DICHROIC BISTABILITY CAUSED BY THE RESONANT OPTICAL ORIENTATION OF IMPURITY CENTERS

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A new optical bistability mechanism for impure cubic crystals in a cavity, the dichroic bistability (DB), is suggested and illustrated by a concrete example. DB is due to the self-induced dichroism that accompanies the nonlinear resonant impurity absorption. The bistability is manifested both in the intensity and in the polarization direction of the radiation passing the ring cavity that contains the crystal.

1. Introduction

An important class of systems with strong optical nonlinearity is formed by cubic crystals containing reorientating (tunneling) impurity centers. Such centers have several equivalent positions (orientations) within a unit cell. The center distribution over orientations may be effectively changed by the polarized radiation that is resonantly absorbed by the centers. This way of orientational ordering, resonant optical orientation (ROO), was investigated for a number of systems (see ref. [1]).

It is essential from the nonlinear optics viewpoint that ROO alters the absorption and refraction of the resonant radiation itself. Thus ROO is a mechanism of radiation self-action. Its peculiar feature is the anisotropy caused by the orientation of the impurities along the singled out directions (certain crystalline axes). Hence ROO gives rise to the linear dichroism and as a consequence the self-induced turn of polarization plane (SITPP) of the resonant radiation appears in impure crystals [2,3].

In the present paper we show that SITPP may result in a new type of optical bistability, the dichroic bistability (DB), in case of a cubic crystal mounted in a cavity. For certain systems DB proves to appear under extremely weak intensities. This is a consequence of the presence of unstable directions of the polariza-

tion plane under SITPP [2,3].

Let consider the case when the linearly polarized radiation propagates in a cubic crystal along the [001] axis (z-axis) and its frequency falls into the center of an impurity absorption band (so that the resonant impurity-induced contribution to the refraction may be neglected). Then, the radiation polarization plane may be shown [2,3] to turn to the nearest axis of either ⟨100⟩ or ⟨110⟩ type depending on the type of impurities. In the corresponding cases the ⟨1̄10⟩ or ⟨100⟩ axes, which separate the ranges of "attraction" to the mutually perpendicular limiting stable polarization directions (⟨100⟩ or ⟨110⟩ axes) are obviously the unstable directions for the polarization plane [‡]. Small deviations of electric vector E from the unstable directions grow rapidly (as a rule) with the crystal thickness. In the presence of feedback (cavity) this may result in the turn of the E-vector directed along (or close to) the unstable direction over the finite angle towards one or another stable limiting directions, thus producing optical bistability.

Dichroic bistability is analysed below for the impure crystal imbedded into a ring cavity. We assume the resonance conditions to be fulfilled both for

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[‡] In the case of ⟨110⟩ centers the direction of SITPP (towards ⟨100⟩ or ⟨110⟩ axes) may be intensity dependent. For sake of simplicity such dependence is ignored below.

the impurity absorption and for the cavity, and only the forward mode is supposed to exist.

2. The dichroic bistability criterion

With allowance for the self-induced transmission anisotropy one may describe the cubic crystal transmission in the [001] direction in terms of two coefficients T_x, T_y

$$T_\kappa = E_\kappa(d)/E_\kappa(0), \quad \kappa = x, y. \tag{1}$$

Here $E_\kappa(d)$ and $E_\kappa(0)$ are the field components at the input ($z = 0$) and output ($z = d$) of the crystal. The x- and y-axes are chosen along the limiting stable polarization directions.

Parameters T_x and T_y are determined by the type of impurities, their total concentration and their distribution over orientations. The latter depends on the field. Therefore T_x, T_y depend on $E_x(0)$, $E_y(0)$ and, generally speaking, $T_x \neq T_y$. It is precisely the difference between T_x and T_y that results in SITPP (it is obvious from eq. (1) that $E_y(d)/E_x(d) \neq E_y(0)/E_x(0)$ at $T_x \neq T_y$).

