ECE 185

ACOUSTO-OPTIC MODULATION OF LIGHT

I. Objective: To study the interaction between light and sound waves in matter, and determine the characteristics of an acousto-optic (A-O) modulator.

II. References:

1. N. Uchida and N. Niizeki, "Acousto-optic Deflection Materials and Techniques", Proc. IEEE, 61, 8, p. 1073 (August 1973).
2. Yariv, Introduction to Optical Electronics, Chapter 12, "Interaction of Light and Sound", 2nd edition, Holt Rinehart and Winston (1971).
3. R. Adler, "Interaction between Light and Sound", IEEE Spectrum, p. 42 (May 1967).

III. Theory:

1. Introduction.

The phenomena of interaction between sound and light generally can be separated into three regions:

(a) (~10MHz) Low acoustic frequency region. The simple phase-grating theory developed by Raman and Nath can well explain the multi-order diffraction phenomena observed in this region. The region is also called the "Raman-Nath diffraction" region.

(b) (~100MHz) High acoustic frequency region. When the frequency of the acoustic wave is raised, the diffraction to higher orders is eliminated and, at certain angles of incidence of light, energy exchange between the zeroth- and the first-order light beams becomes predominant. This type of diffraction is called the "Bragg reflection".

(c) Moderate frequency region. The preceding two cases give the diffraction features occurring at the two extreme and idealized cases. In this "transition" region the Raman-Nath equation has no analytic solutions, and the diffraction is characterized as the mixture of those of the Raman-Nath diffraction and the Bragg reflection.

Since we are more interested in the light-sound interaction in high-frequency Bragg devices, we will discuss this region more detail.

2. Bragg Diffraction

(a) Particle model.

Many of the features of Bragg diffraction of light by sound can be deduced if we take advantage of the dual particle-wave nature of light and of sound. According to this picture a light beam with a propagation vector k and frequency ω can be considered to consist of a stream of particles (photons) with a momentum $\hbar k$ and energy $\hbar\omega$). The sound wave, likewise, can be thought of as made up of particles (phonons) with momentum $\hbar k_s$ and energy $\hbar\omega_s$. The diffraction of light by an approaching sound beam can be described as a series of collisions, each of which involves an annihilation of one incident photon at ω_i and one phonon and a simultaneous creation of a new (diffracted) photon at a frequency $\omega_d = \omega_s + \omega_i$, which propagates along the direction of the scattered beam. The conservation of momentum requires that the momentum $\hbar(k_s + k_i)$ of the colliding particles is equal to the momentum $\hbar k_d$ of the scattered photon, so

$$\vec{k}_d = \vec{k}_s + \vec{k}_i \tag{1}$$

The conservation of energy takes the form

$$\omega_d = \omega_s + \omega_i \tag{2}$$

From Eq. (2) we learn that the diffracted beam is shifted in frequency by an amount equal to the sound frequency. Since the interaction involves the annihilation of phonon, conservation of energy decrees that the shift in frequency is such that $\omega_d > \omega_i$ and the phonon energy is added to that of the annihilated photon to form a new photon.

From the momentum-conservation relation (1) we can derive the Bragg condition,

$$2\lambda_s \sin\theta = \frac{\lambda}{n} \tag{3}$$

where λ_s is the sound wavelength, λ is the light wavelength, θ is the angle between the incident or diffracted beam and the acoustic wavefront, as shown in Figure 1, and n is the refractive index of the acousto-optic cell.

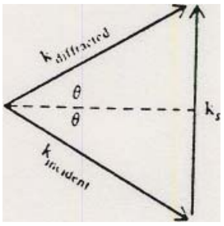


Fig. 1. Momentum-conservation relation.

(b) Diffraction efficiency. Under the Bragg condition, the coupled-wave theory can be used to analyze the Bragg diffraction of light by acoustic wave. The two light beams k_{incident} and $k_{\text{diffracted}}$ are coupled because of a sinusoidal perturbation in the density of the material of the A-0 cell. The diffraction efficiency can be obtained from the analysis.

$$\eta = \frac{I_d}{I_i} = \sin^2(\frac{\omega l}{2c}\Delta n) \tag{4}$$

where I_i and I_d are the intensities of the incident beam and the diffracted beam, respectively; ω is the angular frequency of light; l is the interaction distance between the two beams and is equal

$$l = \frac{width\ of\ acoustic\ wave}{\cos\theta} \tag{5}$$

Δn is the amplitude index change due to the strain s and can be expressed as

$$\Delta n = \frac{n^3 p}{2} s \tag{6}$$

In Eq. (6) p is the photoelastic constant of the matter. The strain is related to the acoustic intensity I_a by

$$s = \sqrt{\frac{2I_a}{\rho v_s^3}} \tag{7}$$

where v_s is the velocity of sound in the matter and ρ is the mass density. Combining (4), (6), and (7), we obtain

$$\eta = \sin^2\left(\frac{\pi l}{\sqrt{2}\lambda}\sqrt{MI_a}\right) \qquad \text{(at } \theta_B\text{)} \tag{8}$$

where $M = (n^6 p^2) / (\rho v_s^3)$ is defined as the diffraction figure of merit.

