Polarized Light

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In this lab report the study of the changes in the polarization state of light is shown. Different kind of components such as birefringent and optical active materials are placed in the path of the beam with the purpose of see how this components change the polarization of light. How this changes affect to the different wavelengths and hence to the refractive index are measured in order to obtain a relation between them.

I. INTRODUCTION

As is well known, light is electromagnetic waves which are transverse waves consisting of both an electric and a magnetic component. One property of transverse waves is that they can oscillate in more than one orientation. The description of this oscillating behavior is called polarization. The polarization of the wave can be divided into three different types of polarization: Linear, Circular, or Elliptical.

In this lab different optical components that change the polarization state of light will be studied. This is done by using the principle of birefringence in an anisotropic media and by using an optically active media. By measuring the optical properties with a grating spectrometer, the wavelength dependence of the refractive index, i.e. the dispersion of the media, will be determined.

II. THEORETICAL BACKGROUND

Calculations and measurements of this report are based in the concept of polarization state of the light and how it changes. The polarization of the light depends on the electric field components in a electromagnetic wave. Three main states of the polarization of the light are possible: linear, circular and elliptical.

$$E(x,y,z,t) = E_{0x}sin(kz-\omega t+\delta)e_x + E_{0y}sin(kz-\omega t)e_y \quad (1)$$

We now analyze the electric field to see the polarization status. Electric field of a wave propagating in the z axis can be defined by the two x- and y- components as we can see in equation 1. The polarization of light depends now on the amplitude of both components and the phase difference between them. To have circular polarization is necessary that both components have the same amplitude, but not for linear or elliptical polarization. However, amplitudes change the shape and direction of polarization. Taking into account this fact, polarization can be described depending on the phase difference as shown in figure 1

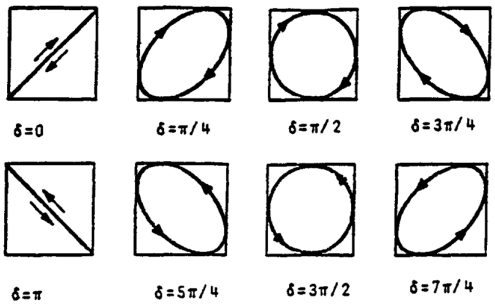


FIG. 1: polarization angles

From equation 1 is easy to demonstrate how every polarization can be decomposed into two other polarization. i.e., if have equation 2 and 3 as two linear polarized waves, the sum of both is a circular polarization as shown in 1 supposing $\delta = \pi/2$.

$$E_1(x,y,z,t) = E_{0x}sin(kz-\omega t+\pi/2)e_x \quad (2)$$

Certain components can change the polarization state. When light passes through a polarizer, the state of the polarization of light changes from one shape to another.

$$E_2(x,y,z,t) = E_{0y}sin(kz-\omega t)e_y \quad (3)$$

In fact, there is something interesting to see in this kind of components related to the intensity of the light. The effect called `Malus's Law` says: *When a polarizer is placed in the path of a polarized light, the intensity of the light transmitted is directly proportional to the square of the cosine of the angle between the initial polarization and the axis of the polarizer.*

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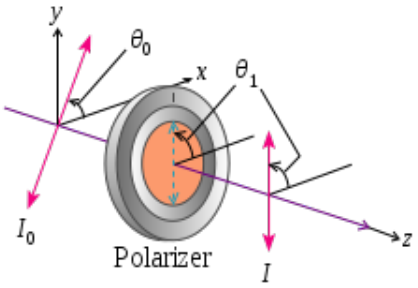


FIG. 2: Malus law

Where $\theta = \theta_1 - \theta_0$ and I_0 is the initial intensity.

$$\mathrm{I}\ \alpha\ cos^2(\theta) \tag{4}$$

As equation 4 shows, the transmission of intensity is maximum when the initial polarization and the axis polarization are parallel.

In this report, two main components are used: birefringent material and optical active material. Both change polarization state of light but they are not the same.

