Optica Applicata, Vol. XXXI, No. 3, 2001

Polarization bistability in a smectic-A liquid crystal

Bronisław Pura, Michał Wierzbicki, Jan Petykiewicz, Grzegorz Ratusznik

Faculty of Physics, Warsaw University of Technology, ul. Koszykowa 75, 00–662 Warszawa, Poland.

Zbigniew Wrzesiński

Faculty of Production Engineering, Warsaw University of Technology, ul. Narbutta 85, 02–524 Warszawa, Poland.

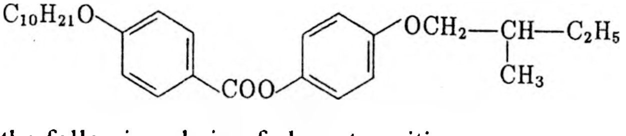
We report the measurements the of laser light polarization transmitted through the smectic-A phase of a liquid crystal placed inside the Fabry-Pérot optical resonator. All four parameters of polarization were measured simultaneously by an ellipsometer of a special construction. Optical polarization bistability phenomenon was observed, in which polarization parameters of outgoing light depend nonlinearly on the intensity of the input beam. We propose a theoretical explanation of this phenomenon, based on the concept of orientational nonlinearity of liquid crystal's molecules.

1. Introduction

The polarisation bistability in liquid crystals was investigated in several papers [1]–[3]. Measurements of this effect in liquid crystals were almost exclusively performed in nematics. In this paper, we present experimental results on polarization bistability in a smectic-A liquid crystal. In the ordered phase, the polarization change of the electric field **E** vector with respect to the direction of the long axes of the molecules can be observed. The ellipsometer at our disposal allows measurement of all four Stokes parameters. We will present the results of measurement of the phase difference Δ between the two components E_x and E_y of the electric field of output light, together with an attempt at interpretation.

2. Sample characteristic

In the liquid crystal composed of the molecules of 4-(2-methylobutyloxy)-phenyl 4 -decyloxylobezoate characterized by the chemical formula



the following chain of phase transitions can appear:

$$K\,(44.5°) \rightarrow S_C\,(50°) \rightarrow S_A\,(65°) \rightarrow I.$$

The liquid crystal was placed in an amorphous quartz container of dimensions 4 mm×20 μm. This container was placed inside an electric furnace, at constant temperature with the accuracy to ±0.1 °C. The sample was heated up to the temperature of 80 °C, at which it attains isotropic phase *I* and, subsequently, slowly cooled to the temperature of 50 °C when it attains the smectic-A phase S_A. During the cooling process, the sample was under the influence of a uniform external magnetic induction $B = 5 \times 10^3$ Gs oriented parallel to the surface of the sample. Consequently, the molecular long axes of the smectic phase were almost parallel to the magnetic field direction.

3. Experimental setup

The experimental setup is presented in Fig. 1. The direction of the incoming wave of argon-laser light with the wavelength $\lambda = 514$ nm (Lexel 3500) of constant linear polarization was almost perpendicular to the bottom plane of the container with the

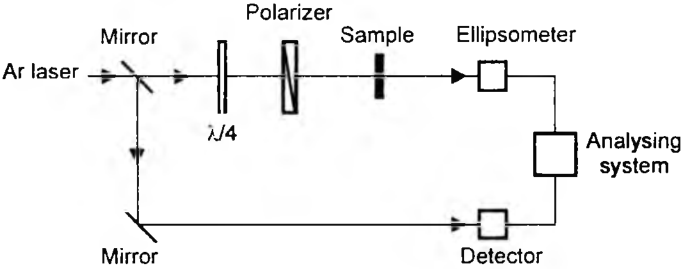


Fig. 1. Experimental setup (λ/4 denotes the quarter-wave retarder).

