Abstract
Acousto-optic components use a range of different materials in a variety of configurations. These can be heard described by terms such as isotropic and anisotropic. While these all share the basic principles of momentum and energy conservation, these different modes of operation have very different performances. In general, acousto-optic effects are based on the change of the refractive index of a medium due to the presence of sound waves in that medium. Sound waves produce a refractive index grating in the material, and it is this grating that is "seen" by the light wave. These variations in the refractive index, due to the pressure fluctuations, may be detected optically by refraction, diffraction, and interference effects. Reflection may also be used. The principal area of interest is in acousto-optical devices for the deflection, modulation, signal processing and frequency shifting of light beams. This is due to the increasing availability and performance of lasers, which have made the acousto-optic effect easier to observe and measure. Technical progress in both crystal growth and high frequency piezoelectric transducers has brought valuable benefits to acousto-optic components' improvements. Along with the current applications, acousto-optics presents interesting possible application: it can be used in nondestructive testing, structural health monitoring and biomedical applications, where optically generated and optical measurements of ultrasound gives a non-contact method of imaging.

Index Terms: acousto-optic, refraction, modulation, diffraction, deflection, transducer, isotropic, anisotropic

1 Introduction
In 1922 Ikon Brillouin, the French physicist, was dealing with the question of whether the spectrum of thermal sound fluctuations in liquids or solids could perhaps be determined by analyzing the light or X-rays they scattered. The model he used was one in which the sound induces density variations, and these, in turn, cause fluctuations in the dielectric constant. Using a small perturbation approximation to the wave equation (physically, weak interaction), he formulated the problem in terms of a distribution of scattering sources, polarized by the incident light and modulated in space and time by the thermal sound waves. Another result found by Brillouin is that, with the assumption of a simple isotropic change in refractive index through density variations, the scattered light is of the same polarization as the incident light. In a later monograph, he shows that this is true to a very good approximation, even in the case of strong interaction where the perturbation theory fails.

During the 1960s, the character of acousto-optics changed completely. The invention of the laser created a need for electronically manipulating coherent light beams, for instance deflecting them. As photons have no charge, it is obvious that this can only be achieved by electronically varying the refractive index of the medium in which the light travels. This can be accomplished directly through the electro-optic effect, or indirectly through the acousto-optic effect. The latter method, however, has certain advantages, which are almost immediately obvious. Deflection, for instance, is as if it were built in through the dependence of the diffraction angle on acoustic wavelength and, hence, acoustic frequency. Frequency shifting, extremely important for heterodyning applications, is similarly inherent in the diffraction process through the Doppler shift. Modulation should be possible by varying the amplitude of the electrical signal that excites the acoustic wave. And, what is perhaps the most important aspect, the sound cell, used with a modulated carrier, carries an optical replica of an electronic signal that is accessible simultaneously for parallel optical processing. All of these aspects were ultimately incorporated in devices during the period 1960-1980, a period that is characterized by a truly explosive growth of research and development in acousto-optics.

With the interest in practical applications of acousto-optics, a demand arose for more sensitive acousto-optic materials. Whereas before acousto-optic parameters had mainly been studied in the context of crystallography, the emphasis now shifted to device optimization. Smith and Korpel proposed a figure of merit for diffraction efficiency (now called $M_2$) and demonstrated a simple dynamic measurement...
technique, later modified by Dixon and Cohen to include shear-wave effects. Many of the materials investigated were anisotropic, and it was soon discovered that anisotropic operation led to special advantages in certain cases.

2 Acousto-Optic Interaction

2.1 Acousto-Optic Effect

The acousto-optics is a field of physics that studies the interaction between sound and light. This interaction effect based on the diffraction of light by periodic modulation of the refractive index of a transparent optical material, which is generated by acoustic wave propagation in that environment. Given the distinct nature of sound waves (electromagnetic waves) and acoustic waves (elastic waves), their interaction occurs only by indirect means. In other words, the acoustic wave changes the behavior of light in a given medium by means of deformation of the material, changing its optical properties. For this reason, acousto-optical devices are constituted by a crystal coupled to a piezoelectric transducer, which converts a radio frequency signal into mechanical disruption, subsequently subjecting the medium to the optical beam.

