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OPTICS AND LASER PHYSICS

Entrainment of Polaritons in Rotating Ruby

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A luminescent trace has been observed in a ruby crystal ($Al_2O_3 : Cr^{3+}$) that rotates at a frequency of 2 to 200 Hz and is irradiated by 532-nm coherent electromagnetic radiation. A method has been proposed to determine the lifetime of the excited electronic state of chromium ions from the measurement of the length of an arc of the trajectory of a light spot on the surface of a rotating ruby single crystal. A "comet trace" formed at the passage of radiation through the rotating crystal near the absorption band of the material has been detected inside the ruby crystal. It has been shown that the theory based on the analysis of the motion of polaritons in the rotating reference frame is in satisfactory agreement with experimental results.

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INTRODUCTION

Studies of the optical characteristics of moving media, beginning with Michelson's and Fizeau's experiments, concern the fundamental problems of physics regarding the principle of relativity and the speed of propagation of optical radiation in moving reference frames [1, 2]. These studies are also of applied significance for control of trajectories of spacecrafts and moving devices for their localization in space and establishment of the characteristics of motion. The investigation of characteristics of the propagation of light in noninertial reference frames, in particular, in rotating optically transparent bodies, is of particular interest. Such studies have been already performed in optical materials probed by laser radiation whose wavelength is far from the absorption bands [3–6]. The aim of this work is to study the optical characteristics in a rotating insulator probed by laser radiation whose wavelength is close to the absorption band of this insulator. In this case, the dispersion of the refractive index of the medium moving in a noninertial reference frame is very significant. We study a ruby single crystal characterized by the existence of intense luminescence in the red spectral range, as well as by the absorption and anomalous dispersion of the refractive index in the violet, green, and red spectral ranges [7–9].

EXPERIMENTAL

We studied oriented cylindrical ruby single crystals with a length of 5–8 mm and a diameter of 10 mm. The crystallographic c axis coincided with the z axis of rotation. The bases of a cylinder were polished and parallel to each other. The layout of the setup is shown in Fig. 1. A YAG laser generating the second optical harmonic (532.0 nm) and operating in the cw regime was used as a source of exciting radiation. Lens *2* focused laser radiation on rotating ruby disk *3* glued on the shaft on the electromotor. The secondary radiation appearing in the ruby was guided through lens *5* to color filter *6* and was focused in the plane of photodetector *7* (Spiricon BeamGage).

Focusing of radiation inside the ruby disk made it possible to enhance the observed effect of generation of polaritons. The color filter in front of the input of the photodetector was necessary for only radiation induced by the excitation of ruby atoms, rather than laser radiation, to reach the aperture of the photo camera. The 532-nm second optical harmonic of a YAG laser was used to excite the electronic state of chromium ions introduced into the ruby crystal matrix.

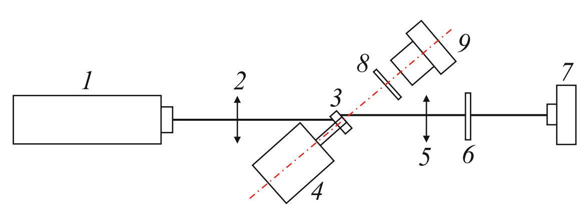

Fig. 1. (Color online) Layout of the experimental setup: (*1*) YAG garnet laser generating the second optical harmonic, (*2*) converging lens, (*3*) oriented ruby crystal disk, (*4*) electromotor, (*5*) converging lens, (*6, 8*) red filters, (*7*) photodetector (Spiricon BeamGage), and (*9*) digital camera.

