3...) with intensities given by Bessel functions.



Q>>1 : This is the **Bragg regime**. At one particular incidence angle $_B$, only one diffraction order is produced - the others are annihilated by destructive interference.



In the intermediate situation, an analytical treatment isn’t possible and a numerical analysis would need to be performed by computer.

Most acousto-optic devices operate in the Bragg regime, the common exception being acousto-optic mode lockers and Q-switches.

Wave vectors constructions

An acousto-optic interaction can be described using wave vectors. Momentum conservation gives us :

$$\vec{K}_d = \vec{K}_i +/- \vec{K}$$

$K_i = \frac{2\pi n_i}{\lambda_0}$ – wave vector of the incident beam.

$K_d = \frac{2\pi n_d}{\lambda_0}$ – wave vector of the diffracted beam.

$K = \frac{2\pi F}{V}$ – wave vector of the acoustic wave.

Here F is the frequency of the acoustic wave traveling at velocity v. ni and nd are the refractive indexes experienced by the incident and diffracted beams (these are not *necessarily* the same).

Energy conservation leads to : $F_d = F_i +/- F$

So, the optical frequency of the diffracted beam is by an amount equal to the frequency of the acoustic wave. This “Doppler shift” can generally be neglected since $F \ll F_d$ or F_i, but can be of great interest in heterodyning applications.

Acousto-optic components use a range of different materials in a variety of configurations. These can be heard described by terms such as *longitudinal*- and *shear-mode, isotropic* and *anisotropic*. While these all share the basic principles of momentum and energy conservation, these different modes of operation have very different performances - as shall be seen.

Characteristics of the diffracted light

Isotropic Interactions

An **isotropic** interaction is also referred to as a **longitudinal-mode** interaction. In such a situation, the acoustic wave travels longitudinally in the crystal and the incident and diffracted laser beams see the same refractive index. This is a situation of great symmetry and the angle of incidence is found to match the angle of diffraction. There is no change in polarization associated with the interaction.
These interactions usually occur in homogenous crystals, or in birefringent crystals cut appropriately.

In the isotropic situation, the angle of incidence of the light must be equal to the Bragg angle, θ_B:

$$\theta_B = \frac{\lambda F}{2v}$$

where $\lambda = \lambda_0/n$ is the wavelength inside the crystal, v is the acoustic velocity and F is the RF frequency.

The separation angle θ between the first order and zero order beams is twice the angle of incidence and, therefore, twice the Bragg angle.

$$\theta = \frac{\lambda F}{v}$$

The diffracted light intensity I_1 is directly controlled by the acoustic power P :

$$I_1 = I_0 \sin^2 \sqrt{\eta} \qquad \text{with} \quad \eta = \frac{\pi^2}{2\lambda_0^2} M_2 \frac{L}{H} P$$

Here I_0 is the incident light intensity, M_2 is the acousto-optic figure of merit for the crystal and H and L are the height and length of the acoustic beam. λ_0 is the wavelength of the incident beam.

$$\frac{I_1}{I_0} = \sin^2 \frac{\pi}{2} \sqrt{\frac{P}{P_0}} \qquad \text{with} \quad P_0 = \frac{\lambda_0^2}{2M_2} \frac{H}{L}$$

Diffraction efficiency (relative) is the ratio I_1/I_0:
For a given orientation, if the RF frequency is slightly different from that required to match the Bragg criterion, diffraction will still occur. However, the diffraction efficiency will drop. The situation is shown in the figure below, where the acoustic wave-vector, K, is longer than the ideal "Bragg" wave-vector, K_0.

A complicated analysis leads to the result:

$$\frac{I_0}{I_1} = \eta \operatorname{sinc}^2 \sqrt{\eta + \frac{\Delta\phi^2}{4}}$$

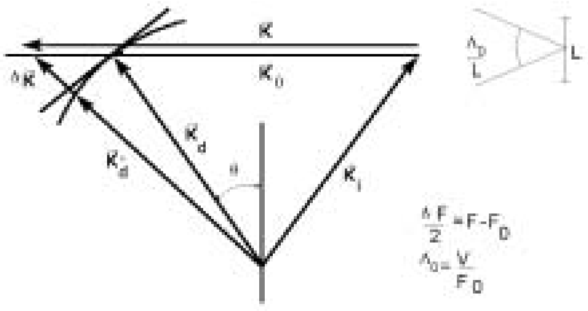
where $\Delta\phi = \Delta K.L$ and is called the "phase asynchronism".

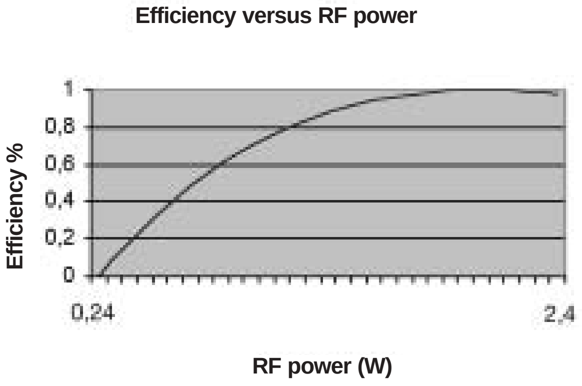
In the isotropic case : $$\Delta\phi = \frac{\pi\lambda}{v} \frac{\Delta F}{2} \frac{L}{\Lambda_0}$$

At the correct Bragg frequency, $\Delta\phi = 0$ (F=Fo) and efficiency is maximum.

When $\Delta\phi$ increases, diffraction efficiency decreases and will continue to decrease down to zero.
If there is a lower limit on the acceptable diffraction efficiency, then this puts a limit on $\Delta\phi$. This, in turn, implies a maximum ΔF - and defines the RF bandwidth for the device.

To increase this RF bandwidth, the ratio Λ_0/L (the acoustic divergence) can be increased.
As the RF frequency varies, the diffracted beam's direction changes. This is the basis behind acousto-optic deflectors.

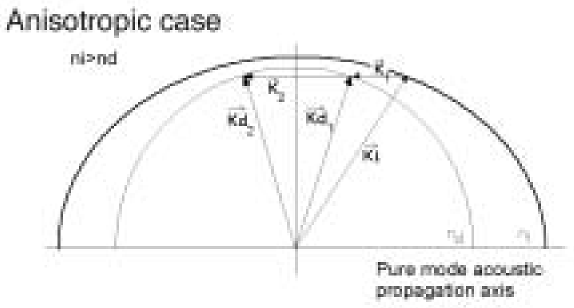




Anisotropic interaction

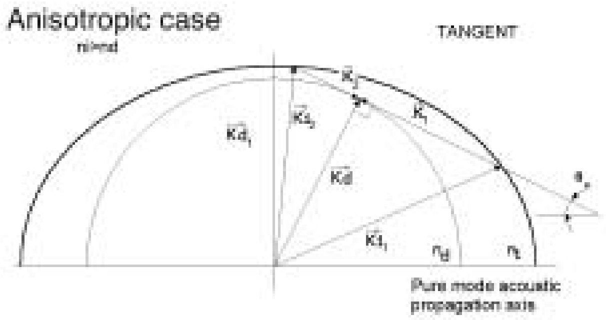
In an **anisotropic** interaction, on the other hand, the refractive indexes of the incident and diffracted beams will be **different** due to a change in polarization associated with the interaction. This can be seen in the figure below where the acoustic wave vector K_1 connects the index curves of the incident and diffracted waves. (K_2 simply represents a similar interaction at a very different RF frequency).

The same asymmetry which causes the difference in refractive indexes also causes the acoustic wave to travel in a **"shear-mode"** and, in the particular example of tellurium dioxide, this results in a drastic reduction in the acoustic velocity.



Anisotropic interactions generally offer an increase in efficiency and in both acoustic and optical bandwidth. They are used almost universally in large aperture devices. The reduction in the acoustic velocity, seen in shear-mode tellurium dioxide, lends this material to be used in high resolution deflectors.

The increased bandwidth available from shear-mode devices can be seen most immediately in the figure below where the interaction configuration is chosen so that the acoustic wavevector lies tangential to the diffracted beam's index ellipse.



This means that the length of the acoustic wave-vector can vary quite grossly while only producing small changes in the length of the diffracted beam's wave-vector. So, in this situation, ΔK (and, hence, $\Delta\phi$) is quite insensitive to changes in RF frequency.

Shear-mode interactions are very much more complex to analyze, requiring detailed information on crystal cut, refractive indexes, orientation. However, these interactions have a lot of advantages and most deflectors and all AOTFs will use shear-mode interactions. The reduced acoustic velocity makes these devices very much slower than longitudinal-mode units and this can be seen as a disadvantage in some circumstances.

ACOUSTO-OPTIC EFFECTS ON THE LIGHT BEAM

In summary, the Bragg interaction has four basic properties which are highly used in the devices. Some of the properties are coexisting in all devices: for instance, a modulator is also a fixed frequency shifter, a deflector can also be used as a variable shifter or modulator.
The main difference between each device is due to the design strategy which is different and most often antagonist to match the application 's purposes. At this step, it is very important for the component designer to work closely with the applications engineers.

1. Deflection
The angular deviation of the diffracted beam is proportional to the acoustic frequency. Deflectors are based on this principle.

2. Amplitude modulation (Intensity)
The diffracted beam intensity is a function of the acoustic power. Modulators (q-switches) use this property.

3. Frequency shifting
A frequency shift is introduced by the acoustic interaction (+/- equal to the acoustic frequency). So, any acousto-optic device can be used as a fixed or variable frequency shifter.

4. Tunable Wavelength Filtering
Wavelength selection can be carried out with large spectral band sources since only one wavelength will match the Bragg condition. This property is used in acousto-optical tunable filters.

