

An Introduction to Acousto-Optics

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ABSTRACT

This paper is a brief introduction to acousto-optic phenomena. We present to the reader the mathematical formalism used to describe this phenomena as well as the common picture of the interaction between light and sound. In addition, we describe some simple applications of acousto-optic devices.

1. Introduction

In the year 1885, Lord Rayleigh attempted to describe the effects of earthquakes in terms of what we now call surface acoustic waves [Rayleigh, 1885]. In his treatise, Rayleigh set in motion the field of acoustics. Thirty-seven years later and building upon previous work, Léon Brillouin set out to analyze thermal acoustic fluctuations in liquids and solids by the scattering of light or X-rays off of changes in the refractive index of the medium [Brillouin, 1922]. In his paper, Brillouin gave the first look at the theoretical explanation of what has become known as acousto-optic diffraction. He used an analogy to diffraction gratings to determine binding equations on the output light. From his theory he was able to predict some of the common phenomena known today regarding acousto-optic (AO) devices, namely the deflection of light and the frequency shift of the deflected light.

An acousto-optic effect is produced by generating an ultrasonic wave in an optically transparent material. As the acoustic wave travels through the medium, it causes periodic variations in the index

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of refraction. For instance, in a crystalline solid, the wave produces compressions and rarefactions in the crystal lattice. Because the changes in the refractive index are periodic, the material behaves much like a diffraction grating, with site spacing equal to the wavelength of the ultrasonic wave. This is known as the elasto-optic effect, and was first proposed by Raman and Nath, 1935.

Typically the acoustic wave is launched into the medium by a piezo-electric transducer. Application of an electric field to the transducer has the effect of deforming the material, producing an internal strain. This strain is transmitted to the acousto-optic medium which is mechanically coupled to the transducer. The acousto-optic medium can be liquid (such as water), solid (such as lead molybdate), or even gas (such as water vapor). Any strain in the material should produce a change in the refractive index. Incident light on the acousto-optic medium will scatter off variations in the refractive index. The scattering of light can be tuned to create destructive interference between certain wavelengths, thereby constructing an optical filter.

Other common uses of acousto-optic media include devices for modulating light for communication, deflecting light, convolving or correlating signals, optical matrix processing, analyzing the spectrum of signals, optical sources, laser mode lockers, Q-switchers, delay lines, image processing, general and adaptive signal processing, tomographic transformations, optical switches, neural networks, optical computing, and much more.

The applications of acousto-optics are extremely rich as is the theory. In this paper we present the underlying mathematical formalism describing acousto-optic effects. In addition, we present the common picture of the phonon-photon interaction wherein an incident photon collides with an existing phonon to produce the AO effect. Lastly we give an overview of a few of the above applications of AO devices.

2. Acoustical Wave Theory

In this section we present a brief overview of the mathematics that are needed to describe acousto-optic phenomena. We assume that the reader is familiar with electrodynamics, including waveguides, and the physics of solid media.

2.1. Electrodynamics of Unbounded Media

Consider a slab of material with a periodically varying permittivity ϵ . Within the medium, Maxwell's equations may be written as

$$\nabla \times \mathbf{E} = -\mu \frac{\partial}{\partial t} \mathbf{H} \quad \nabla \times \mathbf{H} = \frac{\partial}{\partial t} (\epsilon \mathbf{E}) \quad (1)$$

Naturally, the displacement field is $\mathbf{D} = \epsilon \mathbf{E}$. By Gauss's Law, $\nabla \cdot \mathbf{D} = 0$. With some manipulation we arrive at the wave equation inside the medium

$$\nabla^2 \mathbf{E} - \mu \frac{\partial^2}{\partial t^2} (\epsilon \mathbf{E}) = 0 \quad (2)$$

Now consider the following dielectric constant

$$\epsilon(y) = \sum_{n=-\infty}^{\infty} \epsilon_n e^{i \frac{2n\pi}{\lambda_a} y} \quad (3)$$

where λ_a is the wavelength of the acoustic wave and the coefficients ϵ_n are assumed to be known. We seek solutions of the wave equation $E_x = f(y)e^{\pm i k_z z}$. Using this solution we find a wave equation for our function $f(y)$:

$$\frac{\partial^2 f}{\partial y^2} + [\omega^2 \mu \epsilon(y) - k_z^2] f = 0 \quad (4)$$

