

Manual for PE-0100 Double Refraction of Light

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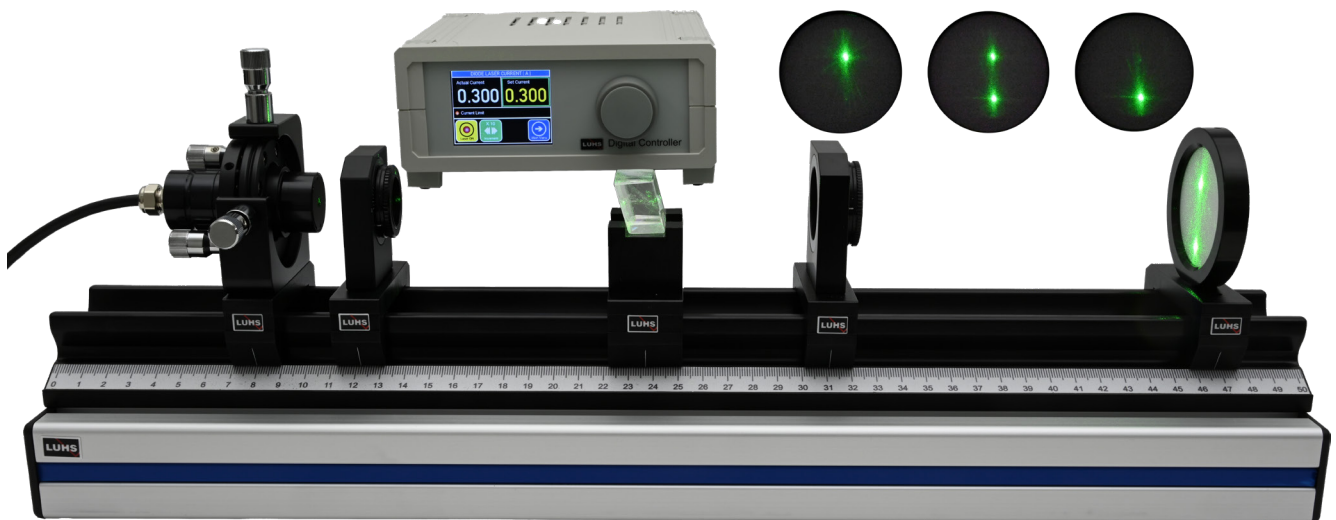
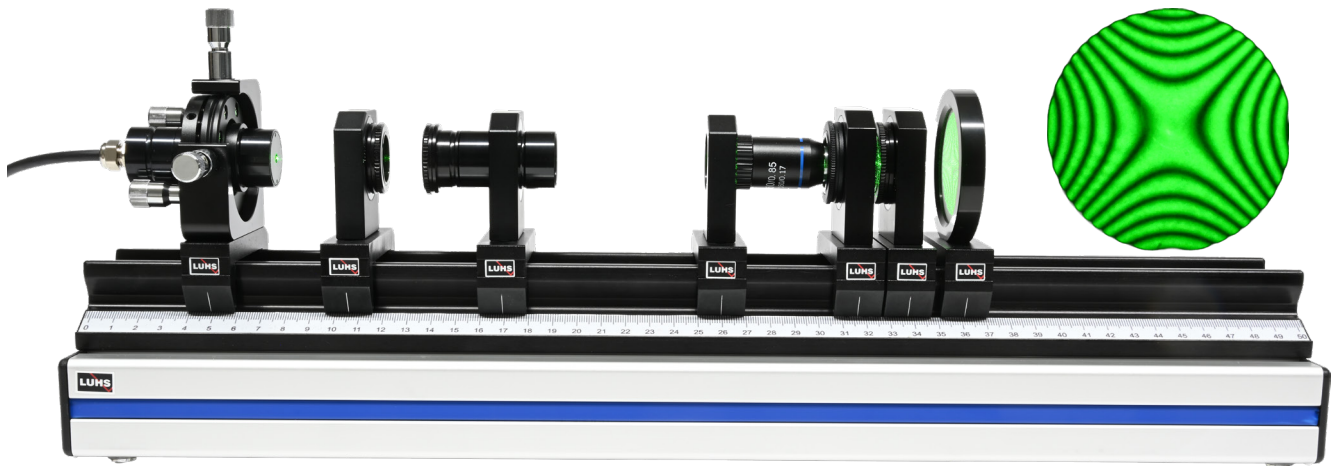


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1.0 Introduction

Erasmus Bartholin was the first one who reported his observation on double refraction in 1669. He examined a calcite crystal: not the sole crystal exhibiting double refraction, but one with an exceptionally pronounced display of this effect. His discovery and its first scientific explanation by Christian Huygens in 1674 marked the beginning of the studies on optical crystal properties.

More than 100 years later crystal optics got new impulses through Dominique Arago, who studied the polarization and optical activity, and Jean-Baptiste Biot who defined the first principles of crystal optics, by differentiating in particular uni-axial and bi-axial crystals - principles which are still valid today.

Birefringent materials are important components in optics, for example as half- and quarter-wave plates or as Lyot filters to tune laser lines. Double refraction or birefringence can also be induced in crystal like polymers by external electrical fields or stress.

The experiments may start with the observation of birefringence shown by calcite crystal. The green probe laser is directed to the calcite and the splitting of the laser beam in ordinary and extraordinary rays are observed. The polarization of these rays is measured by using the rotary polarization analyser.

As an example of a biaxial crystal a Pockels cell containing a Lithium Niobate crystal is used and in a conoscopic set-up impressive interference pattern are created when the high voltage is applied. Furthermore the optical retardation for different voltage levels is measured and the so called halve wave voltage determined.

The creation of an conoscopic image requires a birefringent material where the optical axis is oriented parallel or perpendicular to the incident light beam (Fig. 1).

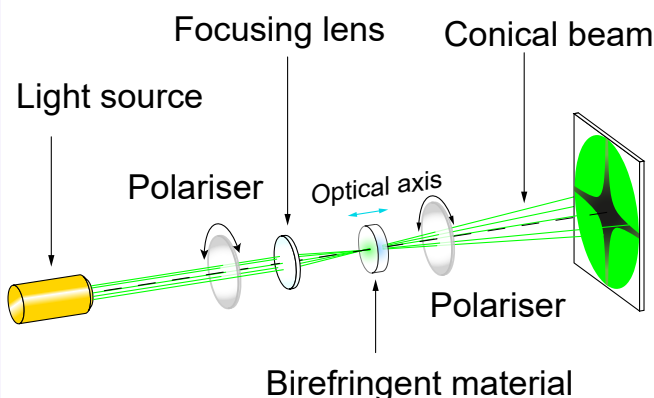


Fig. 1: Conoscopic set-up

In this experiment we are using a laser emitting a wavelength of 532 nm (green). The light passes the first polarizer. A focusing lens creates the “conical” light beam which traverses the birefringent material. The second polarizer is aligned orthogonally to the first one. In direction of the optical axis, the material behaves isotropic and there will be no change in the polarization stage of the incident light. The corresponding image on the screen remains dark. All other rays propagating inclined to the optical axis undergo a change to their polarization in such a way, that a fraction can pass the orthogonally oriented polarizer. Consequently, a typical intensity distribution results which is a fingerprint for the specific birefringent material. Areas with same in-

tensity (same retardation) are termed as isogyres, places of same birefringence. Conoscopy is a very important method to find the optical axis of raw crystals in optic manufacturing as well as quality control for LCD displays.

Another method for examining birefringent materials uses parallel light that passes through the sample. For this reason, this method is also called orthoscopic (Fig. 2).

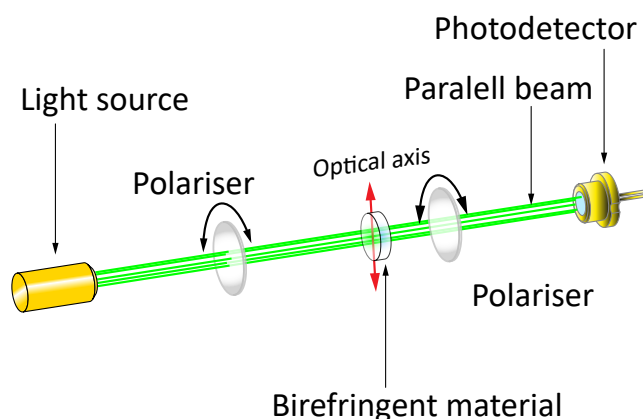


Fig. 2: Orthoscopic set-up

The birefringent material is placed between two rotatable polarizers. By means of a photodetector, the transmitted intensity is measured as a function of the angle orientation of either the birefringent material or the polarizer. Without any material between the two polarizer the famous Malus' law can be verified.

2.0 Fundamentals

In this chapter, we will discuss light as electromagnetic radiation and introduce Maxwell's equations, which can be used to describe the interaction between light and matter. Of particular interest is the interaction with birefringent media. We will not discuss these using Maxwell's equations—which are quite challenging—but will instead introduce the Jones formalism.

2.1 The miracle of the light

Light, the giver of life, has always fascinated human beings. It is therefore natural that people have been trying to find out what light actually is, for a very long time. We can see it, feel its warmth on our skin but we cannot touch it.

The ancient Greek philosophers thought light was an extremely fine kind of dust, originating in a source and covering the bodies it reached. They were convinced that light was made up of particles.

As human knowledge progressed and we began to understand waves and radiation, it was proved that light did not, in fact, consist of particles but that it is an electromagnetic radiation with the same characteristics as radio waves. The only difference is the wavelength.

We now know, that the various characteristics of light are revealed to the observer depending on how he sets up his experiment. If the experimentalist sets up a demonstration apparatus for particles, he will be able to determine the characteristics of light particles. If the apparatus is the one used to show the characteristics of wavelengths, he will see light as a wave.

The question we would like to be answered is: What is light in actual fact? The duality of light can only be understood using modern quantum mechanics. Heisenberg showed, with his famous „Uncertainty relation“, that strictly speaking, it is not possible to determine the position x and the impulse p of a particle of any given event at the same time.

$$\Delta x \cdot \Delta p_x \geq \frac{1}{2} \hbar \quad (1.1)$$

If, for example, the experimentalist chooses a set up to examine particle characteristics, he will have chosen a very small uncertainty of the impulse Δp_x . The uncertainty Δx will therefore have to be very large and no information will be given on the location of the event.

Uncertainties are not given by the measuring apparatus, but are of a basic nature. This means that light always has the particular property the experimentalist wants to measure. We determine any characteristic of light as soon as we think of it. Fortunately the results are the same, whether we work with particles or wavelengths, thanks to Einstein and his famous formula:

$$E = m \cdot c^2 = h \cdot \nu \quad (1.2)$$

This equation states that the product of the mass m of a particle with the square of its speed c corresponds to its energy E . It also corresponds to the product of Planck's constant h and its frequency ν , in this case the frequency of luminous radiation.

2.2 Optics and Maxwell's Equations

It seems shooting with a cannon on sparrows if we now intro-

duce Maxwell's equation to derive the interaction of light and matter. Actually we will not give the entire derivation rather than describe the way. The reason for this is to figure out that the disciplines Optics and Electronics have the same root namely the Maxwell's equations. This is especially true if we are aware that the main job has been done by electrons but it will be done more and more by photons. Accordingly future telecommunication engineers or technicians will be faced with a new discipline the optoelectronic.