CONSTITUTION OF A BRAGG CELL

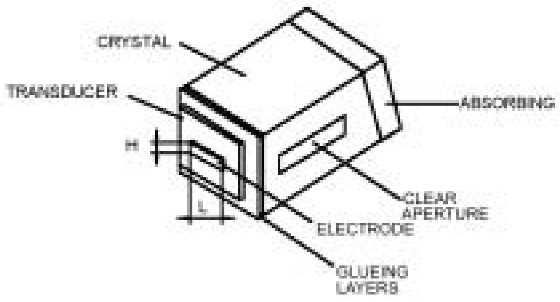
Although acoustic interactions can be observed in liquids, practical devices use crystals or glasses as the interaction medium, with RF frequencies in the MHz to GHz range.
A piezo-electric transducer generates the acoustic wave when driven by an RF signal (figure 6).

The transducer is placed between 2 electrodes. The top electrode determines the active limits of the transducer. The ground electrode is bonded to the crystal.

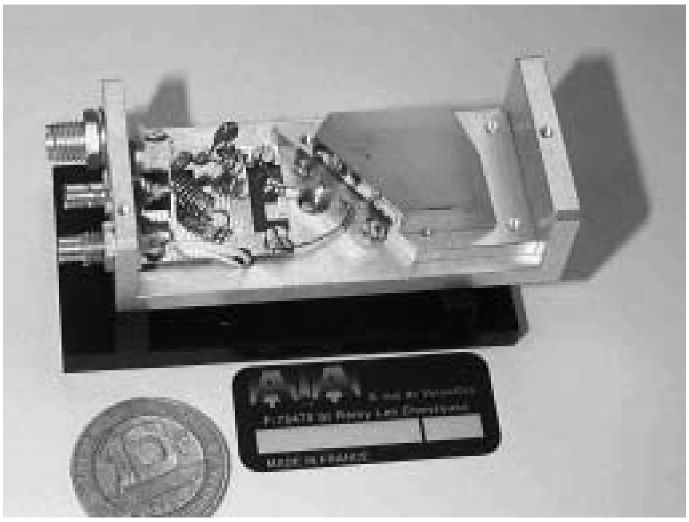
The transducer thickness is chosen to match the acoustic frequency to be generated. The height of the electrode H depends on the type of application, and must exceed the laser beam diameter. For a deflector, it is selected in order to collimate the acoustic beam inside the crystal during propagation.
The electrode length L is chosen to give the required bandwidth and efficiency.
The shape of the electrode can be varied for impedance matching or to "shape" the acoustic wave.
An "apodization" of the acoustic signal can be obtained by optimizing the shape of the electrode.

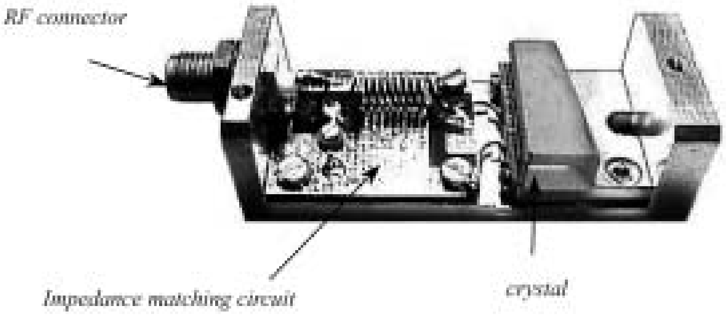
An impedance matching circuit is added to couple the transducer to the driver. Indeed, this circuit is necessary to adapt the Bragg cell to the impedance of the RF source (in general 50 Ohms), to avoid power returned losses. The RF power return loss is characterized with the VSWR of the AO device.

The crystal will generally be AR coated to reduce reflections from the optical surfaces. Alternatively, the faces can be cut to Brewster's angle for a specific wavelength.
A variety of different materials can be used. All have their own advantages and disadvantages.



Length of the crystal : typically 3 to 50 mm
Transducer thickness : typically 1 to 100 µm
Electrode thickness : typically 0.1 to 10 µm





ACOUSTO OPTIC MATERIALS

A.A. Opto-Electronic produces standard, general purpose acousto-optic components for use from 180 nm tu 11 µm, as well as custom products for specific applications.
A variety of different materials are used depending on the wavelength, laser power and precise application. A.A. also develops devices for use with specific lasers : Dye, YAG, Ti:Saph…

†he following gives an overview of the main characteristics of the most used materials for acousto-optic devices.

Material	Type	Optimum optical range for AO application (nm)	Incident optical polarization (*)	Refractive index	@ λ (nm)	Max CW laser power density (W/mm^2)	Acoutic velocity (m/s)	M_2 AO figure of merite ($10^{-15} S^3/kg$)	@ λ (nm)
Ge	Crystal	2500 - 11000	Linear//	4	10600	5	5500	180	10600
Doped Glass	Glass	500 - 650	Unpolarized	2.09	633	1	3400	24	633
$Ge_{33}AS_{12}Se_{55}$	Glass	1100 - 1700	Unpolarized	2.59	1064	1	2520	248	1064
As_2S_3	Glass	700-900	Unpolarized	2.46	1150	1	2600	433	633
$PbMoO_4$	Crystal	450 - 1100	Unpolarized	2.26/2.38	633	0.5	3630	36	633
TeO_2	Crystal	450 - 1100	Linear ⊥	2.26	633	5	4200	34	633
TeO_2	Crystal	350 - 4500	Linear-Circular	2.26	633	5	620	1200	633
SiO_2 (fused silica)	Glass	200 - 200	Linear ⊥	1.46	633	> 100	5960	1.5	633
SiO_2 (fused silica)	Glass	200 - 200	Unpolarized	1.46	633	> 100	3760	0.5	633

(*) : // and ⊥ means parallel and perpendicular to the acoustic wave direction for optimum AO coupling

APPLICATION NOTES

Modulators

Such a device allows the modulation of the light intensity. The Bragg interaction regime with only one diffracted order is used for these devices.

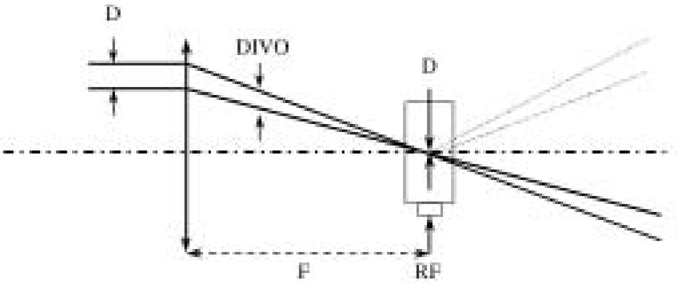
Rise time:
The rise time (T_R) of the modulator is proportional to the acoustic traveling time through the laser beam. The rise time of a fast modulator must be very short:

$$T_R = \beta \frac{\phi}{V}$$

β: constant depending on laser beam profile
ϕ: beam diameter
V: acoustic velocity
ϕ is the only parameter to minimize T_R. Consequently, one focuses the incident light beam on the acoustic beam in order to reduce the beam diameter and reduce rise time.
β is equal to 0.66 in the case of a TEM00 beam.

$$T_R = 0.66 \frac{\phi}{V} \quad \text{(TEM00, } 1/e^2 \text{ dia)}$$

D: beam diameter before the lens
F: focal length of the lens
DIVO: incident laser beam divergence
D = α*F*λ/ϕ: diameter of the light beam in the crystal.
α: constant depending on beam profile (=4/π for TEM00 beams)



Limitations
To allow the interaction, (L) must remain sufficiently large compared with the acoustic wavelength.

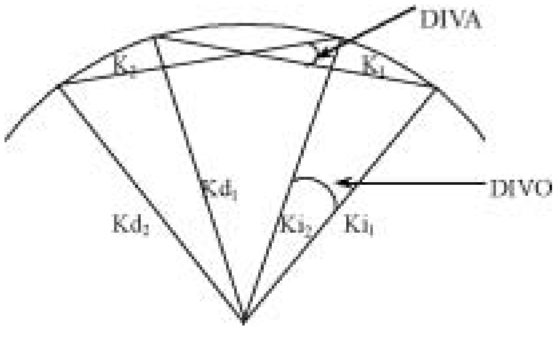
The light beam has a divergence which cannot be neglected. To preserve the efficiency of the interaction on all the bandwidth ΔF, it is necessary to reach the Bragg conditions for all the "angles" of the light beam.

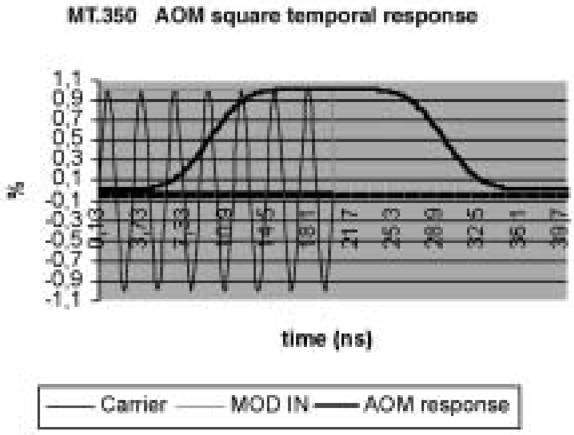
For this purpose, the acoustic divergence (DIVA) (=Λ/L where Λ is the acoustic wavelength and L the dimension of the ultrasonic source) must compensate for light divergence DIVO.

If DIVO>>DIVA : the "asynchronism" is very large for the directions of incidence far away from the Bragg angle, and then the interaction will not occur correctly. The section of the diffracted light beam is then elliptic.

If DIVO<<DIVA : the bandwidth is reduced. An acoustic divergence slightly higher than the light divergence makes it possible to neglect the ellipticity all while maintaining the bandwidth.

