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Laser-induced anisotropy in terbium-gallium garnet

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Abstract. We observed that a $Tb_3Ga_5O_{12}$ crystal when illuminated at the terbium ion resonance, becomes optically uniaxial. The optical axis is found to be along the beam-propagation axis. The origin of this symmetry breakdown is a thermal effect. Our observation of a conoscopic pattern is accounted for by a quadratic stress and refractive index distribution model. By spatial integration of the conoscopic pattern, the laser-induced stress birefringence variation as a function of the incident beam power is determined.

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Thermal self-focusing and thermal birefringence attracted extensive studies in a solid-state amplifying medium, especially in Nd:YAG, because these effects set an intrinsic limitation to the generation of high-power fundamental transverse-mode laser beams [1–3]. Recently these effects have been found to be important in other types of materials such as electro-optic crystals, ceramics, and semiconductor-doped glasses, because they yield a complicated spatial pattern in the far-field image [4–6]. It has been reported [6] that an optically uniaxial crystal ($LiNbO_3$) may become biaxial under heating. Although numerous data concerning laser crystals may be found in the literature, for other types of materials only a few quantitative results are available. Our work on a $Tb_3Ga_5O_{12}$ crystal, a typical magneto-optical material revealed an optical symmetry breakdown under resonant illumination. The $Tb_3Ga_5O_{12}$ crystal has the point symmetry of $m\bar{3}m$, it belongs to the cubic system, which is optically isotropic. While it was illuminated strongly at the Tb^{3+} resonance, we observed self-focusing [7]. The refractive index becomes beam-power dependent. We report a phenomenon accompanying the self-focusing: a power-dependent polarisation distribution variation. We show a simple experimental arrangement which enables one to determine the laser-induced thermal stress birefringence. In cases where a high quality of polarisation and a beam shape is necessary, a good knowledge of this birefringence in the corresponding material becomes indispensable.

1 Experiment

The $Tb_3Ga_5O_{12}$ is illuminated with a cw Ar^+ laser operated at λ=488 nm with waist size 0.9 mm ($1/e^2$ radius). The beam power is varied with a halfwave plate and a polariser combination. A parallel plane cylindrical sample with radius $r_0 = 5$ mm and thickness $L = 3$ mm is placed between crossed polarisers. With increasing incident beam power (P), the dark field of view behind the second polariser becomes bright, leaving only a cross remaining darkened, the orientation of the cross being along the crossed polarisers. To record the transmitted beam pattern, a CCD camera acquires the image on a screen placed behind the second polariser. This information is transferred to an image monitor and a Macintosh computer, where all data are stored, processed, and analysed (Fig. 1). To measure the power dependence of the

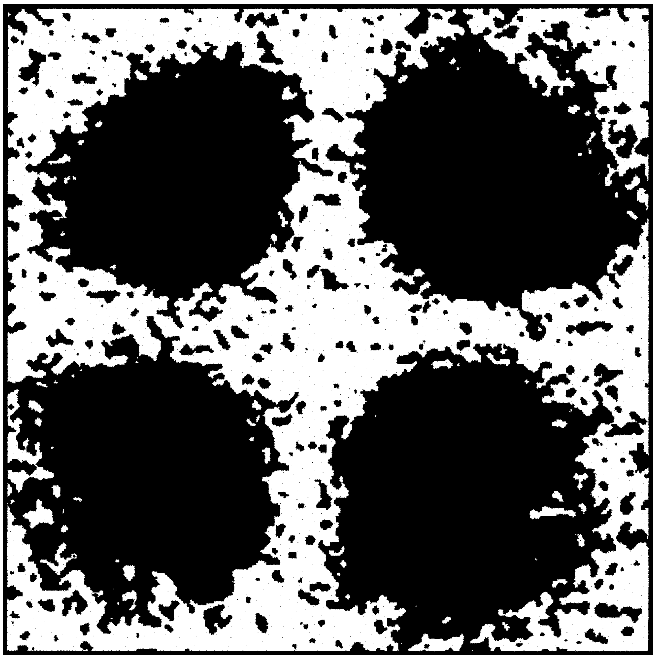

Fig. 1. Conoscopic pattern due to laser-induced stress birefringence in $Tb_3Ga_5O_{12}$

signal forming this conoscopic pattern, two photodiodes are used. One of them replaces the camera. It collects the whole light transmitted through the second polariser, we denote this signal P_c. The other one measures the input beam power. Both photodiode signals are fed to a digital oscilloscope. P_c is normalised to the total transmitted beam power at the exit face of the sample, i.e. before entering the second polariser. We denote this quantity as the relative transmitted intensity, I_{exp}. It is dimensionless. We will see in the following that this quantity is directly comparable to a theoretical integration. All measurements are carried out at room temperature. The process of the conoscopic pattern formation is found to be reversible. Figure 2 shows the relative transmitted intensity, I_{exp}, as a function of the beam power (P).

