.

Physicist-Engineer Nanotechnology and Quantum Applications

Specialization Laboratory Measurement 2:

Light polarization modulation using a liquid crystal cell: detection of malaria pigment

Abstract. In this laboratory exercise, you will gain experience in the sensitive detection of light polarization. In the first occasion, you will characterize the optical retardation of a voltage-controlled liquid crystal cell. Based on the knowledge you gain, you will construct a polarization modulation setup in the second part, which you will apply to detect malaria pigment crystals in a suspension.

Warning. In these experiments, you will use a laser diode. It is safe when handled correctly, but improper use can cause eye injuries. Before entering the lab, read and understand all safety rules. During the measurement, follow all instructions in the *Measurement tasks* section and always ensure personal and group safety. If unsure, ask lab supervisors and follow their guidance.

Theoretical summary

I

1 Introduction to light polarization

An electromagnetic plane wave is characterized by its wave vector $\mathbf{k}$, angular frequency ω, intensity, and phase, which you learnt how to measure and exploit in different metrologies in the previous semesters. Since the electric and magnetic fields of the radiation are vector quantities, their orientation is also an important property of the electromagnetic wave, which can influence how the wave propagates and interacts with matter. In this exercise, we will introduce polarisation-related optical phenomena and learn how to study them.

The polarization of light is defined by the orientation of the oscillating electric field vector, **E**. As light is a transverse electromagnetic radiation (at least in vacuum or in isotropic media such as air), i.e. **E** oscillates in the plane perpendicular to the propagation direction, its orientation can be represented by a 2D vector termed as the Jones vector:

$$\mathbf{E} = \begin{pmatrix} E_{0x}e^{i\delta_x} \\ E_{0y}e^{i\delta_y} \end{pmatrix} \tag{I.1.1}$$

In this representation, the electric field of a plane wave is expressed as a two-component complex vector, corresponding to the phases, δ_x & δ_y, and field amplitudes, E_{0x} & E_{0y}, along the two orthogonal transverse directions. The Jones vectors of the most frequently used polarization states are shown in Tab. I.1.1.

Polarization state	Jones vector
Horizontal polarization (H)	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$
Vertical polarization (V)	$\begin{pmatrix} 0 \\ 1 \end{pmatrix}$
+45° polarized light (D)	$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix}$
-45° polarized light (A)	$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix}$
Left circularly polarized light (L)	$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ +i \end{pmatrix}$
Right circularly polarized light (R)	$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -i \end{pmatrix}$

Table I.1.1. Representation of the main light polariyation states as Jones vectors

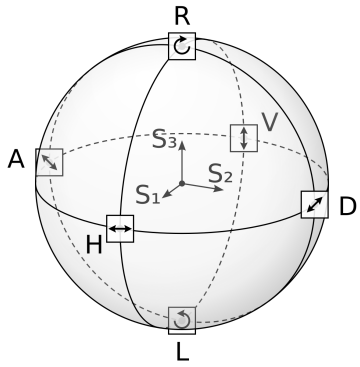

Figure I.1.1. Polarization states can be represented on the Poincare sphere.

In the Jones formalism, an optical element transforms the Jones vector of the incoming polarization state to the vector of the outgoing polarization state. Neglecting nonlinear interactions weak at low intensities, these transformations are linear and thus are represented by the so-called Jones matrices. The effect of an optical component is obtained by multiplying the Jones vector of the incoming state with the matrix of the optical element, which makes this formalism especially powerful for analyzing polarizing optics.

For example, an ideal linear polarizer acts as a projection operator. It transmits only the component of the electric field parallel to its transmission axis and blocks the orthogonal one. When a linearly polarized light with polarization axis spanning angle ϕ with the axis of the polarizer, the outgoing beam has the following form:

$$\begin{pmatrix} \cos\phi \\ 0 \end{pmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{pmatrix} \cos\phi \\ \sin\phi \end{pmatrix} \tag{I.1.2}$$

As the intensity, I measured by the detector is proportional to the square of the magnitude $I \sim |\mathbf{E}|^2$, the transmitted intensity follows Malus' law, namely $I \sim \cos^2\phi$. In case of real polarizers, the intensity does not reach zero even for orthogonal polarizers, but there is a tiny intensity $I_\perp$. The quality of polarizers is defined by the extinction ratio, which is the intensity ratio measured between crossed and parallel polarizers, $I_\perp/I_\parallel$.

