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Experimental Studies of Polarization of Laser Radiation in a Rotating Optical Glass

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Abstract—The results of experiments on observation of rotation of the plane of polarization of coherent laser radiation with wavelength $\lambda = 0.632991$ μm after propagation through a rotating optical disk made of TF3 glass with refractive index $n = 1.71250$ are analyzed. The experiments were conducted at angle of ray incidence on the flat disk surface $\vartheta_0 = 60°$, and the rotational speed of the disk was varied from 0 to 200 Hz in both directions. The results indicate that rotation of optically transparent, homogeneous, and isotropic dielectric causes rotation of linear polarization of the monochromatic electromagnetic plane wave by several tens of degrees. At a rotational speed of 3 Hz, the rotation of polarization reached $\Delta\varphi = 70°$ for the vertical component of laser output polarization. The dependences of the angle of rotation of polarization and the degree of polarization of the rays on rotational speed are nonlinear and are attributed to the appearance of substantial anisotropic properties in a rotating dielectric.

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INTRODUCTION

The dependence of polarization of light on the motion of a medium was first investigated theoretically by H. Lorentz [1] and experimentally by H. Fizeau [2]. Although the experiments did not corroborate the hypothesis that rotation of plane of polarization must depend on Earth's motion, these studies resulted in the development of optics of moving media.

Attempts to measure the angle of rotation of the plane of polarization of light on velocity of the medium led to the conclusion that the effect of rotation of plane of polarization in a moving medium is small, and its influence in the experiments is minor. However, as follows from the experimental results presented in this work, this is not always the case.

First of all, it will be advantageous to analyze the existing theory of propagation of a plane electromagnetic wave in a rotating homogeneous isotropic optically transparent dielectric medium in the geometrical optics approximation.

From the point of view of classical electrodynamics, at normal incidence of a ray on an interface with tangential discontinuity of velocity, i.e., on a plane surface of a rotating optical disk (OD), the ray does not experience deviation. This follows from the existence of a tangential invariant in the case of tangential discontinuity of velocity [3]. In other words, tangential projections of the wave vectors of incident, transmitted, and reflected waves are equal to each other and vanish at normal incidence.

At oblique incidence, light experiences longitudinal and transverse dragging effects [4]. The first one is known as the Fizeau effect and linearly depends on optical path length in the medium and its velocity. The second effect appears due to ray propagation in the medium at an angle, the value of which depends on the rotational speed of the OD. The exit point of the ray from the disk gets displaced, and the value of the displacement depends on disk thickness d and number of passes N that the ray makes between the flat surfaces of the OD. However, the ray must exit the plane-parallel slab at the same angle as was its angle of incidence on the first surface.

The effect of rotation of the plane of polarization of a linearly polarized monochromatic electromagnetic wave incident on a rotating disk perpendicular to its surface was predicted by E. Fermi [5].

Mechanical rotation of the optical medium must cause rotation of polarization of radiation propagated through a rotating cylinder by the angle

$$\Delta\varphi = \left(n_g - \frac{1}{n_\varphi}\right)\frac{\Omega L}{c}, \tag{1}$$

where n_g and n_φ are the refractive indices for the group and phase velocities, respectively; L is the path length in the medium, Ω is the angular frequency of the cylinder; and c is the speed of light.

However, this effect is very small. For typical optical glasses and parameters of motion ($\Omega = 1000$ rpm, $L = 10$ mm), the resulting angle is of the order of a microradian.

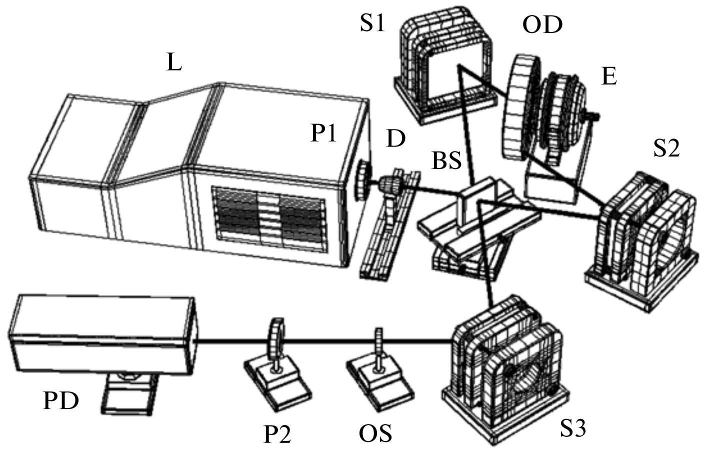

Fig. 1. Experimental arrangement.

