Experimental study of thermally induced depolarization in Nd:YAG ceramics

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Abstract: Spatial modulation of a laser beam with a transverse size of the order of one grain size is experimentally found at thermal depolarization in Nd:YAG ceramics. This effect, which was theoretically predicted earlier, is typical for ceramics only, with no analogs either in glasses or in single crystals.

OCIS codes: (140.6810) Thermal effects; (160.3380) Laser materials.

References and links

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1. Introduction

Recently, increasing attention has been focused on the use of polycrystalline ceramics made of cubic crystals as an active medium (see Refs. [1-5] and references therein), as Q-switchers (Cr:YAG) [6], and as a magneto-optic medium in Faraday isolators (TGG, TAG, TSAG) [7,8]. Despite poor optical quality of the first TGG ceramic samples, there is no difficulty, in principle, in creating high-quality magneto-optic ceramics. Modern technology allows

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fabrication of ceramic optical elements with good optical quality, large aperture, and high concentration of doped ions. Ceramics have a unique set of properties that single crystals and glass do not possess. For lasers with high power (average and peak), ceramics offer three major advantages: First, they have a large aperture, like that in glass (450 mm [9]), and high thermal conductivity like that in single crystals. Second, ceramics can be made of crystals that cannot be grown as single crystals, in principle, but have good properties such as $Nd:Y_2O_3$, TAG, TSAG, and so on. Third, the thermal shock parameter in ceramics is three times as that in single crystals [10]. It is therefore very promising to employ ceramics in high-power lasers. Thus the investigation of thermal effects, including polarization effects, in ceramic optical elements becomes important.

Thermally induced birefringence in Nd:YAG ceramics was experimentally studied for the first time in Refs. [2,11,12]. The results of these studies show that depolarization in ceramics is similar to that in a single crystal with the [111] orientation. However, no theoretical verification of this fact was reported. Moreover, as pointed out in [4], the authors of Refs. [11,12] interpreted their experimental findings based on an erroneous assumption that the thermally induced birefringence is independent of the orientation of crystallographic axes.

In its general form the problem of thermally induced birefringence at an arbitrary orientation of the crystal was solved analytically in Ref. [13]. The orientation of crystallographic axes of each ceramic grain is random, leading to random nature of the depolarization in ceramics, as was first reported in Ref. [4]. In this and subsequent theoretical studies [7,8], a theory of thermally induced birefringence in ceramics was developed, and analytical expressions for depolarization of radiation both in initially isotropic elements (active elements, Q-switchers) [4,7] and gyrotropic elements (Faraday isolators and Faraday mirrors) [8] were derived. In addition, the efficiency of depolarization compensation by all methods used for single crystals and glasses was investigated.

The most essential specificities of ceramics are related to the effect, which has no analog in either glasses or single crystals–that is the depolarization dispersion [4]. Since rays separated by a distance equal to approximately a grain size l_g pass through a statistically independent set of grains, the depolarization dispersion leads to spatial modulation (both amplitude and phase) of the beam after it has passed through a polarizer. Thus both the polarized and depolarized parts of the radiation that have passed through a thermally loaded ceramic element always have a small-scale modulation with a characteristic size less than l_g and a depth that is dependent on the ratio of sample length to grain length. In our report we shall present the results of experimental observation and investigation of this effect.

2. Experimental results

The schematic diagram of the experiment is shown in Fig. 1. The sample was a Nd:YAG (2.3 at. % Nd) ceramic element. The element was a cylinder of 8.5 mm in length and 8 mm in diameter, with average grain size of approximately 70 μm. Radiation from a CW Yb:fiber laser with power of P_0 = 50 W (wavelength of 1076 nm) was used both to heat the ceramic sample and to measure the depolarization. The beam on the sample was Gaussian-shaped with radius r_0 = 0.5 mm. For increasing of heating power, the beam was propagated twice through the sample using a mirror (8). An image of the output face of the sample was relayed by a lens (11) onto a CCD camera (12). Due to the polarizer (9) with contrast 900, the intensities of polarized and depolarized beams on the CCD camera were almost identical, allowing simultaneous measurement of their distributions.

