REFRACTION OF GLANCING LIGHT FROM AIR TO GLASS

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This paper presents some experimental results indicating that a light beam propagating near the refracting surface deflects from its initial direction of propagation. The depth of the deflection zone is estimated.

By classical views light rays propagating exactly in parallel to the refracting surface are not refracted. However, such is not the case. Acloque and Guillemet[1] in the experiments with two right–angle complanar prisms and optically less dense uniform plates, fabricated from glass and other material cemented together, observed a faint light propagated from the second prism at an angle of incidence being about 1–2′ smaller than the critical angle when they investigated the reasons for initiation of lateral wave in the process of total internal reflection (faint light on the side of the beam reflected at critical angle). In their opinion the radiant intensity rapidly decreased as the distance from the point of incidence to the input edge of the second prism increased. The above–considered experimental scheme was used by Osterberg and Smith[2] who observed refraction of glancing rays from air to the second prism. Their results turned out to be in qualitative agreement with the data of Ref. 1.

As authors noted, reasons for passing of glancing light energy to a denser medium were imperfectly understood. In the effort to show that at critical angle of incidence of light ray it may pass to a less dense medium and then to a denser medium and in this way to explain the initiation of lateral wave, these researchers failed to have a thorough grasp of the essence of this phenomenon. Otherwise they would use only one prism and glancing ray.

Independently of the above–mentioned works, refraction of glancing light was revealed in Refs. 3–9 in experiments on light propagation along the interface between liquid and solid media with slightly different refractive indices. It was established in Refs. 3 and 6 that the above–considered refraction was due to the existence of a zone in a less dense homogeneous medium above the interface between the two media which deflected light rays toward an optically denser medium. Its depth was equal to 5–14 μm for the examined media.

According to Ref. 5, the refracted flux may increase several times in the case of refraction of glancing rays by weakly absorbing plates fabricated from optical glass in comparison with transparent plates.

The experimental evidence for new phenomenon referred to as refraction of light rays propagating out of a refracting surface at the angles up to 14° were presented in Ref. 7 together with the data on the exponential increase of the efficiency of ray deflection at different levels within the zone approaching to the interface. Experiments on the total internal reflection were performed in Ref. 9 to estimate the depth of light energy penetration into the second medium, ray intensity, and energy distribution over the interface. In this work the displacement of a reflected beam was observed that exceeded many times the beam displacement in experiments of Goos and Henken.[10]

There a new phenomenon of ray splitting into an ordinary ray and an extraordinary ray propagating at some angle to the ordinary ray was described and total internal reflection and accompanying phenomena were interpreted on the basis of the existence of a deflection zone at the interface. Above all, refraction of glancing rays suggests the possible refractive index gradient in optically homogeneous glass plates and liquids. But this phenomenon was also observed in air being a less dense medium in which the formation of relatively large gradient of optical density sufficient for noticeable ray deflection was obviously unreal.

At first glance refraction of glancing rays may be easy explained by the fact that points on the wavefront, by Huygens principle, are sources of secondary waves propagating in various directions. In this case a portion of waves passes through the refracting surface into the second medium and forms the refracted beam in it.

To elucidate whether this principle is the objective reality, we analyze the results of experiments on refraction of glancing light from air performed with the use of the scheme shown in Fig. 1. An objective of focal length 50 mm forms the image S' of the slit S of width 30 μm in the plane of the front face of a right–angle equilateral prism fabricated from the K–8 optical glass. The slit is illuminated by a parallel light beam at a wavelength of 0.53 μm. The refractive index of glass n for green rays is equal to 1.5193. The length of refracting face l_r is equal to 10 mm.

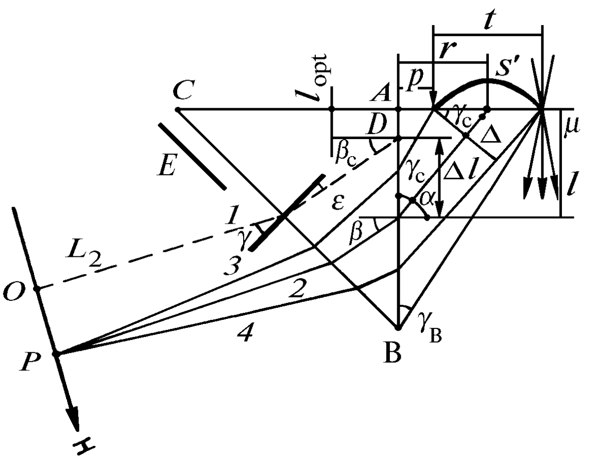

FIG. 1. Experimental scheme for investigation of refraction of a glancing light.