The refractive index of anisotropic materials may be sensitive for light polarization. Geometric symmetries provide useful insights to such optical anisotropies. For example, there are two principal refractive indices in axially symmetric crystals such as tetragonal or hexagonal materials, where the unique axis is label as c axis. When the light polarization

Remark. The four-component Stokes formalism is capable of describing partially polarized light as well, but the discussion of this more complicated formalism is out of the scope of the present note.

is perpendicular to the c axis, i.e. the propagation is parallel with this axis, the beam is termed as ordinary and the corresponding refractive index is noted as n_o. In contrast, when the polarization is parallel to the c axis, the extraordinary beam has refractive index n_e. This optical phenomenon, where a compound exhibits a refractive index (or absorption coefficient) difference for orthogonal linearly polarized states, is referred to as birefringence (or linear dichroism), $n_o \neq n_e$ ($\kappa_o \neq \kappa_e$). For a light beam propagating normal to the c axis, the polarization of the outgoing beam changes as follows:

$$\begin{bmatrix} e^{i\frac{\omega}{c}n_o d} & 0 \\ 0 & e^{i\frac{\omega}{c}n_e d} \end{bmatrix} = e^{i\frac{\omega}{c}n_o d} \begin{bmatrix} 1 & 0 \\ 0 & e^{i\frac{\omega}{c}\Delta n d} \end{bmatrix} \sim \begin{bmatrix} 1 & 0 \\ 0 & e^{i\delta} \end{bmatrix}, \tag{I.1.3}$$

where $\Delta n = n_e - n_o$, d is the thickness of the sample and $\delta = \frac{\omega}{c}\Delta n d$ is a phase shift between the horizontal and vertical light polarizations, which is also termed as retardation. When the incoming beam is polarized either along the c axis or in the perpendicular directions the polarization state remains the same after transmission. However, when the incident beam is 45° polarized, a phase shift appears between the two linearly polarized components. By properly tuning the refractive index difference and the thickness to achieve $\delta = \pm\pi/2$, a $\lambda/4$ waveplate switching between linearly and circularly polarized states can be constructed.

Question. Can you prove the above statement that such a birefringent plate can convert linear and circular polarizations to each other?

2 Liquid crystal retarders

Molecules with anisotropic shape may also possess optical anisotropies. However, liquid and gas phases show no optical anisotropy as the molecules are randomly oriented due to thermal fluctuations. Interestingly, there are liquid crystal (LC) phases lying between the crystalline solid and disordered liquid phases. Nematic LCs are organic compounds consisting of elongated, needle-like molecules with ordered orientation, though their center of mass remains disordered. The orientation of the molecules is called the director of the LC. The advantage of the LC phase is that the director can be easily controlled using an electric field. This allows the application of LC as a voltage-controlled waveplate, which is used in liquid crystal displays (LCDs) and other modern photonic applications.

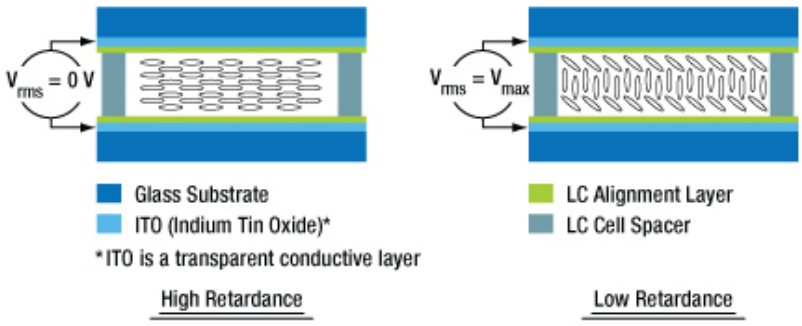

Figure I.2.1. The orientation of LC molecules is ordered in the nematic phase, which creates an optical anisotropy. When an electric field is applied in the perpendicular direction, the molecules align with the field and the retardation is controlled by tilting the LC molecules. The image is reproduced from Thorlabs.com.

The structure of an LC cell used for the laboratory exercise is shown in Fig. I.2.1. The glass substrate plates are first coated with a thin layer of electrically conductive but

optically transparent indium tin oxide (ITO), followed by a thin alignment layer, which is polished to create microscopic grooves. These grooves align the LC molecules in one direction close to the surface, and the interaction between the molecules forces the same director on the entire LC cell sandwiched between two substrates.

