Reduction of thermally induced depolarization of laser radiation in [110] oriented cubic crystals

Ivan Mukhin, Oleg Palashov, and Efim Khazanov

nstitute of Applied Physics, 46 Uljanov Street, 603950 Nizhny Novgorod, Russia

Abstract: The first measurements of thermally induced depolarization in a [110] oriented cubic crystal at powerful heat release were made. It was demonstrated that depolarization in a crystal with such orientation may be less than in analogous crystals having orientation [001] or [111]. In a TGG crystal, for example, maximum depolarization value was 10% and dropped down to 3% with a further increase of radiation power in full conformity with the theoretical predictions.

OCIS codes: (140.6810) Thermal effects; (260.1440) Birefringence.

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1. Introduction

The power of both, pulsed periodic and cw lasers has grown dramatically in the recent years. The average power of modern solid-state lasers amounts to kilowatts and even tens of kilowatts. The main problem restricting solid-state laser power is unavoidable heat release in active elements due to pump absorption. It leads to changes in refractive index, degradation of laser characteristics, strain, and even to destruction of active element. One of such depolarization effects is photoelastically induced radiation depolarization, i.e., different polarization at different points of the beam cross-section [1, 2]. Studies of the thermally induced depolarization in active elements were initiated back in the 1960s [3-5] and are continued up to the present. Depolarization in an amorphous medium (glass) was investigated in ample detail rather fast [6-9].

Thermally induced depolarization in isotropic crystals (crystals with cubic symmetry, such as garnets) was studied in many works [10-20]. The influence of crystal orientation on depolarization was first investigated in [18]. But the results presented in [18] are true for the [111] orientation only because of the mistake which was first pointed to in [19]. The authors of [18] supposed that the directions of intrinsic polarizations coincide with radial and tangential directions. The same erroneous statement can be found in the classical book [2].

Expression for the permittivity tensor $\mathbf{\Delta B}$ for the [001] orientation were obtained in [1, 19, 20], where it shown that depolarization with this orientation may be less than with [111]. The authors of [1, 20] also considered and derived approximate expressions for the [110] orientation. The used approximation, however, does not hold for the great majority of laser crystals, such as, e.g., YAG, GGG, GSGG, YGG. Depolarization for the [110] orientation was calculated in [21], but the results hold true only for uniform heating and have the errors pointed to in [22].

The first analytical expressions for the $\mathbf{\Delta B}$ tensor for any cubic crystal with arbitrary orientation and arbitrary axially symmetric power density distribution of heat generation were obtained in [23] using the procedure proposed in [18]. The authors of [23] showed that the [001] orientation is the best one at small heat generation. In [22] some general theorems about physical singularity of the [001], [111] and [110] orientations were proved and the problem about the best and the worst orientations for arbitrary power of heat generation was solved. Theoretical results for the case of small power of heat generation in crystals with [110] orientation were confirmed in experiments [22]. In all the above works elastic properties of a crystal were regarded to be isotropic, although, strictly speaking, it is merely a good approximation [24].

The conditions under which depolarization in a [110] crystal at large heat generation power may be much less than in a crystal having orientation [001] or [111] were found in [21, 22]. However, those findings have not been confirmed experimentally. In the current paper we present the first experimental study of depolarization in a [110] oriented cubic crystal at large thermal loads and demonstrate its advantage over the [001] and [111] orientations. In Sec. 2 specific features of polarization distortions in crystals with [110] orientation are described. Results of measuring depolarization in a [110] oriented terbium gallium garnet are presented in Sec. 3, where the obtained experimental results are

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compared with theoretical data. In the Conclusion we discuss prospective applications of crystals with [110] orientation for reducing polarization distortions of powerful laser radiation.

