Effect of circular polarization on the propagation of light through an optical fiber

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The rotation of the speckle in a multimode optical fiber upon a change in the sense of the circular polarization of the propagating light has been observed experimentally. This effect had been predicted previously. In a sense, this effect is the inverse of the "Rytov" rotation of the polarization plane.

The effect of the circular nature of the polarization on the twisting of an originally planar trajectory of a geometric-optics beam was studied in Ref. 1. This effect is related to the well-known "Rytov" rotation of the polarization plane for a trajectory with a nonzero twisting.[2-4]

The following expression was derived for the trajectory twisting angle for an optical fiber with a parabolic profile of the refractive index:[1]

$$\delta\phi = (\lambda\delta nz)/(\pi r^2 n_{co}^2), \tag{1}$$

where λ is the wavelength, r is the radius of the lightguiding core of the fiber, $\delta n = n_{co} - n_{cl}$, n_{co} is the refractive index at the axis of the fiber, and n_{cl} is the refractive index of the cladding. Estimates for multimode fibers yield values which could easily be measured. In an ordinary fiber the concept of a ray is applicable only over

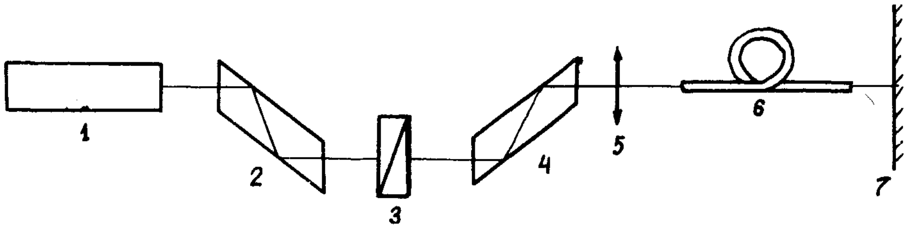

FIG. 1. Experimental layout. *1*—He–Ne laser; *2,4*—Fresnel rhombi; *3*—polarizer; *5*—objective; *6*—optical fiber; *7*—screen.

distances $l < 0.1$ cm, but this effect should be seen as a rotation of the speckle through a coresponding angle.

In this letter we are reporting an experimental test of the effect of the circular nature of the polarization on the twisting of an originally planar trajectory of a ray, as predicted in Ref. 1.

According to the assumptions underlying the derivation of expression (1), the effect could occur only in a fiber in which the depolarization is weak; i.e., the linear polarization of the light should be retained after the light passes through the fiber. Unfortunately, we have not been able to find a multimode graded-index fiber which would maintain a linear polarization over a reasonable distance. Studies were accordingly carried out on a multimode fiber with a stepped index profile. The radius of the lightguiding core of the fiber was $r = 100\ \mu$m; the difference between the refractive indices of the quartz core and the transparent polymer cladding was $\Delta n \sim 6 \times 10^{-3}$.

The experimental apparatus is shown schematically in Fig. 1. The linearly polarized lightly from a He–Ne laser *1* ($\lambda = 0.63\ \mu$m) is sent through a Fresnel rhombus *2* in order to produce circularly polarized light. Polarized *3* makes it possible to achieve a linear polarization in any orientation. The light then passes through a second Fresnel rhombus, *4*. With the appropriate linear polarization, set by polarizer *3*, light with either a right-hand or left-hand circular polarization passes through objective *5* to the entrance of fiber *6*. We follow Ref. 5 in saying that a wave $E = (e_x + ie_y) \times \exp(-i\omega t + ikz)$, where (e_x, e_y, e_z) is the standard right-handed triad of vectors, has a "right-hand polarization." The sense of the circular polarization can easily be changed by rotating polarizer *3* through 90°. The speckle in the light emerging from the fiber is displayed on screen *7*, on which there is a polar-coordinate grid.

A linear polarization is preserved over distances of 30–40 cm in this fiber, but no changes could be found in the speckle when the sense of the circular polarization was changed. At fiber lengths greater than 2 m, in contrast, the light leaving the fiber was polarized to a greater extent, and the changes in the speckle were irregular. In a fiber about 1 m long, the linear polarization was basically retained, so there was the hope that the predicted effect might be observed. Indeed, when the polarization circulation direction was reversed, there was a "flow" of the speckle pattern in the clockwise or counterclockwise direction. The sign of the effect agreed with the predicted sign:

When the circulation was switched from left-hand to right-hand, the speckle "flowed" in the clockwise direction. This flow was accompanied by changes in details, but the basic features retained their shape as they moved in a circle.

The speckle patters of left-hand- and right-hand-polarized light were photographed on the screen in order to determine the rotation angle. A negative image taken in right-hand-polarized light was projected onto a photograph of an image in left-hand-polarized light. When the basic features of the speckle were brought into coincidence, the coordinate grids were found to be separated by an angle $\phi = 1.4 \pm 0.5°$. An estimate from (1), with δn replaced by Δn, for the same fiber length, $l = 96$ cm, yields an angle of 3.2°. The apparent reason for this quantitative discrepancy is that the profile of the refractive index was assumed to be parabolic, rather than stepped, in the derivation of expression (1). In our experiments, however, we did find the correct sign for the effect, and we found an agreement in terms of the order of magnitude of the rotation angle. These circumstances suggest that we have experimentally observed (for the first time, we believe) an effect of the circular nature of polarization on the twisting of an originally plane trajectory of a ray.

We would like to propose "optical ping-pong effect" or "optical Magnus effect" as a name for this effect, predicted previously and now observed. We are thinking of a table-tennis (ping-pong) ball which is incident normally on a rough table surface. If the ball is spinning around an axis, it will deviate from the normal in the corresponding direction after it bounces. A deviation of the same sign occurs because of the Magnus effect when a spinning ball moves through air.

A photon which has undergone repeated reflections in a fiber with a stepped index profile or which has undergone a repeated smooth refraction in a graded-index fiber might be likened to a ping-pong ball. The sign of the circular polarization corresponds to the direction in which the ball is spinning. Curiously, the sign of the optical effect is the same as that of the mechanical effect if the spin or rotation of the photon is understood as the rotation of the electric field as a function of the time in a given fixed cross section $z = \text{const}$.

Another way to describe the effect is to work from the analogy between light waves and de Broglie waves. In quantum-mechanical terms our effect might be thought of as an interaction of the photon's spin (polarization degree of freedom) with the projection of its orbital angular momentum onto the axis of the fiber. However, we are not offering any mathematical foundation for this assertion.

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