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Investigation of light polarization in CdS in the presence of two-photon absorption

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Abstract. It is shown that, under the two-photon absorption in CdS, the increase in the azimuth of polarization causes a smooth change of the large semi-axis angle rotation, ellipticity, focal parameter, and eccentricity of the polarization ellipse. When the angle of phase lag $\delta = 40^{\circ}$, the minimum value of ellipticity and the maximal values of focal parameter and eccentricity will be realized.

Keywords: CdS, two-photon absorption, ellipticity, ellipse of polarization.

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1. Introduction

As usual, the two-photon absorption coefficient is measured for the orientation of the electric vector **E** of an electromagnetic wave in parallel to the optical axis *C* of a uniaxial crystal or at the right angle to it [1-3]). Influence of the polarization azimuth on the light intensity in uniaxial crystals was studied in articles [4-6]. However, the polarization ellipse form was not studied in these and other articles. We have investigated the influence of the polarization azimuth on the large semi-axis angle rotation, ellipticity, focal parameter, and eccentricity of the polarization ellipse of light traveling in CdS and have found equations describing the polarization mode in CdS in the presence of two-photon absorption.

2. Samples and measuring method

Plane-parallel uniaxial single crystals CdS of 5 mm in thickness were used. Light flux falls at the right angle to the input surface of these crystals (Fig. 1). The optical axis in these crystals is parallel to the input surface (Fig. 1, insert a). Single crystals CdS were positioned between a polarizer and an analyzer. A fixed angle φ (polarization azimuth) between the optical axis and the vector **E** was set by crystal rotation. A ruby laser with 20-ns pulse duration and 1-pm half-width was a light source. ELU-FT photomultipliers served as light detectors. Intensity of light on the input (I_0) and on the output (I) of a sample was determined with an error of at most 10 %. A variation of the intensity was fulfilled by rearrangement of neutrally grey filters from a set located before a sample into the set located after a sample.

In the presence of two-photon absorption, the reciprocal transmission $1/T$ of the sample linearly depends on I_0 [1, 3]:

$$\frac{1}{T}=\frac{I_0}{I}=\frac{\exp(Kd)}{(1-R)^2}+\frac{\beta\left[\exp(Kd)-1\right]}{K(1-R)}I_0=A+BI_0, \qquad (1)$$

where K and β are the coefficients of one-photon and two-photon absorption, d and R is the thickness and reflection coefficient of the sample, and A and B are constants. Using the experimentally determined values I and I_0, we plot a dependence $1/T = f(I_0)$ (Fig. 2, points), where every point was averaged over 20-30 measurements. The empiric dependence of $1/T$ on I_0 is approximated by a straight line by the method of least squares. The point, where this line crosses the ordinate axis, gives the constant A, and the line slope gives the constant B. Inserting A and B in the formulas

$$K=\frac{1}{d}\ln[A(1-R)^2], \qquad (2a)$$

$$\beta=\frac{BK(1-R)}{A(1-R)^2-1}, \qquad (2b)$$

we estimated K ($K = 1.8\ \text{cm}^{-1}$) and β. The error of estimation of K is ±10 %, and that of β equals ±20 %. Fixing the polarization azimuth φ for the set of values ψ, we evaluated the dependence of $1/T = f(I_0)$ and then the value of I which corresponds to a certain fixed value of I_0 (Fig. 2). Estimating the values of I and ψ in this way, we obtained the dependence $I = f(\psi)$ (Fig. 3a, points).

