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First Results of Measurements of the Rotation Speed Effect on the Spatial Entrainment of Light in a Rotating Medium

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Abstract—We consider the first results of measurements of the effect of a velocity vector field in a rotating transparent medium on the light propagation velocity c in this medium. Laser radiation with a wavelength of $\lambda = 0.632991$ μm passed through a rotating optical disk with $n = 1.7125$ in an interferometer, where the beam path length projected on the flat disk surface was $l = 30.4$ mm, the disk thickness was $d = 20$ mm, and the angle of light incidence on the flat disk surface was $\vartheta_0 = 50.7°$. The disk rotation speed was varied up to 380 Hz, which corresponded to a projection of $V_{2n} = 36$ m/s of the medium velocity onto the wave vector of the electromagnetic wave. The experimental data confirmed to the first approximation the classical linear dependence of the shift of interference fringes on the velocity of a rotating medium.

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This Letter is devoted to the optical anisotropy arising in a moving medium, where the velocity of light propagation depends on the velocity and direction of motion of the medium. In a rotating medium, the light trajectory is curved [1], and the additional path related to the curvature of rays can be comparable with the path difference observed in the longitudinal Fizeau effect. This fact is due to violation of the Snell law at the tangential discontinuity of the light propagation velocity, which (together with the curvature of the trajectory) leads to a shift of the point of light exit from the medium. This complex phenomenon is treated as the transverse entrainment (drag) of light in the moving medium.

The transverse entrainment can be observed for radiation propagating in a rotating optical disk (OD). In 1977, Bilger and Stowell [2] performed an experiment with light propagating in a rotating OD arranged in a laser ring interferometer. The results were interpreted in terms of the Fizeau effect. However, since the rotating disk features a tangential discontinuity of the light propagation velocity on the flat surface, the phase shift in circulating electromagnetic waves was related to both longitudinal and transverse entrainment of the wave. This is confirmed by calculations based on a solution to the dispersion equation, which show that an additional shift of the interference pattern in such experiments can amount to about 20% of the value due to the longitudinal Fizeau effect [3].

Below, we consider the results of interferometric experiments in which the optical anisotropy of light propagating in a rotating transparent medium has been studied as a function of the rotation speed. Here, by the optical anisotropy we imply the dependence of the velocity of light on the velocity and direction of motion of the medium where it propagates. The entrainment of light in a moving medium was studied using an interferometer, in which the light was introduced via a flat surface of a rotating OD [4, 5]. In this scheme, the effect of the trajectory curvature is minimum and can be ignored. In order to reliably measure the light entrainment as dependent on the OD rotation speed, it was necessary to increase the interval of variation of this speed. This task was solved using an interferometer scheme depicted in Fig. 1, which was also provided with a means of differential compensation that eliminated the influence of seismic, acoustic, and thermal noise, as well as variations of the refractive index of air.

In the proposed scheme, the beam of laser L is divided by beam splitter BS into two beams. These beams are directed by mirrors M_1 and M_2 so as to pass via the OD in opposite directions. As a result of the OD rotation, one beam acquires a positive, and the other beam, a negative phase shift. Then, the two beams are mixed in the BS, and the mixed beam directed by mirror M_3 passes through optical system OS and strikes photodetector PD. Reversal of the direction of OD rotation leads to a change in the direction of the shift of interference fringes observed in the aperture plane of the PD. The optical path length in the OD was increased due to the multiple reflection of beams from mirror flat surfaces (the front flat surface was mirror coated in the central part, and the rear surface was entirely mirror coated).

To the first approximation, the proposed scheme is equivalent to a one-pass Fizeau interferometer. Let us

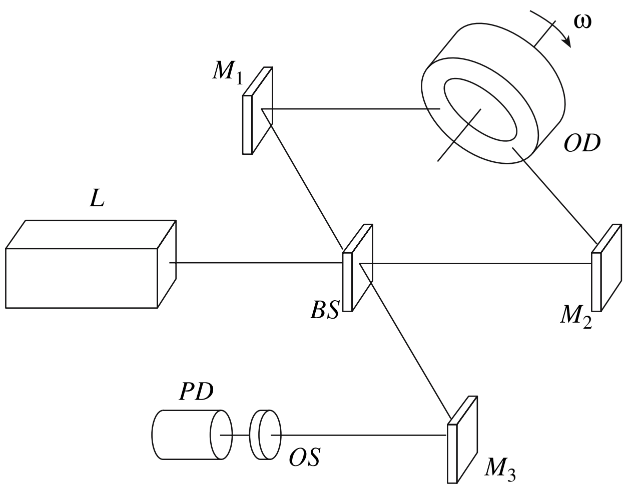

Fig. 1. Schematic diagram of a double-beam two-pass interferometer with a rotating optical disk (see text for explanations).

consider this scheme in an inertial frame where the interferometer is at rest, so that $\beta = V/c = 0$, where V is the linear velocity of the medium and c is the velocity of light in vacuum. The velocity field in the transparent medium is characterized by the quantity $\beta_{2n} = \pm V_{2n}/c$, where V_{2n} is the projection of the medium velocity onto the wave vector of the electromagnetic wave in the inertial frame of the interferometer. In the approximation adopted (i.e., with neglect of the Snell law violation), the light wave of frequency ω_0 is incident from the first medium ($n_1 = 1$) onto the interface with the second medium having the refractive index n_2 (in the inertial frame, this medium is at rest). For the normal beam incidence, a solution to the dispersion equation is determined by the invariants $I_t = k_t = k_0\sin\vartheta_0 = 0$ and $-I_1 = \omega_0(1-\beta) = \omega_0$ [6].

