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LASERS AND THEIR APPLICATIONS

Variation of Optical Characteristics of Polarized Laser Radiation in Dielectric upon Its Low-Frequency Rotation and Heating

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Abstract—The results of experiments in which coherent laser radiation with wavelength $\lambda = 0.632991$ μm experienced rotation of its plane of polarization, beam deviation, and change of intensity after propagating through an optical disk made of TF3 glass with refractive index $n = 1.71250$ and glued to a gyromotor, are discussed. The experiments were conducted at angle of incidence of the beam on a flat surface of the optical disk $\vartheta_0 = 60°$. The rotational frequency of the disk was varied from 2 to 10 Hz for two directions of rotation. At low speed of rotation, the main factor causing mechanical deformations and, as a result, changes in optical characteristics of radiation propagated through the optical disk is heating of the metal–glass interface.

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Methods of defectoscopy, where mechanical stress in the material is determined by measuring the angle of rotation of the plane of polarization of radiation propagated through the sample, are well known. There is also the opposite challenge of modulating optical properties by means of mechanical stress. However, inducing controlled mechanical stress of large amplitude is rather difficult [1, 2].

The effects of rotation of the plane of polarization of laser radiation and birefringence appearing in an optical glass rotating with a frequency of up to 200 Hz were discovered in [3]. It was demonstrated that the discovered phenomena nonlinearly depend on the rotational speed of the disk at rotational frequencies below 100 Hz. In addition, for steady-state rotational frequency f, anisotropy of optical properties is characterized by relaxation time $\tau = 10^2...10^3$ s. The evolution of optical properties of a dielectric in the range of rotational frequencies below 10 Hz occurs relatively slowly [4], which requires additional investigation.

In the present work, we conducted detailed studies of the angle of rotation of the plane of polarization of laser radiation, ellipticity, depolarization, variation brightness of the light beam, and angular deviation of the light rays propagated through a rotating plane-parallel plate made of TF3 glass. The measurements were conducted in the region of infralow rotational frequencies with long signal integration time and under conditions in which temperatures of the electromotor surface and disk were controlled. Measurements were conducted with the help of a setup in which mechanical stress is used for controlling optical properties of coherent electromagnetic radiation (Fig. 1).

Radiation from power stabilized laser L was passing though polarization turret P that allowed selecting single-frequency radiation with polarization vector oriented either horizontally or vertically from two orthogonally polarized components of the laser radiation. After that, radiation propagated through optical disk D glued to gyromotor G that enabled disk rotation at a given rotational frequency f. The beam emerging from the disk was propagating through analyzer A that allowed measuring the angle of rotation of the plane of polarization. Part of the radiation was reflected from mirror M that could be rotated in two planes into the arm designed for controlling parameters of the radiation, where it was scattered from lens DL and was incident on photodetection system S. A fast phototransistor was used as a detector. The signal from the phototransistor was fed into a broad-band amplifier, followed by a 12-bit ADC connected to a personal computer. The optical disk was set into rotational motion by a three-phase asynchronous motor G, the rotational frequency of which was controlled by VDF-EL Micro Type Drive (Delta Electronics).

In the experiments, we used a stabilized cw He–Ne laser LGN-302 with an output power of 0.7 mW in each polarization component.

The angle of rotation of the plane of polarization was determined from the angle of rotation of analyzer A. At the beginning of the experiment, the orientation of the axis of analyzer A was set perpendicular to that of polarizer P, which minimized intensity of the signal transmitted by the combination of the polarizer and analyzer to the photodetector. In the course of the

