INSTITUT d'OPTIQUE GRADUATE SCHOOL ParisTech | LEnsE Laboratoire d'Enseignement Expérimental

Labwork in photonics.

Polarization.

Rooms	**P1**	**P2**	**P3**	**P4**
	S1.13		S1.15	S1.19

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Engineer - 2nd year - S7 -Palaiseau
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Polarization : "Well begun is half-done [1]"

The purpose of polarization labs is to illustrate recurring experimental situations where you will be brought to understand the effect of polarization on the propagation of a light wave. They use some of the concepts covered during the first year course and it is important to read it again before starting the labs.

The educational objectives of the four sessions are summarized below. Before the first lab, you must know:

- the definitions of linear and circular birefringence,
- the effects of a half-wave plate and a quarter-wave plate on a given polarization state,
- the polarization state exiting a birefringent plate illuminated by a linear polarization state at 45° of its neutral axes,
- the influence of the wavelength on the birefringence properties of a material,
- the definition of Brewster's angle.

At the end of the session, you should know:

- how to produce a given polarization state,
- how to analyze a given polarization state, using several methods,
- how to measure a linear birefringence, using several methods,
- how to characterize a medium having a circular birefringence,
- how to make an amplitude modulation with electro-optic materials.

[1] Mary Poppins, 1964

The following few basic questions should help you prepare the polarization labs. **You must have answered these questions before you start your first polarization lab session.** The answers can be found in your polarization lecture notes and/or in the appendices.

The written answers will be graded out of 10 and given to the teacher **at the beginning of the first polarization lab session**, regardless of the lab by which you start.

Furthermore, you must prepare each session by reading the booklet and answering the questions of preparation. Instructions are given at the beginning of each subject.

P1 What is the effect of a polarizer on light?

P2 What is meant by saying that a material is "birefringent"?

P3 What is the operating principle of a wave plate? What is the definition of a neutral axis?

P4 What is the phase shift introduced by a $\lambda/4$ plate (quarter-wave plate or QWP)? Same question with a $\lambda/2$ plate (half-wave plate or HWP).

P5 What is the effect of these plates on an incident linear polarization state?

P6 Do the properties of a wave plate depend on wavelength? If yes, how so?

P7 What is the "ellipticity" of polarized light?

P8 What is the polarization exiting a wave plate when it is illuminated by a linearly polarized light at $45°$ from the neutral axes of the plate?

P9 How are "transverse electric" (TE or S) and "transverse magnetic" (TM or P) polarizations defined? What is Brewster's angle?

Lab 1

Polarization. Methods and components.

If this is your first polarization lab session, do not forget to prepare the questions page 4 (graded out of 10, they should be handed to the teacher at the beginning of the session).

The goal of the first session is the study of various phenomena of polarization related to the linear birefringence of materials.

The first part is a review of the basics of your first year course. Prepare questions in advance, and check your observations match what you expected.

Parts 2 will lead to an oral presentation. You must have thought about the theoretical issues of these parts before the session, and have prepared schemes to explain the method of analysis of a polarized state.

Contents

Equipement:

- A polariscope (see figure 1.1) : wooden structure equipped with a dichroic polarizer (bottom stage), a graduated dichroic analyzer (top stage) and two intermediate stages with mounts that allow rotations of exactly 45°. You can use the polariscope with either monochromatic or white light. To change the light source, just rotate the polariscope.
- A set-up on a bench, using a mercury lamp with a green filter or white light.

- Samples and wave plates: **handle them with special care and place them back in their boxes after use.**
- A setup to observe interferences with white convergent light.

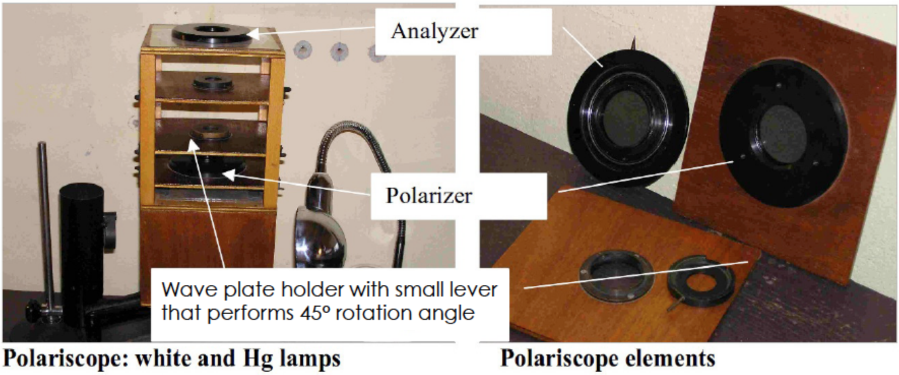


Figure 1.1 – The different components of a polariscope.

1 Study of polarizers and wave plates with the polariscope

In the first part you will study the properties of some dichroic polarizers and wave plates. For this purpose you will shine monochromatic light on the polariscope. You should be able to go over this introductory part quickly, especially if you have already done the other polarization lab sessions.
Maximum time to spend on this first part: 45 minutes.

1.1 Find the axis of a polarizer using reflection at Brewster's angle

At Brewster's angle, the TM polarization (the one parallel to the incidence plane) is not reflected at all. The intensity of the light reflected by a glass plate (or by the linoleum of the floor) will therefore go to zero when analyzed through a particular direction of the axis of a polarizer. This property is used in photography for filters or anti-reflex polarizers.

P1 Write the formula for Brewster's angle for an air-glass reflection. Calculate this angle for an ordinary glass of refractive index $n = 1.5$.

In order to find Brewster's angle with a good accuracy, you can illuminate a glass plate fixed on the table with a well oriented desk lamp.

⇝ Practice orienting the axes of several polarizers using Brewster's angle. With this method, orient the analyzer of the polariscope (using the rotating ring adjustable from below) so that the direction of the needle corresponds to the direction of the transmitted polarization. In the following part, the tip will indicate the absolute direction of the axis of the polariscope.

For convenience, you can place the top polarizer (analyzer) so that its axis corresponds to the graduation 0 of the mount.

1.2 Study of half- and quarter-wave plates

For this part, you will use the polariscope with a mercury lamp with a green filter to select its green line.
You can use different kinds of wave plates: mica wave plates, polymer wave plates (made of plastic), quartz wave plates (the small ones). Unless otherwise specified in the text, use the plastic plates that are less fragile and less expensive than the others.

Find the neutral axes of the wave plates

⇝ Cross the analyzer and the polarizer axes in the absence of the wave plate under study. Then place a half-wave plate (HWP) between crossed polarizer and analyzer plate and rotate it in order to reach minimum light transmission without rotating the analyzer or the polarizer.

Q1 Explain in a simple way why this method allows you to find the directions of the neutral axes of the wave plate. Is the direction perpendicular to a neutral axis, a neutral axis as well?

Half-wave plate

⇝ Keep the half-wave plate (HWP) designed for the green line of the Hg lamp (546.1 nm) between crossed polarizer and analyzer. Put one of the neutral axes of the plate along the direction of the incident polarization (imposed by the direction of the polarizer). This orientation of the wave plate will be taken as a reference. Rotate the plate by an arbitrary angle θ with respect to your reference and then rotate the analyzer.

Q2 Can you find the extinction again? What kind of polarization exits the HWP?

⇝ Rotate the plate by $\theta = 45^\circ$ using the mount that allows **rotations of precisely 45°**.

Q3 Determine the output polarization. Is it the expected result?

Quarter-wave plate

⇝ Replace the HWP by a quarter-wave plate (QWP) designed for the green line of the Hg lamp. Find the neutral axes of this plate. Using the calibrated rotating mount, adjust the neutral axes of the QWP at $\theta = 45^\circ$ from the direction of the polarizer.

Q4 What do you observe when you turn the analyzer? What kind of polarization exists the QWP? Explain your observation using a few sentences and sketches.

⇝ Now turn the QWP by half the calibrated angle (about 20°). Note for which directions of the analyzer the intensity of the transmitted light reaches a maximum and a minimum.

Q5 Verify that the obtained polarization is elliptical and compare with the expected direction of the major axis of the ellipse.

2 Analysis of a polarization state

For this part of the tutorial you have at your disposal an optical bench, two lenses, two polarizers and two quarter-wave plates (the mounts of the two plates are graduated and the 0 indicates the direction of the slow neutral axis). You have to find how to produce and analyze a given state of polarization.

