ELEC4620 - Survey research - Pockels effect in Lithium Niobate and its use for light modulation in optical communications

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Abstract

This survey research project aims at understanding how it is possible to control certain properties of light such as phase, polarization and amplitude through the use of an electro-optic signal. It is motivated by the importance of numerous multiplexing techniques relying on the control of such parameters in order to increase the maximum channel capacity in optical communications. We started by describing birefringence in a quantitative manner and how it influences light propagation in a birefringent medium. Then we studied the Pockels effect (also known as first order electro-optic effect, a non-linear effect), and how crystalline symmetry influences it. We chose to present Lithium Niobate ($LiNbO_3$), a specific crystalline material that exhibits this effect. Finally, we explored a few techniques and devices that enable to control light properties, in particular waveplates and phase/polarization/amplitude modulators. The techniques presented are simple application cases using Lithium Niobate. It does not make an exhaustive list.

Contents

1 Non-isotropic mediums

1.1 Dielectric tensor

In anisotropic medium, we need a second-order tensor in order to describe the relation between the electric field $\boldsymbol{E}$ and the electric displacement $\boldsymbol{D}$

$$\frac{1}{\epsilon_0}\begin{pmatrix} D_x \\ D_y \\ D_z \end{pmatrix} = \begin{pmatrix} \epsilon_{xx} & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{yx} & \epsilon_{yy} & \epsilon_{yz} \\ \epsilon_{zx} & \epsilon_{zy} & \epsilon_{zz} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}$$

Assuming there is no current in the medium ($\boldsymbol{j} = 0$) and using the conservation of energy, it is possible to demonstrate that the $\boldsymbol{\epsilon}$ tensor is symmetric [1]. Then we can diagonalize it and choose to use the principal axis as the axis of our Cartesian coordinate system. These specific axes are called the principal dielectric axes of the medium. The dielectric tensor we use is then a diagonal matrix with real and positive coefficients.

$$\boldsymbol{\epsilon} = \begin{pmatrix} \epsilon_x & 0 & 0 \\ 0 & \epsilon_y & 0 \\ 0 & 0 & \epsilon_z \end{pmatrix}$$

1.2 Birefringence and the index ellipsoid

Birefringence is defined as an optical property of a medium who has a refractive index that depends on the polarization and the direction of the light going through it. In fact, any anisotropic medium will exhibit birefringence. If the medium is a crystal, its geometry will define the form of its dielectric tensor.

No birefringence	Isotropic Cubic	$\epsilon_x = \epsilon_y = \epsilon_z$
Uniaxial birefringence	Hexagonal Tetragonal Trigonal	$\epsilon_x = \epsilon_y \neq \epsilon_z$
Biaxial birefringence	Orthorhombic Monoclinic Triclinic	$\epsilon_x \neq \epsilon_y \neq \epsilon_z \neq \epsilon_x$

Table 1: Birefringence and dielectric tensor form for different Bravais lattices

Later we will consider the lithium niobate crystal, which has a trigonal structure. Hence we will mainly focus on uniaxial birefringence and do our calculations with $\epsilon_x = \epsilon_y$. In such a case, the axis with a different refractive index is called the *optic axis* of the medium. It's refractive index is referred to as the *extraordinary* index n_e. The two other axis are named *ordinary axis* and their refractive index is called the *ordinary* index n_o. In order to study uniaxial birefringence, let's first express the energy density of an electric field $\boldsymbol{E}$ in the medium:

$$W_e = \frac{1}{2}\boldsymbol{E}\cdot\boldsymbol{D} = \frac{1}{2}\left(\frac{D_x^2}{\epsilon_{xx}} + \frac{D_y^2}{\epsilon_{yy}} + \frac{D_z^2}{\epsilon_{zz}} + 2\frac{D_xD_y}{\epsilon_{xy}} + 2\frac{D_yD_z}{\epsilon_{yz}} + 2\frac{D_zD_x}{\epsilon_{zx}}\right)$$

$$\frac{X^2}{\epsilon_{xx}} + \frac{Y^2}{\epsilon_{yy}} + \frac{Z^2}{\epsilon_{zz}} + 2\frac{XY}{\epsilon_{xy}} + 2\frac{YZ}{\epsilon_{yz}} + 2\frac{ZX}{\epsilon_{zx}} = 1$$

With $X = \frac{D_x}{\sqrt{2W_e}}$, $Y = ...$, etc. However, X, Y and Z are not distances (unitless). And when considering the principal dielectric axis:

$$\frac{X^2}{n_x^2} + \frac{Y^2}{n_y^2} + \frac{Z^2}{n_z^2} = 1$$

This equation describes an ellipsoidal energy surface called the index ellipsoid. It will interceipt the X, Y, Z axis at n_x, n_y, n_z respectively. It can be used to determine the refractive index that a light ray propagating in a certain direction and polarized in a certain way will "see". In our case (x and y are ordinary axis, z is extraordinary axis), since $\epsilon_x = \epsilon_y$, the ellipsoid has a cylindrical symmetry around the z-axis. We draw the propagation direction $\boldsymbol{k}$ from the origin of this new cartesian space, and we name θ the angle formed between the extraordinary axis z and $\boldsymbol{k}$. The plane perpendicular to $\boldsymbol{k}$ and passing by the origin will intersect the ellipsoid by forming an ellipse. We call this plane the polarization plane. One of the semi-axis of this ellipse will always be $a = n_o$, whereas the other axis (b) depends on θ.

