ECE 185

ELECTRO-OPTIC MODULATION OF LIGHT

I. Objective: To study the Pockels electro-optic (E-O) effect, and the property of light propagation in anisotropic medium, especially polarization-rotation effects.

II. References:

1. A. Yariv, Optical Electronics (3Ed.), Ch.l and 9.
2. G. Fowles, Introduction to Modern Optics (2Ed.), Ch.2 and 6.
3. M. Born & E. Wolf, Principles of Optics (6Ed.), pp.47-51.

III. Background:

1. E-O Effect

When certain kinds of birefringent crystals (e.g., uniaxial crystals) are placed in an electric field, their refractive indices are altered by the presence of the field. This effect is known as the Pockels electro-optic effect.

The light propagation characteristics in crystals can be fully described by means of the index ellipsoid,

$$\frac{x^2}{n_x^2} + \frac{y^2}{n_y^2} + \frac{z^2}{n_z^2} = 1 \qquad (1)$$

where the directions x, y and z are the principal dielectric axes. The effect of an electric field E on the propagation is expressed most conveniently by incorporating the changes in the coefficients of the index ellipsoid,

$$\Delta\left(\frac{1}{n^2}\right)_i = \sum_{j=1}^{3} \gamma_{ij} E_j, \qquad i = 1, \ldots, 6$$

$$j = 1, \ldots, 3 \qquad (2)$$

where γ_{ij} is called the electro-optic tensor.

The six terms in $\Delta\left(\frac{1}{n^2}\right)_i$ indicate that in the presence of an electric field the principal dielectric axes are no longer the same as x (i=1), y (i=2), and z (i=3) axes. The equation of the index ellipsoid (Eq. 1) must now be written in the more general form

$$\left(\frac{1}{n^2}\right)_1 x^2 + \left(\frac{1}{n^2}\right)_2 y^2 + \left(\frac{1}{n^2}\right)_3 z^2 + 2\left(\frac{1}{n^2}\right)_4 yz$$

$$+ 2\left(\frac{1}{n^2}\right)_5 xz + 2\left(\frac{1}{n^2}\right)_6 xy = 1 \quad (3)$$

where $\left(\frac{1}{n^2}\right)_{1,2,3} = \left(\frac{1}{n^2}\right)_{x,y,z} + \Delta\left(\frac{1}{n^2}\right)_{1,2,3}$ and $\left(\frac{1}{n^2}\right)_{4,5,6} = \Delta\left(\frac{1}{n^2}\right)_{4,5,6}$

Example: Consider the E-O effect in KD*P.

KD*P which is also known as KD2P04 is the crystal used in this experiment. The electro-optic tensor of KD*P is quite simple since the only non-vanishing element is γ_{63} . Therefore, only the z-component of E contributes the E-O effect. Using Eqs. (2) and (3), we obtain

$$\frac{x^2}{n_o^2} + \frac{y^2}{n_o^2} + \frac{z^2}{n_e^2} + 2\gamma_{63}E_z xy = 1 \quad (4)$$

where $n_1 = n_2 = n_o$, $n_3 = n_e$, since the crystal is uniaxial. (n_o - index of refraction for the ordinary ray, n_e - index of refraction for the extraordinary ray.)

In order to put Eq. (4) in a diagonal form, we need to transform the coordinate system (x, y, z) into a new coordinate system (x', y', z') by rotating the (x, y) axes at $+45^o$.

$$x = x' \cos45° - y' \sin45° \quad (5)$$
$$y = x' \sin 45° + y' \cos45°$$
$$z = z'$$

Upon substituting Eq. (5) in Eq. (4), we have

$$\left(\frac{1}{n_o^2} + \gamma_{63}E_z\right)x'^2 + \left(\frac{1}{n_o^2} - \gamma_{63}E_z\right)y'^2 + \frac{z'^2}{n_e^2} = 1 \qquad (z=z') \quad (6)$$

