Observed transverse shift of a focal spot upon a change in the sign of circular polarization

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This transverse shift $\Delta x \sim \pm\sigma$ was observed experimentally when half of a lens ($y>0$) was illuminated by a circularly polarized plane wave $(\hat{\mathbf{e}}_x + i\sigma\hat{\mathbf{e}}_y)\exp(ikz)$. The observation was carried out in z-polarized scattered light.

As light propagates through an optically inhomogeneous, locally isotropic medium, one observes that the polarization affects the trajectory, and vice versa.[1-4] Until recently, it was believed that the polarization and the propagation were mutually independent in a homogeneous and isotropic medium. However, it was recently shown[5] that, when we are dealing with a superposition of a large number of plane waves (e.g., in the case of a converging beam), some new effects can arise because of an interference of the 3D electromagnetic field vector. Let us imagine that we illuminate the upper half ($y>0$) of a lens made of an isotropic material with a circularly polarized plane wave $\mathbf{E}=E_0(\hat{\mathbf{e}}_x + i\sigma\hat{\mathbf{e}}_y)\exp(ikz)$. Here we have $\sigma=+1$ for light with a right-hand circular polarization, and $\sigma=-1$ for light with a left-hand circular polarization. It was shown in Ref. 5 that a switching of the sign of σ leads to a transverse shift Δx of the "center of gravity" of the focal spot:

$$\Delta x \sim \frac{\sigma\lambda\theta}{2\pi}. \tag{1}$$

Here λ is the wavelength of the light, and θ is the angle at which the rays converge at the focal spot. It was pointed out in Ref. 5 that this shift is impossible in principle to observe by examining the focal spot through a microscope pointed at the beam. It was suggested that a dichroic phosphor be used to observe the focal spot through secondary emission.

In this letter we are reporting observation of this effect in some scattering media. The media were (1) some synthetic opals prepared by A. V. Simonov at the Chelyabinsk Artistic Articles Factory and (2) a solution of laundry soap.

Figure 1 is a schematic diagram of the apparatus. According to Ref. 5, if the left half of the lens, $y>0$, is observed (the observation is carried out along the beam propagation path), then when the circular polarization is switched from left-hand to right-hand the focal spot should move downward, i.e., in the direction $x>0$.

A device for switching the sign of σ was constructed on the basis of a tunable $\lambda/4$ plate.[6] This device provided a circular-polarization quality 0.99 ± 0.01. A converging beam was shaped with an OM-3 short-focus objective from an MBI-15 microscope. The radius of the focal spot, $a_0(\mathrm{HW}e^{-1}\mathrm{M})$ (the half-width of the focal spot of a Gaussian

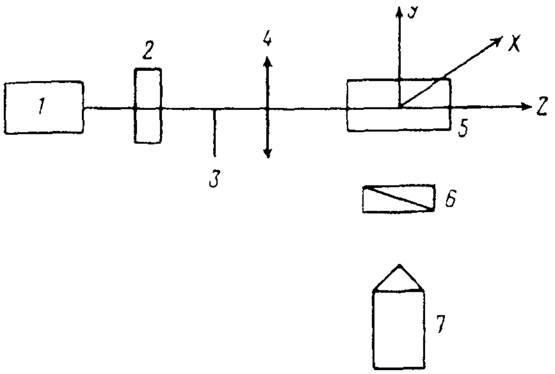

FIG. 1. Optical layout of the experimental apparatus. *1*—He–Ne laser, $\lambda = 0.63$ μm; *2*—Device for switching the sign of the circular polarization; *3*—shutter; *4*—short-focus objective; *5*—scattering object, either a synthetic opal or a cell holding a soap solution; *6*—polarizer; 7—optical magnification and observation system.

beam at the level of e^{-1} of the maximum intensity), was found from the convergence angle of the light beyond the objective, $\theta_0(\text{HW}e^{-1}\text{M})$. At the wavelength $\lambda = 0.63$ μm, it was $a_0 = \lambda/2\pi\theta_0 \approx 1.5$ μm.

The polarizer was positioned in such a way that it was possible to observe a scattering of light caused exclusively by the "forbidden" z components of the optical field. In this case the transverse shift reaches its maximum value:[5]

$$\Delta x(|E_z|^2) \approx \sigma a_0. \qquad (2)$$

The optical system produced a magnified image of the focal spot and made it possible to measure the width of the spot. It was also possible to measure the transverse shift of the center of gravity of the spot. The system formed a magnified image in two steps. First, a 10× intermediate image was produced; then this image was observed under an MBS-10 microscope. This particular optical arrangement made it possible to carry out observations at a magnification of 70× and also to incorporate a polarizer in the arrangement.

According to a visual estimate, the polarizer resulted in an intensity discrimination by a factor of more than 100, in approximate agreement with the angular factor $\theta_0^2 \approx 5\times 10^{-3}$. This result indicates that the scattering is scalar not only in the soap solution but also, to our surprise, in the synthetic opal, which is essentially a quartz synthetic single crystal with an opalescence.