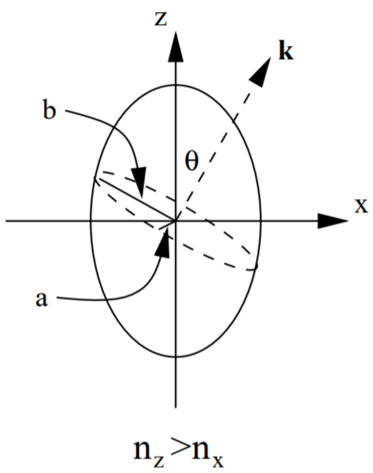

Figure 1: Index ellipsoid

$$X^2 + Y^2 = (n_e \cos(\theta))^2$$
$$Z^2 = (n_e \sin(\theta))^2$$

Inserting these two equations into the ellipsoid formula, we get:

$$n_e(\theta) = \left(\frac{\cos^2(\theta)}{n_o^2} + \frac{\sin^2(\theta)}{n_e^2} \right)^{-1/2}$$

It means that for that propagation direction $\boldsymbol{k}$, if the light is polarized in the $\{\boldsymbol{Z}, \boldsymbol{k}\}$ plane it will see $n_e(\theta)$. On the other hand, if it is polarized in the $\{\boldsymbol{Y}, \boldsymbol{X}\}$ plane it will always see n_o. Below are described some of the most simple cases:

- If light is propagating parallel to the extraordinary axis, it will only see the ordinary index n_o, whatever her polarization.
- If light is propagating perpendicular to the extraordinary axis and its polarization is along the extraordinary axis, it will see the extraordinary index n_e

- If light is propagating perpendicular to the extraordinary axis and its polarization is perpendicular to the extraordinary axis, it will see the ordinary index n_o

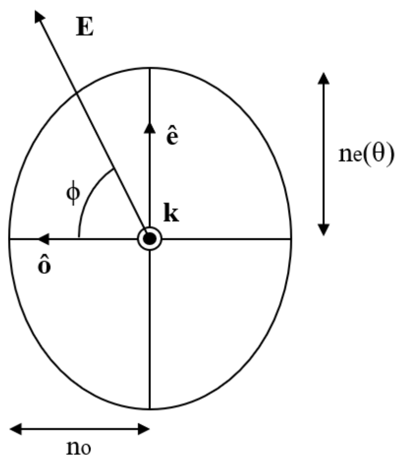

Figure 2: Polarization plane

For an arbitrary linear polarization, we can decompose the electric field in two parts ($\hat{e}$ and $\hat{o}$ are unit vectors): $\boldsymbol{E} = E\sin(\phi)\hat{\boldsymbol{e}} + E\cos(\phi)\hat{\boldsymbol{o}}$. The part in the $\{\boldsymbol{Z}, \boldsymbol{k}\}$ plane (along $\hat{\boldsymbol{e}}$) is referred to as the *extraordinary ray*, whereas the part in the $\{\boldsymbol{Y}, \boldsymbol{X}\}$ plane (along $\hat{\boldsymbol{o}}$) is referred to as the *ordinary ray*.

1.3 Double refraction

According to what we have seen previously, when a light ray composed of both an extraordinary and an ordinary ray enters a birefringent medium, the extraordinary ray will be refracted in a different way than the ordinary ray since the refractive indexes they experience are different. The only way for these to ray to follow the same path is to enter the medium with a normal incidence. If the refractive indexes inside the medium are constant in space and the surface of the medium is a plane, the extraordinary and ordinary ray will be parallel once they have exited the medium.

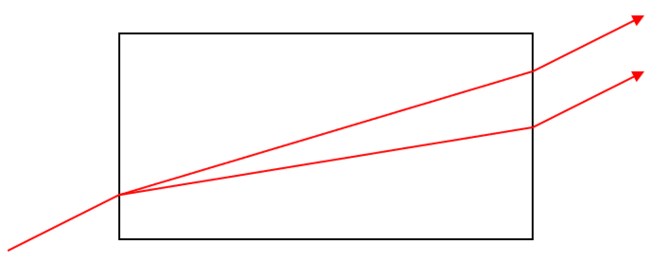

Figure 3: Double refraction

2 Pockels effect

The Pockels effect is an electro-optic effect that changes the refractive index of a medium when applying an electric field to it. It usually induces or change the birefringence. The Pockels effect is sometimes referred to as the first order or linear electro-optic effect (it is however part of non-linear optics). It is commonly used in electro-optical modulators to control the optical properties of a material using an electrical signal. Second order effect is known as the Kerr effect, but will not be considered here.