Due to the parallel alignment of the molecules, the cell becomes birefringent. As discussed at Eq. I.1.3, light polarization does not change when it is aligned along or perpendicular to the director of the LC. However, there is a measurable phase shift between the two linearly polarized components, when the polarization of the incident beam is rotated away from the director by an angle θ. This can be detected if we place a second polarizer, termed as an analyzer, after the cell. The transmitted intensity between parallel/perpendicular polarizers can be obtained in the following way:

$$T_{\parallel} = |\cos^2\theta + \sin^2\theta e^{i\delta}|^2 \tag{I.2.1}$$

$$T_{\perp} = |-\sin\theta\cos\theta + \sin\theta\cos\theta e^{i\delta}|^2 \tag{I.2.2}$$

Of course, the same results hold when the LC cell is rotated instead of the polarizers. For the θ=45° case, the formulas are simplified to:

$$T_{\parallel} = \cos^2\frac{\delta}{2} \tag{I.2.3}$$

$$T_{\perp} = \sin^2\frac{\delta}{2} \tag{I.2.4}$$

By applying a voltage on the cell, LC molecules rotate toward the electric field, thus, the retardation decreases. The voltage, V vs. retardation, $\delta(V)$ characteristics of the LC cell is usually strongly non-linear. Pinning of the director close to the alignment layer causes almost no variation at low voltages and a residual retardation at higher voltages. Importantly, DC voltages leads to electrolysis and degradation of the cell, thus, AC voltages are applied on the LC cell to control its retardation.

As the voltage changes the retardation, the outgoing light polarization state can be controlled by the LC cell. When the optical axis of the LC cell spans θ=45° and the amplitude is large enough ($\delta > \pi/2$) the linearly polarized state of the incident beam becomes circularly polarizer. Larger retardation, $\delta = \pi$ can flip the polarization by 90° as shown in Fig. I.2.2.

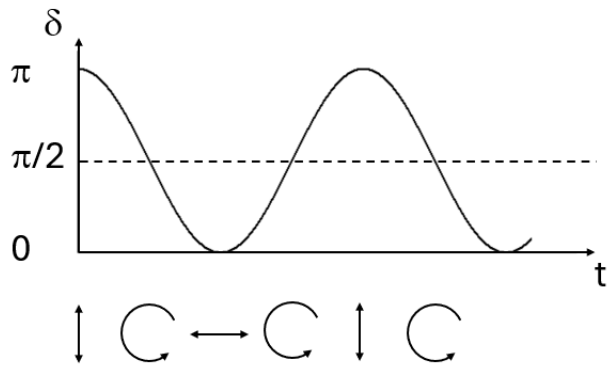

Figure I.2.2. Time dependence of the retardation, δ and the polarizatin state when the incident polarization spans θ=45° with respect to the director of the cell. As the retardation oscillates in time, the outgoing polarization varies as shown in the bottom.

Question. Can you derive the above equations?

3 Optical detection of malaria infection

Malaria is a life-threatening disease spread by some types of mosquitoes. Although it is preventable and curable, hundreds of millions of people are infected each year, placing a significant social and economic burden on many tropical developing countries [2, 3]. Although efficient treatments and diagnostic methods are available, there is still a substantial degree of misdiagnosis of malaria due to resource limitations and certain shortcomings of the most widespread rapid diagnostic tests. Thus, the development of better diagnostic tools is a declared priority on the malaria elimination agenda.

