Laboratory work: Electro-optics

March, 2015

1 Introduction

Nowadays, most of the information is found under electrical form as in computers, mobile phone... The use of the light to transport information is the most effective transport medium, therefore it is necessary to conceive systems able to transform an electric information into a light information.
One of the solutions is to directly modulate the light source according to the electric information (LED, laser diode, ...) Another solution is to modulate, from the exterior, the intensity or the polarization of the light wave: this can be achieved by a Pockels cell using the electro-optic (EO) effect.
Once the information is written on the carrier wave, it is necessary to transport the wave, for example by injecting the wave in an optical fibre. For example, to optimize the existing connections, a higher amount of information is sought to be injected into the fibre. For this, the technique of multiplexing is used. Different signals at different wavelengths are written on the same carrier wave to be transmitted together.
After propagation, the signals have to be demultiplexed to be analysed. With the characteristics of the carrier wave in mind, the use of a grating will lead to the separation of the beams of different wavelengths. Finally, the detectors, which are photodiodes in the case of this experiment, will help to demodulate the signals by transforming the modulation intensity into an electrical modulation.

The final aim of this lab work is to understand the working principle of the different parts of an optical telecommunication, from the writing of the signal onto the carrier wave to the reception.
A lab report is expected at the end of the manipulations with an introduction resuming the aims of the manipulations, the results, the conclusions and remarks.

2 Laser: safety information

Since its invention in 1960, the laser has constantly been developed and new applications are found. Therefore, the number of accidents due to lasers also increased. In most of the accidents, eye damage are reported. The dangerousness of the laser are divided in different classes.
→ Class 1: lasers are not dangerous for the eye in any observation conditions
→ Class 2: lasers are safe under normal conditions. They emits in the visible, the blink reflex of the eye will prevent damage
→ Class 3R: lasers are usually up to 5 mW and involve a small risk of eye damage within the time of the blink reflex. Staring into such a beam for several seconds is likely to cause damage to a spot on the retina
→ Class 3B can cause immediate eye damage upon exposure
→ Class 4 lasers can burn skin, and even scattered light can cause eye and/or skin damage. Many industrial and scientific lasers are in this class
The users have to be careful: a class 1 laser can be dangerous if wrongly used. Thus, be careful and if required:

- Wear the protection goggles
- Make sure that the door is closed and the laser warning light is switched on
- The person switching on the pump diode, make sure everybody in the room has the protection goggles on
- Knock at the door and wait for response before entering the room with the setup
- People in the laser room, respond with clear indications, if somebody is knocking.
- Everybody entering the room remove any jewellery, watches etc.
- Take care to block the light every time you want to use a tool on the setup. This is the most common laser accident: reflecting the laser with a tool in the eyes of a colleague!

For more information refer to a laser safety training/course.

3 Pockels effect and electro-optic modulation

3.1 Theory

The electro-optic effect (EO), also called the Pockels effect, is defined as the dependence of the refractive index (or the birefringence) of the medium to

the application of an external electric field to this medium.
The EO effect is said to be linear, if the variation of the index or the birefringence is proportional to the electrical field.
Only noncentric symmetric crystals can present the EO effect. It is the case of the $LiNbO_3$ crystal, studied here. In other materials, such as glasses or liquids, the variation of the refractive index keeps its sign when the field is reversed, it is therefore proportional to the square of electric field. This is effect is called the Kerr effect.
The EO effect is used to modify the phase, the polarisation or the amplitude of the wave travelling through an electro-optic medium. It gives a way to modify the state of polarisation of a beam through an electric field. Moreover, it enables the transcription of an electric information onto an light beam: that is the aim of an electro-optic modulator.
The equation of the ellipsoid of indices of the $LiNbO_3$ crystal in presence of an electric field can be written as:

$$(\frac{1}{n_0^2} - r_{22}E_2 + r_{13}E_3)X^2 + (\frac{1}{n_0^2} + r_{22}E_2 + r_{13}E_3)Y^2 + (\frac{1}{n_e^2} + r_{13}E_3)Z^2 + 2r_{51}E_2YZ + 2r_{51}E_1XZ - 2r_{22}E_1XY = 1$$