The relation between the variation in the dielectric constants and the applied electric field is described by the third rank linear electro-optic tensor $\boldsymbol{r}$ (27 elements). Since the dielectric tensor $\boldsymbol{\epsilon}$ is symmetric, we can simplify the linear electro-optic tensor as 6x3 matrix. To simplify the expression we replace the indexes: $xx = 1$, $yy = 2$, $zz = 3$, $yz = zy = 4$, $xz = zx = 5$, $xy = yx = 6$.

$$\Delta\left(\frac{1}{\epsilon_i}\right) = \left(\frac{1}{\epsilon_i}\right)_E - \left(\frac{1}{\epsilon_i}\right)_{E=0}$$

$$\begin{pmatrix} \Delta(1/\epsilon_1) \\ \Delta(1/\epsilon_2) \\ \Delta(1/\epsilon_3) \\ \Delta(1/\epsilon_4) \\ \Delta(1/\epsilon_5) \\ \Delta(1/\epsilon_6) \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \\ r_{41} & r_{42} & r_{43} \\ r_{51} & r_{52} & r_{53} \\ r_{61} & r_{62} & r_{63} \end{pmatrix} \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix}$$

The form of this sensor enables us to see wether a material will exhibit Pockels effect or not. In general, $\Delta(1/\epsilon_i) = \sum_k r_{ik} E_k$. For a material with an inversion symmetry, when applying the inversion operator to the equation:

- the parameters $\Delta(1/\epsilon_i)$ remain unchanged
- the parameters r_{ik} remain unchanged because the $\boldsymbol{r}$ matrix is centrosymmetric
- $\boldsymbol{E}$ becomes $-\boldsymbol{E}$

Then $\sum_k r_{ik} E_k = -\sum_k r_{ik} E_k$, which is only possible if $r_{ik} = 0$ for all i and k. Hence materials with inversion symmetry do not exhibit Pockels effect.

3 Lithium Niobate

All informations in this section are coming from [3].

3.1 General crystal characteristics

Lithium Niobate ($LiNbO_3$) is an artificial dielectric crystal that was first synthesized by Bell Labs in the 1960s. It is a ferroelectric crystal (with a Curie temperature of 1210°C) which exhibits birefringence, piezoelectric, pyroelectric, electro-optic, photo-elastic and bulk photovoltaic effects. It is nowadays a widely used electro-optic material.

Its structure is made of oxygen atoms in a distorted compact hexagonal configuration. One third of the interstices of the structure are filled with lithium atoms, one third with niobium atoms and rest is vacant. Lithium Niobate has a three-fold rotation symmetry around its c axis, and is thus classified as a trigonal structure crystal. It also has three mirror symmetry planes that are 60° apart from each other.

In order to describe the cristal, we use a cartesian $\{x, y, z\}$ coordinate system. The z axis is parallel to the c axis,the x axis is perpendicular to a chosen mirror plane, and the y axis is parallel to that same mirror plane. When purchasing lithium niobate crystal plates, they are designated as x-, y-, or z-cut