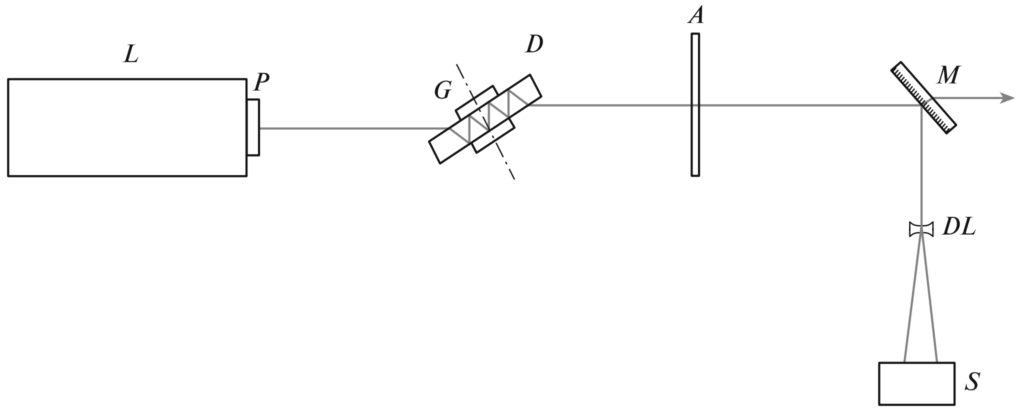

Fig. 1. Optical layout of the experiment.

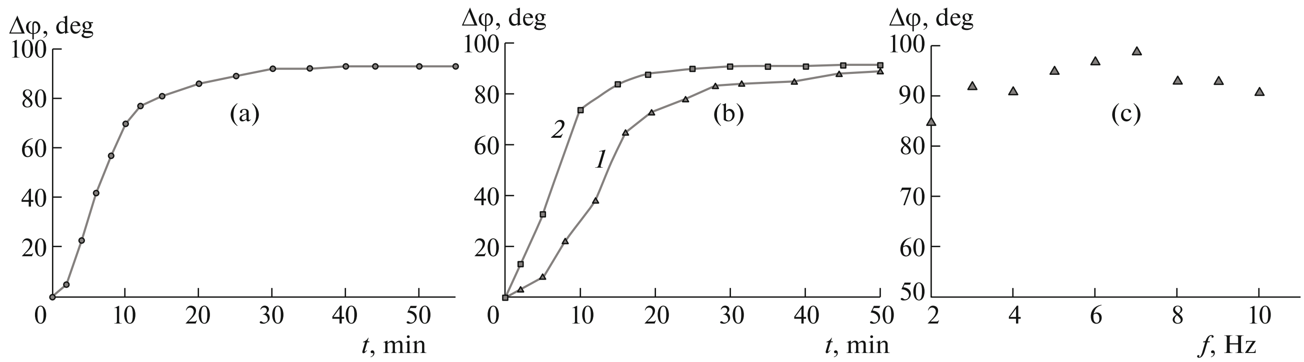

Fig. 2. Experimental time dependence of the angle of rotation of the plane of polarization for horizontal input polarization obtained for rotational frequency of the disk equal to (a) 8 and (b, curve *1*) 1.6 Hz and (b, curve *2*) without rotation; (c) the angle of rotation of the plane of polarization vs. rotational frequency of the disk.

experiment, orientation of analyzer *A* was adjusted to keep transmitted signal at minimum.

The experimental dependences of the angle of rotation of the plane of polarization on time and rotational speed in the region of infra-low rotational frequencies of disk *D* are illustrated in Fig. 2. The transient process of rotation of the plane of polarization recorded at the frequency of rotation equal to 8 Hz is shown in Fig. 2a. The first point on the graph corresponds to the moment of time when gyromotor *G* was set in motion. It can be seen from the plot that the angle of rotation of the plane of polarization reached 93°, while the transient process lasted about 40 min.

Experimentally, it was established that, at low rotational frequencies, modification of the optical properties of glass was weakly dependent on the speed of rotation. Figure 2b depicts the time dependence of the angle of rotation of polarization at rotational frequency of 1.6 Hz (curve *1*) and in the absence of rotation (curve *2*). In the second case, the electric power supplied to the gyromotor was the same as in the first case, but the gyromotor was not moving. It can be seen from comparison of the plots that rotation of polarization occurred slower when the gyromotor with the attached disk was rotating, which can be explained by conversion of part of the electric energy supplied to the motor into mechanical energy and by natural cooling. When the disk was stationary, all electric energy was converted to heat and the influence of stressed state of the material on polarization revealed itself more quickly.

In the course of the experiments, we also measured transient rotation of the plane of polarization in the frequency interval from 2 to 10 Hz in 1-Hz steps and plotted the dependence of the angle of rotation of the plane of polarization on rotational frequency of the disk (Fig. 2c) under steady-state conditions. The lower boundary of the frequency interval was limited by the lowest possible rotational speed of the motor.