For a better accuracy of your measurements, it is strongly recommended to verify the exact orientation of the neutral axes of the quarter wave plates and the axis of the polarizers. This is probably not exactly 0!

2.1 General method using a quarter wave plate

You will use the monochromatic light generated with a Hg lamp with a green filter.

⇝ Place the unknown mysterious element on the optical bench.

In this part, the objective is to analyse the light vibration after it.

⇝ Check first that all plates of the setup are illuminated under normal incidence with parallel beams.

Q6 Birefringent plates are designed to be used at normal incidence. What happens if this condition is not fulfilled?

The first step is to check whether the polarization state is linear or more complex.

⇝ Form the image of the source on a screen and add a polarizer on the light path. Observe what happens when you rotate the polarizer.

Q7 What can be expected in general, depending on the different types of polarization states?

In our case, the vibration is totally polarized (there is no unpolarized component). The idea of the analysis is then to transform the polarization state into a linear polarization which will be easy to characterize with an analyzer.

⇝ Place the previous polarizer (used as an analyzer) in the direction such that the intensity is minimum, then place a quarter-wave plate before, so that one of its neutral axes is aligned with the axis of the analyzer.

Q8 What kind of polarization exits the QWP? Why? What are the possible directions of this polarization?

Q9 Choosing a handedness of the incident polarization state, make two sketches corresponding to the two possibilities for positioning the slow axis of the quarter-wave plate. Give the orientation of the linear polarization exiting the plate in each case.

Q10 Following on the example that you chose previously, by which angle and in which direction should you turn the analyzer in order to reach an extinction in each case (depending on the two possible orientations of the quarter-wave plate)? Deduce how the slow axis of the quarter-wave plate should be initially oriented with respect to the analyzer so that the direction and angle of rotation of the analyzer gives exactly the handedness and ellipticity of the polarization state.

Q11 Describe, step by step, a **general** procedure to analyze a polarization state from the above manipulations .

Present it to your lab supervisor, using a few sketches.

2.2 Application to a polarization device

In this part you will use the device called “polariseur photo”.

⇝ Analyze the polarization state exiting the device, depending on the incident polarization state, and for both directions of propagation of light through the device.

Q12 Guess what this “polariseur photo” is made of, from your observations. (Bonus question: this type of polarizing filter is used in photography or in 3D movie glasses, do you see the purpose in each case?)

3 White and convergent light

This section provides more complex examples than those illustrated above, but also encountered much less frequently. Do this part only if you have done and understood all the previous questions. Otherwise, it is better to spend more time to master the basic concepts. This part is not mandatory in the report.

The polarization states exiting a birefringent plate can be predicted fairly well if the plate is illuminated at normal incidence and at a given wavelength. This exercise is more difficult if the light is polychromatic or if the beam is not collimated. The following examples will help you to understand a little better the phenomena under these conditions.

3.1 White light observations with HWP (at 546.1 nm)

The characteristics of the wave plates that you studied in the first part depend on the wavelength.

⇝ Rotate the polariscope in order to illuminate it with white light (use the desk lamp). Cross the analyzer and the polarizer and place a HWP (at 546.1 nm) in between. Adjust the neutral axes of the studied plate at 45° from the direction of the polarizer. Then turn the analyzer to try to recover the extinction.

Q13 Can you reach the extinction in this case? What color do you observe if the analyzer and the polarizer are crossed? parallel?

When rotating the plate around one of its neutral axes, the optical path difference increases or decreases (depending if the rotation is around the ordinary or extraordinary axes).

Q14 Draw a sketch in one of those cases to explain the variation (increase or decrease) of the optical path difference.

⇝ Observe the color variations when you rotate the plate around each of its neutral axes between crossed and parallel polarizers. Carefully write down your observations.

Q15 Use Newton's color scale (given in appendix pg.45) to check that the studied plate is a half-wave plate at 546 nm. What is the optical path difference introduced by this plate?

3.2 Obtaining the slow axis of a birefringent plate

Here we use a set-up that allows us to illuminate convergent white light on a spar crystal (negative uniaxial crystal) that is cut perpendicularly to the optical axis, and placed between crossed polarizers.

Q16 Describe the interference pattern that you observe.

⇝ Rotate the crystal around its optical axis. Then turn the polarizer and analyzer while keeping them crossed.

Reminder of propagation of light in uniaxal crystals. Polarisation is preserved only if the light polarisation direction is along one or the other (ordinary/extraordinary) neutral axis of the crystal.

Q17 Deduce the origin of the black cross. Explain how the interference pattern is formed. In particular, explain why one finds Newton's color scale as one moves away from the white (or black) center of the pattern.

$\rightsquigarrow$ Place a QWP used to analyze a polarization state in the path of the light so that its neutral axis is at 45° from the black cross.

Q18 Explain why two black spots (corresponding to zero path-difference) appear on the interference pattern in the direction of the slow axis.

Lab 2

Birefringence measurements

If this is your first polarization lab session, do not forget to prepare the preliminary questions page 4 (graded out of 10, they should be handed to the teacher at the beginning of the session).

Contents

The objective of this session is to determine as accurately as possible the birefringence of some crystalline plates (that is to say the path difference (OPD) introduced between the two neutral axes) using different methods. Depending on the samples, some methods are applicable or not, more or less accurate, complementary... In any case, it is essential to exploit all the results on site to immediately detect any incompatibilities between the measurements, and **make all the necessary verifications on site**. We will try, for two methods, to estimate the uncertainties and to minimize them.

It is essential that each student should make all measurements by all methods. The order of measurement methods is not very important.

The samples to be studied are quartz plates, placed in the box Polarization B.

These samples are really fragile and expensive (about 300 euros P.U.). Therefore, you must handle them with care and put them back in their boxes after use.

At the end of the session, you will present the principle of the two measurement methods. To prepare it properly, you must answer the questions **P1** et **P2** (the appendix will be helpful) before the session.

Methods used:

- Observation of a channeled spectrum with a USB grating spectrometer
- Measurement of the OPD with a Babinet compensator

During the lab session, you will summarize all the obtained results, for each plate, in a table. You will also draw $\delta(\lambda)$, the OPD as a function of λ for all the measurements and you will verify the obtained trend and the consistency of your results.

1 Preparation

P1 What kind of polarization state exits a birefringent plate when the incident polarization is linear and oriented at $45°$ from the neutral axes of the plate? Precise the orientation of the exiting polarization state. Draw a scheme showing the incident polarization, the neutral axes of the plate, and the exiting polarization state. We keep aside the handedness of the exiting polarization.

P2 Give the relationship between the ellipticity ε of the exiting polarization and the phase shift φ introduced by the plate.

P3 How must be orientated the optical axis of the crystal with respect to the propagation axis in order to observe the effect of their birefringence ?

2 Study of the dark fringes in the white light spectrum

⇝ Carefully align the setup. That means carefully align all the optical components on the optical bench, fix the lenses at the correct position with the auto-collimation method, in order to shine collimated light on the sample. This setup is the same as the one used during the tutorial Polarization 1 to study the quartz rotatory power.

⇝ Orient the polarizer at $45°$ with respect to the vertical axis, and cross precisely the analyzer with it.

⇝ Place the plate under study on the bench and orient its axes at 45° to those of the polarizer and the analyzer.

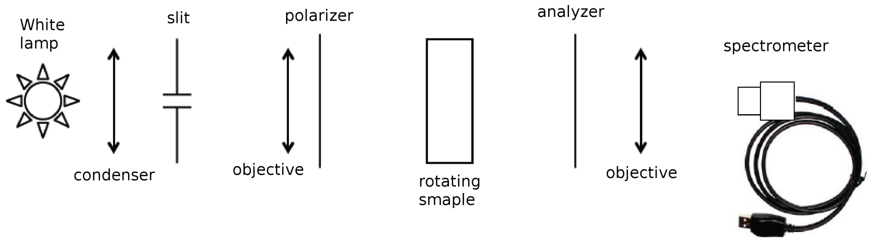


Figure 2.1 – Experimental setup

Q1 Explain clearly and simply the presence of dark fringes in the spectrum between parallel polarizers and between crossed polarizers.

Q2 What is the effect on the spectrum of a sample rotation around the optical axis of the set-up?