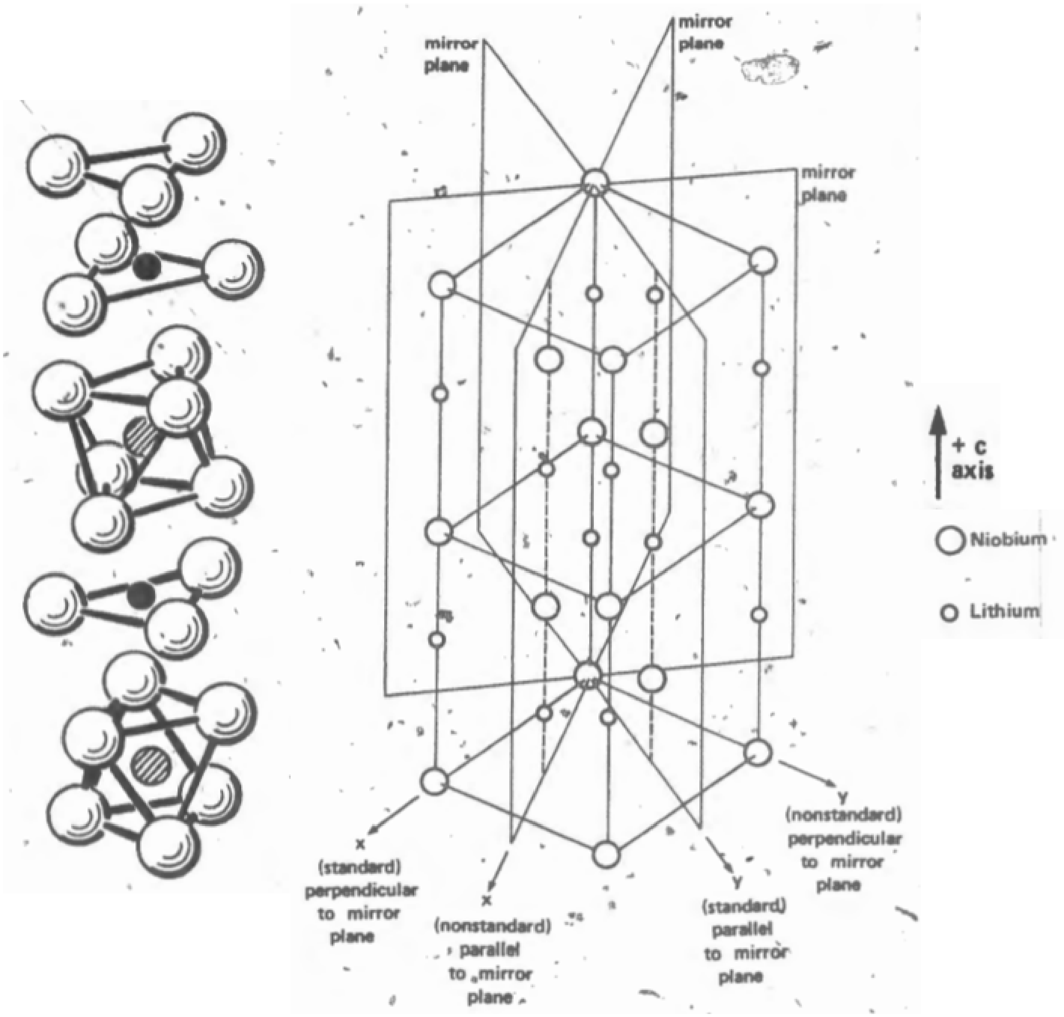

Figure 4: Lithium Niobate crystal

3.2 Permittivity

Since lithium niobate crytal is symmetric around its c axis, the permittivity will be the same for any electric fiel in a plane perpendicular to the c axis. This is a shared property of all trigonal structure crystals, whose permittivity tensor will have the following form:

$$\boldsymbol{\epsilon} = \begin{pmatrix} \epsilon_{11} & 0 & 0 \\ 0 & \epsilon_{11} & 0 \\ 0 & 0 & \epsilon_{33} \end{pmatrix}$$

The refractive indices for different important wavelengths are given in the table below.

λ [nm]	Laser	Stoichiometric $T = 25°C$		Congruently melting $T = 24.5°C$	
		n_o	n_e	n_o	n_e
441.6	He-Cd	2.3906	2.2841	2.3875	2.2887
457.9	Ar	2.3756	2.2715	2.3725	2.2760
465.8	Ar	2.3697	2.2664	2.3653	2.2699
472.7	Ar	2.3646	2.2620	2.3597	2.2652
479.5	Ar	2.3618	2.2596	2.3568	2.2627
488.0	Ar	2.3533	2.2523	2.3489	2.2561
496.5	Ar	2.3470	2.2468	2.3434	2.2514
501.7	Ar	2.3435	2.2439	2.3401	2.2486
514.5	Ar	2.3370	2.2387	2.3326	2.2422
530.0	Nd	2.3290	2.2323	2.3247	2.2335
632.8	He-Ne	2.2910	2.2005	2.2866	2.2028
693.4	Ruby	2.2770	2.1886	2.2726	2.1909
840.0	GaAs	2.2554	2.1703	2.2507	2.1719
1060.0	Nd	2.2372	2.1550	2.2323	2.1561
1150.0	He-Ne	2.2320	2.1506	2.2225	2.1519

Table 2: Refractives indices of lithium niobate

For details about the way these values have bee measured, see [3]. From these values we see that lithium niobate has a negative birefringence. Indeed, if we apply an electric field parallel to the optical axis of the crystal, the induced oxygen dipoles will have a net depolarizing effect on their other oxygen neighbors, thus the extraordinary electric susceptibility χ_e is reduced. On the other hand, if we apply an electric field perpendicular to the optic axis, the induced oxygen dipoles will have a polarizing effect on their neighbors, thus increasing the ordinary electrical susceptibility χ_o. Since $n = \sqrt{\epsilon_{rel}} = \sqrt{\epsilon_{nul}(1 + \chi)}$, we deduce that $n_o > n_e$, which means that the birefringence is negative.