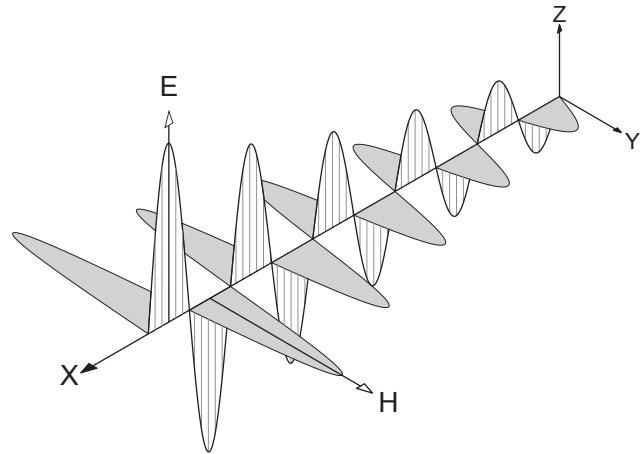


Fig. 3: Electromagnetic Wave

We consider now the problem of interaction with light and matter. The key to the description of optical phenomena are the set of the four Maxwell's equations as:

$$\nabla \times \vec{H} = \varepsilon \cdot \varepsilon_0 \cdot \frac{\partial \vec{E}}{\partial t} + \sigma \cdot \vec{E} \quad \text{and} \quad \nabla \cdot \vec{H} = 0 \quad (1.3)$$

$$\nabla \times \vec{E} = -\mu \cdot \mu_0 \cdot \frac{\partial \vec{H}}{\partial t} \quad \text{and} \quad \nabla \cdot \vec{E} = \frac{4\pi}{\varepsilon} \cdot \rho \quad (1.4)$$

ε_0 is the dielectric constant of the free space. It represents the ratio of unit charge (As) to unit field strength (V/m) and amounts to 8.859 1012 As/Vm.

ε represents the dielectric constant of matter. It characterises the degree of extension of an electric dipole acted on by an external electric field. The dielectric constant ε and the susceptibility χ are linked by the following relation:

$$\varepsilon = \frac{1}{\varepsilon_0} \cdot (\chi + \varepsilon_0) \quad (1.5)$$

$$\varepsilon \cdot \varepsilon_0 \cdot \vec{E} = \vec{D} \quad (1.6)$$

The expression (1.6) is therefore called „dielectric displacement“ or simply displacement.

σ is the electric conductivity of matter.

The expression

$$\sigma \cdot \vec{E} = \vec{j}$$

represents the electric current density

μ_0 is the absolute permeability of free space. It gives the relation between the unit of an induced voltage (V) due to the presence of a magnetic field H of units in Am/s. It amounts to 1.256 106 Vs/Am.

μ is like ε a constant of the matter under consideration. It describes the degree of displacement of magnetic dipoles under the action of an external magnetic field. The product of permeability μ and magnetic field strength H is called

magnetic induction.

ρ is the charge density. It is the source which generates electric fields. The operation ∇ or div provides the source strength and is a measure for the intensity of the generated electric field. The charge carrier is the electron which has the property of a monopole. On the contrary there are no magnetic monopoles but only dipoles. Therefore $\nabla \cdot \vec{H} = 0$ is always zero.

From (1.3) we recognize what we already know, namely that a curled magnetic field is generated by either a time varying electrical field or a flux of electrons, the principle of electric magnets. On the other hand we see from (1.4), that a curled electromagnetic field is generated if a time varying magnetic field is present, the principle of electrical generator.

Within the frame of further considerations we will use glass and air as matter in which the light propagates. Glass has no electric conductivity (e.g. $\sigma = 0$), no free charge carriers ($\nabla E = 0$) and no magnetic dipoles ($\mu = 1$). Therefore the Maxwell equations adapted to our problem are as follows:

$$\nabla \times \vec{H} = \epsilon \cdot \epsilon_0 \cdot \frac{\partial \vec{E}}{\partial t} \quad \text{and} \quad \nabla \cdot \vec{H} = 0 \quad (1.7)$$

$$\nabla \times \vec{E} = -\mu_0 \cdot \frac{\partial \vec{H}}{\partial t} \quad \text{and} \quad \nabla \cdot \vec{E} = 0 \quad (1.8)$$

Using the above equations the goal of the following calculations will be to get an appropriate set of equations describing the propagation of light in glass or similar matter. After this step the boundary conditions will be introduced.

Let's do the first step first and eliminate the magnetic field strength H to get an equation which only contains the electric field strength E .

By forming the time derivation of (1.7) and executing the vector $\nabla \times$ operation on (1.8) and using the identity for the speed of light in vacuum:

$$c = \frac{1}{\sqrt{\epsilon_0 \cdot \mu_0}}$$

we get:

$$\Delta \vec{E} - \frac{n^2}{c^2} \cdot \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \quad (1.9)$$

$$\Delta \vec{H} - \frac{n^2}{c^2} \cdot \frac{\partial^2 \vec{H}}{\partial t^2} = 0 \quad (1.10)$$

These are now the general equations to describe the interaction of light and matter in isotropic optical media as glass or similar matter. The Δ sign stands for the Laplace operator which only acts on spatial coordinates:

$$\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

The first step of our considerations has been completed. Both equations contain a term which describes the spatial dependence (Laplace operator) and a term which contains the time dependence. They seem to be very „theoretical“ but their practical value will soon become evident.

Light can be described as an electromagnetic wave oscillation. We treat the optical element as an assembly of numerous dipoles. These dipoles are defined by the nature and configuration of the electron shells present in each atom or molecule. The electromagnetic field of the light excites these

dipoles, causing them to deviate from their equilibrium state (susceptibility). The dipoles absorb energy of the light (virtual absorption) and send them out again. However, a dipole cannot send its beam in the direction of its own axis. If a crystal has two kind of dipoles, which are at a particular angle to each other, they can only emit and absorb light within the area of their angles. If the process of absorption and emission is slower in one kind of dipole than in the other there will be a phase shift. Macroscopically it seems as if there were a higher refractive index. A change in beam direction takes place because of the different dipole directions, i.e. there are two separate beam directions within the component. If a parallel light beam penetrates into this kind of material the result is, indeed, two beams leaving the crystal. In this case both beams are polarized perpendicularly to each other and have a phase shift between each other.

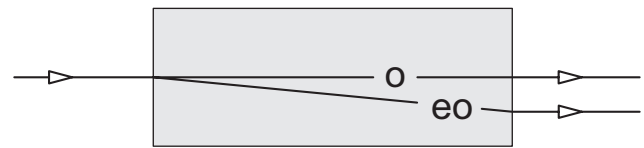


Fig. 4: Birefringent crystal

This phenomenon is called birefringence. These two marked directions of the crystal also have two distinctive refractive indices. Since one beam appears to be violating the Snell's law, it is called extraordinary (eo) and the one behaving normally is ordinary (o). Crystal quartz and calcite are materials which behave in this way. There are also a series of other crystals but these two have proved successful in laser technology. Thin plates, used as optical retarder are mostly made out of quartz because it is hard enough for this purpose.

The phenomenon of birefringence originates from the internal makeup of materials. In isotropic materials, light moves uniformly in all directions, yielding only one refracted ray. However, in anisotropic materials such as crystals, the molecular structure causes light to refract differently depending on its polarization and the internal axes of the material. This discrepancy causes the light to split into two distinct rays, each traveling its own route through the material.

The best-known birefringent crystals are calcite and natural quartz, also known as rock crystal. In the following, we will take a closer look at these two crystals to better understand birefringence.



Fig. 5: The image above shows the double refraction of a calcite crystal.

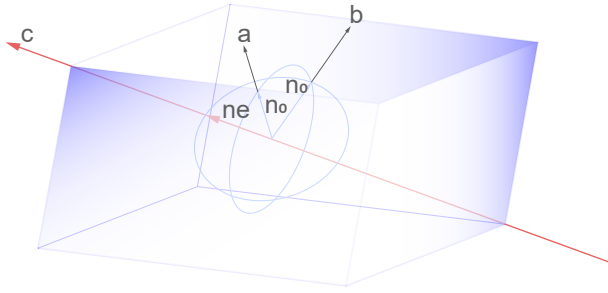


Fig. 6: Calcite crystal with optical axis C

The refractive index at a wavelength of 580 nm for the ordinary ray is $n_o = 1.6584$ and for the extraordinary ray is $n_e = 1.4864$. The magnitude of the birefringence is given by the difference $n_e - n_o$: $1.4864 - 1.6584 = -0.1720$. Therefore, this Calcite crystal is referred to as optically negative. As we will see below, this value is very high compared to that of a quartz crystal.



Fig. 7: Natural grown quartz crystal (left) and its exact structure (right).

The ordinary ray has a refractive index of 1.544, and the extraordinary ray has a refractive index of 1.533 at a wavelength of 580 nm. The magnitude of the birefringence is given by the difference $n_e - n_o$: $1.533 - 1.544 = 0.009$. Therefore, this crystal is referred to as optically positive.

We will now investigate the case where a beam enters the crystal at an angle θ , instead of being exactly parallel to either of the two primary axes (see Fig. 8).

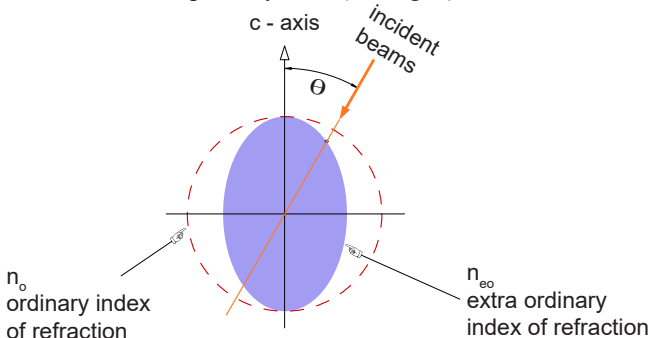


Fig. 8: Incident beam under an angle of θ

To do this, we would have to plug the boundary conditions of the respective crystal into the Maxwell equations and solve them. While this is possible, it is quite challenging. Therefore, we want to introduce a formalism that is much simpler yet still yields accurate results. This formalism is known as the Jones formalism.

The effectiveness of the Jones formalism stems largely from its ability to represent complex wave physics through simple school-level mathematics (matrix multiplication) without losing vital data like the phase of light. In real-world applications, it grants three distinct advantages that have made it the foundational tool in laser technology and optics

development:

1. "Chaining" components together is extremely simple. When light passes through multiple optical components (e.g., first through a filter, then a prism, then a lens), you simply multiply the matrices of these components together. The light is a simple 2-element vector. Each component is a 2x2 matrix. The result at the end of the system is the simple product:

$$\vec{E}_{\text{out}} = M_n \cdot \dots \cdot M_2 \cdot M_1 \cdot \vec{E}_{\text{in}}$$

That can be programmed on a computer perfectly and in the blink of an eye.

2. It can calculate interference (phase conservation). Other methods measure only the pure brightness (intensity). The Jones formalism, however, works with the complex amplitude of the light wave. Because it mathematically accounts for the phase (i.e., the "up and down" motion of the wave), it can accurately predict how light waves interfere, reinforce, or cancel each other out (interference). This is indispensable for working with lasers and interferometers.
3. Achieving efficiency by focusing on the essentials: Light travels through space in three dimensions. Yet, because polarization changes always happen perpendicular to the propagation direction, Jones simplifies the issue to just two dimensions (X and Y). This approach reduces computation time and keeps the equations very straightforward.

2.3 Jones Formalism

The Jones formalism is named after R. Clark Jones, who first introduced this framework in 1941. In this approach, light is represented as a plane electromagnetic wave characterized by a complex two-dimensional Jones vector that specifies the wave's amplitude. However, the Jones formalism is applicable exclusively to fully polarized, coherent light.

