S1-UE4 Laboratory practice

Contents

Attention: The descriptions in this document are supposed to be a base for ***your preparation*** of the session. They will help you to *find the useful formulas* that are not necessarily mentioned in the description.

Planning

Titles and numbers of the 10 lessons:

1 Geometrical optics
2 Raytracing with Oslo
3 Fourier optics

4 Polarization
5 Monochromator

6 Michelson interferometer 1
7 Michelson interferometer 2
8 Spectroscopy

9 Photodetectors
10 Holography

The table gives the lesson number a certain group will do at a certain date

Dates	Groups 1	2	3	4	5	6	7	8	9	10	11
September 26, 2019	1	2		3		4	5	6		6	8
October 3, 2019	2	6	3	4	1	5			7	8	9
October 10, 2019		3	4		5	6		7	8	9	1
October 17, 2019	3	4		5	6		7	8	9	1	2
October 24, 2019											
October 31, 2019	4		5	6	1	7	8	9	3	2	
November 7, 2019	10	5	10	10	4	8	9	1	2		3
November 14, 2019	5		6	7	8	9	1	2		3	4
November 21, 2019	6	10	7	8	9	1	2	3	4	10	10
November 28, 2019		7	8	9	3	2	6	10	10	4	5
December 5, 2019	7	8	9	1	2		3	4		5	6
December 12, 2019	8	9	1	2	7	3	4		5	7	
December 19, 2019	9	1	2		10	10	10	5	6		7
December 26, 2019											
January 2, 2020											
January 9, 2020	Exam	Exam	Exam	Exam	Exam	Exam	Exam	Exam	Exam	Exam	Exam
January 16, 2020											

GEOMETRICAL OPTICS

<u>As preparation</u> refresh your knowledge on the image formation formula for thin lenses (relationship between image distance, object distance and focal length), autocollimation method for placing a lens.

The goal of this experimental work is to illustrate some basic concepts of geometrical optics: magnification, aperture, field, field depth…

At your disposal, these few lenses with different characteristics: focal length, singlet or doublet,… a few iris diaphragms, a white light source, some slides and slide holders, a screen…

PART A – Basic observations and measurements

A1 – Singlet and doublet lenses:

Make a magnifying image of the filament of the lamp. Use a singlet lens for the projection and replace it thereafter by a doublet with the same focal length.

- Discuss the differences between the two images.
- Is the result different for different orientations of the lenses?
- Name the two main advantages that doublet lenses have compared to singlet lenses..

A2 – Measuring a focal length:

Measure "the focal length" of a lens that you choose using two methods. If the lamp is strong enough, the best object is probably a closed diaphragm on the optical axis.

- Why did I put quotation marks around "the focal length"?
- First measurement method, the auto-collimation method.
- Second measurement method, the Bessel method: If $D > 4f$, then $f = \frac{D^2 - d^2}{4D}$, here D is the distance between object and screen and d is the distance between the two lens positions where a sharp image is obtained.
- Compare the results for both methods and do not forget to explain the calculation of the uncertainties for both methods.

PART B – Imaging systems

We can define *Aperture* and *Field* for any imaging system. As illustrated in Figure 1:

- The system *aperture* is related to the amount of light that can be transmitted for an object point that is located on the optical axis.
- The *field of view* is related to the size of the object that can be imaged by the system

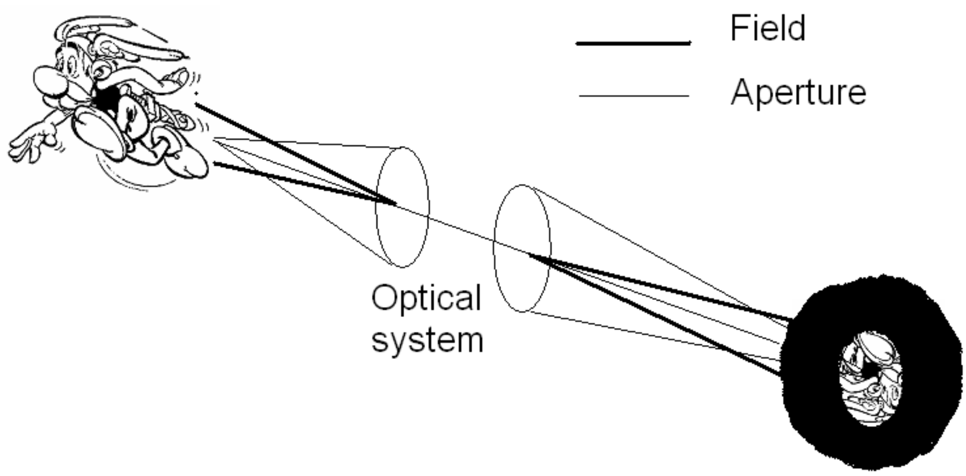


Figure 1: Illustration of the definitions of field and aperture(s) of an imaging system

We will consider here imaging systems like slide projectors or microscopes in which the object, supposed to be plane and non-diffusing, must be first illuminated before being imaged. The complete system can therefore be divided in two subsystems, namely the illuminating and the imaging systems for which the required optical properties are different. However, field and aperture aspects are in close relation between these two sub-systems.

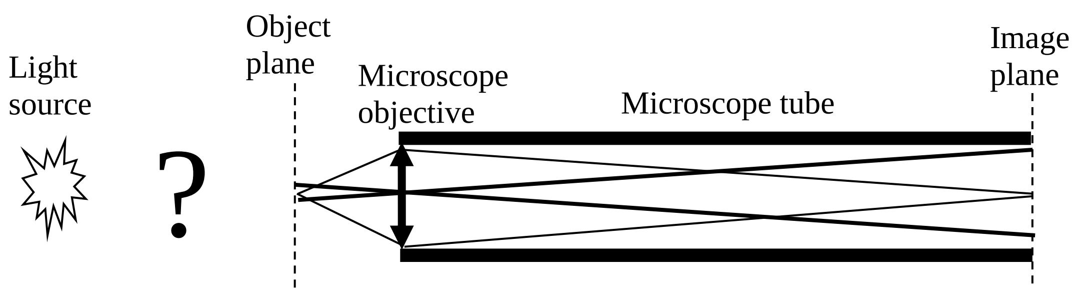
B1 – Slide projector:

Build a system that works like a slide projector. In particular think about the major properties required for the illumination system and for the imaging system.

- Justify the system design and the choice for the lenses.

B2 – Microscope illumination system:

In microscopy, once aperture and field of view have been fixed by the choice of the magnification microscope objective, it can be of great importance to illuminate the object under observation respecting these field and aperture values.
The so-called Köhler-illumination allows to obtain a homogeneous illumination of the object where one can adjust separately and independently field and aperture of the illumination beam. (Luminosity may be kept constant by regulating the lamp intensity).



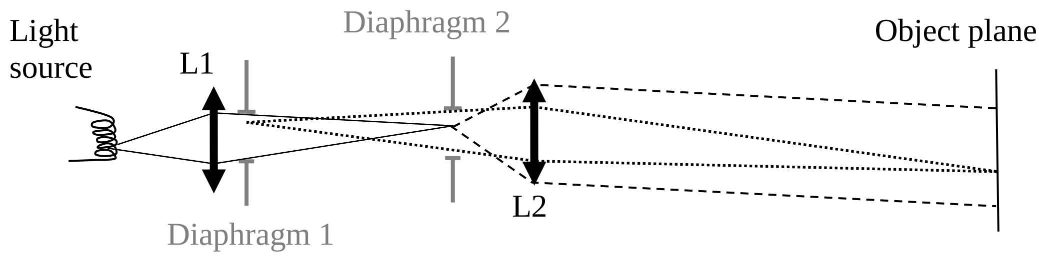


Figure 2: Schematics of a microscope illumination system. Diaphragm 1 should be close to Lens 1 (L1). All other distances depend on the chosen lenses and have to be set in order to reproduce the paths of the indicated ray bundles.

- Realize the setup given in Figure 2.
- Explain how the setup works. In particular, explain the roles of the diaphragms.