3.3 Pockels effect

Considering what we have seen before and the geometric properties of lithium niobate, the linear electro-optic can be described with only four independent coefficients. The linear electro-optic tensor can be written as:

$$\boldsymbol{r} = \begin{pmatrix} 0 & -r_{22} & r_{13} \\ 0 & r_{22} & r_{13} \\ 0 & 0 & r_{13} \\ 0 & r_{42} & 0 \\ r_{42} & 0 & 0 \\ -r_{22} & 0 & 0 \end{pmatrix}$$

The order of magnitude for the electro-optics coefficients r_{ij} is 10^{-12} to 10^{-11} [m/V]. In particular, r_{13} is approximately equal to $10.0{*}10^{-12}$ [V/m] for light with a wavelength of $\lambda = 633$ [nm].

The empty elements in the $\boldsymbol{r}$ matrix tells us that it is possible to modify the refractive indexes without rotating the principal axis. Indeed if we apply an electric field in the z (3) direction only, the dielectric constants ϵ_1, ϵ_2 and ϵ_3 only will be changed. Hence the principal axis remain the same. In such case, we can derive an equation to see how the dielectric constant and refractive index evolve as a function of the applied electric field.

$$\Delta\left(\frac{1}{\epsilon_i}\right) = \Delta\left(\frac{1}{n_i^2}\right) = \frac{1}{n_i'^2} - \frac{1}{n_i^2} = r_{i3}E_3$$

$$n_i'^2 = \frac{n_i^2}{1 + n_i^2 r_{i3} E_3}$$

Assuming that $n_i^2 r_{i3} E_3 << 1$ (which is true given the order of magnitude of each parameter), the change in n_i can be approximated [2] by:

$$\Delta n_i \approx \frac{1}{2} n_i^3 r_{i3} E_3$$

It is important to notice that the true change in refractive index is not linearly proportional to the electric field (despite the effect being called linear electro-optic effect), but the approximation gives a linear relationship.

4 Electro-optic modulators and other applications

Illustrations and concepts in this section have been taken and adapted from [1] and [2].

4.1 Waveplates

A first and easy to understand application of birefringence is a device called waveplate. Lets consider a linearly polarized light ray propagating in vacuum with a wavelength λ that enters an uniaxial birefringent medium with normal incidence (to avoid double refraction). Its polarization is a combination of both ordinary (phase velocity $v_o = c/n_o$) and extraordinary polarization (phase velocity $v_e = c/n_e(\theta)$). We note $\hat{\boldsymbol{o}}$ and $\hat{\boldsymbol{e}}$ the unit vectors parallel to the direction of ordinary and extraordinary polarization of the ray. Before entering the medium, the $\boldsymbol{E}$ field expression is:

$$\boldsymbol{E} = E(\hat{\boldsymbol{o}}\cos(\phi)\cos(\boldsymbol{k}\cdot\boldsymbol{r} - \omega t) + \hat{\boldsymbol{e}}\sin(\phi)\cos(\boldsymbol{k}\cdot\boldsymbol{r} - \omega t))$$

Once in the medium the $\boldsymbol{E}$ field expression becomes:

$$\boldsymbol{E} = E(\hat{\boldsymbol{o}}\cos(\phi)\cos(n_o\boldsymbol{k}\cdot\boldsymbol{r} - \omega t) + \hat{\boldsymbol{e}}\sin(\phi)\cos(n_e(\theta)\boldsymbol{k}\cdot\boldsymbol{r} - \omega t))$$

Hence after travelling a distance d through the medium, the induced phase difference between the two rays will be:

$$\tau = \frac{2\pi(n_o - n_e(\theta))d}{\lambda}$$

It means that we can engineer the lenght d of the waveplate in order to obtain a particular phase shift between the two rays. (It is worth noticing that a certain waveplate will only be efficient for a certain wavelength λ)

A common waveplate is the half-waveplate for which $\tau = (2N+1)\pi \leftrightarrow d = \frac{(2N+1)\lambda}{2(n_o - n_e(\theta))}$. It means that the light that enters the waveplate linearly polarized with a space angle ϕ will exit it linearly polarized but with an angle $-\phi$. In the case where $\phi = 45°$, the output ray polarization is perpendicular to the input's one.

$$\begin{aligned}\boldsymbol{E} &= E(\hat{\boldsymbol{o}}\cos(\phi)\cos(n_o\boldsymbol{k}\cdot\boldsymbol{r}-\omega t)+\hat{\boldsymbol{e}}\sin(\phi)\cos(n_e(\theta)\boldsymbol{k}\cdot\boldsymbol{r}-\omega t+(2N+1)\pi))\\ &= E(\hat{\boldsymbol{o}}\cos(\phi)\cos(n_o\boldsymbol{k}\cdot\boldsymbol{r}-\omega t)-\hat{\boldsymbol{e}}\sin(\phi)\cos(n_e(\theta)\boldsymbol{k}\cdot\boldsymbol{r}-\omega t))\end{aligned}$$

Another common waveplate is the quarter-waveplate for which $\tau = \frac{(2N+1)\pi}{2} \leftrightarrow d = \frac{(2N+1)\lambda}{4(n_o-n_e(\theta))}$. It means that if a light ray enters the waveplate linearly polarized with its $\boldsymbol{E}$ field equally split between $\boldsymbol{e}$ and $\boldsymbol{o}$, it will exit the waveplate with a circular polarization. The inverse is also true since a ray entering with circular polarization will exit the waveplate with a linear polarization. Two quarter-waveplate can then be used in serie to make a half-waveplate.