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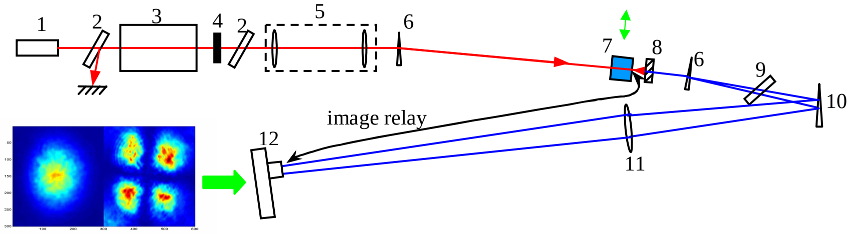

Fig. 1. Schematic of the experiment: (1) laser, P_0=50W (wavelength 1076nm); (2) polarizer; (3) Faraday isolator; (4) λ/2 plate; (5) telescope; (6) spar wedge; (7) sample; (8) nontransmitting mirror; (9) polarizer; (10) glass wedge; (11) lens, focal length 516 mm; (12) CCD camera.

At a given laser power, the ceramic element was moved 20 times in and out of the beam path so that each new position was shifted relative to a previous one by a value more than l_g in a random direction. Therefore, for each ray with transverse coordinates (r,φ) we obtained 20 random realizations of the intensity of the depolarized beam I_d and of the beam with initial polarization I_p (Fig. 2). The depolarization degree was determined as $\Gamma = I_d/I_0$, where $I_0 = (I_d + I_p)$. Average values $\langle I_0\rangle(r,\varphi)$, $\langle I_d\rangle(r,\varphi)$ and dispersions $D_0(r,\varphi)$ and $D_d(r,\varphi)$ were found over an ensemble of 20 realizations (see their distributions in Fig. 2). Note that a small intensity modulation was observed also in the total beam I_0, which is due to the non-ideal quality of the sample. This led to a nonzero value of D_0. Nevertheless, the measured value of average-normalized root-mean-square deviation for the total beam $(D_0)^{1/2}/\langle I_0\rangle$ was much less than for the depolarized beam $(D_d)^{1/2}/\langle I_d\rangle$ (see Fig. 3). This confirms the random character of the depolarization in ceramics.

Theoretical predictions of a large value of depolarization degree dispersion D_Γ [4] (comparable with $\langle\Gamma\rangle$ in some points of cross section) are also well confirmed by the experiment (see Fig. 2). At a relatively small power, the theoretical dependence D_Γ on heat release power is quadratic and quantitatively coincides with the experimental one for any integration domain, see Fig. 4. All theoretical dependences shown in Figs. 2 and 4 were plotted by formulas presented in Refs. [4,7,8]. As the Figs. 2–4 show, the experimental data are in good quantitative and qualitative agreement with theoretical predictions.

3. Conclusion

Let us summarize the results. We have observed in experiment the effect of strong dispersion of thermally induced depolarization in ceramics, which we earlier predicted theoretically. This effect is specific to ceramics only and has no analogs either in glasses or in single crystals. The consequence of this effect is that both the polarized and depolarized radiations always have a small-scale intensity modulation with a characteristic transverse size of the order of a grain size. Depth of this modulation increases with increasing heat release power and decreasing ratio of sample length to grain length.

