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The Effect of Light Entrainment Observed in an Optical Disk Interferometer

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Abstract—We observed a spatial effect of the light entrainment at a wavelength of $\lambda = 0.63299$ μm by an optical disk with a radius of $R_0 = 0.06$ m rotating at a frequency of $\omega = 25$ Hz. A relative shift of the interference pattern, monitored by the time of the interference band motion across the aperture of a photodetector for the disk rotating in the opposite directions, amounted to $\Delta = 0.0094 \pm 0.0025$ of the interference bandwidth.

The propagation of an electromagnetic radiation in a rotating medium is determined by superposition of the primary wave and the secondary waves appearing as a result of the interaction of the electromagnetic radiation with atoms of the moving medium. By solving a dispersion equation, it is possible to determine the radiation wavevector in any local region of the trajectory with an allowance for a spatial distribution of the medium velocity [1]. The solution was repeatedly verified in experiment, but the complexity of such investigations allowed only certain particular cases to be studied such as the longitudinal Fizeau effect [2, 3] and the normal velocity break [4, 5], in which the light beam is affected by either normal or tangential components of the medium velocity.

Propagating in a rotating medium, the electromagnetic wave is simultaneously affected by both normal and tangential components of the motion. Therefore, experimental observation of the spatial effect of the light wave entrainment is verification of the total solution of the dispersion equation.

Below we present the results of a series of experiments on the measurement of a shift of the light interference pattern in the scheme of a double-beam two-pass disk interferometer (Fig. 1). In this scheme, the light beam from laser *1* incident on a beam divider *3* was split into two beams. These beams entered the optical disk *3* to be reflected from flat mirror surfaces. The exit beams reflected from angle prism *4* changed paths, passed through the optical disk in the reverse direction, and entered the divider again. Mixed on the divider mirror, the beams passed through an objective lens *5* to display the interference pattern on a screen *8*. The light intensity was measured by photodetector *6* (a photodiode of the FD256 type operating in the generator mode).

The light source was an LGN-302 laser operating at $\lambda = 0.63299$ μm and producing the beam with a power of $P_0 \approx 0.84$ W for both horizontal and vertical polarization components. The rotating medium was a disk with a diameter of 120 mm and a thickness of 30 mm made of an LK5 grade glass ($n = 1.4766$ for $\lambda = 0.63299$ μm). In order to increase the optical pathlength by multiple reflections, the disk edge surfaces were mirror coated so as to provide for the reflection coefficient $R = 0.9$.

Reversal of the disk rotation direction resulted in inversion of the sign of the phase shift between interfering light beams and, accordingly, of the direction of the shift of the interference pattern. Since the optical

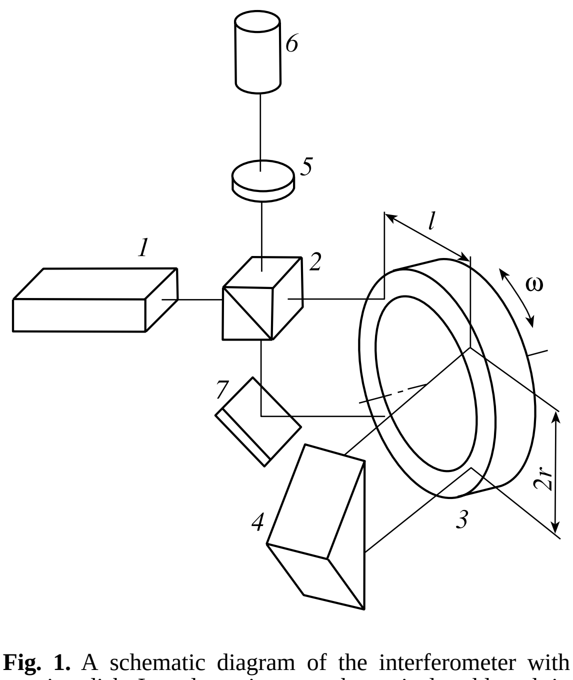

Fig. 1. A schematic diagram of the interferometer with rotating disk. In order to increase the optical pathlength in the rotating medium, a reflecting coating was deposited onto the disk front central part and rear flat edge surfaces.