Nevertheless, the angle of rotation of the plane of polarization of light with wavelength $\lambda = 632.8$ nm after propagation through a 100-mm-long rod with a diameter of 20 mm was measured as a function of its rotational speed [6]. The rod was made of SF57 glass with a refractive index of 1.840 at $\lambda = 632.8$ nm and was rotated with an angular velocity of up to 6000 rpm.

The obtained experimental data showed that the angle of rotation of the plane of polarization was about $\Delta\varphi = 2 \times 10^{-6}$ rad at a rotational speed of 100 Hz.

In another set of experiments, coherent radiation was passing though a cylinder rotating with a speed of 30 Hz. It was found that optical rays incident perpendicular to the flat surface of the cylinder experienced substantial deviation [7]. The authors used an optically active medium. As a result, the propagation time of radiation through the medium increased by several orders of magnitude due to multiple processes of radiation absorption and emission in an optically inverted medium. This leads to increased displacement of radiation in the direction perpendicular to its direction of propagation.

In addition, the effect of rotation of the plane of polarization of a monochromatic radiation in a nonuniformly moving medium was predicted in [8, 9].

It should be noted that expression (1) was obtained for an optically homogeneous isotropic medium. It is usually assumed that the optical properties of the rotating disk change little, so that the latter remains isotropic during rotation.

However, upon rotation of the OD, there appear radial and tangential deformations, the deformation tensor components being dependent on the chosen model of the rotating medium (cylinder, thin disk, pipe, etc.) [10].

As a result, the refractive index of initially isotropic optical disk attains anisotropy and value of the latter depends on the speed of disk rotation and is inhomogeneous across the OD volume. The influence of mechanical rotation of the optical medium on polarization of coherent radiation can thus become substantial.

In this work, we present the results of measurement of changes of polarization characteristics of electromagnetic radiation passing through a rotating OD as a function of its rotational speed.

The experimental arrangement is shown in Fig. 1. Radiation of power stabilized laser L passed though polarizer P1, which allowed setting the initial polarization of the radiation at the input of the interferometer (vertical, horizontal, or both components present simultaneously). After that, radiation passed through diaphragm D, which had two functions: cleaning the mode of the beam and protection from radiation reflected from the interferometer. Beamsplitter BS divided irradiation into two rays that propagated in a ring interferometer in opposite directions. In so doing, they experienced reflections from mirrors S1 and S2 and passed though optical disk OD mounted on the shaft of electromotor E. Rays emerging from the ring interferometer were reflected by mirror S3, propagated though optical system O, polarizer P2, and were incident on a photodetector.

The setup was mounted on a passively vibration-isolated optical table, so that the influence of vibrations created by the electromotor on the measured signal was below the noise level, i.e., below 1 mV.

The rays in the registration plane were aligned either to form an interference pattern or be spatially separated, which allowed measuring their individual polarization characteristics. The rotational speed and direction of rotation of the motor were controlled by a Delta Electronics VFD-EL frequency drive.

For analysis of the characteristics of the radiation, we used either a Glan polarizer or a 48-mm SUNPAK (PL) film polarizer as polarizer P2. The optical disk was made of TF3 glass with refractive index $n = 1.71250$ at $\lambda = 0.6328$ μm.

The optical disk had the following parameters: diameter $D = 62$ mm, and thickness $d = 10$ mm. The flat surfaces of the OD had a metallic reflective coating of radius $R_1 < D/2$ for increasing optical path length in the moving medium. The disk had a hole with diameter $D_0 = 37$ mm for its mounting on the motor's shaft. The disk axis of rotation was aligned in the horizontal plane. An electromagnetic wave was incident in the horizontal plane on the flat surface of the OD at angle $\vartheta_0 = 60°$. The plane of the wave vector trajectory in the OD lay at distance $r = 20.5$ mm above the optical axis of the disk. The ray made $N = 6$ reflections from the mirror surfaces, so that optical path length of the ray in the medium in projection on flat surface of the disk was $l = 41$ mm.