A list of acousto-optic properties of some materials commonly used is shown in the Table 1.

Note: $M_\omega = M_{\text{material}} / M_{H2O}$

Table 1. List of A-0 properties of some materials

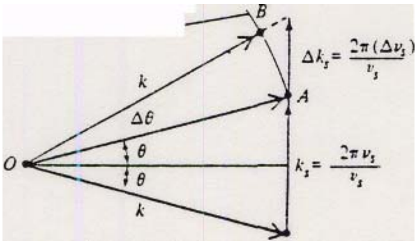
MATERIAL	ρ, (10^3 kg/m^3)	v_s (km/s)	n	p	M_ω
Water	1.0	1.5	1.33	0.31	1.0
Extra-dense flint glass	6.3	3.1	1.92	0.25	0.12
Fused quartz (SiO_2)	2.2	5.97	1.46	0.20	0.006
Polystyrene	1.06	2.35	1.59	0.31	0.8
KRS-5	7.4	2.11	2.60	0.21	1.6
Lithium niobate ($LiNbO_3$)	4.7	7.40	2.25	0.15	0.012
Lithium fluoride (LiF)	2.6	6.00	1.39	0.13	0.001
Rutile (TiO_2)	4.26	10.30	2.60	0.05	0.001
Sapphire (Al_2O_3)	4.0	11.00	1.76	0.17	0.001
Lead molybdate ($PbMO_4$)	6.95	3.75	2.30	0.28	0.22
Alpha iodic acid (HIO_3)	4.63	2.44	1.90	0.41	0.5
Tellurium dioxide (TeO_2) (Slow shear wave)	5.99	0.617	2.35	0.09	5.0

(c) Deflection angle change (Δθ) as a function of the sound frequency.

The momentum vector diagram originally introduced in Fig.1 is closed and the beam is diffracted along the direction θ6 as given by Eq. (3). Now let the sound frequency change from ν_s to $\nu_s + \Delta\nu_s$. Since $k_s = 2\pi\nu_s/v_s$, this causes a change of $\Delta k_s = 2\pi(\Delta\nu_s)/v_s$ in the magnitude of the sound wave vector. Since the angle of incidence remains the same and the magnitude of the diffracted k vector is unchanged, its tip is constrained to the circle locus shown in Fig.2, we can no longer close the momentum diagram and thus momentum is no longer strictly conserved. The beam will be diffracted along the direction that least violates the momentum conservation. This takes place along the direction OB, causing a deflection of the beam by $\Delta\theta$. Since the angles θ and $\Delta\theta$ are all small and that $k_s = 2\pi\nu_s/v_s$, we obtain

$$\Delta\theta = \frac{\Delta k_s}{k} = \frac{\lambda}{n v_s}\Delta\nu_s \tag{9}$$

so that the change of the deflection angle is proportional to the change of the sound frequency.



Circle of radius k centered on O

Fig. 2. Momentum diagram illustrating how the change in sound frequency from ν_s to $\nu_s + \Delta\nu_s$ deflects the diffracted light beam from θ to $\theta + \Delta\theta$.

(d) Number of resolvable spots. The diffraction angle of a gaussian beam is

$$\theta_d = \frac{4\lambda}{\pi n d} \tag{10}$$

where D is the gaussian spot diameter.

The number of resolvable spots is defined as

$$N = \frac{\Delta\theta}{\theta_d} = \frac{\pi}{4}\Delta\nu_s\tau \tag{11}$$

where $\tau = D/v_s$ is the time it takes the sound to cross the optical beam diameter.

EXPERIMENTAL PROCEDURE.

PART I. AOM characteristics.