The transformations are expressed through Jones matrices. By employing these matrices, the Jones formalism facilitates the modeling and examination of optical systems where a light beam traverses multiple optical elements.

A plane light wave propagating in z direction is described by the expression:

$$\vec{E}(z, t) = \text{Re}(A \cdot e^{i(\omega t - kz)})$$

or:

$$\vec{E}(z, t) = (A_x \cdot \cos(\omega t - kz + \delta_x), A_y \cdot \cos(\omega t - kz + \delta_y))$$

Usually, the equation mentioned above describes an ellipse located in the xy plane. Here, A is the amplitude, ω is the angular frequency, t is time, k is the wave number, and δ is a phase shift.

We separate two special cases:

$$A_x = A_y = A \text{ and } \delta_x = 0, \delta_y = \pm\pi/2.$$

The electrical E vector rotates on a circle with constant amplitude, circularly polarized light is produced

$$A_x = A_y = A \text{ and } \delta_x = 0, \delta_y = 0 \text{ or } \pi.$$

The electrical E vector swings back and forth on a line which goes via the origin and is defined by (1,1) or (-1,1). Linear polarized light is produced.

2.4 Using the Jones vector

$$\vec{J} = \begin{bmatrix} A_x \cdot e^{i\delta x} \\ A_y \cdot e^{i\delta y} \end{bmatrix}$$

$$\vec{E}(z, t) = \text{Re}(\vec{J})$$

A_x and A_y are normalized in such a way that

$$|\vec{J}| = 1$$

Expressing circularly polarized light using the Jones notation, we obtain:

Right circular

$$\vec{J}_+ = \frac{1}{\sqrt{2}} \cdot \begin{bmatrix} 1 \\ i \end{bmatrix}$$

Left circular

$$\vec{J}_- = \frac{1}{\sqrt{2}} \cdot \begin{bmatrix} 1 \\ -i \end{bmatrix}$$

Linear polarized

$$\vec{J}_1 = \frac{1}{\sqrt{2}} \cdot \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

Linear polarized 90° turned

$$\vec{J}_2 = \frac{1}{\sqrt{2}} \cdot \begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

Matrix P , which defines a Polarizer:

$$P_x = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}; P_y = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

Matrix R which defines a rotator:

$$\text{Rotator } R(\theta) = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}$$

To rotate polarizer for a given angle θ the following equation is applied:

$$P(\theta) = R(-\theta) \cdot P \cdot R(\theta)$$

Retarder or Phase shifter V with phase shift δ :

$$V = \begin{bmatrix} e^{-i\Delta\delta/2} & 0 \\ 0 & e^{i\Delta\delta/2} \end{bmatrix}$$

Retarder rotated by angle θ :

$$V(\theta) = R(-\theta) \cdot V \cdot R(\theta)$$

The Jones vector, after matrix operations, contains the field in the x and y directions. From this, the normalized intensity is calculated.

$$\vec{J}_{\text{out}} = M_n \cdot \dots \cdot M_2 \cdot M_1 \cdot \vec{J}_{\text{in}}$$

$$\begin{pmatrix} E_x^{\text{out}} \\ E_y^{\text{out}} \end{pmatrix} = M_n \cdot \dots \cdot M_2 \cdot M_1 \cdot \begin{pmatrix} E_x^{\text{in}} \\ E_y^{\text{in}} \end{pmatrix}$$

$$I^{\text{out}} = |\vec{E}|^{\text{out}} = |E_x^{\text{out}}|^2 + |E_y^{\text{out}}|^2$$

Transmitted Intensity T :

$$T = \frac{I}{I_0} = \frac{|\vec{E}|^2}{|\vec{E}_0|^2} = \frac{|E_x|^2 + |E_y|^2}{|E_x^0|^2 + |E_y^0|^2}$$

Example, a beam of light polarized linearly in the x -direction strikes an ideal linear polarizer that is rotated by 45°.

$$\vec{E}_{\text{in}} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} M_{\text{pol}}^{45^\circ} = \frac{1}{2} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

$$\vec{E}_{\text{out}} = M_{\text{pol}}^{45^\circ} \cdot \vec{E}_{\text{in}}$$

$$\vec{E}_{\text{out}} = \frac{1}{2} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0.5 \\ 0.5 \end{pmatrix}$$

Transmission T :

$$T = \frac{I}{I_0} = \frac{|\vec{E}_{\text{out}}|^2}{|\vec{E}_{\text{in}}|^2} = \frac{|E_x^{\text{out}}|^2 + |E_y^{\text{out}}|^2}{|E_x^{\text{in}}|^2 + |E_y^{\text{in}}|^2} = \frac{0.25 + 0.25}{1 + 0} = 0.5$$

This yields the same value as Malus's law would.

Jones' formalism does not explicitly display the wavelength of light. However, it is contained within the phase shift delta, which includes the pertinent refractive index that depends on the wavelength of the light striking it. If one intends to compute and create an optical component like a half-wave plate, it must be done for the defined wavelength. To achieve this, we apply the Sellmeier equations, which provide the refractive index for both the ordinary and extraordinary axes as a function of the wavelength..

2.5 Sellmeier equation

In optics, the Sellmeier equation is an empirically derived functional description of how the refractive index n of a light-transmitting medium depends on the wavelength λ of light. The equation is named after Wolfgang von Sellmeier, who published it in 1871, drawing on the Cauchy equation and the Kramers–Kronig relation. It is primarily used in technical optics to describe the dispersion of optical glass and other optical materials.

$$n_o^2 = 2.3573 - 0.01170 \cdot \lambda^2 + \frac{0.01054}{\lambda^2} + \frac{1.3414 \cdot 10^{-4}}{\lambda^4} - \frac{4.4537 \cdot 10^{-7}}{\lambda^6} + \frac{5.9236 \cdot 10^{-8}}{\lambda^8}$$

$$n_e^2 = 2.3849 - 0.01259 \cdot \lambda^2 + \frac{0.01079}{\lambda^2} + \frac{1.6518 \cdot 10^{-4}}{\lambda^4} - \frac{1.9474 \cdot 10^{-6}}{\lambda^6} + \frac{9.3648 \cdot 10^{-8}}{\lambda^8}$$

Fig. 9: Sellmeier equation for quartz

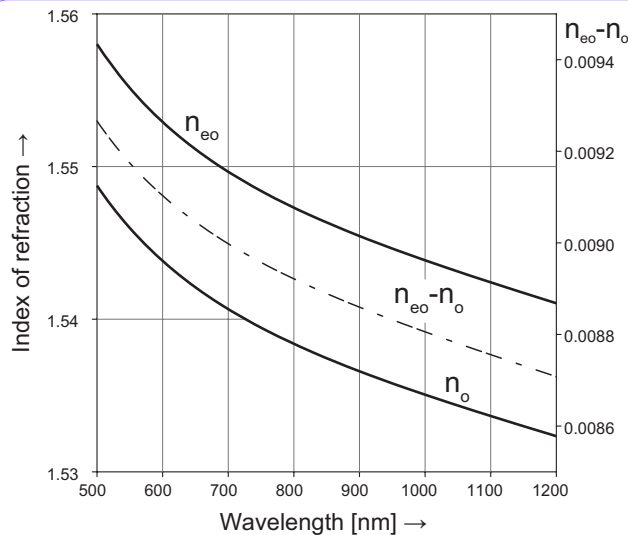


Fig. 10: Dispersion curve for the ordinary and extraordinary refractive index calculated with the Sellmeier equation

We have now collected the necessary tools to compute, for instance, a technical element, a half-wave plate designed for a wavelength of 580 nm.

To achieve this, a hollow drill bit is utilized to carve out a cylinder of sufficient thickness from the quartz crystal in the a-direction (Fig. 7), meaning perpendicular to the optical c-axis.

We cut a slice of thickness d from the cylinder; however, we still need to calculate the value of the thickness d .

A half-wave plate causes a phase shift of π radians, equivalent to a delay of half a wavelength, $\lambda/2$, between two orthogonally polarized beams. Consequently, the thickness d required for this phase change is given by the formula below:

$$d = \frac{\lambda}{2 \cdot n_e} - \frac{\lambda}{2 \cdot n_o} = \frac{\lambda}{2 \cdot \Delta n}$$

Using the Sellmeier equations, we calculate the extraordinary and ordinary indices of refraction as $n_e = 1,54463$ and $n_o = 1,55375$. The difference Δn is 0,00912, and thus the thickness is calculated as $d=0,032$ mm.

The calculated thickness is impractical from a manufacturing standpoint. Therefore, the thickness d is adjusted so that a practical thickness of, for example, 1 mm is achieved, while the effect of a half-wave plate is retained. Such plates are also referred to as multi-order plates. For $m=0$, they are called zero-order plates.

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

If we assume a value of 30 for m , we get a thickness of 0.96 mm.

So far, we have tacitly assumed that the optical c-axis of the quartz crystal lies in the plane of the cut surface of the sliced plate. But what is the situation in practice, and how can we determine this?

To determine the optical axis precisely, three methods are primarily used:

1. The visual/morphological method (geometry): If the quartz has well-developed natural crystal faces, the axis can be determined directly by visual inspection.
2. The polarized light method (polariscope):
3. Conoscopy: In order to obtain the most precise and de-

finite determination in mineralogy and gemstone testing, the use of convergent polarized light is essential, and this technique will be explained in the following discussion..

2.6 Conoscopy

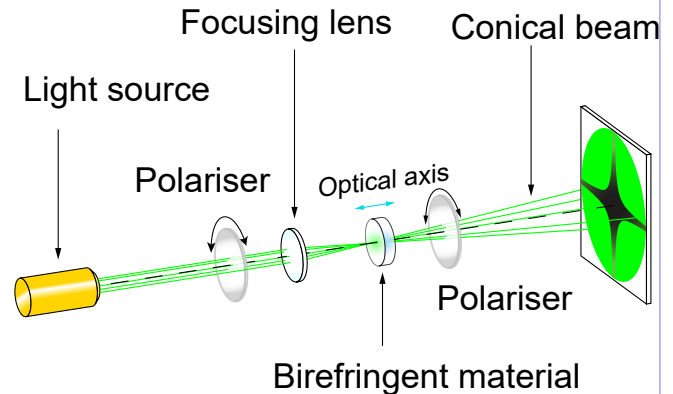


Fig. 11: Principle set-up of a Conoscope

A light source emits parallel rays. The first polarizer ensures a defined polarization. Behind the first polarizer, a lens causes the beam to diverge and pass through the birefringent sample. The second polarizer blocks or transmits the beam depending on the polarization state of the incident beam. The transmitted intensity is imaged on a screen. Depending on the position of the polarizer and the properties of the birefringent material, a mandala-like pattern emerges, which allows conclusions to be drawn about the birefringent crystal and its orientation.

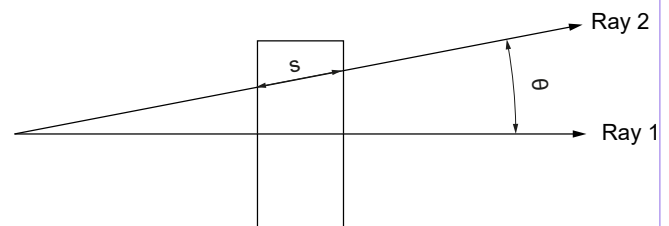


Fig. 12: Ray propagation in a birefringent sample

The principle is easy to explain: Ray 2 passes through the birefringent material. The path length s is longer than that of Ray 1, and depending on the crystal's properties, Ray 2 undergoes a phase shift relative to Ray 1. As a result, when they pass through a polarizer, the two rays have different intensities. This can be calculated for simple rays, but for a conical beam it becomes quite complicated, so we will limit ourselves to analyzing the conoscopic images that we will observe in the following experiments.

