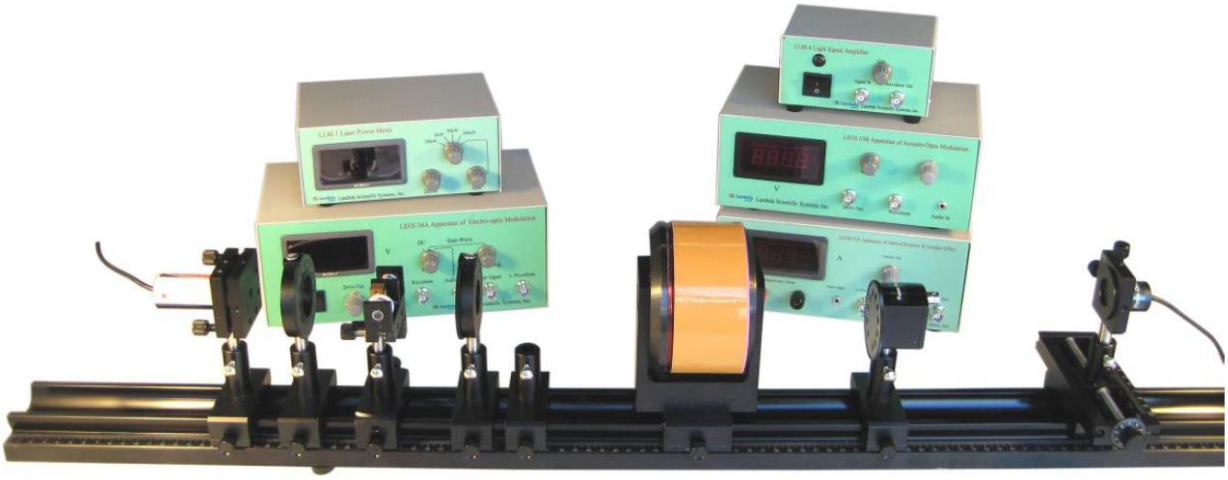
Lab 3 Light Modulation by Acousto-Optic, Electro-Optic and Magneto-Optic Effects

EECS 4614 Electro-Optics

Fall 2025

Professor Simone Pisana



1 Safety

Warning: the semiconductor laser in this lab is a **class IIIb laser**. **Avoid direct eye exposure to the laser beam!**

Follow the laser safety guidelines discussed in the first session and the laser safety manual. If you are unsure about anything, ask your TA.

Acknowledgement: This lab handout is based on the equipment instruction manual provided by Lambda Scientific.

2 Optical Rotation and Faraday Effect – for reference only, you completed this in part 1 of the lab

2.1 Introduction

As discovered by Michael Faraday in 1845, when a ray of light with linear polarization passes through a medium, the plane of polarization of the light rotates by a certain angle if a magnetic field is applied to the medium along the propagation direction of the light. This phenomenon is called as the Faraday effect.

The Faraday effect has found many applications. It can be used to study the structure of a substance. For example, the distinct Faraday effect can be used to analyze hydrocarbons with different structures; in semiconductor physics, the Faraday effect can be used to measure the effective mass of carriers and study the structure of energy bands; in electrical engineering, the Faraday effect can be used to measure the current and magnetic field of an electric circuit; particularly, in laser technology, optical isolators are made by using the Faraday effect and they have become the indispensable components in multi-stage laser amplifiers and high-resolution laser spectroscopy. In addition, components widely used in laser communication and laser radar, such as optical circulators and modulators, are also based on the Faraday effect.

2.2 Theory

2.2.1 Faraday Effect

As seen in Figure 1-1, if the applied magnetic field is not strong, then the rotation of the plane of polarization is proportional to the magnetic induction B and the length of the medium L,

$$\theta = VBL \text{ or } \theta = V\int_0^L Bdl \tag{1-1}$$

where V is the Verdet constant, which depends on the medium and the wavelength of the light (dispersion). It represents the magneto-optic characteristic of the medium.

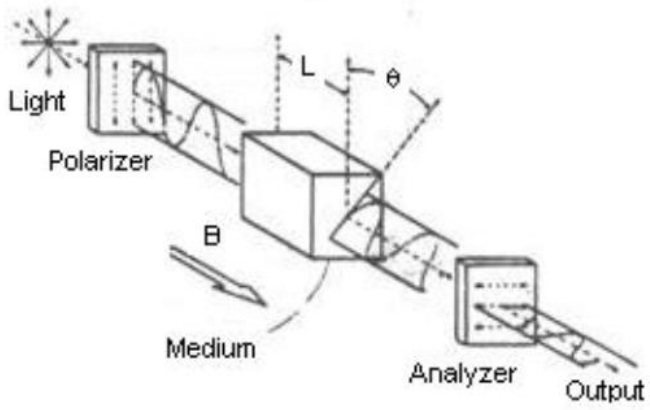


Figure 1-1 Schematic of Faraday effect

Almost all media exhibit the Faraday effect. However, the rotation direction of the plane of polarization may vary from medium to medium. If the magnetic field is induced by a coil wound round the medium, and the rotation of the plane of polarization is in the same direction as the current flow in the coil, it is called positive rotation (V>0); otherwise, it is called negative rotation (V<0).

For a certain medium, the Faraday rotation direction depends solely on the direction of the magnetic field independent of the propagation direction of light. This is the major difference between Faraday effect and effect of **optical activity**. For an optically active medium such as glucose solution, the direction of the polarization rotation of the light through the medium depends on the propagation direction of the light. When viewed along and against the propagation direction of the light, the directions of the polarization rotation are against each other. Hence, if light travels back and forth to complete a round trip in an optically active medium, the plane of polarization of the light restores to the original state and therefore the polarization of the light does not rotate.

By contrast, if the applied magnetic field is fixed, when light travels back and forth in a magneto-optic medium for one round trip, the Faraday rotation angle is doubled. Therefore, light can be allowed to travel in the magneto-optic medium for many round trips to enhance the Faraday effect.

Similarly, optical dispersion also exists in Faraday effect as the Verdet constant is a function of the wavelength of light. When a ray of white light with linear polarization passes through a magneto-optic material, the polarization rotation of violet light is larger than that of red light. It has been proven by experiment that the Verdet constants of magneto-optic material decrease with an increase in the wavelength of light. The curve of optical rotatory dispersion (V-λ) is also called the Faraday rotation spectrum.

2.2.2 Magneto-Optic Modulation

If an AC electric current is supplied to the exciting coil, then an AC magnetic field is applied to the medium forming a magneto-optic modulator (now the exciting coil is called the modulating coil). If the magneto-optic modulator is placed between a polarizer and an analyzer, and no current is supplied to the coil, then the output intensity of a linearly polarized light beam going through the system is defined by the Malus's law, as

$$I = I_0 \cos^2(\alpha)$$

where α is the angle between the axes of the polarizer and the analyzer.

When an AC current is supplied to the coil as $i = i_0\sin(\omega t)$, then an AC magnetic field is created as $B = B_0\sin(\omega t)$. Correspondingly, the Faraday rotation angle is modulated as $\alpha_F = \alpha_{F0}\sin(\omega t)$. Now the output intensity of the light exiting from the analyzer becomes

$$I = I_0 \cos^2(\alpha + \alpha_F) = \frac{I_0}{2}\left[1 + \cos 2(\alpha + \alpha_F)\right] = \frac{I_0}{2}\left[1 + \cos 2(\alpha + \alpha_{F0}\sin \omega t)\right]$$

where α_{F0} is the range of modulated Faraday rotation angle. This equation describes the fundamental principle of magneto-optic modulation.