The signal was processed by a National Instruments PCI-6132 analog-to-digital converter (ADC) with a sampling rate of 2.5 MHz and 14-bit resolution per channel. The signal from the photodetector was fed into the ADC, and the digital sequence of the signals was further processed on a PC within the LabVIEW environment.

METHOD OF MEASURING THE ANGLE OF ROTATION OF POLARIZATION AND ELLIPTICITY OF EACH OF THE TWO RAYS AS A FUNCTION OF THE OD ROTATIONAL SPEED

At the first stage of the experiment, we measured the change of polarization of two rays passing the OD in opposite directions.

In the experiments, we used a stabilized single-frequency cw He–Ne laser LGN 302 with an output power of 0.7 mW in each generation component. The changing position of the output filter wheel allowed selection of the spectral component of radiation, an either horizontally or vertically linearly polarized single-frequency component.

After the laser output was stabilized, the interfering rays were vertically separated, which allowed conducting experiments with each of the two spots producing the interference pattern separately.

Before starting the motor, we measured the dependence of photodetector (PD) voltage on the Glan prism angle for different spectral components of the radiation (vertically and horizontally polarized components). Figure 2 (curve *1*) shows the dependence corresponding to an initially horizontally polarized component at the laser output (for vertically polarized component, the curve is similar but is shifted by 90° and has a different amplitude). The minima of intensity of light transmitted through the polarizer correspond to the polarizer orientation perpendicular to polarization of light at the output of the OD. For the two rays that passed the OD in opposite directions, this angular position differed by approximately 20°. The difference of absolute angular position of polarization

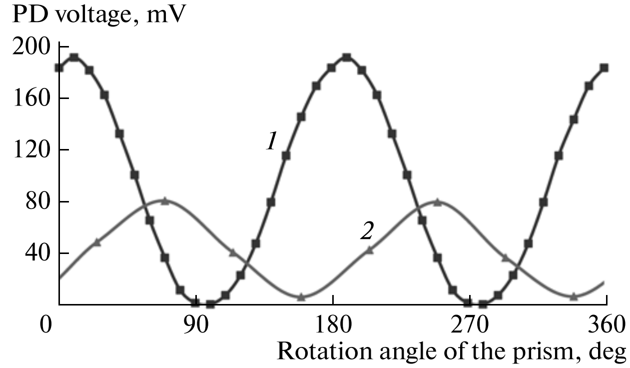

Fig. 2. Photodetector voltage as a function of angle of rotation of the polarizer for horizontal polarization of the laser output: (*1*) stationary OD, (*2*) at rotational speed of the OD equal to 80 Hz.

of rays passing through the OD in opposite directions is explained by their different trajectories, as a result of which the rays interact with the beamsplitter (BS) under different conditions (one ray passes through the BS two times, while the other experiences two reflections from the BS).

After starting the motor, the intensity of spots of light changed and the rotation of polarization could be measured by adjusting the orientation of the Glan prism.

As an example, in Fig. 2 (curve *2*) we show the dependence of the PD voltage on the angle of rotation of the polarizer for a rotational speed of the OD equal to 80 Hz (following a transient phase that lasted about 15 min). As follows from the plot, at polarizer angle $\varphi = 100°$, the signal increased to about 60 mV. It can also be seen that the polarizer must be turned by angle $\Delta\varphi = 60°$, i.e., set to 160°, in order to achieve a minimum of the signal. At this point, the PD voltage had a nonzero value of about 5 mV, which indicates the appearance of elliptical polarization in the beam after propagation through the rotating OD.

For convenience, below, we will assign a zero value to the polarizer position corresponding to transmitted light minimum. A negative angle on the plot corresponds to clockwise rotation of the plane of polarization, while a positive angle corresponds to its counterclockwise rotation. The direction of rotation of the prism (clockwise or counterclockwise) was chosen from the point of view of an observer watching the prism in the direction of ray propagation, i.e., from the OD side.

Experimentally, we found that rotation of the plane of polarization of the rays was dependent on the rotational speed of the OD. In so doing, the direction of rotation of the plane of polarization of the rays passing through the OD in opposite directions was opposite to each other.