The positions of the dark fringes **between polarizer and analyzer either crossed or parallel** can be traced back to the value of the optical path difference for specific wavelength values.

The contrast of the interference fringes is maximal if the neutral axes of the plate are at 45° of parallel or crossed polarizers.

For crossed polarizers, the intensity at the output of the analyzer is:

$$I = I_0 \sin^2\left(\frac{\varphi}{2}\right) = I_0 \sin^2\left(\frac{\pi\delta}{\lambda}\right)$$

You can see the extinction of all wavelengths for which the optical path difference introduced by the plate is an integer multiple of the wavelength, ie $\delta = k\lambda_k = (n_e - n_o)e$.

For parallel polarizers,

$$I = I_0 \cos^2\left(\frac{\varphi}{2}\right) = I_0 \cos^2\left(\frac{\pi\delta}{\lambda}\right)$$

You can see the extinction of all wavelengths for which the optical path difference introduced by the plate is a half integer multiple of the wavelength, ie $\delta = (k + 1/2)\lambda_{k+1/2} = (n_e - n_o)e$.

The measurement of the wavelength of two successive dark fringes (corresponding to k and $k+1$) or of two dark and bright successive fringes (corresponding to k and $k+1/2$) allows in principle to determine simply the value of k (by solving an equation with one unknown). But beware, the variation of birefringence with wavelength, even if it is small, sometimes makes this determination difficult: we never find an integer value of k! Remember this and use the fact that the birefringence $n_e - n_o$ decreases with increasing wavelength (Cauchy's law) to determine k (by solving an inequality with one unknown).

Practical method to check each studied plate:

- Enter into an Excel spreadsheet, in ascending or descending order, all the measured values of the wavelengths corresponding to the dark fringes between crossed and parallel polarizers.
- Then determine the value of k, **positive integer,** for each dark fringe.
- Calculate the optical path difference for each dark fringe and plot the OPD as a function of wavelength: $\delta(\lambda) = k\lambda_k$ or $(k+1/2)\lambda$.
- Check the consistency of your measurements and calculations, in particular the expected decrease of the OPD with the wavelength.

Note To check the value of k, positive integer, you can also use the following calibration points of the quartz birefringence:

$$\text{at } \lambda = 0.45\ \mu\text{m},\ n_e - n_o = 0.00937$$
$$\text{at } \lambda = 0.70\ \mu\text{m},\ n_e - n_o = 0.00898$$
$$\text{at } \lambda = 0.789\ \mu\text{m},\ n_o = 1.5442 \text{ and } n_e = 1.5533.$$

⇝ Carefully measure all the observed (and relevant) dark fringes **for polarizers first crossed and then parallel**. Determine the values of k corresponding to each dark fringe.

Q3 Explain why the value of k is easy to determine if there are very few dark fringes (less than 2).

Q4 For all plates studied, plot the optical path difference as a function of wavelength. Deduce the value of the optical path difference at 546.1 nm (green line of mercury).

Ask the teacher to check your results.

3 Babinet compensator

A Babinet compensator is made of two birefringent prisms glued together (see figure below). The extraordinary axis of the second prism is oriented along the ordinary axis of the first prism in order to compensate its birefringence. As a result, the overall birefringence introduced by the Babinet is directly proportional to the path length difference between the two prisms. Therefore, the birefringence varies linearly with the position of the Babinet along the x axis.

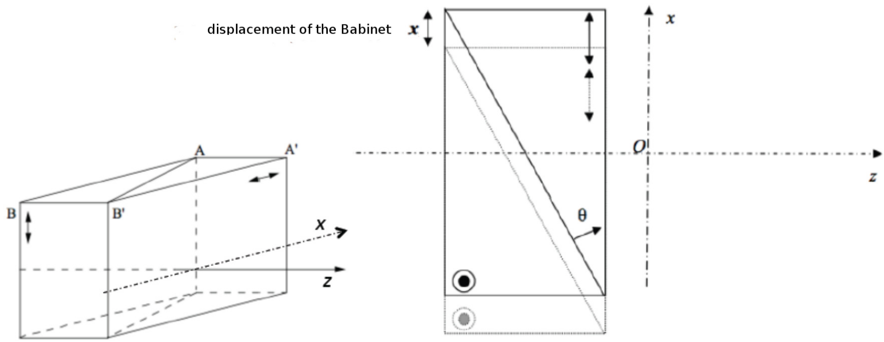


Figure 2.2 – Babinet compensator

For a displacement x, the optical path difference can be written:

$$\delta_\lambda(x) = 2[n_e(\lambda) - n_o(\lambda)] \tan(\theta)x = K_{cal}(\lambda)x$$

Note that $\delta(0) = 0$.

Let us consider a Babinet compensator between crossed polarizer and analyzer. Its neutral axes are at 45° with respect to the polarizer and the analyzer axis for maximum contrast. You can then observe interference fringes equidistant and parallel to the edge of the prisms (Oy) whose interfringe in the plane xOy is equal to:

$$i(\lambda) = \frac{\lambda}{2[n_e(\lambda) - n_o(\lambda)] \tan(\theta)} = \frac{\lambda}{K_{cal}(\lambda)}$$

Under white light illumination, there are fringes following Newton's color scale with white central fringe (for $\delta = 0$) between parallel polarizers or with black central fringe between crossed polarizers.

Method for measuring birefringence: If we add between the polarizer and the analyzer a birefringent sample whose neutral axes are parallel to those of the Babinet compensator, the fringes move proportionately to the additional OPD introduced by the sample. We can then measure the shift of the Babinet compensator required to bring the central fringe back in the center of the field and deduce directly the optical path difference introduced by the sample. The transverse displacement of the Babinet compensator is measured on the vernier of the micrometer screw with high precision.

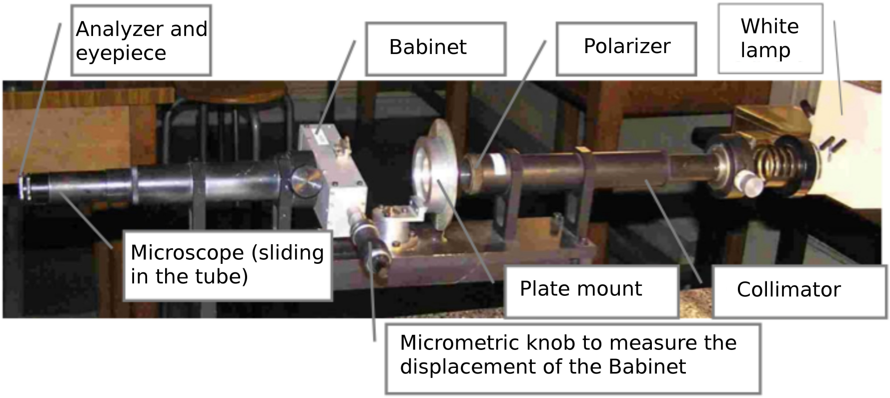


Figure 2.3 – Experimental setup

3.1 Settings

⇝ Illuminate properly the Babinet compensator. Direct illumination of the slit of the collimator by the lamp, without condenser, is sufficient to cover the entire aperture of the Babinet compensator, as long as you place the lamp close enough to the slit and you orient it properly.

⇝ Without compensator, cross polarizer (located at the end of collimator) and analyzer (attached to the microscope eyepiece). Install the compensator (it slides at the entrance of the tube containing the fixed front viewfinder).

⇝ Make the focus on the crosshairs etched (the viewfinder slides inside the tube). Turn the Babinet compensator to find the extinction and then turn it of 45°. Fringes of high contrast should appear.

3.2 Calibration of the Babinet compensator

We can then **calibrate the Babinet compensator with monochromatic light** (mercury lamp equipped with a green filter). You need to measure as accurately as possible the interfringe (often called the Babinet compensator period).

Q5 Determine as precisely as possible the Babinet compensator interfringe at the wavelength of the green line of mercury. **This is about 2.4 mm. Repeat the measurement until you get close to this value.** Give the accuracy of your interfringe measurement.

This calibration allows the measurement of the optical path difference introduced by a plate at the wavelength of the green line of mercury (546.1 nm) (if this OPD is less than the maximum OPD measurable with the Babinet compensator).

Q6 What is the maximum measurable OPD with the Babinet compensator?