As stated above the linearly polarized radiation is not depolarized at strictly resonant impurity absorption, i.e.

$$\mathrm{Im}(T_x T_y^*) = 0 \quad \text{at } \mathrm{Im}(E_x(0)E_y^*(0)) = 0. \tag{2}$$

Therefore parameters $T_{x,y}$ may be written in the form

$$T_\kappa = t_\kappa \exp(i\varphi_d), \quad t_\kappa = |T_\kappa|, \quad t_\kappa \equiv t_\kappa(E(0), \psi(0)),$$

$$E(0) = [|E_x(0)|^2 + |E_y(0)|^2]^{1/2},$$

$$\psi(0) = \arctan[E_y(0)/E_x(0)],$$

$$\mathrm{Im}(E_y(0)E_x^*(0)) = 0. \tag{3}$$

Here $\varphi_d = 2\pi d/\lambda_c$ (λ_c is the light wavelength in crystal). Parameter $\psi(0)$ is the angle between the polarization plane and one of the limiting polarization directions (x-axis). Since both the limiting stable polarization directions and the unstable ones are the symmetry axes the angular dependence of t_κ has the following properties

$$t_x(E(0), \psi(0)) = t_y(E(0), \pi/2 - \psi(0)),$$

$$t_\kappa(E(0), \psi(0) + n\pi) = t_\kappa(E(0), \psi(0)),$$

$$t_\kappa(E(0), \psi(0)) = t_\kappa(E(0), -\psi(0)). \tag{4}$$

The characteristic angular dependence of $t_{x,y}$ for the case of ROO is plotted in fig. 1.

In the stationary regime the field $E(0)$ at the crystal input is made up of the external field entered the ring cavity $E^{(i)}$ and the field $E(d)$ (the crystal output field) reflected by the cavity mirrors

$$E_\kappa(0) = E_\kappa^{(i)} + R\,e^{i\varphi_c}E_\kappa(d), \quad \kappa = x, y. \tag{5}$$

Here R is the feedback factor ($R < 1$), φ_c is the phase shift introduced by the cavity (the reflection at the crystal surfaces is neglected). We assume, that $\varphi_c + \varphi_d = 2\pi n$ (the sharp tuning).

Eqs. (1), (5) with allowance for the explicit form of T_κ determine the relationship between the field passed the cavity (it is proportional to $E(d)$) and the incident field (it is proportional to $E^{(i)}$). Bistability (and multistability) means that this relationship is non-single-valued. The field strength for which the uniqueness is lost (bifurcation points) is determined from the equation

$$\det(\partial E_\kappa^{(i)}/\partial E_{\kappa'}(d)) = 0. \tag{6}$$

In the case of linearly polarized incident radiation eqs. (1), (3), (5), (6) reduce to the equation for t_x, t_y, which is the necessary condition for the bistability to be possible. Under the ROO-induced optical nonlinearity (cf. fig. 1) the extreme field at which the bistability occurs is determined by either the condition
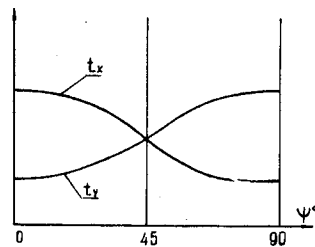

Fig. 1. Angular dependence of the transmission coefficients t_x, t_y for the crystals containing reorienting centers (schematically).

$$RE(0)\, \partial t_x(E(0),0)/\partial E(0) = 1 - Rt_x(E(0),0), \qquad (7)$$

or

$$R\left[\frac{\partial t_x(E(0), \psi(0))}{\partial \psi(0)}\right]_{\psi(0)=\pi/4} = Rt_x(E(0), \pi/4) - 1. \quad (8)$$

Eq. (7) is the ordinary condition of absorptive bistablity in a ring cavity. The condition (8) is nonstandard. It points out that bistability may be caused by the dependence of parameters $t_{x,y}$ on the polarization plane orientation, i.e. by the self-induced dichroism. Eq. (8) is the DB condition. The concrete system where the dichroic bistability may be realized is examined below (for this system the SITPP was revealed experimentally [4]).

3. Theory of dichroic bistability for the F_A(Li)-centers in KCl

The reason of the effective orientational ordering of tunneling centers under relatively weak resonant radiation is their characteristic reorientation probability in the excited state, W_e, exceeding greatly that in the ground state, W_g. The characteristic "nonlinear" radiation intensities are determined by the reciprocal value of the product of the resonant absorption cross-section and the ratio of reorientation probabilities W_e/W_g. There is the category of reorienting centers for which W_g is negligibly small at low temperatures while the probability of the reorientation resulting from photoexcitation $W_e \sim I$. For such centers even weak (non-laser) resonant radiation appears to be "strong" and gives rise to ROO.