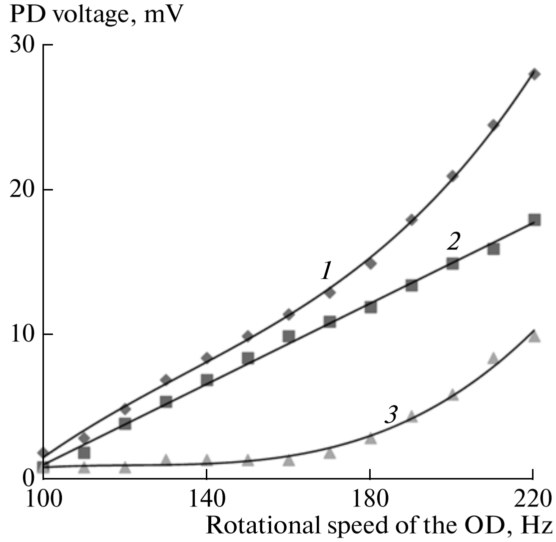

Fig. 3. Photodetector signal amplitude as a function of rotational speed of the OD for initial position of the polarizer (*1*), after polarizer rotation for minimum signal (*2*), and their difference (*3*).

The measurements showed that, in the range of rotational speed values between 0 and 100 Hz, the character of changes of polarization was substantially different from that in the range from 100 to 200 Hz. Subsequent measurements showed that the angle of rotation at a low rotational speed of the OD was large, reaching $\Delta\varphi = 90°$.

It was also found that, after the OD reached the working rotational speed, the rotation of the plane of polarization had a relatively long transient phase. The duration of this transient process was dependent on the rotational speed of the OD. Hence, in order to measure the dependences reliably, before taking data, we waited a sufficient time at each fixed rotational speed of the OD for the rotation of the plane of polarization to reach equilibrium. Depending on the rotational speed, this time varied from 5 to 15 min.

In addition, measurements made for different directions of rotation of the OD did not reveal any substantial difference in the value of the angle of rotation of the plane of polarization for the same value of the rotational speed. On the other hand, had the rotation of the plane of polarization been caused by the Fermi effect, the direction of rotation of the plane of polarization for chosen initial polarization would change direction upon changing the direction of mechanical rotation of the OD. Apparently, this was not the case. Consequently, the rotation of the plane of polarization was not related to the direction of rotation and was caused by rotation of the CD itself.

MEASUREMENT OF PHOTODETECTOR SIGNAL AMPLITUDE AS A FUNCTION OF ROTATIONAL SPEED OF THE OPTICAL DISK

As a result of the experiment, we measured the amplitudes of the PD signals for initial orientation of polarization and after its rotation, along with the angle of rotation of the plane of polarization, for different values of the rotational speed of the OD. We used a Glan prism as a polarizer. At the initial stage of the experiment, we found the angle of the polarizer corresponding to the minimum transmission of light, at which the signal was at the noise level. After that, we measured the first value of the signal amplitude at this position of the polarizer for all values of the OD rotational speed. We used a fast S5821-01 PIN photodiode (Hamamatsu) as a photodetector. The photodiode signal was amplified in a preamplifier with a band-pass RCL filter.

The starting rotation of the disk caused the photodetector signal to increase due to rotation of the plane of polarization; this signal increase was recorded. In order to determine the angle of rotation of the plane of polarization, the Glan prism was rotated to minimize the intensity of transmitted light. This value was also recorded. Then, pairs of signal amplitudes measured at the initial position of the polarizer and after its rotation for a minimum of the transmitted signal were compared. The measurements were conducted in the interval of rotational speed values between 100 and 220 Hz in 10-Hz steps, which yielded 13 pairs of signal amplitudes. The results of the measurements obtained for vertical initial polarization of the laser are presented in Fig. 3.

The time interval between successive measurements was about 1–2 min, which was necessary for the disk to achieve stable rotation at a new speed. Hence, the data do not contain information on the relatively long transient phase during which polarization was changing at constant rotational speed of the OD. In general, the obtained results indicate that the plane of polarization of the radiation passed through the rotating OD experiences rotation and the angle of rotation of polarization increases with increasing the rotational speed of the OD.

It also follows from the presented data that, after the OD achieves a stable regime, rotation of polarizer could not suppress the PD signal to an ultimately low level, i.e., to the noise level. For horizontal initial polarization of the laser radiation, the PD signal amplitude at rotational speed of 220 Hz decreased from 28 mV by approximately a factor of 1.5 to about 18 mV. For vertical polarization of the laser radiation, the PD signal amplitude at a rotational speed of 220 Hz decreased from 50 mV by approximately a factor of 2 to about 25 mV.

