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The dependence of optical anisotropy parameter on dopant concentration in Yb:CaF_2 and Tb:CaF_2 crystals

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ABSTRACT

Optical anisotropy parameters of Yb^{3+}:CaF_2 with different concentrations of Yb^{3+} ions (2.6, 3, 4.2 at.% Yb^{3+}) and 10 at.% Tb^{3+}:CaF_2 crystals were determined from measurements of thermally induced depolarization. It was shown that the optical anisotropy parameter depends on dopant, if its concentration is sufficiently high. The crystallographic axes orientation at which there is no thermally induced depolarization was found for each studied crystal.

1. Introduction

CaF_2 crystals are widely used for fabricating passive optical elements (lenses, optical windows, polarizers) [1] as well as active optical elements, when doped with rare earth ions such as Yb^{3+}, thanks to their good thermooptical [2], laser [3], and spectroscopic [4–7] properties. CaF_2 doped with Tb^{3+} allows using it as a magneto-active material in Faraday isolators and rotators [8].

The quality of high average power laser radiation greatly depends on thermal effects arising due to the heat release (partial absorption of laser radiation, quantum defect etc.) which results in heating of the optical element, and in arising temperature gradients and thermal stresses. One of such effects is thermally induced birefringence arise due to photoelastic effect and resulting in depolarization of transmitted polarized radiation. Depolarization of radiation deteriorates its quality and leads to the power losses in the polarized field. Quantitatively, this effect is determined by integral depolarization γ, that is the ratio between the power of depolarized component of the field to the totally polarized beam power. For Faraday isolators at high average power, thermally induced depolarization fully determines the isolation ratio that is its basic characteristic [9]. Thus, in applications with special requirements for the quality of radiation and its polarization, reducing of the thermally induced depolarization at high average power is important.

The magnitude of thermally induced depolarization is known to depend on the orientation of crystallographic axes of the optical element [10] and takes on its minimum value at the orientation determined by the optical anisotropy parameter ξ [11,12]. Moreover, for a negative value of the parameter ξ, the cubic crystal has a "zero depolarization" orientation, which is called [C] in Ref. [13], at which thermally induced depolarization does not arise and the direction of this orientation is defined by the value of optical anisotropy parameter ξ.

The optical anisotropy parameter ξ of the crystal of cubic symmetry *m3m*, *-43 m*, and *m3* is defined by

$$\xi = \frac{\pi_{44}}{\pi_{11} - \pi_{12}} = \frac{2 \cdot p_{44}}{p_{11} - p_{12}} \cdot \frac{c_{11} - c_{12}}{2 \cdot c_{44}}, \quad (1)$$

where π_{ij} are piezooptic coefficients, p_{ij} are photoelastic coefficients, and c_{jk} are the elastic stiffness coefficients ($i, j, k = 1 \ldots 6$), as the photoelastic effect is described by the 4^{th} rank tensors [14].

The parameter ξ depends on wavelength [15] and on temperature [16]. In some materials, the value of the coefficients π_{ij}, p_{ij}, and c_{jk} depends on dopant concentration [17]. In CaF_2 crystals doped with active ions clusters arise, while the fluorite structure is retained [18,19]. It changes the properties of the crystal lattice and may affect the value of the optical anisotropy parameter ξ, hence, the direction of "zero depolarization" orientation.

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In the present work the dependence of parameter ξ on dopant concentration in Yb^{3+}:CaF_2 crystals (0,2.6, 3, 4.2 at.% Yb^{3+}) was investigated and its value was determined for 10 at.% Tb^{3+}:CaF_2. Two different methods were used to create the thermally induced birefringence in the optical elements as well as to measure the value of the parameter ξ. The results of measurements were compared to data obtained earlier in undoped CaF_2 crystals.

2. Experiment

Five crystal samples were investigated in experiment. Four of them with [001] orientation of the crystallographic axes: CaF_2 ($L = 7.5$ mm, $d = 12$ mm), 2.6 at.% Yb^{3+}:CaF_2 ($L = 5.2$ mm, $d = 10.9$ mm), 4.2 at.% Yb^{3+}:CaF_2 ($L = 6.2$, $d = 10.9$ mm), 10 at.% Tb^{3+}:CaF_2 ($L = 18.6$ mm, $d = 10.2$ mm) and a 3 at.% Yb^{3+}:CaF_2 sample having size ($2.9 \times 11.5 \times 11.5$ mm) with orientation determined by the Euler angles $\alpha = 36°$ and $\beta = -86°$. The samples' orientation was measured by a Bruker D8 Discover diffractometer.

All the studied samples were weakly absorbing at the wavelength of 1070 nm. Thermally induced depolarization in Tb^{3+}:CaF_2 and Yb^{3+}:CaF_2 crystals was not recorded in experiment using Yb:fiber ($\lambda = 1070$ nm) with CW radiation power up to 1.5 kW [8]. Therefore, temperature gradients were created by heating the optical element by two methods such as "laser heating" and "side surface heating" proposed in this work. The arising depolarization was registered in all the cases by probe laser radiation at the wavelength of 1070 nm.

"Laser heating" of the optical element was performed by the heating radiation that is well absorbing in the studied materials. The sources of laser radiation were a diode laser at $\lambda = 940$ nm with $P_{max} = 30$ W for Yb^{3+}:CaF_2 samples and CO_2 laser at $\lambda = 10.6\ \mu$m, $P_{max} = 30$ W for all studied samples [Fig. 1(a)].