Optical activity is related to a rotation in the linear polarization of light, thus, an optical active material is often called a rotator. Another way to see this phenomena is the following: any polarization can be decomposed into two, e.g., a linear polarization could be decomposed into two circular polarization, a LCP (left-circular polarization) and a RCP (right-circular polarization). The linear polarization will remain unchanged if the LCP and RCP have the same phase velocity, but it will rotate if they travel at different phase velocities.

The rotation of the light can be easily measured with the equation 5, where λ_0 is the wavelength of the light and ρ is the rotation of the polarization state. The smaller the wavelength, the bigger the rotation. In this lab session, the source of light used is white light so when this light go through the crystal, every wavelength is rotated differently than the others. In this lab, the setup is designed to transmit certain polarizations so by rotating the crystal we could "block" different colours. The order in which this colours are blocking when the crystal suffers a clockwise rotation (observer looking into the light) determines if the crystal is dextro-rotatory or levo-rotatory. If the order in which colours are blocking is from higher wavelengths to lower ones, then is a dextro-rotatory crystal and if the order is the opposite, levo-rotatory.

$$\rho = \frac{\pi}{\lambda_0}(n_- - n_+) \tag{5}$$

On the other hand, birefringence is defined as the variation of the refractive index depending on the polarization and propagation direction of light, therefore, this component will have different refractive index for different wavelengths. This effect will help us to construct wave retarders so is not linear polarized light rotating like in the optical active devices but a material that retards different components of the electric field of the wave and change the state of the polarization of the light. The relation between the refractive index and the wavelength is one of the scopes of this report.

III. EXPERIMENTAL METHOD

The experiment started with aligning the experimental setup, except for the crystal, as shown in figure 3. The Czerny-Turner spectrometer, figure 5, was selected to have a grating of 300 lines/mm and a wavelength of 550 nm. A white light source was used throughout all of the experiment and first used without any crystal to obtain a spectrum with maximum intensity as close as possible to 65000 counts.

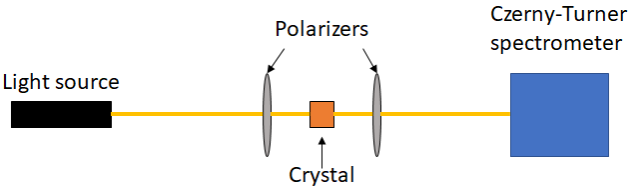


FIG. 3: Schematic picture of the experimental setup used in the laboratory exercise.

The principles of birefringence was then studied using three quartz crystals of different thicknesses (0.24, 1 and 3 mm). These crystals was placed, one at a time, between the two linear polarizers. The different effects on the polarization of the light when the light passes through the crystals was observed by rotating both the crystal and the second polarizer. The spectrum was then analyzed both qualitatively, by looking at the spectrum and understanding the fundamentals, and quantitatively, by taking measurements and making calculations of the phenomena.

In order to determine the relation between refractive index and the wavelength, an analysis of the spectrum of the birefringent was made in the **WinSpec** software. It is known that there will be a maximum in the spectrum when the phase difference between the different wavelengths is $\delta = (2m+1)\pi$ [1]. Using this and that m is decreasing by one for each new maximum when we move towards higher wavelenghts [1], we get:

$$d\Delta n(\lambda) = (2m+1)\frac{\lambda}{2} \tag{6}$$

It is not possible to get the relation between refractive index and wavelength only with equation 6. To do this one more equation is needed. *Sellmeier equation* can be

used for this purpose, however we will use equation 2 instead, which gives:

$$n = A + \frac{B}{\lambda^2} \tag{7}$$

The procedure is the following: We choose three different wavelengths in m ,$m-p$ and $m-q$ as is shown in Figure 4. By combining equation 6 and equation 7 we obtain the following system of equations for the tree wavelengths:

$$\begin{cases} d(A + \frac{B}{\lambda_1^2}) = (2m+1)\frac{\lambda_1}{2} \\ d(A + \frac{B}{\lambda_2^2}) = (2(m-p)+1)\frac{\lambda_2}{2} \\ d(A + \frac{B}{\lambda_3^2}) = (2(m-q)+1)\frac{\lambda_3}{2} \end{cases} \tag{8}$$

Now we have three variables (m, A and B) and can solve the system of equations in order to obtain Δn as a function of wavelength.