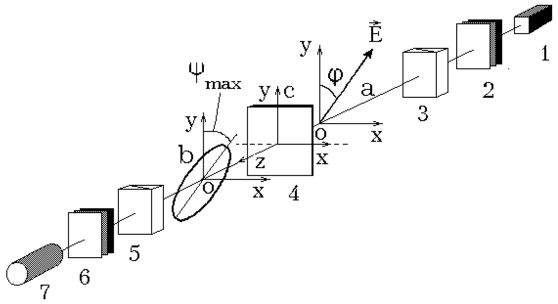

Fig. 1. Experimental setup used for the research of the influence of two-photon absorption on light polarization: a ruby laser (1); sets of calibrated neutrally grey filters (2) and (6); polarizer (3) (Glan prism); single crystal CdS, optical axis of which is parallel to the y axis (4); analyzer (5) (Glan prism); photomultiplier ELU-FT (7). In insert **a**, we show the orientation of the polarization vector of an electromagnetic wave **E** relative to the optical axis C on the input surface of the uniaxial crystal, and φ is the polarization azimuth. In insert **b**, we display the form of the polarization ellipse on the output surface of the crystal, ψ_{max} is the angle, on which the major semi-axis of the polarization ellipse will rotate relative to the optical axis C after the transmission of light through the crystal.

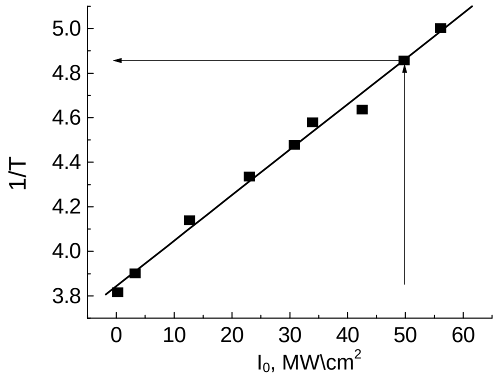

Fig. 2. Dependence of the reciprocal transmission $1/T$ versus intensity I_0 of a linearly polarized light which falls onto the input surface of a crystal CdS of 5 mm in thickness at the right angle. The azimuth of polarization φ = –15°, ψ_{max} is the angle between the orientation of the polarization vector of an electromagnetic wave after an analyzer and the optical axis C. Points present the experiment data, and the solid line is the result of calculations by formula (1). ψ_{max} = –60°. Arrows show the method of determination of the intensity on the output of a sample.

2. Influence of two-photon absorption on light polarization

Let a monochromatic linearly polarized light flux fall onto the surface of a uniaxial crystal at the right angle (Fig. 1). It is possible to consider that, in such a crystal, two components of the light flux are traveling along one way, if the azimuth $\varphi \neq n\pi/2$, (n = 0, 1, 2, 3,…). In one of the components, **E**⊥C, and **E**||C in the other one. Immediately after the input surface of the crystal, the intensities of these components are as follows:

$$I_{0\perp} = I_0 \cos^2\varphi\ ,\quad I_{0\parallel} = I_0 \sin^2\varphi\ . \tag{3}$$

On the output surface of the crystal, these intensities are equal to

$$I_\perp = \frac{I_0(1-R_\perp)^2\cos^2\varphi\; e^{-K_\perp d}}{1+\dfrac{\beta_\perp I_0(1-R_\perp)\cos^2\varphi}{K_\perp}\left(1-e^{-K_\perp d}\right)}, \tag{4}$$

$$I_\parallel = \frac{I_0(1-R_\parallel)^2\sin^2\varphi\; e^{-K_\parallel d}}{1+\dfrac{\beta_\parallel I_0(1-R_\parallel)\sin^2\varphi}{K_\parallel}\left(1-e^{-K_\parallel d}\right)}. \tag{5}$$

On the output from an analyzer, the intensity of light equals

$$I = I_\perp\cos^2\psi + I_\parallel\sin^2\psi + \sqrt{I_\perp I_\parallel}\,\sin(2\psi)\cos\delta\,, \tag{6}$$

where δ is the phase lag angle.

Influence of two-photon absorption on the polarization of light that travels in CdS is studied at I_0= 50 MW/cm^2 for a few polarization azimuths. For all values of φ, the dependence $I = f(\psi)$ looks like such that is presented in Fig. 3a. The dependence (solid line) calculated by formula (6) is put in agreement with experimental data (points) by the choice of δ. At the optimum value δ = –40°, the error of approximation is less than 5 %. Values of the minimum ($I = I_{min}$) and maximal ($I = I_{max}$) intensities, and the angle $\psi = \psi_{max}$, on the achievement of which $I = I_{max}$ were easily found using the information from Fig. 3. Then, by using the well-known correlation between the intensity I and the electric field strength E [7],

$$E[\text{V/cm}] = 27.46\cdot I^{0.5}\,[\text{W/cm}^2], \tag{7}$$

we obtained the form of the polarization ellipse (Fig. 3b).