2.1.1 Stationary Wave

Consider a periodic acoustic wave that induces a deformation in a material, variable in time and space, defined as $S[1]$. A progressive acoustic wave can be expressed by

$$S(r,t) = S \sin(Kr - \Omega t)$$  \hspace{1cm} (2.1)

A stationary wave, on the other hand, is the combination of two progressive waves with the same amplitude, frequency and wavelength that propagate in the same direction but opposite signals, given by

$$S(r,t) = S \sin(Kr) \cos(\Omega t)$$  \hspace{1cm} (2.2)

where $K$ represents the propagation constant and $\Omega$ the radian frequency. They are both related with the sound velocity

$$K = \frac{\Omega}{V} = \frac{2\pi}{\Lambda}$$  \hspace{1cm} (2.3)

By the action of the acoustic column, the variation of the permittivity of the medium, both in time and in space can be expressed by

$$\Delta \varepsilon(r,t) = \Delta \varepsilon \sin(Kr - \Omega t)$$  \hspace{1cm} (2.4)

When an optical wave interacts among the $\omega$ frequency, its interaction with the periodic modulation described in (2.4) and that generates the phase grating, can give rise to diffraction of the incident beam $\omega \pm \Omega$. The diffracted light may, however, interact again with the acoustic rescattering through the column, producing more diffraction orders $\omega \pm q\Omega$ frequencies, where $q$ is the order of diffraction and can take positive or negative values. The approach of the phase-grating in the acousto-optic interaction considered is not sufficient to completely define the effect of diffraction. For example, this model cannot explain the diffraction of a single order (for sufficiently high values of $L$), or provide the optical angle of incidence that enables efficient diffraction. It is therefore necessary to analyze the interaction between the elements of the sound waves and light, i.e., from the point of view of photon-phonon collision.

2.1.2 Photon-Phonon Collision

For photons and phonons have the momentum and its energy well-defined, it’s necessary to consider the optical and acoustic waves are flat and monochromatic. Therefore, the width $\Lambda$ of the transducer should be high enough to ensure the production of wavefronts with a single frequency. A collision process follows the two fundamental principles: the momentum conservation principle and energy conservation law [2]. The expression corresponding to the energy conservation is given by

$$\omega_{+1} = \omega_0 + \Omega$$  \hspace{1cm} (2.5)

The interaction described by Eq.(2.1) is called the upshifted interaction. Figure 4.2(a) shows the wave vector diagram, and Figure 4.2(b) describes the diffracted beam being upshifted in frequency.

![Figure 2.1 - Upshifted Interaction: wave vector diagram (left); experimental configuration (right).](image)

Suppose now that we change the directions of the incident and diffracted light as shown in Figure 2.1. The conservation laws can be applied again to obtain two equations similar to Eq. (2.4). The two equations describing the interaction are now

$$\omega_{-1} = \omega_0 - \Omega$$  \hspace{1cm} (2.6)
2.2 General Formalism

To analyze this phenomenon, will present a formal analysis based on the theory developed by Raman and Nath, applied to an acoustic column. This approach considers the periodic nature of sound and decomposes the orders of the total electric field in different directions. Starting from the Maxwell equations and applying the coupling theory of plane waves, we obtain the Raman-Nath equations that describe the mutual. The solution of these equations defines the amplitude of various diffraction orders. The concept of coupling the waves, in this case applied to the optical beam, means that waves can’t propagate independently of the waves of different frequencies coupled. This coupling is induced by the acoustic wave, by action of the temporal variation of the optical properties of the medium.