Since the slab has a periodically varying permittivity, the function $f(y)$ can be written as a sum over modes

$$f(y) = \sum_{n=-\infty}^{\infty} f_n e^{i \left[\frac{2n\pi}{\lambda_a} + \beta_0 \right] y} \quad (5)$$

where the term β_0 represents some superimposed linear phase variation to allow for plane wave propagation through the slab. Using the above equations for $f(y)$ and $\epsilon(y)$ we can solve¹ the wave equation and get

$$\omega^2 \mu \left(\sum_{m=-\infty}^{\infty} \epsilon_{n-m} f_m \right) - \left[\left(\frac{2n\pi}{\lambda_a} + \beta_0 \right)^2 + k_z^2 \right] f_n = 0 \quad (6)$$

for each harmonic n . There are certain values of β_0 , such as 0, so that the waveguide modes will be symmetric and the eigenvalues for each pair of symmetric eigenmodes of the above system of equations will be identical. These values are

$$\beta_0 = \frac{N_B \pi}{\lambda_a} \quad (7)$$

¹for details see Scott, 1992

for any integer $N_B \neq 0$. This condition is known as the *Bragg condition* and the nature of each pair of symmetric eigenmodes will be different depending on whether N_B is odd or even [Scott, 1992].

2.2. Electrodynamics in Modulated Media

Let us now turn our attention to an acousto-optic device. An acousto-optic cell is an acoustic slab waveguide operating in the SV/P mode. The SV mode is a vertically polarized shear wave. A P wave is a longitudinal compressive wave, where the direction of the displacements in the medium coincides with the direction of propagation.

If we assume a simple sinusoid for our dielectric constant, namely

$$\epsilon(y) = \epsilon \left[1 + M \cos \frac{2\pi}{\lambda_a} (y - vt) \right] \quad (8)$$

then $\epsilon_0 = \epsilon$ and $\epsilon_1 = \epsilon_{-1} = \epsilon M/2$. We can very easily find the electric field inside the medium:

$$E_x = \sum_{n=-\infty}^{\infty} E_n e^{i\omega_n t} e^{i\beta_n y} \quad (9)$$

where $\beta_n = \beta_0 + 2n\pi/\lambda_a$ and $\omega_n = \omega - (2n\pi/\lambda_a)v$. Equation 6 now becomes

$$\left(\frac{\omega_n^2 \mu \epsilon M}{2} \right) \left[E_{n-1} + \frac{2}{M} \left(1 - \frac{\beta_n^2}{\omega_n^2} \mu \epsilon \right) E_n + E_{n+1} \right] = k_z^2 E_n \quad (10)$$

Again there is one equation for each mode. One can solve this system of equations and find the coefficients E_n . [Scott, 1992]

2.2.1. Plane Wave Scattering

Now assume that our slab has a width L . For the incident fields at the surface of the slab ($z = 0$) take

$$E_x^i = e^{i(\omega t + \beta_0 y)} \quad (11)$$

$$H_y^i = \frac{\sqrt{k^2 - \beta_0^2}}{\omega \mu} e^{i(\omega t + \beta_0 y)} \quad (12)$$

Then the reflected fields in the air will be

$$E_x^r = \sum_{n=-\infty}^{\infty} E_n^r e^{i(\omega_n t + \beta_n y)} \quad (13)$$

$$H_y^r = \sum_{n=-\infty}^{\infty} -\frac{\sqrt{k^2 - \beta_n^2}}{\omega_n \mu} E_n^r e^{i(\omega_n t + \beta_n y)} \quad (14)$$

The transmitted fields in the modulated medium can be written as sums over the waveguide modes p .

$$E_x^w = \sum_{p=-\infty}^{\infty} F_p(1 + R_p e^{-2ik_{z,p}L} f_p(y, t)) \quad (15)$$

$$H_y^w = \sum_{p=-\infty}^{\infty} \frac{k_{z,p}}{\omega_n \mu_d} F_p(1 - R_p e^{-2ik_{z,p}L} f_p(y, t)) \quad (16)$$

where

$$f_p(y, t) = \sum_{n=-\infty}^{\infty} f_n^p e^{i(\omega_n t + \beta_n y)} \quad (17)$$

$k_{z,p}$ is the propagation constant in the z-direction for the p th waveguide mode. μ refers to the air whereas μ_d refers to the dielectric medium. R_p is the reflection coefficient of the p th waveguide mode at the rear surface of the slab. f_n^p are known from solving the eigenvalue problem. Continuity of the electric and magnetic fields can now be used to find F_p .