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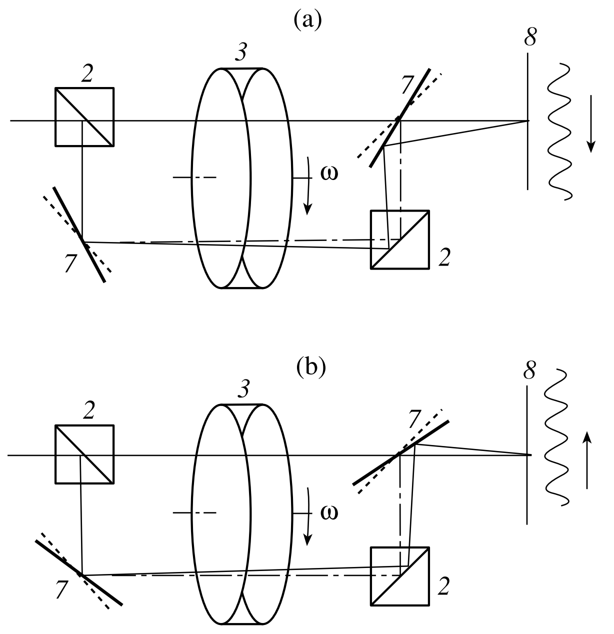

Fig. 2. A schematic diagram of the beam path from divider *2* to screen *8* for different positions of mirror *7* in the scheme of Fig. 1. A change in the mutual arrangement of the interfering beams results in (a) downward or (b) upward shift of the interference pattern for the disk rotating in the same direction.

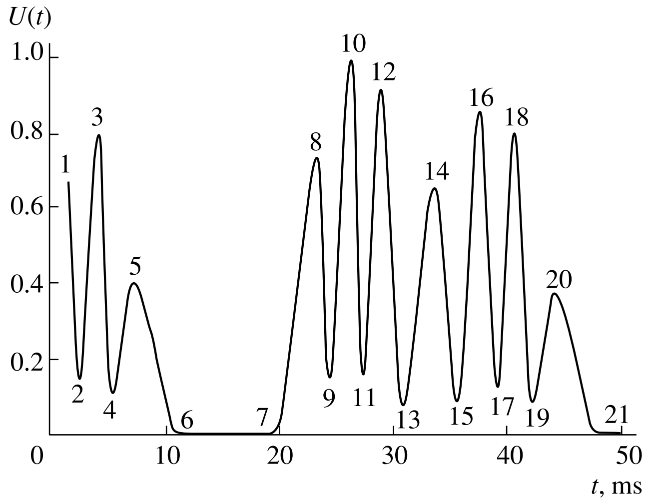

Fig. 3. Time variation of the relative photodetector output signal voltage.

scheme is such that the interfering light beams travel by the same path, the interferometer is sensitive neither to vibrations nor to the stationary displacements, elastic deformations, and wedge distortions of the disk.

At the same time, the observed shift of the interference pattern is influenced by the photoelastic effect, which can also change magnitude depending on the disk rotation velocity and direction. In order to exclude this factor, we performed several series of experiments with the disk rotating in the forward and reverse direction for various mutual arrangement of the beams (Fig. 2), which was provided by adjusting the position of mirror *7*. For the disk rotating in one direction, the photoelasticity phenomenon led to a shift of the interference patterns in the same direction, while the spatial light entrainment effect shifted the interference patterns in opposite directions for the alternating relative beam positions.

By adjusting the mirrors and beam divider, it was possible to obtain an interference pattern in the form of contrast parallel fringes of equal inclination. The rotation of the disk produced a shift of the interference bands, whereby three interference bands passed across the photodetector aperture first in one and than in the reverse direction. A shift of the interference pattern related to the phase shift of the interfering light beams (caused by the spatial entrainment effect or by the photoelasticity phenomenon), rather than to the kinematic motion of the disk, has to change the time period between the interference band passages across the photodetector aperture depending on the direction of rotation.

Figure 3 shows the time variation of the photodetector output voltage for the optical disk rotating clockwise and the mutual arrangement of beams such as depicted in Fig. 2. These patterns were obtained using oscillograms recorded by an S1-118A oscillograph with the temporal instability of sweep not exceeding $0.02(T + 4) \times 10^{-9}$ s, where T is the sweep duration. The oscillograms were digitized with the aid of a Kodak DC240 camera possessing a resolution of 1344 × 971 pixel. The time coordinates of the points in the oscillogram were determined graphically on a Pentium II PC. The distance between points 13 and 15 in Fig. 3 in various series of measurements corresponded to a conditional time interval $t_{15} - t_{13} \approx 800$–1000 pixel.

As can be seen from Fig. 3, the region of points 14 and 6, 7 correspond to a moment when the interference pattern shift is suspended (band stop) and the direction of rotation is reversed. This was checked in the regime of manual disk rotation at a 1° step. The signal amplitude difference between points 8 and 20, 10 and 18, and 12 and 16 is explained by rotation of the interference bands, whereby different parts of the same band passed across the photodetector aperture in the forward and reverse directions.