2.2.1 Isotropic Material

In a given material, the interaction between an electric \( E(r, t) \) and a sound field \( S(r, t) \) can be described from Maxwell’s equations. Consider a non-homogeneous optical medium, non-magnetic \( (\mu = \mu_0) \) and isotropic, which the permittivity is given by \( \varepsilon(r, t) \). Whereas isotropic medium, the electric permittivity is reduced to a scalar.

\[
\varepsilon(r, t) = \varepsilon + \Delta \varepsilon(r, t) \quad (2.7)
\]

After some manipulation, it was possible to see the following expression

\[
\nabla^2 E - \mu_0 \varepsilon \frac{\partial^2 E}{\partial t^2} = \mu_0 \Delta \varepsilon \frac{\partial^2 E}{\partial t^2} \quad (2.8)
\]

which gives us the chance to study strong interaction. The second term of the expression is, the coupling theory of plane waves, the polarizations of the medium caused by the action of the sound field. Due to this polarization, the waves of different frequencies coupled only spread independently, or cannot propagate without changing its magnitude, phase, or polarization. This phenomenon is due to the sinusoidal nature of the acoustic beam as it will verify later. Consequently, a monochromatic plane wave is not solution of (2.8).

Thus, the electric field can be expressed as a linear combination of plane waves of different frequencies and amplitudes variables

\[
E(r, t) = \sum_q E_q(r) e^{-i\omega_q t} = \sum_q E_q(r) e^{i(k_q r - i\omega_q t)} \quad (2.9)
\]

Note that the coupling efficiency between two wave components of different frequencies depends on the direction of polarization and optical and acoustic propagation is largely affected by the amount of phase coupling in asynchronism. The phase asynchronism is expressed in the arguments \( k_q - 1 = k_q - K \) and \( k_q + 1 = k_q + K \).

There are two experimental configurations that enable practical interest a strong phase synchronization: the Raman-Nath system and Bragg regime. Both issues will be analyzed further.

2.2.2 Anisotropic Material

In the case of propagation of a monochromatic optical wave in anisotropic medium, the field \( E \) is not necessarily perpendicular to \( k \). To analyze the spread in this medium, the field \( E_q \), which propagates according to the direction of \( k_q = k_q \hat{e}_q \), can be separated into its transverse and longitudinal components:

\[
E_q = E_{q,T} + E_{q,L} \quad (2.10)
\]

As \( \nabla \cdot E_{q,T} = 0 \) and \( \nabla \cdot E_{q,L} \neq 0 \), we obtain a similar equation (2.8) from the transverse component of the electric field:

\[
\nabla^2 E_{q,T} + k_q^2(k_q, \omega)E_{q,T} = -\omega_q^2 \mu_0 \Delta P_{q,T} \quad (2.11)
\]

2.3 Raman-Nath Regime

Considering upshifted interaction, we see that the vector \( K \) can be oriented through an angle \( \pm \Lambda/L \) due to the spreading of sound in order to have only one diffracted order of light generated (i.e., \( k_{+1} \)), we have to impose the condition

\[
L \ll \frac{\Lambda^2}{\Lambda_0^2} \quad \text{or} \quad Q \ll 1 \quad (2.7)
\]

where \( Q \) represents the Klein-Cook parameter. The Raman-Nath diffraction in an anisotropic medium, which involves varying the bias between successive orders, is generally not possible since it entails successive phase synchronism between the various diffraction orders. [5]
2.4 Bragg Regime

Bragg diffraction is characterized by the generation of two scattered orders. For downshifted interaction \((\phi_{\text{inc}} = \phi_B)\) we have diffracted orders 0 and -1, whereas for upshifted interaction \((\phi_{\text{inc}} = -\phi_B)\), we have orders 0 and 1.

There exist phase synchronism between the 0-th and the -1-st orders when \(\cos \phi_{-1} = \cos \phi_0\), implying \(\phi_{-1} = -\phi_0\), as \(\phi_{-1} \neq -\phi_0\) because different scattered orders must exit at different angles. Hence, referring to Figure 2.4 (left) \(\phi_0 = \phi_B = \phi_{\text{inc}}\), and \(\phi_{-1} = -\phi_B = -\phi_{\text{inc}}\). Thus, the 0-th and the -1-st orders propagate symmetrically with respect to the sound wavefronts. Similar arguments may be advanced for the upshifted interaction case as shown in Fig. 2.4 (Right).