2.3 Apparatus Structure & Specifications

2.3.1 Structure

The main electric unit provides magnetizing current and modulation audio signal for the magnetic coil.

There are three wiring terminals on the magnetic coil marked as "COM.", "MOD." and "MAG.", respectively. If ignoring boundary effects, the magnetic field induction inside the coil can be calculated by using Ampere's law:

$$B = \mu_0 NI / L$$

where μ_0 is the vacuum permeability, $\mu_0 = 4\pi\times10^{-7}$ H·m^{-1} $\approx 1.2566\times10^{-6}$ H·m^{-1}; N is the number of turns; I is the current in unit of Ampere; and L is the length of the coil in unit of meter.

The magnitude of magnetic field inside a coil is proportional to the current applied. For example, the magnetic field magnitude of the coil in this apparatus can be calculated as ~ 40.2 mT when the

applied current is 1.0 A, which can be further verified using a Teslameter with a longitudinal probe. **Note**: uniform magnetic field is in the middle portion of the coil. Figure 1-2 shows a photo of the experimental setup for optical communication of audio signal via M-O effect.

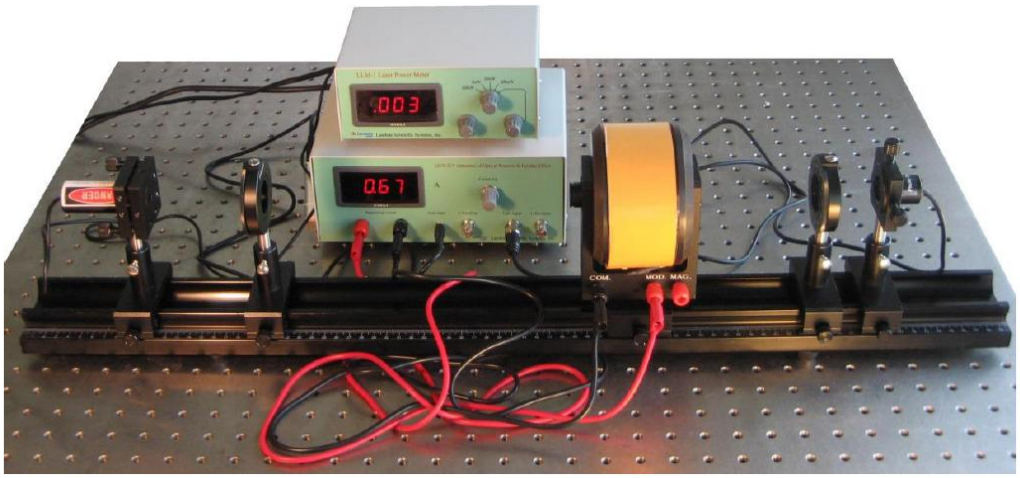


Figure 1-2 Experimental setup of optical communication of audio signal via M-O effect

2.3.2 Parts and Specifications

Description	Specifications	Qty
Optical bench	Length: 1.2 m	1
Main unit	(1) DC power supply: 0~3 A adjustable (magnetizing source) (2) Current amplifier of photodiode detector (3) Built-in speaker	1
Diode laser	4 mW at 650 nm with 2-D adjustable holder	1
Polarizer	Including rotary holder	2
Magnetic coil	Dimensions: outer diameter: 110 mm; length: 50 mm Number of turns: 1600 Central hole diameter: 10 mm	1
Laser power meter	3-1/2 digits Scale: 200 μW, 2 mW, 20 mW, 200 mW Resolution: 0.1 μW	1
Power meter probe	Hole apertures: 0.5, 1, 2, 3, 4, 6 mm Slit widths: 0.2, 0.3, 0.4, 0.8, 1.2 mm	1
Teslameter with probe	Range: 0 ~ 2000 mT	1
Photo-triode detector	For optical communication demonstration	1
Sample	Φ6 mm; length: 30 mm	1
Audio signal source	iPod nano	1
Cable	Red/black cables (1 each), BNC cables (3), audio cable (1)	6
Slide		5

Warning:

1) Turn off the power of the main unit before connecting/disconnecting wires or cables.

2) To avoid overheating the coil, do not supply large magnetizing currents to the coil over long periods of time.

2.4 Experiments

2.4.1 Observe Faraday effect and find relationship of rotation angle vs magnetic field

1) Set up apparatus per Figure 1-3.

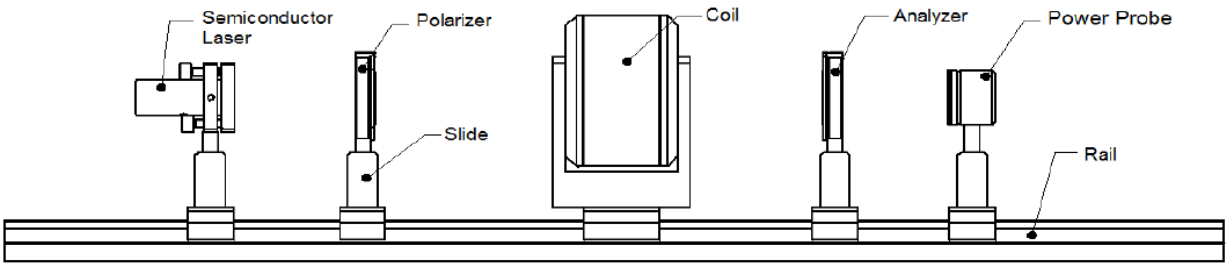


Figure 1-3 Schematic of setup

2) Wiring: connect "Magnetizing Current" of the main electric unit to the coil at terminals "COM." and "MAG." using the pair of black and red wires. Then connect laser diode and power probe to "Laser" and "Power Probe", respectively, on the rear panel of the power meter, and turn on power. **Note**: since the output of the semiconductor laser is already polarized, the "Polarizer" shown in Figure 1-4 can be rotated to adjust the incident light intensity to prevent power meter saturation. This experiment should be conducted in the absence of ambient light.

3) Align the laser beam to pass the aperture of the coil and the sample. The end surface of the sample (to be located inside the coil) should be perpendicular to the laser beam.

4) Align the axes of the polarizer and the analyzer perpendicular to each other.

5) Rotate the analyzer until the light intensity from the power meter is zero or minimum. Record the angular scale of the rotary holder for the analyzer. Then turn on power of the main unit. **Note:** select Φ6.0 aperture in front of the power probe and use the 1-D adjustable slide to mount the power probe on the optical rail. Adjust the range and zero offset of the power meter to have most sensitivity to the zero light condition of the crossed polarizer/analyzer pair.

6) Turn "Current Adj" knob **SLOWLY** to increase the magnetizing current of the coil to 0.5 A. Now the reading on the power meter will change. **Note**: Turn the "Current Adj" SLOWLY so that the current reading increases slowly and steadily until the desired current reading is reached and stabilized.

7) Rotate the analyzer again until the reading on the power meter becomes minimal again. Record the angular scale of the analyzer and compare it with the angular scale recorded in step 5). The angle rotated by the analyzer is the Faraday rotation angle, α_F.

8) Repeat steps 6) to 7) three times to get averaged data, filling the table below.

9) Increase the magnetizing current SLOWLY in interval of 0.5 A. Repeat steps 6) to 9). Plot the measured Faraday rotation angle α_F vs. B curve using the table below. Note: the magnetic field B can be measured by using the supplied Teslameter by inserting in the bore of the magnet instead of the sample.