It should be noted that, in the entire range of rotational frequencies, the rotation of the plane of polarization was close to 90°. The fact that the effect did not diminish rapidly when the rotational frequency was approaching zero can be explained by an increase in current running in the gyromotor windings, which caused an increase in its temperature. As a result,

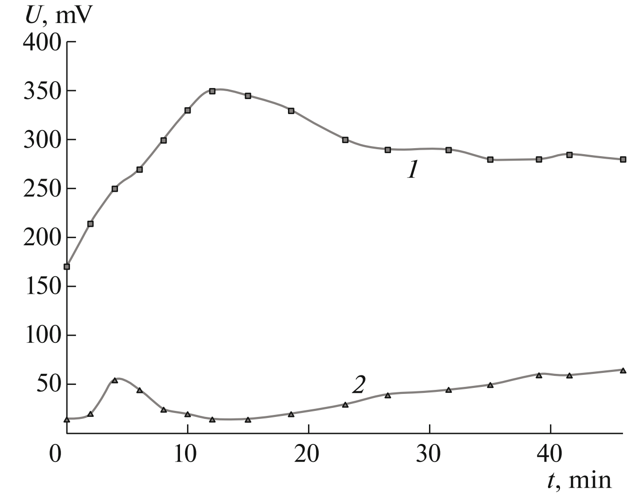

Fig. 3. Voltage across the photodetector as a function of time for (*1*) parallel and (*2*) perpendicular relative orientation of the axes of analyzer *A* and polarizer *P*.

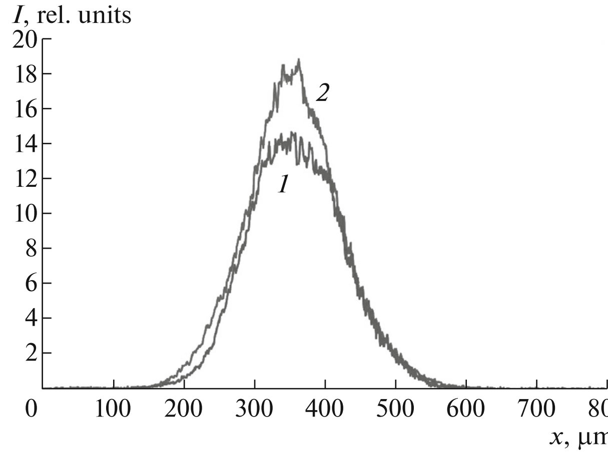

Fig. 4. The dependence of laser radiation intensity in the photodetection plane on coordinate x for a (*1*) stationary and (*2*) rotating disk.

dielectric that was in contact with the metal surface of the gyromotor was brought into a stress state.

Further measurements allowed us to conclude that the angle of rotation of the plane of polarization was independent of the component of polarization chosen at the output of laser *L* and on the direction of disk rotation.

Thus, nonlinear dependence $\Delta\varphi(f)$ in the range of rotational frequencies of up to 100 Hz can be explained by stress in the glass induced by heating. With increasing rotational frequency, the current decreases, the heat dissipation due to convective cooling of the rotating rotor of the motor increases, thus reducing heating of the disk. As a result, stress in the glass and anisotropy of optical properties decrease. At rotational speeds above 100 Hz, other elastic properties of glass caused by its rotation start revealing themselves, which leads to modification of the $\Delta\varphi(f)$ dependence [3, 4].

In addition to effects related to rotation of the plane of polarization, in the course of experiments, we also discovered the effect of angular deviation of the laser beam in vertical plane. The magnitude of the deviation in entire range of infra-low frequencies was 0.075°–0.077°. Similarly to the rotation of the plane of polarization, the effect turned out to be independent of the chosen component of polarization at the output of laser *L* and the direction of disk rotation.

It was found in the experiment that transient processes in glass material are accompanied by transformation of linearly polarized radiation into elliptically polarized radiation. To investigate changes of the state of polarization of the laser radiation, we obtained time dependences of voltage across the photodetector, which appears upon incidence of radiation on the photodetector for both parallel and perpendicular positions of the polarizer and analyzer axes (Fig. 3). The results are presented for rotational frequency of the disk equal to 9 Hz, and the measurements were performed in the brightest spot of radiation scattered from lens *DL*, i.e., its center.