2.4.1 Non Birefringent Diffraction

Birefringence is the optical property of a material having a refractive index that depends on the polarization and propagation direction of light. For a not birefringent diffraction or isotropic medium, the angles of incidence and diffraction have equal magnitude but opposite signs. For a monochromatic incident optical wave, there is always a single value \(k\) which satisfies the condition of phase synchronism for both cases of Bragg diffraction, depending on the \(\theta_i\) signal. In the Bragg diffraction in isotropic medium, \(K\) and \(F\) values, which check the condition of phase synchronism take the following values

\[
0 \leq K \leq 2k \\
0 \leq F \leq \frac{2nV}{\lambda_0}
\]

(2.8)

knowing that in the Bragg regime are produced only two diffraction orders \(q = 0\) and \(q = \pm 1\), we concluded that there is a complete periodic transfer of power between \(E_0\) and \(E_i\) and vice-versa, and the intensity of the two orders in the output acoustic column \((z = L)\) given, in both cases, by

\[
\frac{I_0(L)}{I_i(0)} = \left| \frac{E_0(L)}{E_i(0)} \right|^2 = \cos^2 kL
\]

(2.9)

\[
\frac{I_0(L)}{I_i(0)} = \left| \frac{I_{-1}(L)}{I_0(0)} \right|^2 = \sin^2 kL
\]

(2.10)

2.4.2 Birefringent Diffraction

In an anisotropic material, the respective ranges of \(K\) and \(F\) are given by

\[
|k_i - k_d| \leq K \leq |k_i + k_d| \\
\left| \frac{n_i - n_d}{\lambda_0} \right| V \leq F \leq \left| \frac{n_i + n_d}{\lambda_0} \right| V
\]

(2.11)

Due to the change of the polarization of the incident and diffracted waves, there may be two situations in birefringent diffraction amid anisotropic. At first, for \(k_q < k_i\), the Bragg diffraction occurs only if the angle of incidence is inserted in the following range

\[
\frac{\pi}{2} \geq |\theta_i| \geq \cos^{-1} \left( \frac{k_q}{k_i} \right)
\]

(2.12)

In the second case, when \(k_q > k_i\) for any incident angle (except \(\theta_i = 0\)), there are two possible values for the parameter \(K\): one for the upshifted diffraction and other to downshifted. When \(\theta_i = \pm \pi/2\), the phase synchronization settings are collinear, i.e. \(k_q\) and \(k_i\) may be parallel or antiparallel, but both are collinear with \(K\).

2.4.3 The Near-Bragg Regime

Consider now the approximation \(\omega \approx \omega_1 \approx \omega_{-1}\) and the general case where there is perfect phase synchronization

\[
\Delta k = k_q - k_i \pm K
\]

(2.13)

where the positive sign refers to the downshifted diffraction and the negative sign in the upshifted [7]. Considering the propagation medium with impedance \(Z\), the optical intensity is given by

\[
I = \frac{2|E|^2}{Z} = \frac{2k}{\omega \mu_0} |E|^2
\]

(2.15)

where \(k\) is the coupling coefficient for the Bragg regime and is expressed by
or, for the Raman-Nath regime,

$$|k| = \frac{\pi}{\lambda_0} \left( \frac{M_2 \ell}{2} \right)^{\frac{1}{2}}$$  \hspace{1cm} (2.17)$$

For isotropic media, when the RF frequency does not correspond exactly to the frequency that checks the criterion of Bragg diffraction efficiency decreases. When $$\Delta k = 0$$, the frequency takes the optimal value that ensures maximum efficiency. When $$\Delta kL \neq 0$$ the diffraction efficiency decreases, which is the lower limit that sets the width of the band device. To increase the bandwidth can be increased if the ratio $$\Lambda/L$$ designated by acoustic mismatch.

2.5 Stationary Wave Diffraction

So far the acousto-optic diffraction has been analyzed only for progressive acoustic waves. We see that each diffraction order $$k_q$$ defined by a wave-vector and $$\theta_q$$ diffraction angle is defined by a single frequency $$\omega_q = \omega + q \Omega$$. This is not the case, however, for the diffraction stationary waves. A stationary wave can be defined as an aggregation of two propagating waves in opposite direction, with wave vectors $$K$$ and $$-K$$. Thus, their interaction with the acoustic wave produces simultaneously two diffraction orders with frequencies $$\omega \pm \Omega$$ (upshifted and downshifted), each corresponding to each direction of the diffraction to verify the condition of phase synchronism.

