Beam splitting due to the finite size of the medium during total reflection

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Experiments have revealed a bireflection: a splitting of an incident beam into two elliptically polarized beams under total-reflection conditions.

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Levanyuk and Gladkiĭ[1] have discussed some effects which stem from the deviation of the actual symmetry group of a crystal of finite size from its point symmetry group. One such effect is a surface anisotropy, whose macroscopic manifestations lie just at the fringe of experimental observation capabilities. Since the normal to a boundary is a preferred direction, an obliquely incident wave could give rise to anisotropic effects unrelated to the change in the structure of the crystal at the surface and due exclusively to the finite size of the medium. In this letter we report the direct experimental observation of a bireflection: the splitting of an electromagnetic beam, upon reflection from the boundary between isotropic media under total-reflection conditions, into two elliptically polarized beams displaced symmetrically from the plane of incidence.

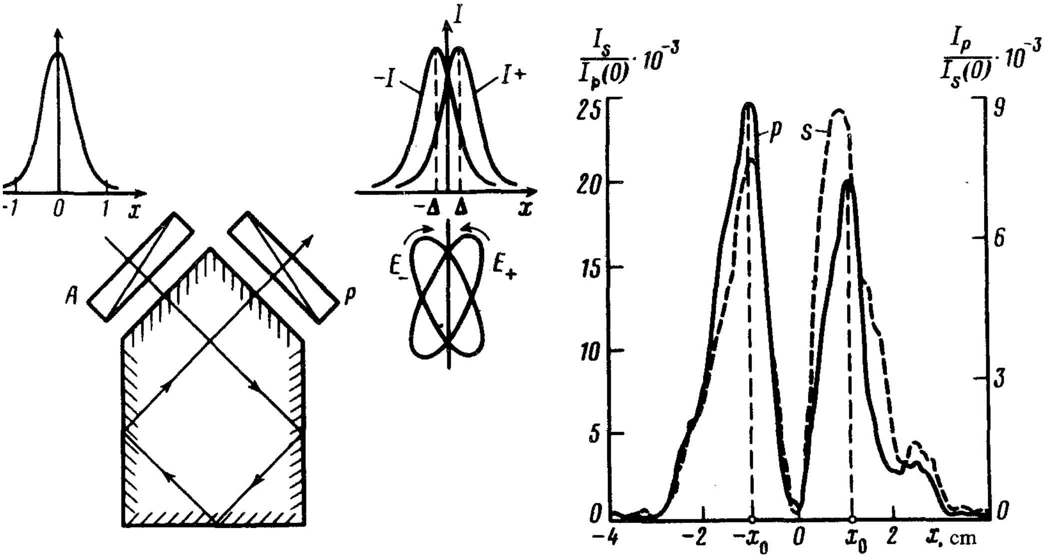

FIG. 1. a—Experimental arrangement; b—intensity distribution along the x axis when the analyzer is crossed with the polarizer.

The experiments were carried out in the millimeter wavelength range on a quasioptical apparatus. A beam with an approximately Gaussian intensity distribution, linearly polarized either in the plane of incidence (p) or perpendicular to this plane (s), was incident at an angle of 45° and underwent triple total reflection by the lateral faces of a Teflon prism with a refractive index $n = 1.432$ (Fig. 1a). The polarizer and analyzer were metal gratings which gave the beam a polarization linear within $\sim 10^{-4}$. We studied the intensity distribution of the reflected beam in the direction perpendicular to the plane of incidence (along the x axis). The crystal detector was positioned inside a metal waveguide with a cross section of 1.6×0.8 mm. With the analyzer crossed with the poalrizer, we observed in the reflected beam not total extinction but some well-resolved peaks positioned symmetrically with respect to the plane of incidence (Fig. 1b). The height of the p-polarization peak is nearly four times that of the s-polarization peak. Changing the profile of the incident beam (by changing the beam divergence) did not affect the observed pattern. With the analyzer parallel to the polarizer, the peaks disappeared.