3.0 Description of the components

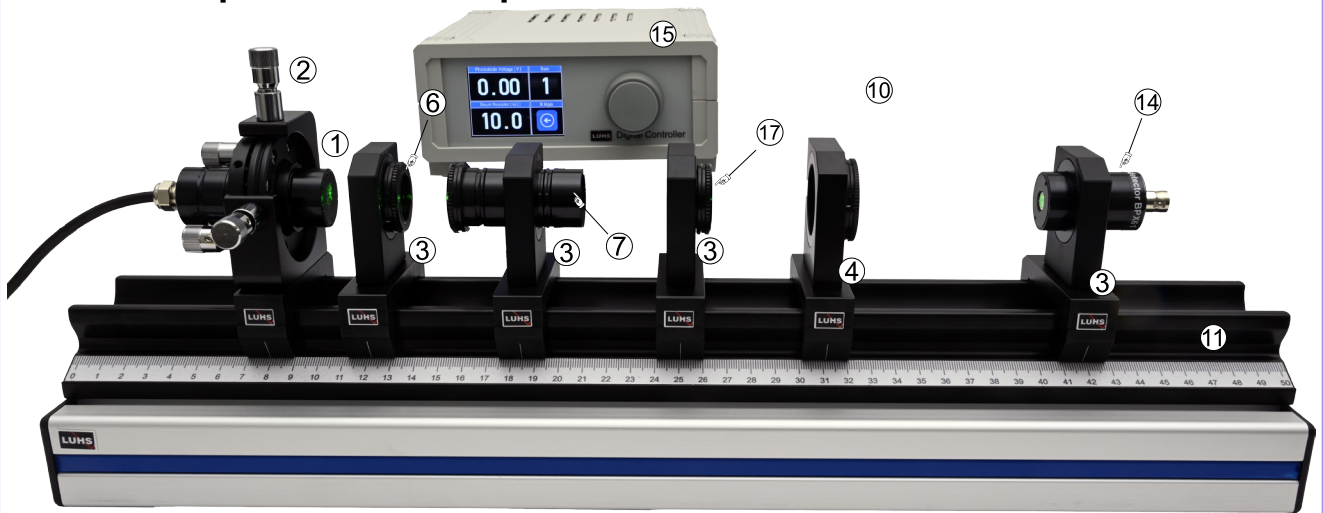


Fig. 13: Experimental setup for characterizing a crystalline quartz plate

- | | |
|--|---|
| 1 LQ-0020 Green (532 nm) DPSSL in $\varnothing 25$ housing | 9 OC-0830 Optical quartz plate in C30 mount |
| 2 MM-0420 Four axes kinematic mount on carrier MG20 | 10 OC-0713 Polarizer in C30 mount |
| 3 MM-0020 Mounting plate C25 on carrier MG20 | 11 MP-0150 Optical Bench MG-65, 500 mm |
| 4 MM-0038 Mounting plate C30-S on carrier MG20 | 12 OM-0030 Pockels Cell 19 mm |
| 5 MM-0110 Translucent screen on carrier MG20 | 13 DC-0360 Pockels Cell HV Driver, digital |
| 6 OC-0710 Polarizer in C25 mount | 14 DC-0250 SiPIN Photodetector |
| 7 OC-0360 Beam Expander x6 in $\varnothing 25$ housing | 15 DC-0040 LED and Photodiode Controller |
| 8 4O-0050 Microscope objective 60x $f=2.8$ mm | 16 OC-0820 Calcite crystal on rod and carrier |
| 8A4O-0030 microscope objective 10x, NA=0,25 | 17 OC-0840 Quarter-wave plate in C25 mount |

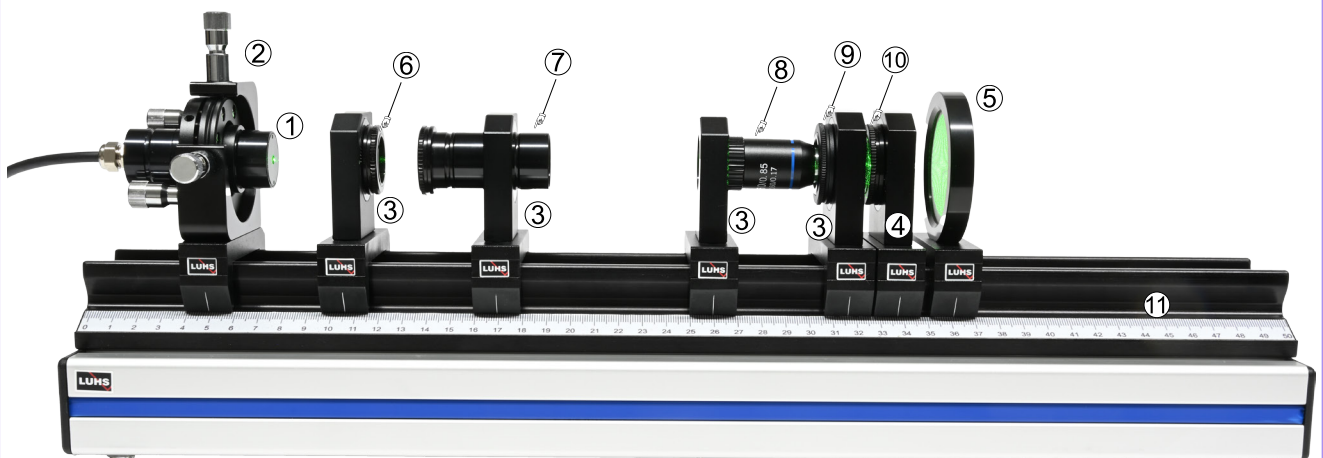


Fig. 14: Set-up as Conoscope with a Quartz crystal plate

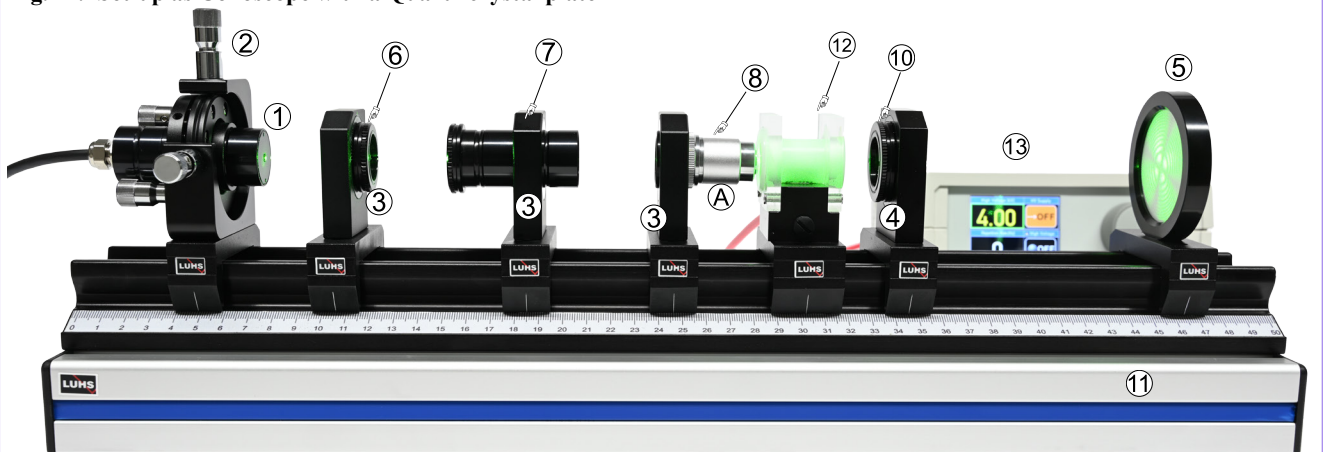


Fig. 15: Set-up as Conoscope with a Pockels Cell

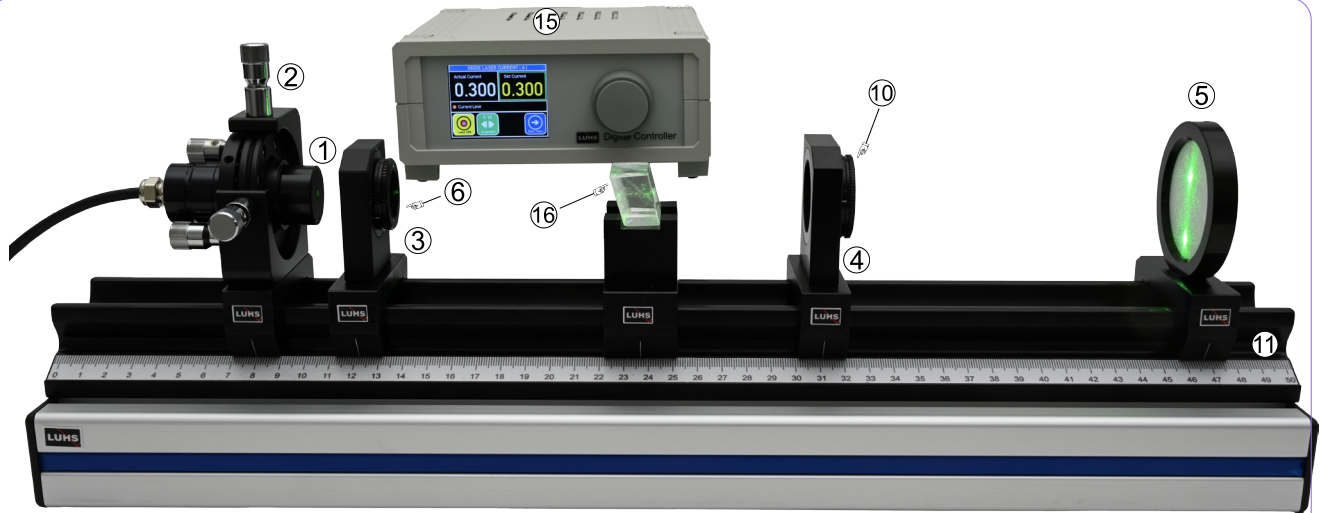
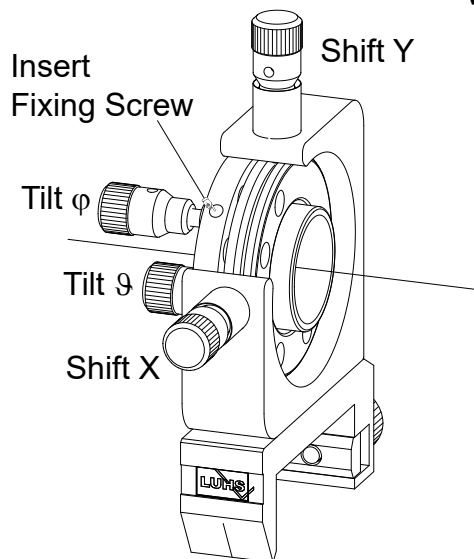


Fig. 16: Set-up with Calcite crystal

3.1 Green (532 nm) DPSSL (1)

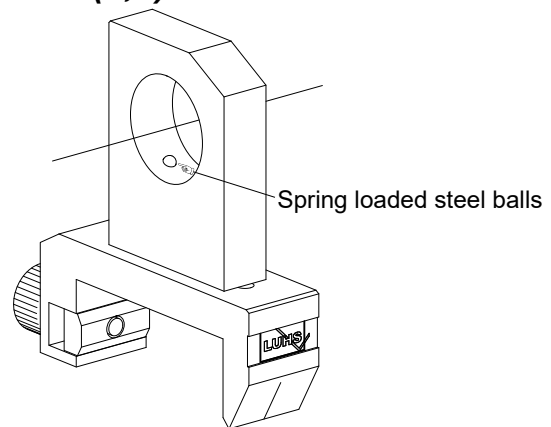
A green (532 nm) emitting DPSSL (Diode Pumped Solid State Laser) is housed within a C25 casing and operated using the “DC-0040 Controller”. The output power is less than 5 mW. The diode laser connects to the MK2 controller via a 15-pin SubD HD connector. An EEPROM inside the connector stores the laser diode's data, which the controller reads and displays upon connection.