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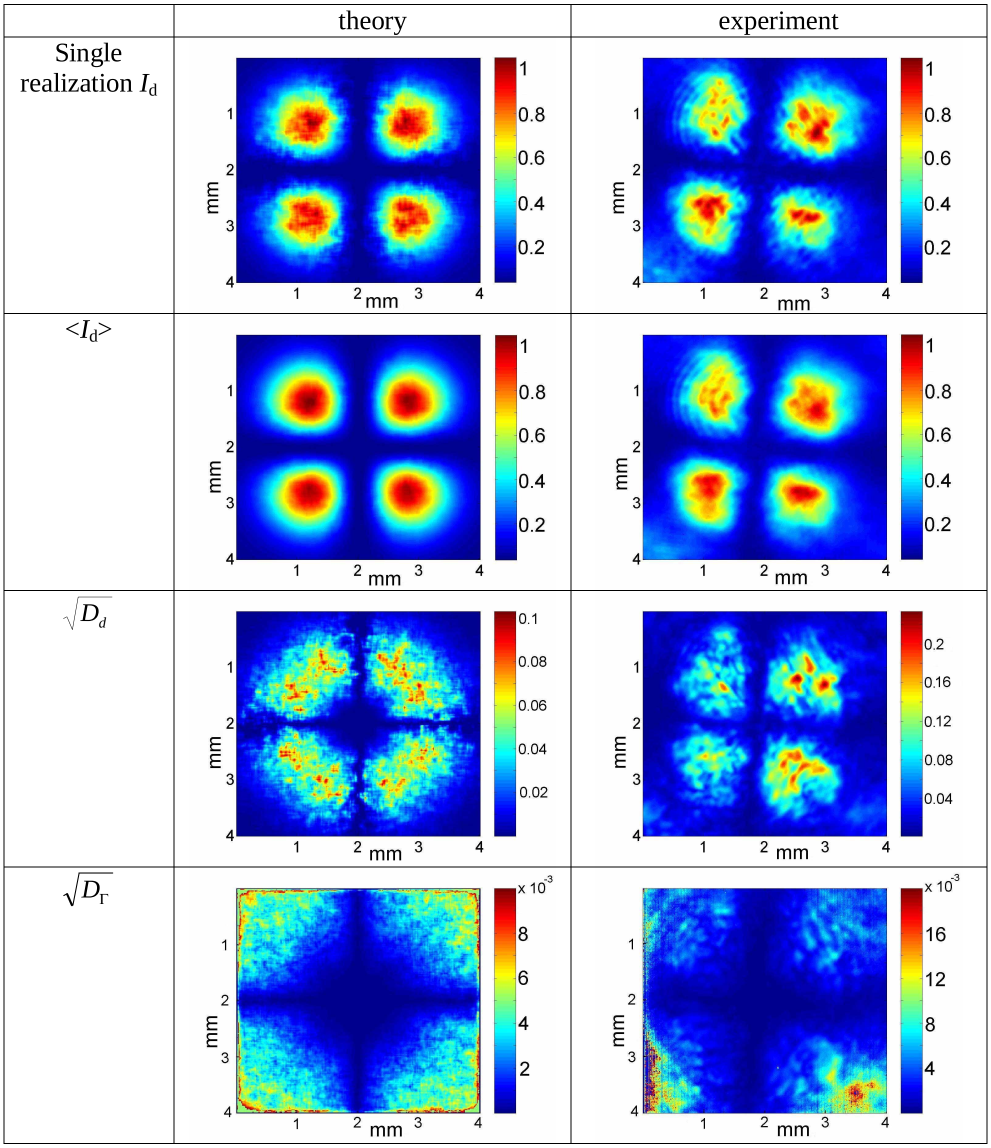

Fig. 2. Theoretical and experimental distributions I_d, $\langle I_d \rangle$, $\sqrt{D_d}$, $\sqrt{D_\Gamma}$.