The X, Y and Z axes are orthogonal and are defined with respect to the crystallographic axes a, b and c of the crystal.
In the modulator used, the light travels along the optical axis (Z), and the electric field E_2 is applied along Y. Z, E_1 and E_3 disappear as they have no influence on the polarisation direction of the wave.
The equation then becomes:

$$(\frac{1}{n_0^2} - r_{22}E_2)X^2 + (\frac{1}{n_0^2} + r_{22}E_2)Y^2 = 1$$

And the birefringence induced by the field is:

$$\Delta n_{12} = -n_0^3 r_{22} E_2$$

Where $n_0 = 2.285$ and $r_{22} = 6.4 10^{-12}$ International System Units are the ordinary refractive index and the electro-optic coefficient to consider.
The phase shift Γ induced by the field E_2 is:

$$\Gamma_{12}(E_2) = -\frac{2\pi}{\lambda} L_3 n_0^3 r_{22} E_2$$

Where $L_3 = 40mm$ corresponds to the length of the crystal.

E_2 can be expressed as a function of the applied voltage V_2 and the distance between the electrodes ($d_2 = 2mm$):

$$E_2 = \frac{V_2}{d_2}$$

When a voltage V_2 is applied to the crystal, the refractive index n_Y is changed by the EO effect. This induces a change in the propagation speed of E_Y according to E_X and the creation of a phase shift between E_X and E_Y.
If this phase shift is equal to π, an incoming linear polarisation will be rotated by $90\,^\circ$ at the outcome of the modulator. The voltage necessary to obtain this result is called the half wave tension V_π.

Questions

- What is the unit of the electro-optic coefficient r ?
- What is the expression for the half wave voltage V_π ?
- Calculate V_π
- What is the refractive index variation of the crystal when V_π is applied?

3.2 Setup

The He-Ne laser (L) does not emit linear polarised light. Therefore, a polariser has to be placed right after the laser.
The detector (D) is put at the very end of the optical table.
The polariser (A) used as an analyser placed right before the detector D. It should be positioned on 45 °.
Put the a half wave plate (L/2) right after the laser and its polariser, and turn it until minimal intensity is achieved. The outcoming polarisation should be oriented at 45 °.
Put a quarter wave plate (L/4) before A and turn it to obtain a minimal intensity. One of the neutral lines of the plate is then aligned on the direction of A.
Put the modulator (M) behind L/2. The cell should be carefully oriented such that the beam travels through the whole crystal. Connect M to its power supply.
The polarisation entering the modulator will be oriented at 45 ° with respect to the neutral lines of the crystal.

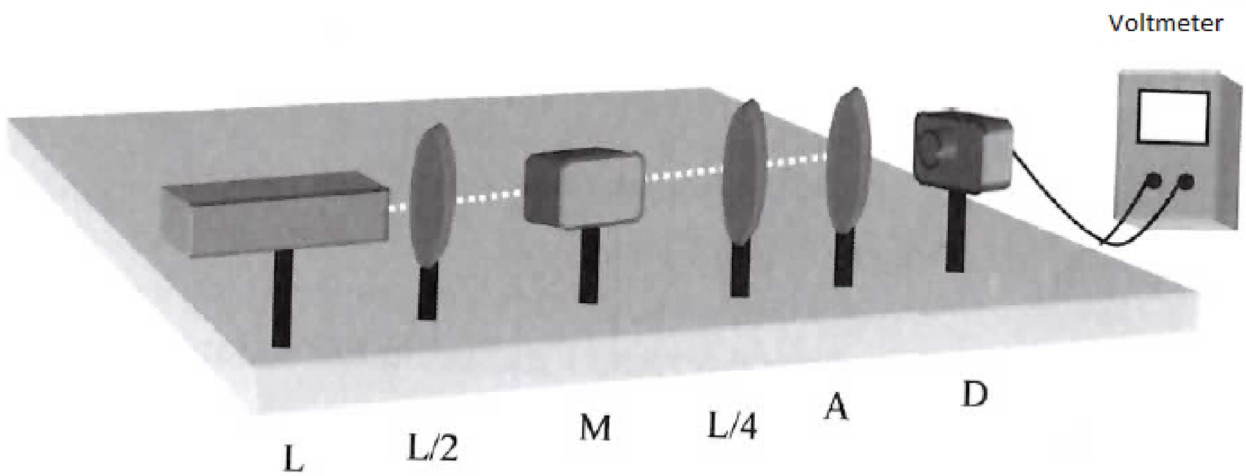


Figure 1: Setup to be built

The $LiNbO_3$ crystal has any wavelength and a variable birefringence, the out coming polarisation is generally elliptical, but as the incident polarisation is set at 45 °, its fields $E_X(t)$ and $E_y(t)$ have the same amplitude before and after the modulator (the attenuation is supposed to be negligible).
It can then be shown that in this situation a quarter-wave plate, where its neutral axes are oriented at 45 ° with respect to the crystal ones, restores a

linear polarisation at the output of the setup.