In so doing, we can assume that intensity of the radiation is proportional to voltage across photodetector *S*.

It can be seen from the diagrams that the degree of ellipticity of the radiation was the highest during the first minutes of the experiment. By the tenth minute, radiation became linearly polarized. After that, the component of intensity induced by depolarization started to increase with time almost linearly.

It can be seen from curve *1* that the intensity of the signal that passed through polarizer *P* and analyzer *A* for parallel orientation of their axes was changing. We hypothesized that the laser spot in the plane of detector *S* could experience focusing (shrinking) due to mechanical deformations of disk *D* induced by the increase in temperature. To exclude the possibility of the influence of focusing, photodetector *S* was replaced by the Spiricon beam profiler, which allowed making an unambiguous conclusion whether this effect was present. The obtained distributions of radiation intensity across the spot of light are presented in Fig. 4.

It follows from Fig. 4 that radiation intensity within the spot of light in the localization plane, i.e., on the light-sensitive matrix of the photodetector, was changing. In so doing, the shape of intensity distribution across the spot of light did not change, which, in the first approximation, indicates the absence of beam focusing (shrinking). Apparently, the observed variation of intensity was caused by decreased losses of radiation upon propagation in the disk when the latter was heated.

The nonlinear dependence of the angle of rotation of the plane of polarization and other optical properties of radiation propagated through the optical disk on rotational frequency [3] in the low-frequency region can be explained within the framework of the thermoelastic model. Currents flowing in the windings of electric motor *G* cause an increase in its temperature, which results in an increase of linear dimensions of the motor and heat transfer to optical disk *D* that is in contact with the motor. The thermal expansion coefficient for steel from which the gyromotor is fabricated is $\alpha = 1.2\times10^{-5}$ K^{-1}, whereas the corresponding coefficient for glass is $\alpha = 9\times10^{-6}$ K^{-1} [5]. This problem becomes particularly important at infra-low frequencies, where the speed of the incoming air flow is low, so that it cannot cool the rotating system. One can assume that the growth of anisotropy of optical properties of glass in the low-frequency region is caused by growing stress in the glass induced by increasing temperature of parts of the disk adjacent to gyromotor *G*.

The dependence of the refractive index of material on wavelength and temperature has the form [5]

$$n_T = n_R + (T - R)\left(\frac{dn}{dT}\right)_{\text{smoothed}}, \qquad (1)$$

where T is the temperature of the material, R is the room temperature, n_T and n_R are the refractive indices at temperatures T and R, respectively, and dn/dT is the thermo-optical coefficient.

Expression (1) allows one to determine the effect of variation of the refractive index of the disk made of heavy flint glass from the experimentally obtained temperature data. The thermo-optical coefficient of TF3 glass in the temperature range between 20 and 120°C is $dn/dT = 57\times10^{-7}$ K^{-1} [6]. Assuming that the refractive index at room temperature is $n_R = 1.71250$, for a temperature change of about 20°C during the measurements, we obtain $n_T = 1.71261$. The change of $\Delta n = 10^{-4}$ is too small to explain the observed optical phenomena.

It is known that the duration of the transient phase of rotation of the plane of polarization increases with decreasing frequency [3, 4]. Therefore, we conducted long-term measurements of heating and cooling of disk *D* and motor *G* on the time scale corresponding to the time of transient rotation of the plane of polarization. Figure 5 shows the corresponding results of measuring the temperature of the disk surface and the gyromotor, which were rotated with rotational frequency of 8 Hz for 1 h before being stopped.

It follows from the plots that, during rotation, the temperature of gyromotor *G* increased by 20°C, while that of the disk increased by 14°C. Note that the disk and the gyromotor did not experience substantial heating at high rotational frequencies.