4.2 Modulators

Phase modulation Phase modulation can be done by controlling the refractive index along certain axis with an electric field. We can take a simple example with the light propagating parallel to the extraordinary axis z ($\theta = 0$) in lithium niobate. We apply an electric field along this axis in order to preserve the principal axis orientation. The light enters the medium linearly polarized in the ordinary plane x, y with any direction (angle ϕ) since the applied electric field will change the refractive indexes along the two ordinary axis in the same manner (same electro-optic coefficients r_{13}). The electric field of the light ray is $\boldsymbol{E_{in}} = E\cos(\psi - \omega t)\hat{\boldsymbol{o}}$. If we change the ordinary refractive index by $\Delta n_o = n_o' - n_o$, then the light will exit the medium (after a distance L) with a phase difference $\Delta\psi$ given by:

$$\psi' = \frac{2\pi}{\lambda}(n_o + \Delta n_o)L = \psi + \Delta\psi$$
$$\Delta n_o \approx \frac{1}{2}n_o^3 r_{13} E_z$$
$$\boldsymbol{E_{out}} = E\cos(\psi + \Delta\psi - \omega t)\hat{\boldsymbol{o}}$$

The voltage required to obtain $\Delta\psi = \pi$ is called the *half-wave voltage*.

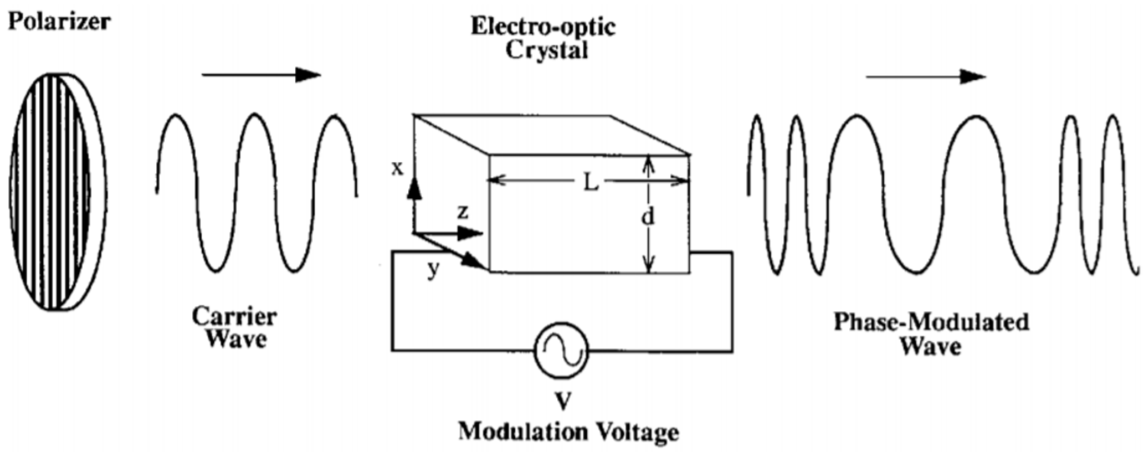

Figure 5: Phase modulation implementation

In other mediums with different symmetry properties, we might need to polarize the light along a specific axis in the polarization plane, since the effect of the applied electric field will be different for each axis x and y.

Polarization modulation Polarization modulation can be done using a principle similar to the one used in waveplates. The main difference and advantage is that we can use an electric field to vary the refractive indexes of the medium, and thus we do not rely anymore on the wavelength λ nor the length of the light path L in order to obtain a specific polarization state. We will consider an application using lithium niobate. Light propagates along one of the ordinary axis (x or y, we choose y)($\theta = 90°$). It must enter the medium linearly polarized such that the $\boldsymbol{E}$ field is equally decomposed on the x and z axis ($\phi = 45°$). Once again, the electric field is applied along the z axis so that the principle axis remain the same.

