

Teaching optics

Set-up for spontaneous and induced birefringence measurements

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The paper presents a simple polarization-interference set-up for demonstration of temperature dependence of birefringence and both electrooptical phenomena which can be used for the students laboratory and scientific investigation.

Keywords: birefringence, ferroelectric material.

1. Introduction

A polarized light beam passing through a linearly birefringent crystal is divided into two beams linearly polarized in perpendicular planes and then propagates with different velocities.

When a light beam is passing through a crystal, the phase shift between the fast and the slow light waves is related to the linear birefringence by:

$$\Delta\gamma = \frac{2\pi}{\lambda_0} \Delta n L \quad (1)$$

where λ_0 – wavelength of the light in vacuum, L – length of the light path through the sample, D – linear birefringence [1–3].

When the light exits the crystal, both interfering beams give in effect either a linear, circular or elliptical beam depending on the phase shift.

For the crossed arrangement of a polarizer and an analyzer the intensity of light leaving the system is given by

$$I = I_0 \sin^2(2\varphi) \sin^2\left(\frac{\Delta\gamma}{2}\right) \quad (2)$$

where I_0 – the intensity of light leaving the system when $\sin(2\varphi) = \pm 1$ and $\sin(\Delta\gamma/2) = \pm 1$, φ – the azimuth of the first eigenvector related to the analyzer [4].

Using formula (2) we can calculate the phase shift between the fast beam and the slow one. The maximum change of the light intensity exiting the system is achieved when $\varphi = \pm 45^\circ$, then formula (2) is given by

$$I = I_0 \sin^2 \left(\frac{\Delta\gamma}{2} \right). \quad (3)$$

Birefringence Δn of the medium can be changed, *e.g.*, by temperature, external electric or magnetic fields (the electro- or magneto-optical effects). Especially, spontaneous birefringence changes are interesting in ferroelectric crystals in the phase transition temperature region.

Methods and measurement results of the spontaneous birefringence within the ferroelectric phase transition as well as the linear and quadratic electrooptic effects (the Pockels and the Kerr effects) are presented and discussed.

2. Spontaneous birefringence in ferroelectric materials

In centrosymmetric ferroelectric crystals in paraelectric phase the spontaneous birefringence has the nature of the spontaneous Kerr effect:

$$\delta\Gamma \sim rP_s^2 \quad (4)$$

where: r – electrooptical coefficient, P_s – spontaneous polarization [1, 2].

It is known that the temperature dependence of the spontaneous polarization P_s in ferroelectrics exhibiting the 2-nd order phase transition can be described as [5, 6]:

$$P_s = \pm \sqrt{-\frac{\alpha}{\beta}(T - T_c)} \quad (5)$$

where: α, β – free energy expansion coefficients, T_c – the Curie–Weiss temperature.

A subject of this work, *i.e.*, $(\text{NH}_2\text{CH}_2\text{COOH})_3 \cdot \text{H}_2\text{SO}_4$ (TGS) crystal exhibiting the second-order ferroelectric phase transition at about 322 K, is one of the most important and best known ferroelectrics. Above this temperature, it belongs to centrosymmetrical point group $2/m$ of rhombohedral system, but below the transition point it is ferroelectric and belongs to the point group 2 of monoclinic system, therefore the linear birefringence in ferroelectric phase has the Kerr phenomenon character.

The single crystals of TGS were grown from water solution by slow evaporation at constant temperature. Crystals of good optical-quality were obtained after a few weeks. TGS samples for the birefringence investigation were cleaved perpendicular to the b -axis and cut perpendicular to a - and c -axis out of optically clear crystals and polished to a thickness of about 3 mm.

The TGS crystals are recommended for spontaneous birefringence measurements carried out in students laboratory. The reasons are numerous. Measurements in a wide

temperature range, including the phase transition temperature, can be carried out without the cryogenic liquid. The TGS crystals are easy to grow and exhibit a good optical quality with right orientation and are of a relatively large size.

3. Experimental and results

3.1. Temperature changes of spontaneous birefringence

We used a polarizing-interfering technique, presented in Fig. 1, for the birefringence measurements. The method has long been one of the basic techniques used in studying of the spontaneous and induced birefringence in crystals.

A system of the spontaneous birefringence change measurement is shown schematically in Fig. 2. The optical thermostat is one of the basic elements of the measuring system. The thermostat consists of two coaxial cylinders, a heater, a thermocouple and a PT-100 temperature sensor. A polarizer, an analyzer, an He-Ne laser (the light source) and a photodetector are necessary elements of the measuring system. A 660-type UNIPAN temperature controller was used to ensure a continuous temperature variation.