3.3 Measurement of the sample birefringence

⇝ Replace the mercury lamp with a white light source. The polarizer and analyzer are crossed and the direction of the axes of the compensator is at 45° with respect to the axis of the polarizers. Bring back the central dark fringe on the reticle. Press on the red button of the micrometer screw. This position will serve as a reference.

⇝ Place the plate in order to keep the dark fringe centered.

Q7 Explain why you align its neutral axes with the axis of the analyzer and polarizer.

⇝ Turn the plate by $45°$ around the optical axis. The black fringe is no longer centered. You must translate the compensator to bring back the dark fringe in the center. While doing so, check if the successive colors that you observe are consistent with corresponding Newton's color scale.

Q8 Measure the displacement of the Babinet compensator to bring back the dark fringe centered. Explain how this measurement allows direct calculation of the optical path difference introduced by the sample at the calibration wavelength (546.1 nm).

Note: to have a dark fringe well contrasted in the presence of the plate, it is important that the axes of the plate are well aligned with those of the Babinet compensator.

Q9 Calculate the OPD introduced by the plate at 546.1 nm. Evaluate the accuracy of this measurement.

Q10 Check that the value obtained is consistent with the values obtained by the method of channeled spectrum.

Present to the teacher the principle of the two measurement methods (oral presentation graded out of 5 points).

4 Conclusions on the set of measurements

Q11 For each plate, make a summary of the results obtained by the three methods. Explain why, for some samples, some methods are not appropriate.

Q12 For each plate, draw the optical path difference as a function of wavelength with the bars of uncertainty.

Q13 For each method, evaluate the accuracy of the results.

Q14 Determine the thickness of each plate, assuming that it is indeed a quartz plate cut parallel to the optical axis.
We can use the variation of $n_e - n_o$ of quartz as a function of wavelength:

$$n_e - n_o = 8.678.10^{-3} + \frac{145.025}{\lambda^2} \text{ with } \lambda \text{ in nm.}$$

5 Non-normal incident illumination on a birefringent sample.

⇝ Go back to the channeled spectrum set-up. Put the studied sample between crossed polarizer and analyzer, with its neutral axes at 45° from the polarizer axis. To make the observations easier, perform the alignment so that one neutral axis of the sample is vertical.

⇝ Incline slightly the sample so that the incident beam has a small angle with the entrance face. What is the consequence on the channeled spectrum?

Q15 Drawing help from the **index surface** of an uniaxal medium, makes the relation between a sample rotation and the path difference between both polarisation projection explicit. In which case the wider the incident angle the larger the path difference due to the plate ?

⇝ Rotate the sample by 90°. The other neutral axis is vertical. Follow the same procedure and note the consequence on the channeled spectrum.

Q16 Can we learn from the experimental observation around which axe the sample rotation is carried out ? Is it possible to determine which one is the slow/fast axis ?

Interpret your observations.

Lab 3

Analysis of polarization states using a rotating analyzer

If this is your first polarization lab session, do not forget to prepare the questions page 1 (graded out of 10, they should be handed to the teacher at the beginning of the session). Prepare question **P1** to **P3** before the session.

Contents

An ellipsometer is a widely used industrial device in particular for characterizing thin film deposition (thickness, indices). The purpose of this session is to study the working principle of a *rotating analyzer ellipsometer*. Through the first part of this session, you will become familiar with this device. **An oral presentation will end this part (section 3).** The ellipsometer is used in a second part to determine the nature of the vibration transmitted through a birefringent plate or reflected on a metal surface as a function of the incidence angle and the nature of the incident electromagnetic wave.

1 Preparation

P1 Recall the definitions of the transverse magnetic, TM (also called P-polarization) and transverse electric TE polarization (S-polarization).

The **intensity** coefficient of reflection R_{TE} and R_{TM} versus the incidence angle are plotted on the graph on figure 3.1:

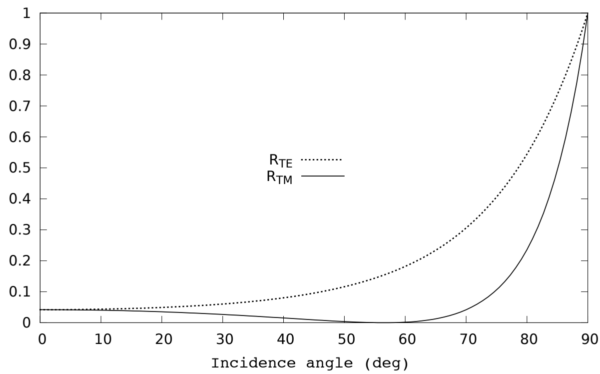


Figure 3.1 – Intensity coefficient of reflection R_{TE} and R_{TM} versus the incidence angle (standard glass $n = 1,515$ at $633\,\mathrm{nm}$)

P2 For what incident polarization is the intensity of the reflected beam minimal? Does this result depend on the angle of incidence?

P3 Calculate the value of Brewster's angle for a standard glass ($n = 1.515$ at 633 nm).

2 Experimental set-up

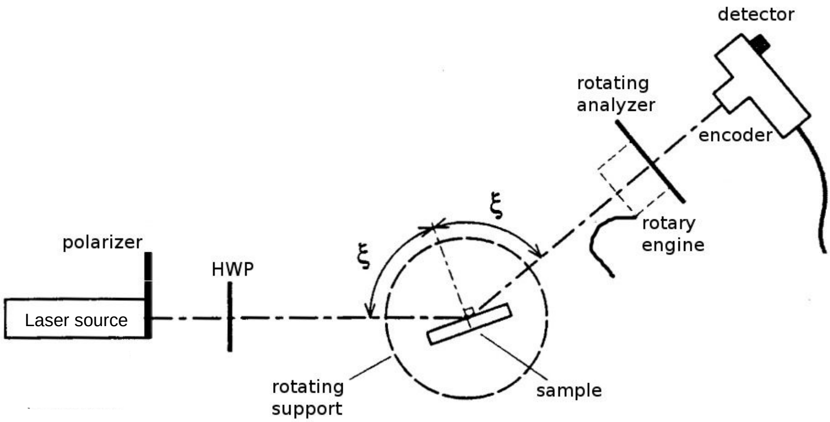


Figure 3.2 – Set-up scheme

The light source is a laser at $640\,\mathrm{nm}$, a polarizer is placed in the laser output.

The detector consists of a large sensitive area photodiode ($\varnothing \simeq 11$ mm) associated with a current-voltage amplifier carefully designed to have low noise and gain as constant as possible in its useful bandwidth. It has a selector for choosing between three sensitivities. The voltage delivered by the detector is assumed to be proportional to the received flux. First, we will visualize this signal with an oscilloscope.

The rotating analyzer consists of a linear polarizer, driven in rotation by an electric motor. Its rotational speed, displayed in revolutions per second on the LCD control unit of the encoder (the computer must be on), can be adjusted with the voltage of the drive motor.

An incremental encoder of angular position (orange box) is used to pinpoint the angular position of the analyzer. The model used delivers a signal, `TOP0`, which gives a single 'top' per turn, and a signal noted T, consisting of 4096 rising edges per turn. The `TOP0` signal frequency is denoted f_0 in what follows.

The incremental encoder plays an important role in the acquisition system of the signal you will use in the second part of the labwork.

3 Qualitative observation with the scope

We first use the red laser at $\lambda = 640$ nm, equipped with a polarizer at its output.

⇝ Carefully align the arm of the goniometer supporting the rotating analyzer and the detector on the direction of the laser beam. Turn on the power supply of the detector and the computer. Send the output signal of the detector on the oscilloscope. Also send the signal `TOP0` on the second channel of the oscilloscope and trigger the sweep of the oscilloscope on this signal (very narrow 5V TTL signal).

⇝ Apply power to the drive motor of the rotating analyzer with the DC supply provided for this purpose and set the speed of rotation (viewed on the display of ENCODER MANAGEMENT BOX) to about ten turns per second. **(Avoid exceeding 25 turns/s).**

⇝ Choose the sensitivity of the detector to have a signal sufficiently strong (several volts) but not saturated on the oscilloscope. The detector delivers a voltage proportional to the normal light flux it receives apart from a very low dark voltage. (The polarizer can, if necessary, be used to limit the flux hitting the detector to avoid a saturation).

Q1 Explain the observed signals on the oscilloscope with Malus' law, especially the relationship between the frequency of the signal from the detector and the frequency f_0 of `TOP0`.