Magnetizing Current (A)	Magnetic Field	Rotation Angle	Mean	Error
0.5				
1.0				
1.5				
2.0				
2.5				

10) By plotting the data and conducting linear curve-fitting to the data, the Verdet constant of the sample can be calculated from equation (1-1) with a sample length of 30 mm.

11) Move the semiconductor laser to the other end of the rail, let the beam pass through the sample from the other end. Repeat steps 5) to 7), observe the direction of polarization rotation and compare the result with the previous result.

12) Exchange the red/black wires of the magnetizing current to reverse the current direction of the coil. Observe the change of polarization rotation direction and find the rules.

Report the observations to the TA.

2.4.2 Study and observe the characteristics and applications of magneto-optic modulation

1) Set up the system per Figure 1-2 and use the photo-triode to replace the power probe.

2) Wiring: connect “Magnetizing Current” of the main unit to the coil at terminals “COM.” and “MOD.” using the pair of black and red wires. Connect the photo-triode detector to “Light Signal” terminal and audio source to “Audio Input” terminal of the main unit. If you don’t have a suitable audio source, you may use a 10-100 mV sine wave in the audio frequency range.

3) Adjust optical path to make the beam pass through the sample material and fall onto the active area of the photo-triode detector.

4) Turn on the red switch on the back panel of the main unit and music from the audio source should be heard from the built-in speaker in the main unit.

5) Block the laser beam with a hand, the sound from the speaker should stop; remove the hand from the laser beam, the sound should be heard again. This indicates the audio signal is indeed modulated by the laser light via magneto-optic effect.

6) Rotate the analyzer to adjust the volume of the music from the speaker.

Report the observations to the TA.

3 Crystal Electro-Optic Effect

3.1 Introduction

Electro-optic effect is a change in the refractive index of a crystal as induced by an electric field. By using a laser amplitude modulator employing the transverse electro-optic effect of a typical LiNbO3 crystal, students can

1) understand electro-optic effect and its applications
2) measure the half-wave voltage and electro-optic coefficient of crystals
3) observe a change in optical properties of crystals due to electro-optic effect
4) observe the interference of focused polarized light as caused by electro-optic effect
5) conduct optical communication experiment via electro-optic effect

3.2 Theory

When an electric field is applied to a crystal or liquid, the refractive index of the crystal or liquid is altered. This phenomenon is called the electro-optic effect, which has been applied to many important areas in science and technology. With a short response time (10^{10} Hz), electro-optic effect can be used by shutters in high-speed photography and optical choppers in speed of light measurement. After the emergence of lasers, the research and development of electro-optic effect have advanced rapidly. So far, electro-optic devices have been widely applied to areas such as laser communication, laser ranging, laser display, and optical data-processing.

3.2.1 Linear electro-optic effect and refractive index ellipsoid

Typically, the change in the refractive index of an electro-optic crystal to an electric field can be expressed as

$$n = n_0 + aE_0 + bE_0^2 + \ldots \tag{3-1}$$

where a and b are constants, and n_0 is the refractive index of the crystal in the absence of an electric field. The second term in equation (3-1) is linearly proportional to the electric field, called the linear electro-optic effect or the Pockels effect; while the third term is the quadratic electro-optic effect, also called the Kerr effect. Pockels effect exists only in crystals that are lack of inversion symmetry while Kerr effect can exist in any materials but it is generally much weaker than the Pockels effect.

As seen in Figure 3-1, when light propagates in an anisotropic crystal, the propagating velocities of light in the crystal are different for different propagating directions or different oscillation directions of the electric vector (polarization), resulting in different refractive indices. Normally, a refractive index ellipsoid is used to describe the relationship among the refractive index of the material, the propagating direction and the polarization state of light.

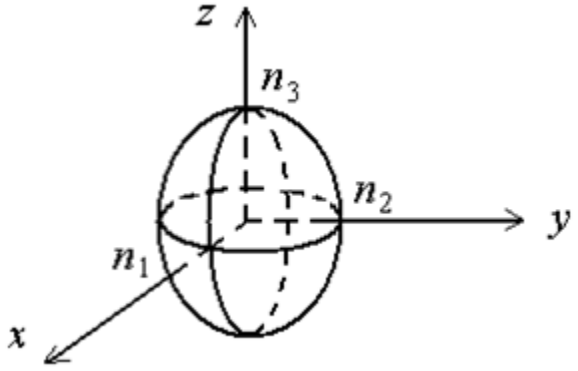


Figure 3-1 Refractive index ellipsoid in the absence of an electric field

In the absence of an electric field, the refractive index ellipsoid of an anisotropic crystal can be expressed with principal axis coordinates

$$\frac{x^2}{n_1^2} + \frac{y^2}{n_2^2} + \frac{z^2}{n_3^2} = 1 \tag{3-2}$$

where n_1, n_2, and n_3 are the principal refractive indices of the crystal along the principal axes of x, y, and z, respectively. When an electric field is applied, the shape and orientation of the above refractive index ellipsoid are subject to change and hence the ellipsoid equation becomes

$$\frac{x^2}{n_{11}^2} + \frac{y^2}{n_{22}^2} + \frac{z^2}{n_{33}^2} + \frac{2yz}{n_{23}^2} + \frac{2xz}{n_{13}^2} + \frac{2xy}{n_{12}^2} = 1 \tag{3-3}$$

Generally speaking, the linear electro-optic effect of a crystal is classified into two categories, longitudinal electro-optic effect and transverse electro-optic effect. The former refers to as the electro-optic effect of a crystal when an electric field is applied along the propagating direction of light in the crystal; while the latter is the electro-optic effect when the electric field is applied perpendicularly to the propagating direction of light in the crystal. Normally, longitudinal electro-optic effect is used for KDP-type crystals while transverse electro-optic effect is used for LiNbO3-type crystals. In this experiment, the linear electro-optic effect of a LiNbO3 crystal is studied. By using the transverse electro-optic modulation technique, the half-wave voltage and electro-optic efficient of a LiNbO3 crystal can be measured, and its output optical characteristic can be observed.

A LiNbO3 crystal consists of a trigonal lattice (3M point group), with a third axis of rotation along the principal z-axis (the propagating direction of light in the crystal). LiNbO3 is an uniaxial crystal ($n_1=n_2=n_o$) whose refractive index ellipsoid is a rotational ellipsoid described by

$$\frac{x^2+y^2}{n_o^2}+\frac{z^2}{n_e^2}=1 \tag{3-4}$$

where n_o and n_e are the refractive indices of the ordinary ray and extraordinary ray, respectively. When an electric field is applied along the principal x-axis, the uniaxial crystal becomes a biaxial crystal, and the cross-sectional projection of the refractive index ellipsoid is changed from circle to ellipse, described by

$$\left(\frac{1}{n_0^2}-\gamma_{22}E_x\right)x^2+\left(\frac{1}{n_0^2}+\gamma_{22}E_x\right)y^2-2\gamma_{22}E_xxy=1 \tag{3-5}$$

where γ_{22} is the electro-optic coefficient of the crystal.