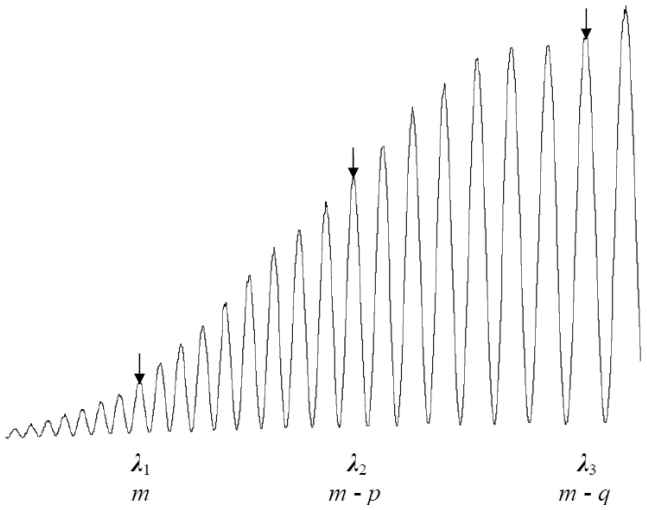


FIG. 4: Three different wavelengths of the spectrum

The lab then continued with investigation of optically active media. This was done using two different quartz crystals. A similar qualitatively analysis was done as with the birefringent crystals by changing the rotation of the crystal and rotating the last polarizer. The quantitative analysis was done by setting the the polarizers to be perpendicular to each other. The crystals was then placed between them, one at a time. With the crystal in place the last polarizer was rotated in steps of 5 degrees clockwise with the spectrum being registered every for every step. The data was then used to calculate the angle of rotation as a function of wavelength.

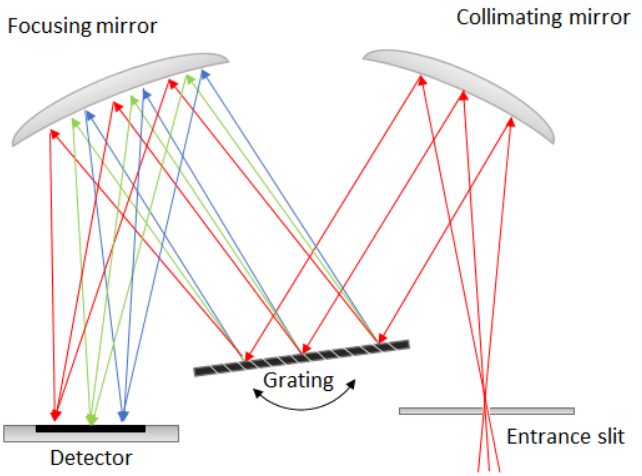


FIG. 5: Schematic of the Czerny-Turner spectrometer used in the laboratory exercise.

IV. RESULT & ANALYSIS

The first system studied was the birefringent crystals where we consecutively studied three sets of crystal of incriminating lengths and then we were interested in finding what was the difference of refractive index as was discussed in the previous sections. We first studied a crystal of length 0.24 mm which gave us a spectrum as shown in Figure.6, from it we can see that there is an alternating intensities count for the orthogonal and perpendicular polarization's, and when we set the polarizer at 45^o in respect to each other we see we get a signal for all the wavelengths.

From the fact that we see these alternating movement, one can deduce that there is an effective change in index of refraction. Only the light that has linear polarization can have a minimum, the light that has some type of circular polarization all ways a=has a component that can be transmitted threw the linear polarizers. from this fact we can see that the birefringent medium has a different index of refraction for different directions of polarization since it ads a phase change in the polarization altering the type of polarization it is, thus creating circular polarization form linearly polarized light .