These results are direct evidence that there are two elliptically polarized reflected beams which are propagating parallel to each other.[1)] The ellipses traced out by the field vectors of the two beams are identical and symmetric with respect to the plane of incidence. The ellipses are traced out in opposite directions. Let us sum two Gaussian beams which are displaced $\pm\Delta$ from the plane of incidence and which have electric vectors

$$E_{\pm} = (E_s \pm i\kappa E_p) \exp[-(x \pm \Delta)^2 / 2a^2]$$

(a is the beam half-width in the intensity, and the parameter κ is a measure of the polarization). For a p-polarized incident beam, we calculate the intensity distribution along the x axis to be

$$\frac{I_s(x)}{I_p(0)} = |\kappa|^2 \,\mathrm{sh}^2 \frac{x\Delta}{a^2} \exp\left(-\frac{x^2}{a^2}\right), \tag{1}$$

where $I_p(0)$ is the intensity of the p component of the reflected beam in the plane of incidence. For the s polarization, the ratio $I_p(x)/I_s(0)$ differs from (1) by a factor of $|\kappa|^{-4}$. These expressions are shown by the curves in Fig. 1b. Substituting into these expressions the experimental values of x_0, $I_s(x_0)/I_p(0)$, $I_p(x_0)/I_s(0)$ (Fig. 1b), and a (experimentally, $a = 9$ mm), we find the value $|\kappa|^2 = 2$ and a splitting $2\Delta = 1.1\lambda$ (λ is the wavelength in the prism).

The physical reason for the observed beam splitting is the appearance of an inhomogeneous wave at the boundary under total-reflection conditions. The field of such a wave has a momentum component perpendicular to the plane of incidence, and the reflected beam should undergo a lateral displacement.[2] The magnitude of this displacement can be estimated by arguments based on energy conservation.[3] The lateral displacement has extreme values for the right-hand (+) and left-hand (−) circularly polarized components of the inhomogeneous wave. The corresponding polarizations of the reflected wave with ellipticity parameters $\kappa = \kappa_\pm$ are found from the Fresnel formulas. After some simple calculations, we find (ϕ is the angle of incidence)

$$\Delta_\pm = \pm \frac{\lambda}{\pi} \frac{2n^3 \operatorname{ctg}\phi}{n^4 - 1},$$
$$\kappa_\pm = \pm \frac{n\,(2n^2 \sin^2\phi - 1)^{1/2}}{n^2 \sin^2\phi + i\,(n^2 \sin^2\phi - 1)^{1/2}}. \tag{2}$$

For the critical angle for total reflection we then find $\Delta_\pm = \pm 0.6\lambda$, $|\kappa_\pm|^2 = n^2 = 2.05$, in good agreement with the experimental values of these quantities, reported above.

In some further experiments we rotated the plane of polarization in the incident beam away from the plane of incidence. We observed a redistribution of the intensity between the side peaks without any change in the splitting 2Δ. We thus conclude that during total reflection the field of the inhomogeneous wave splits into two natural circular polarizations (by analogy with circular birefringence), and the reflected wave splits into two natural elliptical polarizations with parameters κ_+ and κ_- which depend on the relative refractive index and the angle of incidence ϕ. Associated with each of these circular polarizations is a lateral displacement in one direction or the other from the plane of incidence; this displacement gives rise to the observed splitting of the reflected beam.2)

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1)The contribution of diffractive spreading to the appearance of the additional component of the polarization—not present in the original beam—is nearly two orders of magnitude weaker than the observed effect.

2)The special role played by a circular polarization of an inhomogeneous wave with respect to the time evolution of the field vectors and of the Poynting vector has been emphasized by Fedorov.[2]

[1] A. P. Levanyuk and V. V.Gladkiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **31**, 651 (1980) [JETP Lett. **31**, 614 (1980)].
[2] F. I. Fedorov, Dokl. Akad. Nauk SSSR **105**, 465 (1955); Tr. Inst. Fiz. Mat. Akad. Nauk Ukr.SSR **1**, 11 (1956).
[3] N. N. Kirstofel', Uch. Zap. Tartusskogo Univ. No. 42, 95 (1956). No. 42, 95 (1956)

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