⇝ Insert a half-wave plate (HWP) at 640 nm on the beam path and make the linear polarization rotate. Observe the changes of the signal from the detector viewed on the oscilloscope.

Q2 Interpret the signal obtained as a function of the orientation of the HWP. Take particular note of the direction of travel of the signal when you rotate the HWP and explain it.

⇝ Remove the half-wave plate and replace it by a quarter-wave plate.

⇝ Insert now a quarter-wave plate (QWP) on the linearly polarized beam.

Q3 Interpret the signal obtained as a function of the orientation of the QWP. How can the quality of this wave plate be checked. What is the influence of a non-normal incidence of the laser beam?

Q4 Fill in the table shown in the appendix below to illustrate the one-to-one correspondence between the contrast γ and phase Φ of the observed sine wave, and the polarization state (ellipticity ε, orientation θ of the ellipse) of the light which is incident on the rotating analyzer.

Q5 What is the mathematical relationship between γ and ε? And between Φ and θ?

4 Quantitative measurements with the computer

Simple measurements of phase and amplitude of a sine wave on the oscilloscope allow, strictly speaking, to determine the polarization state of a completely polarized beam hitting the rotating analyzer. However, these measurements are tedious and not very accurate. They can be very usefully computer-assisted. The objective of the next part is to get started with the acquisition software of ellipsometry measurements.

4.1 Using the acquisition and processing software

⇝ Remove the QWP before you move on.

⇝ Run the VI (Virtual Instrument) called
`Rotating Polarizer v2018.VI.`

This VI can acquire the detector signal, simultaneously view the detector signal and its FFT and calculate the parameters useful for polarimetry.

The sinusoidal signal detected can easily be written as:

$$S(r) = V_0[1 + \gamma \cos(4\pi r + \Phi)]$$

where r is the angular position expressed *in turns*, V_0 the average value, Φ the phase at origin and γ the modulation rate. The average value of the signal being arbitrary (it depends on the laser power and detector sensitivity), the information on the polarization is only contained in the modulation rate γ and the phase Φ. The Fourier transform of $S(r)$ whose argument is an *angular frequency* in turns^{-1} has a continuous component at *0 turn*$^{-1}$ of amplitude V_0 and a sinusoidal component at *around 2 turns*$^{-1}$ of amplitude $V_0\gamma/2$ and phase Φ:

$$S(r) = V_0 + \frac{\gamma V_0}{2} e^{i(4\pi r+\Phi)} + \frac{\gamma V_0}{2} e^{-i(4\pi r+\Phi)}$$

The two values γ and Φ are extracted in the LabVIEW program by fast Fourier transform (FFT) of the detector signal on *integer* numbers of revolutions of the analyzer. You will use the normal operation mode in the following (*orange button in the External clock position*). In that case, the acquisition of the signal $S(r)$ is synchronized with the encoder (rising edges of T). The amplitude $\gamma V_0/2$ and phase Φ values to be measured are properly calculated because the acquisition is perfectly synchronized with the sine signal at **2 turns**$^{-1}$.

Note about the Fourier Transform: In fact, as a result of non-uniformities of the rotating analyzer which introduce small distortions reoccurring at every turn, the actual signal is periodic in turn, except for some fluctuations and measurement noise, and it is decomposed into Fourier series having its fundamental at ± 1 turn $^{-1}$ and harmonics at ± 2, ± 3, ... turns^{-1}. Its FFT therefore presents peaks at these particular frequencies standing out from residual background noise. The peaks at 0 and ± 2 turn^{-1} are normally highly preponderant. The quantities γ and Φ, calculated as described above may be subject to random errors related to the noise signal and systematic errors due to deterministic imperfection of the analyzer.

⇝ Without any plate on the beam path, run the VI and observe the different results displayed: acquired signal, FFT, normalized amplitude and phase of harmonic 2.

Q6 Describe the spectrum, and identify the line(s) we are interested in. Discuss briefly the origin(s) of the other lines.

From this, the program computes the ellipticity ε and the orientation of the ellipse, and then plots it.

Q7 For a linear polarization, do we get a perfectly vanishing ellipticity? Why? Comment on the effect of stray light on the measured value of ε.

⇝ From now on, make sure to minimize stray light (using a colored filter and/or some black paper to shield the detector).

⇝ Using the HWP, check, by rotating the plane of polarization in a given direction, that the ellipse is plotted as the electric field of the light would be seen by an observer looking towards the light source.

4.2 Preparing a state of polarization

Here we will show that using a HWP and a QWP, starting from an initial linear polarization, one can prepare any polarization state (with arbitrary ellipticity and orientation).

Q8 First, how can one locate the neutral axes of the plate?

⇝ Then, using only a QWP, prepare a polarization state with a given ellipticity, say $\varepsilon = 30°$, oriented at $\theta = \varepsilon$.

⇝ Finally, use the HWP to change the orientation of θ arbitrarily, without changing ε.

4.3 Mesuring birefringence

⇝ Use this device to determine (modulo λ) the retardation induced by the unknown plate (a piece of adhesive tape on a microscope slide). To do so, first identify the neutral axes of the plate, and then orient them at $45°$ of the incident linear polarization.

5 Circular birefringence

⇝ The initial polarization is now linear. Put the quartz plate (sample labeled `OCP445`, thickness $L = 1.0$ mm) in the path of the beam.

Q9 What is the state of polarization at the output?

Q10 Does it change when the quartz plate is rotated around its axis? Does the plate behave like the waveplates you have studied before?

⇝ Now produce circular polarization before the plate.

Q11 What is the state of polarization after the plate?

One says that the plate shows *circular birefringence*. The angle of rotation of the polarization plane is $\alpha = \rho L$, where, to a good approximation $\rho \propto \lambda^{-2}$ (this is called Biot's law). For quartz, tabulated data give $\rho = \pm 22.09°/\text{mm}$ at the sodium D-line (589.3 nm). The $\pm$ sign arises from the fact that the rotation can occur to the left or to the right.

⇝ Come back to the situation of a linear incident polarization and measure the rotation angle α induced by the sample.

Q12 Check that the measured α and the data above are consistent with each other.

Q13 Is the quartz specimen is left- or right-rotatory?

⇝ Measure the rotation angle α induced by the thick quartz plate ($L = 7.7$ mm).

Q14 Is this specimen left or right-rotatory?

⇝ Use the green laser (with the polarizer!) to measure α at $\lambda = 532$ nm for both plates.

Q15 Is Biot's law fulfilled?

6 Reflection on a substrate

We use again the red laser.

So far, the *absolute* orientation of the polarization in the laboratory, e.g. with respect to the table, was not determined. To do so, we will use the phenomenon of polarization by reflection on glass at the Brewster angle ξ_B.

⇝ Using the glass plate (with a darkened back side to avoid reflections by the back interface) on the goniometer, find the appropriate incidence angle and the appropriate orientation of the incident linear polarization such that the reflected beam intensity vanishes.

Q16 Then, what is the orientation of the incident polarization with respect to the table? Record the corresponding value of the orientation of the ellipse given by the computer.

Q17 Give the experimental value of the Brewster angle that you measure, and use this to estimate the refractive index of the glass plate.

⇝ Show that for both S and P polarization, the output polarization remains linear whatever the angle of incidence ξ. (In practice, in order to have a strong enough signal, we restrict the range of measurments to $\xi > 60°$).

⇝ We now use a linear polarization at $45°$ (equal superposition of S and P).

Q18 Is the output polarization still linear? Does it depend on ξ?