This means that an initially linearly polarized light becomes elliptically polarized after propagating though a rotating OD. In other words, the degree of polarization decreases with an increase in the rotational speed of the OD; i.e., depolarization of radiation increases.

The measurements the results of which are illustrated in Fig. 3 were repeated several times on different days. The dependence of the PD signal amplitude on the rotational speed of the OD was reproducible rather well.

The presented results do not include the relatively slow transient rotation of the plane of polarization, which took place after the rotational speed of the disk reached the chosen value. These specificities were analyzed in subsequent studies.

MEASUREMENT OF ROTATION OF POLARIZATION AND DEPOLARIZATION OF THE RAY PASSING THROUGH THE ROTATING DISK AS A FUNCTION OF TIME

In the course of the experiments, we found that the PD signal amplitude and the angle of rotation of polarization drift over time, while the rotational speed of the OD remains fixed. It has been suggested that, after the OD attains the chosen rotational speed, there was a transient process during which the plane of polarization slowly rotated as a function of time.

To verify this hypothesis, we measured the angle of rotation of polarization of the ray and its degree of ellipticity as a function of time. The experiment was conducted at a rotational speed of 150 Hz. The Glan prism was used as a polarizer.

In the experiment, we obtained an interference pattern in the plane of the PD for vertical polarization of the laser radiation. As was shown in the previous measurements, the planes of polarization of the two rays passing the OD in opposite directions made an angle of about 20° with respect to each other even when the OD was not rotating. This should introduce ellipticity in polarization of the combined beam.

The interference pattern represented a fringe pattern on the screen installed in the PD plane. Upon rotation of the OD, the fringes shifted periodically, so that light intensity within the PD aperture was varied in time. This resulted in time dependence of the PD voltage.

In the experiment, we measured the peak amplitude of the time-dependent signal. Before the experiment, the rays were aligned to have a maximum signal intensity (bright part of the spot) on the PD aperture.

After starting the laser and stabilization of its parameters, the polarizer was turned to minimize the transmitted signal. After starting disk rotation, we measured the signal amplitude at the peak of the time dependence of the PD voltage for initial angular orientation of the prism holder and after rotation of the polarizer by some angle due to rotation of the plane of polarization of the rays (the prism was turned for the minimum of the signal again). After that, the prism was turned back to the original position. This procedure was repeated in 28 measurements. The interval between the measurements was 5 min.

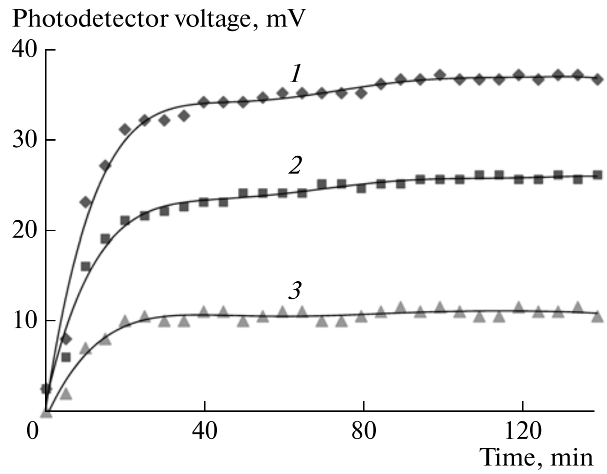

Fig. 4. Peak photodetector voltage amplitude as a function of time at a rotational speed of 150 Hz (*1*) for the initial position of the polarizer, (*2*) after polarizer rotation for the minimum signal, and (*3*) their difference.

The results of measuring the PD voltage amplitude at its maximum as a function of time are presented in Fig. 4.

As can be seen from Fig. 4 (curve *1*), the signal amplitude in the first few minutes after starting OD rotation was about 10 mV, while, 20 min after beginning of the experiment the signal, the signal amplitude at the peak of the time-dependent response exceeded 30 mV. For the 2 h of measurements, this value was exponentially increasing toward a level of 36–37 mV.

After rotation of the polarizer to achieve a minimum of the transmitted signal, the PD voltage amplitude was recorded every 5 min, which resulted in the dependence shown by curve *2*. In general, curve *2* is similar to curve *1*, but voltage amplitudes are approximately a factor of 1.5 smaller.