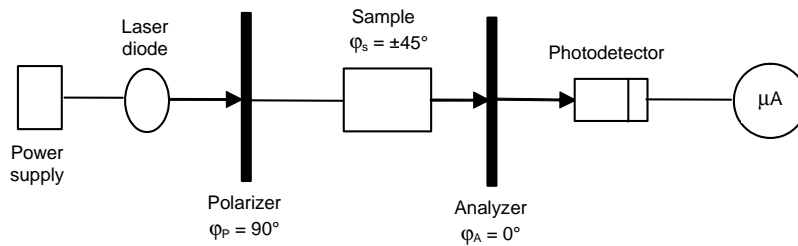


Fig. 1. Schematic diagram illustrating polariscope method.

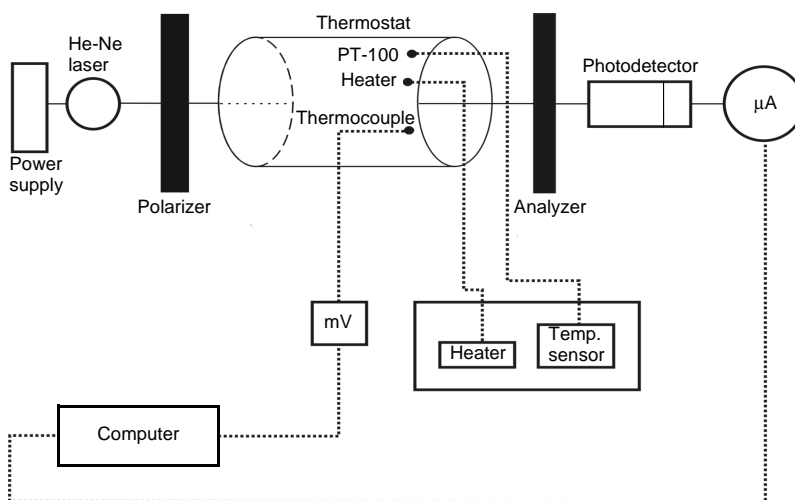


Fig. 2. Diagram of the birefringence measuring method.

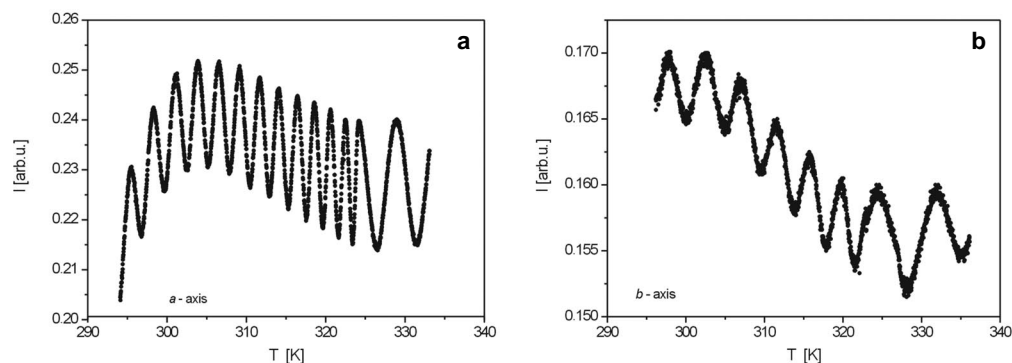


Fig. 3. Temperature dependence of the system transmission (see Fig. 2), *i.e.*, the photodetector current. Samples are cut perpendicular to *a* (**a**) and *b* (**b**) axes.

The birefringence measurements were carried out at temperature ranging from 295 to 335 K. Each heating survey was carried out at a constant temperature rate of 0.2 K/min. The sample was placed between two crossed polarizers.

The intensity changes promoted by the temperature variation are read by the photodetector and recorded by a computer system.

In order to calculate an anomaly in the crystal spontaneous birefringence changes it is necessary to measure the system transmission and temperature in temperature range including the phase transition point, Fig. 3. The measuring system was not protected against the changing daylight, which had an influence on the shape of the spectrum (see Fig. 3). These changes had not any significant impact on birefringence results.

The temperature dependence of the spontaneous birefringence changes of TGS crystals calculated from the results presented in Fig. 3a and 3b is shown in Fig. 4.