2. Features of polarization distortions in crystals with [110] orientation

In the simplest case, crystallographic *abc* axes coincide with the *xyz* directions (Fig. 1), which corresponds to the [001] orientation. The *rφz* correspond to the *xyz* coordinates in the cylindrical frame of reference. For a cubic crystal, arbitrary position of the *abc* axes may be specified by means of two successive turns of the system of coordinates *xyz* relative to the crystal lattice by two Euler angles α and β [18]: by angle α around the *z* axis, and then by angle β around the *y* axis. Thus, by varying the values of α and β one can obtain any desired crystal orientation. By virtue of physical equivalence of crystallographic axes *a, b* and *c*, the some orientations are physically equivalent. For example, [011] ($\alpha=-\pi/2$, $\beta=\pi/4$), [110] ($\alpha=\pi/4$, $\beta=-\pi/2$), [101] ($\alpha=0$, $\beta=-\pi/4$), [$\bar{1}$01] ($\alpha=0$, $\beta=\pi/4$), and so on. Hereinafter we will consider it to be one orientation and refer to it as to [110].

Let the incident polarization radiation make angle θ with the *x* axis, and the profiles of heat sources (further referred to as pumps) and of transient (test) radiation be defined by functions $F_h(r)$ and $F_L(r)$, respectively. The eigen polarizations of thermally induced birefringence $\mathbf{e_1}$ and $\mathbf{e_2}$ are directed at angle Ψ to the *x* and *y* axes (Fig. 1).

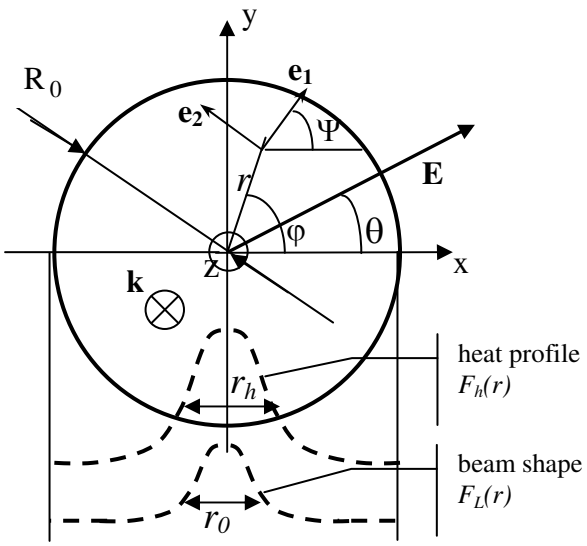

Fig. 1. Cross-section of cylindrical active element; e1 and e2 are intrinsic polarizations at the point (r,φ); E is polarization of incident radiation.

The depolarization ratio γ of the radiation transmitted through the crystal will be understood as the ratio of the power of radiation polarized along the *y* axis to the total power. An exact analytical expression for γ in a cubic crystal of arbitrary orientation with arbitrary axially symmetric heat generation was derived in [23]. The main feature of polarization distortions in a cubic crystal as compared to glass is that the directions of eigen polarizations of thermally induced birefringence $\mathbf{e_1}$ and $\mathbf{e_2}$ do not coincide with the radial and tangential directions ($\Psi\neq\varphi$, see Fig. 1). This leads to the dependence of γ on crystal orientation. This effect is associated with anisotropy of the photoelastic effect in cubic crystals: $2p_{44}\neq p_{11}-p_{12}$, where p_{ij} are the elements of photoelasticity tensor ($2p_{44}=p_{11}-p_{12}$ in glass).

Anisotropy of the photoelastic effect results also in the dependence of γ on angle θ [1, 19, 20, 22, 23]. In what will follow the indices "min" and "max" will designate the minimum and the maximum values of γ with the variation of angle θ. The only exception

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[22] is the [111] orientation for which γ is independent of θ. Indices "min" and "max" are not given for this orientation here.

In the case of small heat release, γ depends quadratically on the normalized heat power p [23]:

$$p = \frac{P_h}{\lambda\kappa}\alpha_T \frac{n_0^3}{4}\frac{1+\nu}{1-\nu}(p_{11}-p_{12}), \tag{1}$$

where κ, ν, and α_T, are, respectively, heat conductivity, Poisson's ratio and thermal expansion coefficient; P_h is heat power in a crystal, and λ is test radiation wavelength. At infinitely large heat release ($p \to \infty$), γ tends to γ_∞. In terms of real laser installations, most interesting is the regime intermediate between the two approximations described above (p>>1). In this case, depolarization value oscillates about γ_∞, with the oscillation amplitude decreasing with increasing p. Depolarization as a function of pump power is plotted in Fig. 2 for three crystal orientations calculated by the formulas from [23].