By taking principal axis transform, equation (3-5) can be rewritten as

$$\left(\frac{1}{n_0^2}-\gamma_{22}E_x\right)x'^2+\left(\frac{1}{n_0^2}+\gamma_{22}E_x\right)y'^2=1 \tag{3-6}$$

Considering $(n_0)^2\gamma_{22}E_x<<1$, equation (3-6) can be simplified as

$$n_{x'}=n_0+\frac{1}{2}n_0^3\gamma_{22}E_x$$
$$n_{y'}=n_0-\frac{1}{2}n_0^3\gamma_{22}E_x \tag{3-7,8}$$

Hence, equation (3-6) can be rewritten as

$$\frac{x'^2}{n_{x'}^2}+\frac{y'^2}{n_{y'}^2}=1 \tag{3-9}$$

where x' and y' are called the inductive axes of the LiNbO3 crystal.

3.2.2 Theory of electro-optic modulation

If a laser is used as a tool to carry information, one must load the signal to be carried onto the laser radiation. This process is called laser modulation and the apparatus used in this process is called laser modulator. On the contrary, the restoration process of carried signal from modulated laser radiation is called demodulation. Because the laser acts with a signal carrying function, it is called a carrier. Similar to radio modulation, laser modulation can take forms of continuous amplitude modulation, continuous frequency modulation, continuous phase modulation, or pulsed modulation. By comparison, intensity modulation is the most common method, in which the strength of a modulation signal is proportional to the intensity of an optical carrier so that the intensity of the laser is regulated by the modulation signal. The reason why intensity modulation is common is that photo-receivers respond to the change in optical intensity not amplitude.

There are many mechanisms for laser modulation, such as mechanical modulation, electro-optic modulation, acousto-optic modulation, magneto-optic modulation, or source current modulation. Among them, electro-optic modulation is fast and simple, and hence it is widely applied to laser modulation technology and mixed optical bistable devices.

3.2.2.1 Transverse electro-optic modulation

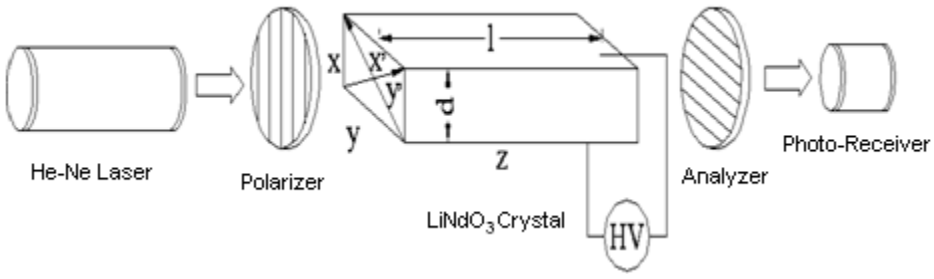


Figure 3-2 Schematic of transverse electro-optic modulation

Figure 3-2 shows the schematic of a laser amplitude modulator using the transverse electro-optic effect of a LiNbO3 crystal. The polarization of a polarizer is aligned along the x-axis while the polarization of an analyzer is parallel to the y-axis. Thus, the projections of the incident light on axes x' and y' at the surface of incidence (z=0) are identical with complex amplitudes as

$$E_{x'}(0)=A,\quad E_{y'}(0)=A \tag{3-10}$$

Hence, the intensity of the incident light is

$$I_i \propto \overline{E}\cdot\overline{E^*} = \left|E_{x'}(0)\right|^2 + \left|E_{y'}(0)\right|^2 = 2A^2 \tag{3-11}$$

After going through an electro-optic crystal with a length of L, a phase delay of δ is produced between the two components

$$E_{x'}(L) = A, \quad E_{y'}(L) = Ae^{-i\delta} \tag{3-12}$$

After transmitting through the analyzer, the resultant complex amplitude is the addition of the x' and y' components projected on the y-axis

$$\left(E_y\right)_o = \frac{A}{\sqrt{2}}\left(e^{i\delta} - 1\right) \tag{3-13}$$

Correspondingly, the intensity of light transmitted through the analyzer is

$$I_t \propto \left[\left(E_y\right)_o\left(E_y\right)_o^*\right] = \frac{A^2}{2}\left[\left(e^{i\delta} - 1\right)\left(e^{-i\delta} - 1\right)\right] = 2A^2\sin^2\frac{\delta}{2} \tag{3-14}$$

Based on equations (3-11) and (3-14), the transmittance of the crystal is

$$T = \frac{I_t}{I_i} = \sin^2\frac{\delta}{2} \tag{3-15}$$

From equations (3-7) and (3-8), the phase delay can be further expressed as

$$\delta = \frac{2\pi}{\lambda}\left(n_{x'} - n_{y'}\right)L = \frac{2\pi}{\lambda}n_0^3\gamma_{22}U\frac{L}{d} \tag{3-16}$$

where U is the applied voltage, d is the thickness of the crystal, and λ is the wavelength of the laser. Obviously, the phase delay depends on the voltage applied. When the applied voltage is increased to a certain value, a phase delay of π can be achieved, corresponding to an optical path difference of λ/2 and 100% transmittance. Such voltage is called the half-wave voltage of the crystal denoted by U_π, an important parameter to describe the electro-optic characteristic of an electro-optic crystal. For a given crystal, a smaller half-wave voltage is preferred, which means smaller modulation voltage can be used.

From equation (3-16), the half-wave voltage can be expressed as

$$U_\pi = \frac{\lambda}{2n_0^3\gamma_{22}}\left(\frac{d}{L}\right) \tag{3-17}$$

Obviously, the half-wave voltage depends on the dimensions of the crystal, linearly proportional to the length of the crystal but inversely proportional to the spacing between electrodes.

Substituting equation (3-17) to (3-16), we get

$$\delta = \pi\frac{U}{U_\pi} \tag{3-18}$$

Thus, equation (3-15) can be rewritten as

$$T = \sin^2\frac{\pi}{2U_\pi}U = \sin^2\frac{\pi}{2U_\pi}(U_0 + U_m\sin wt) \tag{3-19}$$

where U_0 and $U_m\sin(wt)$ are the dc and ac voltages applied to the crystal, respectively; U_m is the amplitude of the ac voltage and w is the modulation frequency. For a given crystal with a known laser wavelength, the half-wave voltage is a constant, and then the transmittance of the crystal depends solely on the applied voltage.

3.2.2.2 Effect of dc bias voltage on optical output characteristic of electro-optic crystal

If $U_0=U_\pi/2$, and $U_m<<U_\pi$, as seen in Figure 3-3 (a), the modulation voltage should be selected within a certain range to achieve a linear modulation with high-efficiency. Now, equation (3-19) can be rewritten as

$$T = \sin^2\left(\frac{\pi}{4} + \frac{\pi}{2U_\pi}U_m\sin wt\right) = \frac{1}{2}\left[1 + \sin\left(\frac{\pi}{U_\pi}U_m\sin wt\right)\right] \tag{3-20}$$

Considering $U_m<<U_\pi$, equation (3-20) can be approximated as

$$T \approx \frac{1}{2}\left[1 + \frac{\pi U_m}{U_\pi}\sin wt\right] \propto \sin wt \tag{3-21}$$

Although the amplitudes of the output and modulation signals are different, their frequencies are identical and therefore the output signal is distortion free, called linear modulation.

If $U_0=0$, and $U_m<<U_\pi$, as shown in Figure 3-3 (b), equation (3-19) becomes

$$T = \sin^2\left(\frac{\pi}{2U_\pi}U_m\sin wt\right) \approx \frac{1}{4}\left(\frac{\pi}{U_\pi}U_m\right)^2\sin^2 wt \approx \frac{1}{8}\left(\frac{\pi}{U_\pi}U_m\right)^2(1-\cos 2wt) \propto \cos 2wt \tag{3-22}$$

It is apparent from equation (3-22) that the output frequency is twice of the modulation frequency, resulting in frequency-doubling distortion.