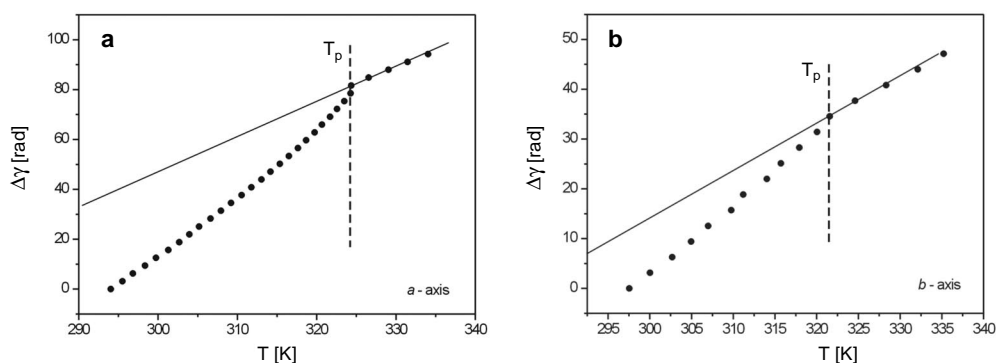


Fig. 4. Temperature dependence of the phase shift between the fast and the slow light waves in TGS crystals.

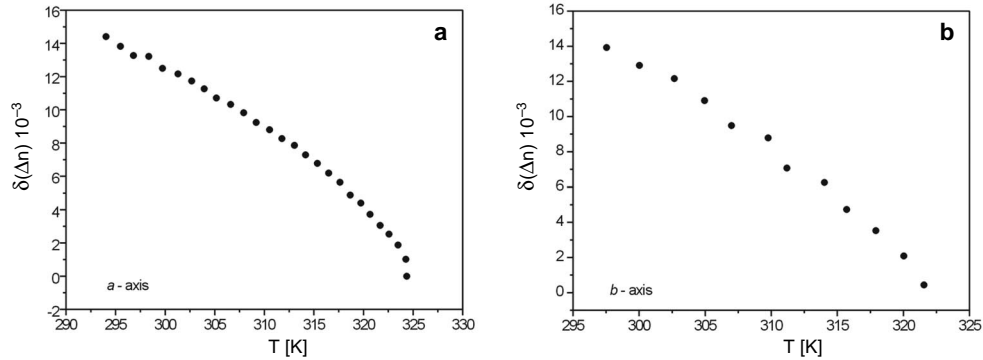


Fig. 5. Temperature dependence of the linear birefringence changes in TGS crystals.

The birefringence along the b -axis (Fig. 4a) and the a -axis (Fig. 4b) agrees well with the previous spontaneous birefringence studies [6].

Using temperature dependence of the system transmission (Fig. 3a and 3b) one can calculate the phase shift between the fast and the slow light waves and the spontaneous birefringence changes.

The temperature dependence of phase shift between the fast and the slow light waves for TGS crystals cut along the a - and the b -axis is presented in Fig. 4.

For appropriate temperatures in Fig. 3 we collected the minimum and maximum values of the intensity of light and based on this we calculated the temperature dependence of the phase shift between fast and slow light waves (Fig. 4). From Fig. 4 we can clearly see that the phase transition temperature point T_p is at 322 K.

Using formula (1) we can calculate changes of spontaneous birefringence in TGS crystals for a - and b -axis directions. The spontaneous birefringence changes of TGS crystals as a function of temperature are presented in Fig. 5a and 5b.

3.2. Induced birefringence – electric field changes

The birefringence change induced by electric field is called an electrooptical effect. When the birefringence change $\delta(\Delta n)$ is a linear function of an electric field then the phenomenon is a linear electrooptical effect (the Pockels effect). The effect can be described in a very simplified way as

$$\delta(\Delta n) = cE. \quad (6)$$

When the birefringence change is proportional to the square of the electric field intensity the phenomenon is called the Kerr effect

$$\delta(\Delta n) = CE^2. \quad (7)$$

Using Eqs. (1), (2) and (6) or (7) we can obtain relation between the intensity of the light changes after crossing the system presented in Fig. 6

$$I = I_0 \sin^2 \left(\frac{2\pi}{\lambda_0} LcE \right) \quad (8)$$

and in the case of Kerr effect

$$I = I_0 \sin^2 \left(\frac{2\pi}{\lambda_0} LCE^2 \right). \quad (9)$$

The investigation of the Pockels and the Kerr effects consists in determining changes in the intensity of polarized light passing through the system as a function of an electric field intensity.

A schematic diagram of the measuring set-up for linear and quadratic electro-optical effect studies is shown in Fig. 6. The system consists of a light source (a laser diode), a power supply, a polarizer, either the Pockels or the Kerr cell, an analyzer, a photodetector and an amplifier.