Lastly, let us remind that the efficiency of the modulator is related to √P/Po and that Po is inversely proportional to L. For a maximum acceptable value of Po by the crystal (which takes account the maximum power that can withstand the crystal), one reaches a limit of the efficiency.

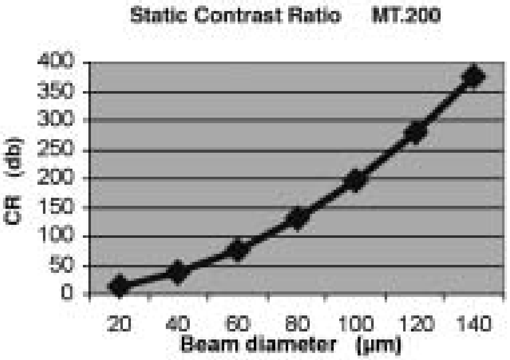




Contrast ratio (static and dynamic)
The incident laser beam properties have a significant impact upon modulator performances (temporal response and extinction ratio). The static contrast ratio measures the ability of the modulator to separate the different diffraction orders

(especially 0 and 1st orders). As a consequence, the lower carrier frequencies and highly focused beams will be a physical limitation of the static extinction ratio. The Gaussian profile (TEM00) gives the best performances and will be considered in the following part. The far field 1st order beam (propagating at angle $+\theta B$) is typically separated from the 0 order ($-\theta B$) with a beam block which is placed such that angles up to 0 are stopped (angles higher than $+2\ \theta B$ can also be stopped to suppress higher orders scattering light).
TEM00 static contrast ratio can be written as :

$$CR = \int_0^{2\theta_B} I(\theta)d\theta \ \ / \ \ \int_{-\infty}^{+\infty} I(\theta)d\theta$$



The static CR is physically limited by imperfection of the crystal and scattered light.
The dynamic contrast ratio is the reduction of the CR due to the finite response time of the AOM.
This leads to a reduction of the contrast ratio of ON light intensity to OFF light intensity in dynamic operation. The dynamic contrast ratio is directly related to the modulation bandwidth of the modulator.

Analog Modulation bandwidth
The rise time is a convenient and easy tool to characterize a modulator' s temporal response. However, a more complete characterization can be useful for accurate results. The AOM temporal response is a linear convolution integral which can be analyzed with Fourier transforms to get the Modulation Transfer Function (MTF) of the AOM.
Without giving detailed calculations, the MTF of an acousto-optic modulator in response to a Gaussian input light profile is:

$$MTF(f) = \exp\left(\frac{-f^2}{f_c^2}\right) \qquad fc = \frac{\sqrt{8}V}{\pi\phi}$$

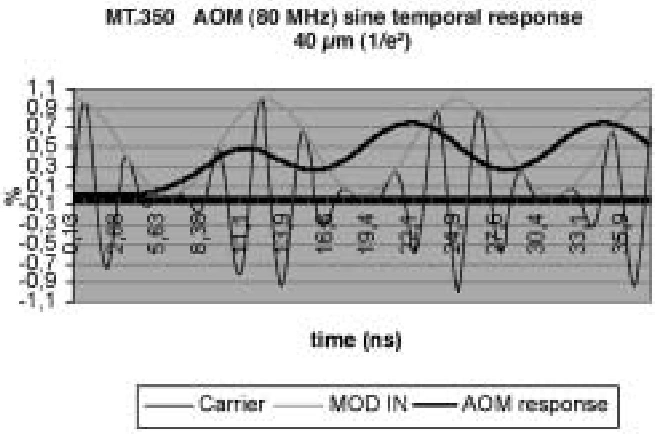
V: acoustic velocity, Φ : beam diameter ($1/e^2$)
Fc : frequency to the $1/e^2$ response rolloff

An other common measure of frequency response rolloff is the analog modulation bandwidth at –3dB (50% reduction point) which is related to fc by

$$F_{-3dB} = \sqrt{\log_e 2}\, f_c$$

From which we can deduce the relationship between f_{-3dB} and rise time :

$$F_{-3dB} \approx \frac{0.48}{T_r}$$

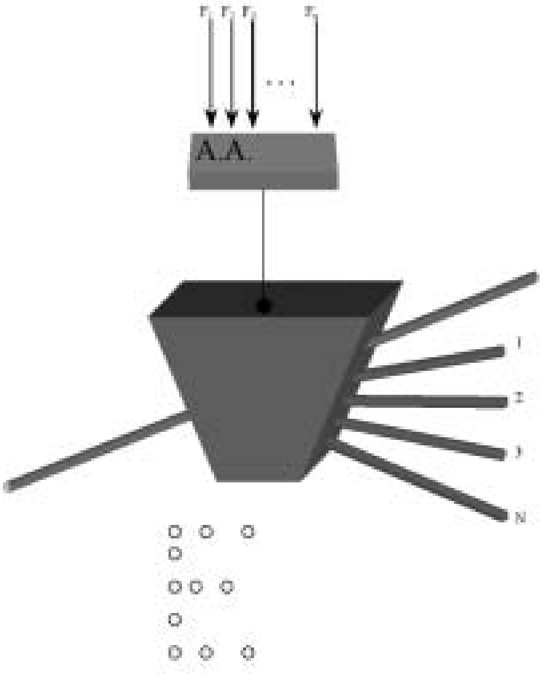


Best performances
rise time: 4-8 ns
efficiency : 70-85 %

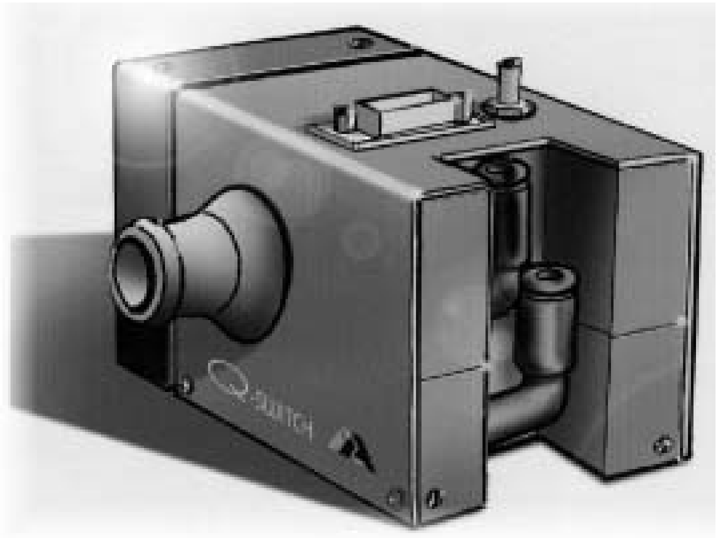
Applications
- Laser Printing
- Transmission of a video signal
- Noise eater
- Locker-mode

Specific application
Multi-beam modulators. Several discrete frequencies ($F_1,F_2,\ldots,F_n$) belonging to the bandwidth of the modulator are sent in the modulator. The diffracted beams are ordered separately, in different directions.

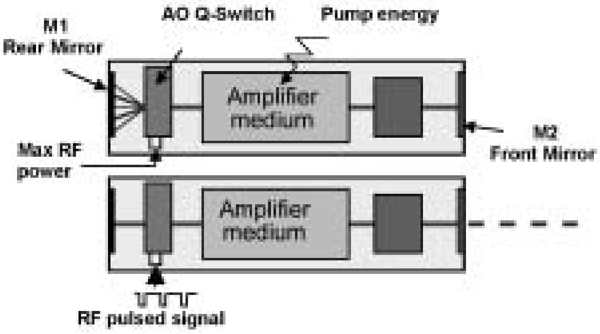
A scanning system (for example deflecting) in the perpendicular direction allows, amongst other thing application, to form characters (printer).



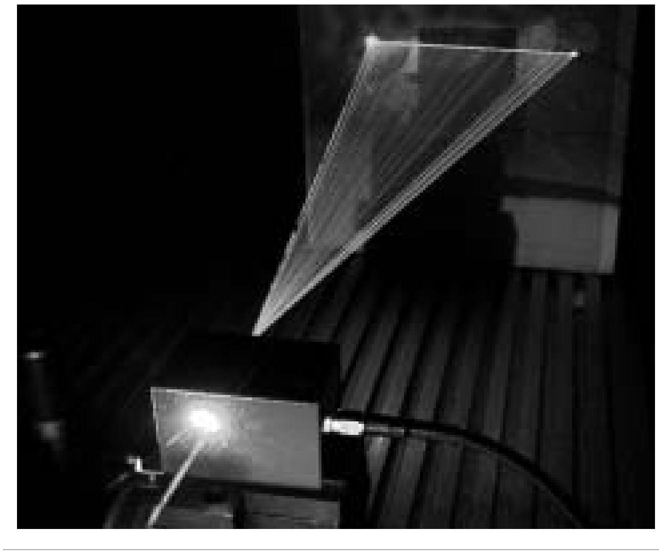
Q-Switches



Q-Switches are special modulators designed for use inside laser cavities. They are designed for minimum insertion loss and to be able to withstand very high laser powers. In normal use an RF signal is applied to diffract a portion of the laser cavity flux out from the cavity (Raman Nath or Bragg regime). This increases the cavity losses and prevents oscillation. When the RF signal is switched off, the cavity losses decrease rapidly and an intense laser pulse evolves.



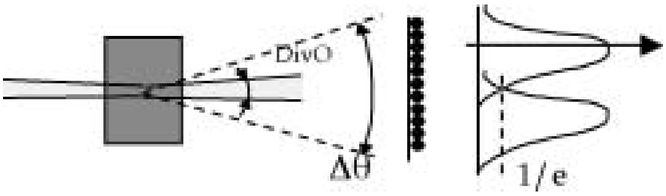
Deflectors



This component is used to deflect the light beam.
In most applications, a high resolution is requested. For this purpose, one uses large-sized crystals (up to 30 mm or more) in order to work with large beam diameters, decrease optical divergence and increase resolution.