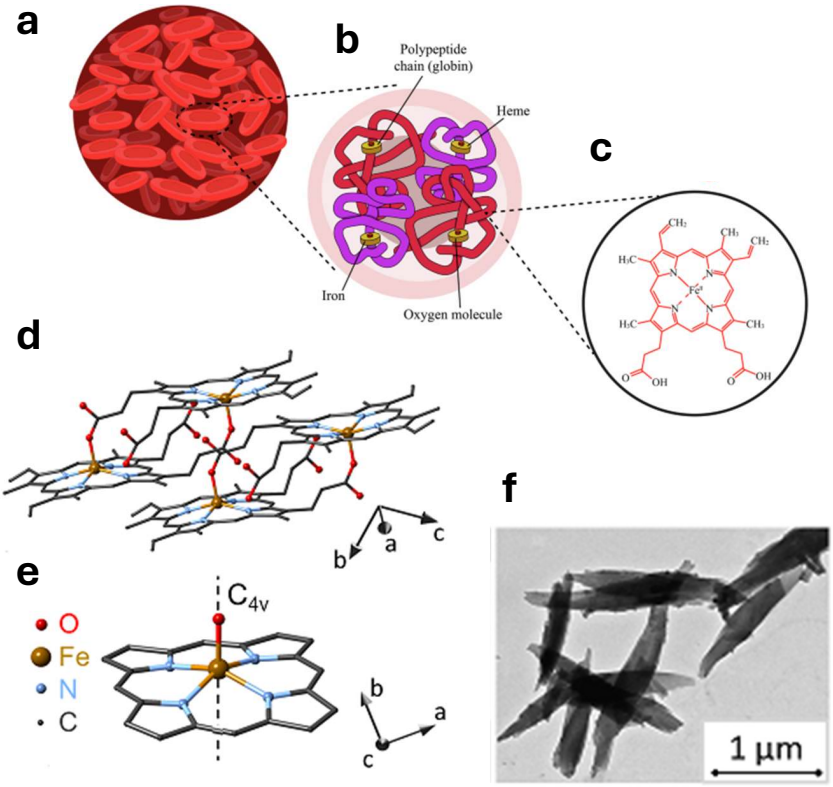

Figure I.3.1. a) Red blood cells contain b) hemoglobin protein responsible for oxygen transport in the blood. c) The heme part of the hemoglobin is an iron-containing complex, where oxygen can bind and unbind. d) Anizotropic (monoclinic) crystal structure of hemozoin. e) Local environment of iron in hemozoin. f) Transmission electron micrographs of typical hemozoin crystallites. The images are reproduced from the cited publications [4, 5].

Malaria is caused by single-cell parasites, called *Plasmodium*, which, after a mosquito bite, travel to the liver, grow, divide and get back to the bloodstream. The parasites invade red blood cells and digest the hemoglobin of the host cell (see Fig. I.3.1). As a byproduct, iron-containing heme molecules are liberated, which form needle-shaped organic crystallites called hemozoin. As these sub-micron crystallites concentrate the iron content of hemoglobin (and the valency of iron is Fe^{3+} in these crystals), hemozoin shows paramagnetic behavior.

By exploiting these properties, the research group led by I. Kézsmárki at the Department of Physics, BME, developed a magneto-optical method to diagnose malaria infection [5]. The main idea of the diagnostics is as follows: The sub-micron hemozoin crystallites

in the blood sample are aligned when placed in an external magnetic field. Due to the low symmetry of the hemozoin, an optical anisotropy appears for linear polarization along and perpendicular to the magnetic field. Finally, this linear anisotropy should be measured in order to sensitively detect the malaria infection, which will be the final task in this exercise, as well.

There are several possibilities to detect small polarization changes by using balanced photodetectors, modulating light polarization by rotating polarizing elements or by photoelastic modulators. Here, we will implement a polarization modulation technique by applying an LC cell. The image of the optical setup is shown in Fig. I.3.2. Light propagates from the source, which is a laser diode, through a film polarizer, and then it goes through an LC cell 45° rotated with respect to the polarizer. Next, the beam goes through the sample holder, which fixes a cuvet in a magnetic field of about $\sim 150\,\mathrm{mT}$. The field is normal to the permanent magnet plates, and it should be aligned parallel with the initial polarizer. Finally, the light goes through an analyzer and reaches the detector.

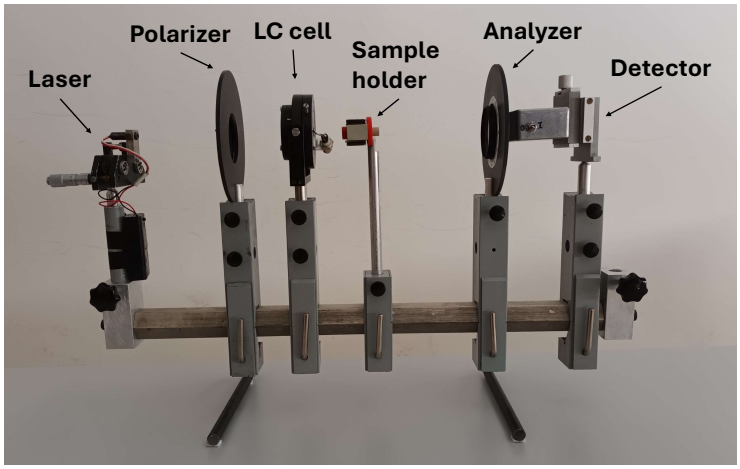

Figure I.3.2. Image of the optical setup used for the detection of hemozoin samples.

We follow how light polarization changes using Jones formalism. The electric field amplitude at the detector can be determined as:

$$E_{det} = E_0 \begin{pmatrix} \cos\theta & \sin\theta \end{pmatrix} \begin{bmatrix} e^{-\frac{\omega}{c}\kappa_\parallel d} & 0 \\ 0 & e^{-\frac{\omega}{c}\kappa_\perp d} \end{bmatrix} R^{-1}(45°) \begin{bmatrix} 1 & 0 \\ 0 & e^{i\delta(V)} \end{bmatrix} R(45°) \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \qquad \text{(I.3.1)}$$

where $R(45°)$ represents a matrix rotating by 45°, $\kappa_\parallel$ and $\kappa_\perp$ are the extinction coefficients describing light absorption for light polarization along and perpendicular to the magnetic field and θ is the angle of the analyzer. The light intensity reads as:

$$I \sim |E_{det}|^2 = \frac{|E_0|^2}{2} e^{-2\frac{\omega}{c}\kappa_0 d} \times \\ \left[\cos^2\theta e^{\frac{\omega}{c}\Delta\kappa d} + \sin^2\theta e^{-\frac{\omega}{c}\Delta\kappa d} + \left(\cos^2\theta e^{\frac{\omega}{c}\Delta\kappa d} - \sin^2\theta e^{-\frac{\omega}{c}\Delta\kappa d}\right)\cos\delta(V)\right], \qquad \text{(I.3.2)}$$

where the average and difference of the extinction coefficients are introduced, $\kappa_0 = \frac{\kappa_\parallel + \kappa_\perp}{2}$ and $\Delta\kappa = \kappa_\parallel - \kappa_\perp$, respectively. In order to realize sensitive lock-in detection, we will modulate the retardation by modulating the voltage on the LC cell: $\delta \approx \delta_0 + \delta_f \cos 2\pi f t$ around a specific working point $\delta_0 = \pi$. (Due to the non-linear characteristics of the LC cell, $\delta(V)$, this formula is valid only approximately.) Using the so-called Jacobi-Anger

expansion formula, a Fourier series of the retardation can be obtained. The first non-vanishing harmonics are:

$$\cos\delta = -\cos(\delta_f \cos(2\pi f t)) = J_0(\delta_f) - 2J_2(\delta_f)\delta_f \cos(2\pi 2 f t) + \dots \tag{I.3.3}$$

where J_n (n=0 and 2) are the n-th Bessel function of the first kind (see Fig. I.3.3). Therefore, the first two terms in the Fourier series of the intensity are:

$$I_0 = \frac{|E_0|^2}{2} e^{-2\frac{\omega}{c}\kappa_0 d}\left[\cos^2\theta e^{\frac{\omega}{c}\Delta\kappa d} + \sin^2\theta e^{-\frac{\omega}{c}\Delta\kappa d} + \left(\cos^2\theta e^{\frac{\omega}{c}\Delta\kappa d} - \sin^2\theta e^{-\frac{\omega}{c}\Delta\kappa d}\right) J_0(\delta_f)\right],$$
$$I_{2f} = -\frac{|E_0|^2}{2} e^{-2\frac{\omega}{c}\kappa_0 d}\left(\cos^2\theta e^{\frac{\omega}{c}\Delta\kappa d} - \sin^2\theta e^{-\frac{\omega}{c}\Delta\kappa d}\right) 2J_2(\delta_f). \tag{I.3.4}$$

To normalize the signal, we will measure the ratio of these two components:

$$\frac{I_{2f}}{I_0} = -2J_2(\delta_f)\frac{\cos^2\theta e^{\frac{\omega}{c}\Delta\kappa d} - \sin^2\theta e^{-\frac{\omega}{c}\Delta\kappa d}}{\cos^2\theta e^{\frac{\omega}{c}\Delta\kappa d} + \sin^2\theta e^{-\frac{\omega}{c}\Delta\kappa d}}, \tag{I.3.5}$$

where we neglected the small term, proportional to J_0 from the DC component.

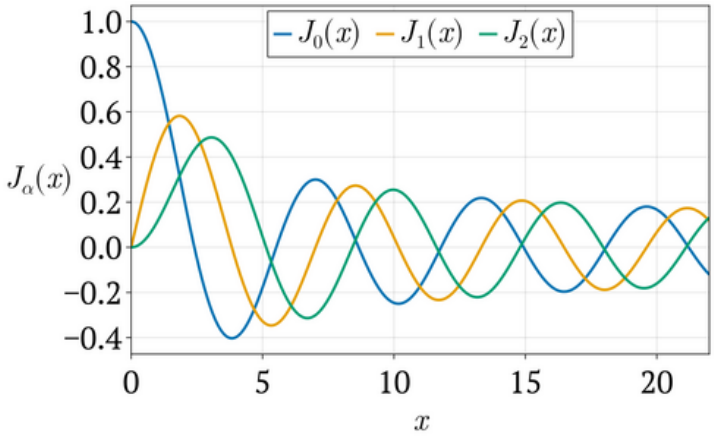

Figure I.3.3. Bessel functions.

We will study two cases. First, without a sample, i.e. $\Delta\kappa = 0$, we will calibrate the setup and measure the sensitivity around $\theta = \pi/4 + \varepsilon$ by small, ε rotations of the analyzer:

$$\frac{I_{2f}}{I_0} = -2J_2(\delta_f)\cos 2\theta = -2J_2(\delta_f)\sin 2\varepsilon \approx -2J_2(\delta_f)2\varepsilon \tag{I.3.6}$$

To achieve the highest sensitivity, δ_f should be tuned to the maximum of the Bessel function J_2, which is close to $\delta_f \approx \pi$.