Understanding the effect a birefringent crystal has will interacting with light we want to see what happens if we have a longer crystal. So now we look at the spectrum from a crystal with a length of 1 mm

From Figure. 7 one can observe the same effect for the three different arrangements of the polarizers (parallel, orthogonal and 45^o). Now we can also see that since the crystal length is longer we have a more rapidly oscillating signal since this difference in index a refraction adds more of a face shift since it interacts for a longer time

with the incoming light. Now to try to measure the difference of index of refraction in this crystal we study a longer crystal and we apply the methodology explained previously. The crystal used was 3mm long in Figure.8 we only plot the arrangement where the polarizers are parallel to each other and the peaks selected to calculate the index of refraction.

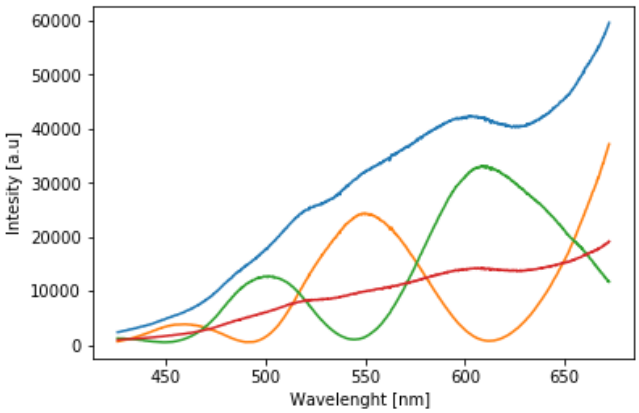


FIG. 6: Birefringent crystal of 0.24 mm analyzed for the two different arrangement between polarizers

With these we find the index of refraction dependent of the wavelength as shown in Figure.9 where we can see the in total it is approximately 0.001 which would be enough to add a considerable phase shift in to create he effect seen in the previous figures.

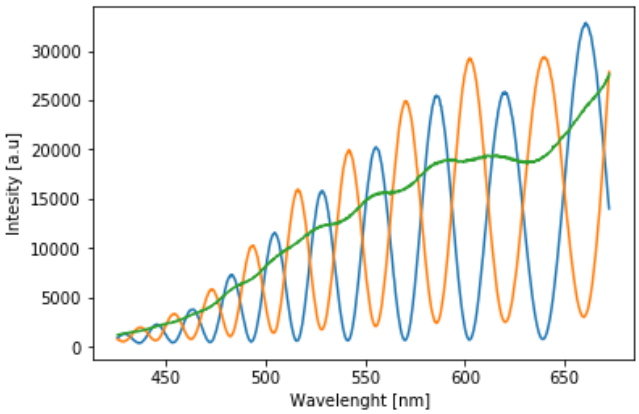


FIG. 7: Birefringent crystal of 1 mm analyzed for the two different arrangement between polarizers

Now we change to an optically active medium, where as was mentioned before rotates the polarization but dose not add a phase difference. This phenomenon can be seen in Figure.10 where we can see that for a different angles of the analyzer we have complete attenuation of certain wavelengths, this shows that a linear polarizes is able to cancel out all wave lengths thus this wavelength must have linear polarization. From this fact we can understand that linear polarization is coming into the optically active crystal and linear polarization is leaving but at that has a different angle of vibration.

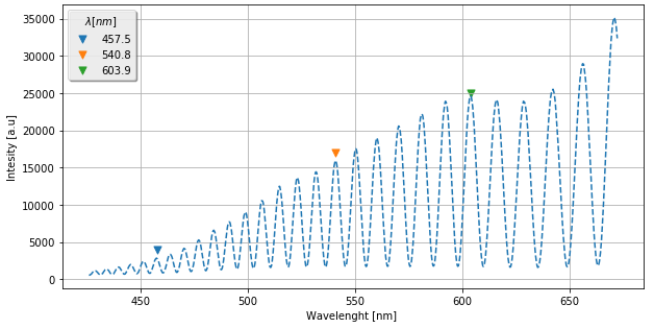


FIG. 8: Birefringent crystal of 1 mm analyzed where we show the parallel arraignment of the polarizers and the peaks used to find the index of refraction