2.3. Special Cases

We now examine two special cases of diffraction within an acoustically modulated medium. These cases will be revisited in a following section when we examine the phonon-photon picture of AO phenomena.

2.3.1. Bragg Scattering

Take an acousto-optic cell operating at $N_B = 1$. There are two primary waveguide modes. These have unnormalized eigenvectors (1,1) and (1,-1). The electric fields corresponding to these modes are

$$E_1(y, t) = \sqrt{2} e^{i(\omega + \pi v/\lambda_a)t} \cos \left[\frac{\pi}{\lambda_a} (y - vt) \right] \quad (18)$$

$$E_2(y, t) = i\sqrt{2} e^{i(\omega + \pi v/\lambda_a)t} \sin \left[\frac{\pi}{\lambda_a} (y - vt) \right] \quad (19)$$

If both waveguide modes have similar propagation constants in the z-direction, and if $k_z^w L \approx \pi/2$ with $L \approx \lambda/4$, where λ is the wavelength of light, then directional coupling will take place. This means that the $n = 0$ mode will couple to the transmitted $n = -1$ mode, and the transmitted $n = 0$ mode will be isolated. In addition, the $n = -1$ mode will be frequency shifted upwards by $2\pi v/\lambda_a$

the frequency of the acoustic wave. The other modes destructively interfere and produce no output out of the device. This type of diffraction is known as Bragg diffraction, or Bragg scattering, since this is exactly what happens in Bragg scattering of X-rays or electrons off of a solid lattice.

2.3.2. Raman-Nath Scattering

In Raman-Nath scattering, also known as Debye-Sears scattering, the thickness, L , of the cell is much less than a quarter wavelength. It is so thin that there is no significant interaction between the even and odd waveguide modes. In this case, the normally incident electromagnetic field will be spread out into a number of grating modes, each of which is shifted in frequency either up or down by an integer number of the acoustic wave frequency. This case is more complicated to analyze since it involves all of the Fourier modes. In general sidebands of like order are equal in amplitude and decrease as a function of n .

3. Phonon-Photon Interactions

The previous section outlined the dirty mathematics involved in acousto-optics. There exists a much more simplistic and tractable viewpoint which involves phonons.

3.1. Heuristic Theory

Phonons are massless particles inside a solid which represent sinusoidal oscillations of the lattice. Phonons can be created and destroyed, just like photons. Each photon has an energy and a momentum given by the frequency of light. Each phonon has an energy and a momentum given by the frequency of the sound wave in the medium. We define the following

$$E_\gamma = \hbar\omega_\gamma \quad \mathbf{p}_\gamma = \hbar\mathbf{k}_\gamma \quad \omega_\gamma = \frac{c}{n}|\mathbf{k}_\gamma| \quad (20)$$

$$E_a = \hbar\omega_a \quad \mathbf{p}_a = \hbar\mathbf{k}_a \quad \omega_a = v|\mathbf{k}_a| \quad (21)$$

where v is the acoustic velocity, c is the free-space speed of light, and n is the refractive index of the medium. phonon-photon collisions can be described by elementary physics. We assume that there will be energy-momentum conservation throughout the collision. There is no loss to heat since the collision is elastic. Consider an incoming photon with wave vector \mathbf{k}_γ . It then collides in