3.2 Four axes kinematic mount(2)



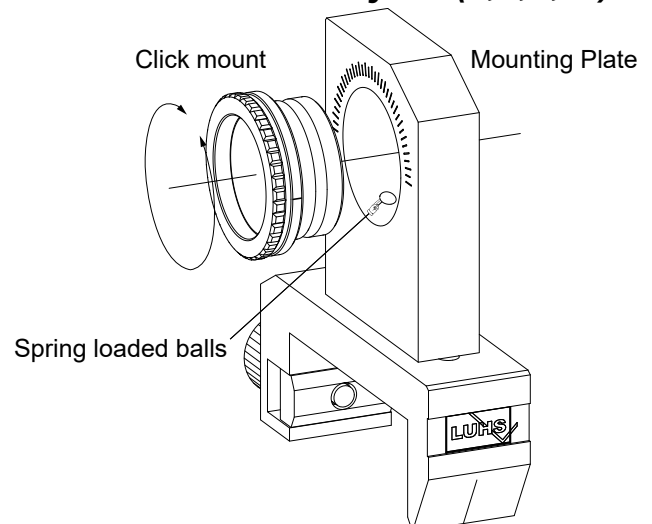
This frequently needed component is ideal for the fine adjustment of lenses, microscope objectives, diode laser, and so on for the optical axis of the rail set-up. The displacement area is 5x5 mm and 10x10 degrees, respectively. Different mounts can be attached to the adjustment holder. This model provides a holder for 25 mm cylindrical components. The component is inserted into the adjustment holder and is kept in position by a grub screw with a nylon tip. Four precise fine-pitch screws of repetitious accuracy allow the translational (X; Y) and azimuthal (ψ ; ϕ) adjustment.

3.3 Mounting plate C25/C30 on carrier (3,4)



This frequently used component is ideal to accommodate parts with a diameter of 30 or 25 mm where it is kept in position by three spring loaded steel balls. Especially C25 or C30 mounts having a click groove are firmly pulled into the mounting plate due to the smart chosen geometry. The mounting plate is mounted to a 20 mm wide carrier.

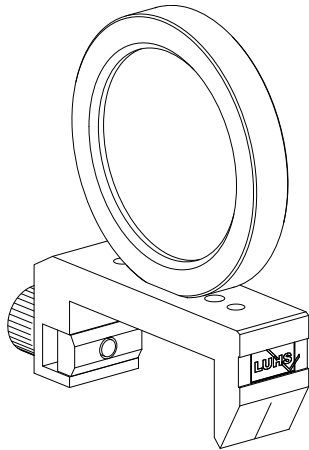
3.4 Polarization Analyser (3,6;4,10)



A click mount contains a polarizing film (6 and 10) that functions as a polarization analyser. The mount is inserted

into the mounting plate (3 and 4), where it can rotate. It is held in place by spring-loaded balls.

3.5 Translucent screen (5)



In a round holder a sheet of translucent paper is fixed with a retaining ring. This component is useful to image and visualize optical rays. Furthermore, the translucence allows the convenient photographic recording from the opposite side with digital cameras for a quick picture for the students measurement report.

3.6 Beam Expander (7)

The beam expander is based on a Galilean telescope with one concave lens as entry lens and a plano-convex as exit lens. The expansion ratio is defined by the ratio of the focal length of the lenses. The entry lens is mounted into a C25 mount which screwed to the 25 mm housing at which end the exit lens is mounted. This beam expander has an expansion rate of 6. The telescope is aligned for far sight view and can be slightly changed by turning the C25 mount to change the parallel wave front into curved ones. The beam expander is used to enlarge the laser beam to provide an almost parallel beam of coherent light.

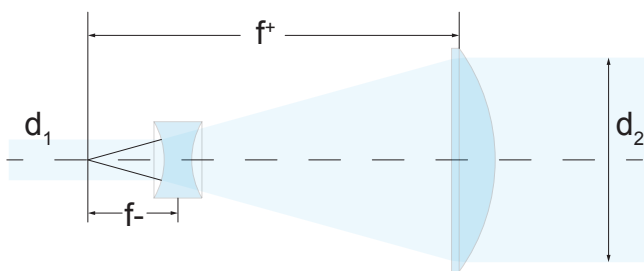
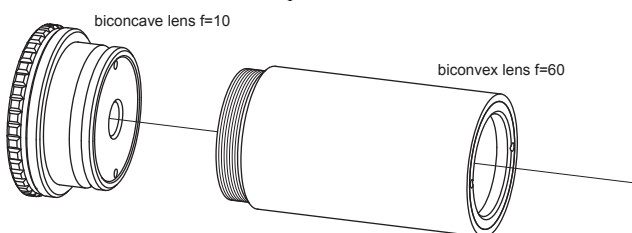


Fig. 17: Galilean beam expander

Expansion ratio or magnification:

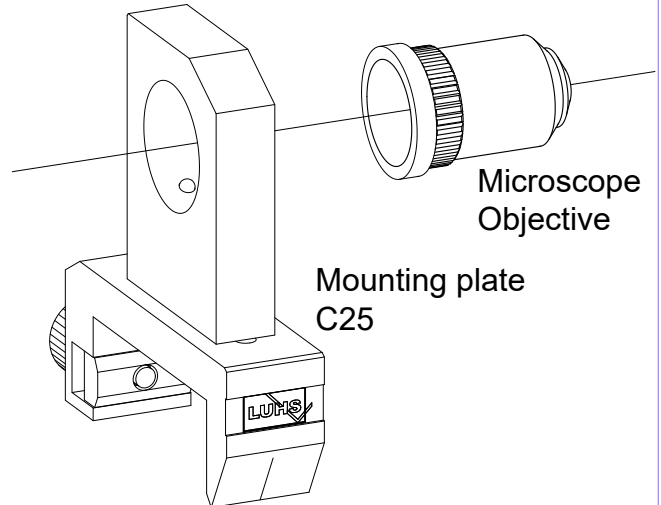
$$\frac{d_2}{d_1} = \frac{f^+}{f^-}$$



The provided beam expander consists of a combination of a biconcave ($f=10$) and biconvex lens ($f=60$) forming the so

called Galilean beam expander with a magnification of 6. The beam expander can be separated in such a way that the lenses can be used independently.

3.7 Microscope objective (8, 8A)



For the conoscopy experiment, we need a light cone that is as steep as possible, which is produced using a convex lens. Lenses with a short focal length have a small diameter, and therefore a small numerical aperture unless more than one lens is used, as is the case with microscope objectives. In the experiment, we use microscope objectives with magnifications n_{mag} of 10 and 60. The focal length can be calculated from the magnification as follows:

$$f = \frac{160}{n_{\text{Mag}}}$$

Microscope objectives typically have an RMS (W 0,8" × 1/36") mounting thread. In our application, an adapter from RMS to $d=25$ mm is screwed on. This allows the objectives to be inserted into the mounting plate, where they are held in place by the spring-loaded balls.

3.8 Optical quartz plate (9)



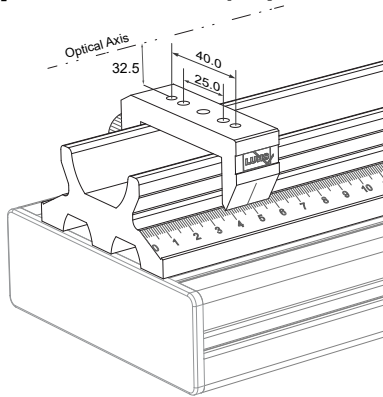
A quartz plate made from natural quartz with a thickness of 7 mm has a diameter of 25.4 mm and is cut parallel to the optical axis of the crystal. The quartz plate is mounted into a C30 mount and is placed into the mounting plate (4) where it is kept in position by three spring loaded steel balls.

3.9 Quarter-wave plate (17)



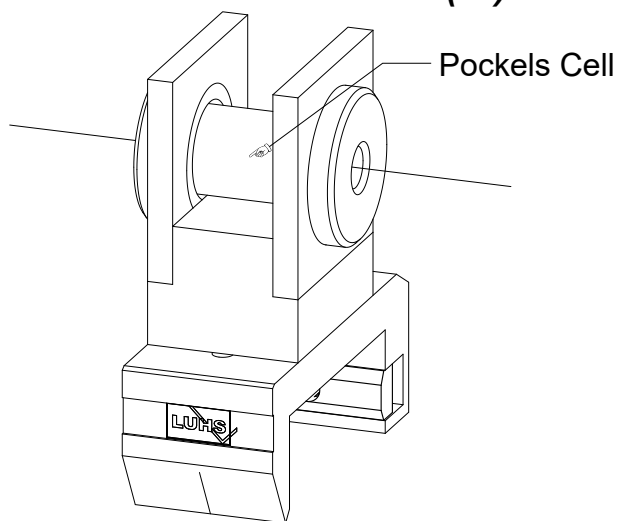
A film sheet polarizer is set into a C25 mount with a tick mark as vertical polarization indicator. The free opening is 20 mm.

3.10 Optical Bench(11)



The rail and carrier system provides a high degree of integral structural stiffness and accuracy. Due to this structure it is a further development optimized for daily laboratory use. The position of the carrier on the optical rail can be precisely adjusted thanks to the attached ruler and the markings on the carrier. The optical height of 32.5 mm above the carrier surface and the mounting holes are compatible with all other systems like from MEOS, LUHS, OWIS and LD Didactic. Consequently, a high degree of system compatibility is achieved.

3.11 Pockels Cell 19 mm (12)



The active q-switch consists of a DKDP crystal (potassium di-deuterium phosphate ($KD^*P = DKDP$)). Applying a high voltage to it, a phase retardation results which value depends on the applied voltage. The properties of the crystal are as follows:

Material:	DKDP
Dimension:	19 x 28.5 mm
Clear Diameter	8 mm
Quarter wave voltage:	3300 V
Contrast ratio:	1000:1
Clear aperture:	8 mm

The crystal is operated with the controller (13) which has the following properties:

Output voltage:	2000..4000 V
Switching time:	10 ns @ 4000 V
Repetition rate:	0 .. 2kHz

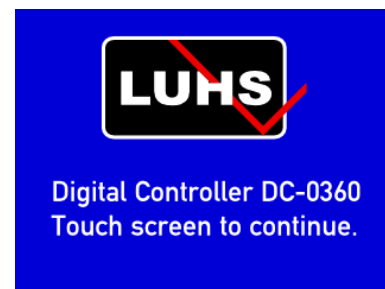
3.12 Pockels Cell HV Driver (13)



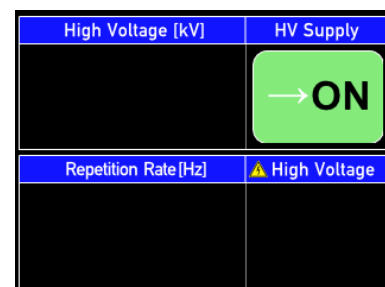
The Pockels cell controller is operated by a microprocessor touch panel and a rotary knob to set numerical set values. Pressing the knob pushes an emergency stop.