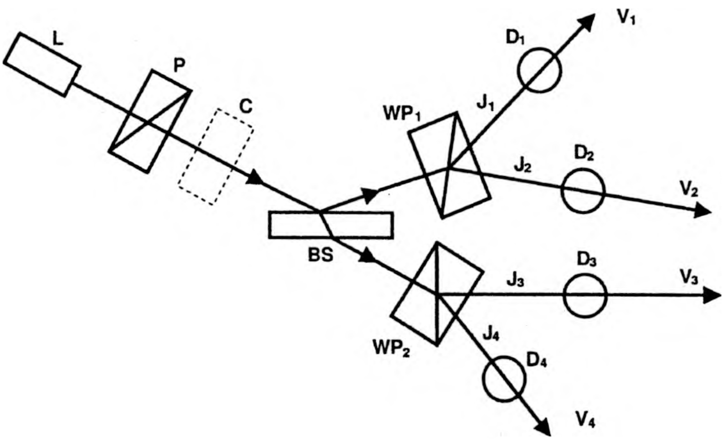


Fig. 2. General scheme of the Stokes ellipsometer. BS is the beam splitter, WP_1 and WP_2 are Wollaston prisms, D_1, D_2, D_3 and D_4 – linear photodetectors which produce electrical output signals V_1, V_2, V_3 and V_4. L is the Argon laser light source, P – the polarizer and S – the sample. C is the quarter-wave retarder which is introduced during calibration of the instrument.

smectic-A sample. The quarter-retarder and polarizer were used to fix the polarization plane of the laser beam. The system of two half-reflecting mirrors directed part of the input light to the detector which measured the intensity of the input light. The beam diameter was equal to approximately 1.5 mm. Since the polarization of the wave was set to be constant, we rotated the liquid crystal around the direction of the laser beam up to 360°. The intensity of the incoming wave was varied in the interval from 0 mW to 800 mW. The change in the polarization of the transmitted wave was measured by the Stokes ellipsometer (Fig. 2).

4. Description of the ellipsometer

The method of determining the light polarization which is applicable not only to a continuously working optical source but also to pulsed sources is based on the simultaneous determination of all four Stokes parameters [4], [5]. When determining the Stokes parameters simultaneously for a nanosecond duration, the mechanical or rotating ellipsometric methods are not applicable. The simultaneous measurement can be accomplished by using the optical system presented in Fig. 2. In this system, the state of polarization of the light beam is determined by dividing it into four beams J_1, J_2, J_3, J_4 using a beam splitter and two beam splitting Wollaston prism polarizers. The light fluxes of the four beams are detected by four photodetectors producing four proportional electrical output signals. For each spectral line the vector of light flux **J** is related to the input Stokes vector $\mathbf{S} = (S_1, S_2, S_3, S_4)$ by the linear transformation

$$\mathbf{J} = \hat{M}\mathbf{S} \tag{1}$$

where $\hat{M}$ is the instrument matrix. The unknown Stokes vector **S** is given by

$$\mathbf{S} = \hat{M}^{-1}\mathbf{J} \tag{2}$$

where $\hat{M}^{-1}$ is the matrix inverse to $\hat{M}$. All four Stokes parameters can be determined when the instrument matrix $\hat{M}$ is non-singular.

Generally, the instrument matrix $\hat{M}$ has sixteen elements which can be determined from a set of sixteen independent linear equations. These equations are generated from relation (2) by using a polarized light source and recording the electrical output signals that correspond to four different input polarization states described by four linearly independent Stokes vectors. Usually the set of reference polarization states consists of three linear polarizations 45° apart and one right or left circular polarization. The calibration process is essential for the accuracy of the instrument.