In the synthetic opal, the observed focal spot consisted of fixed speckle spots. In the soap solution, the speckle spots flickered. The visual nature of the observation of the focal spot implies that we apparently determined its diameter d_{obs} in accordance with the e^{-2} condition. If the observed intensity distribution is Gaussian, the quantity $a_0(\text{HW}e^{-1}\text{M})$ can be found as $a_0 = d_{\text{obs}}/2\sqrt{2}$. The quantity d_{obs} was approximately 5 μs in the measurements on both the synthetic opal and the soap solution. The estimate $a_0 \approx 1.75$ μm, which was obtained by visual observation, corresponds approximately in magnitude to that calculated from the angular spectrum in the far zone.

The size of the speckle spots was about $0.1d_{obs}$ during observations in the synthetic opal. For scattering in the soap solution the size of the speckle spots was far smaller, right at the resolution of the optical system used by us.

A transverse shift of the focal spot upon a change in the sign of the circular polarization was observed during scattering of light in various regions of two samples of synthetic opals. We determined the sign of the effect and measured the magnitude of the shift during observation in both the right and left halves of the objective. Repeated observations gave us confidence that the sign of the effect was correct (it agreed with the theoretical prediction in Ref. 5) and made it possible to estimate the magnitude of the shift as about $0.3d_{obs}$, i.e., $\Delta x_{obs}(|E_z|^2) \approx 1.5\ \mu m$. During observation of the focal spot in the soap solution, bright flashes of light scattered by moving microscopic particles hindered the measurements. However, we can reliably assert that the sign of the effect was the predicted sign, and that the magnitude of the shift was smaller than d_{obs}.

To make sure that there were no parasitic effects upon the switching of the sign of the circular polarization, we put a polarizer in front of the objective in some control experiments. When the sign of σ was switched, linearly polarized light still passed through the objective. In this case we observed no change in the intensity distribution in the focal spot. When the objective was completely illuminated (i.e., when both halves were illuminated), the intensity distribution near the focal spot changed in the course of the change in the sign of the circular polarization. However, we can confidently assert that the "center of gravity" of the focal spot does not shift after the change in the sign of σ, in agreement with the theory.

In summary, it can be asserted that we have observed a transverse shift of the focal spot upon a change in the sign of circular polarization. The sign of the effect is as predicted. Quantitative estimates of the observed magnitude of the effect agree with the theory of Ref. 5.

It seems to us highly unusual that a change in the sign of circular polarization of light can lead to a shift of a beam even in vacuum. We would like to stress, however, that according to Ref. 5, the effect conforms completely to standard classical electrodynamics. Furthermore, the primary property of the light waves which was utilized here was their

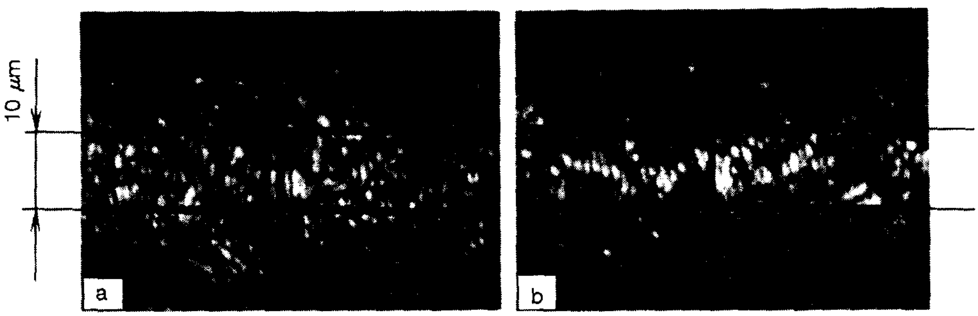

FIG. 2. Image of the focal spot during illumination of the right half of the lens ($y<0$) by circularly polarized light. a—$\sigma=-1$; b—$\sigma=+1$.

transverse nature. Accordingly, effects of this sort should occur for transverse waves of any nature, e.g., acoustic.

The shift can be detected visually quite well, while photographically it is elusive because the shift is small. Nevertheless, we were able to record a photograph which unambiguously demonstrates a shift of the focal spot (Fig. 2).

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[1] S. M. Rytov, Dokl. Akad. Nauk SSSR **18**, 2 (1938).
[2] M. Berry, Proc. R. Soc. London A **392**, 45 (1984).
[3] A. V. Dooghin, N. D. Kundikova, V. S. Liberman, and B. Ya. Zel'dovich, Phys. Rev. A **45**, 8204 (1992).
[4] V. S. Liberman and B. Ya. Zel'dovich, Phys. Rev. A **46**, 5199 (1992).
[5] N. B. Baranova, A. Yu. Savchenko, and B. Ya. Zel'dovich, JETP Lett. **59**, 232 (1994).
[6] I. V. Goltser, M. Ya. Darsht, N. D. Kundikova, and B. Ya. Zel'dovich, Optics Commun. **97**, 291 (1993).

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