SOME SPECIFIC FEATURES OF REFRACTION OF GLANCING LIGHT AND LIGHT PASSING THROUGH A REFRACTIVE SURFACE FROM AIR TO GLASS

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It has been found experimentally that when glancing light is refracted, the maximum intensity in a refracted beam is caused by rays that initially propagate at a distance of about 5 μm *from a refractive surface. The reason for the formation of the refracted edge rays has been elucidated. The maximum intensities of the refracted and glancing beams have been compared. It has been established that the maximum intensity of the refracted beam passing from air to glass is equal to that of the beam passing from transparent glass to liquid. It has been proved experimentally that the main contribution to the refracted glancing beam passing from air to glass comes from the initial region of the face about* 1 mm *in length. The reason for this is clarified. The efficiency of light ray deflection in this zone has been increased. The reason for a delayed decay of the intensity of the refracted light with the increase of the angle of departure of rays leaving the refractive surface has been given.*

New experimental data on the refraction of glancing light and light passing through a refractive surface from air to glass are given in the present paper that is a continuation of Refs. 1 and 2. The experiments were based on the scheme described in Ref. 1. A monochromatic beam (λ = 0.53 μm) of width 27 or 300 μm in the image plane S' of a slit S being a light source with angular half-width γ_h = 1.4 or 0.32° was used in the experiments. An image of the slit S' was constructed on the front plane of refractive bodies.

As shown in Ref. 1, refraction of the glancing light is due to the formation of a zone above the surface of bodies that deflects the light rays in two different directions on both sides of the initial direction of light propagation. According to Refs. 2 and 3, the efficiency of deflection in this zone decreases with distances from the refractive surface and from its edges. According to Ref. 1, the maximum intensity of the refracted beam at the photomultiplier input $J_{opt.max}$ is produced by the glancing rays coming from the center of S' and being most intense.

For the glancing rays refracted at critical angles as they passed through the opposite faces of a plane-parallel plate (see Fig. 1) moved along the μ axis by screwing in a micrometer screw, the distance Δμ between the centers of S' at the instant of the maximum intensities of the refracted rays R_1 and R_2 was by 9.4 μm greater than the thickness of the plate. Therefore, the glancing rays come at points with $J_{opt.max}$ after their refraction at points located at the distance h = 4.7 μm from the refractive surface. The fact that h is equal to the distance from the screen to the center of S' at the instant of the maximum intensity of the edge ray flux[3] Φ_{B11} is indicative of the common factors engendering the refraction of the glancing rays and the formation of the edge light at the screen edges.

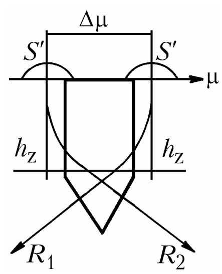

FIG. 1. Scheme of refraction of the glancing light passing from air to glass.

The sine of the incidence angles differs increasingly more from unity as the distance between the points of the ray incidence and the input edge A of a prism fabricated from K8 glass decreases (see Fig. 1 of Ref. 1) due to ray deflection in a more efficient zone. For this reason, the incident rays refracted at different angles smaller than the critical angle of refraction engender the edge light E_1 (see Fig. 2 of Ref. 2). Part of the edge light is repeatedly deflected in the deflection zone of the front face[3] engendering the edge rays E_2. For the glancing rays passing from the

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plate to optically denser liquid, the deflection zone is not formed and the edge light consists only of the rays E_1. The formation of the edge rays $E_{1,2}$ due to deflection of the glancing light in the most efficient region of the zone, i.e., at very small distances from the face, is also confirmed by the fact that the fluxes of rays $E_{1,2}$ achieve their maxima before $J_{\text{opt.max}}$ is reached when S' moves beyond the frontal face of the prism. In this case, the distance between the centers of S' with $J_{\text{opt.max}}$ and maximum intensities of rays $E_{1,2}$ was about 5 μm.

When going from red to green light with $\lambda = 0.638$ μm with the use of an interference filter, the glancing flux Φ_g from S' of width 27 μm was decreased by a factor of 3.9 and the reflected flux was decreased by a factor of 3.35. Practically identical attenuation of fluxes is indicative of the absence of essential difference between the depths of the deflection zones and their efficiency for green and red light.

Due to small angular divergence, a beam of ordinary refracted rays (refracted at critical angles and angles close to them) has approximately the same width near the hypotenuse face of the prism 7.1 mm high as at a distance of 112 mm from this face at the photomultiplier input.