5. Experimental results

We have measured the change of the phase difference Δ between two components E_x and E_y of the electric field of the transmitted wave as a function of the intensity of the incoming wave. The measurements were performed for different orientations of the

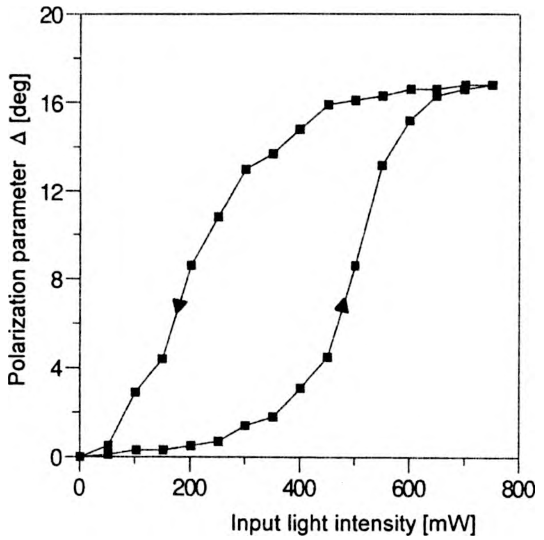


Fig. 3. Phase difference Δ (in degrees) between two linear components of polarization of the output light as a function of the input light intensity, measured for the electric vector **E** of input light perpendicular to the director **n** of the liquid crystal.

vector **E**, of the linearly polarized incoming wave, with respect to the direction **n** of the molecular long axes, *i.e.*, the direction of the uniform magnetic field in which the sample was initially placed. The bistable character of the changes of Δ as a function of the incoming wave intensity is observed only for $\mathbf{n} \perp \mathbf{E}$, and this result is presented in Fig. 3. Within the interval of temperatures from 50 °C to 65 °C the detected polarization bistability is temperature independent. When the temperature of the sample is increased above 65 °C and the liquid crystal is in isotropic phase, the polarization bistability effect disappears. In the following section a theoretical explanation of the bistability phenomenon in the smectic-A liquid crystal is presented.

6. Theoretical description

We will assume that the interaction of a strong optical wave with the liquid crystal in which it propagates induces the rotation of the liquid crystal's "director" by an angle $\delta\varphi$ proportional to the intensity of the wave [7], [8], which is stable in time [8] and has a character of a periodical spatial modulation

$$\delta\varphi = \gamma(E_x E_y^* + E_x^* E_y). \tag{3}$$

Due to the rotation of the "director" there appears a light intensity dependent term of the electric polarization **P** of the medium. This is the cause of orientational optical nonlinearity of the liquid crystal, and consequently due to the interaction between the wave propagating in the medium and the wave scattered by the periodic structure, we can observe the phenomenon of optical polarization bistability [9]–[11].

Because of the uniaxial anisotropy of the medium two Cartesian components of the light wave will behave as the ordinary and the extraordinary waves. We assume that the propagation velocity of these waves is perpendicular to the initial direction of the "director".

In the customary slow amplitude approximation used in nonlinear optics [9] from Maxwell equations we obtain equations describing the changes of two complex components of the electric field of light inside the medium (A denotes forward propagating wave, B denotes the scattered backward propagating wave):

$$\frac{\mathrm{d}A_k}{\mathrm{d}z} = -i\Gamma_k[(|A_{2-k}|^2 + |B_{2-k}|^2)A_k + 2A_{2-k}B_{2-k}B_k^*], \tag{4}$$

$$\frac{\mathrm{d}B_k}{\mathrm{d}z} = -i\Gamma_k[(|B_{2-k}|^2 + |A_{2-k}|^2)B_k + 2B_{2-k}A_{2-k}A_k^*] \tag{5}$$

where $k = 1, 2$ denotes two Cartesian components. The material parameters are

$$\Gamma_k = \gamma\omega\frac{n_1 - n_2}{2n_1n_2c} \tag{6}$$

where γ from Eq. (3) describes the strength of nonlinearity, n_1 and n_2 are refractive indices of the medium, ω is the frequency of the light wave, c is the speed of light.