We can characterize any ellipse by the angular position of its major half-axis relative to the Carthesian coordinates, by the contraction factor, eccentricity, and focal parameter, and each of these parameters depends on the coefficient of two-photon absorption.

The angular position of the major semi-axis ψ_{max} depends on the polarization azimuth φ in the following way:

$$\text{tg}\,(2\psi_{max}) = \frac{2I_\perp^{0.5}I_\parallel^{0.5}}{I_\parallel - I_\perp}\cos\delta\ . \tag{8}$$

While approximating the empiric dependence $\psi_{max} = f(\varphi)$ in Eq. (8), we used the values $R_\perp = R_\parallel = 0.2$,

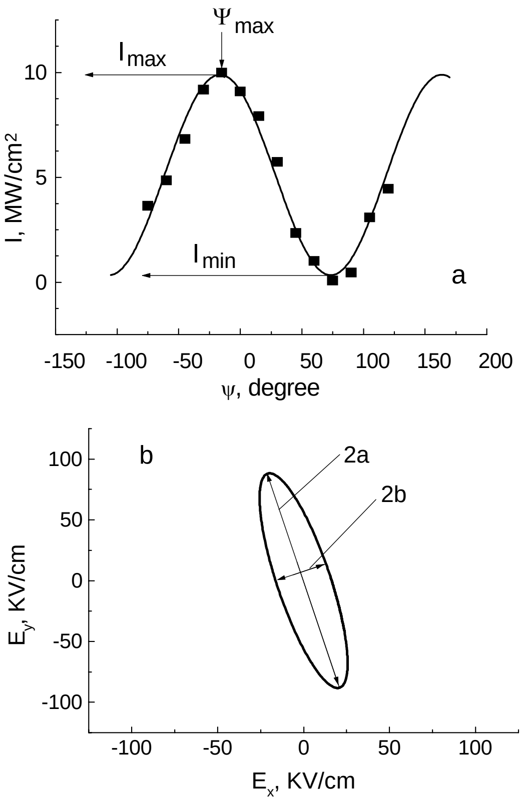

Fig. 3. Light intensity I going out of a CdS crystal versus the rotation angle of an analyzer ψ (a) and the form of a polarization ellipse (b). Points are the experimental data, and the solid line is the result of calculations by formula (5). The polarization azimuth $\varphi = -15^o$, and $I_0 = 50$ MW/cm^2. 2a and 2b stand for the lengths of the major and minor axes of the polarization ellipse, respectively.

and $I_0 = 50$ MW/cm^2, as well as the values of $K_\perp$, $K_{||}$, $\beta_\perp$, and $\beta_{||}$ determined from the dependences $1/T = f(I_0)$ measured at $\varphi = 0$ and $\varphi = 90^o$. It is shown that the calculated (Fig. 4a, solid line) and empiric (Fig. 4a, points) dependences numerically agree with each other.

The deviation of an ellipse from a circle is characterizes by the contraction factor or the ellipticity

$$\chi = \frac{b}{a}\sqrt{\frac{I_{\min}}{I_{\max}}}\,, \tag{9}$$

where b and a are the lengths of the minor and major semi-axes of the polarization ellipse (Fig. 3b), $I_{\min}$ and $I_{\max}$ is the minimum and maximal intensities on the analyzer output (Fig. 3a). The intensities $I_{\min}$ and $I_{\max}$ are estimated by formula (6), in which the known values of $K_\perp$, $K_{||}$, $\beta_\perp$, and $\beta_{||}$ were inserted. The angle $\psi_{\max}$ was estimated by formula (8) and also was inserted in formula (6). In total accordance with formula (9) at $\varphi = 0^o$ and $\varphi = 90^o$, the ellipse degenerates into a straight line. The maximal approaching to a circle is achieved at $\varphi = -45^o$ (Fig. 4b).