Because the beam is bounded by the slit S'' of width 3.5 mm placed in front of the objective at a distance of 71 mm from S and this slit transmitted only rays that form a central maximum in the focal plane of the

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objective, the angular half–width of the beam coming from S' is $\gamma_r = 1.4°$ and amplitude distribution over the width of S' is Gaussian. The image S' of width 32 μm transmitted 0.974 of the net flux. The beam axis is parallel to the refracting face. As the prism moves perpendicular to the axis of glancing beam towards S', after some time the refracted flux originates that propagates from it. This flux was recorded by a photomultiplier placed at the distance L_2 = 111 mm from hypotenuse face. The distance L was counted off along the beam axis at the instant the refracted light intensity reaches its maximum $J_{opt\ max}$. The ray with maximum intensity $J_{r\ max}$ was taken as the refracted beam axis. To record the intensity distribution of the refracted rays over the beam width $J_r = f(H)$, a slit of width 0.15 mm was placed at the photomultiplier input, then photomultiplier was moved perpendicularly to the beam axis.

It was experimentally found that a region of the face with the most intense refraction of glancing rays was at the distance l_{opt} = 0.22 mm from the input edge A at the instant the intensity of the refracted beam reached its maximum $J_{opt\ max}$, and the S' axis was at the distance r = 4.7 μm from this region. In this case the axial ray *1* propagating within the prism at the critical angle β_c arrived at the input of the photomultiplier at the point O.

Let us consider the process of changing of the refracted flux in more detail by the examples of some characteristic cases.

Case 1. The left edge of the image S' is at the distance p_1 = 8.7 μm from A. In this position sloping rays from the right edge of S' are incident on the edge of refracting face at the angle $\gamma_B = 0.23° < \gamma_r$ and hence this face screens almost half the flux. Because the intensity of sloping rays decreases as the angle of their deflection from the glancing beam axis increases, whereas the transmission of the face, on the contrary, increases, the most efficient refraction of glancing rays will happen at the angle γ_c, which corresponds to the most optimal combination of the above–indicated factors ($\gamma_c = 57.3° r_1/l_1$, where l_1 is the distance from A to the point of incidence of most intense ray *2* in this case). The distance from S' to the refracting face (along ray *2*) is small in comparison with the distance to the photomultiplier. Consequently, rays *2*, *3*, and *4* on the initial section of the path can be considered parallel. In this case the geometric path difference between the central and edge rays $\Delta = 0.5t \sin\gamma_c$, where t is the width of the image S' of the slit.

The direction of the axial ray of the refracted beam, arriving at the point $P_1(P)$, at which the geometric path difference between rays *3* and *4* is zero, differs from the direction of ray *1* by the angle $\Delta\beta = \beta - \beta_c$ given by the formula $\sin \Delta\beta = (1 - \cos\gamma_c)/(n \cos\gamma_c \cos\beta)$. According to this formula, even for $\gamma_c = \gamma_r$, $\Delta\beta = 0.6'$, i.e., ray *2* is practically parallel to ray *1*. For the above–indicated value of n_1, the point P_1 is at the distance H_1 = 1.42 mm from the point O and the most intense refraction of rays *2* happens at the distance $\Delta l = \Delta l_1 = H_1(\cos \varepsilon)/(\cos\gamma \cos\beta_c)$ = 1.9 mm from the point D. Then $l_1 = l_{opt} + \Delta l_1$ = 2.12 mm, $\gamma_c = 0.67°$, and $\Delta = 0.35\lambda$. Because $\Delta < 0.5\lambda$, the refracted beam intensity at the point P_1 is determined by summing over the rays coming from the whole S'. The distribution of J_r over the width of refracted beam under considered conditions is shown by curve *1* in Fig. 2 and its flux is determined by the area enclosed between this curve and the X axis.

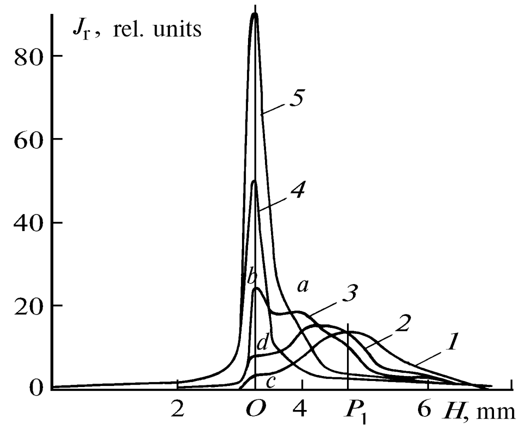

FIG. 2. Intensity distribution over the width of refracted beams at various distances of glancing light beam from the refracting surface.

Case 2. The image S' is overlapped by the front face of the prism from the left at a distance of 11.3 μm. Therefore, the wave amplitude at the input of photomultiplier at the point $J_{r\ max}$ would be less than the light amplitude in the previous example. Correspondingly, $J_{r\ max}$ would decrease, but it conversely increased 6.5 times up to $J_{opt\ max}$ (see curve *5*) and the refracted flux Φ_r became maximum.