3.3 Transfer function

The phase shift $\Gamma_{12}(V)$ induced by the crystal modulator is proportional to the applied voltage V_2. If attenuation is neglected, it can be shown, that the transfer function of the setup has the expression:

$$T = \frac{I}{I_0} = \frac{1}{2}\left[1 - C.\sin\left(\Gamma_{12}(V_2) - 2\beta\right)\right]$$

Where β is the angle of the analyser with respect to a fixed axis, I_0 and I are the beam intensities before the modulator and at the end of the setup. The factor C, smaller or equal 1, is the modulation contrast (for a perfect crystal, C equals 1).
The transfer function of the setup can be determined experimentally by measuring the intensities induced by the rotation of the analyser (β) or by the application of a voltage at edges of the crystal (Γ_{12}).

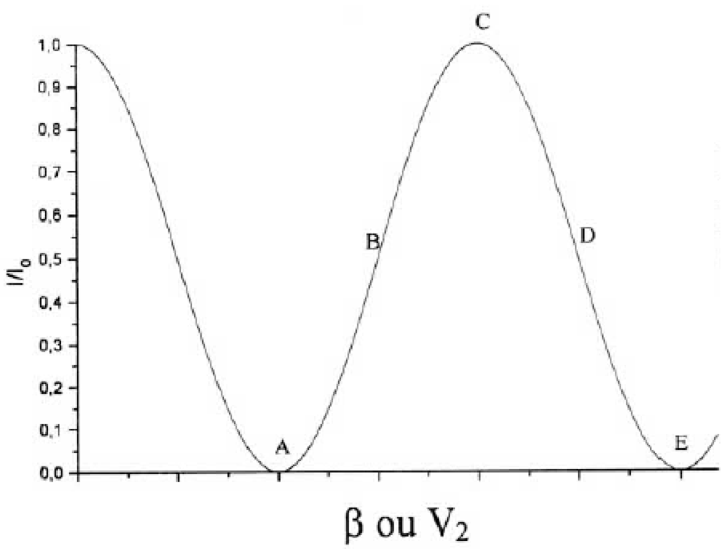


Figure 2: Transfer function of the setup and its characteristic working points A, . . . , E

Questions

- Measure the voltage at the photodiode (proportional to the transmitted intensity) as a function of the angle β (from $-90\,^\circ$ to $90\,^\circ$ by steps of $5\,^\circ$).
- Draw $V = f(\beta)$, which represents the transfer function of the setup.
- Note, as precisely as possible, the angles corresponding to the different working points A to E.
- What are your conclusions?

There is another way to obtain the same transfer function, which is to keep the direction of the analyser fixed and to rotate the polarisation at the exit of the modulator. This can be done by the EO effect, by applying a continuous voltage at the modulator.

Questions

- Measure the voltage at the photodiode as a function of the continuous voltage V_2 applied to the modulator (from 0 to 400 V).
- Draw $V = f(V_2)$ and deduce the experimental value of V_π.
- Conclusions.

The continuous voltage is set to 0. Use the intern function generator and set the frequency to 1 kHz. The gain allows you to modify the amplitude of the alternative signal applied to the modulator.
Replace the voltmeter by an oscilloscope. Connect the AC/100 exit of the supply on one of the channels of the oscilloscope and the detector on another channel.
The application of an alternative voltage V_{AC} to the modulator will allow to modulate the birefringence at a certain frequency. This will have a modulation of the polarisation at the exit of the modulator, converted in an intensity modulation, as a consequence.
The electric signal applied to the crystal will be written onto the carrier wave as an intensity modulation.
The photodetector is used to demodulate and transform the intensity modulation in a voltage modulation, which can be observed on an oscilloscope (or heard on loudspeaker).
With the help of the function $V = f(\beta)$ drawn, set the working points A, B, C, D and E.

Questions

- Measure the frequency and the phase of the signal at every point.
- Replace the oscilloscope by the loudspeaker: what can you hear?
- Conclusions.

3.4 Application of the transmission to a radio signal

Connect a radio output at the entrance of the amplifier and place the switch on the 'external' position. The amplification gain is controlled by the potentiometer 'gain'. Connect the output of the photodiode to the loudspeaker.