In the Raman-Nath diffraction, shown in Fig. 2.5, the even diffraction orders, including the order 0, resulting from the contribution of all the multiple positive frequencies and $$\Omega$$ of even order of negative, while the odd diffraction orders result of multiple positive and negative $$\Omega$$ of odd order.

In the Bragg diffraction, the angle of incidence can be $$\theta_i$$ or $$-\theta_i$$, because $$K$$ and $$-K$$ exist simultaneously. In both cases, two frequencies are generated ($$\omega \pm \Omega$$) in $$k_q$$ direction as seen in Figure 2.6. To occur in chain, this process originates two branches: one diffracted toward $$k_q$$ with frequencies of odd order, $$\omega \pm (2m+1)\Omega$$, and another beam in the direction $$k_i$$ suffering no diffraction and contains the frequency even order, $$\omega \pm 2m\Omega$$.

3 Acousto-Optic Modulation

3.1 Acousto-Optic Modulator

As we seen, there is a relation between the diffraction efficiency and the intensity of acoustic wave, such that the optical intensity of the diffracted beam can be controlled by the intensity of the acoustic signal. It is based on this principle that operates the acousto-optical modulator (AOM). The acousto-optical modulation is therefore an amplitude modulation of an optical beam by an acoustic signal, electronically controlled. A MAO can operate in the Raman-Nath regime or in the Bragg regime, by assigning the device in the latter case as cell Bragg. When the efficiency value is low, the efficiency of diffraction of first-order modulator operating in the Raman-Nath scheme is equivalent to the diffraction efficiency of a Bragg cell [3].
analysis, it’s possible to define the bandwidth for an optical beam Gaussian profile

\[
f_{m}^{3dB} \approx \begin{cases} 
\frac{0.75 \tau_a}{0.86 - 0.13 a \tau_a} & \text{with } a \ll 1 \\
0.86 - 0.13 a \tau_a & \text{with } a \gg 1
\end{cases} \tag{3.1}
\]

\[
t_r \approx \begin{cases} 
0.65 \tau_a, & \text{with } a \ll 1 \\
(0.45 + 0.25 a)\tau_a, & \text{with } a \gg 1
\end{cases} \tag{3.2}
\]

### 3.1.1 Performance Analysis

Until now we saw that to improve the performance of the AOM, \( \tau_a \) and \( a \) parameters must be minimized. However, it’s not completely true because both depend on the diameter of the optical beam waist \( w_0 \). For a given modulator with a deviation, the value can be reduced by reducing the \( \Delta \theta_a \) and consequently increasing the diameter \( w_0 \). Increased \( w_0 \) however, corresponds to an increase of \( \tau_a \), contributing to degrade bandwidth and speed of the modulator. Thus, to achieve high bandwidth and speed of modulation, the optical beam has to be focused in a reduced diameter region along the interaction region. It is necessary, therefore, be a compromise between efficiency and bandwidth. As we seen in the previous chapter, the acousto-optic modulating, modulates the amplitude of the signal. In practice it must be determined depending on the value of the design performance requirements, which defines \( \tau_a \) and other device characteristics.

### 3.2 Progressive Waves Modulation

Modulators operating progressive waves are the most common. Most modulators take the configuration of figure 3.2 and assume small angles of incidence \( \theta_i \). The acousto-optic cell comprising a transparent material is coupled to a piezoelectric transducer at one end and an angled face at the opposite end. This coated absorbent material has the function of reflecting the acoustic wave such that it does not interact with the optical beam incident. The piezoelectric transducer, in turn, converts an RF signal into an acoustic signal and enables the coupling of its output to the acousto-optic cell, giving rise to a mechanical wave that propagates in the middle with a spectral frequency corresponding to the frequency of the RF signal.