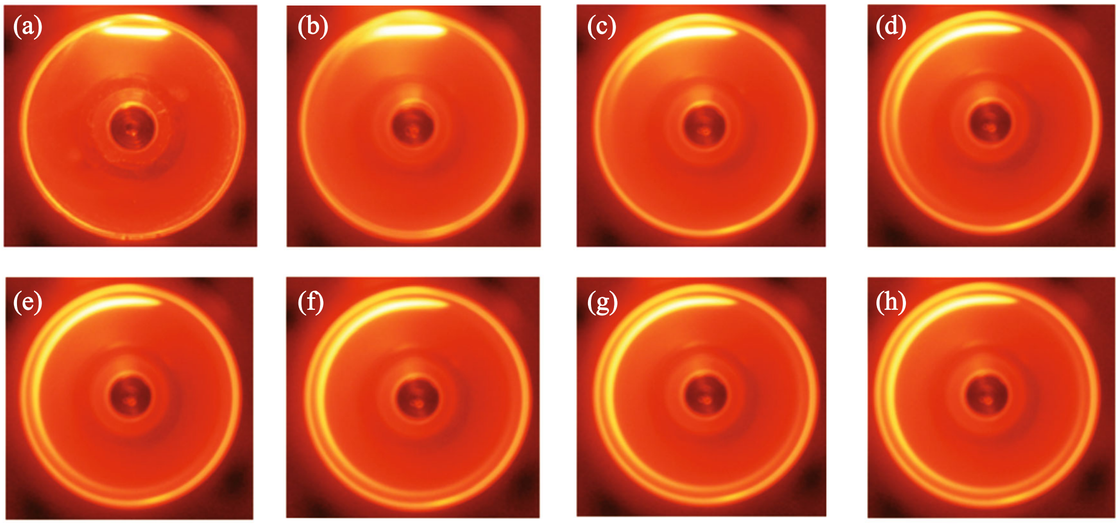

Fig. 2. (Color online) Images of the trajectory of a laser ray in the rotating ruby crystal at frequencies of rotation f = (a) 0, (b) 2.1, (c) 5.0, (d) 10.4, (e) 16.4, (f) 20, (g) 23.3, and (h) 40.0 Hz.

When green radiation of this laser passed through the ruby disk, the trajectory of red radiation inside the sample was observed, which was due to the luminescent properties of ruby [9]. In order to analyze the form of the trace of the focused laser ray on the surface of the rotating crystal, we photographed the front face of the crystal with digital camera *7*. The optical characteristics in rotating ruby were studied with a rotating device at frequencies of rotation from 2 to 200 Hz.

RESULTS OF STUDIES

Figure 2 shows the images of the trajectory of a laser ray in the rotating ruby crystal at various frequencies of rotation. As is seen in Fig. 2, the trajectory of light on the front surface of the crystal has the form of an arc whose length varied at the variation of the frequency of rotation of the crystal. It was revealed that the length of the arc trace of the laser ray on the surface of the rotating ruby crystal increased with the frequency of rotation. With a further increase in the frequency of rotation, the arc was transformed to a circle.

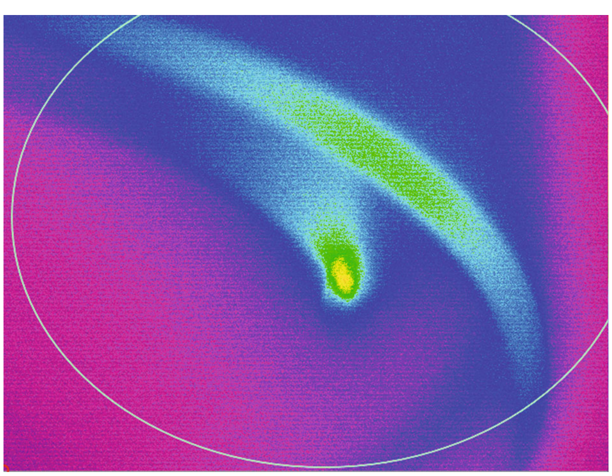

Fig. 3. (Color online) Image of the trajectory of a ray on the back surface of rotating ruby obtained on image sensor *7* (Fig. 1) at the frequency of rotation f = 83 Hz.

The photograph of the rotating ruby single crystal disk from the opposite side (Fig. 1) reveals a figure in the form of a “comet tail” (Fig. 3). The area of the comet tail increases with the frequency of rotation.