Questions

- What do you obtain?
- Analyse the phenomenon and give an application of this kind of setup.

3.5 Change of the polarisation state

3.5.1 Orientation of a linear polarisation

The setup to consider is one realised in the first part of this work. The detector is connected to the voltmeter. Apply the voltage V_π to the modulator.

Questions

- Measure the voltage V at the detector output as a function of the angle β of the polariser.
- Draw $V = f(\beta)$ on a diagram with polar coordinates.
- Compare this result to the one obtained without applied field.
- Conclusions.

3.5.2 Transformation of the polarisation state

Apply a voltage equal to $V_{\pi/2}$ to the modulator (half of V_π).

Questions

- Measure the voltage V at the detector output as a function of the angle β of the polariser.
- Draw $V = f(\beta)$ on a diagram with polar coordinates.
- Conclusions.
- What would happen if the continuous voltage applied to the modulator would be different than $V_{\pi/2}$ and V_π?

4 Measurement of the electro-optic coefficient

4.1 Theory

The natural birefringence is the difference between the refractive indices and is written as:

$$\Delta n_{jk} = n_k - n_j$$

Where n_k and n_j are the refractive indices in the k and j directions.

When an electric field is applied to the crystal, the electrons, molecules or ions, are reoriented by modification of the polarisation of the medium. This macroscopic rearrangement modifies the refractive index of the medium.
This phenomenon is called the EO effect and the induced birefringence is given by:
Where r_α is the EO coefficient.

$$\Delta n'_{jk} = -\frac{1}{2} n_k^3 r_\alpha E_p$$

The phase shift Γ between the component of the polarisation of a beam induced by the natural birefringence and the birefringence of the EO effect by travelling through a crystal can be expressed as:

$$\Gamma_{jk} = \frac{2\pi}{\lambda} L_i(\Delta n_{jk} + \Delta n'_{jk})$$

where L_i is the length of the crystal in the propagation direction of the beam.

In general, the voltage applied to the crystal is assumed to be composed of a continuous voltage V_{dc} and an alternative component V_{ac}:

$$V_p = E_p D_p = V_{dc} + V_m \sin(\omega_m t)$$

Applying this voltage causes a phase shift in the crystal between the principal components of the polarisation of the beam. The phase shift Γ equals:

$$\Gamma = \Gamma(0) + \Gamma_{dc} + \Gamma_m \sin(\omega_m t)$$

where $\Gamma(0) + \Gamma_{dc}$ represents the static phase shift travelling through the crystal.

Questions

- Show that the phase shift caused by the application of a static electric field E_{dc} can be written as $\Gamma_{dc} = -\frac{r_\alpha}{A} V_{dc}$ where A is a coefficient which you will express as a function of the wavelength, the refractive index of the material n_α, the thickness of the sample in the direction of the applied field D_p, the length of the crystal in the direction of propagation L_i and of π.
- Knowing that π is expressed in radians, what is the unit of A?

The linear electro-optic tensor of a non centre symmetric medium is represented by a $6 * 3$ matrix (18 $r_{ij,k}$) coefficients) relating the six dielectric relative impermittivities $\eta_{ij} = \frac{\varepsilon_0}{\varepsilon_{ij}}$ to the three components E_k of the applied field.
The Pockels coefficients $r_{ij,k}$ are expressed in $m.V^{-1}$. The $LiNbO_3$ crystal studied here is an uni-axial crystal belonging to the 3m crystalline class. Therefore, the tensor becomes:

$$r_{ij,k} = \frac{\partial \eta_{ij}}{\partial E_k} = \begin{bmatrix} 0 & -r_{22} & r_{13} \\ 0 & r_{22} & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{51} & 0 \\ r_{51} & 0 & 0 \\ -r_{22} & 0 & 0 \end{bmatrix}$$

The equation of the $LiNbO_3$ indices in presence of an electric field can be written as :

$$\left(\frac{1}{n_0^2} - r_{22} E_Y + r_{13} E_Z\right) X^2 + \left(\frac{1}{n_0^2} + r_{22} E_Y + r_{13} E_Z\right) Y^2 + \left(\frac{1}{n_e^2} + r_{33} E_Z\right) Z^2$$
$$+ 2 r_{51} E_Y YZ + 2 r_{51} E_X XZ - 2 r_{22} E_X XY = 1$$

where n_0 is the ordinary index, n_e is the extraordinary index in absence of an applied electric field.
The $LiNbO_3$ modulator crystal contained in the cell is a rectangular parallelepiped cut along three axes X, Y, Z. The electric field is applied along the Y axis, and the beam travels parallel to the Z axis.