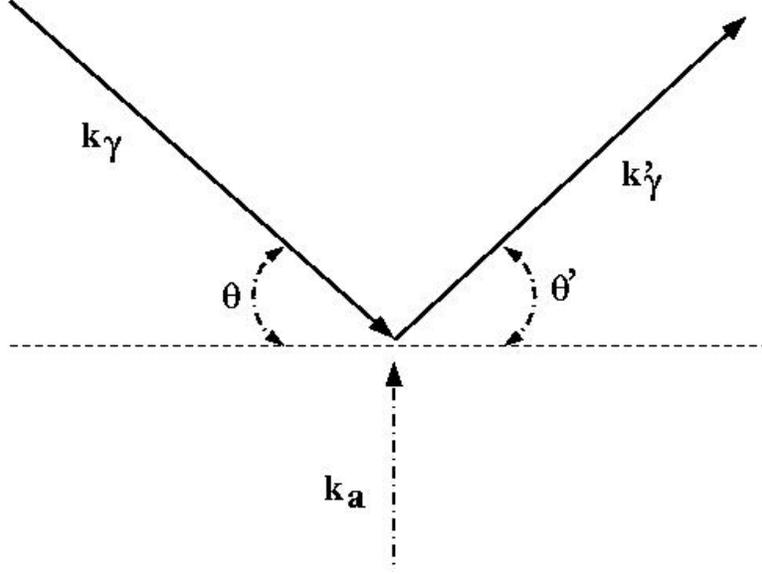


Fig. 1.— *Phonon Annihilation: The incoming photon absorbs an existing phonon in the lattice. The exiting photon has gained energy and momentum from the destruction of the lattice vibration.*

the medium and either creates or destroys a phonon. Given the outgoing photon wave vector \mathbf{k}'_γ and frequency ω'_γ , creation of a phonon would imply,

$$\mathbf{k}'_\gamma = \mathbf{k}_\gamma - \mathbf{k}_a \quad \omega'_\gamma = \omega_\gamma - \omega_a \quad (22)$$

and phonon destruction would imply

$$\mathbf{k}'_\gamma = \mathbf{k}_\gamma + \mathbf{k}_a \quad \omega'_\gamma = \omega_\gamma + \omega_a \quad (23)$$

Consider the case in Figure 1 in which an incoming photon absorbs a lattice vibration. We have the following equations to conserve energy-momentum:

$$k_\gamma \cos \theta = k'_\gamma \cos \theta' \quad (24)$$

$$k'_\gamma \sin \theta' = k_a - k_\gamma \sin \theta \quad (25)$$

$$k'_\gamma = k_\gamma + \frac{nv}{c} k_a \quad (26)$$

If k_a , k_γ and nv/c are specified, then the above equations can be used to uniquely determine the incoming angle θ , the only incoming angle that conserves energy and momentum. We define the *Bragg angle* θ_B by

$$\theta_B = \sin^{-1} \left(\frac{k_a}{2k_\gamma} \right) = \sin^{-1} \left(\frac{\lambda_\gamma}{2\lambda_a} \right) \quad (27)$$

In the particular case of $\frac{vn}{c}k_a \ll k_\gamma$ we obtain $k'_\gamma \approx k_\gamma$, and therefore $\theta' = \theta$. This then implies that $\theta = \theta_B$ is required for phonon annihilation.

As we saw in the previous section, there are an infinite number of Fourier modes in the lattice. Each mode n will have a frequency $n\omega_a$ and will produce diffracted beams with energy $\omega'_\gamma = \omega_\gamma + n\omega_a$ at an angle $(1+n)\theta_B$ to the incoming beam. The two main cases of diffraction by an AO device (Bragg and Raman-Nath diffraction) can be described as limits of the above process. The limiting parameter is defined as

$$Q = \frac{k_a^2 L}{k_\gamma} = 2\pi \frac{\lambda_\gamma L}{\lambda_a^2} \quad (28)$$

where L is the width of the acoustic beam in the medium.

3.2. Special Cases

We now examine the two special cases outlined in §2.3 from the point of view of phonon-photon interactions.

3.2.1. Bragg Regime

When $Q \gg 1$, which can be accomplished by having a very wide slab of material, the diffraction is said to be in the *Bragg regime*. As mentioned in §2.3.1, the main characteristic of Bragg diffraction is two output beams: the undiffracted beam or carrier beam, and the principal diffracted beam or the sideband beam. The sideband beam will be frequency shifted either up or down depending on the direction of the incoming carrier beam. This case is similar to Bragg diffraction of X-rays in a crystal lattice [Bragg and Bragg, 1932]. It turns out that other orders are produced within the acousto-optic device, but these orders destructively interfere since they are not phase matched. The only order which is phase matched throughout the lattice is the principal diffracted order. This is easily seen from a phase front diagram.