The intensity $J_{\text{opt.max}}$ was decreased by a factor of 2.61 when the distance from the refractive face to the photomultiplier along the axial ray was increased by a factor of 2.72 (see Ref. 1). A decrease in the intensity would have been smaller by a factor of 2.15, if the glancing beam had not come divergent in the vertical plane from the back focus of an objective spaced at 59 mm from S'.

According to our measurements, the maximum intensity of the refracted light with the electric vector in the refraction plane J_p was by a factor of 2.33 higher than that with the electric vector in the plane orthogonal to the refraction plane J_s. Moreover, $J_p/J_s = n^2$.

The maximum refracted flux $\Phi_{\text{r.max}}$ was equal to $\Delta\Phi_g$ coming from the central part of S' 0.7 μm wide. If we considered the distance at which the axis of S' was at the instant of $J_{\text{opt.max}}$ as the zone boundary, Φ_r would be $0.7/4.7 = 0.15$ of the total flux of the glancing rays entering this zone. The major part of the refracted rays is reflected from the face thereby intensifying the edge light on the illuminated side. Therefore, Φ_{B11} is equal to $0.09\Phi_g$ (see Ref. 3).

For green light, the intensity $J_{\text{opt.max}}$ at the photomultiplier input is equal to 0.1 of the maximum intensity of the glancing ray J_g achieved at a distance of 107.5 mm from S'. When we use a He–Ne laser as a source, $J_p/J_g = 0.19$ and $J_s/J_g = 0.107$.

As our measurements have shown, $J_{\text{opt.max}}$ in the refracted flux coming from the prism was practically equal to that in the glancing light passing from a transparent plate fabricated of LK5 glass to dimethylphthalate ($n_{\text{rel}} = 1.0236$) irrespective of the great difference between the refractive indices of the refractive surfaces.

Figure 2 shows variations in the intensity of the refracted rays as functions of the distance of the incidence point of the glancing light from the front edge of the prism measured with a scanning slit placed at a distance of 3 mm from the hypotenuse face of the prism.

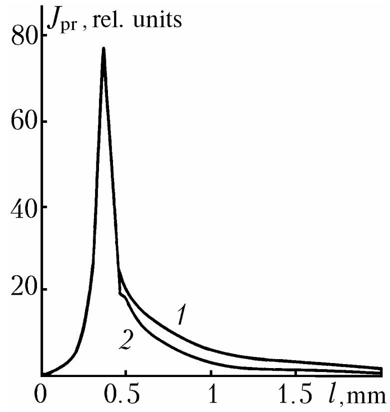

FIG. 2. Variations in the intensity of the refracted glancing rays across the length of the refractive face.

Curve *1* is for S' 27 μm wide and curve *2* is for S' 300 μm wide. Here, l denotes the distance along the refractive face. In the first case, the intensity of light propagating along the face decreases with the increase of l ($\gamma_h = 1.4°$) and in the second case, it remains practically unchanged ($\gamma_h = 0.32°$). These curves show that the major part of the glancing rays is refracted in the initial region of the face.

Thus, J_{pr} is 0.1 and 0.05 of $J_{\text{pr.max}}$ when the rays are refracted at distances of 0.37 and 0.6 mm from the point of their most efficient refraction for S' 300 μm wide. These distances are equal to 0.58 and 0.98 mm for S' 27 μm wide, i.e., they are larger in spite of a decrease in the intensity of the glancing light along the face.

In connection with the decrease of the efficiency of light deflection in the zone in the direction from the prism to its external boundary, the rays refracted near the front edge of the prism at greater distances from it and still deflected in the subsequent region of the zone with constant efficiency along the face length are incident on the regions of the face located at greater distances.

Due to a gradual decrease in the efficiency of deflection of the glancing rays in the initial region of the zone as the distance from the front edge to the point of ray incidence increases, the angles of the incidence of the glancing rays on the face will decrease progressively until the major part of rays is deflected in the region of the zone with constant efficiency along the face length. Smaller angles of ray incidence result in the decrease of the transmissivity of the face. However, this decrease of the refracted flux should be compensated due to an increase in the intensity of light incident on the face caused by the decrease of the efficiency of deflection of the glancing rays upon entering the zone. For this reason, the refracted light must come from the entire face. However, it primarily comes from its initial region.