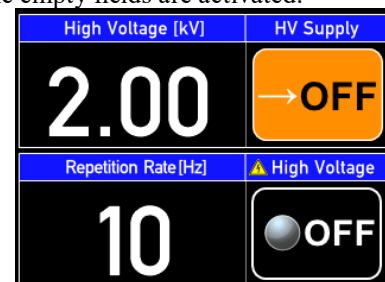
The controller is operated by a wall plug power supply providing 12 VDC at 1A. The high voltage is available at a special high voltage BNC connector.



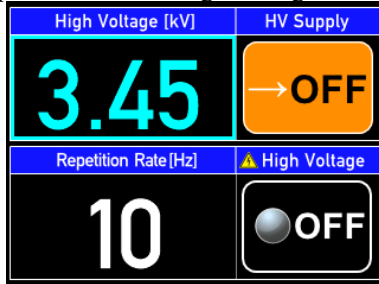
Right after switching on the controller, the start screen appears. To continue to the next screen a touch to it is required.



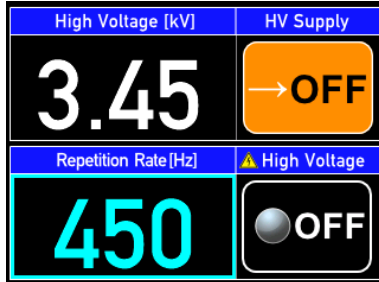
The high voltage module located inside the controller, has its own supply which is switched on by tapping the "ON" button. The empty fields are activated.



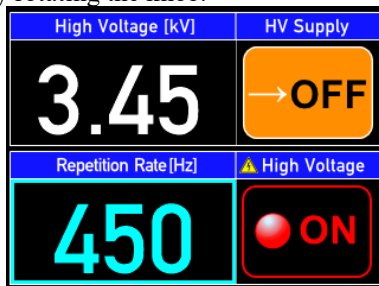
The additional elements on the screen allow the setting of the high voltage amplitude and repetition rate. The values are only applied when the “High Voltage” is activated.



By tapping the high voltage display it will be activated and by turning the knob the set value is modified accordingly.

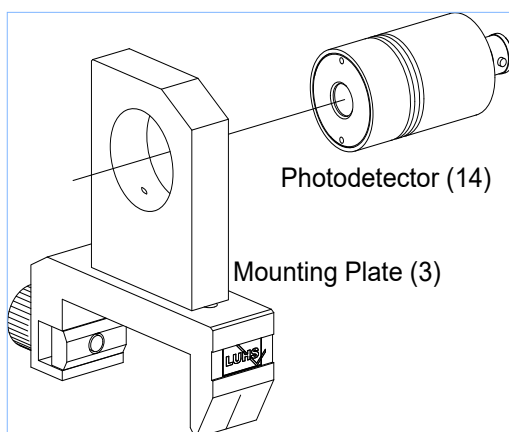


Activating the “Repetition Rate” display allows the setting the value by rotating the knob.



The set values are instantly applied when the “High Voltage” button is activated.

3.13 SiPIN Photodetector (14)



A Si PIN photodiode is integrated into a 25 mm housing with two click grooves (PD). A BNC cable and connector is attached to connect the module to the MK1 diode laser controller (15). The photodetector module is placed into the mounting plate (3) where it is kept in position by three spring loaded steel balls.

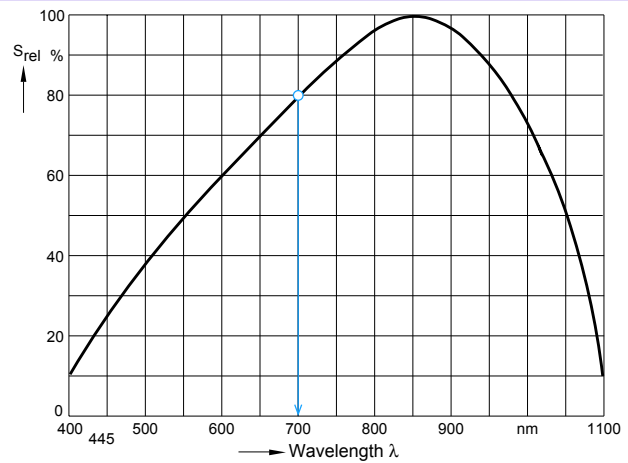


Fig. 18: Sensitivity curve of the BPX61 photodiode

Parameter	symbol	value
Rise and fall time of the photo current at: $R_L=50\ \Omega$, $V_R=5V$, $\lambda=850\ \text{nm}$ and $I_p=800\ \mu\text{A}$	t_r, t_f	20 ns
Forward voltage $I_F = 100\ \text{mA}$, $E = 0$	V_F	1.3 V
Capacitance at $V_R = 0$, $f = 1\ \text{MHz}$	C_0	72 pF
Wavelength of max. sensitivity	$\lambda_{S_{max}}$	850 nm
Spectral sensitivity $S \sim 10\%$ of S_{max}	λ	1100
Dimensions of radiant sensitive area	$L \times W$	7 mm ²
Dark current, $V_R = 10\ \text{V}$	I_R	$\leq 30\ \text{nA}$
Spectral sensitivity, $\lambda = 850\text{nm}$	$S(\lambda)$	0.62 A/W

Basic parameters of Si PIN photodiode BPX61

The Mk2 controller contains a digital resistor and provides +12 VDC for the reverse voltage of the photodiode. They are connected to the BNC input (PDIN) as shown in the schematic of Fig. 19. At the output PDOUT of the signal box a signal is present which is given by the following equation:

$$I_c = \frac{U_c}{R_s} = \frac{U_{display}}{R_s \cdot \text{Gain}}$$

I_c is the photo current created by illuminating the photodiode with light. U_c is the voltage drop across the selected load resistor R_s . $U_{display}$ is the value of U_c displayed on the controller's touch screen multiplied by the selected gain (GAIN).

To convert the measured voltage U_c into a respective optical power we use of the spectral sensitivity $S(\lambda)$ [A/W], which depends on the wavelength of the incident light according to Fig. 18. From the we take the value for $S(850\text{nm})$ as 0.62 A/W. To obtain the value for another wavelength, 445 nm for instance, we have to multiply this value with the $S_{rel}(445\ \text{nm})$ from Fig. 18 (23% or 0.23).

The detected optical power P_{opt} in W is given as:

$$P_{opt} = \frac{I_c}{S(\lambda)}$$

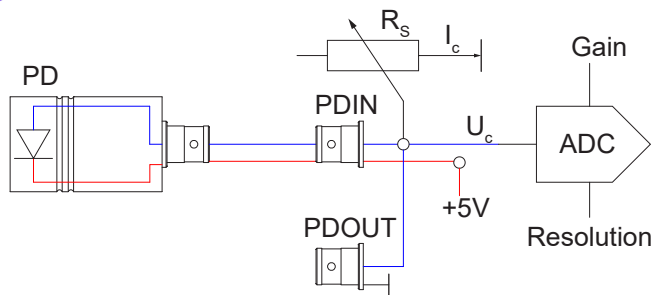


Fig. 19: Photodiode schematic

The photo voltage U_c is internally connected to a high precision ADC from which the microprocessor reads the value of the U_c and the value of the load resistor R_s and displays their values on the touch screen of the MK2 controller. It must be noted that the measured power is correct only if the entire light beam hits the detector. Based on the selected load resistor the sensitivity will be high for higher resistors but the rise and fall time will be longer. For fast signals, a low resistor should be used, however the sensitivity will be lower.

3.14 Digital Diode Laser Controller (15)



This microprocessor operated device contains a laser diode controller and a photodiode amplifier. A touch panel display allows in conjunction with the digital knob the selection and setting of the parameters for the attached laser or photodiode.

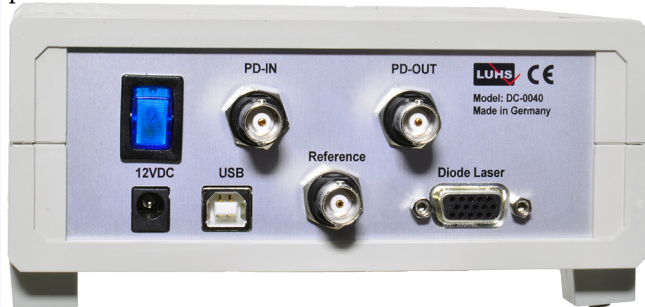


Fig. 20: Digital Diode Laser Controller MK1

The laser diode module is connected via the 15 pin HD SubD panel jacket (LD). The controller reads the EEPROM of the laser diode and sets the required parameter accordingly. The MK1 is powered by an external 12V/ 1.5 A wall plug supply. A USB bus allows the connection to a computer for remote control. Furthermore, firmware updates can be applied simply by using the same USB bus.

The MK1 provides an internal modulator which allows the periodic switch on and off of the diode laser. A buffered synchronization signal is available via the BNC jacket (MOD). Furthermore, the duty cycle of the modulation signal can

be varied in a range of 1...100 % to enable the measurement of thermal sensitivity of the optically pumped laser crystal.

The controller is equipped with industrial highly integrated circuits for the bipolar Peltier cooler (Maxim, MAX 1978) as well as for the injection current and modulation control (iC Haus, iC-HG) of the attached laser diode.

The photodetector is connected via the provided BNC cable to the PD-IN BNC panel jack. The analogue photo voltage is available at the PD-OUT panel jack.

When the LED or laser is operated in modulated mode, the reference modulator signal is available at the "REFERENCE" BNC connector. Further detailed specifications are given in the following section of the operation software.

Diode laser controller screens

When the external 12 V is applied, the controller starts displaying the screen as shown in the figure below.

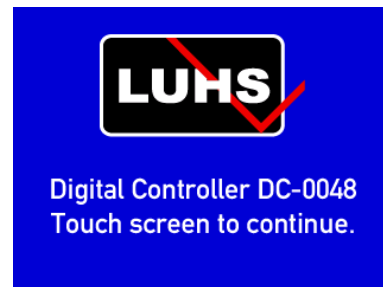


Fig. 21: Start screen

Laser Safety

The first interactive screen requires the log in to the device since due to laser safety regulations unauthorized operation must be prevented. In general, this is accomplished by using a mechanical key switch. However, this microprocessor operated device provides a better protection by requesting the entry of a PIN.

After entering the proper key, the next screen is displayed and the system is ready for operation.



Fig. 22: Authentication screen

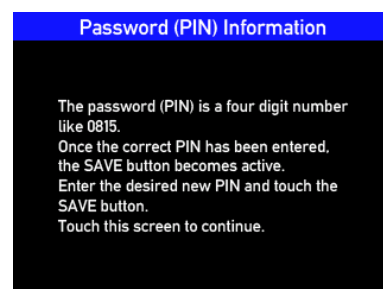
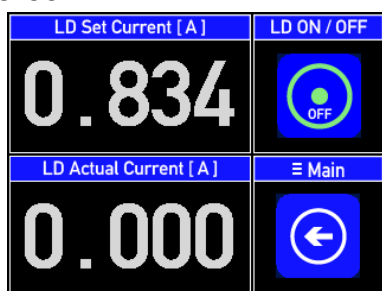


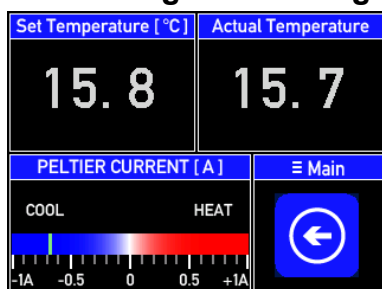
Fig. 23: Information for the password

Main Screen



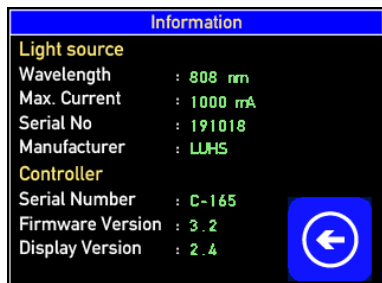
For immediate “Laser OFF” just tap the yellow button. To set the injection current simply tap the injection current display and turn the settings button (SET).