Let us now compute the intensity of the diffracted beam. The Bragg cell acts as an optical delay line with time delay $\tau = nL/c$ and phase shift $\phi = L\beta$ radians, where $\beta = \omega_a n/c$ is the propagation constant (i.e., the number of cycles per 2π units of length). The acoustical wave inside the cell varies the index of refraction, n , by Δn . Therefore the incremental phase excursion over a length dl is $d\phi = \beta \frac{\Delta n}{n} dl$. The incremental amplitude of the principal diffracted beam is $dS = d\phi I_0/2$,

where I_0 is the amplitude of the incident optical beam. There is an associated equation for the carrier amplitude, C , since the carrier loses energy to the diffracted beam. The solutions of the two equations are simply $S = I_0 \sin\left(\frac{L\pi\Delta n}{\lambda_a}\right)$ and $C = I_0 \cos\left(\frac{L\pi\Delta n}{\lambda_a}\right)$. Naturally the sideband power increases as a function of the length of the interaction region, and is a maximum when $L = \frac{\lambda_a}{2\Delta n}$.

We define the *modulation index*, m , of the AO cell as the square root of the efficiency of transferring energy into the sideband:

$$m^2 = \left(\frac{S}{C}\right)^2 = \sin^2\left(\frac{L\pi\Delta n}{\lambda_a}\right) \quad (29)$$

We define the acousto-optic figure of merit $M_2 = n^6 p^2 / \rho v^3$, where p is the effective elasto-optic coefficient, ρ is the material density, and v the acoustic wave velocity. Making use of the elasto-optic coefficient, can write $\Delta n = n^3 p s / 2$, where we have introduced s as the induced strain [Korpel, 1981]. Naturally s is a function of both position and time because of the acoustic wave in our cell. Introducing the acoustic power as $P_a = \frac{1}{2} \rho v^2 s^2$ we can write the modulation index as

$$m = \left| \sin\left(\frac{\pi L}{\lambda_a} \sqrt{\frac{M_2 P_a}{2}}\right) \right| \quad (30)$$

Recall from electronics that the acoustic power is related to the acoustic voltage squared. Therefore we see that the modulation index is linearly proportional to the acoustic voltage for small values of the argument of the sine function. Therefore the diffracted light amplitude is linearly proportional to the input voltage to the transducer. To increase the intensity of the diffracted beam, simply increase the voltage of modulation signal.

3.2.2. Raman-Nath Regime

If $Q \ll 1$ then we are in the Raman-Nath or Debye-Sears regime of the acousto-optic device. We assume that the material is thin enough so that we can neglect multiple optical diffraction effects within the sound field. We can model this system by a moving phase grating as done first by Raman and Nath, 1935. As mentioned in §2.3.2, all of the Fourier modes in the crystal modulate the incoming light. The amplitude of the diffracted orders is given by

$$A_n = (-i)^n I_0 J_n\left(\frac{2\pi\Delta n L}{\lambda_a}\right) \quad (31)$$

where J_n is the Bessel function of order n and I_0 is the incident electric field amplitude [Korpel, 1981]. Naturally the amplitude of the carrier beam is given by

$$A_0 = \sqrt{\sum_{n=-\infty}^{\infty} I_0^2 - A_n^2} \quad (32)$$

If we attempt to limit ourselves to only the first order sidebands (as in Bragg diffraction) then we obtain

$$C = I_0 \cos\left(\frac{\pi\Delta nL}{\lambda_a}\right) \quad S_{\pm 1} = -i I_0 \sin\left(\frac{\pi\Delta nL}{\lambda_a}\right) \quad (33)$$

just as before. Note that since the Bessel functions are symmetric with respect to positive and negative orders, the amplitudes of the diffracted beams of like orders should be the same, and should drop off as the amplitude of the Bessel functions decrease as a function of increasing order.