Equations (4) and (5) together with the boundary conditions describing the reflection of light from the boundaries of the liquid crystal sample are solved

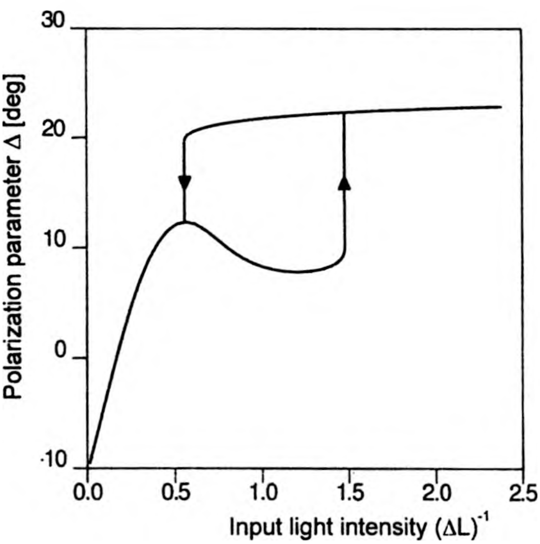


Fig. 4. Theoretical dependence of phase difference Δ (in degrees) between two linear components of polarization of the output light as a function of the input light intensity, for the case of electric vector $\mathbf{E}$ of input light perpendicular to the director $\mathbf{n}$ of the liquid crystal. Light intensity is in arbitrary units $(\Gamma L)^{-1}$.

numerically to determine the polarization state of the outging wave which in experiment was measured by the ellipsometer. For the particular liquid crystal which was measured the refractive indices are $n_1 = 1.83$ and $n_2 = 1.56$. The parameter γ [7] which determines the nonlinear effect depends on the elastic constant K_2 of the liquid crystal [12], which is of the order 10^{-12} N. The frequency of light is determined from the wave length of the Argon laser.

In Figure 4, we present the results of numerical integration of Eqs. (4) and (5) for the case of input linear polarization perpedicular to the optical axis of the liquid crystal. Light intensity is expressed in an arbitrary unit $(\Gamma L)^{-1}$, where Γ is the mean value of material paramters Γ_1 and Γ_2, and L is the length of the cavity. The bistability threshold, *i.e.*, the value of light intensity when the jump of polarization occurs, depends on the parameter γ from Eq. (3) which determines the strength of orientational nonlinearity.

7. Conclusions

Optical polarization bistability was observed in the smectic-A liquid crystal. We believe that this phenomenon occurs due to the orientational nonlinearity of liquid crystal's molecules, which try to orient themselves along the direction of the electric field of the standing light wave induced in the medium by the strong laser beam trapped inside the Fabry-Pérot resonator. The simple theoretical description we propose is able to show that such a phenomenon can be observed. To obtain the exact fitting of the shape of the experimental curve we would need more profound assumptions, *i.e.*, instead of plane waves we should use Gaussian beams and take into account the spherical shape of mirrors in the Fabry-Pérot interferometer.

Acknowledgments – This work was supported by the grant No. 8 S 507 018 of the Polish Committee for Scientific Research (KBN).

References

[1] LLOYD A. D., Opt. Commun. **64** (1987), 3.
[2] BULLER G. S., CAMPELL R. J., WALKER A. C., Opt. Commun. **75** (1990), 93.
[3] PETYKIEWICZ J., STROJEWSKI D., Opt. Quantum Electron. **22** (1990), 131.
[4] AZZAMA R. M. A., Optica Acta **32** (1985), 1407.
[5] BRUDZEWSKI K., J. Modern Opt. **38** (1991), 889.
[6] BORN M., WOLF E., *Principles of Optics*, Pergamon Press, London, 1965.
[7] TABIRYAN N. V., SUKHOV A. V., ZELDOVICH B. YA., Mol. Cryst. Liq. Cryst. **132** (1986), 1.
[8] SHEN Y. R., *The Principles of Nonlinear Optics*, Wiley-Interscience, New York, 1984.
[9] GIBBS H. M., *Optical Bistability*, Acad. Press, New York, 1985.
[10] WINFUL H. G., MARBURGER J. H., GARMIRE E., Appl. Phys. Lett. **35** (1979), 5.
[11] KUHTAREV N. V., Ukr. Fiz. Zh. **27** (1982), 291.
[12] DE GENNES P. G., *The Physics of Liquid Crystals*, Clarendon Press, Oxford, 1974.

Received December 15, 2000
in reviced form February 19, 2001