DISCUSSION OF THE EXPERIMENTAL RESULTS

The observed effect of formation of the trajectory of the ray in the form of an arc on the front surface of the sample (Fig. 2) is due to the finite lifetime of the impurity electronic state of the chromium ion excited in ruby crystals irradiated by green laser radiation (λ_r = 694.3 nm). According to experiments, the lifetime of atoms of the crystal lattice of ruby in the excited state (laser transition R_l) is about $\tau \approx 3.4$ ms [10]. The lifetime of such a state can also be estimated from experiments with a rotating ruby (Fig. 2). Within the model of the single ring application of radiation, the intensity of radiation at the point of incidence of the ray on the surface of the crystal is $I_1 = I_0(1 + \exp(-T/\tau))$, where I_0 is the intensity of laser radiation at the input of the crystal, T is the period of rotation of the disk, and τ is the lifetime of the excited state. Here, $I_0 \exp(-T/\tau)$ is the intensity of residual radiation after one turn of the crystal, i.e., after the time T. The intensity at another point of the light ring spaced in time by t from the point of incidence is $I = I_0 \exp(-t/\tau)(1 + \exp(-T/\tau))$. The life-

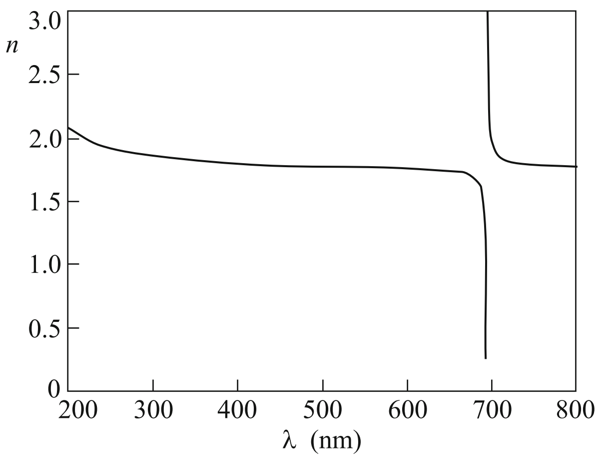

Fig. 4. Refractive index of ruby *n* versus the wavelength λ.

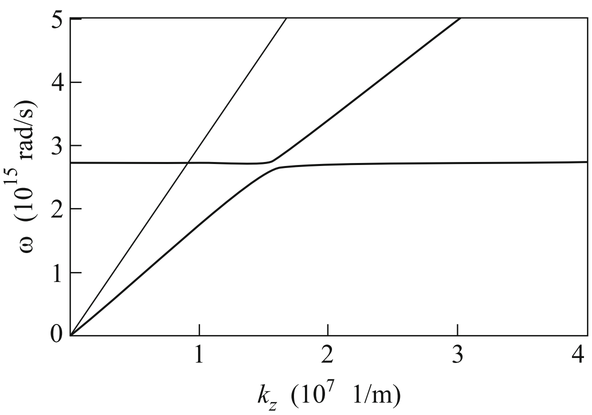

Fig. 5. Dispersion relation (3) for polaritons in the ruby crystal in comparison with (thin solid straight line) the dispersion relation for photons in vacuum.

time $\tau = t/\ln(I_1/I)$ can be determined by measuring I_1, I, and t. Substituting experimental data, we obtained $\tau_{\exp} \approx 5$ ms, which is close to the τ value obtained when studying the time characteristics of photoluminescence in ruby.

The formation of the comet tail (Fig. 3) at the rotation of the ruby disk can be attributed to the manifestation of the polariton effect [11–13]. In view of this circumstance, we present necessary information from the theory of polaritons concerning the $Al_2O_3:Cr^{3+}$ crystal under discussion. The quantum state corresponding to the excitation of an electron of the outer shell of the Cr^{3+} ion is manifested in the form of a sharp weak band in the absorption spectrum of ruby at a wavelength of 694.3 nm. The state under discussion is metastable and is characterized by a very small oscillator strength. The equation of motion of the valence electron in the field of an electromagnetic wave can be represented in the form

$$\ddot{u}_x = -\omega_r^2 u_x + eE_x. \tag{1}$$

Here, u_x is the displacement of the valence electron from the position of equilibrium, $\omega_r = 2\pi c/\lambda_r$ is the frequency of the resonance transition corresponding to the wavelength $\lambda_r = 694.3$ nm, e is the elementary charge, and E_x is the x component of the electric field strength. The z axis of the rotation of the ruby crystal coincides with the crystallographic axis c of this crystal.