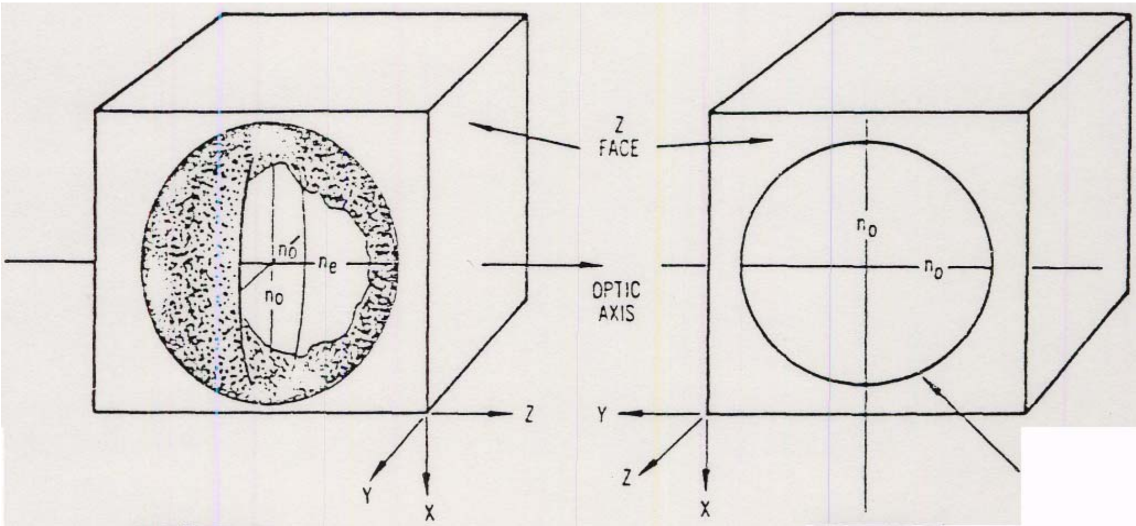
Since $\gamma_{63} E_z \ll n_o^{-2}$, the new indices of refraction along the x', y' and are, respectively,

$$n_{x'} \cong n_o - \frac{n_o^3}{2}\gamma_{63}E_z \quad (7a)$$

$$n_{y'} \cong n_o + \frac{n_o^3}{2}\gamma_{63}E_z \quad (7b)$$

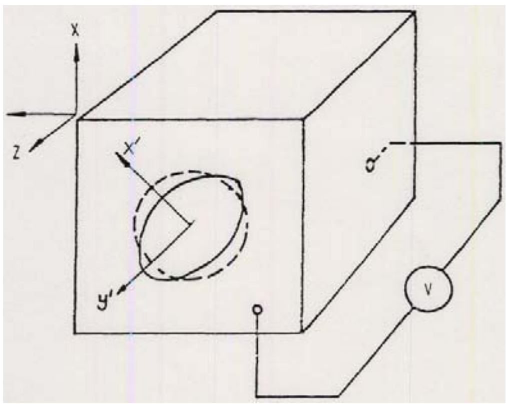
$$n_{z'} = n_e \quad (7c)$$

Fig.1 shows that in the absence of an electric field there is only one value of refractive index for any light polarization in the x-y plane propagating in the direction along the optic axis. When an electric field is applied parallel to the optic axis (Fig.2), the shape but not the orientation of the index ellipsoid is changed. As the shape of the ellipsoid changes, so does its projection on the x-y plane. From a circle at no voltage, the projection becomes an ellipse with x', y' axes, making a 45 degree angle with the x and y crystallographic axes.



Orientation of index ellipsoid Projection of index ellipsoid

Fig.1. Index of ellipsoid without applied electric field.



Induced axes x' and y'

Fig. 2. Index of ellipsoid with applied electric field. (The length of the ellipse axes in the x' and y' direction are proportional to the indices of refraction in these two directions.

2. E-O Retardation

When a laser beam is incident normally on the (x', y') plane of the above crystal with its polarization vector along the y direction, as shown in Fig.3, there will be a phase difference Γ at the output plane z = l between the two mutually orthogonal components polarized along x' and y'. The phase difference Γ is called the electrooptic retardation, and is equal to

$$\Gamma = \frac{\omega}{c} | n_{x'} - n_{y'} | l = \frac{\omega n_o^3 \gamma_{63} V}{c} \qquad (8)$$

where V = E_z l is the applied voltage along the z axis of the crystal, ω is the angular frequency of the Incident optical field, and c is the light velocity in free space.