Set up acousto-optic modulator with an unfocused He-Ne laser beam and measure the relationships between the following parameters:
a) Diffraction efficiency vs. angle of incidence
b) Diffraction efficiency vs. frequency of drive power
c) Diffraction efficiency vs. drive power

Before taking measurements check that 0-minute mark on the rotational mount with AOM corresponds to the normal beam incidence. Set input beam at I_{in} = 15mW.

a1) Sweep through the angles to find the Bragg angle (rotate AOM clockwise):

1. FREQ: 80MHz
2. VOLT: 1000mV (amplitude)
3. MINS: Sweep from 0 to 60 minutes in increments of 5 mins
4. Plot the diffraction efficiency ($\eta = I^{(+1)}/I_{in}$) as function of incident angle.

a2) Repeat measurements as in a1) for the -1st diffraction order (rotate AOM counterclockwise).

b) Once you have found the Bragg angle sweep through the frequency:

1. MINS: stay at Bragg angle (+1st order)
2. VOLT:1000mV (keep it constant when change frequency)
3. FREQ: Sweep from 50 to 100MHz in increments of 5MHz (take more measurements around optimum (central) frequency)
   Note: The Bragg angle varies with frequency, so you will need adjust the photodetector position.
4. Plot the diffraction efficiency as function of frequency.
5. Find the central frequency and calculate the RF bandwidth on 3db level.

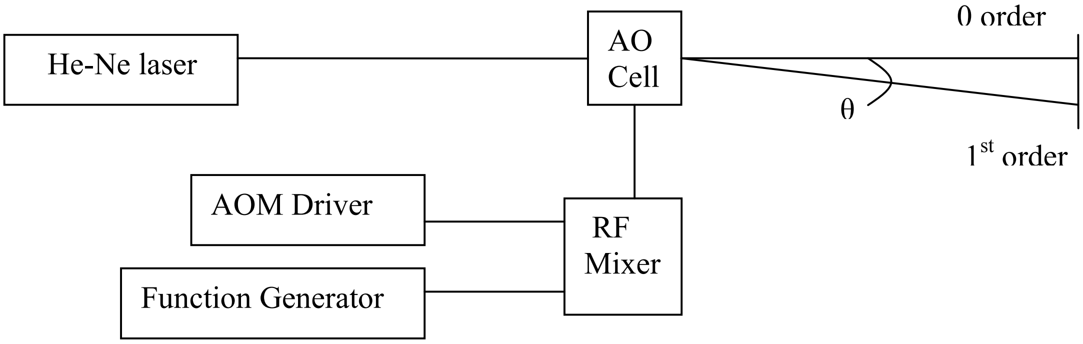
c) On optimum frequency sweep through the voltage input

1. FREQ: optimum
2. MINS: stay at Bragg angle (may need adjustment)
3. VOLT: Sweep from 1V to 11V. (Check appearance of high diffraction orders)
4. Plot the diffraction efficiency as function of voltage.

PART II. Spectral Analysis.

AOM are often used for RF and micro wave spectral analysis. Here we will use an AOM to determine frequency components of RF signals.

1. Set up a screen with ruled graph paper at least 2m from the AO cell. (To increase a distance between 1st and 0 order spots you may use mirror to reflect them and observe on the wall.)



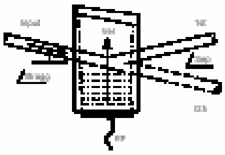
Set output frequency of AOM driver at optimum value and amplitude of 500mV. Observe 0 order and diffracted (+1st) order spots on the screen. Measure the distance from AO cell and +1st order spot. Measure the distance between +1st and 0 order spots. Calculate the Bragg angle and period of the grating inside the AO cell.
Find acoustic wave velocity propagating in the AO cell and compare with the velocity given in AOM specification.

2. To simulate RF signal of unknown frequency use functional generator and RF mixer.
Set the function generator on 10MHz sine wave with the amplitude of 500mV and connect it to L-input of RF Mixer. Connect AOM driver output to R-input of RF Mixer.
Connect RF Mixer output to AO cell input. If done correctly, there should be zero order spot and two more bright spots observed on the screen.
Measure the distances from the centers of these spots and zero order spot.
Determine frequency components of RF signal applied to AO cell.

PART III. Modulation of Laser Beam.

1. Set the amplitude of AOM driver signal to 1500mV at optimum frequency. Set the amplitude of function generator to 100mV at 1kHz sine wave. Connect the output of function generator to Analog In of AOM driver. Observe 1kHZ modulated RF signal on the oscilloscope. Apply this signal to AO cell.
Observe the +1st order spot. To observe amplitude modulation of intensity in this spot take signal from the power meter Analog Output and apply it to oscilloscope.
Check the frequency of modulated signal.

2. Use the output from audio player to modulate the signal applied to AO cell.
Observe audio signal transmitted by laser beam on the oscilloscope. You can also hear it if you connect headphones to the power meter output.