Case 3. The image S' is beyond the front face at a distance of 1.3 μm from it. It is obvious that the refracted beam moves in parallel to its previous positions as the distance between S' and prism changes until edge rays *3* and *4* or nearest to them are incident on the refracting face. This means that under these conditions $\gamma_c = 0.67°$. Then for r_2 = 14.7 μm, l_2 = 1.26 mm, Δl_2 = 1.04 mm, and H_2 = 0.8 mm. Indeed, maximum a of J_r = 19 rel. units is seen in curve *3* at a distance of 0.8 mm from the axis of the beam with $J_{opt\ max}$ (from the point O). But at the same time stronger maximum b is seen on the axis of the optimal beam of J_r = 24.5 rel. units. It corresponds to most intense refraction of rays at the distance l_{opt} from the edge A. Central rays from S' are most intense. To form maximum, they must arrive at the point D at the angle $\gamma_c = 57.3° r_2/l_{opt} = 3.8°$, which is larger than the angular half–width of glancing beam with the width of S' being decreased insignificantly, so that the growth of γ_r cannot be attributed to narrowing of the wavefront. Assume, however, that the wave from S' can propagate at the above–indicated angle. In this case eight zones with the geometric path difference of $\lambda/2$ between the edge rays of adjacent zones fall within the width of S' with their center at the maximum b. The adjacent zones will tend to cancel and $J_{r\ b}$ would be close to zero, but actually it exceeds $J_{r\ a}$ resulting from the reinforcement of waves from the whole image S'.

Case 4. The image S' is overlapped by the front face from the left at a width of 20.3 μm. In comparison with previous example, the wave amplitude at the point of $J_{r\ max}$ would decrease several times, and $J_{r\ max}$ would decrease even to a greater extent, but it really increased 2.6 times compared to $J_{r\ a}$ (curve *4*).

According to classical views decrease of the width of the open part of the wavefront must be accompanied by increase in the angular width of the refracted beam. In our case the beam sharply narrowed when S' was overlapped at a distance of 11.3 μm and then the half–width of the distribution $J_r = f(H)$, being equal to its width between the points at which $J_r = 0.5\, J_{r\,max}$, remains constant.

As is seen, the Huygens––Fresnel principle gives no way of explaining the above–considered facts. Refracted beam formed on the basis of this principle has lower Φ_r and $J_{r\,max}$ which is several times less in comparison with $J_{opt\,max}$.

It has been also found that dependence of refracted ray intensity on the axis of optimal beam on the degree of overlap of the image S' by the front face of the prism $J_{opt} = f(\mu)$ is similar to the intensity distribution of glancing rays over the width of the image of slit S, $J_{s'} = f(\mu)$ characterized by the ratio of the reduction of glancing flow $\Delta\Phi_r$ to small increase of the distance of overlap of the image of slit $\Delta\mu$. It follows from this fact and equal arguments of the above–indicated dependences that J_{opt} is not determined by the entire width of S' but is proportional to the intensity of rays coming from much smaller region close to the refracting face, because the values of J_{opt} when S' starts to move beyond the prism are equal to these values at the end of overlap.

For $p_1 = 8.7$ μm the rays coming from the left edge of S' may not fall within the refracting face at the distance from the input edge being shorter than $l = 57.3° \, p_1/\gamma_r = 0.355$ mm.

Nevertheless, J_r on the axis of optimal refracted beam amplifies, as is seen from the weak maximum c in curve *1*. To do this the rays coming from left edge of S' must reach the face at the distance l_{opt} from the point A. This is possible only if the rays deflect from their initial direction beyond the angular beam width.

Consequently, a zone of light ray deflection exists in air near a denser medium. Since this zone affects a small region of the left edge of S' under these conditions as judged from the low amplitude of maximum c, the depth of zone of noticeable deflection of light rays from their initial direction is approximately equal to 9 μm.

It is obvious that the entire depth of this zone is significantly larger since the above–given estimate ignores the depths at which the rays are deflected at smaller angles. As p decreases from 8.7 to 3.7 μm, the number of glancing rays in the zone increases. The resultant intensity on the axis of the optimal beam becomes higher (see curve *2*, maximum d).

In the second case the center of S' is at a distance of 4.7 μm from the prism, i.e., at the center of effective region of the zone. Consequently, the maximum flux of glancing rays that are incident on the region of the face at the distance l_{opt} from the input face passes through it. Thus the intensity in the optimally refracted beam reaches maximum.

When S' is widened up to 300 μm and the width of S'' is narrowed down to 0.5 mm, the ratio $J_{s'\,max}/J_{opt\,max}$ and distribution of J_r over the width of the optimal beam remain uncharged, although open part of the wavefront increases by an order of magnitude and γ_r decreases down to 0.32°. This fact supports the conclusion that J_{opt} is independent of the width of S' until its central part becomes smaller than the depth of the zone, and testifies that primary contribution to the refracted light comes from the axial glancing rays.

Refraction of glancing light in the absence of sufficiently large refractive index gradient in air and impossibility to explain this phenomenon on the basis of classical views readily suggest the unknown mechanism of light interaction with matter that gives rise to deflection of light rays from their initial direction of propagation.

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