If $U_0=U_\pi$, and $U_m<<U_\pi$, then equation (3-19) can be approximated as

$$T \approx 1-\frac{1}{8}\left(\frac{\pi U_m}{U\pi}\right)^2(1-\cos 2wt) \propto \cos 2wt \tag{3-23}$$

Similarly, the output signal still suffers from frequency-doubling distortion.

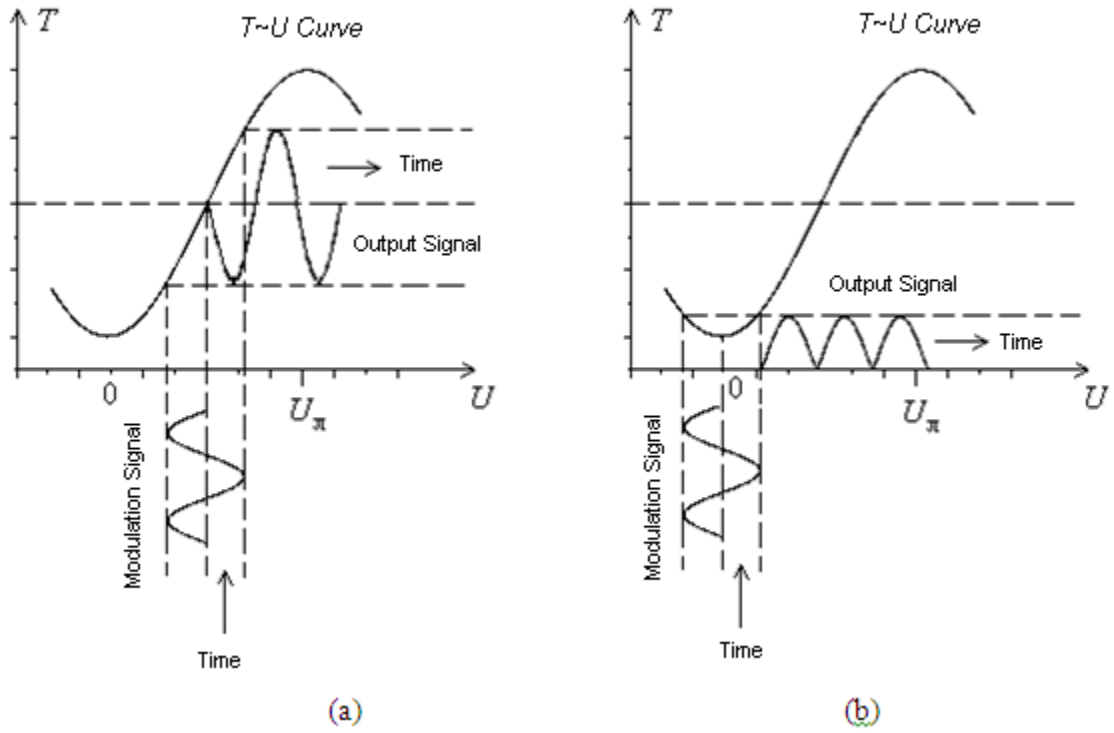


Figure 3-3 Effect of dc voltage bias on output characteristic of electro-optic crystal

In summary, if dc voltage bias U_0 is selected at 0 V or near the half-wave voltage U_π, nonlinear electro-optic modulation occurs, and the output signal suffers from distortion. If $U_0=U_\pi/2$, but $U_m>U_\pi$, nonlinear electro-optic modulation still occurs because the requirement of small-signal modulation is not met. In the latter case, though the dc voltage bias is selected in the linear region, the output signal still suffers from distortion.

3.3 Apparatus Structure & Specifications

3.3.1 Structure

The main unit consists of driving voltage output for E-O crystal, voltage meter, mode selection switch, terminals of modulated signal and demodulation.

The 3-1/2 digital voltmeter is used to display the driving voltage to the E-O crystal. When “Mode” is selected at “Sine-Wave” or “Audio In”, it shows the average voltage approximately. The “Drive Vol.” knob is used to adjust the DC bias voltage applied to the E-O crystal. The “Amplitude Adj.” knob is used to adjust amplitude of sine modulation signal to the E-O crystal, which can be monitored via the “Waveform” terminal on an oscilloscope. The “Mode” selection switch can be used to select DC, Sine-wave or Audio signal to drive the E-O crystal. Audio modulation signal is added to the main unit from the “Audio In” jack and the “Light Signal” port is connected to a photo diode detector, as shown in Figure 3-4.

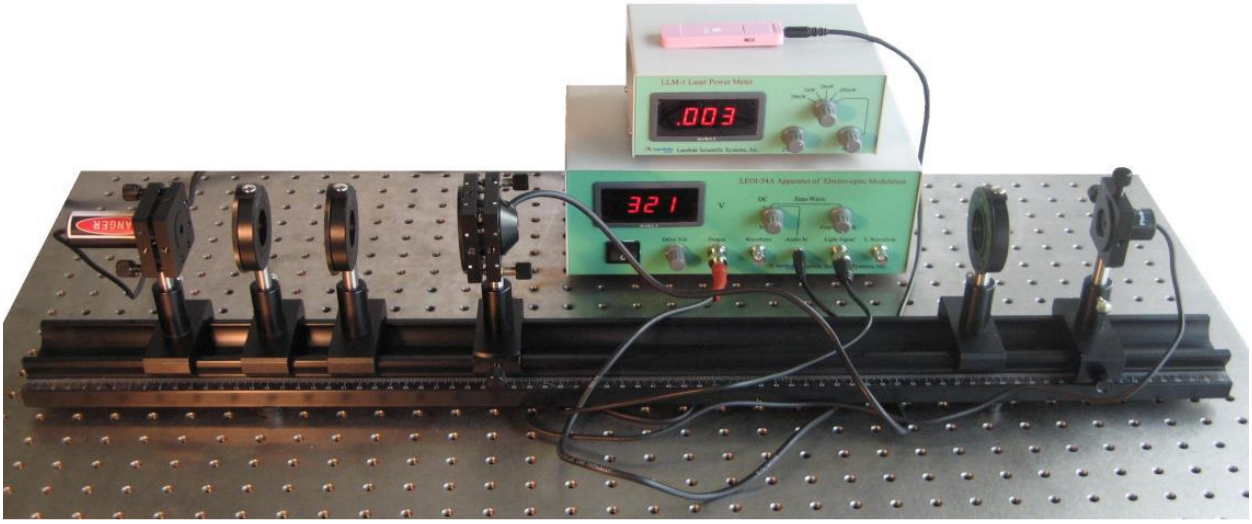


Figure 3-4 Experimental setup for optical communication of audio signal vie E-O effect

3.3.2 Parts and Specifications

Description	Specifications	Qty
Optical bench	Length: 1.2 m	1
Main unit	Drive voltage Vmax ≥ 1600 V with built-in speaker	1
Diode laser	4 mW at 650 nm with 2-D adjustable holder	1
Polarizer	Incl holder, 360° rotary, scale 1°, aperture 27 mm	2
$LiNbO_3$ crystal	Clear aperture: 5 mm × 5 mm with 3-D adjustable holder	1
Laser power meter	3-1/2 digits Scale: 200 μW, 2 mW, 20 mW, 200 mW Resolution: 0.1 μW	1
Photo diode detector	Incl 2-D adjustable holder, ±2.5 mm	1
Beam expander lens	Incl 2-D adjustable holder, 40 X	1
λ/4 wave plate	Incl holder, 360° rotary, scale 1°, aperture 27 mm	1
White screen	100 mm × 80 mm	1
Audio source	iPod nano	1
Cable	BNC cables (3) and audio cable (1)	4
1-D adjustable slide	Range: 10 mm	1
Slide		5

3.4 Experimental Examples

3.4.1 Study optical axis characteristics of LiNbO3 crystal

The uniaxial and biaxial crystal characteristics of a LiNbO3 crystal are studied in the absence and presence of a driving voltage, respectively, by observing the related interference pattern of a convergent polarized light beam passing through the E-O crystal.