Resolution

Static resolution N
The resolution previously defined can be described as static resolution. It is defined as the number of distinct directions that can have the diffracted beam. The center of two consecutive points will be separated by the laser beam diameter (at $1/e^2$) in the case of a TEM00 beam.



$$N = \frac{\Delta\theta}{DIVO}$$

Δθ: deflection angle range
DIVO: laser beam divergence

$$N = \frac{\pi}{4}\Delta F\frac{\phi}{V}$$ for a TEM00 laser beam

ΔF: AO frequency range
ϕ: beam diameter ($1/e^2$)
V: acoustic velocity

$$T_a = \frac{\phi}{V}$$ Access time

Ta is called access time of the deflector. It corresponds to the necessary time for the acoustic wave to travel through the laser beam and thus to the necessary time for the deflector to commutate from one position to another one.
A deflector is often characterized with the time x bandwidth product Ta x ΔF.

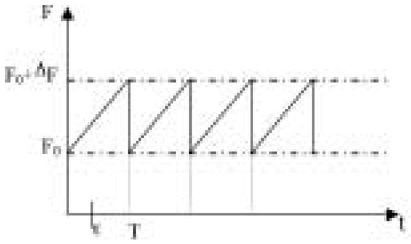
Dynamic resolution N_d
When the field of the frequencies does not consist any more of discrete values but of a continuous sweeping, it is necessary to define the dynamic resolution, which takes account of the “ gradient “ of frequencies.

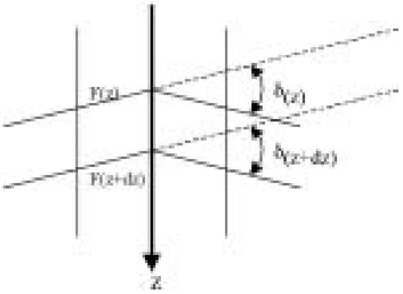
In the case of a linear frequency sweeping:
In Z=O (at the crystal’s entry), the frequency F is equal to:

$$F = F_0 + \frac{\Delta F}{T}t$$

In Z, the frequency is equal to

$$F = F_0 + \frac{\Delta F}{T}t - \frac{\Delta F}{T}\frac{Z}{V}$$





The angle of deviation (δ) is now a function of the distance (z) and of time (t).

$$\delta = \delta(Z,t) = \frac{\lambda F}{V} = \frac{\lambda}{V}\left(F_0 + \frac{\Delta F}{T}\left(t - \frac{Z}{V}\right)\right)$$

$$d\delta = \frac{\lambda}{V}\left(\frac{\partial F}{\partial t}dt + \frac{\partial F}{\partial Z}dZ\right)$$

In z and z+dz, the angle of deviation is not the same one. There is focusing, in only one plan, of the diffracted beam. It is significant to notice this effect of cylinder lens, intervening during sequential sweeping (television with raster scan, printing…).
Equivalent cylindrical focal length:

$$F_{Cyl} = \alpha^2 \frac{V}{\lambda \frac{dF}{dt}}$$

-dF/dt: frequency modulation slope
-V: acoustic velocity
-α: parameter depending on beam profile
(=1 for rectangular shape, ≈1.34 for TEM00)

The dynamic resolution translates a consecutive reduction in the number of points resolved for this purpose.
It can be written versus static resolution as:

$$N_d = N\left(1 - \frac{T_a}{T}\right) + 1$$

- Nd: dynamic resolution
- N : static resolution
- Ta : access time
- T : sweeping time from Fmin to Fmax

Examples:

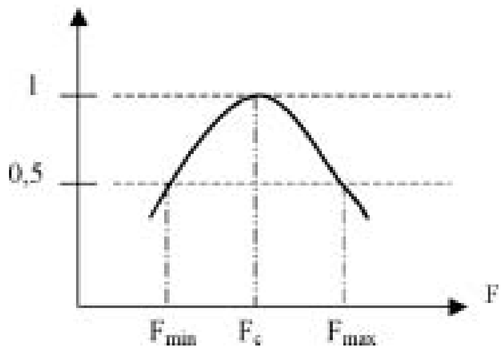
N	Ta (µs)	T (µs)	Nd
1000	10	50	800
2500	50	50	1

Efficiency and bandwidth

The bandwidth is limited to an octave to avoid the overlap of orders 1 and 2.

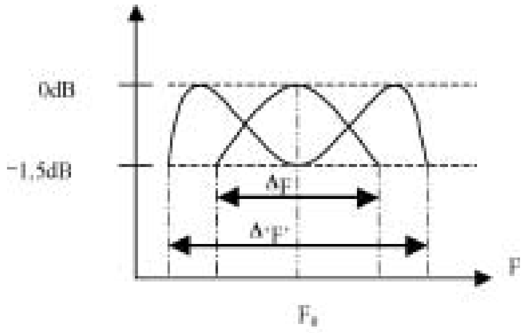
The efficiency curve versus frequency has the following shape for:

Standardized effectiveness



Some applications require a quasi-constant efficiency on all the bandwidth. This can be obtained by decreasing width (l) of the ultrasonic beam, but with the detriment of the maximum efficiency.

Particular case of anisotropic interaction: the bandwidth of the anisotropic interaction can be increased compared with isotropic interaction.
With specific interaction angles, there can be two synchronism frequencies to match the Bragg conditions, so that the deflection angle range can be broaden with good efficiency.



Standardized effectiveness

Applications

- Generation of images, (printing, photolithography…)
- Compensation of the angular errors of the polygonal mirrors,
- Cavity dumper (the acousto-optical component is placed in the laser cavity and makes it possible to obtain pulsed laser of great energy),

▲ particular application 1: radio frequency spectrum analyzer
An RF signal to be analyzed is transformed into an acoustic signal of same frequency. The incident laser beam is deflected

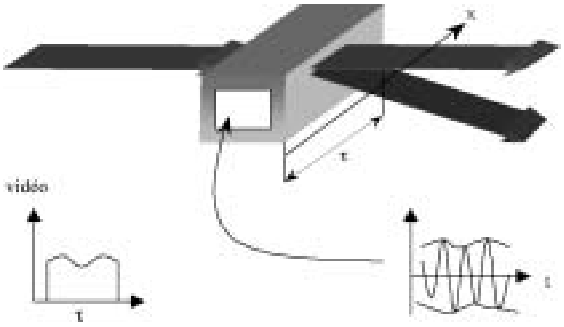
with an angle proportional to the frequency present in the crystal with intensity proportional to RF power (true only with the low powers) .

It is then possible to carry out the spectral analysis in real time of the RF signal limited simply by the access time of the deflector.
The incident laser beam is collimated and increased to illuminate all the aperture of the crystal and to thus allow obtaining a great number of points of resolution.

The diffracted light beam from the deflector is focused on a CCD camera using a Fourier lens. The diffracted signal is converted and can be integrated.

It is possible to carry out particularly compact systems of analysis with low power consumption.

▲ **Particular application 2**
" Scophony "
A carrier wave frequency F_0 is modulated by a video signal.

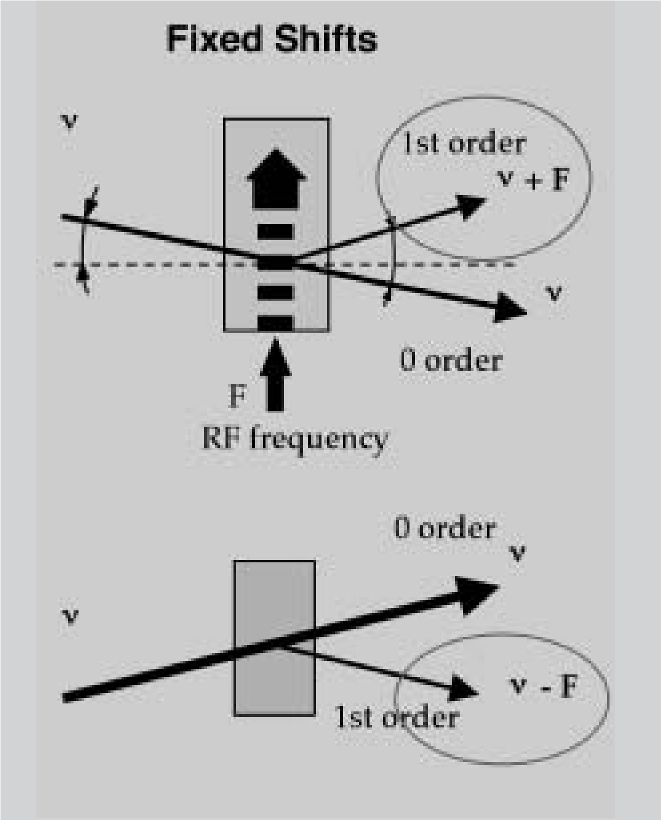


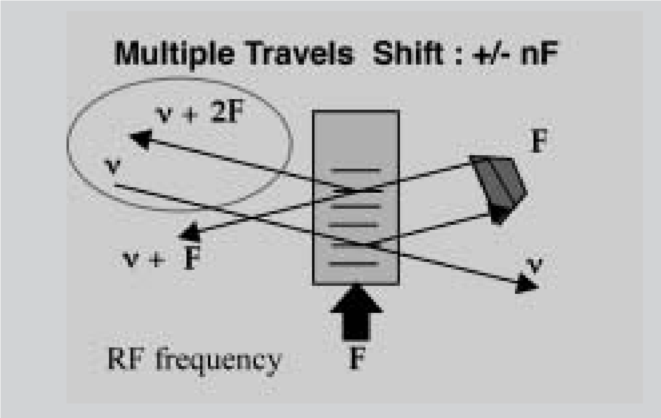
The angle of deflection is fixed by the frequency of the carrier frequency.
The efficiency of the deflector is a function of the distance from the transducer. (x)

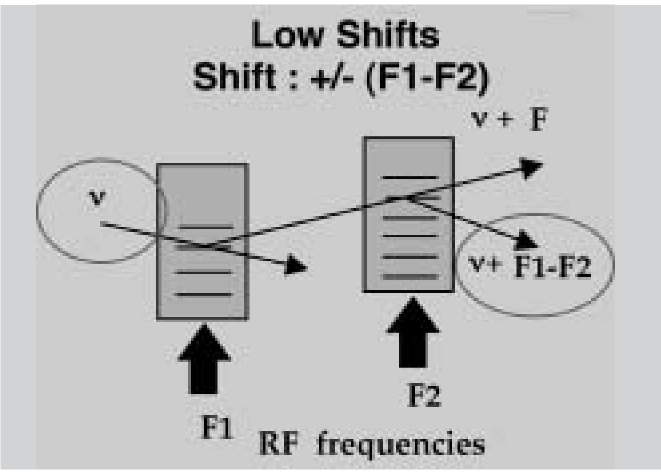
When the deflector contains the video signal corresponding to the access time (Ta), a laser flash gives a deflected light signal, which is the exact spatial representation of the temporal video signal.