Next, the analyzer is set to the most sensitive $\theta = \pi/4$ position and the sample is measured:

$$\frac{I_{2f}}{I_0} = -2J_2(\delta_f)\frac{e^{\frac{\omega}{c}\Delta\kappa d} - e^{-\frac{\omega}{c}\Delta\kappa d}}{e^{\frac{\omega}{c}\Delta\kappa d} + e^{-\frac{\omega}{c}\Delta\kappa d}} = -2J_2(\delta_f)\tanh\left(\frac{\omega}{c}\Delta\kappa d\right). \tag{I.3.7}$$

By knowing the calibration constant, $-2J_2(\delta_f)$, the extinction coefficient difference can be determined.

Measurement tools

II

List of Measurement Tools.

- *Analog Discovery 3* measurement device realizing waveform generator, oscilloscope, lock-in amplifier (Digilent AD3, Fig. II.1.1). To communicate, use the WaveForms software. If your laptop has USB-C connector to communicate, please install this software prior to the laboratory to make data acquisition simpler
- Two channel signal generator (Siglent SDG 1062X, Fig. II.1.2).
- Laser diode; wavelength 650 nm.
- Rotatable film polarizers.
- LC cell (Thorlabs LCC1111U-A) mounted on a rotatable holder.
- Sample holder with rotatable magnet and 20 mm long cuvette (see Fig. II.1.3).
- Photodetector.

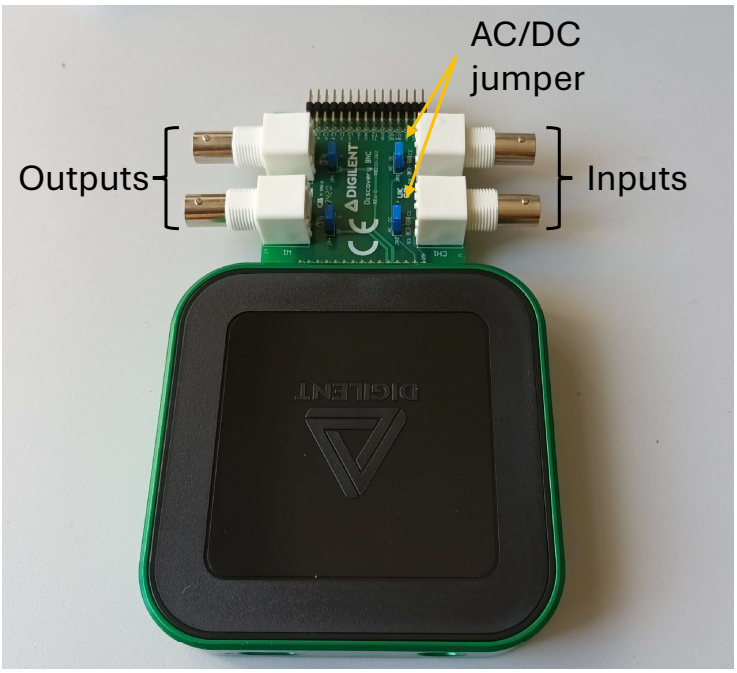

Figure II.1.1. Analog Discovery 3 measurement card. The BNC outputs and inputs are located on the left and right sides, respectively. The AC and DC coupling can be switched by the jumpers of the board.

Figure II.1.2. Two channel signal generator.

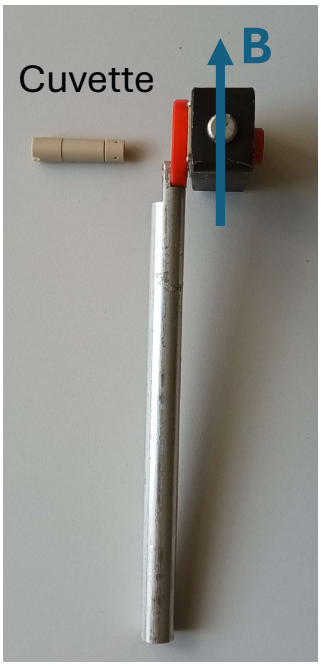

Figure II.1.3. Cuvette and sample holder fixing permanent magnets.

Measurement Tasks

III

Warning. This measurement involves a laser diode. It is safe when handled correctly!
Mandatory safety precautions:

- **Never** stare directly into the beam.
- Protect lab partners by blocking the beam (e.g., with the detector, even when unused).
- Remove reflective jewelry before starting.

Hint for the Lab Notes. Evaluate *all* tasks and parameters—*including those* in "Hint for the Lab Report"—**during** the lab. If time is short, make rough estimates.