The method of "side surface heating" is based on axisymmetric heating of the optical element's side surface by a uniformly coiled wire through which electric current is running [Fig. 1(d)]. The advantage of this heating method is its universality – axisymmetric heating is done independent of the magnitude of laser radiation absorption in material, which makes it applicable for various crystals without using heating laser radiation. The measurement scheme becomes more compact and makes use of laser sources of probe radiation of relatively low power and different wavelengths for measuring the optical anisotropy parameter ξ in a wide spectral range.

The value and sign of the optical anisotropy parameter ξ are determined by the two different methods proposed in Ref. [12]: either by measuring the power dependence of integral depolarization in two positions of the crystal, determined by angle θ [Fig. 1(b)]: $\gamma(\theta = 0)/\gamma(\theta = \pi/4) = \gamma_1/\gamma_2 = \xi^2$, or by measuring $\phi_0(\theta)$, where ϕ_0 is the angle of rotation of the local depolarization distribution, known as the "Maltese cross". In case of $\xi > 0$ "Maltese cross" oscillates, while θ changes from 0 to 2π and in case of $\xi < 0$ "Maltese cross" rotates [Fig. 1(c)].

The experiment on application of the "laser heating" method is presented schematically in Fig. 1(a). After passing the calcite wedge (3) linearly polarized radiation of a Yb:fiber laser at $\lambda = 1070$ nm with $P_{max} = 50$ W was transmitted to the sample (4) where it was combined with heating radiation at an angle $< 5°$. After passing the sample, the heating radiation was withdrawn from the scheme and the probe radiation was transmitted to the CCD camera. Glan prism (5) was adjusted to the crossed position relative to the calcite wedge, allowing registering the depolarized field component by the CCD camera. When the Glan prism (5) was rotated by 90°, the main field component was registered. Heating radiation was not used at "side surface heating", and the sample was placed in the heating element [Fig. 1(d)]. The contrast of the scheme, between the two positions of the Glan prism (5), was $\approx 10^{-5}$ in both cases.

3. Results

The dependence of integral depolarization on heating radiation power $\gamma_i(P)$, $(i = 1,2)$ for each crystal was measured by the method of "laser heating". The $\gamma_i(P)$ curves for Yb^{3+}:CaF_2 (2.6, 4.2 at.% Yb^{3+}) and 10 at.%Tb^{3+}:CaF_2 are plotted in Fig. 2(a and b). The quadratic dependence of depolarization on heating power corresponds to predominance of thermally induced depolarization over "cold" one, determined by crystal defects and measuring system contrast. The values of parameter ξ for Yb^{3+}:CaF_2 (2.6, 4.2 at.% Yb^{3+}) crystals were found from the ratio of integral depolarizations γ_1 and γ_2 and were -0.47 ± 0.03 for both crystals; for a Tb^{3+}:CaF_2 crystal ξ was equal to -0.61 ± 0.04.

The $\phi_0(\theta)$ curves for Yb^{3+}:CaF_2 (2.6, 4.2 at.% Yb^{3+}) ("laser heating"), for CaF_2 and Tb^{3+}:CaF_2 ("side surface heating") are plotted in Fig. 2(c). For Yb^{3+}:CaF_2 (0,2.6, 4.2 at.% Yb^{3+}), the parameter ξ was -0.47 ± 0.03. The optical anisotropy parameter ξ for the Tb^{3+}:CaF_2 crystal was -0.63 ± 0.03.

A typical $\gamma_i(t)$ plot obtained with the "side surface heating" method for two crystal positions corresponding to γ_1 and γ_2 is shown in Fig. 2(d). The decrease of thermally induced depolarization with time is caused by decreasing value of temperature gradients and heating the volume of the sample. In the course of time

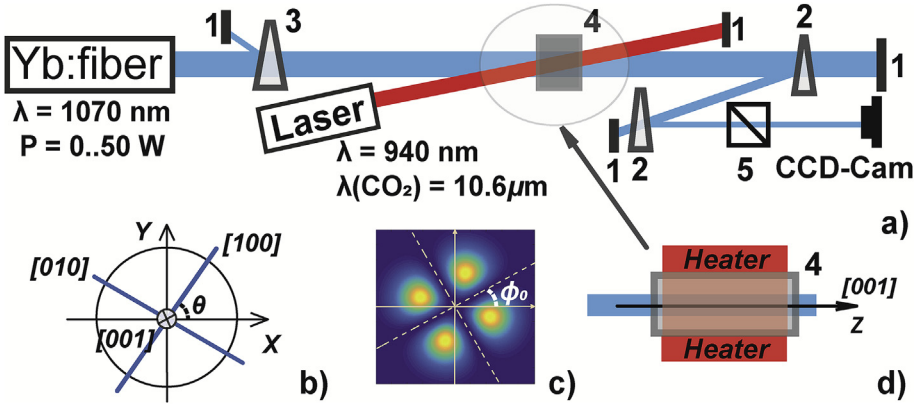

Fig. 1. Scheme of the experiment on determining the optical anisotropy parameter ξ of CaF_2, Yb^{3+}:CaF_2 and Tb^{3+}:CaF_2 crystals. Heating by laser radiation ("Laser heating"): 1–radiation absorber, 2–fused silica wedge, 3–calcite wedge, 4–studied sample, 5–Glan prism (a), orientation of crystallographic axes of the sample, angle θ (b), "Maltese cross" distribution of depolarized field component, angle ϕ_0 (c), scheme of axisymmetric heating of optical element by uniformly coiled wire ("side surface heating") (d).