In the absence of electric field, the retardation is Γ = 0 and the optical field is still linearly polarized along x at the output plane. The two components of electric vector along x' and y' are expressed as

$$e_{x'} = A\cos\omega t \qquad (9a)$$

$$e_{y'} = A\cos\omega t \qquad (9b)$$

When the electric field is applied such that Γ = π/2, then

$$e_{x'} = A\cos\omega t$$

$$e_{y'} = A\cos(\omega t - \pi/2) = A\sin(\omega t)$$

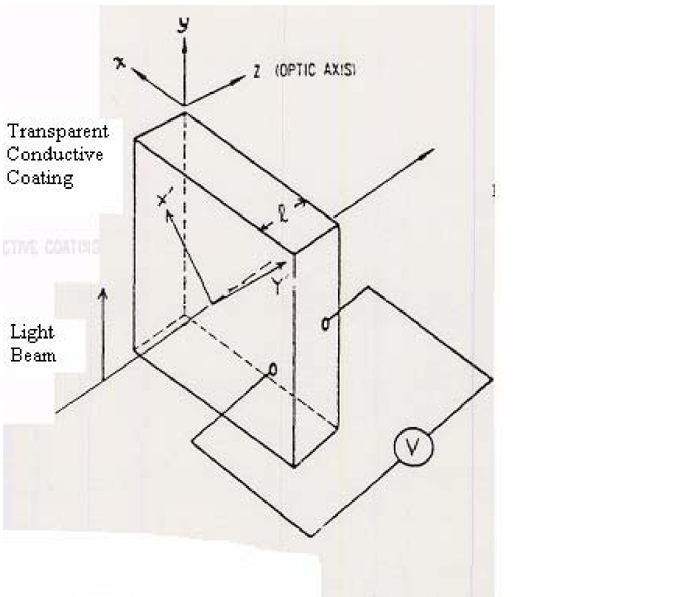


Fig.3 Pockels Longitudinal Modulator.

This electric vector is circularly polarized in the clockwise sense, and the crystal behaves like a quarter-wave plate. When the applied electric field is doubled, we have $\Gamma = \pi$.
Thus,

$$e_{x'} = A\cos\omega t \tag{10a}$$

$$e_{y'} = A\cos(\omega t - \pi) = -A\cos(\omega t) \tag{10b}$$

and the light is again linearly polarized along the x direction, i.e., at 90° with respect to its input direction of polarization. The applied voltage for such half-wave retardation is called the half-wave voltage, and is equal to, from Eq. (8),

$$V_\pi = \frac{\lambda}{2n_o^3\gamma_{63}} \tag{11}$$

where $\lambda = 2\pi c/\omega$ is the free space wavelength. The diagrams illustrating the rotation of optical electric vector as a function of various applied voltages are shown in Fig.4.

3. <u>E-O Modulator</u>

An examination of Fig.4 reveals that we may control the optical energy flow by sandwiching the crystal between two polarizers, whose polarizations are either parallel or perpendicular to each other. A typical configuration of a E-0 modulator which uses two crossed polarizers is shown in Fig.5.
In the cross-polarized E-0 modulator, the applied voltage and the intensity of the transmitted beam are related by

$$I_{out} = I_{in}\sin^2\left(\frac{\pi}{2}\frac{V}{V_\pi}\right) \tag{12}$$

where I_{out} and I_{in} are the output and input beam intensities, respectively. It appears that while retardation is a linear function of voltage, intensity has a sine-squared relation to that voltage.

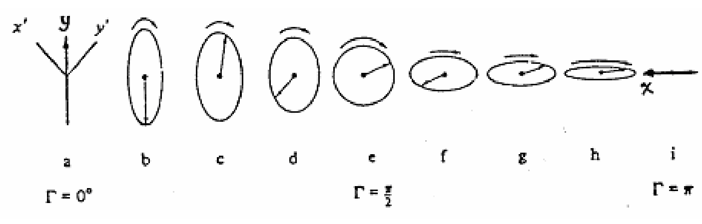


Fig.4. Rotation diagrams of optical electric vector under various applied voltage.