1 Basic characterization of film polarizers

Fix the laser diode and the photodiode on the opposite ends of the optical rail. Place two polarizers in between leaving space for the LC cell and the magnetic sample holder, which will be inserted later. Connect the output of the photodiode to the input of the Analog Discovery 3 (AD3) to measure its output. For this, connect AD3 to your laptop via its USB-C cable, and start WaveForms software, where you can measure DC voltages (Voltmeter application) as well as AC signals (Scope application). There is a hardware switch between AC and DC coupling in the inputs of AD3: select the proper coupling using the blue jumper. Turn on the laser and the photodiode, and direct the laser into the active area of the photodiode. Optimize the direction of the laser beam by maximizing the DC signal of the detector.

Task 1. Determine the angular dependence of the intensity. Measure the light intensity on the photodetector by noting its voltage while rotating the analyzer step-by-step. (We recommend a step size not larger than 10°.) Consider the potential impact of room lighting. Verify Malus' law, determine the position corresponding to the parallel and perpendicular orientations of the polarizers. Determine the extinction ratio of the polarizers.

Hint for the Lab Notes. Plot the data. Note the parallel and perpendicular orientations of the polarizers.

Hint for the Lab Report. Summarize and evaluate the results graphically. Do the results agree with your expectations?

2 Liquid crystal cell

Insert the LC cell between the polarizers and fix it on the rail. Connect the cell to the Siglent function generator, but first, keep the output of the function generator off. Set the polarizers parallel. By rotating the LC cell, find the orientation when its axis is parallel with the polarizers, and note the orientation.

Rotate the analyzer by 90° and maximize the intensity on the photodetector by rotating the LC cell. In principle, the LC cell should be rotated by 45°. Confirm on the rotation mount if you reached this orientation.

Task 2. Determine the polarization state after the LC cell rotated by 45° with respect to the first polarizer. Measure the light intensity on the photodetector by noting its voltage while rotating the analyzer step-by-step. (We recommend a step size not larger than 10°.)

Hint for the Lab Notes. Plot the data, and comment on the shape. Hint 1: A polar plot could help in visualising. Hint 2: Compare/plot together with the previous case.

Hint for the Lab Report. Determine the zero-voltage retardation and optical path length difference, Δnd in the cell.

Task 3. Determine the retardation of the LC cell as a function of applied voltage. Set the analyzer parallel with the polarizer. Synthesize 2 kHz rectangular signal with the Siglent function generator and gradually, step-by-step, increase its amplitude and measure the transmitted intensity. Do not forget to take into account the possible effect of room light.

Warning. DO NOT APPLY DC VOLTAGES TO THE LC CELL. DC voltages lead to electrolysis and degradation of the cell! Therefore, it is important to drive the cell only with AC voltages.

Task 4. Repeat the previous experiment with orthogonal polarizers. Determine the retardation of the LC cell as a function of applied voltage. Synthesize 2 kHz rectangular signal with the Siglent function generator and gradually, step-by-step, increase it and measure the transmitted intensity. Do not forget to take into account the possible effect of room light.

Hint for the Lab Report. Determine $T_{\parallel}$ and $T_{\perp}$. Deduce the retardation as a function of (RMS) voltage.

3 Detection of hemozoin suspended in water

In this part, you are measuring the linear dichroism of synthetic hemozoin suspended in distilled water. Malaria parazites release similar nanocrystals, thus, this task is suitable to mimic the development of a diagnostic tool. However, the samples contain no parazites, the hemozoin is grown in a chemical laboratory; therefore, there is no risk of infection, and the studyed suspension do not pose any danger.

Insert the sample holder into the light path without any samples. Confirm that the laser beam goes through. Rotate the analyzer to θ=45°. Connect the output of AD3 to the auxiliary (AUX) input of the Siglent waveform generator. (It is on the rear panel.) Select external modulation on Siglent and feed its output to the input of AD3. On the WaveForms software, start the function generator (Wavegen) and synthesize 20 Hz sinusoidal signal with 200 mV amplitude. Confirm that you see an amplitude-modulated square wave on the output of the Siglent function generator.

In order to detect the second harmonic signal, a digital lock-in amplifier implemented in the Scope application of the WaveForms software is used. Start the LockIn (software) by selecting Add Channel on the right-hand side column (see Fig. III.3.1). Configure the lock-in as you learnt in the last semester.

- Set the reference internal and choose the appropriate frequency.
- Instead of a time constant, here you can directly set the parameters of the low-pass filter. Remember: the smaller the cutoff, the less noisy your measurement is, but you should also wait longer. Among the many available low-pass filters, we recommend selecting mode: IIR Butterworth and type: Low-Pass with order: 8. We are encouraging you to try a few others.