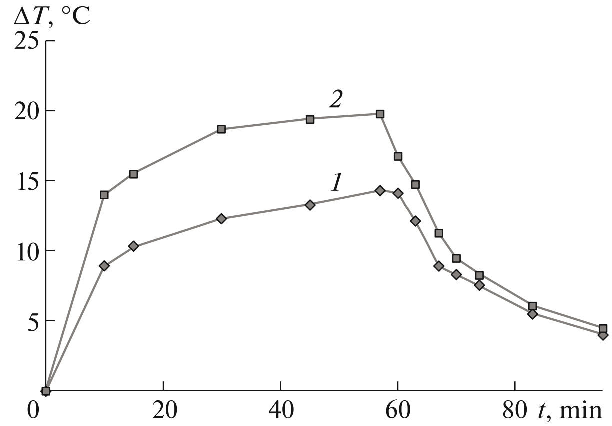

Fig. 5. Experimental time dependence of the change of (*1*) disk temperature and (*2*) motor temperature for rotational frequency of the disk equal to 8 Hz.

In addition, heating of the disk alone by 20°C did not lead to any noticeable changes in optical properties of the glass, as seen from polarization of laser radiation propagated through the stationary disk.

Nevertheless, these results allow making a conclusion about the necessity of taking into consideration the influence of temperature factor when studying the effects occurring in optical disk *D* glued to rotating with infralow frequencies gyromotor *G*.

To calculate stress in the optical disk, let is approximate the gyromotor by a stainless steel cylinder that is tightly inserted into a hole in a disk made of TF3 glass. Since the temperature coefficient of linear expansion of steel is larger than that of glass, the steel disk will apply pressure to the glass disk. For sake of determination, let us assume that both disks are heated by 15°C.

The mechanical stress and deformations of a circular disk are described by the expressions [7]

$$\sigma_\tau^r = \frac{p_1 r_1^2 - p_2 r_2^2}{r_2^2 - r_1^2} \mp \frac{r_1^2 r_2^2}{r^2}\frac{p_1 - p_2}{r_2^2 - r_1^2}, \qquad (2)$$

$$u = \frac{(1-\mu)}{E}\frac{(p_1 r_1^2 - p_2 r_2^2)}{r_2^2 - r_1^2} r + \frac{(1+\mu)}{E}\frac{r_1^2 r_2^2}{r}\frac{p_1 - p_2}{r_2^2 - r_1^2} - \frac{\mu r}{E}\sigma_z, \qquad (3)$$

where σ_r, σ_τ, and σ_z are the radial, the circumferential, and the axial stress, respectively; p_1 and p_2 are the values of pressure at the inner and outer surfaces of the disk, respectively; E is the Young's modulus; and μ is the Poisson ratio.

The upper sign in expression (2) corresponds to the upper index, while the lower sign corresponds to the lower index.

For a stainless steel disk, $r_1 = 0$, $r_2 = a$, $p_2 = p_a$, $\sigma_z = 0$.

For a glass disk, $r_1 = a$, $r_2 = b$, $p_1 = p_a$, $p_2 = 0$, $\sigma_z = 0$.

Hence, for a steel disk,

$$\sigma_{1r} = -p_a, \tag{4}$$

$$u_1 = -\frac{(1-\mu_1)}{E_1} p_a a^2 r. \tag{5}$$

For a glass disk,

$$\sigma_{2r} = \frac{p_a a^2}{b^2 - a^2} - \frac{a^2 b^2}{r^2}\frac{p_a}{b^2 - a^2}, \tag{6}$$

$$u_2 = \frac{(1-\mu_2)}{E_2}\frac{(p_a a^2)}{b^2 - a^2} r - \frac{(1+\mu_2)}{E_2}\frac{a^2 b^2}{r}\frac{p_a}{b^2 - a^2}. \tag{7}$$

The external radius of a stand-alone steel disk should expand by $\alpha_1 a\Delta T$ upon a temperature increase by ΔT, while the external radius of a stand-alone glass disk should expand by $\alpha_2 a\Delta T$. When the disks are glued together, their radii increase by $\alpha_1 a\Delta T + u_1(a)$ and $\alpha_2 a\Delta T + u_2(a)$, respectively, where $u_1(a) < 0$ and $u_2(a) > 0$, because $\alpha_1 > \alpha_2$.