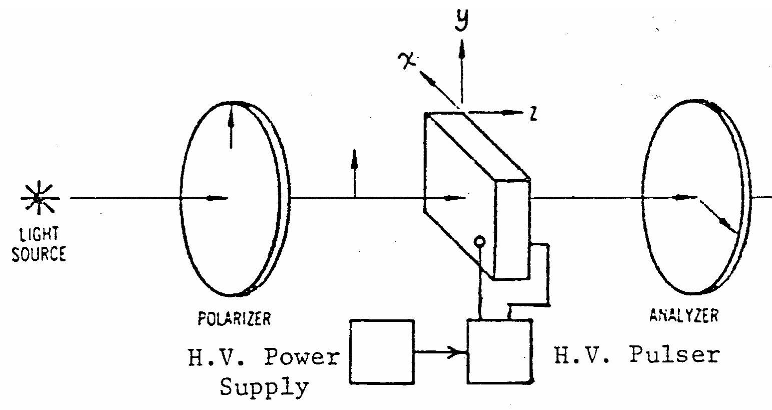
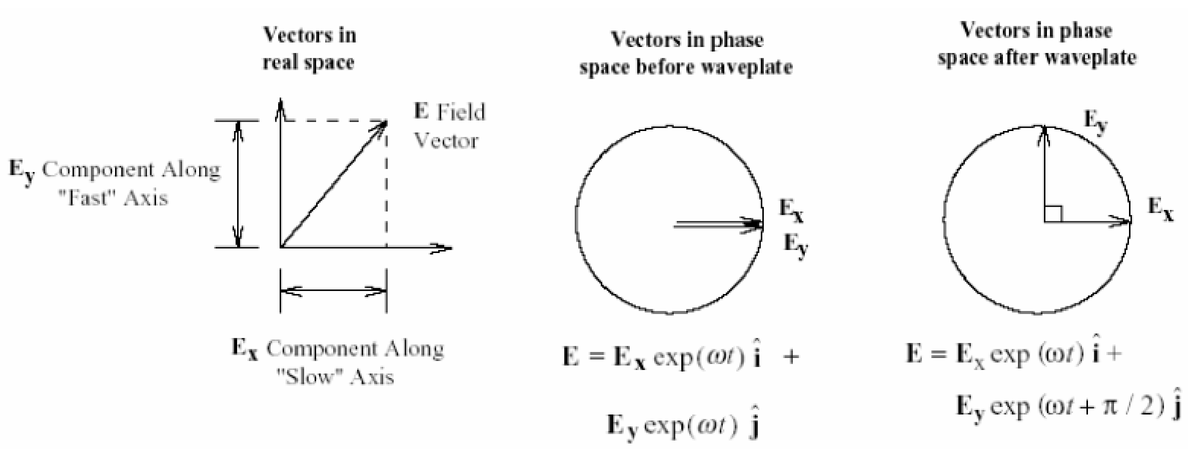


Fig. 5 Intensity modulation -- EOM between crossed polarizers.

IV. Experiments:

PART 1. QUATER WAVE PLATE

Quarter wave plates work by delaying the phase of the polarization component along the slow axis E_x by $\pi/2$ relative to the component along the fast axis E_y. The resultant vector addition of the two components yields circularly polarized light. In order for the wave plates to work correctly, the axes of the wave plate must be positioned at exactly $\pi/4$ radians relative to the direction of polarization. A diagram of how the wave plate works is shown below.

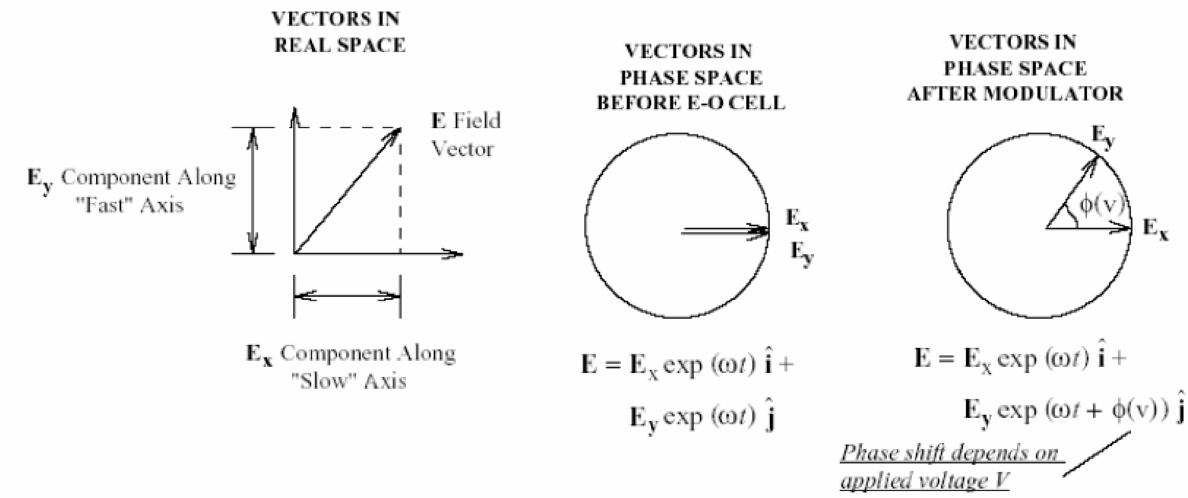


- Verify that $\lambda/4$ wave plate changes linear polarization to circular polarization.
- Use a second $\lambda/4$ wave plate to change polarization from circular to linear.
- Verify that $\lambda/4$ wave plate can be used as an isolator. Explain how to do it.
  Hint: Isolator is used to block out reflected light.