The solution of Eq. (1) in the form of monochromatic plane waves $E_x = E_x^{(o)} \exp i(k_z z - \omega t)$ together with Maxwell's equation leads to the following expression for the square of the refractive index of the medium:

$$n_x^2(\omega) = \varepsilon_x(\omega) = \varepsilon_\infty \left(\frac{\omega_l^2 - \omega^2}{\omega_0^2 - \omega^2}\right)\left(\frac{\omega_{lr}^2 - \omega^2}{\omega_{0r}^2 - \omega^2}\right). \tag{2}$$

Here, both the dispersion properties of the aluminum oxide matrix (the first factor) and resonance from Cr^{3+} particles (second parentheses) are taken into account. In Eq. (2), $\varepsilon_\infty = 1$ is the high-frequency dielectric constant of the material, $\omega_l = 2\pi c/\lambda_l$ is the frequency of the LO mode for aluminum oxide (λ_l = 70 nm), $\omega_0 = 2\pi c/\lambda_0$ is the frequency of the electron resonance in pure Al_2O_3 ($\lambda_0 = 120$ nm [14]), and $\omega_{0r} = 2\pi c/\lambda_{0r}$ and $\omega_{lr} = 2\pi c/\lambda_{lr}$ are the frequencies of resonance transitions in ruby ($\lambda_{lr} = 692.8$ nm and $\lambda_{0r} = 694.3$ nm).

The wavelength dependence of the refractive index $n(\omega)$ of ruby calculated from Eq. (2) is shown in Fig. 4. The dispersion law $\omega(k_z)$ for polariton waves in ruby in the region of resonance of chromium ions is implicitly determined by the relation

$$\omega^2 = \frac{c^2 k_z^2(\omega)}{\varepsilon_x(\omega)}. \tag{3}$$

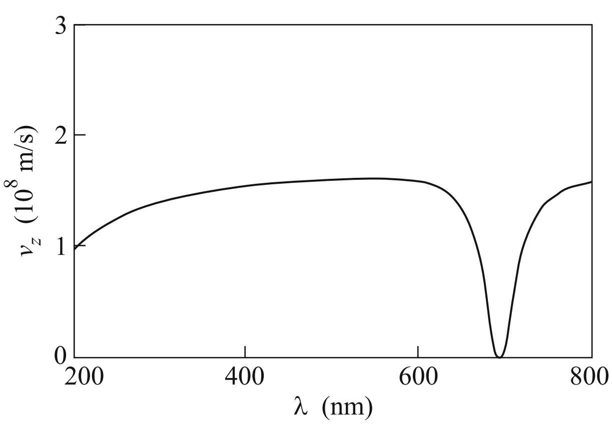

Fig. 6. Wavelength dependence of the group velocity of polariton waves.