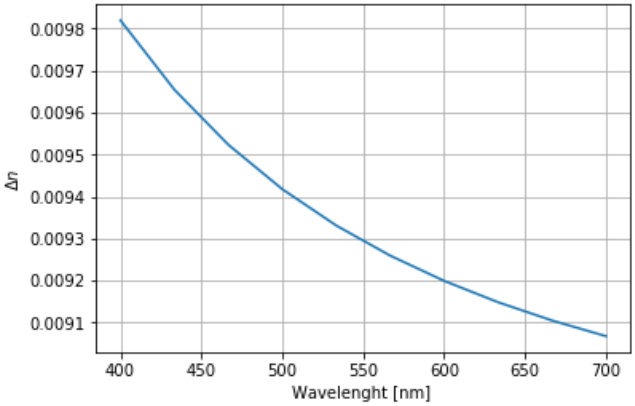


FIG. 9: Difference in index of refraction for the birefringent crystal used

With this we are also interested in studying the rotatory power of the crystal, then with he measured data we can find the rotatory power and using a expression analogs as the one used previously for the index of refraction, We can find how the rotatory power depends on wave length as shown on Figure.11.The rotatory power is larger for shorter wavelengths. This is something one would usually expects since for shorter wavelengths it was more time to interact with the medium and get rotated more. With one of the data points we calculated the difference in index of refraction for the optically active medium and we found it was $\Delta n = 6.10 \cdot 10^{-5}$ which is in the usual ranges. And we also observed that for the convention set the wavelengths scanned went from shorter to longer wavelengths thus making it a levo rotatory.

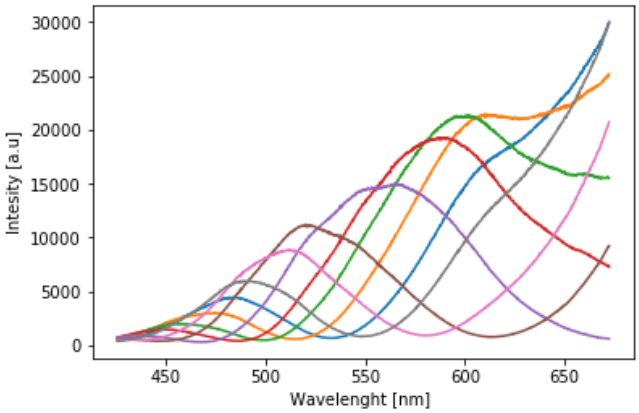


FIG. 10: Optically active medium was scanned for a large set of arrangement of the analyzer polarizer where we can see that all the wavelengths are still linearly polarized.

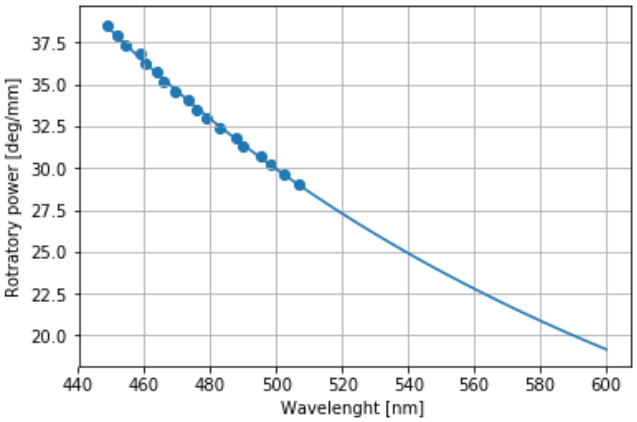


FIG. 11: Rotatory power for an optically active medium of length 90.3 mm where we see it was a higher power of rotation for shorter wavelengths

[1] Optics and Optical Design (FAFF01), "Polarized Light", laboratory guide 2017.

[2] Le Nguyen Binh, Advanced Digital Optical Communications, Second Edition, 2nd Edition.