The magnitude of γ_∞ in a [111] oriented crystal depends neither on material characteristics of the crystal nor on pump and transmitted radiation profiles and is always equal to 0.25. In a [001] crystal, γ_∞ is determined only by the parameter of photoelastic anisotropy $\xi=2p_{44}/(p_{11}-p_{12})$ [22]:

$$\gamma_\infty([001]) = 0.25 - \frac{1}{4}\left|\frac{1-\xi}{1+\xi}\right| \qquad \gamma_\infty([111]) = 0.25 \tag{2}$$

For a YAG crystal γ_∞([001])=12% and ξ = 3.2 [25,26], for a TGG crystal γ_∞([001])=15% and ξ = 2.25 [27].Depolarization in a crystal having orientation [110] strongly depends on both, the ξ and radii of crystal R_0, pump r_h and laser beam r_0. In particular, the magnitude of γ_∞([110]) drops down both, with an increase in R_0 and with an increase of the r_h/r_0 ratio. It is clear from Fig. 2 that for R_0/r_h=1 and R_0/r_o=4, [110] is the best orientation in terms of the minimum of depolarization at large heat power (p>15).

For experimental verification of this theoretical prediction of thermally induced depolarization in a TGG crystal with [110] orientation was measured in a broad range of heat power.

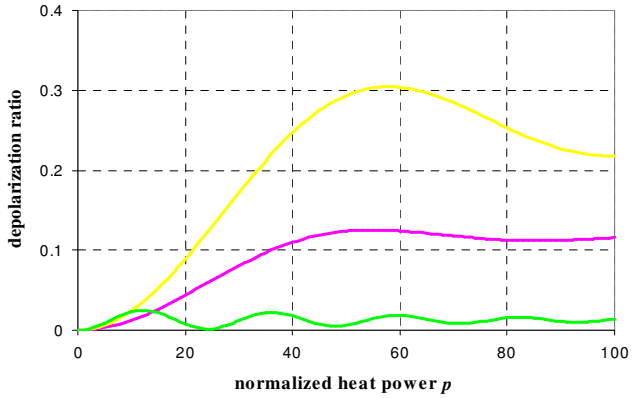

Fig. 2. Curves for γ(p) for different orientations of YAG crystal: [111] (yellow), [001] (pink), [110] at R_0/r_h=1 (homogeneous heating of the crystal) and R_0/r_o=4 (green).

3. Depolarization measurements in a [110] oriented crystal

Experiments aimed at studying depolarization were divided into two parts: quantitative verification of the theoretical predictions, and qualitative experiment confirming that depolarization in a [110] oriented crystal at large heat power is less than in a crystal having orientation [001] or [111].

The first part of the experiment is depicted schematically in Fig. 3(a). Radiation of a cw fiber laser 1 at the wavelength of 1076 nm was used as a pump. The polarization ratio was 30:1. A Gaussian beam with maximum power of 330 W was transmitted through

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telescope 2 that reduced beam diameter down to 0.83 mm. Calcite wedge 3 increased the polarization ratio of the beam up to 10^6:1.

Further, the beam was transmitted through TGG crystals 4, with part of the beam being absorbed in the crystals ($\alpha=4\cdot10^{-3}\text{cm}^{-1}$). To increase heat generation power we used three TGG crystals having orientation [110] and equal size: length 20 mm and diameter 8.3 mm. Laser radiation was used as a pump and a test beam. Part of the beam was separated by a quartz plate 5 and past Glan's prism 6 entered CCD camera 8. Lens 7 transferred the image from the last edge of the TGG crystals to the CCD camera. Each crystal was oriented so as to provide minimum (γ_{min}) or maximum (γ_{max}) depolarization. After that the corresponding value of depolarization was measured in all the crystals.