Frequency Shifters

These components use the modification of frequency of the diffracted light. (Fd=Fi±F) All the applications using optical heterodyning or Doppler effect are using this property.
Note : the frequency shifter is also a modulator as well as a deflector.





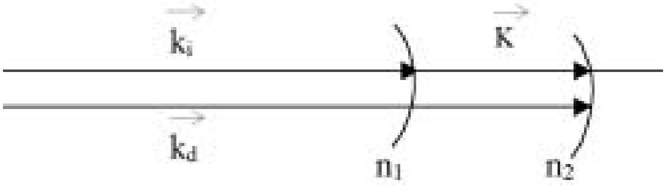


Tunable filters (AOTF)

The extraction of a spectral component of an incoming light source can be carried out by the acousto-optic interaction. The angle of deflection of an acousto-optic deflector is proportional to the optical wavelength. It is thus possible to extract a particular wavelength. The spectral resolution is then limited by diffraction due to finished dimension (D) of the light beam. The limit of the spectral width can be deduced as:

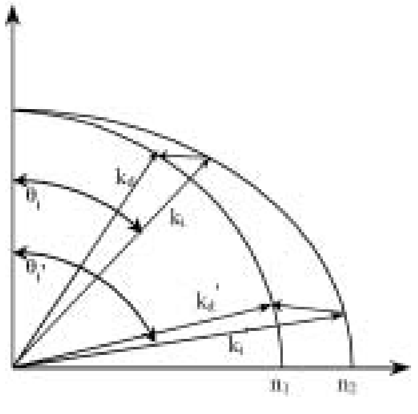
$$\Delta\lambda_0 = \frac{\lambda_0 V}{D}\,\frac{1}{F}$$

A good resolution ($\lambda 0/\Delta\lambda 0$ high) imposes a large dimension (D) of the light beam. The numerical aperture of such systems is thus obligatorily very low and thus their utilization is very limited. The collinear anisotropic interaction makes it possible to tune the filter by simple variation of the acoustic frequency, under significant numerical aperture:



$$\eta = \eta_0 \operatorname{sinc}^2\left(\frac{\Delta k L}{2\pi}\right)$$ (collinear AOTF efficiency)

The non collinear anisotropic interaction, is also usable under a high angle of incidence ($\theta_i \geq 10°$). This last configuration allows the use of materials with high figure of merit coefficients. (TeO2)



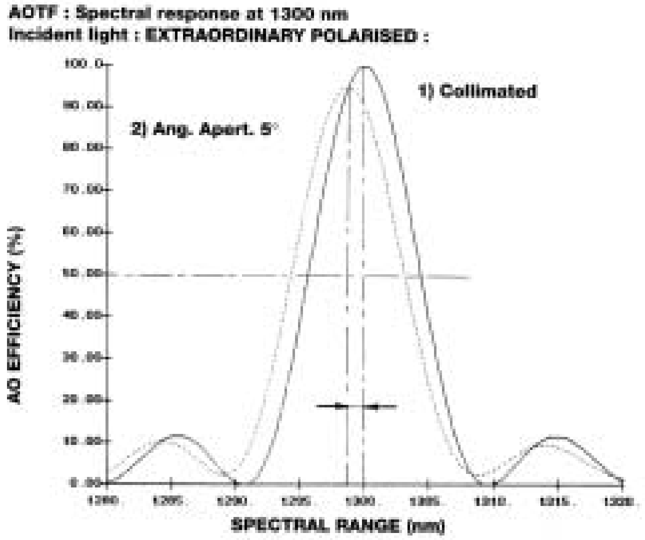
One can show that a large angular aperture is possible as long as the tangents at the point of incidence and synchronism are parallel (the light rays are then parallel in the crystal)

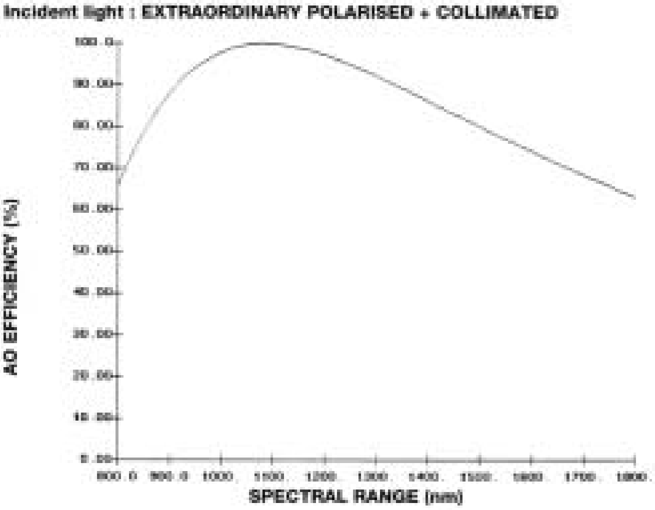
A wide length of interaction (L) and an adequate configuration of the wave vectors (synchronism on a small range of K) guarantee obtaining a low bandwidth and thus a low spectral width ($\Delta\lambda$).

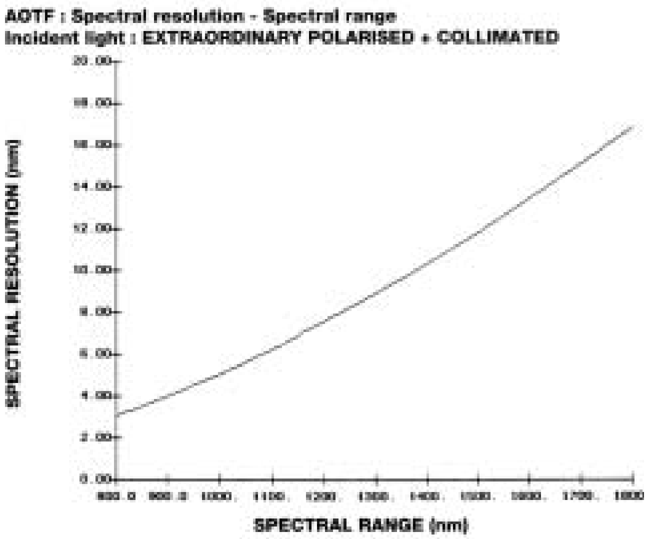
$$\lambda = a\frac{\Delta n(\lambda)}{F} \qquad \Delta\lambda = b\frac{\lambda^2}{L}$$

Δn: birefringence(=$|n_2-n_1|$)
a and b are parameters which depends of θi and θa

Examples:


AOTF : Spectral response at 1300 nm
Incident light : EXTRAORDINARY POLARISED :


AOTF : AO Efficiency -Optical range ; at fixed RF power
Incident light : EXTRAORDINARY POLARISED + COLLIMATED



Characteristics of AOTFs

- The transmitted beam and the diffracted beam can be separated spatially or using polarizers.
- Can work in polarized light, or random polarization (lasers or lamps)
- Access time to a wavelength: several ms
- Temporal sweeping of the spectrum: µs to ms
- Possible auto calibration between each measurement
- Temporal modulation and synchronous detection
- Random or sequential access to any wavelength

Applications

The development of these devices is not so old, and many applications are still to come. The speed of measurements and the absence of any mechanical movement are the remarkable specifications of the acousto-optic filters.

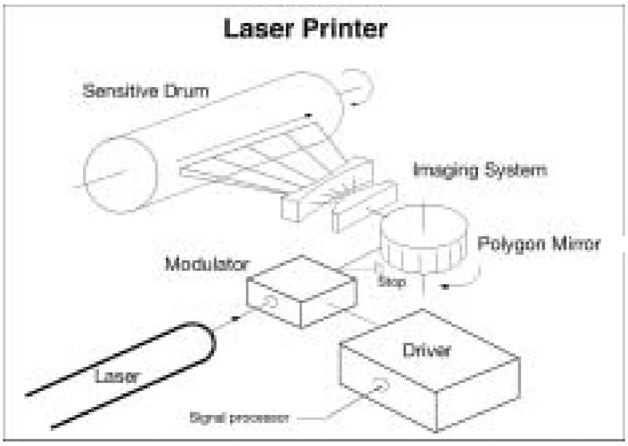
- Multi-spectral imagery (the AOTF is inserted in the imagery system)
- Spectral analysis
- Absorption, fluorescence analysis
- Polarimetric analysis

General

LASER PRINTING
One typical application for acousto-optic modulators is their use in laser printers :

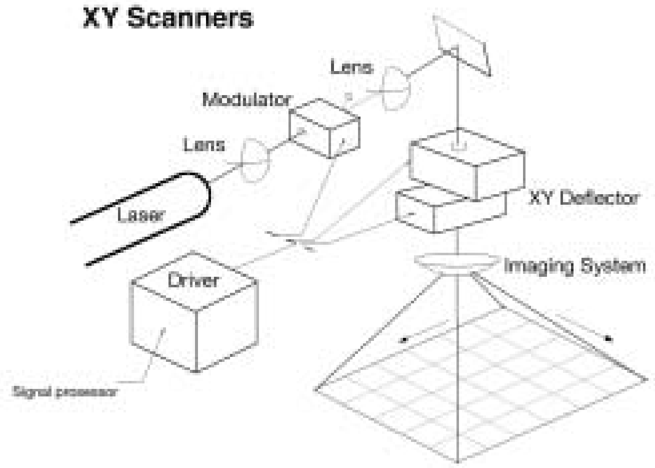
A rotating polygonal mirror scans a laser beam to form a complete line on the surface of a photosensitive drum (usually made from selenium). The laser beam is turned on and off with an acousto-optic modulator so that the scanned line is broken up into individual pixels. In this way, every time a polygon mirror facet goes past, a line of information is “written” to the drum. The drum, in turn rotates so that the document is reproduced line by line.

