ACOUSTO-OPTIC MODULATORS

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The laser invention in 1960 has led to 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 and the use of these components in scientific and industrial applications.

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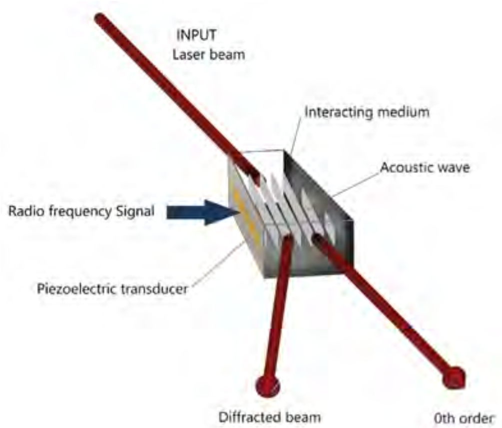
BASIC THEORY OF ACOUSTO-OPTICS

A sinusoidal radio-frequency signal applied to a piezoelectric transducer, bonded to a suitable crystal (interaction medium), generates an acoustic wave (fig. 1). The interaction medium must have photoelastic properties, so that the acoustic wave generated by the transducer and propagating at the acoustic velocity of the material generates « stresses » in the material, causing its refractive index to vary periodically. The refractive index or phase grating thus created has an acoustic wavelength that depends on the frequency of the RF signal, and a refractive index variation amplitude depending on the amplitude of the acoustic wave. Any incident laser beam is diffracted by this grating, generally resulting in a number of diffracted beams in different directions. This is the special case where a single order is diffracted at the output of the component, which is mainly exploited in acousto-optical components for industrial and scientific applications.

Various materials with photoelastic properties are used in acousto-optical components, depending on wavelength (typically from 180nm to 11µm), laser power and final application. The main materials are Tellurium Dioxide (TeO_2), Fused Silica (SiO_2), Quartz, Germanium (Ge) and glasses or doped glasses such as Flints or Chalcogenides.
Depending on their crystallographic orientation, some materials have isotropic optical properties, while others are anisotropic. Isotropic configurations are generally associated with longitudinal acoustic waves (direction of vibration parallel to displacement), while anisotropic configurations are associated with transverse or shear acoustic waves (direction of vibration orthogonal to displacement).
In the case of an isotropic Bragg interaction (fig. 2), the Bragg incidence angle is equal to $\theta_B = \frac{\lambda F}{2v}$ with λ = wavelength, F = carrier frequency, v = acoustic velocity. The separation angle between the 0th and diffracted order is twice the Bragg angle. The diffracted intensity in the 1st order is equal to $I_1 = I_0 \sin^2\sqrt{\eta}$, with $\eta = \frac{\pi^2}{2\lambda_0^2} M_2 \frac{L}{H} P$, with I_0 = maximum intensity in the 0th order, I_1 = intensity in the 1st order, λ = wavelength, M_2 = figure of Merit of the material, H and L, height and width of the acoustic column respectively, P = acoustic power.

Figure 1: Acoustic wave propagating inside a Bragg cell.



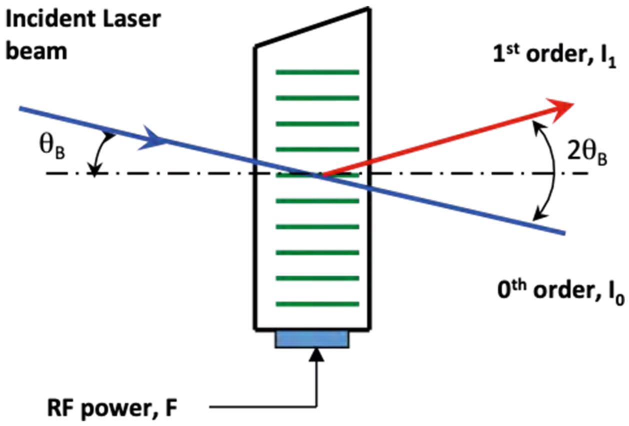


Figure 2: Bragg Isotropic interaction.