Experimental procedures:

1) Place laser, polarizer, beam expander, LiNbO3 crystal, analyzer, and white screen on the rail in sequence. Let the beam expander close to LiNbO3 crystal.

2) Connect power supply of the semiconductor laser (on the rear panel of the laser power meter) and drive source of the E-O crystal (from "Output" of the main unit, **Warning: AVOID wrong wirings**). Turn the "Drive Vol." knob counter-clockwise to minimum.

3) Turn on power of the laser power meter, so laser is on. Adjust the direction of laser and the height of each component to make them in common axis and perpendicular to optical axis. Rotate the polarizer to achieve the maximum transmission of the laser power.

4) Rotate the E-O crystal to make one of its edges parallel to the polarization direction of the polarizer. Observe the pattern on white screen. Rotate the analyser and observe the change of the pattern. Pattern of bright cross lines or dark cross lines or ring lines can be observed. This is an

interference pattern of convergent polarized light passing through a uni-axial crystal, as shown in Figure 3-5.

5) Rotate the analyser to make its polarization parallel and perpendicular to the polarizer, respectively, and the observed interference patterns should be complementary as shown in Figure 3-6.

6) Turn on power of the main unit. Set "Mode" selection switch to DC. Turn the "Drive Vol." knob in clockwise direction to increase the driving voltage while observing the change of pattern on the white screen. It can be observed the pattern is split into two from center. This is a typical interference pattern of convergent polarized light passing through a biaxial crystal, as shown in Figure 3-7.

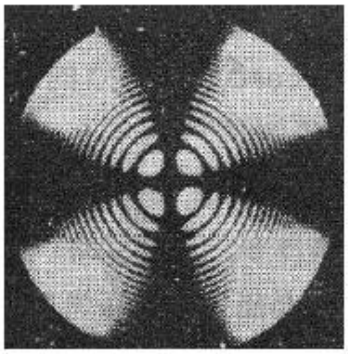


Figure 3-5

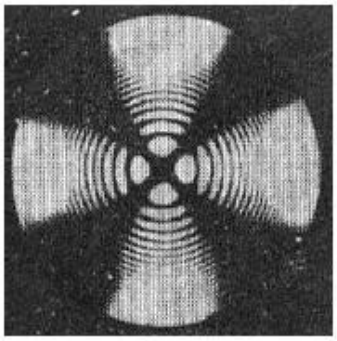


Figure 3-6

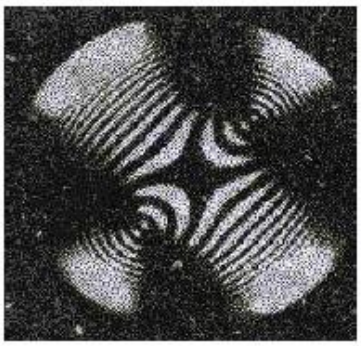


Figure 3-7

3.4.2 Measure electric-optic characteristics and parameters of LiNbO3 crystal

Experimental procedures:

1) Remove the beam expander and the E-O crystal from the previous experiment. Keep the laser, polarizer, analyzer and the white screen on the rail.

2) Turn on the laser power meter. Put the power probe in front of the white screen and align the components to a common optical axis set by the power probe.

3) Rotate the polarizer to make the transmitted laser power maximum. Rotate the analyzer to make the laser light power minimum. Now the polarizer and analyzer are perpendicular to each other.

4) Place the LiNbO3 crystal between the polarizer and analyzer, and adjust its height and direction to make the LiNbO3 crystal coaxial with the laser beam.

5) Adjust the drive voltage of the E-O crystal to minimum, set the Mode switch to DC. Observe the light spot's brightness on the meter. Carefully rotate the LiNbO3 crystal to minimize the power.

6) Adjust the Volt. Adj. knob clockwise to increase the driving voltage of the LiNbO3 crystal while recording the voltage and power reading values. Pay special attention to the

minimum/maxium power values $P_{min}P_{max}$ with their corresponding values V_{min}/V_{max}, and the difference is the half-wave voltage $V_{\lambda/2}$. This should normally be in the range 600-800 V.

7) From the recorded data, calculate the extinction ratio of the system as $M=P_{max}/P_{min}$ and half-wave voltage $V_{\lambda/2}$.

8) Remove the E-O crystal and rotate the polarizer to record the maximum output power P_0 and calculate transmissivity $T=P_{max}/P_0$ of the crystal.

3.4.3 Study influence of static working voltage on waveform

It is apparent from the behavior above that the relationship between driving voltage and output intensity is not linear, except around the half-wave voltage. The nonlinear response will cause waveform distortion for signal modulation. If the static working point of a sinusoidal driving signal is set at 0 V or $V_{\lambda/2}$, frequency doubling of the input signal will occur. To minimize waveform distortion and maximize sensitivity, a good static working voltage point should be used.

Experimental procedures:

1) Replace the power meter probe with photodiode in the previous experiment. Leave the semiconductor laser, polarizer, E-O crystal and analyzer unchanged.

2) Connect the “Waveform” driving signal and the “L-Waveform” of the received light signal to CH1 and CH2 of an oscilloscope, respectively. The BNC output of the photodiode is connected to terminal “Light Signal”.

3) Select the “Mode” switch to “Sine-Wave”. Set the oscilloscope to trigger from the waveform signal.

4) The frequency of the wave is approximately, 1 kHz. In the following parts, set the amplitude to the largest value while keeping the waveform sinusoidal.

5) Turn the voltage adjustment knob “Drive Vol.” to change the static working voltage point while monitoring “L-Waveform” on the oscilloscope. Pay special attention to these static working voltage points (1) minimum “L-Waveform” distortion, (2) maximum “L-Waveform” amplitude, and (3) “L-Waveform” frequency doubling. Compare the results with the previous experiment to understand the impact of a static working voltage point on the modulated light waveform.

6) Demonstrate optical communication of audio signal via electro-optic effect.

Connect the audio signal source to the “Audio In” jack. Switch “Mode” to audio. Observe the waveform on the oscilloscope. Turn on the speaker (switch on the rear panel) to listen to the demodulated audio signal. The volume of the music from the speaker can be adjusted by rotating the analyzer. Block the laser beam with your hand, the sound from the speaker should stop. Remove the hand form the laser beam, the sound should be heard again. This indicates that the audio signal is indeed modulated by the laser light via electro-optic effect.