The information stored electrostatically on the drum’s surface is finally transferred to paper using “toner” – carbon particles.



VIDEO DISC RECORDERS
Information is recorded onto a video disc master using a high power laser (usually Ar^+). The application requires great accuracy in the direction and the intensity of the marking laser at the disc surface since the “pits” formed are generally only a few µm of diameter. An acousto-optic modulator is suitable for its accuracy, speed and reliability.

LASER PROJECTION SYSTEMS
Laser projection systems use a combination of modulators and scanners in a wide range of activities such as: displays, metrology, medical measurements…...
A laser beam is scanned, using either raster or random scanning. Different techniques for scanning include:
-One or two-axis acousto-optic deflectors
-Rotating polygon scanners
-Galvanometric scanners
Most systems will use one (or a combination) of these technologies but all these methods require a mechanism for modulating the scanned beam.
In systems using acousto-optic deflectors, the modulation function can often be carried out by the deflector itself. In other systems, a separate modulator is required.
Working with a single wavelength, a simple acousto-optic modulator can be used. In multi-color systems at very high modulation rates one modulator will be required for each color. At most modulation rates, however, a single polychromatic modulator (AOTF.nC) can be used to control the different wavelengths independently.

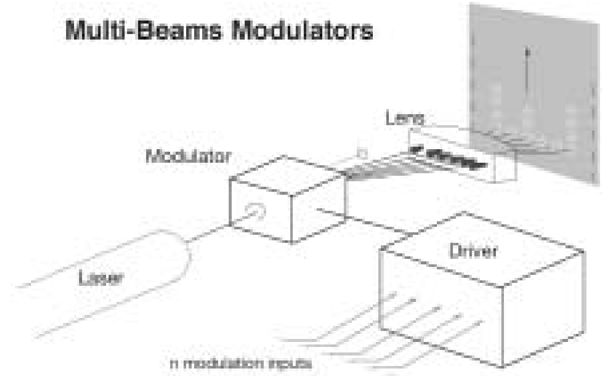


MULTI-BEAM DEFLECTORS

In certain printing applications, characters can be formed conveniently by writing data with several beams simultaneously.

This kind of device is called a “multi-beam deflector” and uses a single modulator crystal driven at several different RF frequencies. This produces a number of output beams, allowing a line of pixels be printed simultaneously. Characters can rapidly be built up by moving a photosensitive medium across the line of pixels or, alternatively, this technique can be used in combination with polygonal mirrors (or deflectors) to increase the printing speed rate.

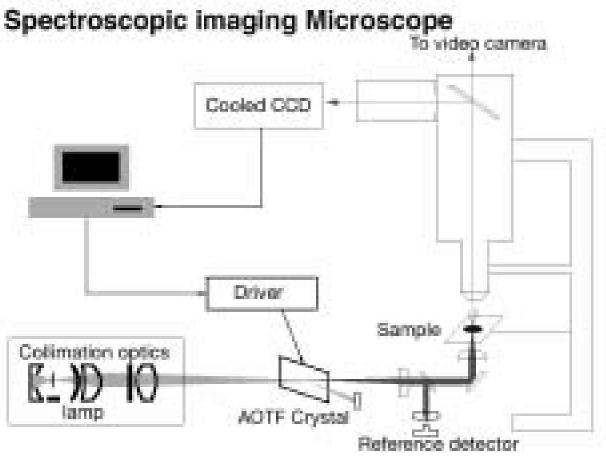
Multi-beam modulators are generally used in custom applications, such as the coding of photographic film.



SPECTROSCOPIC IMAGING MICROSCOPE

In a spectroscopic imaging microscope, an AOTF is used as a programmable filter for a broad-band lamp. The sample is illuminated with near infrared radiation to stimulate the vibrational levels of various molecules, which absorb light at specific wavelengths and proportionally to the molecular concentration. So, a CCD image of the transmitted light is a map of molecular concentration. By varying the pass band of the AOTF, different molecules can be studied and the speed of operation of the AOTF matches the high data acquisition rate of the CCD.

This technique can be very useful in research laboratories for medical diagnostics.



MICROFILMER/MICROFICHER

A microfilm system uses the same principles as a laser printer. However, the polygonal mirror is replaced by an acousto-optic deflector. This device modulates and deflects the laser beam at the same time and can be used since the dimensions of the microfilm are small. Other useful applications for these devices are bdurategraphy and the fabrication of masks for circuit board production.

MONOCHROMATOR

A tunable acousto-optic filter can be used with an incoherent, broad-band source (such as a xenon lamp…). The light is collected and then collimated to match the filter’s aperture and acceptance angle.

The filter is driven with a RF signal whose frequency controls the transmitted wavelength.

At the filter’s output, the transmitted component (typical resolution – several nm) is available for use as a tunable light source.

This method has three main advantages :

-speed : a complete spectrum can be swept in a few milliseconds.

-wavelength and intensity can be controlled. Modulation up to many tens of KHz is possible – for fluorescence studies, perhaps.

-Ease of use, repeatability, and lack of mechanical parts.

The range of applications is vast : molecular absorption spectroscopy, fluorescence spectroscopy, microscopy…

AOTF spectrometers and spectrophotometers are being developed very widely in the pharmaceutical, chemical, food and plastics industries for rapid composition analysis.

CONTACTLESS MEASUREMENTS

Acousto-optic deflectors can be used for 2- and 3-dimensional surface mapping, even with complex shapes. Measurements are made by triangulation. The shape being mapped is scanned with a laser beam (HeNe, laser diode…), controlled accurately by an XY acousto-optic deflector and microprocessor. One or more CCD cameras, looking obliquely, record the positions of the laser spot and, by combining the data used to control the deflector and the measurements from the CCD cameras, a computer can generate a 3-dimensional position for each laser spot, and draw a map of an object.

COLOR MIXER

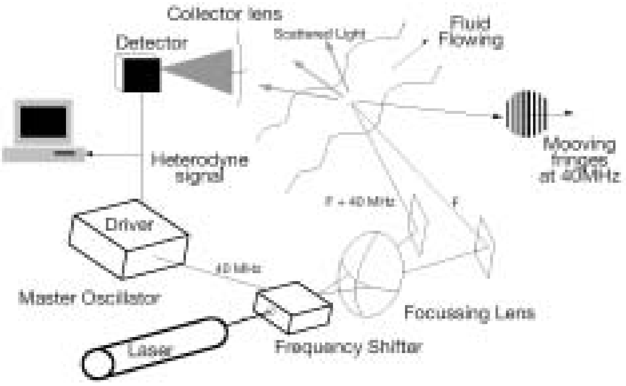
The AOTF.nC is a special filter which allows different lines of a high power laser beam (Ar+, Kr+, mixed gas…) to be controlled independently. Up to 12 lines can be mixed and separately modulated in order to compose different colors. While the main application is laser show field, further applications are being developed in, for instance, colorimetry.

LASER DOPPLER VELOCIMETER

Acousto-optic frequency shifters can be used to generate two optical beams with a fixed (or variable) RF frequency shift between them. This has many applications in diverse fields such as high resolution spectroscopy, telecommunications or metrology.

In the laser Doppler velocimeter, an acousto-optic shifter to generate a 1st order beam shifted by typically 40MHz from the 0th order. The 2 laser beams are then made to cross in a region of interest in a fluid or gas and will produce fringes. When this light is scattered from a particle it is found to be modulated at the 40MHz shift frequency – but slightly Doppler shifted according to the velocity of the particle. So, by sampling the scattered light the speed and direction of the particle's motion can be analyzed.

Laser Doppler veloci meter



MOLECULAR TRAPPING

Molecules can be "trapped" simply with a stationary laser beam, being attracted to the center of the beam by "pressure" of radiation. If the laser beam is focused down hard to create a definite beam waist then the molecule can be trapped in three dimensions.

With the addition of a 2-axis deflector, the laser beam can be moved and molecules can actually be manipulated and moved around.

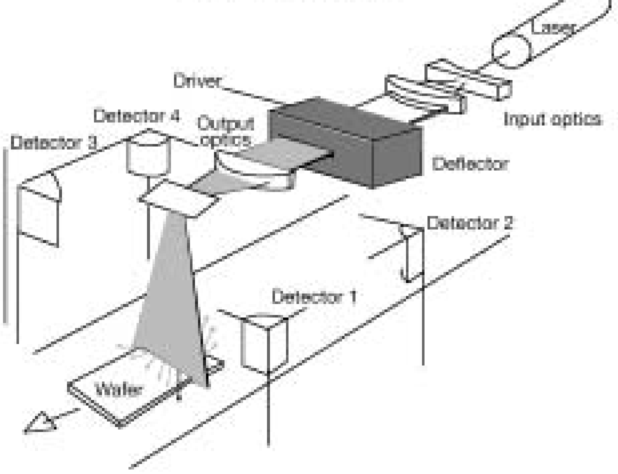
YAG lasers operating at 1064nm are generally used and deflectors are used to scan the laser beam through about one degree. Movements comparable with the pointing stability of the laser beam are used – generally only about 1% of the laser beam's divergence. To get this degree of resolution, and to be able to vary the frequency at the required rates, DDS drivers are used., with frequency steps of around 2kHz.