B3 – Illumination system for dark field microscopy:

In the previous examples, the object was supposed to sufficiently modulate the illumination intensity in order to cause good transmission contrast. For biological samples this is not always true but the object may contain high spatial frequencies, in other words small details, which will diffract or diffuse the light. Imaging using diffracted or diffused light can be used to generate improved contrast.
For high resolution microscopy it is mandatory to collect all this light to reconstruct correctly the image of the object. This is the reason why high magnification microscope lenses must have a large aperture.

Dark field microscopy consists in illuminating the object with a larger aperture than required by the microscope lens, while obstructing its nominal aperture.
In case the object only contains low spatial frequencies, no light can enter the system and the image is completely dark. In case the object contains small light-diffusing details, some scattered light will be able to go through the system and form a bright image of these details on a globally dark background. This is a simple and efficient way to point out small details that could hardly be seen in a bright field.

- Build an illuminating system based on this principle. Use the carton disk to avoid direct light to enter the imaging lens (the one between object and screen). The best object to look at is some transparent tape with a fingerprint on it or the edge of a microscope slide / tape.

PART C – The formula for thin lenses

Make an experimental verification of the fundamental formula for thin lenses.
- Represent the results in a set of graphs.

The results of the measurements need to be unambiguous in the sense that they should not allow any other interpretations than the one you want to prove.

RAY TRACING

As preparation get some information on what ray-tracing programs do and check through the main optical aberrations encountered in imaging devices.

The goal of this experimental work is to use a ray tracing software (OLSO EDU, free downloadable software) and to illustrate the major geometrical aberrations.

The first step is to define the optical system which is reduced to a list of surfaces separating different media, starting from the object/source surface, up to the observation surface (improperly called “image surface” since there may be no sharp image)
For each surface must be specified the position (generally with respect to the previous surface), the shape (plane, spherical, toroidal, curvature radius…), and many other characteristics (mirror or not, grating…)
For each media must be specified the materiel or at least refractive index. Check pages 35 and 36 in the file: OSLOOpticsReference.pdf

Then must be specified the points that are considered on the object surface, the wavelengths that must be used, and what must be calculated.

At a basic level, calculations will be performed using geometrical optics theory that is to say only refraction and reflection laws (Snell-Descartes) for a fan of rays issued from the object/source and propagating through the system up to the last plane. Starting from an object/source reduced to a single point, this calculation can show for example the spreading of the light in the final plane. By moving this plane, it is possible to find a minimum light spot diameter corresponding to the best image that can be obtained of the object (best focus). Contrarily to what is assumed in paraxial optics, this image is not perfect, but more or less enlarged due to optical aberrations.

In order to improve the result, ray tracing programs are able to optimize the system design, that is to say modify the geometrical characteristics of surfaces (curvature radii, distances) in order to minimize the image spot size. The limit for ray tracing is reached as soon as the spot size is lower than the diffraction limit (which is not so easy to achieve…)
At this point the software is able to perform calculations using diffraction theory and give realistic results.

After familiarizing yourself with OSLO (for example follow the beginning of the OSLOUserGuide.pdf file), perform the simulations described on the backside of this sheet and do not forget to save each step so that the teacher can watch what you did before. Write down the results of the simulations that provide answers to the questions.

1) The light source is on axis, located at infinite distance.
Perform ray tracing for a BK7 half-ball lens (plane face in the direction of the source) 50 mm in diameter.
Give the name of the geometrical aberration you can observe.
What about the f-number (= f/D) that quantifies the aperture of the system?

2) Consider a plano-convex BK7 lens, 50 mm in diameter, with a focal length of 200 mm.
The light source is on axis, located at infinite distance.
Is there a preferable orientation to use this lens?
Compare the result with an equivalent symmetrical lens.

3) Still considering the same lenses, consider now that the object is located at 400 mm.
Which one gives the best result?

4) The light source is on axis, located at infinite distance.
Consider a convergent spherical mirror 50mm in diameter, with a focal length of 200 mm.
Is it better or worse than a lens of similar characteristics?
Change this spherical mirror into a parabola (set the conic constant to -1).
What is the result for an on-axis light source, and for a 1°-incidence light source?
Give the name of the aberration you can observe.

5) The light source is located at infinite distance.
Consider a lens 20 mm in diameter, with a focal length of 200 mm.
What is the aberration you can observe when tracing together the response at 0°, 10°, 20°, 30° and 40° incidence.

6) Reduce the lens diameter to 2 mm and observe the evolution of the spot diagram at oblique incidence (40° ?) when translating the image plane around the best focus plane.
Give the name of the geometrical aberration you can observe.

7) Optimize the curvature radii of a single BK7 lens to obtain the minimum spot size for a light source located at infinite distance. For the definition of the merit-function see ‘aberration operands’ on page 360 (346) in OSLOProgramRef6X.pdf.

************* if there is extra-time ************

8) Compare an achromatic doublet to an equivalent singlet lens (infinite, polychromatic source).
You may use this doublet: air, 83.18mm, BK7, -71.12mm, SF5, -247mm, air

9) Calculate the Point Spread Function of a diffraction limited system (achromatic doublet?).

Fourier Optics

As preparation refresh your knowledge on diffraction (Fraunhofer approximation), gratings, imaging and coherence.

The formalism of Fraunhofer diffraction allows us to use the powerful mathematical tools of Fourier analysis in diffraction observations. We call these observations and imaging manipulations "Fourier optics". In these lab experiments, we will observe Fourier image formations and spatial filtering.
When a flat object characterized by a transparency (transmission coefficient for the wave amplitude) $t(x,y)$ is illuminated by a plane wave, the far-field diffracted amplitude in direction (θ_x, θ_y) is given by

$$A(p,q) = \alpha A_0 \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} t(x,y)\exp(-i2\pi px - i2\pi qy)\,dx\,dy$$

with $p = \frac{\theta_x}{\lambda}$ et $q = \frac{\theta_y}{\lambda}$ for $\theta_x, \theta_y << 1$
$A(p,q)$ is the Fourier transform of $t(x,y)$. p and q are called spatial frequencies.

An experimental set-up will be implemented. Propagation of the wave along the different optical elements will be analyzed and interpreted based on the Fourier formalism. A frequency analysis of different bi-dimensional transmission objects will be conducted and spatial filtering will be observed. Questions along the text will guide you in your preparation, your observations and your report.

1. Observation of diffraction patterns

Set-up alignment
The set-up that permits a good observation of Fraunhofer diffraction pattern is shown in figure 1. To observe an image which is not too small, the focal distance of the second length must be at least 1m.

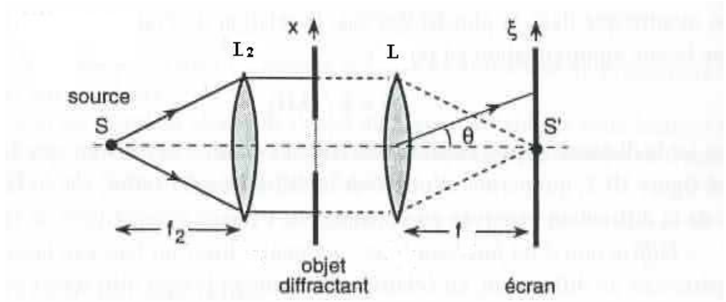


Figure 1 (Sextant, Optique expérimentale)

To increase the luminosity and the size of the diffraction image, we generally use a simplified set-up shown in figure 2.

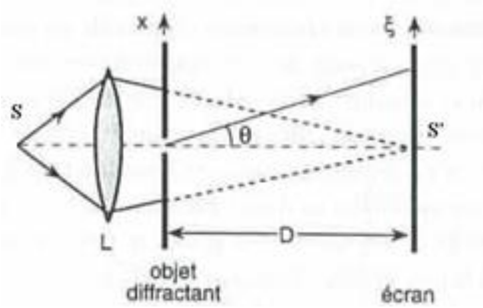


Figure 2 (Sextant, Optique expérimentale)

Build-up this set-up. Laser alignment, lenses centering, quality of the collimated beam are essential for good observations. What are the conditions that permit to consider that the two set-ups are equivalent?