This peculiarity seemingly suggests the low efficiency of the deflection zone at great distances from the front edge of the prism. However, when the efficiency of the zone beyond the region of the face with efficient deflection of the glancing rays is increased by way of ruling fine lines spaced, for example, 1 mm apart and parallel to the front edge, the intensity of the refracted light increases only insignificantly, though the efficiency of the zone in the regions adjacent to the lines becomes approximately equal to that near the front edge. This is confirmed by Fig. 3*a*, in which curve *1* shows the refracted light intensity distribution across the width of the refracted beam at a distance of 118 mm from the refractive face without lines and curve *2* – with the lines for S' 300 μm wide.

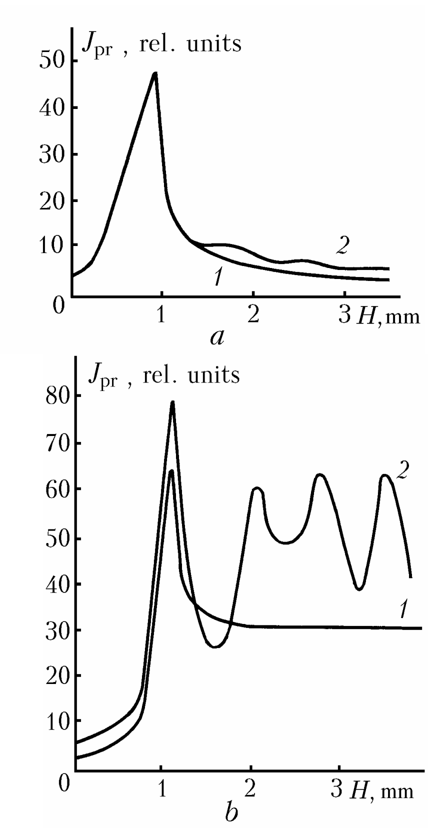

FIG. 3. An increase in the intensity of the refracted glancing rays and rays incident at an angle to the refractive surface caused by ruling of the lines on it.

The increase of the efficiency of the deflection zone in the region of the face with passive refraction of glancing light caused by ruling of the lines is confirmed by an essential increase in the intensity of the refracted rays when the prism is rotated through 0.82° in a counterclockwise direction about the edge *A* for the light be incident at an angle to the face. This is evident from curves *1* and *2* of Fig. 3*b* that show the intensity of the refracted rays at the photomultiplier input without lines on the face and with them, respectively.

As follows from the above discussion, the increase of the efficiency of the deflection zone in the passive region of the face never results in the essential increase of the intensity of the refracted rays until the beam is incident at an angle to the face and its rays are incident on the face without their deflection in the zone. This deflection in the zone increases the angle of the ray incidence. Meanwhile, the glancing rays are incident on the face only after their deflection in the zone. Therefore, the first reason for the low intensity of the refracted rays coming from the passive region of the face is the decreased capability of the glancing rays to deflect toward the face after they have passed the zone from its origin at the front edge of the prism to this passive region.

If the light beam is considered to mean a trajectory of propagation of an elementary light wave associated with a photon, the essence of this process will be easy explained on the basis of the assumption considered in Ref. 4 before a more sophisticated treatment. According to this assumption, photons are in different states as far as the direction of their deflection in the zone is concerned. On their way along the active region of the face, they may change the state in which they deflect toward the face to an intermediate state in which they propagate in the zone without deflection or to an opposite state in which they are deflected from the face at angles determined by the efficiency of the region of the zone in which they find themselves at the instant of changing their state.

In connection with the deflection of the glancing rays in the zone near the front edge of the prism with gradually decreasing efficiency as the points of the ray incidence on the face move away from its origin, the major part of rays will be deflected in the region of the zone with constant efficiency along the face length. This ensures nearly the same angles of ray deflection before and after reflection. Under these conditions, the refracted rays are repeatedly deflected by the zone and engender the glancing rays that deflect toward the face. Because of the loss of half the wave by reflection, these rays are in antiphase with the rays deflected in the region of the zone with still lower efficiency and coming at the same points without preliminary reflection by the face. Mutual attenuation of these rays is the second reason of the low intensity of the refracted glancing light coming from the passive region of the face. The reality of this reason was confirmed experimentally in Ref. 3.

In principle, doubly reflected rays must deflect again engendering the glancing light and the above-described cycle be repeated resulting in arched trajectories of light propagation in the zone. However, in this case the rays not only in antiphase but also the rays with a phase shift of 2π be incident on the passive region of the face and the decay of the intensity be not so sharp. It seems likely that the transit time of light across the region of the zone with low efficiency of deflection to the points of its secondary reflection is comparable to the lifetime of the photon state in which it deflects toward the face. For this reason, the third (and so on) incidence of the refracted rays on the face is highly improbable.