2 Analysis

As is shown in [7], when $Tb_3Ga_5O_{12}$ is excited to the resonance of the $^7F_6 \rightarrow {}^5D_4$ absorption line of Tb ions, the subsequent fluorescence populates the Tb^{3+} ground state sublevels $^7F_0$–$^7F_6$; these emissions in the visible and IR range are well known. The fraction of the absorbed optical power which is not converted into optical emission is conducted as heat to the sample.

As noted in the introduction, the $Tb_3Ga_5O_{12}$ presents a cubic symmetry, it is usually optically isotropic. We denote z as the light-propagation axis, and assume the initial polarisation parallel to the x axis. The dielectric constants of the medium are $\varepsilon_x = \varepsilon_y = \varepsilon_z$. When the exciting light power is low, the sample heating has neither a significant influence on the refractive index, nor on the crystal symmetry. It remains an isotropic medium. Experimentally we observed that a linearly polarised light beam passing through is stopped afterwards by a second crossed polariser, leaving a completely dark field of view.

With increasing beam power, the dark background is replaced gradually by a bright illuminated area with a dark cross whose arms are parallel to the directions of the polariser and the analyser. This pattern means that a distinguished direction is induced: the z direction, with which one dielectric principle axis ε_z coincides. We then have $\varepsilon_x = \varepsilon_y \neq \varepsilon_z$. The crystal becomes then optically uniaxial, similar to the case of a natural uniaxial crystal [8]. The z axis along the light propagation plays the role of the optical axis.

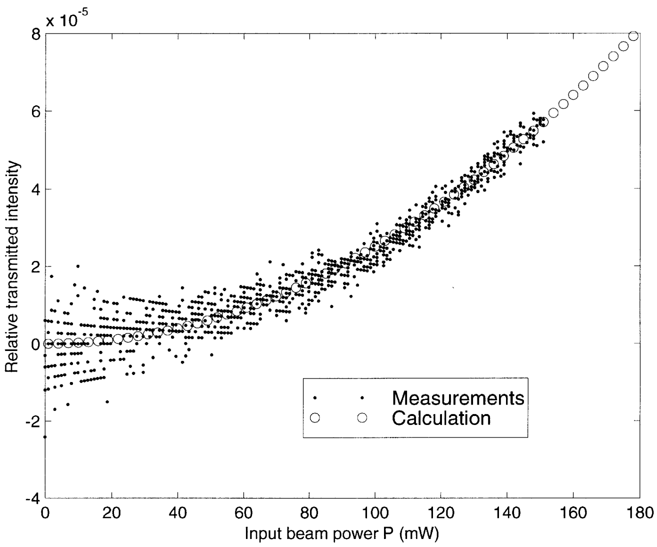

Fig. 2. Relative transmitted intensity as a function of the beam power. Open circles denote the result of our calculation, solid dots are our measurements

It is shown in [9] that in the case of cw operation a cylindrical rod with uniform internal heat generation and constant surface temperature presents a quadratic radial temperature dependence

$$T(r) = T(r_0) + (Q/4K)\ (r_0^2 - r^2) \quad , \tag{1}$$

where r_0 is the radius of the sample, $T(r_0)$ is the boundary condition, K is the thermal conductivity and Q is the heat generation rate per unit volume. This leads to a similar dependence in the index of refraction distribution. The change of the refractive index can be separated into a temperature- and a stress-dependent variation. The temperature-dependent change of refractive index as a function of radius r in $Tb_3Ga_5O_{12}$ is determined in [7]:

$$\Delta n(r) = -2.8 \times 10^{-6} n_0\, P\ \ (r/W_0)^2 \quad . \tag{2}$$

The stress-dependent change of refractive index is more complicated. In fact, the temperature gradient generates mechanical stresses in the material, since the hotter inside area is constrained from expansion by the cooler outer zone. The stresses in a cylindrical free sample caused by a quadratic temperature distribution turn out to be quadratic [9]. These stresses generate thermal strains in the rod, which in turn produce refractive index variations via the photoelastic effect.

Since $Tb_3Ga_5O_{12}$ is a cubic crystal, the indicatrix is a sphere. Under stress the indicatrix becomes an ellipsoid. We can chose a cylindrical coordinates system as described in [9], and the photoelastic changes in the refractive index are

$$\Delta n_r = -(\alpha Q/2K)\ n_0^3 C_r r^2 \quad , \tag{3}$$

$$\Delta n_\phi = -(\alpha Q/2K)\ n_0^3 C_\phi r^2 \quad , \tag{4}$$

where Δn_r and Δn_ϕ are due to the radial and tangential stress components. C_r and C_ϕ are functions of the elasto-optical coefficients of the material, n_0 is the linear refractive index at resonance wavelength, and α is the thermal expansion coefficient. The difference between them, which is called stress birefringence is then

$$\Delta n_r - \Delta n_\phi = (\alpha Q/K)\ n_0^3\ \ C_B r^2 \quad , \tag{5}$$

where C_B is a constant.