Diffraction pattern of a grating
The object is a grating with its lines parallel to y axis.
What do you observe in the Fourier plane?
What happens…

- …when you move the grating in the x direction?
- …when you turn the grating around the optical axis?

From a measurement on the diffraction pattern deduce the number of lines of the grating per mm?

Place a slit close to the grating and observe the diffraction patterns

- when the slit is large compared to the grating period
- when few lines are selected
- when ultimately one line is selected.

Explain theoretically these observations.

2. Spatial filtering

Change the position of the screen to observe the image of the grating as in figure 3.

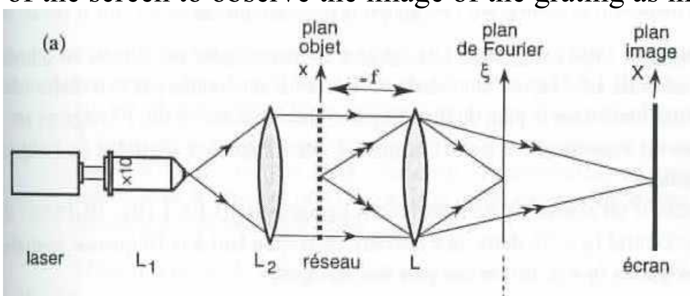


Figure 3 (Sextant, Optique expérimentale)

Low pass filter
Place a slit in the Fourier plane and observe the evolution of the image

- when the slit is large compared to the diffraction period
- when few points are selected
- when ultimately the central point is selected.

Explain theoretically these observations.

Replace the grating by a grid and observe again. When the slit only selects one line, turn it by 90°. What happens?
Using the gained knowledge you should be able to take the Daltons "french comics figures" out of prison.

High pass filter
The object is now a feather or a phase object as a fingerprint.
Observe the diffraction pattern. Then, observe the image of the object and place a small mask in the Fourier plane to hide the centre of the diffraction figure.
Describe your observation and explain it theoretically.

Using a white lamp
Replace the laser by a white lamp, the microscope objective by a lens with a short focal length. A small hole forms the source S.
Observe spatial filtering with this new lighting.
What type of coherence is necessary for spatial filtering?

Polarization of light

Keywords :

- Polarization state, plane of incidence, polarizer, Brewster's angle, Malus' law, retardation plates, degree of polarization

Goals : The aim of this practice course is to study one characteristic of light: Polarization. You will study:

- how polarized light can be obtained,
- how its polarization can be modified or measured,
- how its degree of polarization obtained.

Elements of the experimental setup:

- 1 laser source,
- 2 polarizers,
- 1 quarter-wave and 1 half-wave plates,
- 1 glass plate on a rotation stage,
- 2 photodiode with their amplifier linked to a multimeter.

Bibliography :

- S. Huard, "Polarization of Light" (Wiley).
- J. Goodman, "Statistical optics" (Wiley).

1 Theoretical background

In a dielectric medium, the electromagnetic field of a monochromatic plane wave, verifies the Maxwell's equations. As $\nabla \cdot \mathbf{D} = 0$ (and $\nabla \cdot \mathbf{B} = 0$), the electric field displacement $\mathbf{D}$ (and the magnetic field $\mathbf{B}$) are orthogonal to $\mathbf{k}$, meaning that they vibrate in the plane perpendicular to the propagation direction. The evolution of the direction and the amplitude of the vector $\mathbf{D}$ characterizes the polarization state of the wave. Note that $\mathbf{D} = \varepsilon_0 \, \mathbf{E}$ in freespace.

If the wave propagates along the the vector $\mathbf{z} = (0, 0, 1)$, the complex electric displacement field can then be written as:

$$\mathbf{D}(z,t) = \mathbf{D}_0 \exp(-i(\omega t - kz - \mathbf{\Phi})) \tag{1}$$

with $k := |\mathbf{k}|$ the wavenumber and ω the angular frequency.

The real (part of) electric displacement field can then be written as:

$$\mathrm{Re}\{\mathbf{D}(z,t)\} = \begin{bmatrix} D_x(z,t) = A_x \cos(\omega t - kz - \Phi_x) \\ D_y(z,t) = A_y \cos(\omega t - kz - \Phi_y) \\ 0 \end{bmatrix} \tag{2}$$

In the general case Eq. 2 suggests that, when time increases, the field describes an ellipse in xy-plane. It is elliptically polarized. Particular cases occur :

- If the amplitudes A_x and A_y are equal and the phase shift $\Phi := \Phi_x - \Phi_y$ equals $\pi/2 + p\pi$ (with p integer), the field describes a circle and the light is said circularly polarized;
- If the phase shift Φ equals $0 + p\pi$, the field describes a line and the light is said linearly polarized.

A light is said to be non-polarized if the field varies randomly as a function of time in xy-plane.

2 Production of polarized light

Polarizers.

Polarized light can be produced by a dichroism caused by reflection, diffusion or birefringence. A dichroic polarizer converts any beam of electromagnetic waves into a beam with linear polarization. It transmits a particular direction and absorbs or reflects the perpendicular one. A dichroic polarizer can also be used as an analyzer.

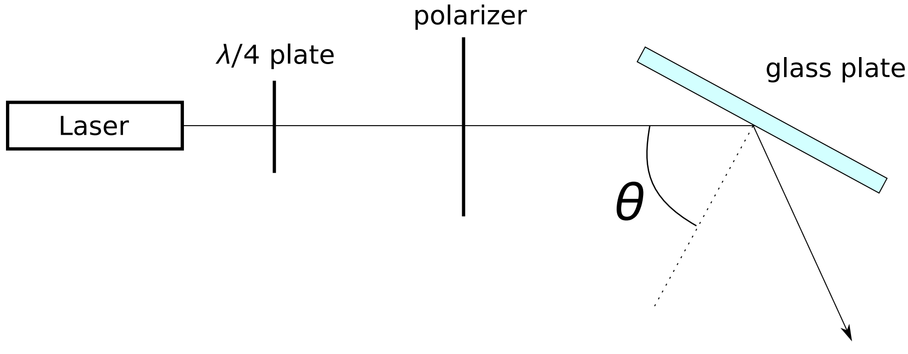


Figure 1: Brewster's angle analysis

Polarization by reflection. Brewster's angle.

Important definition: The resulting electromagnetic radiation after the set {laser + polarizer} is linearly polarized. When this radiation hits some object (*e.g.* a glass plate) at non-normal incidence, one can define the so-called plane of incidence as the plane formed by the normal to the surface and the incident wave vector **k**. If the electric field stays perpendicular to the plane of incidence, it is said to be TE- (or *s*-) polarized. If the electric field vibrates within the plane of incidence, it is said to be TM- (or *p*-) polarized. (The magnetic field is then transverse to the plane of incidence).

From the classical derivation of Fresnel coefficients, it appears that the reflexion coefficient can vanish in one polarization case (TM) for a specific angle of incidence, called Brewster's angle. With the set-up described on figure 1 determine and measure the Brewster's angle. Before starting work, you can check the stability of the laser, especially at start up time, by measuring the intensity of the light traveling through the polarizer solely (attenuation might be needed to avoid saturation of the photodiode). It should remain constant, up to acceptable fluctuations.

- Determine and measure the Brewster's angle as precisely as possible. Explain your procedure.
- List the different sources of uncertainty associated with your procedure.
- How can you reduce the uncertainty on your determination of Brewster's angle?

3 Malus' law

Two consecutive linear polarizers are placed in front of a non-polarized light source. The second one is called analyzer. The transmitted light by both polarizers is measured with a photodiode as a function of the angle between polarizer and analyzer (cf. figure 2).

- Give the theoretical expression of the intensity after the analyzer.
- Retrieve Malus' law experimentally and plot your result.