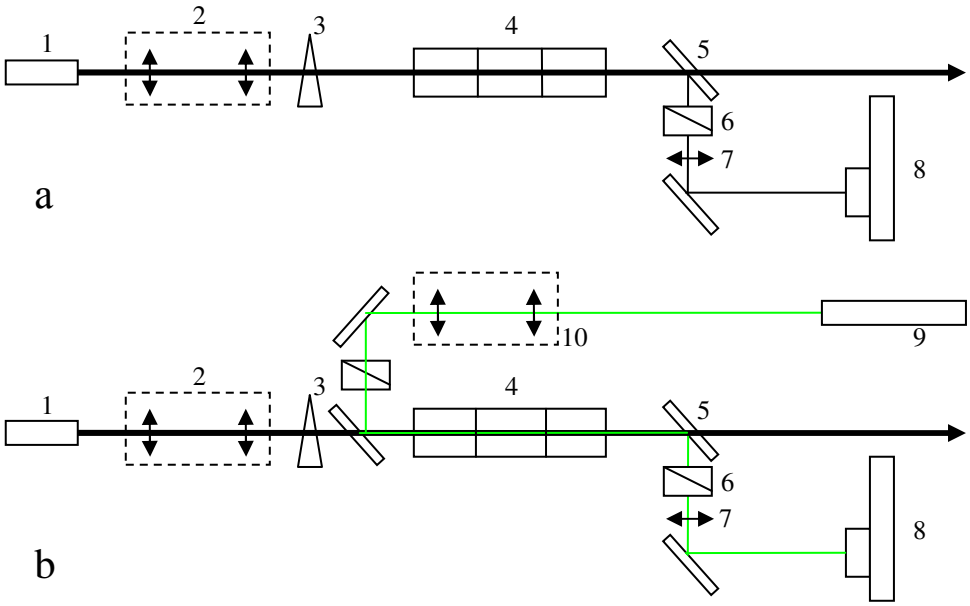

Fig. 3. Schematic of depolarization measurements without (a) and with (b) complementary test laser: 1 – fiber cw laser, 2,10 – telescope, 3 – calcite wedge, 4 – crystals under consideration, 5 – fused quartz plate, 6 – Glan's prism, 7 – lens for image transfer, 8 – CCD camera, 9 – diode laser, $\lambda = 532$ nm.

The results of measurements presented in Fig. 4(a) agree well with the theoretical curves. A small difference of γ_{max} may be attributed to error at mutual alignment of the three crystals. The depolarization reached its maximum at a little less power than that predicted by the theory. The point is that, as the power is increased, the thermal lens in crystals focuses the pump beam (hence, the test beam); and depolarization in a [110] oriented crystal is known to depend on the diameter of transmitted radiation. Curves 3 and 4 in Fig. 4(a) are the theoretical dependences of depolarization on pump power for the [111] and [001] orientations of a TGG crystal. One can see that for the values of crystal radius R_0 and laser beam and heat release radii ($r_h=r_0$) used in our experiment, [111] is the worst orientation, and depolarization γ_{min} in crystals with orientations [001] and [110] will be comparable at large power. With increasing ratios R_0/r_h, R_0/r_0 or r_h/r_0, the magnitude of $\gamma_{min\infty}$ will decrease in a [110] oriented crystal and will remain unchanged in a crystal with [001] orientation.

In the second series of experiments we realized this situation using radiation from laser 9 as a test beam (Fig. 3(b)) at the wavelength of 532 nm. The average power of the green laser did not exceed 20 mW, so its absorption coefficient in TGG is not important. The probe laser wavelength is chosen the shortest to increase the normalized heat release power p (p is inversely proportional to a wavelength of probe radiation). Telescope 10 transformed the beam so that it was 0.45 mm in diameter at the input of the crystals and 0.68 mm at the output (with switched off laser 1). This geometry allows partial

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compensation of thermal lens. The radiation was linearly polarized past Glan's plate 6. Pump beam diameter in the second series of experiments was also reduced down to 0.63 mm at the input of the crystals 4 and to 1.0 mm at the output.