4 Crystal Acousto-Optic Effect

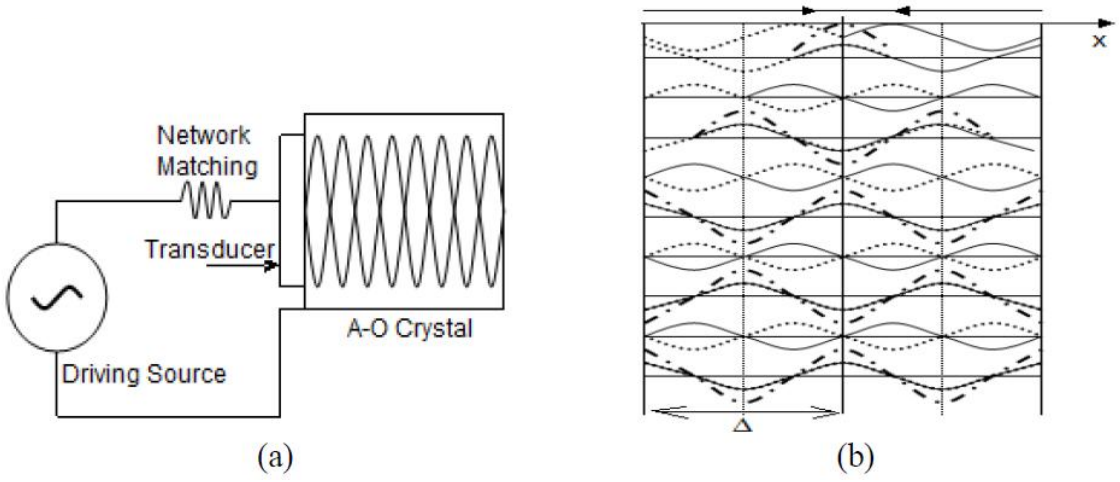
4.1 Introduction

Acousto-optic effect is based on the change in the refractive index of a medium due to the presence of sound waves in the medium. This creates a refractive index grating in the material that can be used to diffract light. It provides a powerful means to the control of the frequency, direction, and intensity of a laser beam. Employing acousto-optic effect, acousto-optic devices such as acousto-optic modulator, acousto-optic deflector, and tunable acousto-optic filter have been applied significantly to areas such as laser technology, optical signal processing, and integrated optical communication.

4.2 Principle of Standing-Wave Acousto-Optic Modulator

Sound wave is an elastic wave (or longitudinal stress wave) causing elastic deformation of the media when propagating in the media. As a result, it stimulates vibrations of all particles in the media along the direction of propagation resulting in dense or sparse changes of medium density. Therefore, the refractive index of the medium is changed periodically.

This acousto-optic effect apparatus uses a standing-wave acousto-optic modulator which is made of a quartz crystal (ZF6) to generate acousto-optic effect. It consists of two portions. One is an acousto-optic crystal consisting of a piezoelectric transducer and an acoustic-optic interaction medium (ZF6). To form a standing-wave in the medium, the two sides of the medium in the direction of sound propagation must be strictly in parallel, i.e. parallelism better than λ/5. Piezoelectric transducer and acousto-optic medium is welded together. The other is an electric drive which is a high frequency and large power sine-wave signal generator. The sine signal provided by the drive is added onto the piezoelectric transducer through network matching. The ultrasonic wave produced by the transducer propagates along +x direction in the medium, and is reflected back by the opposite side of the medium due to total reflection to propagate along -x direction. Therefore, there are two ultrasonic waves of same frequency and same amplitude but traveling in opposite direction in the medium.



(a) (b)

Figure 4-1 Standing wave A-O modulator (a) and standing waves in A-O medium (b)

Figure 4-1(a) shows the schematic diagram of a standing wave acousto-optic modulator while Figure 4-1(b) shows the formation process of ultrasonic standing waves in an acousto-optic medium. In a standing wave, nodal points $\triangle/2$ apart do not vibrate while points in the middle of two nodal points have the maximum vibration.

The vibrations along +x-direction and -x direction can be written as follows:

$$a_1 = A\sin(\Omega t - Kx)$$
$$a_2 = A\sin(\Omega t + Kx) \tag{4-1}$$

Using addition theorem, the synthesized expression of standing waves is:

$$a = 2A\sin\Omega t\cos Kx \tag{4-2}$$

It is apparent from equation (4-2) that displacement a=0 if cosKx=0 when Kx is an odd integer times of $\pi/2$, but maximum displacement occurs if cos$K$x=1 when Kx is an integer times of π. From expression (4-2), the vibration velocity of particles in standing wave can be achieved as:

$$u = 2\Omega A\cos Kx\cos\Omega t \tag{4-3}$$

Expression (4-3) demonstrates that the nodes of particle vibration velocity and the nodes of displacement are both located in the same positions. For a sound wave propagating along x direction, sound pressure p is proportional to variation in displacement along x direction (da/dx), as

$$p \propto \frac{da}{dx} = -2KA\sin\Omega t\sin Kx \tag{4-4}$$

It shows the positions of sound pressure nodes are shifted by $\triangle/4$ from displacement nodes. If oscillation frequency is f, the frequency of where the standing wave "appears/disappears" is 2f. Figure 4-2 shows the distribution of sound pressure and particle vibration velocity of standing waves.

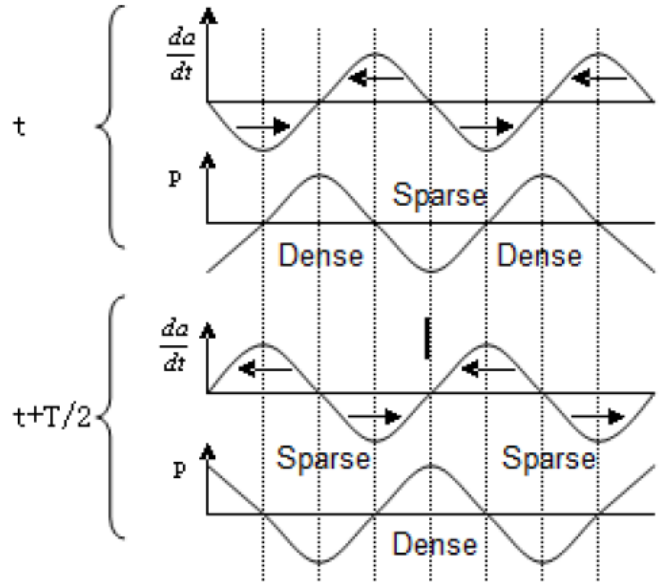


Figure 4-2 Distribution of sound pressure and particle vibration velocity in standing wave

In the presence of an ultrasonic standing wave, refractive index *n(x, t)* of an A-O medium can be written as:

$$n(x,t) = n_0 + \Delta n \sin \Omega t \cos Kx \tag{4-5}$$

where n_0 is the refractive index of the medium in the absence of ultrasound standing wave, $\triangle n$ is the refractive index change by applying ultrasound, Ω and K are the circular frequency and wave number of the ultrasonic wave, respectively.

When a laser beam is incident on medium, diffraction phenomenon will occur similar to that of grating diffraction. In case of perpendicular incidence, the angle of each diffraction maxima is:

$$\sin\theta = mK/k = m\lambda/\Lambda \tag{4-6}$$

where λ is the wavelength of the laser, Λ is the period of the sound grating, and m is the diffraction order. Standing wave acousto-optic modulators are widely used in the measurement of speed of light, mode-locked lasers, frequency shifting and other applications.

4.3 Apparatus Structure & Specifications

4.3.1 Structure

The main unit consists of driving voltage output for A-O modulator, voltage meter, frequency adjustment, and modulated/demodulated signal ports.