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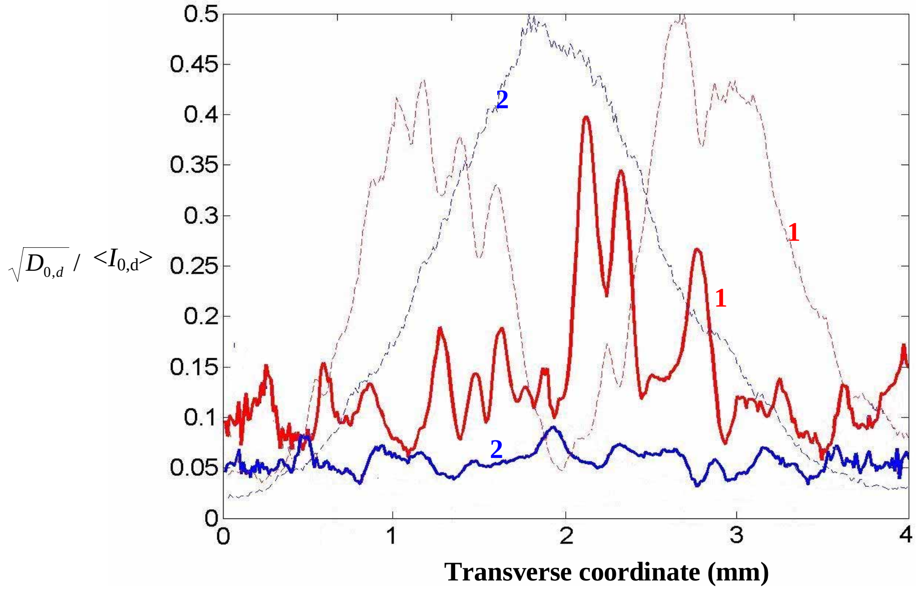

Fig. 3. Transverse distribution of root-mean-square deviation $\sqrt{D_d}$ / <I_d> of depolarized beam (1) and $\sqrt{D_0}$ / <I_0> of polarized beam (2). Dashed lines indicate intensity distributions I_d (1) and I_0 (2).

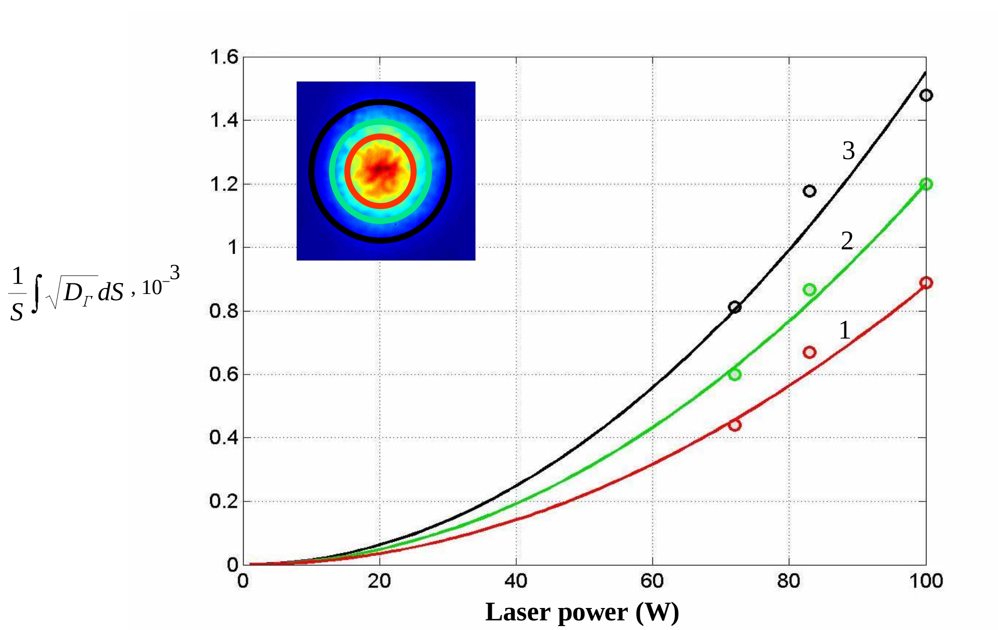

Fig. 4. Theoretical (curves) and experimental (points) dependences of $\sqrt{D_\Gamma}$ integrated over cross section on laser power for various integration domains. The integration domains have radii r_0 (1), 1.22 r_0 (2), and 1.41 r_0 (3) and are shown in the inset.

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