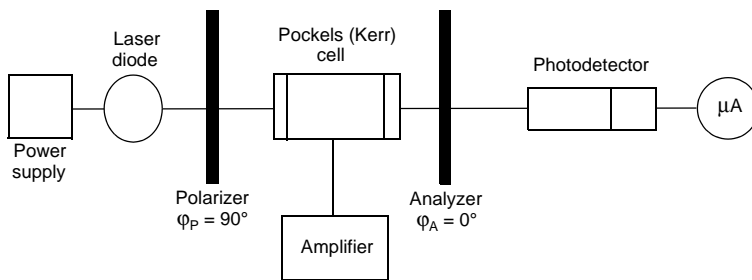


Fig. 6. Schematic diagram illustrating a system for measuring Pockels (Kerr) effect.

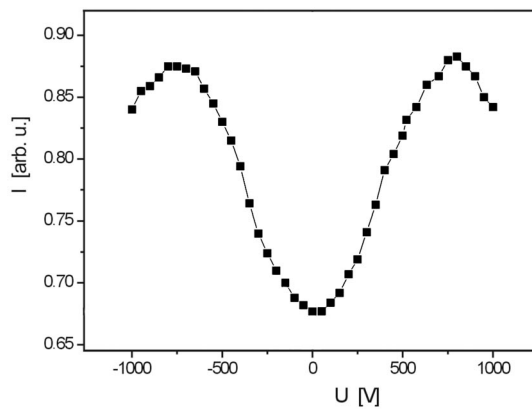


Fig. 7. Transmission of the system as a function of the Pockels cell voltage.

a photodetector, an amplifier and an ammeter. During experiment the dependence of the intensity of light I on the voltage V applied to Pockels cell (Fig. 7) and Kerr cell (Fig. 9) was measured. Using the appropriate formula $\Delta\gamma = 2 \arcsin \sqrt{\frac{I - I_{\min}}{I_{\max} - I_{\min}}}$ we

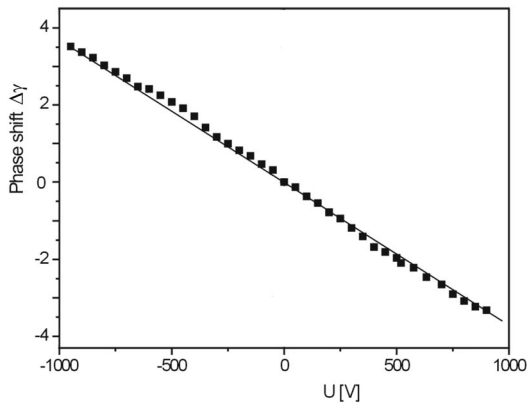


Fig. 8. Phase shift dependence on the voltage for Pockels cell.

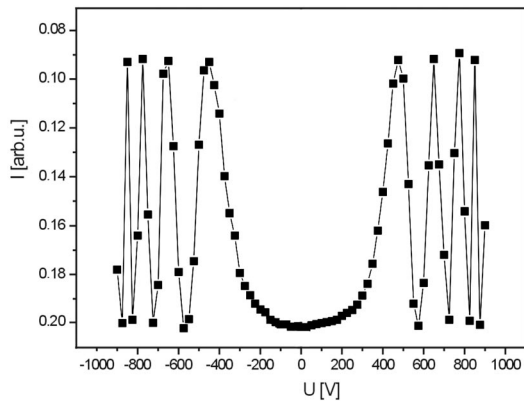


Fig. 9. Transmission of the system as a function of the Kerr cell voltage.

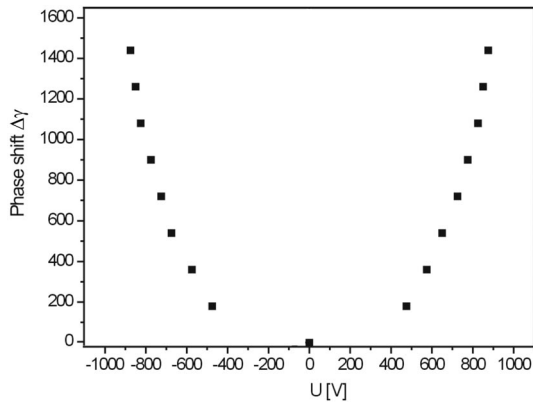


Fig. 10. Phase shift dependence on the voltage for Kerr cell

can obtain a phase shift as a function of the voltage for the Pockels cell (Fig. 8) and Kerr cell (Fig. 10).

Electrooptical measurements were carried out in the voltage ranging from -1000 to $+1000$ V. Results of linear and quadratic optical measurements are shown in Figs. 7 and 8 for the Pockels and Fig. 9 and 10 the Kerr effects, respectively. As could be observed, the data obtained clearly confirm the dependence of birefringence on the intensity of electric fields to be linear for Pockels effect (Fig. 8) and quadratic for Kerr effect (Fig.10). It is worth noting that all of the results presented were taken from students reports.

The set-up presented is suitable for students laboratory, but it can be used for research purposes as well.

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