A deviation of the rotation period T_i in each series of measurements, which was monitored by the difference of coordinates between the identical points 3 and 18, 4 and 19, or 5 and 20, did not exceed 0.5% of the stationary value. The experimentally measured quantities were the coordinates t_{13}, t_{15} and t_{12}, t_{16} determining the width, relative position, and shift of the interference band.

In a nonrelativistic limit, a shift of the interference pattern in the scheme employed is given by the formula

$$\Delta = \frac{4lu_l(n^2-1)}{\lambda c}, \qquad (1)$$

where l is the projection of the light beam pathlength in the optical beam on the flat edge surface, $u_l = \omega r$ is the projection of the medium velocity onto the l direction, ω is the disk rotation frequency, and r is the distance from the line l to the axis of the disk rotation. For the parameters employed inn out experiments ($l = 0.087$ m, $r = 0.0225$ m, $n = 1.4766$, $\omega = 25$ Hz, and $\lambda = 0.63299$ μm), formula (1) yields a theoretical estimate for the band shift relative to the immobile disk: $\Delta = 0.001217$.

The method of determining a shift of the interference pattern using variations of the time of the interference band passage across the photodetector aperture significantly increases the experimental accuracy. First, the shift of the interference pattern is measured for the disk rotating in opposite directions, which leads to a twofold increases in the measured Δ value. Second, the experimentally measured quantity t_{15}–t_{13} represents a doubled shift value. Third, the measurements are conducted for various mutual arrangements of the interfering beams, which results in a shift of the interference pattern in opposite directions for the same rotation direction, which also increases the resulting shift of the interference pattern by a factor of 2. Thus, the experiment is expected to give the value $\Delta_p = 8\Delta = 0.0097$ of the bandwidth.

The experimental series included the measurement of $U(t)$ curves at a resolution sufficient for which the t_{12}–t_{16} part of the pattern to fall within each shot; 25 shots were made for each of the two directions of disk rotation and each mutual arrangement of the interfering beams. The quantity $\Delta t_i = t_{13,\,i} - t_{12,\,i} + t_{16,\,i} - t_{15,\,i}$ gives the time width of the interference band ($i = \overline{1, 25}$). The quantity $\delta t_i = t_{15,\,i} - t_{13,\,i}$ determines the time position of the band relative to the instant of band stop at point 14 for a given direction of rotation and mutual arrangement of the beams. The ratio of these values determines the relative position of the interference pattern expressed in fractions of the bandwidth, which eliminates the possible period variations from shot to shot. After calculating the time coordinates δt_i and Δt_i, we determined the relative spatial coordinates characterizing the interference band positions and widths δx_i and Δx_i, respectively.

The relative position of an interference band closest to the instant of band stop at point 14 correspond to

$$\Delta_i = \frac{\delta x_i}{\Delta x_i}. \tag{2}$$

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Upon averaging over 25 shots, we obtain four quantities determining the required shift of the interference band:

$$\Delta_\ni = (\Delta_+^1 - \Delta_-^1) - (\Delta_+^2 - \Delta_-^2), \tag{3}$$

where the subscripts 1 and 2 refer to two different mutual arrangements of the interfering light beams and the signs “+” and “–” refer to the clockwise and counterclockwise directions of rotation, respectively.

The experimental data processing yielded the following value for the relative shift of the interference pattern (at confidence probability of 0.9):

$$\Delta_\ni = 0.0094 \pm 0.0025 \text{ bandwidth.}$$

As can be seen, the above Δ_p value falls within the confidence interval. The results of calculations performed for the given incidence angle ($\vartheta_0 = 67°$) rotation frequency ($\omega = 25$ Hz), disk radius ($R_0 = 0.06$ m), and refractive index ($n = 1.4766$), a deviation from Snell’s law due to the transverse light entrainment would lead to a shift of the interference pattern about ten times as small as the $\Delta_\ni$ value [6]. The level of sensitivity necessary for the observation of this effect can be provided by increasing ω and/or R_0.

It should be noted that formula (1) was derived assuming that a shift of the interference pattern is determined by the projection of the linear velocity vector of the medium onto the electromagnetic wavevector at each point of a three-dimensional light beam trajectory. The results of our experiments confirmed the validity of this approach. Further increase in the interferometer sensitivity will allow us to study the deviations from formula (1) related to a violation of the law of refraction and to a deviation of the light from rectilinear trajectory in a rotating medium.

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