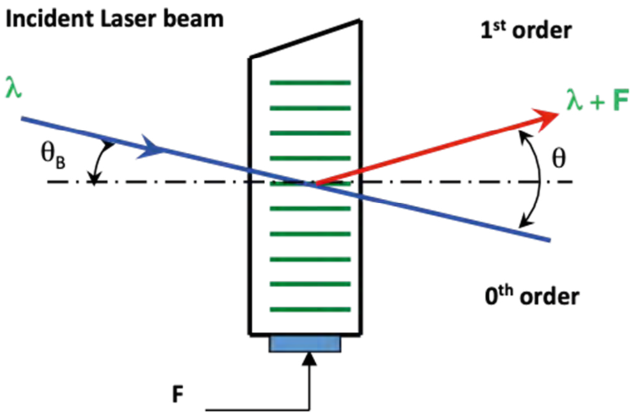
Diffraction efficiency is given as the ratio between the intensity in the 1st order and intensity in the 0th order, $\frac{I_1}{I_0} = \sin^2\frac{\pi}{2}\sqrt{\frac{P}{P_0}}$, with $P_0 = \frac{\lambda_0^2}{2M_2}\frac{H}{L}$, where P_0 is the necessary acoustic power to maximize diffraction efficiency.

THE DIFFERENT MODULATORS

INTENSITY/AMPLITUDE MODULATORS

This type of modulator is used to vary and control the amplitude (intensity) of the diffracted beam. Variation can be continuous between 0 and maximum intensity, or "on/off" as with a shutter. The associated driver provides a fixed frequency adapted to the modulator, whose RF output power can be controlled by an analog or TTL modulation signal. This type of modulator is characterized by its rise time Tr, time to rise diffraction efficiency from 10% to 90% of the maximum, which depends on the laser beam diameter ∅ ($1/e^2$ for TEM00 mode) and the acoustic velocity V, such that $T_r = 0.66\frac{\varnothing}{V}$.
The current modulator family includes special components such as:
- **Q-switches:** these components, placed inside a laser cavity, are designed to create periodic losses, enabling the •••

Figure 3: Frequency shift and angular deviation.



amplifying medium to reconstitute the population inversion and emit a laser pulse when the losses are set to 0. Q-switches operate in the 0th order in either the Bragg or Raman Nath regime.

- **Cavity dumpers** are modulators generally inserted into a mode-locked laser cavity. They operate in the 1st order to separate a single optical pulse from the circulating pulsed energy, allowing nearly all the laser energy to be dumped out of the resonant cavity in the form of a single optical pulse with high peak power and high repetition rate. A cavity dumper offers high peak power and higher repetition frequencies.

- **Pulse pickers:** these components are generally placed after the laser cavity and allow fast pulse extraction of an incoming high repetition pulse train. They can be free space or fiber pigtailed.

- **Mode Lockers** are special devices operating with a standing acoustic wave beating at twice the carrier frequency. They are inserted inside a laser cavity to create high repetition losses in order to generate short pulses.

FREQUENCY MODULATORS (DEFLECTORS/FREQUENCY SHIFTERS)

A frequency shift on the laser beam is introduced by the acousto-optic interaction. The laser frequency is shifted by the amount of the acoustic carrier frequency. The shift can be negative or positive depending on the incident angle. Any acousto-optic device can be used as a fixed or variable frequency shifter. (See fig. 3)

The angular deviation of the diffracted 1st order beam is proportional to the acoustic frequency so that $\theta = \frac{\lambda F}{\nu}$

where θ is the angle between 0th and 1st order. Deflectors are based on this principle. They are used to vary fast and accurately the diffracted laser beam. As there is no mechanical movement, the lifetime and long-term reliability is excellent. We can have

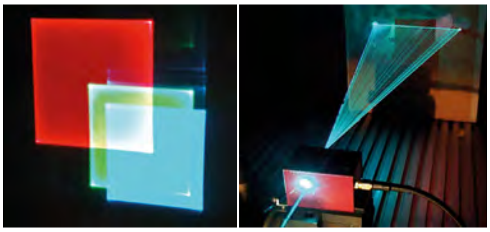


Figure 4: (left) 2 axis RGB deflection, (right) AO 1 axis deflector.

1 axis or 2 axis deflectors using two crossed deflectors (Fig. 4)

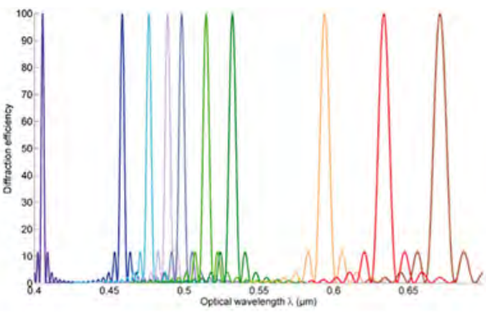
PHASE MODULATORS

A combination of two acousto-optic frequency shifters in series, one in an up-shift configuration and the second one in a down-shift configuration, driven at the same carrier frequency with a controlled phase delay, will introduce on the light beam a controllable phase shift. This optical phase shifting can be used in various applications such as holography, phase measuring profilometry or interferometric applications.