The 3-1/2 digital voltmeter is used to display the driving voltage to the acousto-optic modulator, which can be adjusted through the “VAdj.” knob. The range of the voltage adjustment is 0~12 V.

The "F-Adj." knob is used to adjust the frequency of the driving sound signal between 9-11 MHz to achieve best diffraction effect. The driving waveform and frequency can be displayed on an oscilloscope via the "Waveform" terminal. In addition, an audio signal can be sent to the main unit via the 3.5 mm "Audio In" jack, as shown in Figure 4-3.

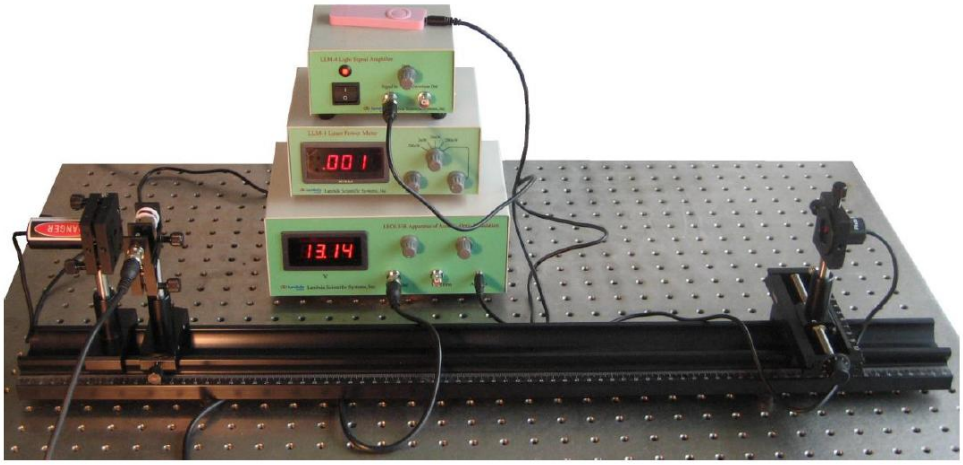


Figure 4-3 Experimental setup for optical communication of audio signal via A-O effect

4.3.2 Parts and Specifications

Description	Specifications	Qty
Optical bench	Length: 1.2 m	1
Diode laser	4 mW at 650 nm with 2-D adjustable holder	1
AO device	Central freq: 10 MHz with 2-D adjustable holder	1
Main unit	Frequency range: 9~11 MHz adjustable	1
Laser power meter	3-1/2 digits Scale: 200 μW, 2 mW, 20 mW, 200 mW Resolution: 0.1 μW	1
Power meter probe	Hole apertures: 0.5, 1, 2, 3, 4, 6 mm Slit widths: 0.2, 0.3, 0.4, 0.8, 1.2 mm	1
Large 1-D translation stage	Range: 90 mm; resolution: 0.01 mm	1
Pin-hole	Φ2.5 mm	1
White screen	100 mm × 80 mm	1
Lens	f =100 mm, Φ38 mm	1
1-D adjustable slide	Range: 10 mm	1
Slide		4
Photo-diode detector	Incl 2-D adjustable holder, ±2.5 mm	1
Light signal amplifier	Model LLM-4 with built-in speaker	1
Audio source	iPod nano	1
Cable	BNC cables (4) and audio cable (1)	5

4.4 Experimental Examples

4.4.1 Observe light diffraction phenomenon of ultrasonic standing wave field

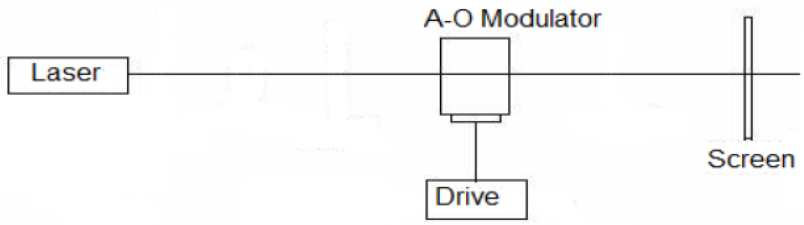


Figure 4-4 Experiment setup of observation of light diffraction

Experimental procedures:

1) Build the setup per Figure 4-4. Turn on laser.

2) Before turning anything on, bring the voltage knob to the minimum. Connect "Drive Out" to the A-O crystal. Turn on power of the main unit. Apply driving voltage to the A-O modulator and adjust the A-O frequency in combination while observing the diffraction spots on the screen. Change the azimuth of the A-O modulator, and observe diffraction spots under different incident angles (7 diffraction spots can be normally observed). **Note**: if necessary, adjust the input impedance of the A-O device by turning the middle screw located on the opposite side of the BNC connector with a flat screwdriver for optimization.

4.4.2 Observe image of ultrasonic standing wave field and measure sound velocity

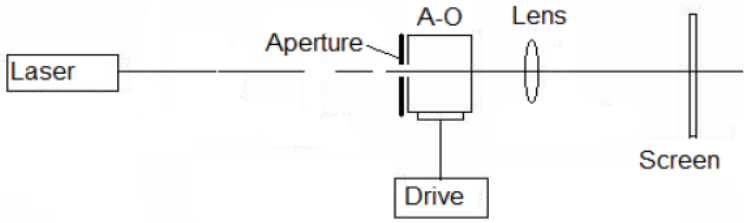


Figure 4-5 Experiment setup of observation of standing wave field image

Experimental procedures:

1) Set up the system per Figure 4-5.

2) Remove the lens and repeat Experiment 1 to achieve the most diffraction spots.

3) Restore the lens and place an aperture in front of the A-O modulator to constrain the size of the incident light beam.

4) Adjust the distance between lens and A-O modulator until a clear image aperture of the diffraction fringes is observed on the screen.

5) Count fringe number N on the screen (normally 13 fringes should be seen including the two on edges), and calculate sound velocity as: $V=2df/N$, where d is the diameter of aperture and f is the frequency of the ultrasonic wave. (d=2.5 mm, f can be checked by connecting the Waveform BNC to an oscilloscope).

4.4.3 Measure diffraction intensity of A-O modulator and calculate diffraction efficiency

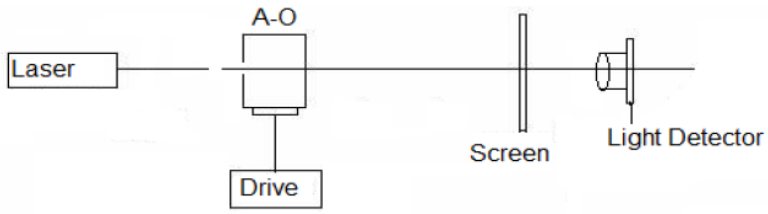


Figure 4-6 Experimental setup of measurement of diffraction intensity

Experimental procedures:

1) Set up the system per Figure 4-6.

2) Repeat Experiment 1 to achieve the most diffraction spots on the screen.

3) Remove the screen and use the optical power meter to measure the intensity of the incident laser, I_0.

4) Mount the power probe on the large translation stage and use an aperture or slit in front of the active area of the detector to let 0, $\pm$1, $\pm$2, $\pm$3…orders enter the detector, respectively, and measure the intensity of each order, I_m.

5) Diffraction efficiency is calculated as $\eta_m=I_m/I_0$.

6) Change the driving voltage and measure the corresponding diffraction efficiency. Plot the relationship curve between driving voltage and diffraction efficiency.