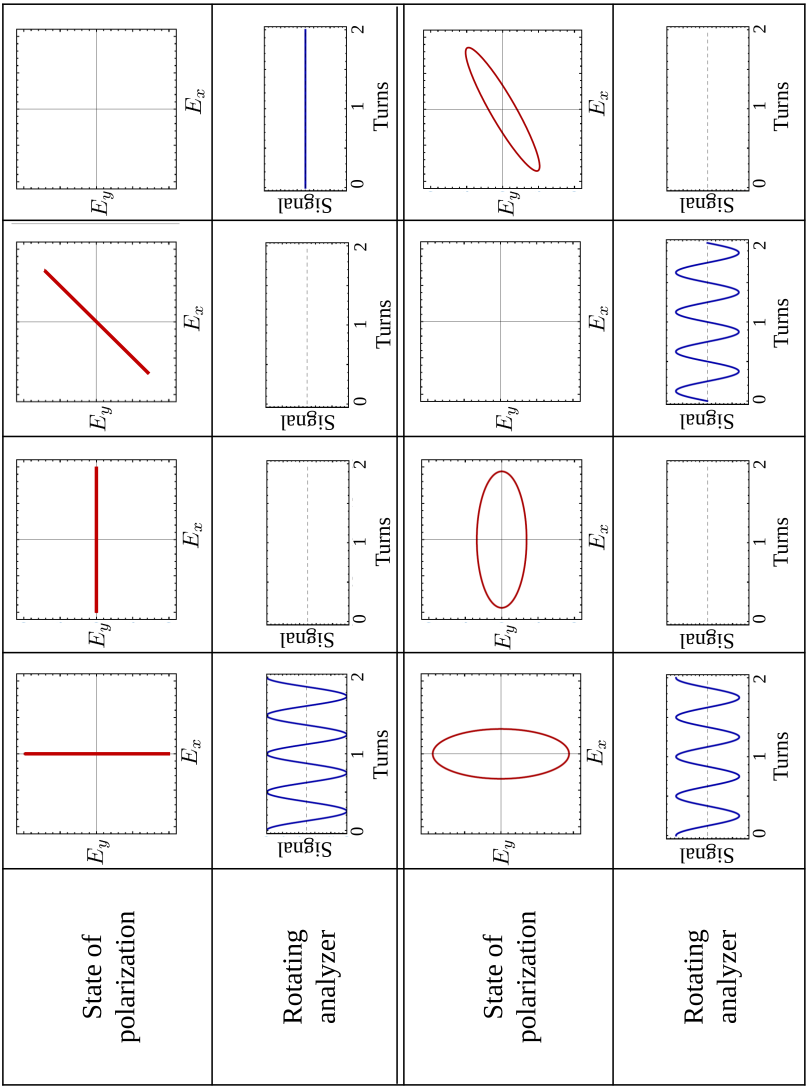
⇝ Perform the same experiments as in the previous question for the gold-coated mirror.

Q19 Is there a Brewster angle?

⇝ Do the same for the dielectric mirror (`BB1-E02` from Thorlabs).

Q20 For an incident linear polarization, in which conditions is the polarization of the reflected wave linear?

Appendix: correspondence between the state of polarization and the signal given by the rotating analyzer



Lab 4

Study of an electro-optic modulator

If this is your first polarization lab session, do not forget to prepare the preliminary questions page 4 (graded out of 10, they should be handed to the teacher at the beginning of the session).

The aim of this session is to study the working principle of an electro-optic modulator and the way it is used.

No written report is asked for this session. You will just have to fill out a result sheet. The questions to be answered on the sheet are marked with a $\diamond$. The questions **P1** to**P4** must be prepared before the session.

Contents

1 Preparation: the electro-optic effect

The electro-optic effect will be seen during the second semester in lecture and in tutorials. The few items below allow us to carry out the labwork on and to under-

stand the birefringence induced by an electric field and the use of an electro-optical component as an intensity modulator.

The application of an electric field on a non-centrosymmetric crystal can cause a change in the refractive index. If the change of index is proportional to the applied field, this phenomenon is called the Pockels effect (this is the case of the KD*P crystal studied in this lab). If, however, the change is proportional to the square of the applied field, this is called the Kerr effect.

The electro-optical effect is thus an effect of electrically induced birefringence. The crystal behaves as a birefringent plate with a slow axis and a fast axis whose indices vary depending on the applied voltage. We describe these variations by changing the index ellipsoid.

In an arbitrary coordinate system $Oxyz$ the equation of the index ellipsoid is:

$$\frac{x^2}{n_{xx}^2} + \frac{y^2}{n_{yy}^2} + \frac{z^2}{n_{zz}^2} + \frac{2xy}{n_{xy}^2} + \frac{2xz}{n_{xz}^2} + \frac{2yz}{n_{yz}^2} = 1$$

In the coordinate system $OXYZ$ of the medium neutral axis, one obtains:

$$\frac{X^2}{n_{XX}^2} + \frac{Y^2}{n_{YY}^2} + \frac{Z^2}{n_{ZZ}^2} = 1$$

The electro-optical effect results in a slight variation of the indices: the coefficients $1/n_{ij}^2$ undergo variations $\Delta(1/n_{ij}^2)$ and become the coefficients $1/n_{ij}'^2$:

$$\frac{1}{n_{ij}'^2} = \frac{1}{n_{ij\,(E=0)}^2} + \Delta\left|\frac{1}{n_{ij}^2}\right|$$

The variations of the coefficients $1/n_{ij}^2$ are calculated by taking the product of the (6 x 3) matrix of the electro-optical coefficients r_{ij}, which depend on the nature of the crystal, by the electric field vector, $\mathbf{E}$. For KD*P, which, without any applied electric field is a uniaxial crystal along Oz, the initial ellipsoid has the following equation:

$$\frac{x^2}{n_o^2} + \frac{y^2}{n_o^2} + \frac{z^2}{n_e^2} = 1 \text{ with } n_o = 1.51 \text{ and } n_e = 1.47 \text{ at } \lambda = 0.6\mu\text{m}.$$

The symmetry properties of the KD*P crystal allow to show that the matrix of the electro-optic coefficients is:

$$\begin{pmatrix} \Delta\left[\frac{1}{n^2_{xx}}\right] \\ \Delta\left[\frac{1}{n^2_{yy}}\right] \\ \Delta\left[\frac{1}{n^2_{zz}}\right] \\ \Delta\left[\frac{1}{n^2_{yz}}\right] \\ \Delta\left[\frac{1}{n^2_{zx}}\right] \\ \Delta\left[\frac{1}{n^2_{xy}}\right] \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ r_{41} & 0 & 0 \\ 0 & r_{41} & 0 \\ 0 & 0 & r_{63} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_Z \end{pmatrix}$$

with $r_{41} = 8.8.10^{-12}\text{m.V}^{-1}$ and $r_{63} = 26.2.10^{-12}\text{m.V}^{-1}$

It can be easily shown that the ellipsoid of KD*P in the presence of an electric field E_z applied along Oz becomes:

$$\frac{x^2}{n_o^2} + \frac{y^2}{n_o^2} + \frac{z^2}{n_e^2} + 2r_{63}E_z xy = 1,$$

where the appearance of a crossed term indicates a rotation of the ellipsoid. In the presence of an electric field along Oz, the neutral axes Ox' and Oy' are at 45° to the axis Ox and Oy.

Making a change of variables one can obtain the equation of the ellipsoid in these new neutral axes:

$$\begin{cases} x' &= \frac{1}{\sqrt{2}}(x+y) \\ y' &= \frac{1}{\sqrt{2}}(y-x) \end{cases} \Rightarrow \left(\frac{1}{n_o^2} + r_{63}E_z\right)x'^2 + \left(\frac{1}{n_o^2} - r_{63}E_z\right)y'^2 + \frac{z^2}{n_e^2} = 1$$

At first-order the equation of the ellipsoid in these new neutral axes can be written as

$$\frac{x'^2}{n_{x'}^2} + \frac{y'^2}{n_{y'}^2} + \frac{z^2}{n_e^2} = 1 \text{ with } \begin{cases} n_{x'} &= n_o - \frac{1}{2}n_o^3 r_{63}E_z \\ n_{y'} &= n_o + \frac{1}{2}n_o^3 r_{63}E_z \end{cases}$$

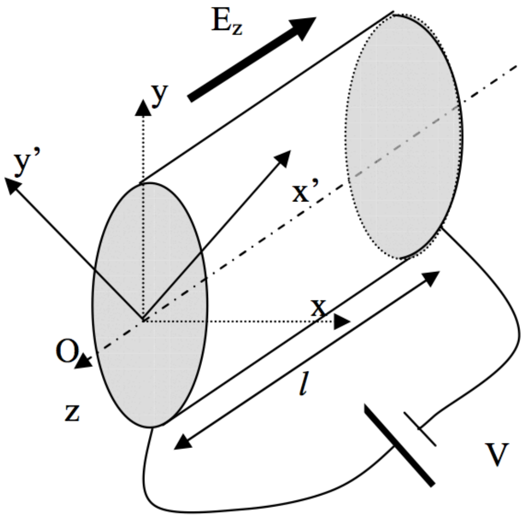


Figure 4.1 – Crystal sheme.