Equating the changes of radii to each other, with (5) and (7), we obtain the expression that allows finding p_a:

$$p_a = \frac{(\alpha_2 - \alpha_1)\Delta T}{\frac{(1-\mu_1)}{E_1} + \frac{(1-\mu_2)a^2 + (1+\mu_2)b^2}{E_2\left(b^2 - a^2\right)}}. \tag{8}$$

Let us choose the following data for estimates: for stainless steel, $\alpha_1 \approx 10^{-5}$ K^{-1}, $E_1 = 2 \times 10^{11}$ Pa, $\mu_1 \approx 0.3$ [2]; for TF3 glass, $\alpha_2 = 5 \times 10^{-6}$ K^{-1}, $E_2 = 5.5 \times 10^{10}$ Pa, and $\mu_2 \approx 0.221$ [6].

Substituting $\Delta T = 30$ K, $a = 17$ mm, and $b = 40$ mm, we find that $p_a = 4 \times 10^6$ Pa. The mechanical stress of the glass disk can be found from (2):

$$\sigma_r = \frac{p_a a^2}{b^2 - a^2} - \frac{a^2 b^2}{r^2}\frac{p_a}{b^2 - a^2}, \tag{9}$$

$$\sigma_\tau = \frac{p_a a^2}{b^2 - a^2} + \frac{a^2 b^2}{r^2}\frac{p_a}{b^2 - a^2}. \tag{10}$$

For $r = 33$ mm (7 mm from the disk edge), we have $\sigma_r = -4 \times 10^5$ Pa and $\sigma_\tau = 2.2 \times 10^6$ Pa, while, for $r = 40$ mm (disk edge), $\sigma_r = 0$ and $\sigma_\tau = 1.8 \times 10^6$ Pa.

According to [8], the difference of refractive indices for ordinary and extraordinary rays is

$$n_e - n_o = B(\sigma_\tau - \sigma_r), \tag{11}$$

where B is the stress optical coefficient that, according to [6], has a value of 1.8×10^{-12} Pa^{-1} for TF3 glass. Thus, in our case, $n_e - n_o \approx 4 \times 10^{-6}$.

The angle of incidence of the laser beam on flat surface of the disk is 60° (Fig. 1). The angle of refraction ϑ_2 is close to 30°. The disk thickness is $d_1 =$ 10 mm. The beam experiences six reflections from the flat mirror surfaces, thus propagating distance $l = \frac{7d_1}{\cos\vartheta_2} = 80.8$ mm.

Using a simple model, let us determine the geometrical path length that the beam has to propagate through the disk material to have its plane of polarization rotated by 90°. We assume that the beam is incident perpendicular to the disk surface and propagates in the disk without experiencing multiple reflections. The difference $n_e - n_o$ in the disk is the same along entire beam path and is equal to 4×10^{-6}. The angle between the plane of polarization and the principal plane is 45°.

The phase difference of the ordinary and extraordinary rays is

$$\delta = \frac{(n_e - n_o)d}{\lambda_0} 2\pi. \tag{12}$$

In our case ($\lambda_0 = 0.63 \times 10^{-6}$ m, $\delta = \pi/2$), we estimate that $d = 80$ mm, which is close to actual path length l of the beam in the disk. We come to the conclusion that the studied optical phenomena, such as the rotation of the plane of polarization, ellipticity, angular deviation of the beam, and variation of its intensity, as well as the dependences of these phenomena on time and frequency in the region of low rotational frequencies, can be qualitatively explained by mechanical stress appearing at the metal–glass interface due to heating.

A more detailed calculation of birefringence requires taking into consideration that the beam propagates through different areas of the disk, and the values of σ_r and σ_τ (and, consequently, the difference $n_e - n_o$) depend on the distance from the disk center. In addition, the angle between the original plane of polarization of the beam and the principal plane constantly changes. Precise calculation of the effects appearing as a result of birefringence of the beam propagating through the disk, which takes into account thermal effects [9] and mechanical vibrations of the rotating disk, constitutes a separate task.

The optical scheme studied in the experiments can be used for developing a device for controlling the parameters of laser radiation. The scheme can be easily implemented and is characterized by low power consumption and large gradient of optical parameters of coherent radiation in the optical disk. The obtained results can be used as a basis for developing the device for high-precision measurement of the difference of indices of refraction $n_e - n_o$, as well as direct measurement of the photoelastic coefficient in optically transparent media.

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