Assuming a transducer with height \( H \) and width \( L \) (corresponding to the length of interaction) the acoustic intensity is given by

\[
I_a = \frac{P_a}{HL} = \frac{\eta_t P_e}{HL} \tag{3.3}
\]

where \( P_a \) is the acoustic power transmitted to the area of interaction, \( P_e \) is the electrical power delivered by the transducer and \( \eta_t \) corresponds to the transducer conversion efficiency of electric power into acoustic power. Now it’s possible to define the efficiency of a modulator operating in the Bragg regime phase synchronization by

\[
\eta_{PM} = \sin^2 \left[ \frac{\pi}{\lambda} \left( \frac{M}{2HL} \eta_t P_e \right)^{1/2} \right] \tag{3.4}
\]

In a AOM for progressive waves, the power \( P_e(t) \) is the one who carries the modulating signal, which varies over time and implies that the efficiency of diffraction also vary in time as well.

### 3.3 Stationary Waves Modulation

A AOM using stationary acoustic waves are used in special cases such as the laser mode locking. This modulator allows sinusoidal amplitude modulation at very high frequencies. Differ from the progressive wave modulator at several respects, notably in structure and performance characteristics. The most important performance characteristics of a standing wave modulator is the diffraction efficiency \( \eta \) and the frequency modulation \( f_m \), defined as twice the acoustic frequency limit of the low efficiency, when operating in the Bragg regime. Instead of an angular face, as in the case of progressive wave modulator shown in Fig. 3.2, the opposite face of the piezoelectric transducer acousto-optic cell is parallel to its extreme, as illustrated in Fig. 3.3.

![Figure 3.2 - Representation of a AOM that works with progressive waves and in Bragg regime.](image)

![Figure 3.3 - AOM for a stationary wave type.](image)

Considering that the cell has a length \( W \), in the direction of propagation of the acoustic wave, it’s possible to obtain a stationary wave when the acoustic wavelength satisfies the condition:
\[ W = m \frac{A}{2} \]  

(3.5)

and \( m \) is an integer value. With that said, the modulator only works for some values of frequencies given by

\[ F = m \frac{V}{2W} \]  

(3.6)

Resonance frequencies are sensitive to variations of the speed of the acoustic wave \( V \), caused by fluctuations in temperature. For this reason, the temperature of the stationary waveform modulator is monitored to maintain a stable and efficient operation. The acoustic power that is delivered by the transducer to the resonant cavity is equal to the acoustic energy stored in the resonant cavity and the \( \gamma_a \) decay rate:

\[ P_a = \frac{f_a^2 + f_a^2}{V} \frac{HLV}{\gamma_a} = \frac{2f_a^2}{V} \frac{HLW}{\gamma_a} \]  

(3.7)

Given the power, now we can establish the expression that defines the efficiency for this modulator

\[ \eta_{PM} = \sin^2 \left[ \frac{\pi}{\lambda} \left( \frac{M_aV}{HLW} \right)^{\frac{1}{2}} L \cos \Omega t \right] \]  

(3.8)

4 Applications

4.1 Deflectors

In contrast to intensity modulation, where the amplitude of the modulating signal is varied, the frequency of the modulating signal is changed for applications in light deflection. Figure 4.1 shows a light beam deflector where the acousto-optic modulator operates in the Bragg regime. The angle between the first-order beam and the zeroth-order beam is defined as the deflection angle \( \Delta \theta_d \)

\[ \Delta \theta_d = \Delta (2\theta_b) = \frac{\Delta K}{k_q} = \frac{\lambda}{n_aV} \Delta F \]  

(4.1)

The number of resolvable angles \( N \) in such a device is determined by the ratio of the range of deflected angles \( \Delta \theta_d \) to the angular spread of the scanning light beam.

\[ N = \frac{\Delta \theta_d}{\Delta \theta_0} \]  

(4.2)

Instead of a single frequency input, the sound cell can be addressed simultaneously by a spectrum of frequencies. The Bragg cell scatters light beams into angles controlled by the spectrum of acoustic frequencies as each frequency generates a beam at a specific diffracted angle. Because the acoustic spectrum is identical to the frequency spectrum of the electrical signal being fed to the cell, the device essentially acts as a spectrum analyzer.