PART 2. ELECTRO-OPTIC MODULATOR.

2.1. Electro-optic modulator as a voltage controlled wave plate.

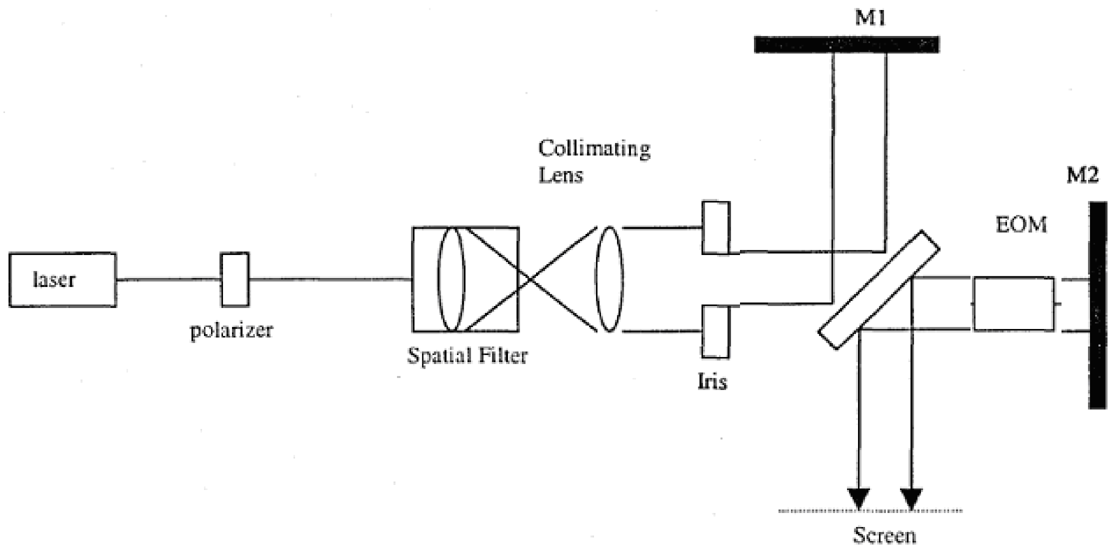
$\lambda/4$ and $\lambda/2$ wave plates produce a fixed phase delay between the two components of the electric field vector. An electro-optic modulator can be thought of as a *voltage controlled* wave plate or a dynamic wave retarder. By applying a voltage across an electro-optic crystal the indices of refraction along the fast and the slow axis change. This is the electro-optic effect. The refractive index changes are not the same along each axis. The resultant vector sum of field components has a term phase term $\varphi(v)$ (see the figure on next page) that is a function of the applied voltage. Thus the phase shift between E_x and E_y can be set through changing the voltage. If an output polarizer is set crossed to the initial laser polarization, a voltage V_π can be applied to create a π phase shift. The output is then blocked by the polarizer. The whole system acts as an intensity modulator.



- Set up the cross-polarized EOM.
- Connect the EO cell to the dc power supply. Collect the output light with a power meter.
- Increase the voltage in steps of $\sim 100V$ and record the output light intensity. Take enough data to go from minimum to just beyond a maximum. This should occur before $3700V$.
- Plot I_{out} / I_{in} vs. V and fit the data to $\cos^2(\pi V/2V_\pi)$. From the graph, deduce quarter-wave $(V_{\pi/2})$ and half-wave (V_π) voltages.
- Calculate the Contrast Ratio (the ratio of maximum to minimum output intensity).

2.2. Use of EOM to convert linearly polarized light to right- or left-handed circular polarized.

- Set up interferometer as shown on the figure below;
- Observe interference of two beams on the screen;
- Connect EO cell to dc power supply;
- Increase voltage to and find $V_{\pi/2}$ by observe the interference pattern;
- Explain your results.



PART 3. MODULATION OF LASER BEAM.

