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Dual-wavelength laser polarimeter and its performance capabilities

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ABSTRACT

A dual-wavelength optical polarimetric approach has been proposed as a means of elimination of the systematic errors and estimation of the optical anisotropy parameters for a single DKDP crystal. Our HAUP-related polarimeter uses two semiconductor lasers with the neighbouring wavelengths of 635 nm and 650 nm. Based on the temperature dependence analysis of small characteristic azimuths of light polarization with respect to the axis of the sample, we found the parameters of imperfections of polarization system. We acquired eigen waves ellipticities in a DKDP crystal and found perpendicular to the optic axis value of the optical rotatory power. Our results correlate positively with previously measured data for KDP crystals.

1. Introduction

High accuracy polarimetric methods are the most precise in crystal optics research. These methods are effectively applied to obtain information about temperature or wavelength dependencies of main optical anisotropy parameters of crystals.

Physical properties of crystals, such as linear birefringence, circular birefringence (also known as optical rotation or optical activity), linear and circular dichroism can be simultaneously studied by high-accuracy universal polarimeter (HAUP) [1–4]. Several modification of HAUP exists, most widely used is the one invented by Kobayashi et al. and which have undergone numerous improvements over time [5–10]. An alternative to solve crystal optics problems is the so-called tilter polarimeter, presented by Glazer and Kaminsky [11,12]. Another option is a spectropolarimeter built by Moxon and Renshaw [13,14]. Main feature of these polarimeters is the full computerization of the measurements process. However, there is a constant need of improvement of the sensitivity, generality and speed of polarimeters by utilizing the up-to-date advances in laser optics.

Main principles of high-accuracy polarimetry can be stated as follows: as little number of elements in the polarization scheme as possible, use of monochromatic light sources (lasers), small input azimuths of light polarization before the sample, precise measuring of light intensities for different polarizer and analyser positions, elimination of systematic errors (parasitic ellipticity and angular error), control of intermediate measuring results for verification of their correctness, full results processing only after completion of the measuring cycle, universality of methods, and possibility of the simultaneous measuring of crystal optical anisotropy parameters.

Universal laser polarimeter, which is similar to HAUP, but uses different principles for data gathering and processing, was designed with participation of the authors of the current work and is used for studying numerous important crystals used in application [15–20]. Polarimeter is based on the basic optical scheme PSA (polarizer-sample-analyser) and allows for a full computer control over the measurements process.

2. Principles of measurings and experimental technique

2.1. Transmission function and characteristic azimuths

For a PSA-system, transmission J of monochromatic light is determined as a function of small changes in the polarizer azimuth θ and the analyser azimuth χ angles (less than 0.01 rad for both) which are measured from the principal crystal axes [16]

$$J(\theta,\chi) = (\theta-\chi)^2 + 4\theta\chi\sin^2(\Gamma/2) + 2\theta[(k+q)\sin\Gamma - \delta\chi\cos\Gamma] - 2\chi[(k-p) - \delta\chi] + \text{const}, \quad (1)$$

where $\Gamma = 2\pi\Delta n d/\lambda$ is the phase difference, d is the thickness of specimen, Δn is the linear birefringence, k is the ellipticity of eigen waves in a studied crystal predefined by optical activity, and λ

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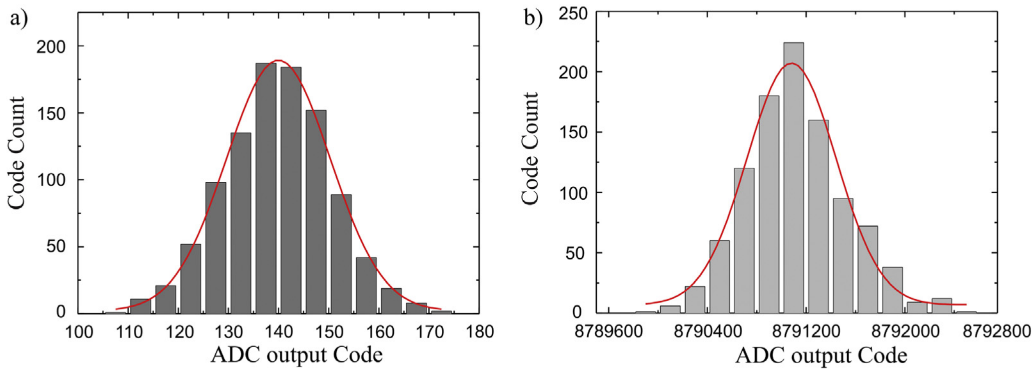

Fig. 1. Random noise histogram for 1000 total number of codes with grounded input (a) and for a half-scale input from photo detection unit (b).

is the wavelength of monochromatic light. In general, one should also define the following values: parasitic ellipticity of the polarizer and analyser p, q, and the angular systematic error $\delta\chi$. In (θ,χ) coordinate system, the transmission function describes the second order surface and projections of the cuts of this surface by the equi-intensity planes have a shape of ellipses. A full set of these projections forms the so-called HAUP maps [6,17].