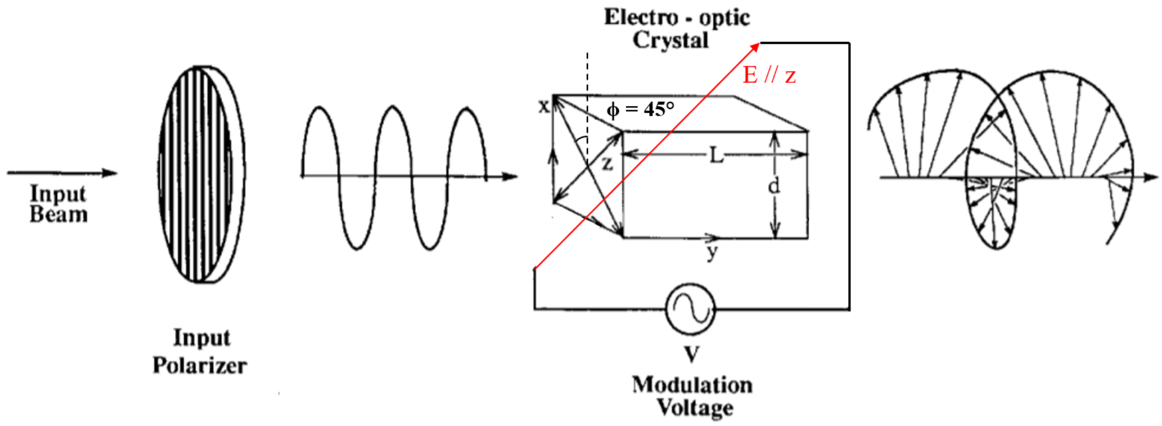

Figure 6: Polarization modulator implementation

$$E_x = \frac{E}{\sqrt{2}} \cos\left(n'_x \frac{2\pi}{\lambda} y - \omega t\right)$$
$$E_z = \frac{E}{\sqrt{2}} \cos\left(n'_z \frac{2\pi}{\lambda} y - \omega t\right)$$

with

$$n'_x \approx n_x + \frac{1}{2} n_x^3 r_{13} E_y = n_x + \Delta n_x$$
$$n'_z \approx n_z + \frac{1}{2} n_z^3 r_{13} E_y = n_z + \Delta n_z$$

and $n_x = n_o$, $n_x = n_o$.

We derive the phase delay between the two components when traveling a distance L:

$$\tau = \frac{2\pi}{\lambda} \left(n_x - n_z + \frac{1}{2}(n_x^3 - n_z^3) r_{13} E_y\right) L = \tau_o + \tau_i$$

We note τ_o the phase delay when no electric field is applied and τ_i the phase delay induced by the application of the electric field. Applying the electric field along the z axis requires a transverse configuration (see "Design considerations"). If we name d the spacing between the two electrodes, then $E = V/d$ and $\tau_i = \frac{\pi}{\lambda}(n_x^3 - n_z^3) r_{13} V \frac{L}{d}$. We call *half-wave voltage* V_π the applied voltage such that $\tau_i = \pi$. Its expression is $V_\pi = \frac{\lambda}{n_x^3 - n_z^3} \frac{d}{L}$. We can then find a new expression of τ that will be more convenient for further calculations:

$$\tau = \tau_o + \pi(V/V_\pi)$$

Note 1: If we do not respect the condition that the $\boldsymbol{E}$ field is equally split between x and z axis ($\phi = 45°$), we will still obtain the same phase delay between the two components, but we will never be able to obtain circular polarization.
Note 2: That kind of device is also called a dynamic retarder.

Intensity modulators It is possible to construct an intensity modulator using a dynamic retarder. As seen previously, a linear polarizer has to be set in front of the birefringent medium to ensure the correct polarization orientation. Then, we add at the output another linear polarizer perpendicular to the one at the input. If we consider the light exiting the dynamic retarder with a delay τ between its two component, then the transmission ratio is:

$$T = I_{out}/I_{in} = E_{out}^2/E_{in}^2 = \sin^2\left(\frac{\tau}{2}\right) = \sin^2\left(\frac{\tau_o}{2} + \frac{\pi V}{2V_\pi}\right)$$

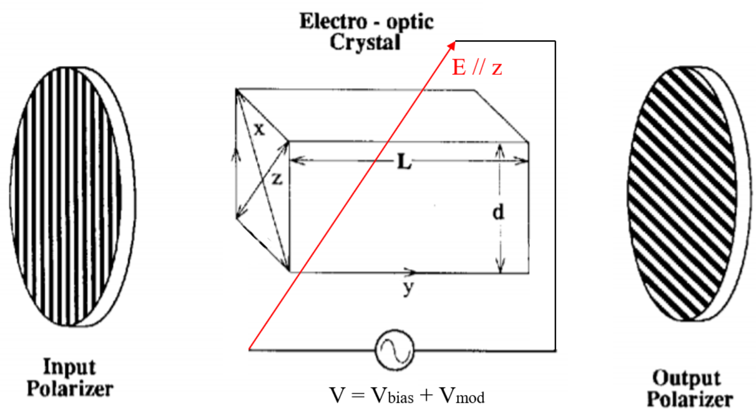

Figure 7: Intensity modulator implementation

We will use a modulation voltage to change τ, which will modify the transmission and thus the amplitude of the electric field of the light ray. We can see the transmission ratio is not evolving linearly with the applied voltage. To maximize the linearity, we want to bias the retarder with a bias voltage V_{bias} such that $\tau(V_{bias}) = \pi/2$. Then $T = 1/2$, and when varying the modulating voltage V_{mod} we get a more linear response.