1205C*

Acousto-Optic Modulator

ISOMET

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APPLICATIONS

- **Modulator**
- **Low Resolution Deflector**

- **Frequency Shifter**

FEATURES

- **Low Drive Power**
- **Small Size**

- **Good Temperature Stability**

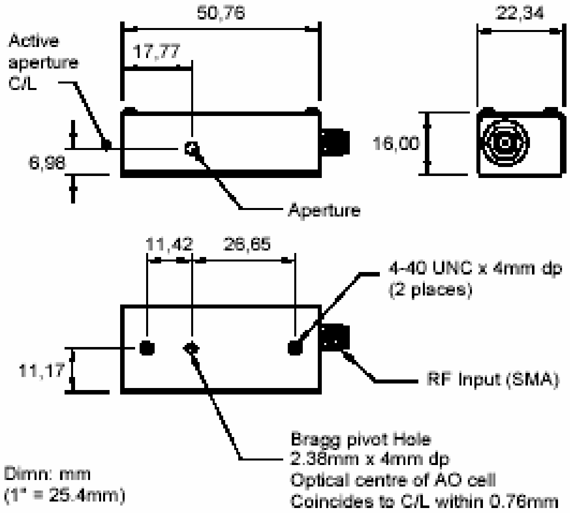
DRIVERS

MODEL 222A-1 (DIGITAL MODULATION)
MODEL 232A-1 (ANALOG MODULATION)

MODEL D301B (VARIABLE FREQUENCY)
MODEL D322B (VARIABLE FREQUENCY & MOD'N)

*** 1205C-1**	**1mm Active Aperture**
1205C-2	**2mm Active Aperture**

OUTLINE DRAWING



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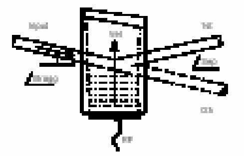

1205C*

Acousto-Optic Modulator

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SPECIFICATIONS

Spectral Range:	.442-> 1.5µm*
Standard Operating Wavelengths:	442nm, 488-633nm
Interaction Medium:	Lead Molybdate (PbMo04)
Acoustic Velocity:	3.63mm/µs
Active Aperture:	1mm and 2mm (see below)
Center Frequency (CF):	80MHz
RF Bandwidth:	30MHz
Input Impedance:	50Ω Nominal
VSWR:	<1.5:1 @ 80MHz
DC Contrast Ratio:	>1000:1 min (>2000:1 typical)

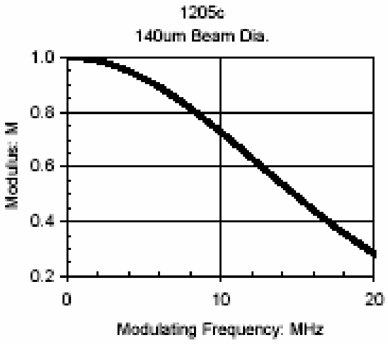
PERFORMANCE vs. WAVELENGTH

Wavelength (nm):	442	488	515	633	830*
RF Drive Power, 1205C-1 (W):	<0.3	<0.4	<0.4	<0.6	<0.8
RF Drive Power, 1205C-2 (W):	<0.4	<0.5	<0.6	<1.0	<1.5
Bragg angle (mrad):	4.9	5.4	5.7	7.0	9.1
Beam Separation (mrad):	9.7	10.7	11.3	13.9	18.3
Static Insertion Loss:	<10	<5	<3	<3	<3

PERFORMANCE vs. BEAM DIAMETER

Beam Diameter (mm):	2.0	1.0	0.34	0.2	0.14
Rise Time (ns):	360	180	60	35	25
Modulation Bandwidth (MHz) @ MTF = 0.5:	1.0	1.9	5.8	10	15
Deflection Efficiency (% @ CF):	90	85	85	80	75

*Operation at near IR wavelengths with reduced efficiency and modulation bandwidth. Special A/R coatings to 1.5µm.



The typical MTF (depth of modulation) curve for the 1205C modulator assuming a 0.14mm beam diameter is shown at the left. For larger beam diameters the abscissa scales linearly. The curve is closely approximated by the function.

$$M \approx \exp - (f/f_o)^2$$

where: f = modulating frequency in MHz
f_o = parameter of modulator related to beam waist diameter = 18MHz (from experimental data)

The value of M from the curve may be used to the sine wave contrast ratio at a particular modulating according to the relation:

$$CR = 1+M/1-M$$

For digital on-off modulation, the contrast ratio will be greater than the value calculated from the above equation

ALL SPECIFICATIONS SUBJECT TO CHANGE WITHOUT NOTICE

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