The main feature of our polarimetric method is the search of the positions of three characteristic azimuth angles $\theta_0, \theta_1, \theta_2$ of the incident light in the PSA system, with the preceding coordination of the polarizers and analysers scales in PA system. The relations for these azimuths can be expressed as [15,16]

$$\theta_0 = (k-p)\cot(\Gamma/2) - \frac{\delta\chi}{(1-\cos\Gamma)}, \tag{2}$$

$$\theta_1 = (k-p)\cot\Gamma - \frac{(k+q)}{\sin\Gamma}, \tag{3}$$

$$\theta_2 = -(1/2)(p+q)\cot(\Gamma/2) - \frac{\delta\chi}{2}. \tag{4}$$

In fact, it is impossible to measure the absolute values of these angles, because the start point for polarizer azimuth is unknown, that is why experimentally only their differences $\Delta\theta_{01} = \theta_0 - \theta_1$, $\Delta\theta_{02} = \theta_0 - \theta_2$, $\Delta\theta_{12} = \theta_1 - \theta_2$ are analyzed. These differences are related to each other through equations derived from Eqs. (2)–(4)

$$\Delta\theta_{01}\sin\Gamma = 2k - p + q - \delta\chi\cot(\Gamma/2). \tag{5}$$

It is easy to see that $\Delta\theta_{01}(1+\cos\Gamma) = 2\Delta\theta_{02}$ and $\Delta\theta_{01}(1-\cos\Gamma) = -2\Delta\theta_{12}$. Therefore, it is enough to determine just two of the characteristic azimuth angles θ_0, θ_1 and θ_2, or one of the differences $\Delta\theta_{01}$, $\Delta\theta_{02}$, $\Delta\theta_{12}$ of characteristic angles and get $\cos\Gamma$. But experimental verification of Eq. (5) is an additional criterion of correct measurements procedures. One should consider the fact that precision of the measurement of the characteristic angles depends greatly on the phase difference Γ.

Characteristic difference (5) alone is not enough to find k and systematic errors p, q, $\delta\chi$. Therefore, we rotate the crystal for 90° around the light beam axis and consider the sign change of k and Γ in Eqs. (2)–(5). By changing the specimen temperature we can alter birefringence and get characteristic azimuths differences that depend on Γ.

Using two sources of light with the values of the wavelengths λ_1 and λ_2 which almost coincide, we can neglect the effects of k value dispersion with some approximation and assume values p, q, $\delta\chi$ to be constant. In this dual-wavelength polarimetric system systematic errors can be differently eliminated. In particular, we will have a set of data for characteristic azimuths which were measured with different laser sources of light. From this point of view the differences $\Delta\theta_{01}$, $\Delta\theta_{02}$, $\Delta\theta_{12}$ for separately λ_1 and λ_2, but also the differences $\Delta\theta_{i\lambda} = \theta_i(\lambda_1) - \theta_i(\lambda_2)$, $(i = 0, 1, 2)$ can be successfully analyzed.

It is enough to use the relation (5) for the elimination of the parasitic errors p, q and $\delta\chi$. In fact, using the relations (2) and (3) for θ_0 and θ_1 azimuth angles the differences $\Delta\theta_{0\lambda}$ and $\Delta\theta_{1\lambda}$ can be expressed as

$$\Delta\theta_{0\lambda} = A_1(k-p) - B_1\delta\chi, \tag{6}$$

$$\Delta\theta_{1\lambda} = A_2(k-p) - B_2(k+q). \tag{7}$$

Here $A_1 = \cot(\Gamma_1/2) - \cot(\Gamma_2/2)$, $B_1 = (1-\cos\Gamma_1)^{-1} - (1-\cos\Gamma_2)^{-1}$, $A_2 = \cot\Gamma_1 - \cot\Gamma_2$, $B_2 = 1/\sin\Gamma_1 - 1/\sin\Gamma_2$, $\Gamma_1 = \Gamma(\lambda_1)$ and $\Gamma_2 = \Gamma(\lambda_2)$.

Since the relations, which are expressed by Eqs. (6) and (7), are linear, the magnitude of systematic errors p and $\delta\chi$ can be defined using procedure of the straight line approximation. As a result, the number of the equations which can be used to eliminate the systematic errors is increased.

2.2. Experimental setup

The measuring procedure is fully automated with independent rotations of both polarizer and analyser, controlled by the stepper motors. In order to measure small intensity changes, the so-called delta-sigma analogue-to-digital converter (ADC) with high resolution is used. Both the polarizer and the analyser are Glan type calcite prisms with a clear aperture of 10 mm × 10 mm. Angle resolution of the setup of stepper motors is approximately of 1.3×10^{-3} deg over the 10° range.

The light transmitted through the analyser is detected with a photodiode FD-288A followed by high impedance operational amplifier AD8646 and 24-bit ADC, which was connected to PC. In photovoltaic mode photodiode generates a small current which is proportional to the level of light intensity I over 6 to 9 decades [21].

Full noise of the registering system in polarimeter depends on the amplifier and ADC parameters and laser stability. Fig. 1 is a noise histogram of the 24-bit ADC with a grounded analogue input (a), and about 2.5 V input range (b). The normal or Gaussian distribution indicates that the noise is random. According to Fig. 1(b) standard derivation $\sigma_I = 360 \pm 45$ LSB (less than 9 bits), so the signal-to-noise ratio is equal to 87 dB. This data confirms that the chosen setup of precise intensity measurements by linearity and signal/noise ratio in a HAUP-type polarimeter is comparable to the well-known photon counting technique [22,23].

For measurements we chose deuterated potassium dihydrogen phosphate $K(H_{1-x}D_x)_2PO_4$ or DKDP single crystal with a level of deuteration $x = 0.93$. Grown by a water-solution method these crystals have a high optical quality and are currently used for electro-optical modulation and frequency conversion [24]. The plate with $d = 0.63$ mm was cut from a crystal perpendicularly to