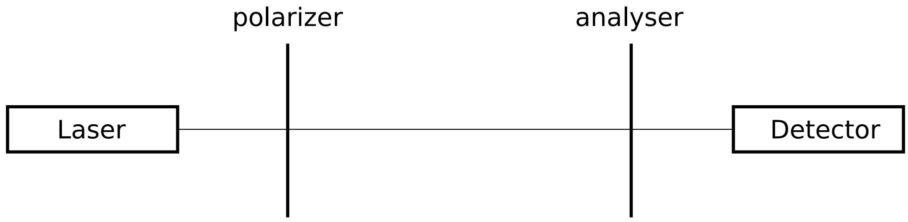


Figure 2: Measurement of the Malus' law

4 Retardation plates

A retardation plate (or wave plate) introduces a phase shift between two particular perpendicular directions called neutral lines NL_1 and NL_2. A beam linearly polarized parallel to NL_1 (resp. NL_2) propagates without polarization modification with a propagation velocity V_1 (resp.

V_2) associated to a refractive index n_1 (resp. n_2). If h is the thickness of the plate, the phase shift between the both beams is:

$$\Phi = \frac{2\pi}{\lambda}(n_1 - n_2)\,h\,. \tag{3}$$

Particular cases occur:

- when $\Phi = \pi$, the retardation plate is a half-wave plate,
- when $\Phi = \pi/2$, the retardation plate is a quarter-wave plate.

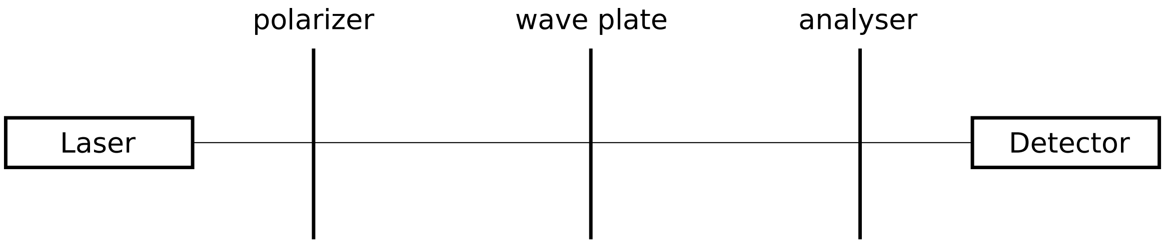


Figure 3: Measurement of the quarter-wave plate effect on a linear polarization.

Determination of the neutral lines of the plate.

- Think about what happens when one observes linear, circular or elliptical polarizations across a rotating analyzer.
- Describe a method that allows to determine the neutral lines of the plate. *Hint*: This question is linked to your conclusion of Sec. 3.
- Apply it to the plates at your disposal.

Study of the effect of a quarter-wave plate on a linear polarization.

As mentioned in previous sections, do not forget to take measurements of the power before the analyzer. This will allow you to take into account the source fluctuations.

- Place the polarizer in front of the light source, align a neutral line of the plate with the polarization of the incident light. Place an analyzer behind the plate. Measure the intensity as a function of the analyzer angle.
- Place the polarizer in front of the light source, tune the quarter-wave plate so that the angle between incident polarized light and neutral lines equals 45°. Place an analyzer behind the plate. Measure the intensity as a function of the analyzer angle.
- Place the polarizer in front of the light source, tune the quarter-wave plate so that the angle between incident polarized light and neutral lines is different from 0° and 45°. Place an analyzer behind the plate. Measure the intensity as a function of the analyzer angle.
- For all cases, deduce the polarization of the light after the wave-plate and explain the results. In order to analyze your measurements extract all characteristic data from them. As in general it is an ellipse these are: direction of long axis, direction of short axis, ratio long/short axis. Give a realistic representation of these ellipses.

Study of the effect of a half-wave plate on a linear polarization
Do the same experiments as above for a quarter-wave plate.

5 Degree of polarization

Background: Coherency matrix

We now consider the problem of describing the state of polarization of a wave. In general, the direction of the electric vector may fluctuate with time in a complicated deterministic or random manner. A useful description is supplied by the so-called coherency matrix[1]. It is defined, given a coordinate system $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ as in Sec. 1, as:

$$J(\mathbf{r}) = \begin{bmatrix} \langle E_x(\mathbf{r},t)\, E_x(\mathbf{r},t)^* \rangle_t & \langle E_x(\mathbf{r},t)\, E_y(\mathbf{r},t)^* \rangle_t \\ \langle E_x(\mathbf{r},t)^*\, E_y(\mathbf{r},t) \rangle_t & \langle E_y(\mathbf{r},t)\, E_y(\mathbf{r},t)^* \rangle_t \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{12}^* & J_{22} \end{bmatrix} \tag{4}$$

The matrix J so defined is called the coherency matrix of the wave. The elements on the main diagonal of J are clearly the average intensities of the $x-$ and $y-$polarization components. The off-diagonal elements are the cross-correlations of the two polarization components. This matrix allows to write in a synthetic manner the polarization state of a wave.

Particular cases

- **unpolarized light**: there is no temporal correlation between E_x and E_y. Off-diagonal coefficients of J are both null.
- **totally polarized light**: full correlation between E_x and E_y, which translates as: $|J_{12}| = \sqrt{\langle |E_x(\mathbf{r},t)|^2 \rangle_t \, \langle |E_y(\mathbf{r},t)|^2 \rangle_t}$. One can show that $\det[J(\mathbf{r})]$=0.

General case and Degree of Polarization (DOP)

In the general case, a wave is partially polarized. Then, citing Goodman again, "*it would be highly desirable, both aesthetically and from a practical point of view, to find a single parameter that will characterize the degree to which a wave can be said to be polarized. For the case of a linearly polarized wave, this parameter should have its maximum value (unity for convenience), for such a wave is fully polarized by any reasonable definition. For circularly polarized light, the parameter should again have its maximum value, for such light can be made linearly polarized, without loss of energy, by means of a quarter-wave retardation plate. For the case of natural light, the parameter should have value zero, for the polarization direction is totally random and unpredictable in this case.*"

One can show that a good definition of the DOP is given by:

$$\mathrm{DOP}(\mathbf{r}) = \sqrt{1 - 4\frac{\det\left[J(\mathbf{r})\right]}{\left(\mathrm{Tr}\left[J(\mathbf{r})\right]\right)^2}}\,. \tag{5}$$

[1] see pages 130 – 136 of : Goodman, J. W. & Haupt, R. L. (2015). *Statistical optics.* Second Edition. John Wiley & Sons.

Measure of the DOP

In order to measure the degree of polarization of the laser source available on the optical bench, one has to provide the matrix coefficients in Eq. 4 and make the use of Eq. 5. Of course, this is independent of the choice of the coordinate system. To make it simple, let Ox be the horizontal axis (parallel to your table) and Oy the vertical axis.

- J_{11} (respectively J_{22}) can be obtained by measuring the flux trough a polarizer at 0° – along Ox (resp. 90° – along Oy).
- The real part of J_{12} be obtained by measuring the flux I_1 trough a polarizer at $45°/Ox$. Then $\mathrm{Re}(J_{12}) = I_1 - (J_{11} + J_{22})/2$.
- The imaginary part of J_{12} is finally obtained by measuring the flux trough a $\lambda/4$ plate with neutral line at $45°/Ox$, and an analyzer at at $45°/Ox$. Then $\mathrm{Im}(J_{12}) = I_2 - (J_{11} + J_{22})/2$.
- $J_{21} = J_{12}^*$

Perform the measurements. Calculate the DOP. Any comment?

CZERNY-TURNER MONOCHROMATOR

<u>As preparation</u> refresh your knowledge on diffraction gratings. Fundamental formula. Theoretical resolution of the diffracted beams. How to measure number of lines of the grating in such a setup?

Two kinds of instruments can be used to performed spectral analysis:

- those based on the use of an interferometer like Fourier Transform Spectrometers
- those based on the use of a light disperser, like monochromators.