The wave vectors of the refracted beams propagating in opposite directions obey the relation

$$k_{2n} = \frac{\omega_0}{c}\frac{-\beta_{2n}(n_2^2-1)+n_2(1-\beta_{2n}^2)}{1-n_2^2\beta_{2n}^2}. \quad (1)$$

The shift of interference fringes depends on the time of light propagation in the opposite directions as

$$\Delta_0 = \frac{c}{\lambda}(t_2-t_1) = \frac{lc}{\lambda\omega_0}(k_{2n,2}-k_{2n,1}) = \frac{2l}{\lambda}\frac{\beta_{2n}(n_2^2-1)}{1-n_2^2\beta_{2n}^2}, \quad (2)$$

where l is the optical path length in the moving medium and λ is the wavelength in the inertial frame, where the medium is resting.

Our experiments were performed with the following system parameters: OD diameter, $D = 45$ mm; projection of the beam path length in the medium onto the flat OD surface, $l = 30.4$ mm; refractive index of the OD glass, $n_2 = 1.7125$; OD thickness, $d = 20$ mm; angle of the primary beam incidence onto the flat OD surface, $\vartheta_0 = 50.7°$; laser wavelength, $\lambda = 0.6329910 \pm 1 \times 10^{-7}$ μm; variable OD rotation frequency, $\nu = 100$–380 Hz. For the indicated parameters and $\nu = 200$ Hz, the expected shift of interference fringes due to the Fizeau effect is $\Delta_0 = 1.18 \times 10^{-2}$.

However, theoretical analysis shows that it is necessary to take into account violation of the Snell law at the tangential discontinuity of the light propagation velocity at the air–glass interface. With allowance for the transverse entrainment of light, the angle of refraction is calculated as [3]

$$\tan\vartheta_2' = \frac{\sin\vartheta_0}{\sqrt{n_2^2-\sin^2\vartheta_0-(n_2^2-1)\beta_{2n}}}. \quad (3)$$

The experiment gives $\beta_{2n} = 6.4 \times 10^{-8}$ for $\nu = 200$ Hz, which corresponds to a deviation of ϑ_2' from $\vartheta_2 = \arctan\frac{l}{3d}$ on a level of 2×10^{-6} deg. Then, the additional shift of interference fringes is calculated as

$$\Delta' = \frac{6d(n_2-1)}{\lambda}\left(\frac{1}{\cos\vartheta_2'}-\frac{1}{\cos\vartheta_2}\right) \cong \frac{(n_2-1)\tan\vartheta_2}{n_2}\Delta_0 = 2.5\times10^{-3}. \quad (4)$$

Thus, the total shift of fringes due to the longitudinal and transverse Fizeau effects is $\Delta_\Sigma = \Delta_0 + \Delta' = 1.43 \times 10^{-2}$.

The interferometer was mounted on two optical platforms with a passive shock absorber system. The OD with a drive motor was mounted on one platform, and the other parts of the interferometer were arranged on the second platform. The experiments were performed with a stabilized He–Ne laser (LGN-302) with an output power of 0.5×10^{-3} W. The reflecting coating on flat mirror OD surfaces was selected in accordance with the laser wavelength. The PD was based on a high-response-speed PIN photodiode (Hamamatsu S5821-01). The whole interferometer was placed in a housing equipped with an active temperature control system, which maintained a preset temperature to within 0.1°C.

The shift of interference fringes was determined by measuring the time of their passage over the PD aperture as described elsewhere [4]. This time interval was recalculated into the shift of interference fringes using elliptic integrals of the second kind as described in [3]. Since the interferometer tuning during all measurements corresponds to the same working point of the phase curve, the shift of interference fringes to the first approximation is proportional to the time of their passage over the PD aperture.

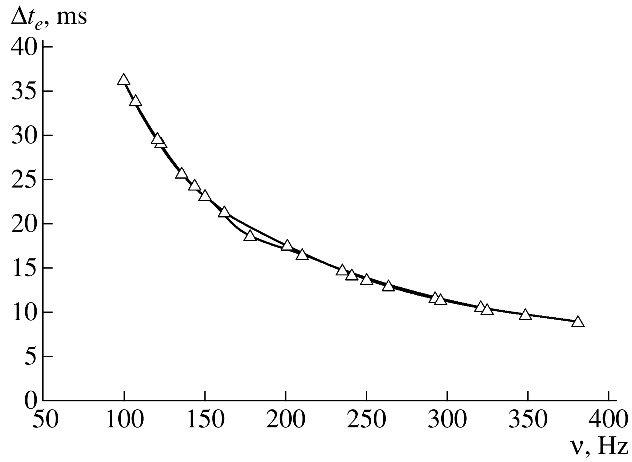

Fig. 2. Experimental plot of the time interval Δt_e of the interference fringe passage over the PD aperture versus OD rotation frequency ν.