In the presence of a field E_z, we get thus two neutral axes Ox' and Oy' in the plane perpendicular to the z-axis, characterized by a birefringence:

$$\Delta n = n_{y'} - n_{x'} = n_o^3 r_{63} E_z$$

Let us consider a monochromatic plane wave linear along Oy propagating in the crystal along the direction Oz.

P1 ◇ Give the expression of the phase shift introduced and show that it is independent of the length l of the crystal. Give the expression of the voltage V_π for which the crystal behaves like a half-wave plate.

P2 Suggest a set-up using the KD*P crystal for modulating the amplitude of a linearly polarized electromagnetic wave.

P3 ◇ Suggest a set-up using the KD*P crystal for modulating the phase of a linearly polarized electromagnetic wave.

P4 ◇ Look for application examples of electro-optic modulators on the internet.

2 Caracterization of the electro-optic modulator

Align the following set-up:

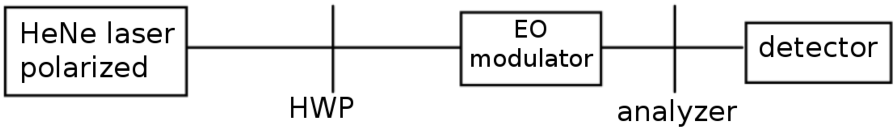


Figure 4.2 – Experimental setup

2.1 Setting the optical axis of the modulator with respect to the laser beam

⇝ Cross the analyzer with the linear polarization state produced by the half-wave plate (HWP).

⇝ Install and align the electro-optic modulator on the laser beam (for the moment, the modulator is not powered).

⇝ Observe the interference pattern obtained after the analyzer.

⇝ Adjust the orientation of the modulator in order to align the center of the black cross and the spot of the laser beam transmitted by the analyzer.

2.2 Setting when the modulator is powered

The high voltage power supply (HV) provides a voltage between 0 and 3000 V.

Warning High Voltage

- Never disconnect a cable when the power is on.
- Use only high-voltage coaxial cables (green) whose core is well protected.
- Never connect a high voltage cable directly to a low voltage cable.

The HV power supply can be adjusted with a potentiometer.

⇝ Apply to the crystal a DC high voltage close to 1500 V.

⇝ Orient the neutral axes of the crystal, Ox' and Oy', at 45° with respect to the analyzer axis.

For this, two methods are possible:

1. Search the extinction by rotating the modulator around its axis. Then, starting from the extinction, turn the modulator by 45° around its axis.

2. Do not touch the modulator (in order not to misalign it). Search the extinction by rotating the half-wave plate and the analyzer. Then turn off the HV power supply and turn the analyzer by 45°, then rotate the half-wave plate to recover the extinction.

Q1 Explain and comment on the method of alignment you have chosen.

⇝ Visually check the intensity variation obtained by varying the voltage applied to the KD*P crystal.

2.3 Study of the characteristic of the transmitted flux as a function of the applied voltage

⇝ ◇ Measure the evolution of the light intensity exiting the analyzer with the HV (between 0 and 3000 V) applied to the modulator.

⇝ ◇ Evaluate the modulation rate obtained, defined by:

$$\eta = \frac{V_{max} - V_{min}}{V_{max} + V_{min}}$$

⇝ ◇ Measure the high voltage corresponding to the maximum transmission. For this voltage, precise the polarization state produced by the modulator. Explain why this voltage is called V_π.

Q2 ◇ Deduce for the measured value of V_π the value of r_{63}, taking into account the fact that the studied modulator is made of two identical crystals in series, subjected to the same field E_z, and whose phase differences add themselves.

2.4 Study of the polarization state produced by the crystal

Q3 ◇ For what value of the applied voltage is the electrooptic crystal equivalent to a half-wave plate? to a quarter-wave plate?

⇝ ◇ Check the polarization state at the exit of the crystal for these two voltage values, by explaining the method.

⇝ ◇ Apply a voltage of 700 V, and then of 1800 V to the crystal. For each case, determine the polarization state obtained. Find out the position of the major and minor axes of the ellipse and measure its ellipticity by a photometric measurement.

Q4 ◇ Deduce the phase difference introduced by the crystal and check that the measured phase difference is consistent with the expected values.

Present the obtained results to the teacher (oral presentation graded out of 5 points).

2.5 Use of the electro-optic crystal as a linear modulator of flux

Q5 ◇ Around what operating point of the characteristic previously obtained can the electro-optic crystal be used as a linear modulator of flux?

We will replace the power supply, that can not be modulated, by a low frequency generator. *In practice: a small blue box for low to high voltage adaptation is used to send the voltage delivered by the low frequency generator directly to the modulator.*
To be in the linear region of the characteristic, you can add a wave plate just before the modulator.

Q6 ◇ What kind of wave plate has the same effect as the previous high voltage applied to the modulator? How should one orient this plate to stay around the operating point chosen in the previous section?

Q7 Explain how to perform this setting.

Q8 ◇ What is the order of magnitude of the set-up bandwidth? Use the oscilloscope to perform this measurement.

⇝ ◇ Use this setup to send through the laser beam a modulation in the audio bandwidth from the tape player mini system.

Q9 Comment and interpret. Show your set-up to the teacher for validation.

⇝ ◇ Measure the modulation rate obtained for a voltage of 20 V peak to peak applied to the crystal. Check that this modulation rate is consistent with the characteristic obtained previously.

Q10 ◇ Comment on the evolution of the flux modulation when changing the orientation of the plate.

If you still have time and curiosity

Remove the plate. Observe, discuss and analyze the intensity distribution obtained at the exit of the analyzer with a non-powered modulator for an incident polarization and the analyzer crossed (black cross observed at the beginning of the session).

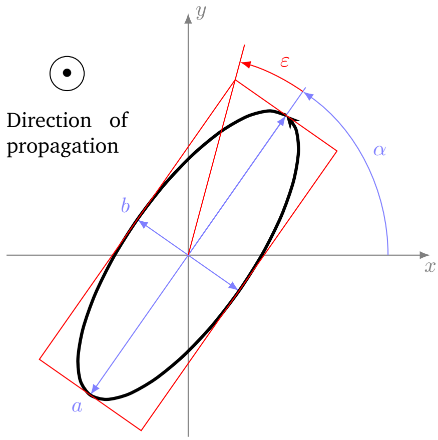
Appendices

Contents

1 Parameters describing an elliptic polarization

1.1 Definitions

Standard quantities defining elliptic polarisation appear on figure 4.3.



α : direction of the major axis of the ellipse
a : dimension of the major axis of the ellipse
b : dimension of the minor axis of the ellipse
$|\tan\varepsilon| = b/a$
ε : ellipticity + handedness
$\varepsilon > 0$: elliptique gauche

Figure 4.3 – Elliptic polarisation properties

1.2 Sense of rotation and dephasing

The projection of the electric field on the large (resp. small) axis denoted E_a (resp. E_b) are dephased by $\pm 90^\circ$. According to the sign of this phase, the ellipticity is left-handed or right-handed as it is illustrated in figure 4.4.

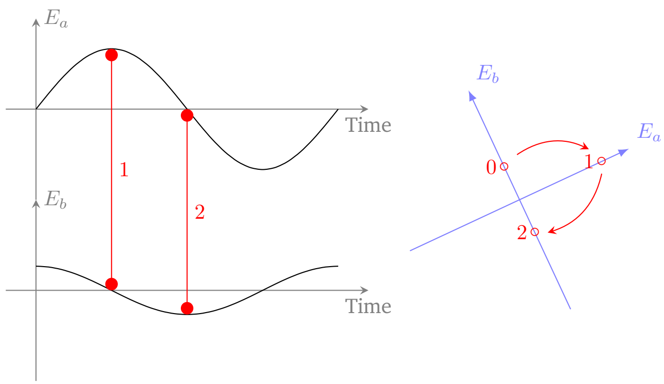


Figure 4.4 – Illustration of the relation between phase shift sign and sense of rotation of the ellipse.

1.3 Elliptic polarisation at the output of a quarter wave-plate

In particular, an elliptical polarization is created if a QWP is placed on the path of a linear polarized wave.

The ellipticity is therefore given by the angle between the direction of the input polarisation and the neutral axis of the QWP. Similarly to the diagram of figure 4.5, the ellipse is included in a rectangle whose diagonal lies on the input polarisation direction.