The main characteristics of these instruments are

- the spectral range that can be addressed
- the spectral resolution
- the transmission efficiency
- …

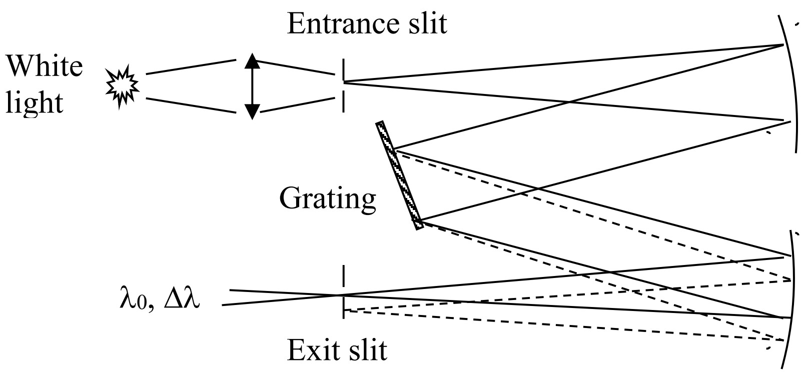
In the case of Fourier Transform Spectrometry, the measured signal, called the interferogram, contains information on the whole spectrum, and the spectrum itself can be obtained from the interferogram by the means of Fourier Transform calculations.

On the contrary, a monochromator is an optical instrument that can extract from the incoming light a small bandwidth $\Delta\lambda$, centered on the tunable wavelength λ_0. By tuning the center wavelength it is possible to sweep a complete spectral range to perform spectral analysis. But a monochromator can also be used as a simple filter to select a wavelength, which is not possible with a Fourier Transform Spectrometer.

The goal of this experimental work is to « build » a monochromator, according to the classical Czerny-Turner design. (See figure)

Basically, a monochromator is based on the use of a light disperser, prism or grating, illuminated with a collimated beam. The angular deviation of the beam provided by the disperser thus allows a geometrical separation of the wavelengths.

According to the following figure, the collimated illumination beam is generated by a thin entrance slit located in the focal plane of a lens or mirror. A second lens or mirror, placed on the dispersed output beam gives an image of the light spectrum in its focal plane. An exit slit thus allows selecting any wavelength λ_0 of the spectrum, with the spectral resolution $\Delta\lambda$.



Changing the selected wavelength λ_0 can be obtained by translating the exit slit in the spectrum plane.

It is also possible to have a fixed exit slit and to rotate the light disperser, which causes a translation of the spectrum. This last configuration is preferable from the optical point of view (it minimizes geometrical aberrations), but also from a practical point of view if an optical instrument must be placed at the exit of the monochromator.

The elements at your disposal are:

- A low pressure Hg spectral lamp
- Two variable slits
- Two converging mirrors
- A grating
- A telescope for alignment

The post holders are slightly magnetic. The elements can anyway fall easily if the clamps are not screwed to fix the post holders. Especially in the dark, take care not to bring any element to fall or to touch optical surfaces.

A few recommendations:

The goal here is to reach the highest spectral resolution, and the monochromator should be able to separate the two yellow mercury lines.
For this, the instrument must be as symmetrical as possible, with incidence angle as low as possible. All parts must be mounted and adjusted precisely.

If you want to use the telescope for checking the parallelism of incoming light: Adjust the telescope so that you see a sharp image of the cross-hair and of a faraway object. Look through the telescope onto one spherical mirror which reflects the illuminated slit. If you see the slit sharp at the same time as the cross-hair, the light coming from the mirror is similar to the light coming from the faraway object. Thus the slit is placed in the focal plane of the mirror.
For checking the parallelism of incoming light, you can also use the auto-collimation procedure: a plane mirror placed after the collimating mirror must image the entrance slit onto itself. (Sharp image of same size.) This procedure is usually easier than the first one.

Questions

- ➢ Show that your monochromator can separate the two yellow lines. (Using your eye after the exit slit or the CCD line camera.)

- ➢ Measure the wavelength of the green line.

- ➢ Measure number of lines of the grating (per mm) with highest possible precision. You need to prepare this part in order to take the right measurements.

- ➢ What is the theoretical resolution we have with this grating? What is the experimental resolution we have? Which components limit the resolution of our setup?

- ➢ What can you say about the diffraction efficiencies of the orders -1, 0, +1 and +2?

Some spectral lines given by a low pressure mercury lamp:

404.7 nm	Violet	435.8 nm	Blue
577 and 579.1 nm	The two yellow lines		

Michelson interferometer I: manipulations

The Michelson interferometer is an amplitude-splitting two beam interferometer. The incident beam is amplitude separated in two perpendicular and physically separated beams of equal intensities. After two different path lengths the two beams interfere and we study the interference pattern. This interferometer permits a lot of interesting experimentations. With a simple set-up, A. Michelson (1852-1931) realized the first measurement of the speed of light in 1878. With E. Morley, in 1887, he realized with its interferometer the famous experiment in which they have shown that the speed of light in Earth was identical whatever the direction of light. A. Michelson obtained the Nobel Price of Physics in 1907.
With this interferometer, we can observe fringes of equal inclination (Haidinger fringes) when the mirrors M_1 and M'_2 (image of M_2 by the beam splitter SR) are exactly parallel. These fringes are rings located at infinity. We also can observe fringes of equal thickness (Fizeau fringes) when the two mirrors M_1 and M'_2 form a small angle. The fringes are parallel lines located on the mirrors.
The interferometer permits the illustration of the two aspects of the coherence of light: temporal coherence or spectral finesse of the source and spatial coherence or geometric extension of the source.

The aim of the experimental work on this first part on Michelson interferometer is to manipulate and adjust a Michelson interferometer, to understand all the observed interference figures with different sources.

1. Description

The Michelson interferometer is composed of 3 optical elements: 2 mirrors M_1 and M_2 and a semi-reflective plate (SR). This plate divides the incident beam in two beams with equal intensities. These two beams, reflected by the two mirrors, interfere when coming back.

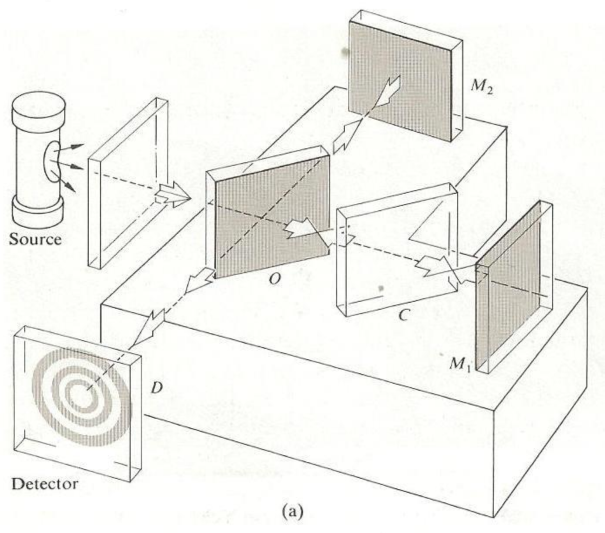


Figure 1: Hecht, Optics

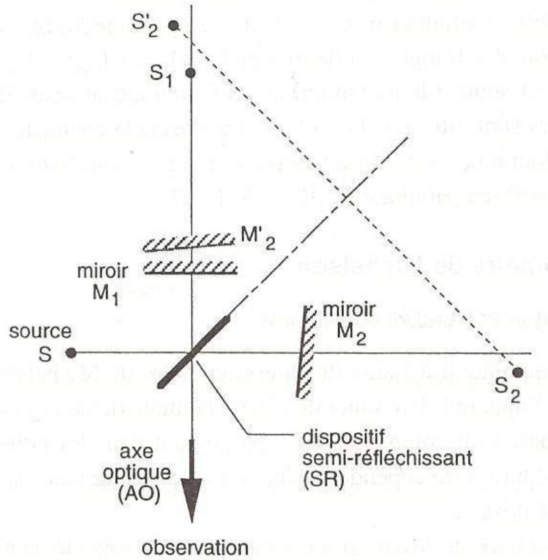


Figure 2: Sextant, Optique expérimentale

An optical path difference can be introduced between the two paths by moving M_2 mirror with a translation mount or by tilting one of the mirrors. "Optical contact" is obtained when M_1 is the exact image of M_2 by SR meaning that M_1 and M'_2 are superimposed.
SR is composed of two identical plates with parallel faces: the beam splitter with an optical

treatment on one face to obtain a semi reflection coefficient and a compensator with role is to compensate the difference of optical path introduced by the beam splitter for the two different paths inside the interferometer. This second element is really important when working with a large polychromatic source, because the path introduced by the beam splitter is angle and wavelength dependent.
Usually, the entrance of the interferometer has an antithermic filter whose role is to avoid mirror deformations with heat.
The observation is operated in a plan perpendicular to the optical axis AO.