The results of the experiment are presented in Fig. 4(b). Curves 6 and 7 were plotted taking into account the change in the beam diameters of both lasers caused by the thermal lens. However, experimental and numerical results agree well only for small pump power. As power is increased, the experiment and the theory agree only qualitatively. This discrepancy is explained by strong thermally induced aberration in TGG crystals. Depolarization strongly depends on the intensity profiles of the pump beam and of the test beam. However, it is rather difficult to control intensity distribution of these beams for each pump power. Besides, the test beam and the pump beam were aligned in experiment to finite accuracy, which could also affect measurement results. Note, there is a small difference between 3,4 and 7,8 curves in Fig. 4 because these curves was calculated for different pump and probe beam profiles.

In spite of some difference in the results of experiment and theory, from Fig. 4 it follows that the depolarization γ in a TGG crystal with orientation [110] did not exceed 10%, and dropped down to 3% with a further power increase, which is in agreement with the theory. Still further increase of power would again give rise to the growth of γ that would reach $\gamma_{min\infty}$. after some oscillations. For the parameters used in the experiment $\gamma_{min\infty}$=5%, and for the [001] orientation $\gamma_{min\infty}$=15%. Thus, the earlier predicted advantage [21, 22] of the [110] orientation at large pump power was confirmed in experiment.

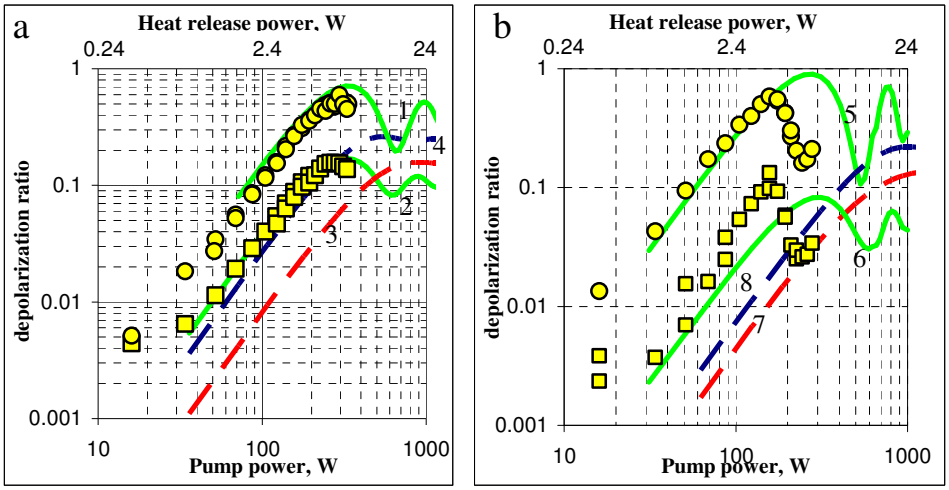

Fig. 4. Experimental (points) and numerically calculated (curves) dependences of depolarization ratio γ on pump power for TGG crystal: γ_{max}([110]) circles and curves 1,5; γ_{min}([110]) squares and curves 2,6; γ_{min}([001]) curves 3, 7; and γ([111]) curve 4, 8

4. Conclusion

We investigated in experiment depolarization in a [110] oriented cubic crystal at large heat generation power. The results of measurements qualitatively and quantitatively confirm correctness of the depolarization theory developed in the works [21, 22]. Experiments confirmed that, at large heat generation power, [110] is optimal orientation, provided that pump and test beam diameters are much less that diameter of the crystal. Thus, in a YAG crystal the [110] orientation is optimal if the diameter of the flat-top pump beam is 3.5 times less than the crystal diameter [22].

The [110] orientation is the most promising for disk geometry of an active element and in crystalline fibers. At the same time, in the case of edge diode pumping, the [110] orientation may be effectively used in rods too.

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