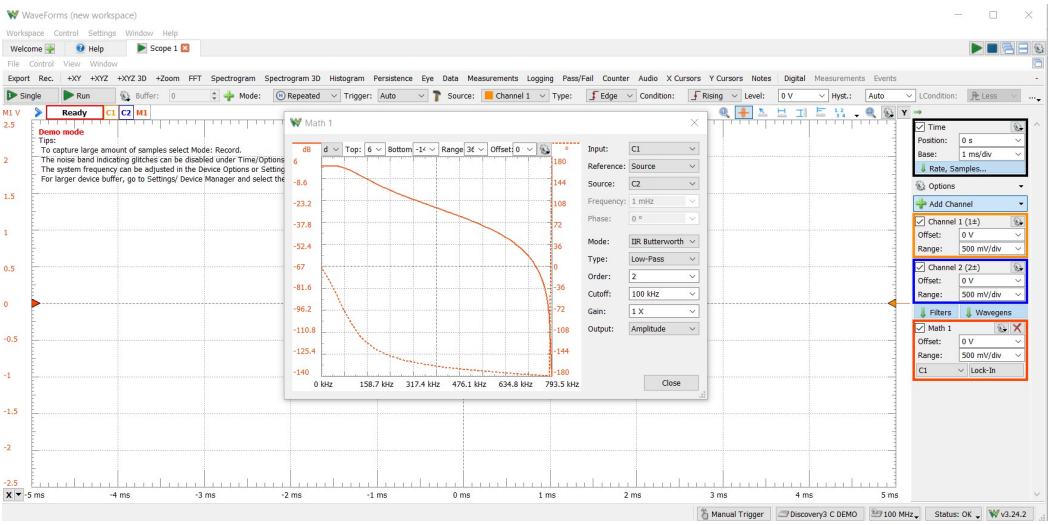

Figure III.3.1. Settings of the Lock-in in the Scope application of the WaveForms.

- Set Time/div large enough to display the lock-in signal after the decay of the transient.

- The average of the lock-in signal can be read by activating the Measurements menu and measuring the average over a meaningful part of the time trace. User-defined cursors can select part of the time trace: click on the X cursors menu and add two cursors from the bottom menu. Finally, set the range in the Measurements window.

Minimize the unwanted first harmonic by tuning the amplitude of the square wave on the Siglent. (For this, you may adjust voltage in finer steps, e.g. 10 mV.) For the measurements, double the reference frequency to detect the second harmonic. On the output measure the real part and maximize it by changing the phase.

Task 5. Calibrate the setup for the linear dichroism measurement. Measure the second harmonic and the DC signal as you rotate the analyzer by max. ±10° around 45°. What happens when you increase the amplitude to 500 mV or change the frequency? Explore the parameters and select the most sensitive combination.

Hint for the Lab Notes. It is essential to plot the calibration curves to confirm if they look as you expect. Select the best settings for the next part and document your choice.

Hint for the Lab Report. Determine the sensitivity by linear regression and compare the different settings.

Task 6. Insert the dense suspension of hemozoin in the light path. Keep the magnet horizontal and measure the signal. Rotate the field by 90°. Record data and explain what you observe.

Task 7. There are cuvettes with 10x diluted suspension and with distilled water. Measure those as well. What can you see from the concentration dependence?

References

[1] Liquid crystal retarders on Thorlabs.com.

[2] L. Arndt, T. Koleala, Á. Orbán, C. Ibam, E. Lufele, L. Timinao, L. Lorry, Á. Butykai, P. Kaman, A. P. Molnár, S. Krohns, E. Nate, I. Kucsera, E. Orosz, B. Moore, L. J. Robinson, M. Laman, I. Kézsmárki and S. Karl, *Magneto-optical diagnosis of symptomatic malaria in Papua New Guinea*, Nature Communications **12**, 969 (2021).

[3] Á. Orbán, J.-J. Schumacher, Sz. Mucza, A. Strinic, P. Molnár, R. Babai, A. Halbritter, B. G. Vértessy, S. Karl, S. Krohns and I. Kézsmárki, *Magneto-optical assessment of Plasmodium parasite growth via hemozoin crystal size*, Scientific Reports **14** 14318 (2024).

[4] X. Chen, H. Zhou, and J. Lv, *The Importance of Hypoxia-Related to Hemoglobin Concentration in Breast Cancer*, Cell Biochem Biophys **82**, 1893 (2024).

[5] A. Butykai, Á. Orbán, V. Kocsis, D. Szaller, S. Bordács, E. Tátrai-Szekeres, L. F. Kiss, A. Bóta, B. G. Vértessy, T. Zelles and I. Kézsmárki, *Malaria pigment crystals as magnetic micro-rotors: key for high-sensitivity diagnosis*, Scientific Reports **3**, 1431 (2013).