2. Role of the different screws

B_1 and B_2 permit to align the compensator to be exactly parallel to the beam splitter
C_1 and C_2 permit a rough control of the orientation of mirror M_2
A_1 and A_2 permit a thin control of the orientation of mirror M_1
C_3 is a translation control of mirror M_2

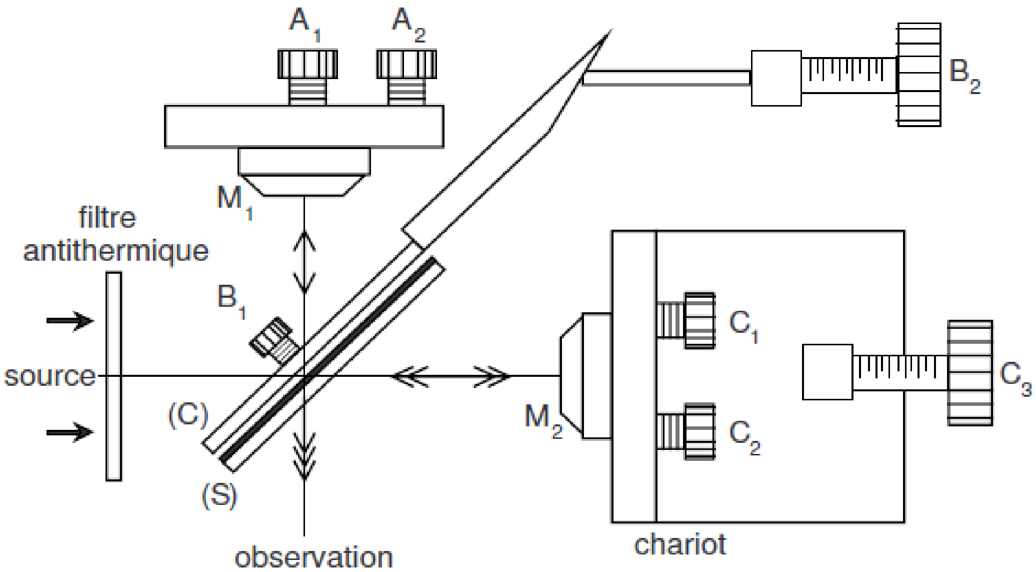


Figure 3 :From Sextant, Optique expérimentale

3. Adjustment near the "optical contact" with the laser

Here a procedure using a laser is described. It is not the only one.

Adjustment of the parallelism of the beam splitter and the compensator
Send the laser in a diagonal way perpendicularly to the beam splitter and compensator. On a far screen, observe the different reflection spots and superpose them to adjust the parallelism between the beam splitter and the compensator.

Rough adjustment of the mirrors
Secondly, after a preliminarily visual adjustment, send the laser at the entrance of the interferometer. On a screen, superpose the two brightest spots by acting on the parallelism of the mirrors.

Adjustment to the "optical contact"
Place at the output of the laser a lens with a small focal length to simulate a point source and

to have beams with different angles. You must observe rings.

To well understand Michelson adjustments (see Hecht, Optics) when it is illuminated by a point source S (figure 2), we must notice that:

- beams that travel through each path of the interferometer and interfere on the screen seem to come from two sources S_1 and S'_2, images of source S from (SR, M_1) and (SR, M_2). If the two mirrors are parallel, S_1 and S'_2 are aligned along the optical axis OA. At “optical contact”, S_1 and S'_2 are at the same place.
- Far from “optical contact”, S_1 and S'_2 are on the OA line and the interference figure is concentric rings. When the distance *e* from S_1 to S'_2 decreases, the rings go towards the center of the figure. Each black ring corresponds to a integer *p* with $2e\cos i_p = p\lambda$. When e decreases, for the same p, $\cos i_p$ must increases and the angle i_p decreases.
- When *e* becomes very small, if the mirrors are not rigorously parallel, the transverse difference between S_1 and S'_2 becomes preponderant and the rings become straight fringes parallel to the coin edge formed by the two mirrors. When the angle between the two mirrors decreases the distance between the fringes increases and the lines bend.
- When the light on the screen is uniform, we are very near “optical contact”.

Move mirror M_2 along the track to see the rings shrink towards the centre. When the interference fringes become straight lines, you must reduce the angle between the mirrors by spreading the lines. If the fringes become curved again, move mirror M_2 along its track. And so on until the light is uniform on the screen. You are very near “optical contact”.
Then, you can change the light source: discharge lamp or white light.

1. Manipulation

For different positions of the mirrors, interference rings or fringes are observed.
To observe rings, different angles for the incident lines are needed, a non-collimated light is needed. When the source is extended (bad spatial coherence), rings are located at infinity.
To observe fringes, a collimated beam is required. When the source is extended, fringes are located on the mirrors. A projection of the mirrors on the screen is necessary.
The contrast is maximum when the optical path is near 0. When the optical path is longer than the spectral coherence length of the source, the interference pattern disappears.
You need to understand the theory before lab course.

The aim of the first lab work on Michelson interferometer is to well understand the conditions which are required to observe the most beautiful patters in each configurations: adjustment of the mirrors (parallel or with an angle?), illumination of the interferometer (collimated, convergent or divergent beam?), imaging of the interferences fringes due to their localisation.

You will observe interference figures with a mercury lamp and then with a withe lamp.

Michelson interferometer II: measurements

In the first part of the experimental work on the Michelson interferometer, you learned how to manipulate and adjust a Michelson interferometer, to understand all the observed interference figures as a function of the mirror's relative positions.

The aim of the experimental work on this second part on Michelson interferometer is

- to measure the frequency interval between the two components of the yellow line of a Na lamp and estimate their linewidths.
- to measure the index of refraction of a small plate and evaluate its flatness.

1. Measure of the spectral interval between the two components of the yellow line of Na

Preparation work:

We consider a configuration of the Michelson interferometer where the two mirrors M_1 and M'_2 are parallel. We call x the distance between the two mirrors.

1- For an incident light wave that is perfectly monochromatic at wavelength λ_0, calculate the intensity I_1 on a detector placed at the centre of the rings as a function of λ_0 and x and deduce the contrast as a function of x.

2- The light is now the superposition of two closed monochromatic lines of equal intensity I_0 at wavelengths λ_1 and λ_2. Calculate the intensity I_2 and deduce the contrast.

3- The source has a spectral width $2*\Delta\nu$ centred on $\nu_0=c/\lambda_0$. To have simple calculations, we suppose that the spectral density of intensity is a constant in the band $[\nu_0-\Delta\nu,\nu_0+\Delta\nu]$ and is null elsewhere. Calculate the intensity I_3 and deduce the contrast.

With the Na lamp, observe the rings of equal inclination. When changing the difference of optical paths by moving M_2 mirror along its axis, observe the visibility of the fringes. Because the yellow line of the Na is a doublet, this visibility increases and decreases several times. By measuring the mirror displacement between two minima of visibility, determine the splitting of the two components of the yellow line of Na. Give a precision for your measurement? How can you improve it?

When you continue to move away M_2, the visibility tends to zero. From this observation, estimate the width of each line of the doublet.

The mean value of the wavelength for the yellow doublet is 589nm.

2. Measurement of the refractive index of a thin plate

Go back to a position where the difference between the optical paths is very near to zero. Put a small angle between the two mirrors and observe fringes. For that, you must modify positions for lamp and lenses and focal lengths of lenses to illuminate and observe the fringes. Change the discharge lamp by a white lamp. You must observe coloured fringes.