POLYCHROMATIC MODULATORS

Wavelength selection can be carried out with large spectral band sources or multiline lasers since only one wavelength will match the Bragg condition. This is generally made using special cuts in anisotropic crystals and using an anisotropic interaction to get high sensitivity to incidence Bragg angle leading to narrow bandpass. This property is used in acousto-optical tunable filters.

Figure 5: Simultaneous selection of 8 laser lines with a polychromatic modulator



A polychromatic modulator/filter can be driven with multiple carrier frequencies to select and modulate simultaneously and independently several laser lines or spectral bands from an incoming wide spectrum laser (fig. 5)?

MULTI-CHANNEL MODULATORS

Multi-channel acousto-optic modulators (fig. 6)enable several beams to be modulated or deflected simultaneously and independently by a single crystal. A network of transducers is applied to the crystal, enabling independent control of the laser beams. Cross-talk between beams is a key parameter for this type of modulator. These modulators are used to parallelize information in high-speed applications such as material processing, metrology or quantum computing.

MARKETS AND KEY APPLICATIONS

QUANTUM OPTICS

Acousto-optic components (AO) are used to manipulate the properties of light such as its frequency, its intensity, its phase or even its position. These properties have been well exploited in various experiments involving entangled photons: the Nobel Physics prize 2022 has been awarded to such experiments where AO devices were used to switch the photons from one polarizer to another in order to determine their respective polarization state. AO was a good candidate due to its ability of deflecting the photons within tenths of ns. The entangled photons have led to major revolutions in the Quantum science and their application are numerous, namely:

Quantum communication - AO devices play an important role in the quantum communication systems such as Quantum Key Distribution (QKD) systems. They assist in preparing, manipulating and measuring the quantum states of photons, in order to allow two parties to generate a shared secret key with absolute security guarantees.

Figure 6: 8 channels quartz modulator, Multiflex project.

Quantum computing - AO devices can be used to manipulate the quantum states of the qubits, the basic units of quantum information. By controlling the phase or frequency of the lasers, AO enable precise state preparation. Additionally, AO can be used to direct the laser beams at individual qubits in the ion chain.

BIOPHOTONICS

Lasers are massively used in biomedical applications due to their ability to emit monochromatic, coherent and high power. These characteristics make lasers valuable tools in various aspects in combination with AO devices to not only perform surgeries and but also in measurement and imaging:

Light sheet microscopy is an advanced imaging technique used in the field of biology and biomedical research. It is particularly well suited for capturing 3D images of biological samples, including living cells and tissues with minimal photodamage and high spatial and temporal resolution. Light sheet microscopy works on the principle of illuminating a thin sheet light through the sample, allowing for rapid imaging of biological processes.

Confocal microscopy is another imaging technique which is used in various field including medical, biology and material science. It is valuable for visualizing complex 3D structures and dynamic processes within the samples. The principle of operation is based on the selective focusing on a specific plane of interest while eliminating out of focus light from other planes. This technique relies on the use of a pinhole to clock unwanted light, resulting in an optical sectioning and improved image quality compared to traditional microscopy.

For both above mentioned techniques, AOTFs (Acousto optic tunable filters) are commonly used to perform intensity modulation on several lasers simultaneously or individually. The AO devices also help to switch from one laser to another. These operations are done quickly due to the fact that there are no mechanical moving parts inside the AO device.

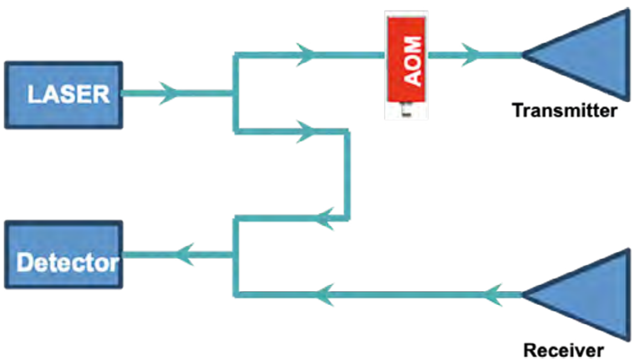


Figure 7: General schematic of a LiDAR involving AO device.