3.1. Laser Pulse Generation with Electro-Optic Modulator.

Giant pulses of optical radiation can be generated by Q-switching an optically pumped laser with an Electro-Optic Modulator. The technique involves controlling the laser beam polarization within the optical cavity, thus introducing optical losses. This prevents premature emission and allows energy to be stored in the laser material through population inversion of the metastable states. When the inversion is maximized, the EOM is deenergized and the available stored energy is discharged in a single high power pulse.

Warning: Insure that High Voltage is *OFF* before connecting cables. Connect all cables *before* applying power.

- Set the Function Generator (FG) at:
    - -Triggering: Internal
    - Frequency: 1Mhz
    - Output amplitude: 1.5V
    - Pulse Repetition: 100ms
- Connect FG output with Pulse In of GS-8 High Voltage Pulser
- Apply voltage from dc power supply to the EO Cell through the GS-8 Pulser.
- Set voltage equal to $V_{\pi/2}$
- Insert $\lambda/4$ wave plate before EO cell;
- Observe laser light pulses on the oscilloscope connected with Analog Out of power meter.
- Measure the pulse repetition rate.

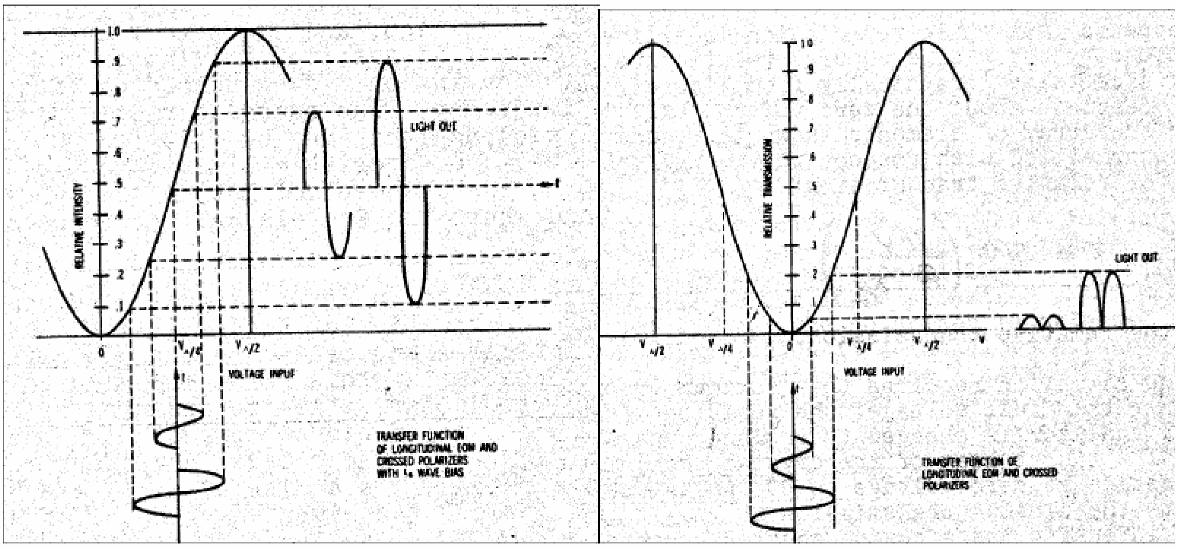
3.2. Intensity Modulation of Laser Beam.

3.2.1. Linear modulation of laser beam can be obtained by applying the combination of dc voltage that biases the optical transmission to the 50% point ($V_{\pi/2}$ voltage) and ac signal voltage (see figure below). Operation at this point may also be obtained by introducing $\lambda/4$ wave polarization retardation at the input to the crystal.

- Set FG output signal to 1kHz sine wave and adjust the amplitude to 3V;
- Use a transformer (1 to 100) to amplify the output signal from FG;
- Apply amplified ac signal (amplitude is about 300V) to the EO cell;
- Observe modulation of laser beam and measure the frequency.

3.2.2. If the modulator is biased at the peak or minimum transmittance, the output light will be frequency doubled.

- Remove λ/4 wave plate before EO cell;
- Observe modulation of laser beam and measure the frequency.
- Describe the observed signal and explain it.



3.2.3. Modulation of laser beam by audio signal.

- Use transformer to amplify audio player output signal;
- Apply amplified audio signal to the EO cell;
- Observe modulation of laser beam on the oscilloscope.
- Connect headphones to the power meter output to hear the signal carried by the laser beam.