If you put a small plate in one of the arm of the interferometer, you lose the fringes. By

moving very gently mirror M_2, you can find the fringes again. From the measurement of the displacement, deduce the refractive index of the plate and its precision. The thickness plate is $(155 \pm 5)\mu m$.
From the observation of the deformation of the fringes, estimate the optical flatness quality of the plate.

Spectroscopy

Spectrometers are optical instruments that measure wavelengths and characterize line profiles. They permit to study the emission of sources or the absorption of mediums.
Monochromators form the images $S_2(\lambda)$ of the entrance slit S_1. For different wavelengths λ of the incident radiation the images are laterally separated. This lateral dispersion is due to spectral dispersion in prisms or diffraction on gratings. An important parameter to characterize a monochromator is its resolving power that measures its capacity to distinguish two nearby wavelengths. It is defined by R= $\lambda / \delta\lambda$ where $\delta\lambda$ is the smallest resolved interval. $\delta\lambda$ depends on different parameters : angular dispersion, widths of the entrance and output slits, aberration, diffraction… The aim of lab 5 is to build and study a monochromator.
The aim of this lab is to use a commercial spectrometer perform typical spectroscopy tasks.

You will
- measure the emitted wavelengths of an H_2 lamp and deduce from these measurements the Rydberg constant
- Characterize the absorption of a solution of $KMnO_4$ as a function of its concentration
- Study the spectrums for absorption and emission of a Ruby or YAG crystal

1. Hydrogen lamp spectrum

With a commercial spectrometer, measure precisely the emitted wavelengths of a hydrogen lamp. Deduce from your measurements the Rydberg constant with the best possible precision. Describe in detail how you obtained the value for the precision of the measurement.

2. Absorbance spectrum

We consider a solution of $KMnO_4$.
With a white lamp, observe the absorption spectrum of the solution. Comments.
With an appropriate light at a given wavelength, measure the absorbance of solutions of different concentrations. Deduce the molar absorptivity (or absorption cross section).

3. Absorption and emission of a crystal (Ruby or YAG)

A Ruby crystal (α-Al_2O_3) includes Cr^{3+} ions whose energy levels have properties that permit inversion of population. A Ruby crystal can serve as the gain medium of a solid state laser (Figure 2).
A YAG crystal ($Y_3Al_5O_{12}$) also includes ions (Nd^{3+}) for laser operation (Figure1).
The aim of this part is to compare the absorption spectrums of these two crystals.

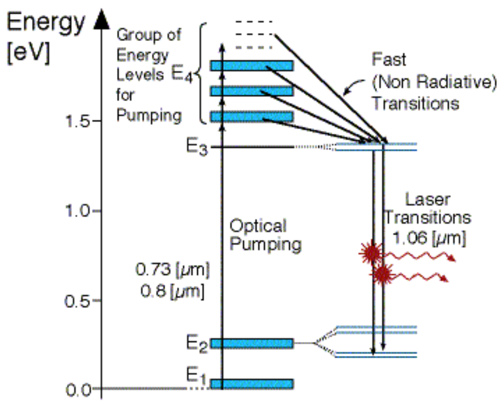


Figure 1: YAG

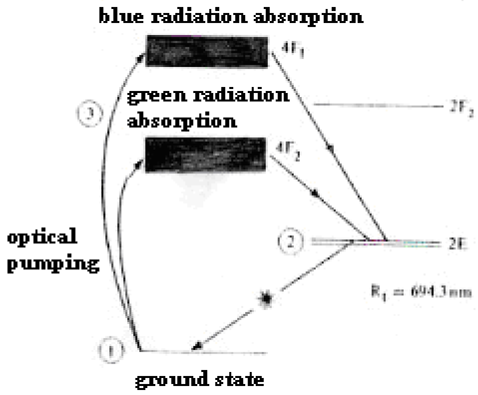


Figure 2: Ruby

Prepare and describe two different set-ups to characterize absorption and emission spectrum of these crystals. Comment.

Photodetectors

In experimental physics, measurement of light flux is often required. The qualities required for an ideal detector are sensitivity, linearity and short rise time.
The most common system for light flux measurement is a photodiode. It is a PN junction where incident photons create charges that increase the inverse current. It is possible to measure the inverse current by measuring the voltage drop on a resistor or the output voltage in a current to voltage amplifier. Photodiodes are hardly nonlinear.
In this lab work, the aim is to characterize the sensitivity of a photodiode and observe how an optimized electronic circuit can improve the linearity and the sensitivity of the detector. The used detector is a BPW21.

As preparation get some information on the working principle of photodiode and the different circuits that allow to use a photodiode.

1. The light source

The light source we will use to study the photodiode is a LED. The LED driver circuit is composed by a protection resistor and a variable power supply that can deliver voltages from 0 V to 12 V. (Take care not to deliver negative voltages).
Using the *light flux power meter* and measuring the voltage on the resistor terminals (that is proportional to the current in the LED), verify that the light **flux** emitted by the LED is proportional to the **current** through the LED (if the current is sufficiently small to avoid heating).
For the following experiments, you will stay in the linear regime of the "light **flux** - LED **current** - characteristics" and express the photodiode response as a function of the LED flux.

2. Electrical characteristics of the photodiode

The current-voltage characteristics of a photodiode can be obtained with the following circuit.

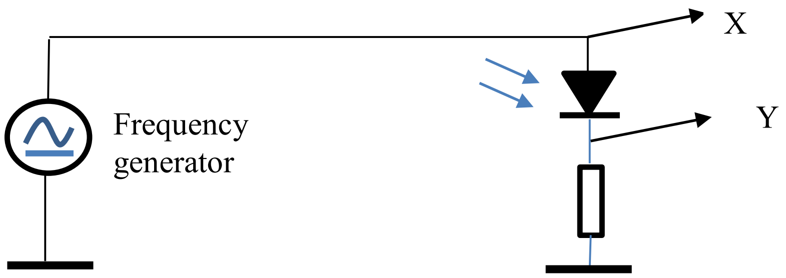


Figure 1: Electrical circuit for current-voltage characteristic

Choose the good parameters of the frequency generator to explore the whole characteristics. Without light, the curve is the typical characteristic curve of a diode. Observe the modifications with light using a rather large large resistor value.

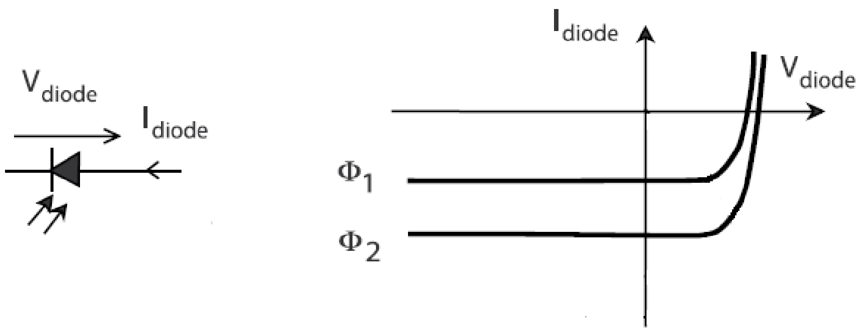


Figure 2: Typical characteristics of a photodiode

Verify that the vertical displacement of the curve is proportional to the incident flux.
The sensitivity of a detector is its ability to measure a flux; it is given by the parameter η

$$\eta = \frac{I_{PD}}{\Phi}$$

where I_{PD} is the photocurrent (A) and Φ the incident light flux (W). In the following you will measure η and its properties of linearity and response time.

3. PHOTOVOLTAIC CIRCUIT

On an optical bench, mount a photodiode in front of the LED. The complete surface of the photodiode must be illuminated for good comparisons.
Mount the photodiode according with a photovoltaic operation.
Plot the photodiode current for two different cases (parallel resistor 470kΩ or 10kΩ) as a function of the LED flux. Compare and explain the observed behavior with the characteristics shown in figure 2. Deduce the sensitivity of your device in a useful light flux domain.

4. PHOTOCONDUCTIVE CIRCUIT

Mount the photodiode according a photoconductive scheme with a continuous generator that delivers between 3 V and 9 V. Repeat your measurements and plot them. Compare with the preceding behavior and explain.