4.2 Tunable Filters

In acousto-optic tunable filters, use is made of the inherent selectivity of the diffraction process to electronically move the optical passband. Most filters of this kind use anisotropic interaction.

![Figure 4.2 – Representation of a Tunable Acousto-Optic Filter.](image)

A parallel beam of quasi-monochromatic light, ray \( a \) in the figure, is incident at an appropriate angle on a low-Q Bragg cell operating at a frequency \( f \). The width of the beam is limited to \( D \) by the entrance pupil of the sound cell. The diffracted beam \( b \) is focused by a lens of focal length \( F \) on a pinhole in the focal plane, situated at \( x_o \). For the diffracted beam \( o \) to fall on the pinhole the wavelength of the light must satisfy the relation

\[ F 2\phi_b = x_o \]  

(4.3)

or

\[ \lambda = \frac{x_o \Lambda}{F} \]  

(4.4)

The spot size formed by the focused beam \( b \) is approximately \( F \lambda / D \). A change \( \Delta \lambda \) moves the center of the spot by \( F \Delta (2\phi_b) = F \Delta \lambda / \Lambda \). Thus, the passband is determined by the condition

\[ \frac{F \Delta \lambda}{\Lambda} = \frac{F \lambda}{D} \quad \text{or} \quad \Delta \lambda = \frac{\Lambda \lambda}{D} \]  

(4.5)
The selectivity of the sound cell itself plays no role, as the cell has a low $Q$. It is, however, possible to reverse this situation by removing the pinhole and relying on the $Q$ of the sound cell instead. The acceptance angle of the device may be estimated by the following expression

$$\psi \approx \sqrt{\frac{2\Lambda}{L}}$$  \hspace{1cm} (4.6)

Because of the square root dependence, this device has a relatively wide acceptance angle.

### 4.3 Demodulation of Signals

From the preceding discussion, we recognize the Bragg cell’s frequency selecting capability. Here we discuss how to make use of this to demodulate frequency modulated (FM) signals [10]. As seen from Fig.4.3, the Bragg cell diffracts the light into angles $\phi_{di}$ controlled by the spectrum of carrier frequencies $\Omega_{di}$, where each carrier has been frequency-modulated. For the $i$-th FM station, the instantaneous frequency of the signal is representable as $\Omega_i(t) = \Omega_{oi} + \Delta \Omega_i(t)$, where $\Omega_{oi}$ is a fixed carrier frequency and $\Delta \Omega_i(t)$ represents a time-varying frequency difference proportional to the amplitude of the modulating signal.

Using Eq.(4.1), the $i$-th FM station is beamed, on the average, in a direction relative to the incident beam given by

$$\phi_{wi} = \frac{\lambda_0 \Omega_{wi}}{2\pi V_s}$$  \hspace{1cm} (4.7)

As a usual practice, the FM variation $\Delta \Omega_i(t)$ is small compared to the carrier $\Omega_{oi}$. For each FM carrier, there will now be an independently scattered light beam in a direction determined by the carrier frequency. The principle behind the FM demodulation is that the actual instantaneous angle of deflection deviates slightly from Eq. (4.7) due to the inclusion of $\Delta \Omega_i(t)$, which causes a "wobble" in the deflected beam

$$\Delta \phi_{di}(t) = \left(\frac{\lambda_0}{2\pi V_s}\right) \Delta \Omega_i(t)$$  \hspace{1cm} (4.8)

Because, in FM, the frequency variation is proportional to the amplitude of the audio signal, the variation in the deflected angle is likewise proportional to the modulating signal.

The factors that limit the performance of acousto-optic FM demodulators have been investigated in the context of the use of a knife-edge detector as well as a bicell detector (two photo-active areas separated by a small gap). The use of a bicell detector has also been able to identify and demodulate a wide range of different types of phase modulation without any a priori information [8].

### 4.4 Bistable switching

**Bistability** refers to the existence of two stable states of a system for a given set of input conditions. Bistable optical devices have received much attention in recent years because of their potential application in optical signal processing. In general, nonlinearity and feedback are required to achieve bistability.