Questions

- Show that the birefringence induced by the field can be written as :

$$\Delta n(E_Y) = -n_0^3 r_{22} E_Y$$

  Hints:

  * Write the ellipsoid equation under the form $\frac{X^2}{n^2{}_1} + \frac{Y^2}{n^2{}_2} = 1$ and express $\frac{1}{n^2{}_1}$ and $\frac{1}{n^2{}_2}$ in function of n_0, r_{22} and E_2.
  * use the relations $d(\frac{1}{n^2}) = -2\frac{dn}{n^3} = \pm rE$ and the approximation $n_1 = n_2 = n_0$ to express dn_1 and dn_2 in function of n_0, r_{22} and E_2.
  * then use $\Delta n = dn_2 - dn_2$ to obtain the searched equation.

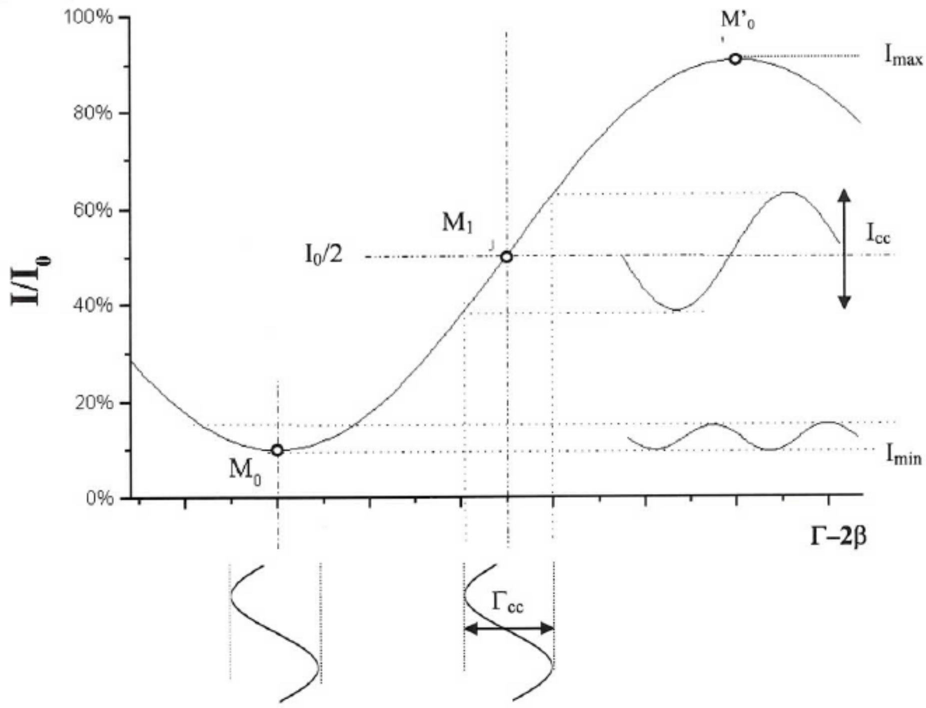
- Show that the expression induced by the phase shift is:

$$\Gamma(V_Y) = -\frac{2\pi}{\lambda} n_0^3 r_{22} \frac{L_Z}{D_Y} V_Y$$

- What is the induced birefringence when a voltage of 100 V is applied?
- What is the induced phase shift?

4.1.1 Measurement of the r_{22} coefficient

The setup does not have to be changed and the detector is connected to the channel 2 of the oscilloscope.
The transfer function of this setup has already been drawn and its working points have been studied.
The transfer function is used to determine experimentally the variations of the induced phase shift $\Gamma(V)$ by measuring the transmitted intensity or by measuring the analyser angle to keep the intensity constant.



V_π **method**

Questions

- Determine V_π according to your measurements done while changing the polarisation

- Deduce r_{22}.

It is also possible to determine this half wave voltage in dynamic. The intern function generator ($f = 1kHz$) has to be used to modulate the signal. The continuous voltage V_{dc} is zero. Turn the analyser until you can observe the signal at the frequency doubling.
Modify the continuous voltage until you can see a second frequency doubling. The continuous voltage has then allowed to go from one extremum to another on the transfer function. You have found the half wave voltage.

Questions

- What is the half wave voltage obtained?
- Deduce r_{22}.