A decrease in the intensity of the refracted light at large distances from the face origin as the width of S' changes from 300 to 27 μm is caused by the fact that the glancing rays incident for the first time on the passive region of the face are deflected at greater distances from the front edge than the rays incident for the second time after their preliminary reflection. Since the half-width of S' equal to 13.5 μm is comparable to the depth of the deflection zone and the intensity of light decreases from the center of S' toward its edges, the intensity of the glancing rays incident for the first time on the passive region of the face is lower than the intensity of rays incident for the second time. Therefore, mutual attenuation of these rays will be less pronounced. When the width of S' is increased up to 300 μm, the flux of the glancing rays does not change with depth of the zone. For this reason, the attenuation of rays incident on the passive region of the face discussed above is more pronounced.

For the rays refracted at a distance of 0.62 mm from the point of refraction of the glancing rays coming to $J_{opt.max}$ and incident on the slit moved along the hypotenuse face, they will achieve their maximum when S' is displaced from its positions at instant of the maximum intensity of the edge rays E_2 incident on the slit and of $J_{opt.max}$ by 7.2 and 2.5 μm, respectively. If we suggest that these edge rays are reflected near the face, the rays coming to the end of its active region will deflect from the level in the zone at a distance of 7.2 μm from the prism. In this case, the flux of the glancing rays incident on the face between the point of their refraction along the axis of the optimal beam and the end of the active region will initially propagate in the layer of the zone 2.5 μm thick and the center of S' will be at a distance of $(7.2 - 2.5) = 4.7$ μm from the prism.

Now we consider a very interesting case of light refraction. The explanation of its essence will vividly confirm the initial phase delay and advance by 0.5π of the edge rays propagating, respectively, to the shadow of the screen and in the opposite direction, relative to the phase of the incident light as well as the difference between the rays as far as the direction of their deflection is concerned.[4]

The rotation of the prism through the angle $i = 0.82°$ discussed above results in the intensified refraction of light over the entire face (Fig. 4, curve *2*) for S' 300 μm wide. Quite the reverse, for S' 27 μm wide the refracted rays come from the smaller region of the face after the prism rotation (Fig. 5, curve *2*). In this case, the intensity of the refracted rays vanishes at the distance $l = 1.23$ mm from the front edge (Fig. 6). This value of l corresponds to $p_1 = li/57.3 = 17.6$ μm. Since at the instant of the maximum flux of the refracted rays the axis of S' is at a distance of 4.7 μm from the edge A, the quantity $(p_1 - 4.7) = 13$ μm is practically equal to the half-width of S'. This means that the projection of the right edge of S' is the boundary of the deflection zone. Therefore, the refracted flux is formed only by the rays that are within the region of propagation of the central rays *1*, though to their right at $\gamma_h = 1.4°$ we observe considerable light flux. The major portion of it propagating at angles smaller than $\delta = (l_f - l)i/l_f = 0.7°$, where $l_f = 10$ mm is the face length, is at glancing angles 0.11–0.82° to the face and must be refracted. Nevertheless, at distances greater than l the refracted light is not observed.

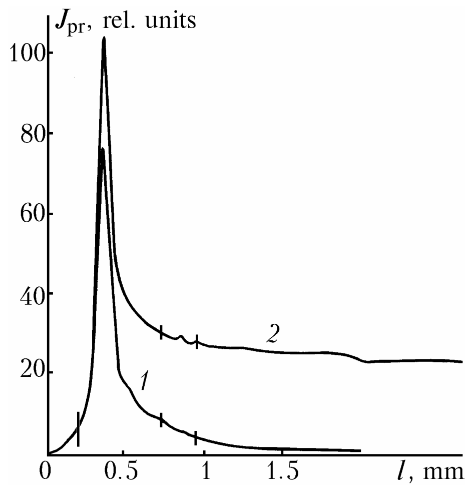

FIG. 4. Distribution of the intensity of the refracted rays across the length of the refractive surface at $i = 0$ and 0.82° for S' 300 μm wide.

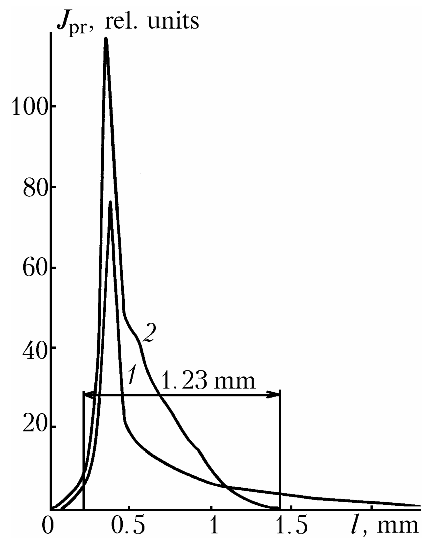

FIG. 5. Distribution of the intensity of the refracted rays across the length of the refractive surface at $i = 0$ and 0.82° for S' 27 μm wide.