The first curve characterizes simultaneous rotation of the plane of polarization and change of the degree of ellipticity. The second curve characterizes the time dependence of ellipticity of the rays. Hence, the difference of curves *1* and *2* yields a quantity characterizing the degree of ellipticity of the rays. This quantity is also illustrated in Fig. 4.

Comparison of the curves in Fig. 4 shows that the degree of ellipticity saturates within the first 20 min and remains unchanged thereafter. We believe that the nonlinear dependence of the interference signal (curve *1*) was due to slow rotation of the plane of polarization as a function of time.

We also measured the dependence of the rotation angle of the plane of polarization of interfering rays as

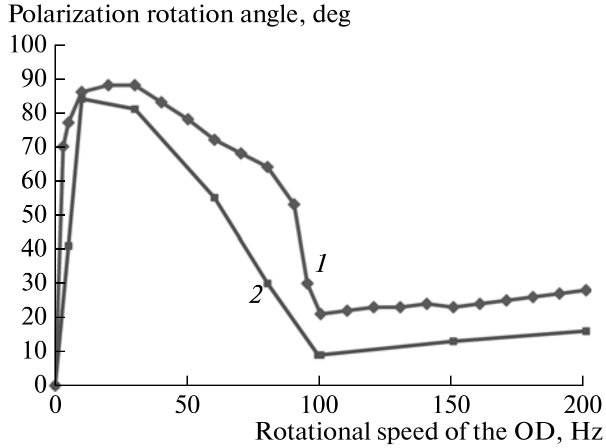

Fig. 5. Angle of rotation of polarization as a function of rotational speed of the OD for vertical (*1*) and horizontal (*2*) polarizations of the laser output.

a function of time at a rotational speed of the OD equal to 150 Hz. Analysis of the data reveals that, within 20 min after beginning of the measurements, the angle of rotation of polarization reached 21° and remained constant thereafter. Consequently, further growth of the signal amplitude was not related either to rotation of polarization or change of ellipticity.

Hence, the transient regime had two phases. In the first phase, both the plane of polarization and the degree of ellipticity experienced changes. This stage was relatively short and lasted about 20 min. At the second stage, the signal amplitude experienced slow changes at a fixed orientation of the plane of polarization and fixed value of the degree of ellipticity. Variation of the signal amplitude for long observation times occurred due to the angular shift of the ray; however, it is important that variation of the signal amplitude was not related to changes of polarization characteristics of the radiation, measurement of which was the goal of the present study.

MEASUREMENT OF THE DEPENDENCE OF THE ANGLE OF ROTATION OF POLARIZATION OF LASER RADIATION AS A FUNCTION OF THE OD ROTATIONAL SPEED

After the laser was turned on and achieved a steady regime of operation, the distribution of intensity of one of the rays was measured in the PD plane for vertical polarization of the laser output, followed by similar measurements for horizontal input polarization.

The prism was turned so that the signal reaching the screen after passing through the prism had minimum amplitude for stationary OD. This was the initial position of the polarizer for all rotational speeds of the OD. After OD rotation started, the signal amplitude increased. The disk rotated counterclockwise when observed along the direction of ray propagation toward the screen.

The first experiment was conducted with vertical initial polarization of the ray. When measurements were conducted at a fixed rotational speed of the OD, a transient process was observed, during which the signal amplitude on the PD increased exponentially. After the voltage amplitude of the time-dependent signal reached saturation, the polarizer was rotated to minimize the signal amplitude. The angle of rotation of polarization $\Delta\varphi$ was determined by changing the orientation of the prism mounted in a rotating holder by an angle that could be read on the scale of the holder. After that, the OD was stopped and the minimum of the signal amplitude slowly returned to its original position. Thereafter, the experiment was conducted at a different rotational speed.

As a result of the measurements, we obtained time dependences of the angle of rotation of the plane of polarization of the rays for both vertical and horizontal initial polarization of the laser radiation and fixed values of the OD rotational speed in the range from 0 to 200 Hz. It should be noted that the angle of rotation of polarization was larger at smaller rotational speed values. With an increase in the rotational speed, the transient process occurred faster.

Using the obtained data, we plotted the dependences of the angle of rotation of polarization as a function of rotational speed for initial vertical and horizontal polarizations of radiation at the output of the laser, including the transient regime in the rotating OD (Fig. 5).