In cylindrical coordinates the principal axes of the induced birefringence are radially and tangentially directed at each point in the sample transverse section. The magnitude of the stress birefringence increases quadratically with radius. As a consequence, a linearly polarised beam passing through the sample will experience a phase difference between the two components along n_r and n_ϕ, respectively. Hence a polarisation change at each point of the transverse section, yields a spatial elliptical polarisation pattern, except for points located along the x and y axes, where the polarisation remains linear. Although this pattern is not random, in the literature it is frequently called a depolarisation [2, 9]. If one places a polariser with its polarisation oriented perpendicularly to the initial polarisation, then the transmitted intensity is

$$I = I_0\, e^{-\beta L}\, \sin^2 2\Phi\, \sin^2((\pi L/\lambda)(\Delta n_r - \Delta n_\phi)) \quad , \tag{6}$$

where Φ is the angle with respect to the initial polarisation and β is the absorption coefficient. By integrating over the cross-sectional area of the sample, the total transmitted intensity can be evaluated. When normalised to the absorption term, $I_0\, e^{-\beta L}$, one gets a dimensionless quantity, I_{th}, which has the same meaning as the experimental quantity I_{exp} defined previously. I_{th} has an analytical P-dependent expression

$$I_{th} = \frac{1}{4}\left(1 - \frac{\sin(C_T P)}{C_T P}\right) \quad , \tag{7}$$

where $C_T = 2n_0^3 \alpha C_B \eta / \lambda K$, η is the fraction of the power dissipated as heat in the sample. This theoretical function is shown together with $I_{exp}(P)$ in Fig. 2. Its agreement with the experiment is very satisfactory. This enables us to extract the value of C_T from the best fit: $C_T = (0.245 \pm 0.003)\ W^{-1}$. Consequently the difference between the radial and tangential refractive index change is

$$\Delta n_r - \Delta n_\phi = 0.245\, (\lambda/2\pi L)\, P\, (r/r_0)^2 \quad . \tag{8}$$

3 Conclusion

A laser-induced optical symmetry breakdown in terbium-gallium garnet has been observed. Our experimental results are in good agreement with a quadratic refractive index distribution model based on the quadratic temperature and a quadratic thermal stress-induced strain distributions. We have shown that the relative transmitted intensity, $I_{exp}(P)$, depends sensitively onto the beam power. Using a simple experimental arrangement, we determined the induced birefringence. Finally, we showed that the laser-induced thermal stress birefringence in $Tb_3Ga_5O_{12}$ in a cylindrical coordinates system at 488 nm is

$$\Delta n_r - \Delta n_\phi = 0.245\, (\lambda/2\pi L)\, P\, (r/r_0)^2 \quad .$$

with P measured in Watt.

The results of the present work explain why the magneto-optical applications of the $Tb_3Ga_5O_{12}$ at the resonance are complicated at high power [10]. The laser-induced symmetry change may lead to numerous interesting applications, for example, in the determination of the material characteristics concerning the heat conversion efficiency and the stress-induced strain coefficients. In addition, this effect can be used to determine the beam polarisation. Compared to natural uniaxial crystals, it is unnecessary to align the beam propagation and the optical axis because the optical axis is the propagation direction itself.

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References

1. S.D. Jackson, J.A. Piper: Appl. Opt. **35**, 1409 (1996)
2. H.J. Eichler, A. Haase, R. Menzel, A. Siemoneit: J. Phys. D: Appl. Phys. **26**, 1884 (1993)
3. G. Cerullo, S. de Silvestri, V. Magni, O. Svelto: Opt. Quantum Electron. **25**, 489 (1993)
4. D.V. Petrov, A.S. Gomes, C.B. de Araujo: Phys. Rev. B **50**, 9092 (1994)
5. T. Chen, S.-J. Sheih, J.F. Scott: Phys. Rev. B **43**, 259 (1991)
6. K. Fujishiro, T. Nakamura, M. Iida: Ferroelectrics **168**, 193 (1995)
7. X. Chen, B. Lavorel, T. Dreier, N. Genetier, H. Misserey, X. Michaut: accepted by Opt. Commun.
8. M. Born, E. Wolf: *Principles of Optics* (Pergamon, Oxford 1964)
9. W. Koechner: *Solid-State Laser Engineering*, 4th edn. (Springer, Berlin, Heidelberg 1996) pp. 393–409
10. X. Chen, B. Lavorel, J.P. Bocquillon, R. Saint-Loup, M. Jannin: accepted by Solid-State Electron.