5. RISE TIME

With a square wave supply on the LED, estimate the rise time of the photodiode in the different electrical circuits. Compare.
Be aware: the LED does not like negative voltage. You must use a square signal with offset (0-5 V).

Holographic interferometry

Leave the laser switched on at all times, its warm up time (for stability) is 30 minutes.

1-Theoretical background

Holography is a technique based on interference principles, which allow the recording of three-dimensional image of an object. Amplitude and phase of the light diffused from the object can be reproduced by the hologram.

Recording principles

The interference pattern created by interference of a wave scattered from an enlightened object and a reference wave is recorded on a holographic plate.
The object is enlightened by a coherent source. It scatters the light. The complex amplitude of this *backscattered light* on the plane of the holographic plate is given by:

$$A_o(x,y) = a_o(x,y)e^{i\varphi_o(x,y)} \tag{1}$$

where the time dependence is unexpressed. A_o contains all optical information on the object.
In the same way, the complex amplitude of the *reference beam* is given by:

$$A_p(x,y) = a_p(x,y)e^{i\varphi_p(x,y)} \tag{2}$$

These both beams interfere and the light intensity I on the holographic plate is:

$$I(x,y) = \left|A_o(x,y) + A_p(x,y)\right|^2 \tag{3}$$

$$= \left|A_o(x,y)\right|^2 + \left|A_p(x,y)\right|^2 + A_o(x,y)A_p^*(x,y) + A_p(x,y)A_o^*(x,y) \tag{4}$$

where a^* is the complex conjugate of a.

The holographic plate is composed of an emulsion in which ‘grains’ with a diameter of 8 nm are generated by the exposure. As the wavelength of visible light is much larger than 8 nm, the change is best described by a change in the “effective refractive index” of the emulsion. In a good approximation the exposed and developed holographic plate can be considered as a “phase plate”: practically no light is absorbed but the phase of the field is modified by traveling through the plate.
If the holographic plate is correctly exposed, we expect a linear relationship between the induced phase change φ and the energy density E used for its exposition:

$$\varphi = \alpha + \beta E \tag{5}$$

where α and β are constants, and $E = I\,\tau$, with τ the exposition time and I the intensity.

For small phase shifts ($\varphi << \pi/2$), we can develop the amplitude transmission coefficient $t = \exp(i\,\varphi)$ and stop after the linear term such that: $t \approx 1 + i\,\varphi = 1 + i(\alpha + \beta I \tau)$
Then:

$$t(x,y) = 1 + i\alpha + i\beta\tau\left|A_o\right|^2 + i\beta\tau\left|A_p\right|^2 + i\beta\tau\, A_o A_p^* + i\beta\tau\, A_p A_o^* \tag{6}$$

Holographic restitution process

The recorded holographic plate, characterized by its transparency given by equation (6), is enlightened by a beam identical to the reference beam A_p.

The transmitted amplitude is then given by:

$$A_r(x,y) = t(x,y)A_p(x,y) \tag{7}$$

$$A_r(x,y) = (1 + i\alpha + i\beta\tau|A_o|^2 + i\beta\tau|A_p|^2)A_p + i\beta\tau|A_p|^2 A_o + i\beta\tau\, A_p^2 A_o^* \tag{8}$$

In the holographic restitution process, three beams are obtained:

- The first term ($\propto A_p$) corresponds to the restitution or reference beam. It is transmitted by the photographic plate and slightly broadened by the speckle pattern $|A_o|^2$.
- The second term is directly proportional to the complex amplitude of the backscattered beam by the object ($\propto A_o$). A three-dimensional virtual image of the object (with all of its properties) can thus be observed through the holographic plate like through a window.
- The last term ($i\beta\tau\, A_p^2 A_o^*$) represents a second image of the object, called conjugate image. This image can be real or virtual depending on the experimental conditions.

2-Experiments

Presentation of the used recording setup

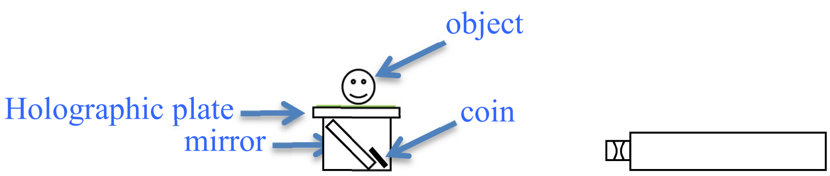


Figure 1: Experimental setup for hologram recording.

The object is put onto the holographic plate to take advantage of the gravity for a good stability. The coin is put onto the lower part of the mirror. A small piece of modeling clay can be used to stabilize it.

The horizontal plate represents the holographic plate with the photosensitive emulsion on the top.

1. Identify the path of the reference beam and the path of the two object beams.
2. Which is the minimum coherence length of the light source with this setup?
3. Why do reflecting (metallic) objects give better contrast in the hologram?
4. Why is it better to put the photosensitive emulsion on the top?

Hologram of a simple object

- Use the painted glass plate to replace the holographic plate and align the laser such that it illuminates more or less homogeneously the whole surface of the glass plate.
- The plate has to be exposed with approximately 200 $\mu J/cm^2$. Use a powermeter to calculate the necessary exposition time of your setup. The surface of the detector in the handheld power meter is circular with a diameter of 8 mm. (check with the teacher)
- Make everything ready for exposure: (check with the teacher)
  - Make sure the room is dark enough (except the green LED which does not expose the plate),
  - check the laser position,
  - check the availability of a metallic object (music box),
  - check the availability of the holographic plate and transport box,
  - check the stopwatch,
  - block the laser,
- Proceed to exposure:
  - Take out the holographic plate and put it with its sticky side up (emulsion up) onto the holder,
  - place the object,
  - start the stopwatch with one hand while removing the beam block with the other.
  - Put the beam block back when the exposition time is reached. (Do NOT switch off the laser.)
  - Put the holographic plate in the transport box remembering the position of the sticky side (emulsion).
- Develop the holographic plate (this can be done without gloves):
  - Make sure the room with development equipment is dark except green LED light
  - Immerse the holographic plate sticky side up (emulsion up) in the developing bath which should be around 25°C. Shake slightly during 6 minutes.
  - Remove from developing bath, pay attention that no drops fall in the other baths, rinse during 1 min using tap water. After this, darkness is no longer required.
  - Immerse the holographic plate sticky side up (emulsion up) in the bleaching bath. Check and take it out when it has become transparent (typically after 4 min.) but pay attention that no drops fall in the other baths.
  - Rinse again during 1 min using tap water.
  - Immerse the holographic plate sticky side up (emulsion up) in the surfactant bath during 1 min.
  - Dry the hologram first using paper (no wiping) then using the hair dryer. Observe the evolution of its color when drying. Greenish color indicates that the hologram is finished.

Study

1. What kind of holograms (object and coin) did you make? Explain why one image can be seen with a white spotlight and the other with the HeNe laser.
2. Why the color of the hologram seen with the white spotlight is green whereas the color of the other one is red?
3. Study the sharpness of the image you see as a function of the distance between illumination source and hologram. Explain.
4. Cover part of the hologram. What happens to the image? Check what you can see at different distances eye – hologram. Explain.
5. When you dry the hologram explain the color of the hologram is progressively moving from deep red to green.

Holographic interferometry

This technique is used in industry to measure very small displacements in random direction.

- Change the plate support to the one with the micrometer screw.
- Train yourself to move the screw by 8±2 μm without watching it.
- Make a double exposure hologram:
  - Read initial position of micrometer screw.
  - Make first exposure (60% of the necessary total time).
  - Move the micrometer screw in darkness.
  - Make second exposure (again 60% of the necessary total time).
  - Develop the hologram.
  - Read final position of micrometer screw.

Study

1. What are the dark lines on the metal beam in the holographic image?
2. Why do the other objects do not have these dark lines?
3. How can you determine the distance the micrometer screw moved from the image?
4. Do the calculation and compare the result to the micrometer screw displacement.