WAFER INSPECTION

A high speed acousto-optic deflector is used to scan a laser beam over an inspection line at high speed and with great accuracy. Light scattered from the wafer is continuously recorded by four detectors placed at the 4 corners of the wafer. The signal from the detectors is analyzed and processed. Depending on the light levels at the 4 detectors, the system can determine the number and position of defects, the presence of dust…...

Production can be stopped if the number of defects exceeds acceptable levels.

Wafer Inspection



POLARIMETRIC HYPERSPECTRAL IMAGERY

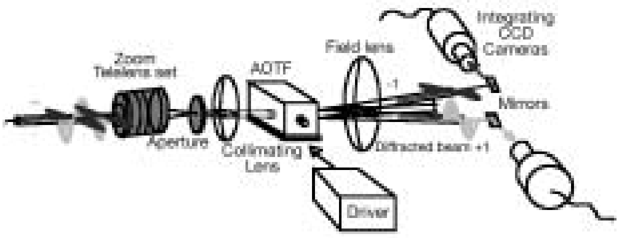
Many laboratories have orientated their researchs using AOTF for polarimetric hyperspectral imagery.

The AOTF technology has opened many potential applications, especially in geoscience, air and space borne remote sensing, target detection, vegetation analysis…

The great advantage using an AOTF is to be capable of measuring spatial, spectral and polarization characteristics of a target, in real time, without moving parts, only with a single instrument.

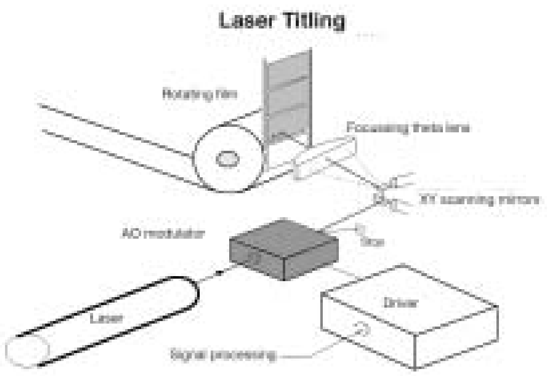
The multiplication of the analysis criterion (multi-spectral images+ H&S polarization images) improve the accuracy of the detection, and let us think to great developments in the near future.

Polarimetric hyperspectral Imagery



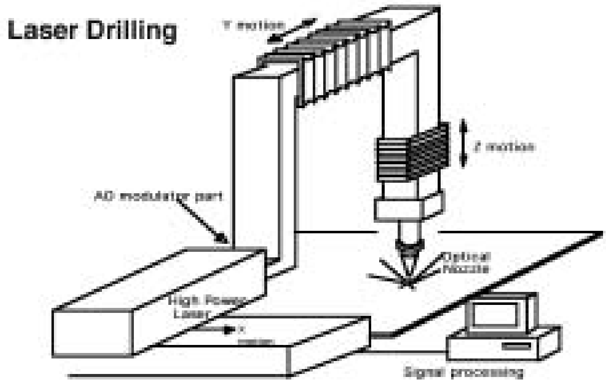
LASER TITTLING

Laser titling is a special application where high visible laser power is involved (generally Ar+). Laser power is focused down to the film where the tittles are written thanks to XY mirrors scanners. The AO modulator is used as a laser switch to obturate laser power between scanner displacement between two characters. It is also used as a laser power regulator in order to optimize the marking power to each kind of film support.



LASER DRILLING / CUTTING

While CO2 (10.6 µm) laser has been a standard for drilling, cutting and welding industry, the market is shared nowadays with other lasers such as Nd:Yag lasers (1.06 µm).
The couple AO modulator+driver is then the best alternative for medium / high laser power fast switch off. It is also used as a power regulator to match the applications / supports requirements in term of laser power level.
This technology can be used in applications ranging from perforating carbonless papers at low powers to welding metal bellows and cutting sunroof openings in auto bodies at higher powers.



RF DRIVERS

To meet the needs of its acousto-optic components over the last 20 years, A.A has developed a comprehensive range of fixed and variable frequency sources with associated RF drivers, operating from 1kHz to 3GHz. A number of techniques are used.

Fixed frequency sources:
Quartz
Fixed PLL

Variable frequency sources:
VCO (Voltage Control Oscillators)
PLL (Phase Locked Loop)
DDS (Direct Digital Synthesizer)

The choice of a driver will be given by the type of AO device and will depend on the application purposes.

Quartz drivers

These drivers have been especially designed to produce RF power levels and frequencies compatible with A.A's modulators. Drivers can be provided at any frequency from 10 to 300 MHz. All models use high stability (<50ppm) crystal controlled oscillators. The RF output can be externally modulated. The settling time varies from 100ns to 3ns depending on the fixed frequency. Usually the driver is coupled internally to a power amplifier; if the output power required is very high then the amplifier will be provided separately, offering RF powers up to 150 W.

PLL drivers (Phase locked Loops)
Phase Locked Loop drivers are VCO based, but stabilize the output frequency against a crystal based reference. The fundamental crystal frequency is divided down and, by changing the division ratio, the output frequency can be altered.
At frequencies over 300MHz, where quartz oscillators may be difficult to build, these sources offer very high performance. Optional amplifiers can be added to increase the output power. These variable frequency drivers will be chosen for their accuracy and stability, but their commutation time is slow : from several µs to ms.
Identical in principle to fixed frequency PLL sources, these units are designed for variable frequency operation. Since the PLL loop needs time to stabilize, these drivers are suitable for high accuracy but lower speed applications.

The typical models cover a wide range from 10 to 3000MHz, with octave or multi-octave frequency ranges. The number of frequency steps can be specified from 100 to > 10000. Frequency control is generally digital, controlled via a parallel or series input.

VCO drivers (Voltage controlled oscillators)

Deflectors or variable frequency shifters require a variable frequency source covering a suitable frequency which might lie anywhere between 10MHz and 2GHz. VCOs are ideal for raster scan or random access. Their stability and linearity will be a limitation for some applications.

For general purpose applications, three types of VCO drivers are available, differing only in their sweep time (Fmin to Fmax.) which can be ≤ 1 µs, ≤ 10 µs or ≤ 100 µs.

The VCO's can be modulated (amplitude) from an external signal. An external medium power amplifier will be required to generate the RF power levels required by the AO device.

DDS drivers (Direct Digital Synthesizers)

To get a high resolution driver with fast switching time, A.A has designed direct digital synthesizers based on monolithic IC circuits. 2 models have already been released, and different units can be designed to specific requirements.

Both models offer high frequency accuracy and stability and extremely fast switching times, generally of a few tens of nanoseconds.

The DAC circuits have been designed with utmost care to obtain clean RF signals, with minimum spurious noise.

Power amplifiers

A.A's acousto-optic amplifiers are linear with large bandwidth and medium or high power.

They are specially designed for AO devices and adjusted at factory to fit the AO frequency range, impedance and necessary RF power..

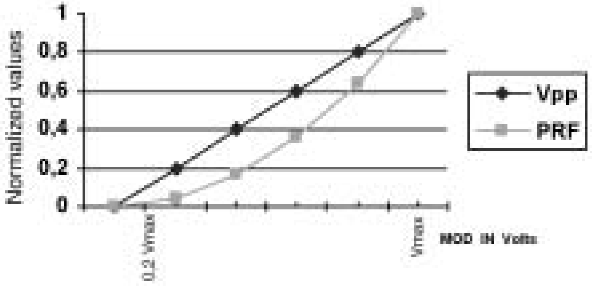
Each amplifier is supplied with its heat sink and all are stable and reliable under all conditions.

Glossary

Output RF power

The output RF power PRF through a 50 Ω load (R) is related to the peak to peak signal amplitude Vpp by the relation :

$$P_{RF} = \frac{V_{pp}^2}{8R} = \frac{V_{pp}^2}{400}$$



VSWR (voltage stationary wave ratio)

This parameter gives an information on the reflected and transmitted RF power to a system.

In order to have the best matching between an acousto-optic device and a radio frequency source/amplifier, one will have to optimize both impedance matching on the source and the driver. Generally, input impedance of an acousto-optic device is fixed to 50 Ohms as well as the output impedance of the driver/amplifier.