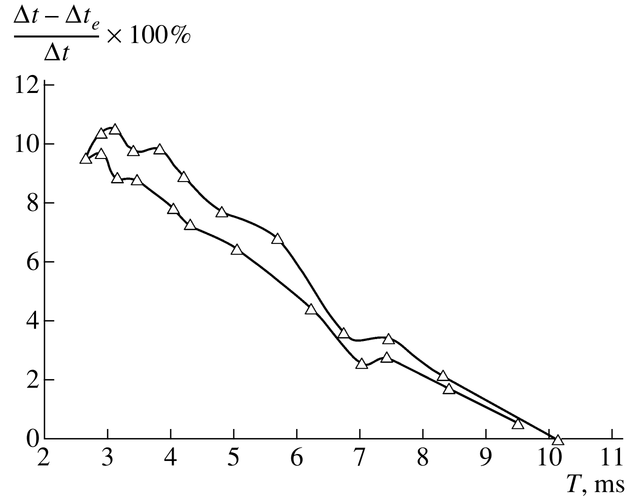

Fig. 3. A plot of the percentage difference between the shift of interference fringes calculated with neglect of the Fizeau effect (Δt) and the experimentally measured value (Δt_e) versus OD rotation period T.

The primary signal conversion was performed by a PCI-6132 analog-to-digital converter (ADC) (National Instruments) operating with an input resolution of 14 digits at a discretization frequency of 1 MHz. The output signals from the PD, a reference photodetector of the laser radiation power monitor, and a temperature sensor were fed to independent ADC inputs. The corresponding ADC output signals were processed by a personal computer in the LabVIEW medium.

In order to increase the experimental statistics and improve the accuracy of signal processing, the time of signal accumulation at a fixed OD rotation speed was 15 s. For example, at a rotation frequency of 200 Hz, this corresponds to 3000 measurements per experimental point. In order to reduce the influence of low-frequency mechanical noise and high-frequency electromagnetic interference, we used a fifth-order Butterworth band filtration of the signals.

Prior to measurements, the interferometer was adjusted so that three interference fringes would pass over the PD aperture during one turn of the OD, in one direction for the first half-period and in the opposite direction for the second half-period. The time interval Δt_e was measured between the moments of the PD aperture crossing by the selected fringe. Since this time is directly proportional to the OD rotation period T, the Δt_e value was normalized to this period.

Figure 2 shows the results of Δt_e measurements, which are plotted versus the OD rotation frequency ν. The experimental curve consists of two branches because the measurements with performed first with ν increased from the minimum value to maximum, after which the frequency was decreased approximately to the initial value. As can be seen, the two branches are very close to each other, which is evidence for a high stability of results. According to Fig. 2, the dependence of Δt_e on ν has a hyperbolic shape, but this plot deviates from the theoretical curve calculated with neglect of the Fizeau effect.

Figure 3 shows a plot of the relative difference between the shift of interference fringes calculated with neglect of the Fizeau effect and the experimentally measured value versus OD rotation period T. As can be seen, this dependence is linear and, to the first approximation, confirms the validity of Eq. (1). At an OD period of about $T = 5$ ms (corresponding to $\nu = 200$ Hz), the measured time interval between fringes decreases by $7 \pm 0.7\%$. This change in the time of passage corresponds to a shift of fringes $\Delta_\Sigma = 1.43 \times 10^{-2}$. The direction of change (increase versus decrease) in the time interval for a fixed OD rotation direction is determined by the interferometer tuning. Thus, using a calibrated interferometer and measuring the time of passage of the interference fringes, it is possible either to determine the shift of fringes or to solve the inverse problem and determine the velocity of motion of the medium.

The experimental data presented above show that the entrainment of light in a rotating medium is proportional to the rotation speed. An analysis of these data confirms the results of calculations based on the exact solution of the dispersion equation with allowance for violation of the Snell law.

The nature of the optical anisotropy in a moving medium is related to the anisotropic properties of interaction forces between atoms in the lattice and has a local character. We may suggest that there is a relationship between the nonlinear processes of interaction of electromagnetic radiation and a moving medium, on the one hand, and the factors responsible for the anisotropy of the cosmic microwave background [7], which is probably due to the space geometry, on the other hand. Then, this relationship can be manifested upon a change in the spatial orientation in experiments on the optics of moving media. Subsequently, it is planned to use our interferometer for laboratory detection of the anisotropy of space. For this purpose, it is necessary to increase the parameter $lV_{2n}(n_2^2 - 1)$ that determines the efficiency of light entrainment in a moving medium.

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