Figure 4.4 shows an acousto-optic bistable device operating in the Bragg regime [9]. The light diffracted into the first order is detected by the photodetector (PD), amplified, summed with a bias $\alpha_0$, and fed back to the acoustic transducer to change the amplitude of its drive signal, which in turn amplitude modulates the intensities of the diffracted light. Hence the feedback signal has a recursive influence on the diffracted light intensities. Note that the nonlinearity involved in the system is a sine-squared function:

$$I_1 = |\psi_1|^2 = I_{inc} \sin^2 \left(\frac{\alpha_0}{2}\right)$$  \hspace{1cm} (4.9)

where $I_{inc} = |\psi_{inc}|^2$ is the incident intensity and we have a system with a nonlinear input ($\alpha$)-output ($I_1$) relationship.
The effective \( a \) scattering the light in the acousto-optic cell is given by the feedback equation,
\[
\alpha = \alpha_0 + \beta I_1 \tag{4.10}
\]
Note that under the feedback action, \( a \) can no longer, in general, be treated as a constant. In fact, \( a \) can be treated as constant during interaction if the interaction time, given as the ratio of the laser beam width and the speed of sound in the cell, is very small compared to the delays incorporated by the finite response time of the photodetector, the sound-cell driver and the feedback amplifier, or any other delay line that may be purposely installed (e.g., an optical fiber or coaxial cable) in the feedback path. We consider this case only. The steady-state behavior of the system is given by the simultaneous solution of Eqs. (4.9) and (4.10).

5 Conclusion

We started with the study by seeing the interaction between the particles and photons phonon, the main differences between the isotropic and anisotropic media and also the diffraction of the beams. As for the latter, it was possible to see the main differences between the Raman-Nath and Bragg regimes, where for the first case there are several orders of diffraction and the second there is only one. Within the Bragg regime, analyzed in detail the birefringent and non-birefringent diffraction, where they were introduced to the upshifted and downshifted modes, to the respective vector diagram, and finally we studied the effect to when the angle of the incident beam is quite small. As we saw, the main difference between this two regimes lies in the orders of the diffracted beams: in Raman-Nath’s regime exists several orders and in Bragg’s regime exists only two.

After that, we focused more on signal processing by first examining in some detail the operation of an AOM. We concluded that there is a dependency between the diffraction efficiency and the intensity of acoustic wave, so that the intensity of the diffracted optical beam can be controlled by the intensity of the acoustic signal. It is based on this principle that operates the MAO, which can work both Bragg system as a Raman-Nath. The performance of this device was also a subject of study and we saw that to obtain a high bandwidth and speed of modulation, the optical beam has to be focused in a reduced diameter region along the interaction region is necessary, therefore, there is a compromise between efficiency and bandwidth, with an acousto-optical modulation amplitude modulation.

In practice, the modulator’s response also depends on the bandwidth of the piezoelectric transducer and the adjacent electronic circuits. The width of the dome of the transducer is characterized by the frequency dependence of efficiency.

The modulation of progressive waves and stationary waves was a point of interest. The main difference lies in the design of the device itself, where in the first case the acousto-optical cell comprising a transparent material is coupled to a piezoelectric transducer at one end and an angled face at the opposite end. For the second case, the opposite face is parallel.

After all the explanation of this phenomenon, are listed a number of applications such as tunable filters, demodulators and bistable systems. The filters operate by irradiating a specially prepared glass, with acoustic vibrations of radio waves generated by a high frequency transducer. The filter can be tuned by varying the frequency of the waves, which only allows a very narrow range of wavelengths to pass through and thereby removing the remaining interval diffraction. Unlike the modulator, where the beam is amplitude modulated, spatially vary the deflector allows the angular position of the optical beam diffracted by electronic variation of the acoustic frequency. While the signal applied to a modulator has variation in amplitude and constant frequency, the baffle the applied signal has constant amplitude and variable frequency. This device therefore operates as a frequency modulator.

6 References


Acousto-Optic Signal Processing: Theory and Implementation, edited by by Norman J. Berg and John N. Lee