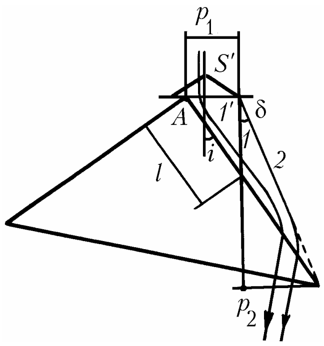

FIG. 6. Scheme of mutual cancellation of rays refracted beyond the projection of the right edge of S′ onto the refractive face at $i = 0.82°$ for S′ 27 μm wide.

The essence of this phenomenon is the following. Since p_1 is large, the right edge of S' finds itself in the region of the deflection zone having low efficiency and producing no essential additional phase shift as the rays pass through it. Therefore, rays *2* held their phase delay of 0.5π relative to the incident light, which arises at the instant of their deflection in the zone of the left screen of the slit S (see Ref. 5). The central rays *1′* undergo a phase advance by 0.5π due to their deflection in the zone in the direction from the face of the prism.[5] Due to the slope of the prism, the rays approach the face until the perpendicular component of their velocity vanishes. Then they deflect from the face but in a less efficient region of the zone and hence have no time to leave this region before the state of photons is changed to intermediate or opposite one. As these rays continue to propagate in the zone, they are incident on the face after the state of photons has been changed to that in which they deflect toward the face. Then they are superposed with rays *2*. These rays attenuate due to the initial phase shift by $[0.5\pi - (-0.5\pi)] = \pi$.

For S' 300 μm wide, the rays *2* pass by the prism and the rays *1′* are superposed with the rays *1* whose phase shift is caused by the geometric path difference and is less than 0.5π. The refracted light comes from the entire face because these rays do not cancel each other.

As was pointed out in Ref. 6, when the prism was rotated in a clockwise direction about the edge A, the intensity of the refracted light gradually decreased and vanished at the angle of rotation $\gamma = 14°$ (see Figs. 1 and 2 of Ref. 6) rather than vanished abruptly. In this case, the light continued to propagate at the critical angle of refraction. It was shown that this phenomenon was caused by preliminary deflection of a number of outgoing rays engendering the glancing light and their subsequent deflection toward the face.

Due to the fact that the intensity of the refracted light is proportional to the glancing flux in the zone, the intensity of the refracted rays J_r of the outgoing beam must be proportional to that of part of the edge light which is engendered by deflection of the outgoing rays in the initial region of the zone and forms glancing rays (at points E). However, it is seen from Table I that as γ increases from 0.13 to 5.22°, the intensity of the glancing light decreases by a factor of 1632, whereas J_e decreases only by a factor of 18.1.

TABLE I.

Serial number	γ, deg	J_{ei}/J_{e7}	J_{ri}/J_{r7}
1	0.13	1632	18.1
2	0.36	211.4	14.7
3	0.59	78.6	12.5
4	1.52	12	6.6
5	2.44	4.6	3.8
6	3.37	2.43	2.5
7	5.22	1	1

In this case, the decay of J_r, highly delayed at small γ, gradually becomes faster and at $\gamma \geq 3.4°$ becomes proportional to J_e. The ratio J_{ei}/J_{e7} was calculated by formula (10) of Ref. 7, where i denotes the serial number of rows in Table I.

The refracted light intensity is small in comparison with the reflected light intensity because of the small angles of the incidence of the rays deflected in the zone toward the face. Therefore, the delayed decay of J_r of refracted outgoing light is most probably due to a more efficient transformation of the rays incident on the face into the refracted beam caused by attenuation of the reflected edge light.

When the glancing rays enter the deflection zone ($\gamma = 0$), the region of the face, after reflection from which the rays are deflected at the same angles as before this reflection and hence form glancing rays, is at a great distance l_g from the origin of the face, because the region of the zone adjacent to the prism edge is more efficient. The rays deflected at shorter distances from the edge are incident on the face beyond this region, closer to face origin, and leave the zone thereby intensifying the outgoing edge light. The transit time of rays incident on the face at great distances after their deflection in the region of the zone having low efficiency and adjacent to the front face of the prism is comparable to the lifetime of the original state of photons characterized by deflection of rays toward the face. Therefore, the probability that these rays will be incident on the face more than twice is very small.