3.2.3. Bandwidth

An item of interest is the bandwidth of an acousto-optic device. A Bragg cell will have some optimum operating frequency, f_a (usually several tens of MHz to hundreds of MHz), which is governed by material properties. Consider now a collection of acoustic waves with center frequency given and a bandwidth of Δf_a . Fraunhofer diffraction theory tells us that the acoustic waves will spread out perpendicular to the direction of propagation. Therefore when an incident photon interacts with a lattice vibration, that vibration will be a combination of several different frequencies. Fraunhofer diffraction gives a spread in angle which is equal to $\Delta\theta = 0.9\lambda_a/L$ at the half power point. Now take the definition of the Bragg angle θ_B and differentiate. We find the following relation

$$\Delta f_a = \frac{2v}{\lambda_\gamma} \cos\theta_B \Delta\theta_B \quad (34)$$

By elementary reasoning, $\Delta\theta_B$ should be equal to $\Delta\theta$. Therefore we find the bandwidth of the AO device to be

$$\Delta f_a = \frac{1.8nv^2 \cos\theta_B}{L\lambda_\gamma f_0} = \frac{1.8nv \cos\theta_B}{\lambda_\gamma} \frac{\lambda_a}{L} \quad (35)$$

The second equality shows that the absolute Bragg bandwidth is proportional to the diffraction spread, λ_a/L , of the AO device as expected from simplistic reasoning.

4. Simple Applications

Acousto-optic devices have found numerous applications in optical signal processing. It would take several books to do justice to the richness of acousto-optic applications. Herein we briefly summarize some of the more common applications of AO devices.

4.1. Acousto-Optic Modulators

One of the most common applications of AO devices is the acousto-optic modulator, or AOM. An AOM consists of a piece of AO material with an ultrasound transducer (typically piezo-electric) on one end and a soft absorber on the other end (to prevent reflections). The transducer takes a radio frequency (RF) of the form $f(t) \exp(i\omega_a t)$. A bulk acoustic wave is generated inside the AO material which propagates through the crystal in the z-direction with velocity v . The wave has the form $f(t - z/v) \exp[i(\omega_a t - k_a z)]$. One can use this form in place of (8) and derive the diffracted electric fields.

4.2. Mode Locking

Some lasers oscillate at a number of frequency modes simultaneously. In practice, the phases of each mode will vary randomly in time. As a consequence the laser output power fluctuates over time. One way to force the laser to be coherent would be to force all of the modes to evolve in the same manner as a function of time. This process is referred to as *mode locking*. Mode locking is useful for generating laser pulses. Consider the case where we have an acousto-optic modulator inside a laser cavity. We set up a standing wave in the Bragg cell with an angular frequency ω_a . The diffraction from the Bragg cell causes a loss inside the cavity. This loss is periodic, and reaches a peak twice in each acoustic period. So the cavity is only lossless for a short interval of time, every $(2\omega_a)^{-1}$ seconds. Modes with random phases will be lossy and will not amplify inside the cavity. Only modes whose phases match the AOM phase will be allowed to grow and produce laser output. The pulses inside the cavity must have durations less than $(2\omega_a)^{-1}$ seconds to avoid being attenuated by the AOM. The laser output will be a train of pulses with period $2\pi/\omega$, where ω is the frequency separation of successive longitudinal laser modes.

4.3. Q-Switching

Q-switching is used to produce short intense pulses of laser light. The idea is to build up a large population inversion inside the gain medium. Then allow the system to deplete that population inversion quickly, generating a short but very powerful pulse of light. There are many devices that can be used to Q-switch a laser, such as a simple shutter, a saturable absorber, a rotating mirror, an electro-optic modulator, or an AO device. When a standing wave is present inside the AOM, light is deflected outside of the cavity, and cannot deplete the population inversion. When the population inversion has reached a maximum, the source to the AOM is switched off, and laser light can pass through the cell without deflection.