Temperature setting and reading



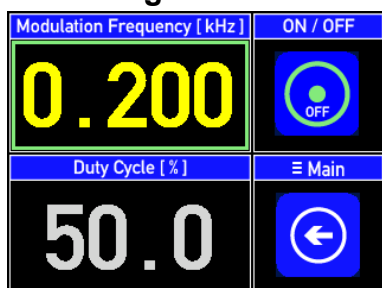
The same is true also for the “Set Temperature” section. When in operation and connected to the laser diode the actual temperature is shown in the “Actual Temperature °C” section. Furthermore the actual current of the Peltier element is shown in such a way, that cooling or heating of the element can be observed.

Information screen



When tapping the Device Info button of the main screen this screen comes up. It again reads and displays the information stored in the EEPROM of the attached diode laser. If an entry exceeds the maximum or minimum limit value retrieved from the EEPROM of the attached diode laser the entry is reversed to the respective minimum or maximum value.

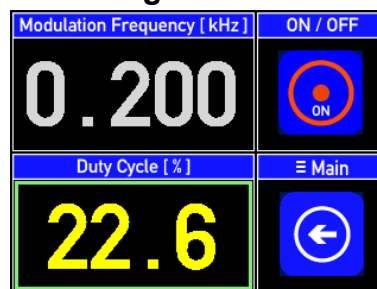
Modulation settings



The diode laser can be switched periodically on and off. This is for a couple of experiments of interest. By tapping the display of the modulation frequency, the entry is activated. Turning the settings knob will set the desired frequency value.

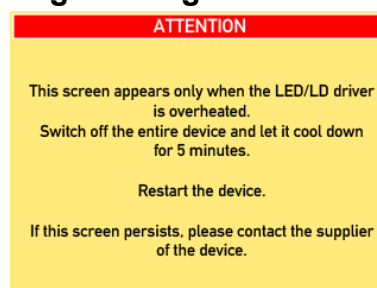
The modulation becomes active, when the Modulator ON/OFF button is tapped.

Duty Cycle settings



For some experiments it is important to keep the thermal load on the optically pumped laser crystal as low as possible or to simulate a flash lamp like pumping. For this reason, the duty cycle of the injection current modulation can be changed in a range of 1...100 %. A duty cycle of 50% means that the OFF and ON period has the same length. The set duty cycle is applied instantly to the injection current controller.

Overheating warning

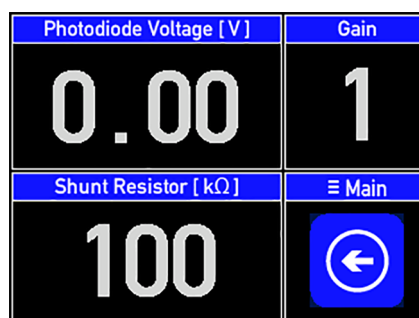


This screen you should never see. It appears only when the chip of the injection current controller is over heated. Switch of the device, wait a couple of minutes and try again. If the error persists, please contact your nearest dealer.

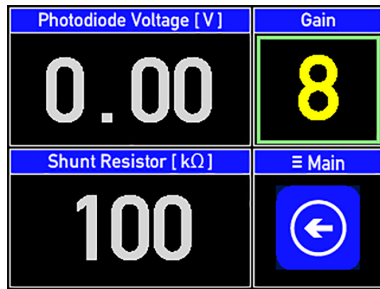


This screen is self-explanatory and appears either when no laser diode is connected or the data reading from the EEPROM is erroneous.

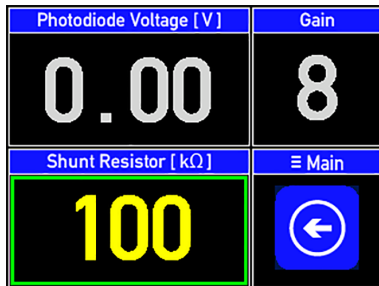
Photodetector Screens



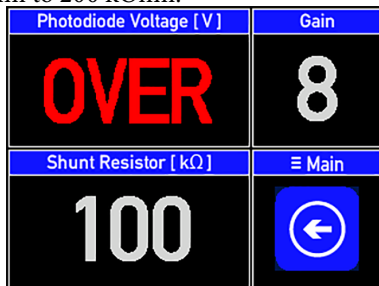
The photodiode page displays the measured photo voltage, the selected shunt resistor and the chosen gain.



Tapping the gain display field switches the gain from 1, 2, 4 and 8.

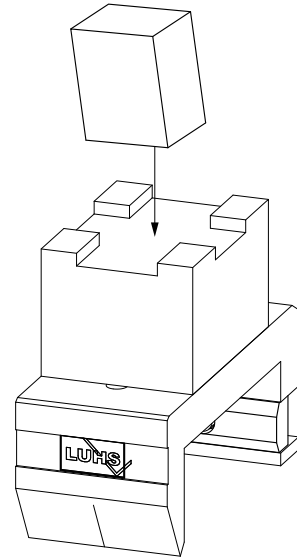


Activating the shunt resistor display field lets one set the shunt resistor by turning the digital knob. The value ranges from 1 kOhm to 200 kOhm.



If the photo voltage exceeds the inter reference voltage of 2.048 V the display shows the overload state. Reduce the gain or the shunt resistor. If the overload state remains although both values are set to minimum values, the injection current should be reduced as well.

3.15 Calcite crystal on support and carrier (16)



To demonstrate the double refraction of calcite, we use a naturally formed crystal. As is typical, the crystal has inclusions, stress cracks, and striations. The outer surfaces are cut and polished. A completely pure crystal is rare and therefore very expensive. The crystal is placed on the holder and can be positioned in various directions.

4.0 Measurements

We begin the series of experiments with orthoscopic setups, which means that parallel light passes through the birefringent samples. We observe the transmitted intensity either using a transparent screen or, for quantitative measurements, using a photodetector.

4.1 Calcite crystal

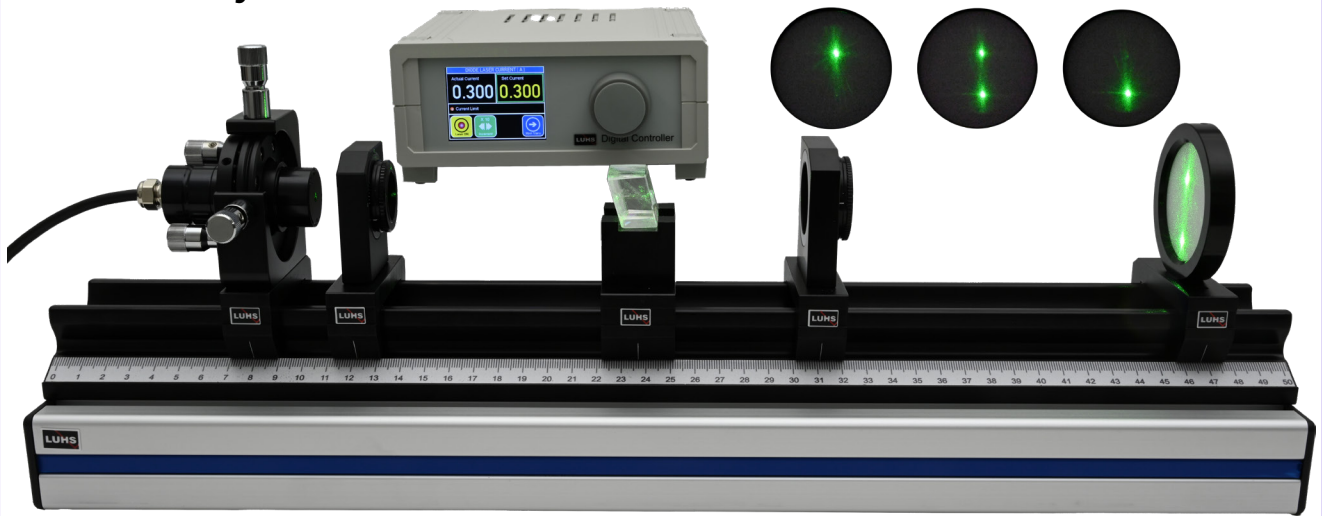


Fig. 24: Orthoscopic set-up with a calcite crystal

In this setup, the green laser beam is not expanded and is sent through the calcite crystal with its low divergence. The polarization analyzer is positioned behind the calcite crystal,

and the transmitted beams are visible on the transparent screen. Depending on the position of the polarizer, you can see the familiar two beams, or just one or the other.

4.2 Quartz crystal

4.2.1 Halve wave plate

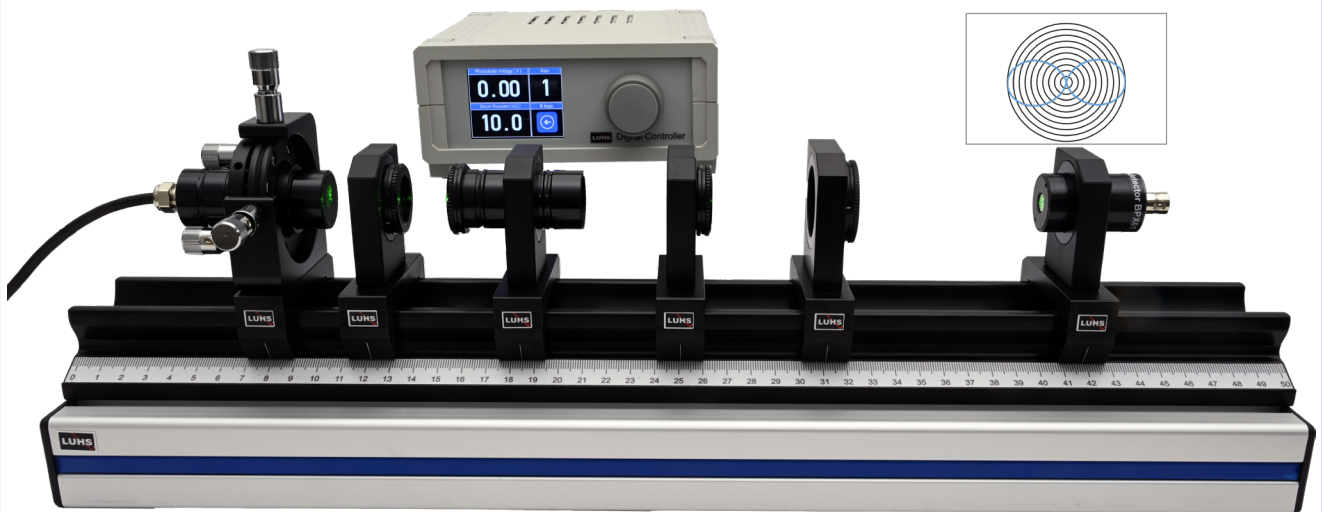


Fig. 25: Orthoscopic set-up with a thin quartz plate.