When the light beam goes out from the refractive face, all the rays entering the zone to the left of the boundary ray[6] and deflected toward the face will form the glancing rays only when they pass a certain distance in the zone. This occurs the sooner, the more efficient is the region of the zone in which they deflect. For this reason, the glancing points of a certain number of rays are beyond the region of the zone in which the efficiency of deflection varies along the face length that is apparently much less than l_g. These rays will further propagate along the arched trajectories until photons change their states (see Fig. 1 of Ref. 6). The closer is the glancing point to the face, the shorter are archs because the efficiency of the zone increases as the distance from the face decreases, the larger is the number of arches in a ray trajectory, the more times the rays are incident on the face and hence the larger number of rays transforms into the refracted beam. In connection with the refraction of rays after different number of their reflection accompanied by the loss of half the wave by each reflection, their path differences will differ and the refracted flux coming from the active region of the zone will not attenuate.

As γ increases, the efficiency of the zone also must increase for the glancing rays to be formed. In this case, the rays form the glancing rays at greater distances from the origin of the zone and of the face. In its turn, the displacement of the glancing points results in the decrease of the number of arches in ray trajectories by the instant of changing of photon states. For this reason, the rate of decay of J_r gradually approaches the rate of variations in the intensity of the glancing edge light.

As is evident from the above discussion, the delayed decay of J_r at $\gamma \leq 3.4°$ is caused by a partial compensation for the attenuation of the intensity of the refracted light due to a smaller number of the glancing edge rays owing to the increase of the probability of their refraction caused by a larger number of the ray incidence on the refractive surface as compared with that at $\gamma = 0$.

Approximately identical intensities of the refracted rays from the glancing beam for a wide range of variation of the relative refractive indices of the two media apparently suggest that at $\gamma = 0$ a certain part of light continue to propagate along the arched trajectories through the active region of the prism face. This is possible for that portion of light whose rays start to deflect toward the face only in the region of the zone uniform across its lengths after they have passed its initial region with nonuniform efficiency when photons were in their intermediate state.

For the reasons discussed above the glancing rays refracted near the back edge of the prism also form the edge light. Its rays interfere with the ordinary refracted rays in the photomultiplier plane and a weak interference pattern can be seen in the region of projection of the back region of the refractive face. The width of fringes is nearly the same as that in the pattern produced by the ordinary refracted light and the edge light coming from the region of the front edge of the prism.

Due to the mutual attenuation of the refracted rays in the passive region of the face, the intensity of the first maximum in the diffraction pattern from the back edge of the prism is by a factor of 36 lower than that of the first maximum in the diffraction pattern from the front edge and is only by a factor of 2.3 higher than that at a distance from the face end.

According to measurements, the distance between the ordinary refracted rays coming to the first maxima of both patterns measured in the plane of the face is less by 0.44 mm than the length of the refractive face. Therefore, the rays producing $J_{\text{opt.max}}$ at the photomultiplier input are refracted at the distance $l_{\text{opt}} = 0.44/2 = 0.22$ mm from the prism edges.

The results of the present paper enable us to draw the following conclusions:

1. The maximum intensity in the light beam refracted at the critical angle from air to glass is caused by the glancing rays deflected in the deflection zone at a distance of about 5 μm from the refractive surface.

2. The light refracted at critical angles is engendered by the glancing rays that are incident at the refractive face at angles whose sinus is equal to unity after their deflection in the zone. The glancing rays deflected at larger angles engender the refracted edge light propagating at different angles from the initial region of the refractive surface.

3. The most intense refracted edge light is engendered by the glancing rays that initially propagate in the region of the deflection zone located by 5 μm closer to refractive surface in comparison with the glancing rays that produce light refracted at the critical angle with maximum intensity.

4. The depth and the efficiency of the deflection zone are practically the same for light rays with different λ.

5. The ratio of the maximum intensity of the refracted glancing light with the electric vector in the refraction plane to that with the electric vector in the orthogonal plane is equal to the square of the relative refractive index.

6. The maximum intensity of the refracted light remains practically unchanged for the glancing rays passing from air to glass and through the interface between the media with $n \to 1$.

7. The major portion of glancing light passing from air to glass is refracted in the initial region of the refractive surface about 1 mm long in the deflection zone 7–8 μm thick.

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