LIDARS

LiDAR is an acronym derived from radar but uses light instead of radio waves. As sensing technology, it can be used to measure distances, create 3D maps and collect information on shape or characteristics of surfaces or objects. LIDAR systems are used in various sectors: autonomous vehicles, meteorology, wind turbines and the list is non-exhaustive. Let's take wind turbine for instance where the LiDAR's role is to measure the speed of the wind as well as its direction and transmit the information to the control system allowing the turbine and the blades to adjust appropriately to the weather conditions. Here, the principle of operation is to send light in a certain direction and thanks to the natural impurities present in the air, the light is reflected and then collected for processing to determine the wind's speed and direction. To achieve this, we need to differentiate between the transmitted and reference beam. This can be done by passing one of two beams into an AOFS (Acousto optic frequency shifter) which will impose a frequency shift (see Fig.7).

OPTICAL TWEEZERS

An optical tweezer is a scientific instrument that uses a focused laser beam to provide an attractive or repulsive force on microscopic particles. The focused beam in the tweezers creates optical traps such that the tiny particles can be held, moved and easily manipulated. AO devices have got a large contribution in this domain. When the RF frequency is tuned on AO devices, the output diffracted beam's position changes. It is this feature that is widely used in the optical tweezers. Indeed, the AODs are used to steer the laser beam precisely and rapidly, enabling optical traps to be repositioned with high accuracy and facilitating the manipulation of particles or the tracking of dynamic biological processes. In addition, several frequencies can be injected at a time and as a result, a single beam is split into multiple diffracted beams and hence creating an array of optical traps simultaneously. This allows to trap and manipulate several particles at the same time, hence improving the efficiency of experiments.

MAIN MANUFACTURERS
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ISOMET (USA)
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INTRAACTION (USA).

MATERIAL PROCESSING

The use of ultra short pulse lasers whose duration is in the picoseconds or even femtosecond range, is quite common in engraving systems. Since the duration of the energy is also short, this limits the amount of heat on the workpiece and hence perform precise removal of the extra material. AO devices are widely used here as pulse pickers. In fact, they are introduced into the high repetition rate laser systems in order to extract a single or several pulses to have a control on the average optical power and hence ensuring a precise control on the energy delivered to the workpiece.

Q-switched lasers are also involved in material processing due to their ability of delivering high peak power pulsed lasers. They are usually nanosecond pulses and these can be produced by introducing an AO Q-Switch inside the laser cavity: when the AO device is ON, it introduces losses inside the laser cavity by diffracting the light out of the cavity and hence suppressing the lasing effect. There is then an accumulation of energy inside the cavity and when the AO device (no diffraction) is OFF, a high intense laser pulse is generated.

HOW TO SELECT A CONVENIENT MODULATOR

While selecting the convenient Acousto Optic device, one needs to consider several factors in order to make sure the device meets the specific requirements. Usually, the help of an expert or engineer in the field is required for further guidance and recommendations.

To help you select the right modulators, we've drawn up the following list of key questions to ask yourself (fig. 8):

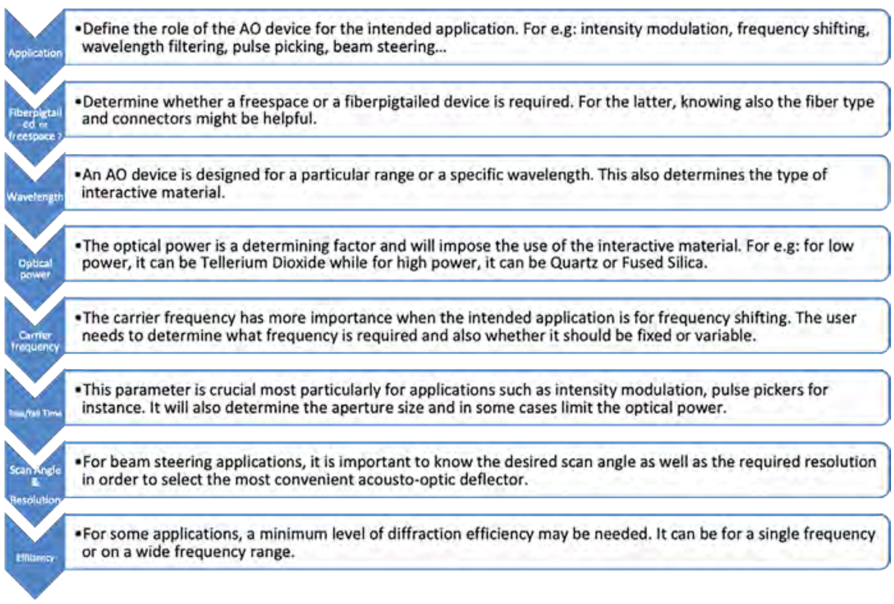

Figure 8: AO Modulator selection guide.