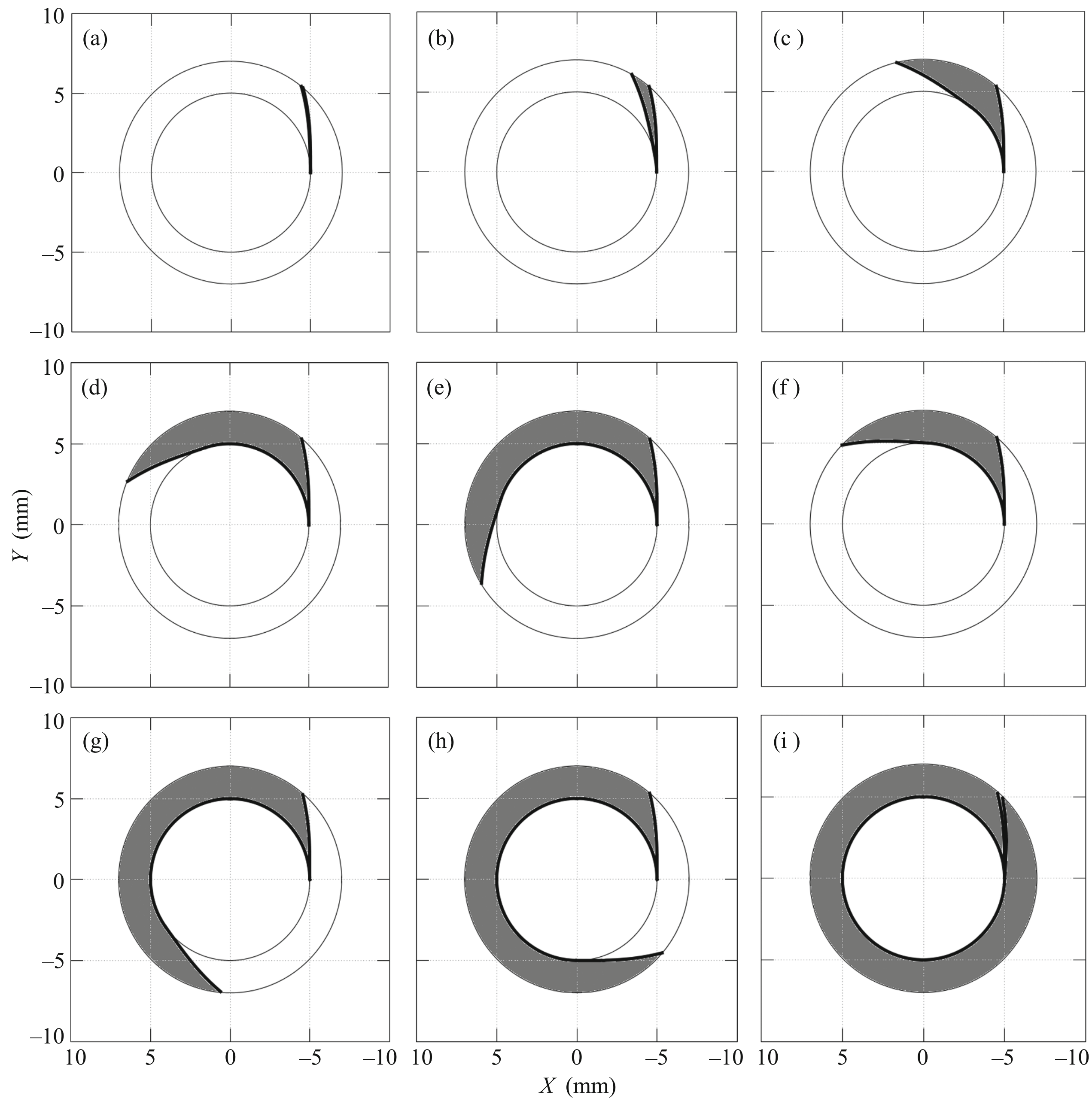

Fig. 7. Calculated trajectories of “traces” of the motion of polaritons at various frequencies of rotation of the disk: (a) 1, (b) 10, (c) 50, (d) 80, (e) 100, (f) 150, (g) 200, (h) 250, and (i) 330 Hz.

The dispersion curves $\omega(k_z)$ for polaritons in a wide spectral range are shown in Fig. 5.

The group velocity dispersion $V_z(\omega)$ for polariton waves in ruby can be obtained from the dispersion law of polaritons given by Eq. (3):

$$V_z(\omega) = \left(\frac{dk_z(\omega)}{d\omega}\right)^{-1}. \quad (4)$$

The wavelength dependence of the group velocity of polaritons calculated by Eq. (4) is shown in Fig. 6. As is seen in this figure, polaritons appearing because of the excitation of the electronic transition in chromium ions in ruby at the frequency ω_r (λ_r = 694.3 nm) are characterized by an extremely low velocity in the rotating reference frame: $V_x \approx 0$, $V_y \approx 0$, $V_z \approx 0$. The law of motion of polaritons appearing inside the rotating ruby crystal at the distance ρ from the axis of rotation in the laboratory reference frame has the form

$$m\frac{d^2\rho}{dt^2} = m\omega^2\rho; \quad \frac{d\varphi}{dt} = \omega. \quad (5)$$

Here, ρ is the radial coordinate of a quasiparticle and ω is the frequency of rotation of the reference frame. In view of the condition of the uniformity of rotation of the disk, the solutions of differential equations (5) have the form

$$\rho(t) = \frac{1}{2}\rho(0)[\exp \omega t + \exp(-\omega t)];$$
$$\varphi(t) = \omega t + \varphi_0. \quad (6)$$

It is necessary to take into account that electron–polariton conversion occurs at any point of the trajectory of the disk according to the lifetime of the electron in the excited state. Therefore, the trace of the laser ray in the form of a finite annular band is observed inside the ruby crystal. According to calculations, at an increase in the frequency of rotation of the disk, this band is transformed to a ring, as is shown in Fig. 7. In this case, a family of curves joining in a continuous comet tail should be observed in the experiment. The trajectories of the laser ray calculated from Eq. (6) are shown in Fig. 7 for various frequencies of rotation of the ruby disk at the focusing of the laser ray at a distance of 5 mm from its axis.