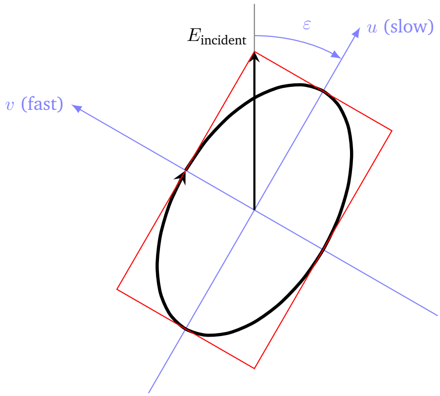


Figure 4.5 – Ellipse at the output of a quarter wave plate for a linear input polarisation. The ellipticity is indeed the angle between the direction of the input polarisation and the neutral axis of the QWP.

The axes of the ellipses are thus oriented in the direction of the neutral axes of the QWP.

1.4 Elliptical polarization at the output of an arbitrary birefringent plate oriented at 45°

In the case of a nondescript birefringent plate the polarisation is elliptical as well. However, nothing can be said in general about the direction of the ellipse axis. In the sole event where the incident input polarisation is oriented at $45^\circ$of the neutral axis, the ellipse axes are along the direction of the input polarisation.

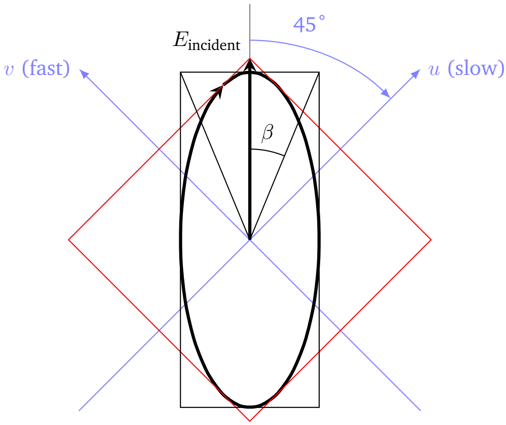


Figure 4.6 – Ellipse at the output of a nondescript birefringent plate.

The angle between a diagonal of the rectangle in which is included the ellipse defined by the extremity of the electric field vector and the direction of the incident polarisation is called β (see diagram on figure 4.6). The angle β fulfil the following relation :

$$\tan|\beta| = \left|\tan\left(\frac{\varphi}{2}\right)\right| \qquad \beta < \pi/2$$

where φ is the phase shift due to the plate (between projections on slow and fast axes).

On the previous scheme, β is rigorously equivalent to ε. But be careful ! In some cases, $\beta > 45°$. In that event, the large axis of the ellipse is orthogonal to the incident polarisation direction. The relation $\tan|\beta| = \left|\tan\left(\frac{\varphi}{2}\right)\right|$ is always valid but $\varepsilon = 90° - \beta$. In order to measure φ, it is sufficient to assess β. It is then possible to infer from β the output ellipticity properties.

Warning : Care must be taken when the polarisation is not at 45° from the plate axes. There, ellipticity and direction of the ellipse axes are not easily obtained as before !

On the following figure 4.7, phase shift introduced by the plate goes from 0 to 180° with a step of 15°. The resulting ellipticity is defined by the ellipse included in a square ($E_u = E_v$) and :

- ellipse axes are fixed at 90 °
- the ellipticity ε is given by $\pm\varphi/2$ $[\pi/2]$)

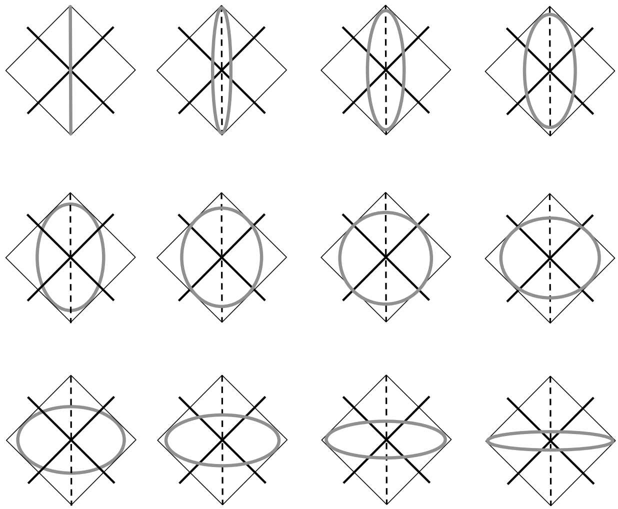


Figure 4.7 – Resulting ellipses with respect to the dephasing introduced by the birefringent plate. The incident polarisation is represented by a bold grey line when the phase is null and dashed otherwise. Its orientation stands at 45° from the neutral axes of the plate appearing in bold black lines.

2 Using a quarter waveplate to measure the ellipticity

It is a two steps method:

1. The small axis of the ellipse is spot thanks to a polariser.

2. A quarter-wave plate is added before the analyser with its slow axis perpendicular to the previously determined minor ellipse axis. This procedure allows to create a linear polarisation that makes an angle ε with the quarter wave plate slow axis. The extinction is recovered rotating the analyser by a ε angle. In this case the rotating angle is smaller or equal to 45°.

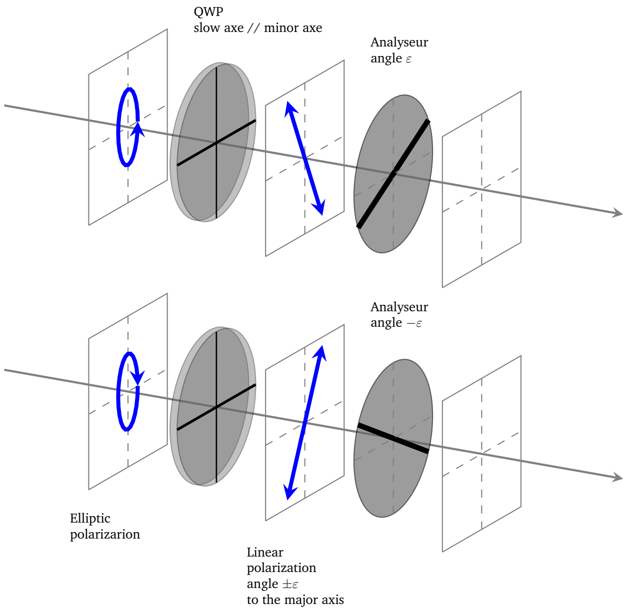


Figure 4.8 – Illustration for the quarter “waveplate method” to measure the ellipse’s main parameters.

3 Newton's color scale

δ in nanometers optical path difference	scale with white center $I = I_0 \cos\left(\frac{\pi\delta}{\lambda}\right)$	scale with black center $I = I_0 \sin\left(\frac{\pi\delta}{\lambda}\right)$
0	white	black
40	white	iron-gray
97	yellowish-white	lavander-gray
158	yellowish-white	grayish-blue
218	brown yellow	clear gray
234	brown	greenish white
259	light red	almost pure white
267	carmin red	yellowish-white
275	dark brownish-red	pale straw-yellow
281	dark violet	straw-yellow
306	indigo	light yellow
332	blue	bright yellow
430	greyish-blue	brownish-yellow
505	bluish-green	reddish-orange
536	light green	red
551	yellowish-green	deep red
565	light green	purple
575	greenish-yellow	violet
589	golden yellow	indigo
664	orange	sky blue
728	brownish-orange	greenish-blue
747	light carmin red	green
826	purple	light green
843	violet purple	yellowish-green
866	violet	greenish-yellow
910	indigo	pure yellow
948	dark blue	orange
998	greenish-blue	bright reddish-orange
1101	green	dark violet red
1128	yellowish-green	light bluish-violet
1151	dirty yellow	indigo
1258	skin color	blue (greenish tint)
1334	brownish-red	sea green
1376	violet	bright green
1426	greyish violet blue	greenish-yellow
1495	greenish-blue	pink (light tint)
1534	blue green	carmin red
1621	pale green	carmin purple
1658	yellowish-green	violet grey
1682	greenish-yellow	greyish-blue
1711	greyish-yellow	sea green
1744	greyish-red mauve	bluish-green
1811	carmin	nice green
1927	reddish-grey	gris green
2007	greyish-blue	almost white grey
2048	green	light red
2338	light pink	light blue green
2668	light blue green	light pink