4.4. Convolvers and Correlators

One can use acousto-optic devices to perform convolution and correlation operations on input signals. The convolution of two time limited (or periodic) signals $f(t)$ and $g(t)$ over the interval $(0, T)$ is

$$x(t) = f(t) * g(t) = \int_0^T f(\tau)g(t - \tau)d\tau \quad (36)$$

There are two methods of implementing the integration: space integration and time integration. One example of time integration convolution is the following. Consider a point source of light which has been modulated (possibly by an AO device, or by using semiconductor laser diodes) with some signal. This light is incident upon a Bragg cell which contains an acoustic signal. This allows one signal to propagate with respect to the other, producing the time offset in the integral. The light exiting the Bragg cell is then collimated and falls on a detector array, such as a charge-coupled device. Time integration can only give one point of the correlator, $x(t_0)$, which is set by the phase difference between the two signals.

Space integration performs the entire convolution, not just a single time point. Consider an AO device with two transducers, one on each end, and offset in the light propagation direction. Two counter-propagating acoustic waves are employed. These waves are modulated by the two signals to be convolved. The interaction between the acoustic waves produces the required convolution, which is read out by an unmodulated light source. The output light is incident on a converging lens which spatially integrates the light. The focus of the lens is at a single photodetector. [Das

and DeCusatis, 1991]

4.5. Spectral Analysis

One of the most well developed uses of AO devices is the power spectrum analyzer. Consider a signal of unknown spectral distribution. Using an RF single-sideband mixer modulate this signal onto some carrier RF frequency suitable for the AO device. Collimate a coherent laser on the AO device which is operating in the Bragg regime. All of the diffracted light will exit at an angle which is dependent on both the acoustic frequency and the frequency of the light. The light then passes through a lens and is focused onto a photodetector array. The principal diffracted beam is offset from the incident beam by an angle $\theta \approx \frac{c}{v} \frac{f_a}{f_\gamma}$ [Berg and Pellegrino, 1996]. There will be small spots adjacent to the principal diffracted beam. Each spot represents a different frequency in the unknown signal. From elementary diffraction, each spot has an angular extent on the order of λ/D , where D is the smaller of the diameter of the optical beam or the effective length of the Bragg cell. This says that the frequency resolution of the spectrum analyzer is $\Delta f = v/D = 1/T_c$, where T_c is the crossing time for an acoustic wave to cross the cell aperture. To increase the resolution, simply increase the length of the acoustic cell and increase the spot size of your laser. This is a simple way to produce the power spectral density of almost any electrical signal.

5. Summary

In this paper we have summarized the essential mathematical elements and formalism for the description of electromagnetic interactions with acoustic waves. We have described the underlying phonon-photon interaction inherent in these interactions and explained the generic outcomes. In addition, we briefly summarized some of the key applications of acousto-optic phenomena: modulators, deflectors, mode lockers, Q-switchers, convolvers, correlators, and spectral analyzers. As mentioned in the introduction, acousto-optic devices can be used in many more applications, and as hinted at the beginning of §4 it would take several books to create a small dent into the world of acousto-optic implementations. We hope that this text has given a sense of the advantages and possible usages of AO devices, as well as some of the theoretical background that is required to fully describe the physics involved.

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Acousto-Optic Beam Deflectors (AOBD) are used to control the position of a laser beam as well as modulation. By careful broadband design of the transducer and by varying the frequency of the drive signal, the angle that the laser beam is deflected will change. The AOBD typically deflects the laser beam over a fraction of a degree to a couple of degrees with a resolution of a few hundred spots to an upper limit of about two thousand spots. Acousto-optic modulators (AOMs) are useful devices which allow the frequency, intensity and direction of a laser beam to be modulated. Within these devices incoming light Bragg diffracts off acoustic wavefronts which propagate through a crystal. Modulation of this incoming light can be achieved by varying the amplitude and frequency of the acoustic waves travelling through the crystal. Acousto-optic filters are a very advantageous means for rapid, electronic wavelength control of ECLs. The wavelength range of an AOTF is typically much broader than the gain bandwidth of an individual diode laser, so there are no wavelength range limitations imposed by the filter, in contrast to the case of electro-optic birefringent tuning. Well-designed AOTFs have high transmittance, so an acousto-optic external cavity has the potential for providing strong feedback. The switching time between random wavelengths is equal to the transit time of the sound wave across the optical beam, which ca