$$V = V_{bias} + V_{mod}$$

We can the use a sinusoidal modulation voltage $V_{mod}(t) = V_m \sin(\omega_m t)$ and the transmission becomes:

$$\begin{aligned} T(t) &= \sin^2\left(\frac{\pi}{4} + \frac{\tau_m}{2}\sin(\omega_m t)\right) \\ &= \frac{1}{2}\left(1 - \cos(\pi/2 + \tau_m \sin(\omega_m t))\right) \end{aligned}$$

If V_m is small, then τ_m is small and thus we can linearize the function:

$$T(t) = \frac{1}{2}(1 + \tau_m \sin(\omega_m t))$$

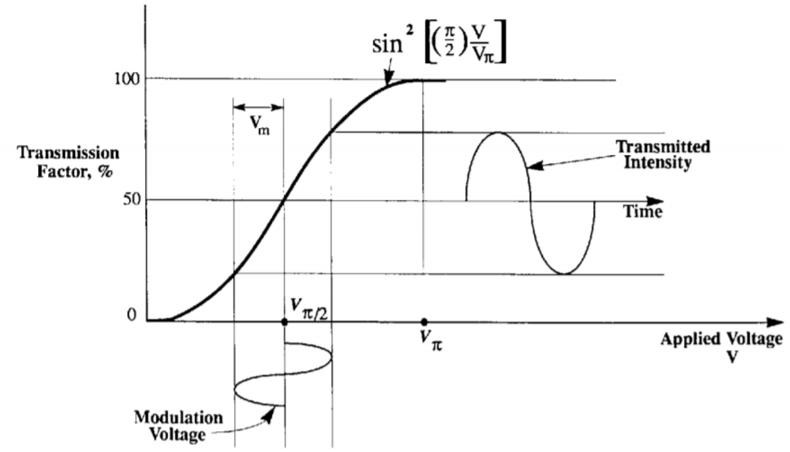

Figure 8: Transmission against applied voltage

If the polarizer at each end of the device were to be parallel, the transmission would be $T = \cos^2(\tau/2)$ and the same principles would apply.

4.3 Design considerations

In order to apply an electric field to the crystal, we need to position two electrodes on opposites sides. There can be two configurations:

- if the light path is perpendicular to the electrodes plane, the configuration is said to be *longitudinal* (since the light path is parallel to the applied electric field). Such configuration requires that the electrodes are transparent or have a small hole so that the light can go through.
- if the light path is parallel to the electrodes plane, the configuration is said to be *transverse* (since the light path is perpendicular to the applied electric field).

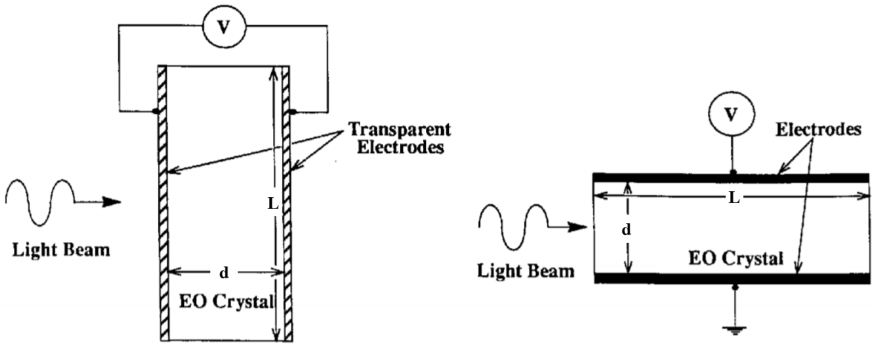

Figure 9: Modulator configuration design

The ratio L/d is called the aspect ratio. The electric field in the cristal is given by $E = V/d$, thus we can minimize d in order to lower the voltage required to obtain a certain field E. However, the capacitance of the system must also be taken into account: $C = \epsilon A/d$ with A the surface of one electrode. If this capacity is to big, the system switching time might be too slow and become a limiting factor for data transfer.

Conclusion

Throughout this survey research project we have explained birefringence and Pockels effect in a quantitative manner, and have seen their implication for light propagating in a medium exhibiting such properties. Then we have presented Lithium Niobate and its properties for electro-optic modulation. Finally we have studied the working principles of a few devices that allow to control certain light properties such as phase, polarization and amplitude.

List of Figures

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References

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