VSWR	POWER reflected %
1.002 / 1	0.0001
1.068 / 1	0.1
1.15 / 1	0.5
1.22 / 1	1
1.5 / 1	4
2 / 1	11
2.5 / 1	18
3 / 1	25

AMPLITUDE MODULATION

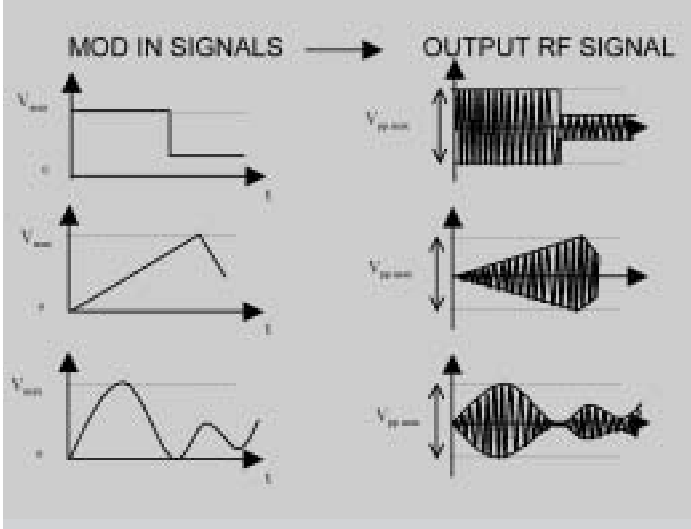
ANALOG MODULATION (0-Vmax)

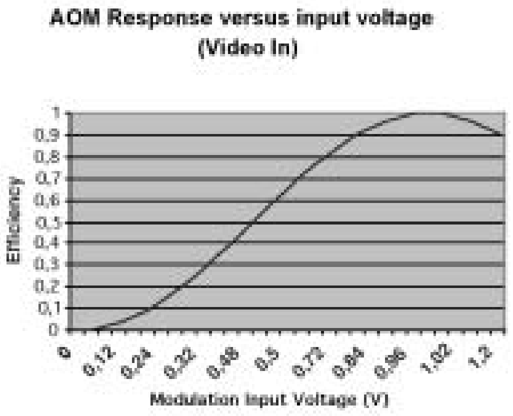
The analog modulation input of your driver controls linearly and continuously the output RF amplitude of the signal from 0 to maximum level.

- When applying 0 V on "MOD IN", no output signal
- When applying Vmax on "MOD IN", maximum output signal level

The output RF waveform is a double-sideband amplitude modulation carrier.

Vmax can be adjusted at factory from 1 V to 10 V.



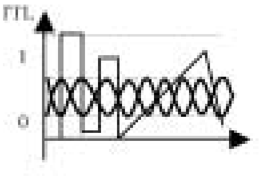


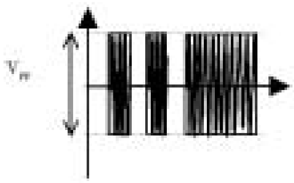
TTL MODULATION (ON/OFF)

The TTL modulation input of your driver is compatible with standard TTL signals. It allows the driver to be driven ON and OFF.

- When applying a “0” level (< 0.8 V) on “MOD IN”, no output signal.
- When applying “1” level (> 2.4 V) on “MOD IN”, maximum output signal level.

It will be noted that a TTL modulation input can be piloted with an analog input signal.



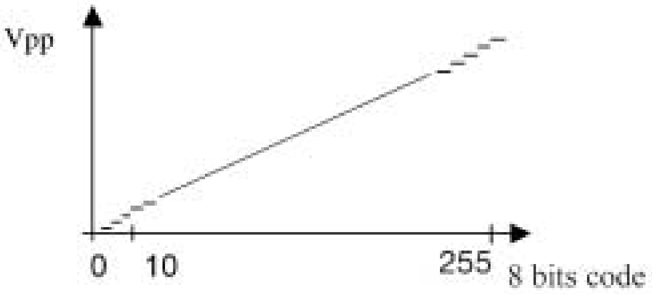


Digital 8 bit AMPLITUDE MODULATION

A byte (8 bit //) controls the amplitude of the output RF signal. A D/A converter converts the 8 bits command (N) on an analog signal which controls linearly the output amplitude.

256 levels are available

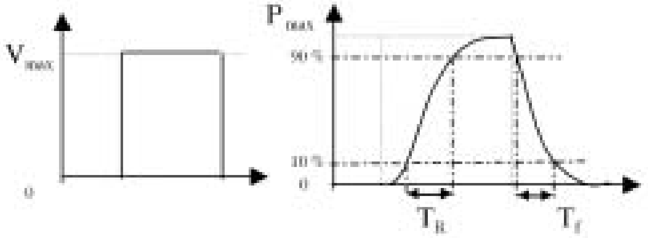
- When N=00000000, no output RF signal
- When N=11111111, maximum output level



RISE TIME / FALL TIME

The rise time Tr and fall time Tf of your driver specified in your test sheet corresponds to the necessary time for the output RF signal to rise from 10 % to 90 % of the maximum amplitude value, after a leading edge front. This time is linked to carrier frequency and RF technology.

The class A drivers from AA, offer the best rise/fall time performances.



EXTINCTION RATIO

The extinction ratio of your driver specified in the test sheet is the ratio between the maximum output RF level (MOD IN = max value) with the minimum output level (MOD IN = MIN value).

A bad modulation input signal can be responsible for the extinction ratio deterioration.

$$Extinction\ ratio = 10 \log(\frac{P_{max}}{P_{min}}) = 20 \log(\frac{V_{pp\,max}}{V_{pp\,min}}) \quad (dB)$$

FREQUENCY CONTROLS

ANALOG CONTROL (0-V$_{max}$)

The analog frequency control input of your driver controls linearly and continuously the output RF frequency of the signal from Fmin (minimum frequency) to Fmax (maximum frequency). The minimum and maximum frequencies are set at factory, and can be slightly adjusted with potentiometers “OFFSET” and “GAIN”.

The typical linearity of the frequency versus input command for standard VCOs is typically +/- 5%.

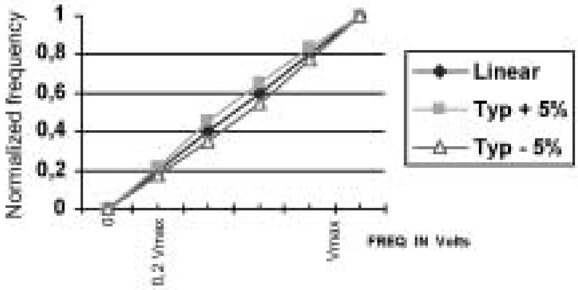
Sweeping time (VCO)

This is the maximum necessary time to sweep frequency from minimum to maximum, or maximum to minimum.

This value will be taken as the maximum random access time, though it depends on the frequency step.

- When applying 0 V on “FREQ IN”, Frequency = F min
- When applying Vmax on “FREQ IN”, Frequency = F max

(Standard frequency control input : 0-10 V / 1KΩ).



8 BITS FREQUENCY CONTROL
A byte (8 bit //) controls the frequency of the output RF signal. A D/A converter converts the 8 bits command (N) on an analog signal which controls linearly the output frequency.
256 steps are available : refer to your test sheet for pin connexions.

- When N=00000000, RF signal frequency = F minimum
- When N=11111111, RF signal frequency = F maximum

AO ADJUSTMENTS AND PRECAUTIONS

Mechanical Precautionary Measures
To avoid any damage to the crystal or glass, make sure that fixing screws and the rotation axis are not so long as to protrude through the base of the device.

Optical Precautionary Measures - Windows cleaning
Use a Q-tip. Clean first with pure ethanol, then with acetone. Most AO devices use soft materials and need careful cleaning.
“Oily stains” should be removed immediately to avoid irreversible marks.

Laser power density
Check the maximum value specified for the given AO device, especially when focusing the laser to maximize bandwidth. With a high power laser, make sure you do not focus directly onto the optical faces.

Laser polarization
Check the specified optical polarization is correct for optimum AO efficiency (random, circular, perpendicular or parallel to the base - depending on device).

Optical aperture
The holes in the housing of the modulator are usually larger than the actual specified optical aperture. The AO device will need to be adjusted, using slight translations perpendicular to the laser beam, to get the beam traveling through the correct area of the crystal and to maximize efficiency.

Incidence angle
For an isotropic interaction, adjust the incidence angle to achieve the Bragg configuration. For a birefringent interaction, work to the sketch of interaction which will be supplied with the unit.

Electrical Precautionary Measures
Do not operate the RF driver without the specified amount of cooling!
Do not operate the RF driver without a load!
(either a suitable 50 W load or an AO device)
Do not exceed the specified values for the power supply and control voltages.

CONCLUSION

The goal of these application notes is not to give a complete overview of acouto-optics, but to give the user the main useful informations to select an acousto-optic device and to start an acousto-optic application.
For more detailed informations several books are available from literature. It will also be a pleasure for AA’s engineers to help the user to set up his application.

CONTENTS

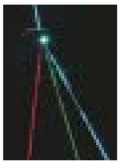
A.A is a world leader in the manufacturing of quality Acousto-optic and radio frequency devices.

Founded in France (1979) as "Automates et Automatismes", for the manufacturing of Pneumatic Automation, A.A evolved in the early 80's, when an Acousto-optic laboratory was created by a spin-off from "Soro", a famous French optical manufacturer, into a design and manufacturing company of optical systems and Acousto-optic devices. In 1988 A.A became a limited company, focused on Acousto-optic and associated radio-frequency drivers.
The telecommunication/microwave division, created in 1994, specializes in providing solutions for the French satellite communication market and microwaves/RF systems for military, spatial and telecom applications.

Close collaboration with universities and research institutes, provided invaluable knowledge and experience in the design and manufacturing processes of Acousto-optic devices and radio-frequency sources. Continuous R&D keeps pace with advances in laser and electronic technology to ensure A.A continues to offer state-of-the-arts products.

A.A. offers its customers solutions from prototype design to large volume manufacturing:
1) In-house design capabilities:
AO design software, opto-mechanical design software, RF/microwave simulation software
2) In-house manufacturing capabilities:
X-ray orientation, crystals and glasses cutting and polishing, coating, metallic deposition, molecular bonding under vacuum, soldering wave-machine for large radio-frequency sources production.
3) In-house test and quality control equipment:
Laser interferometers, network analyzers, spectrum analyzers, digital oscilloscopes, a large range of lasers for final tests and controls, and more.

Mastering all critical areas of the AO and RF technology, allows A.A to accompany its customers from the concept design to large volume manufacturing.
A.A thrives to maintain a high-tech up-to-date line of products and excellent service. Dedicated to customer's satisfaction, A.A's worldwide representation ensures quality products, local support with competitive prices.



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