As follows from the plots, at low rotational speed values of the OD, the angle of rotation of the plane of polarization experienced a sharp increase. At rotational speed of 3 Hz, the angle of rotation of polarization was reaching the value of 70° for vertical component of the laser polarization. At rotational frequencies of 20–30 Hz, the value of $\Delta\varphi$ was reaching maximum of about 90°. With further increase in rotational speed, the angle of rotation of polarization decreased to 10°–20° at 100 Hz and then started slowly increasing again almost linearly with increasing rotational speed. At rotational speed of 200 Hz, the angle of rotation reached 15°–28° for both polarization components.

For horizontal polarization, the values of the angle of rotation were somewhat smaller and the corresponding curve lies below that for vertical polarization, although its shape remains the same. The measurements were conducted using a Glan prism as a polarizer and were verified with a film polarizer. The direction of rotation of the disk did not substantially influence the results. We also conducted measurements with another optical disk with similar geometrical parameters and made of the same kind of glass. The obtained dependences of angles of rotation of polarization on rotational speed were qualitatively similar.

CONCLUSIONS

In the course of the conducted studies, we discovered that polarization of coherent electromagnetic radiation with wavelength $\lambda = 0.632991$ μm transmitted by a rotating optical disk made of TF3 optical glass was dependent on the rotational speed of the disk.

After the OD reached chosen rotational speed, at incidence angle of the ray on the flat disk surface $\vartheta_0 = 60°$, a relatively long transient process of rotation of the plane of polarization was observed. The duration of the transient process was dependent on the OD rotational speed and lasted 15–20 min in the range of rotational speed values between 0 and 200 Hz.

In the experiments, we also detected a variation of the PD signal amplitude in the plane of detection of the interference pattern. During the first few minutes after the disk reached the chosen rotational speed, the PD voltage was about 10 mV, while the peak signal amplitude exceeded 30 mV 20 min after the beginning of the experiment.

The initially linearly polarized light was becoming elliptically polarized after propagating through the rotating OD, and the degree of polarization decreased with increasing rotational speed of the OD.

Experimentally, it was established that rotation of the plane of polarization of the rays after propagation thought a rotating OD was dependent on rotational speed of the disk, and the direction of rotation of polarization of the rays that propagated through the OD in opposite directions was opposite to each other but independent of the direction of rotation of the optical disk.

The measurements showed that the character of changes of polarization in the range of rotational speed values between 0 and 100 Hz was substantially different from that in the range between 100 and 200 Hz. At a low rotational speed of the OD, large angles of rotation of polarization of up to 80°–90° were observed at rotational speed values in the range between 10 and 30 Hz. At a rotational speed of 3 Hz, the angle of rotation of polarization reached 70° for vertical output polarization of the laser. As the rotational speed was increased further, the angle of rotation decreased to 10°–20° at 100 Hz, followed by a gradual increase. At 200 Hz, the angle of rotation of polarization $\Delta\varphi$ reached 15°–28° for both spectral components of polarization at the output of the laser. An interesting specific feature is the fact that the angle of rotation of the plane of polarization decreased at a rotational speed above 30 Hz.

Let us compare the obtained results with those published in [6], where a linear dependence of the angle of rotation of the plane of polarization on rotational speed of the disk was found, with the angle of rotation being $\Delta\varphi = 5 \times 10^{-7}$ at rotational speed of 10 Hz. Here, we measured nonlinear dependence $\Delta\varphi(\Omega)$ and the angle of rotation of polarization at $\Omega =$ 10 Hz reached 86° for vertical and 84° for horizontal components of polarization at the output of the laser. Consequently, the discovered effect is different from the Fermi effect.

Based on the description of the experiment in [6], the laser wavelength, refractive index of the glass, the angular speed of rotation were the same or similar to the corresponding parameters in the present work. However, on our experiment, we used a large-diameter optical disk with mirror reflecting surfaces instead of a cylinder, and the angle of incidence was $\vartheta_0 = 60°$.

Under such conditions, when conducting an experiment with a stationary or slowly rotating optical disk, the latter remained isotropic. Starting from small values of the rotational speed, its dielectric properties attained an anisotropy that had a complex dependence on the rotational speed.

We believe that the discovered nonlinear characteristics of optical radiation propagation in a rotating glass can be attributed to specific features of dynamic transformation of polarizability states of dielectric molecules upon disk rotation, which leads to a dynamic effect of rotation of the plane of polarization of a monochromatic electromagnetic radiation.

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