The comparison of the theoretical predictions shown in Fig. 7d with the experimental results at the frequency of rotation of the disk of 83 Hz shown in Fig. 3 indicates satisfactory agreement.

The experiments with the rotating ruby crystal are generally in good agreement with the theory of luminescence, are consistent with the current concepts of theory of polaritons, and open new possibilities for the study of optical effects in moving media in the region of anomalous dispersion of crystals, where the velocity of polariton waves is extremely low.

CONCLUSIONS

To summarize, the experimental studies of traces of photoluminescence in the ruby single crystal rotating at frequencies from 2 to 200 Hz have established the form of the trajectory of the laser spot on the input surface of the rotating crystal, as well as the form of traces of luminescence inside the bulk of the crystal. Depending on the frequency of rotation of the ruby sample, the trajectory in the form of a finite arc has been observed on the front surface of the rotating crystal. The length of the arc trajectory on the front surface of the crystal depends on the frequency of rotation. At high frequencies of rotation, the arc is transformed to a circle. Thus, the frequency of rotation of the object can be determined from the length of the luminescent trace on the front surface of the crystal.

The lifetime of the electronic state excited by short-wavelength radiation has been estimated from the data thus obtained in satisfactory agreement with the existing experimental data. As a result, a method has been proposed to determine the lifetime of the excited electronic state of luminescent media from change in the shape and intensity of the luminescent trajectory on the front surface of the crystal.

A comet trace has been revealed in photographs of the inner region of the rotating crystal. It has been shown that the calculated shape of the trajectory of the laser ray in the bulk of the rotating ruby crystal is in qualitative agreement with the observed shape. The established properties of the trajectory of luminescence in ruby crystals can be used to develop new methods of navigation and control of the characteristics of devices moving at a variable velocity.

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REFERENCES

1. M. Born and E. Wolf, *Principles of Optics. Electromagnetic Theory of Propagation, Interference and Diffraction of Light,* 7th ed. (Cambridge Univ. Press, Cambridge, 2003), p. 11.
2. *Universe of General Relativity, Einstein Studies,* Ed. by A. J. Kox and J. Eisenstaedt (Birkhauser, Boston, Bazel, Berlin, 2005), Vol. 11, p. 6.
3. E. Wisniewski-Barker, G. M. Gibson, S. Franke-Arnold, R. W. Boyd, and M. J. Padgett, Opt. Express **22**, 11690 (2014).
4. J. B. Götte, S. M. Barnett, and M. Padgett, Proc. R. Soc. London A **463**, 2185 (2007).
5. V. O. Gladyshev, P. S. Tiunov, A. D. Leont'ev, T. M. Gladysheva, and E. A. Sharandin, Tech. Phys. **57**, 1519 (2012).
6. V. O. Gladyshev, D. I. Portnov, V. L. Kautz, and E. A. Sharandin, Opt. Spectrosc. **115**, 349 (2013).
7. T. H. Maiman, Nature **187**, 493 (1960).
8. T. H. Maiman, Phys. Rev. Lett. **4**, 564 (1960).
9. V. S. Gorelik, B. G. Skuibin, N. A. Khusainov, and A. S. Borde, Vestn. Mosk. Tekh. Univ. Baumana, Estestv. Nauki, No. 5, 32 (2014).
10. V. L. Levshin and A. M. Saletskii, *Luminescence and Its Measurements* (Mosk. Gos. Univ., Moscow, 1989) [in Russian].
11. O. S. Litvinov and V. S. Gorelik, *Electromagnetic Waves and Optics,* Ser. Physics in Technical University (Mosk. Gos. Tekh. Univ. im. N. E. Baumana, Moscow, 2006), p. 297 [in Russian].
12. V. S. Gorelik and M. G. Burdanova, Vestn. Mosk. Tekh. Univ. Baumana, Estestv. Nauki, No. 2, 90 (2014).
13. V. S. Gorelik and P. P. Sverbil', Inorg. Mater. **51**, 1104 (2015).
14. M. J. Dodge, *Handbook of Laser Science and Technology,* Vol. 4: *Optical Materials* (CRC, Boca Raton, 1986), Part 2, p. 30.

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