The F_A(Li)-centers in KCl crystal present the example of such impurities [1]. These centers are oriented along the ⟨100⟩ axes, and the ⟨100⟩ axes are the limiting stable polarization directions under SITPP [3,4]. In the simple model [1] the dipole moment of the transition into the nondegenerate electron state is parallel to the center axis. However there is weak absorption of the resonant radiation polarized perpendicular to the center axis (due to the selection rules violation). Just this absorption causes SITPP. The ratio χ of the "transverse" cross-section to the "longitudinal" one is small. $\chi \ll 1$ ($\chi = 0.04$ for nitrogen temperatures and for the He-Ne laser frequency
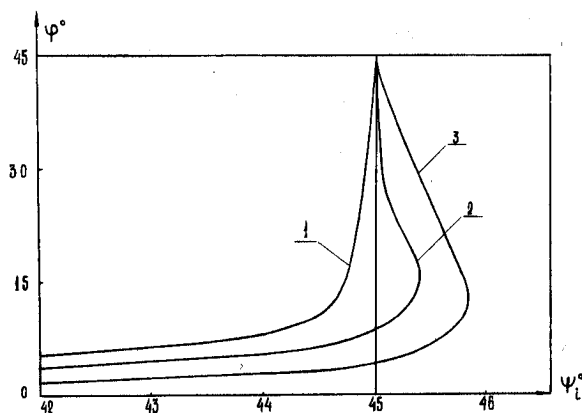

Fig. 2. The dependence of the angle $\psi \equiv \psi(d)$ contained by the radiation polarization plane at the cavity output and the ⟨100⟩ crystal axis on the angle $\psi^{(i)}$ at the cavity input for KCl crystals with F_A(Li)-centers. The curves 1 to 3 correspond to reduced crystal thickness $d = 7;8;11.5$. The "irreducible" parts of the curves are shown (the curves are symmetric with respect to the points $\psi = \psi^{(i)} = 0, \pi/4$). $R = 0.9$.

[5]). The radiation propagation is described by the equations [4,5]

$$dE_\kappa/dz = -E_\kappa[\rho_\kappa(1-\chi) + \chi],$$

$$\rho_\kappa = A|E|^2[|E_\kappa|^2 + \chi(|E|^2 - |E_\kappa|^2)]^{-1}, \quad \kappa = x,y.$$

$$A = \chi[(1-\chi)^2|E_x E_y|^2 + \chi|E|^4]$$

$$\times [\chi(2+\chi)|E|^4 + (1-\chi)^2|E_x E_y|^2]^{-1} \qquad (9)$$

(here z is the dimensionless crystal thickness).

It is seen from eq. (9) that the transmission coefficients $t_{x,y}$ do not depend on the field amplitude $E(0)$ (and $E^{(i)}$). They depend only on the polarization plane orientation $\psi(0)$. Therefore in the system under consideration the absorptive bistability (7) is impossible and only the dichroic one (8) can appear. The criterion (8) with allowance for eq. (9) shows that DB is manifested when the dimensionless crystal length exceeds the critical value

$$d_b = \chi^{-1}(1 - 14\chi + \chi^2)^{-1}(1+\chi)(1+5\chi)\ln R^{-1}$$

$$\approx 0.7 \times 10^2 \ln R^{-1}. \qquad (10)$$

The dependence of the polarization plane orientation at the cavity output ($\Sigma \equiv \psi(d)$) versus that at the

cavity input ($\psi^{(i)}$) obtained by numerical solution of eqs. (1), (5), (9) is plotted in fig. 2. It is S-shaped at $d > d_b$. This means the bistability (the branch where $\partial \varphi / \partial \psi^{(i)} < 0$ is unstable). Owing to the self-induced dichroism the dependence of the transmitted light intensity on $\psi^{(i)}$ is bistable as well. It should be noted that the mechanism of DB described above differs qualitatively from the two beam absorptive bistability proposed in ref. [6] for F_A-centers.

The example considered in the present paragraph demonstrates that the dichroic bistability concerns both the polarization and intensity and can manifest itself at low intensities. We note in conclusion that the dichroic bistability is quite general phenomenon.

For a number of concrete systems it will be analysed elsewhere.

References

[1] F. Luty, in: Physics of colour centers, ed. W.B. Fowler, (Academic Press, NY, 1968) p. 182.

[2] M.I. Dykman and G.G. Tarasov, Sov. Phys. JETP 74 (1978) 1061.

[3] M.I. Dykman and G.G. Tarasov, Optics Comm. 26 (1978) 122.

[4] M.Ya. Valakh, M.I. Dykman, M.P. Lisitsa, G.Yu. Rudko and G.G. Tarasov, Sol. State Commun. 30 (1979) 133.

[5] M.Ya. Valakh, M.I. Dykman, M.P. Lisitsa, E.V. Pidlisny, G.Yu. Rudko and G.G. Tarasov, Fizika tverdogo tela 23 (1981) 418.

[6] G. Litfin, Appl. Phys. B 28 (1982) 134.