In this setup, the green laser beam is expanded using a 6x telescope and passed through the quartz plate. The polarization analyzer is positioned behind the quartz plate. The transmitted intensity is measured this time using a photodetector. The detector is connected to the controller via a BNC cable. The measured signal is displayed on the controller's screen or can be connected to a digital voltmeter

or oscilloscope via the controller's BNC output. The type of quartz plate is not revealed. The students are expected to determine this through their measurements. The transmitted intensity is measured and recorded for specific positions of the rotating quartz plate and the polarizer. From this graph, it is possible to determine whether the plate is a $\lambda/2$ or $\lambda/4$ plate.

4.2.2 Thick quartz crystal Conoscopy

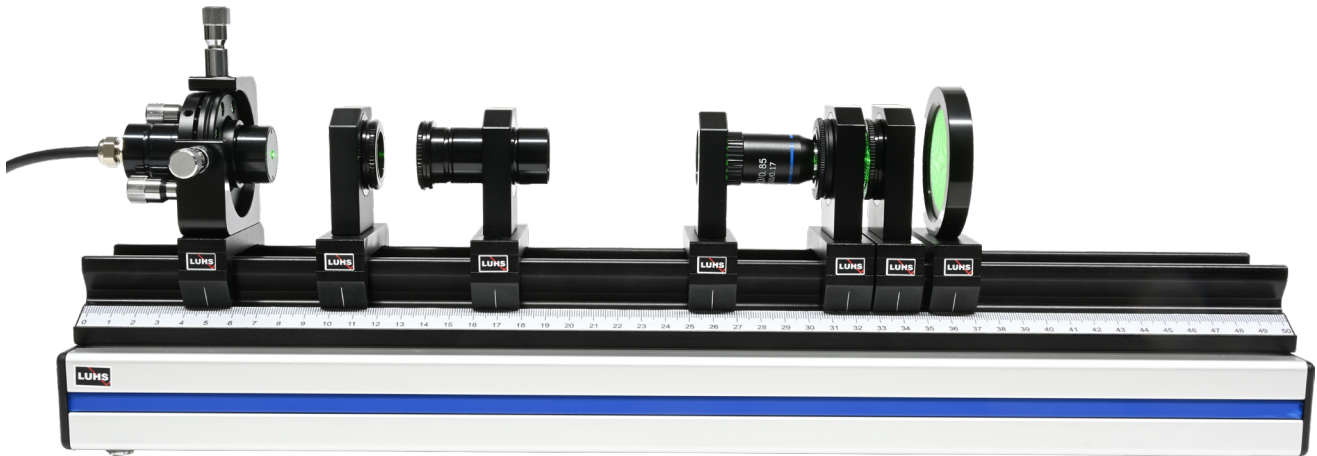


Fig. 26: Conoscopic set-up with a thick (7 mm) quartz plate.

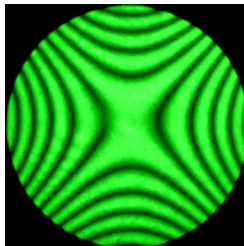


Fig. 27: Example of a conoscopic image of the quartz plate. The picture was taken from behind the transparent screen with a cell phone camera.

mental setup. The beam from the green laser is expanded using a 6x telescope and then directed centrally into the microscope objective, which has a magnification of 60x. Consequently, the focal length is 2.7 mm, producing a steep beam cone. The divergent light passes through the quartz plate and creates a mandala-like pattern on the screen after passing through the polarizer. Depending on the position of the quartz plate and the polarizer, a variety of patterns emerge. From these patterns, we can determine the crystal's principal optical axis and whether the crystal is uniaxial or biaxial.

We begin our conoscopic examinations with this experi-

4.3 Pockels Cell

4.3.1 Pockels cell in conoscopic set-up

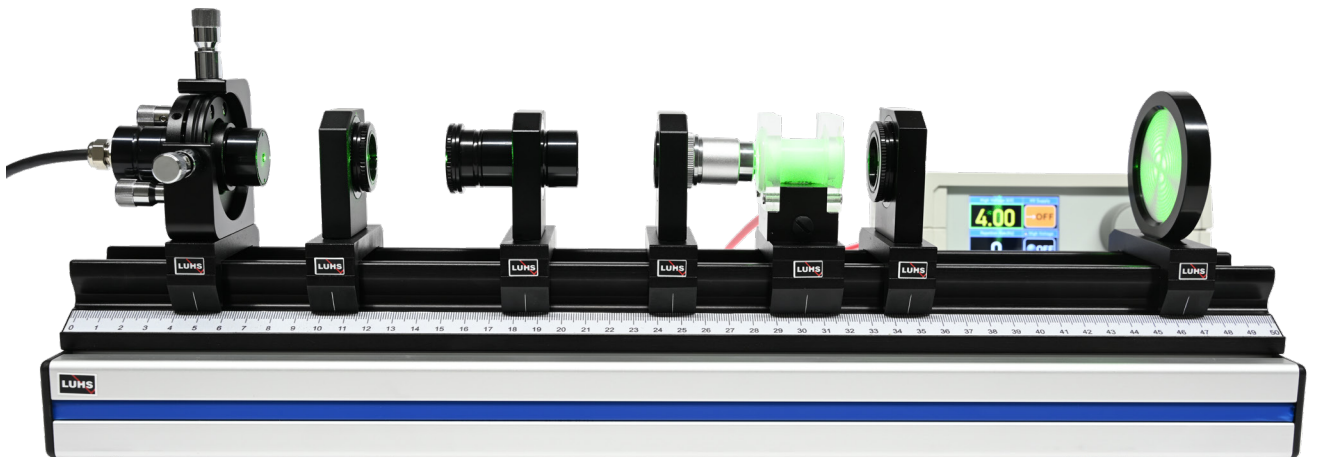


Fig. 28: Conoscopic set-up with the Pockels cell

The optional Pockels cell is used instead of the quartz plate because the crystal, at 28.5 mm, is quite long compared to the quartz plate. For this reason, we use a microscope objective with a magnification of 10 ($f = 16$ mm). The Pockels cell is supplied with an adjustable high voltage of 2000–4000 V from the controller (17). Depending on the position of the polarizer in front of the transparent screen and the selected voltage, various conoscopic images are produced, which can again be captured here with a cell phone camera. The birefringent property of the crystal used can be determined from the structure of these images.

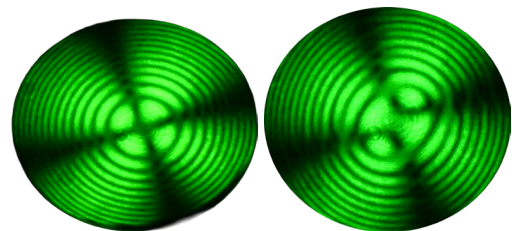


Fig. 29: Images showing the conoscopic representation of the Pockels cell, once without voltage (left) and once with voltage (right). The biaxial nature is clearly evident.

4.3.2 Polarization switching (q-switch)

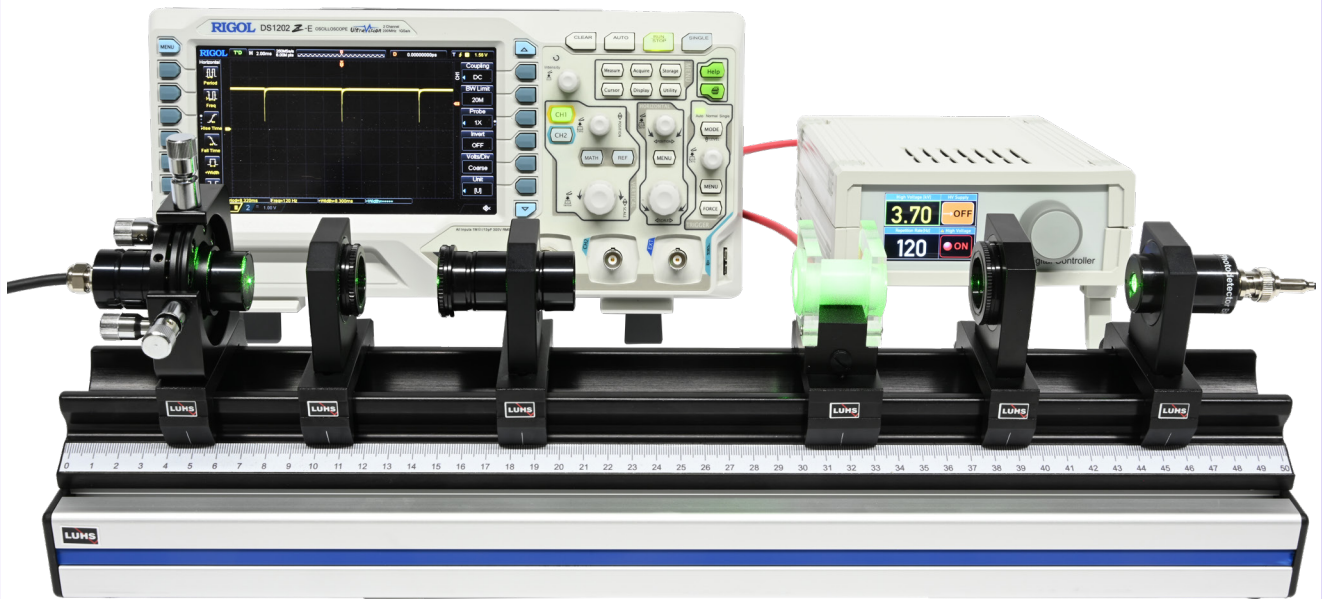


Fig. 30: Demonstration of fast polarization switching with a Pockels cell

One of the main applications of the Pockels cell is the quality switching of laser resonators to generate gigantic laser pulses. For this purpose, the polarization in the resonator is adjusted using the Pockels cell so that laser operation is not possible. Using a short pulse (in the nanosecond range), the polarization is instantly adjusted so that the laser generates a giant pulse; afterward, the Pockels cell blocks the resonator again. In this experiment, we again use an orthoscopic beam path through the Pockels cell. Behind the polarizer, the photodetector is set up to measure the transmitted intensity. In the setup, we have adjusted the position of the polarizer so that transmission is maximized when the Pockels cell is de-energized. This has the advantage of allowing us to better assess the $L/2$ voltage, since the intensity should approach zero at that point.

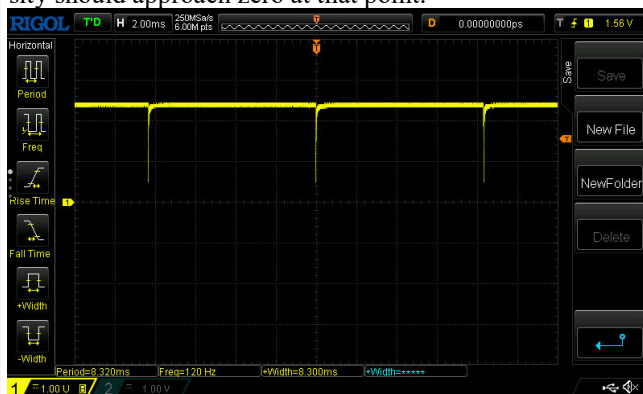


Fig. 31: Polarisation switching with the Pockels cell

The arrow on the left is the zero line. The image shows the transmitted intensity of the Pockels cell, as recorded by a detector. The driver switches the Pockels cell within nanoseconds at a repetition rate of, for example, 120 Hz. When the intensity drops to zero, the Pockels cell rotates by exactly 90° . You adjust the voltage of the Pockels cell and the crossed polarisers to achieve this. This is almost achieved, but you have to keep in mind that the photodiode isn't that fast.