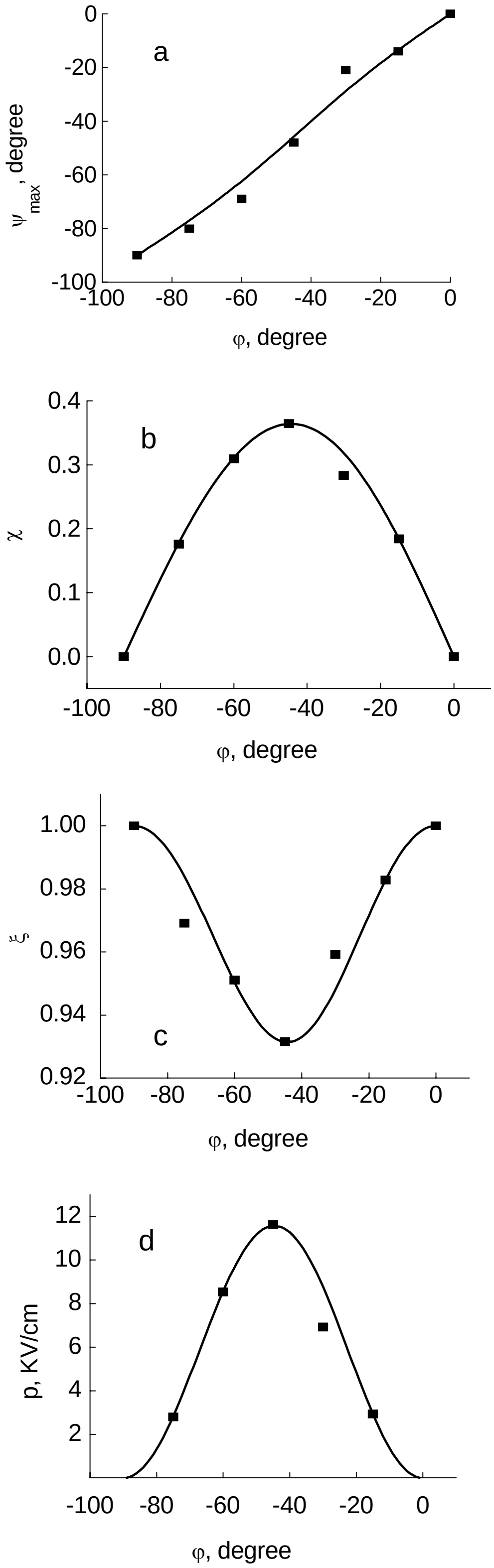

Fig. 4. Rotation angle $\psi_{\max}$ of the major semi-axis of the polarization ellipse relative to the optical axis C (a), ellipticity χ (b), eccentricity ξ (c), and focal parameter p (d) *vs* the polarization azimuth φ. Pumping intensity $I_0 = 50$ MW/cm^2, and λ = 694.3 nm. Solid curves were calculated by formulas (8) – (a), (9) – (b), (10) – (c), (11) – (d).

The ellipse eccentricity reads

$$\xi = \frac{\sqrt{a^2 - b^2}}{a} = \sqrt{\frac{I_{\max} - I_{\min}}{I_{\max}}} \,. \quad (10)$$

In accordance with the data of Fig. 4c, there is the quantitative correspondence between of the empiric dependence ξ on φ and that calculated by formula (10). The minimum value of ξ will be realized on the achievement of the value of $\varphi = -45°$.

$$p = \frac{b^2}{a} = \frac{27.46 I_{\min}}{2\sqrt{I_{\min}}} \,. \quad (11)$$

A focal parameter characterizes a change of the polarization ellipse at points crossing the perimeter by a chord which passes through the focus and is parallel to the minor axis. Dependences p on φ calculated by formula (11) and the empiric data are given in Fig. 4d.

3. Conclusions

We have established the relations describing the influence of two-photon absorption on light polarization in uniaxial crystals. They describe quantitatively the experimentally measured changes of the light polarization under its distribution in CdS. The features of the influence of two-photon absorption on light polarization should by taken into account in the development of high-efficiency second-harmonic generators [8]; transformers of the pulse width into a current [9]; polarization modulator and demodulator of light, and the information transfer by pulses of femto-second duration [10].

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