INVESTIGATION OF FACTORS ENGENDERING THE EDGE LIGHT AND PECULIARITIES OF ITS FORMATION IN OPTICALLY DENSER AND LESS DENSE MEDIA

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Received October 26, 1994

It has been established experimentally that a zone is formed in an optically denser medium above the interface, which is a major source of the edge light produced due to deflection of light rays in two different directions on both sides of the initial propagation direction. It has been found that the edge light coming from optically denser medium exhibits sharply pronounced asymmetry about the direction of light incidence. An explanation for the asymmetry has been provided. The effect of polarization on the edge light coming from denser medium has been examined. It has been demonstrated experimentally that diffraction zones in denser and less dense media deflect the same light rays in opposite directions.

This work continues investigations described in Ref. 1. They demonstrate that a zone is formed above a body surface in which incident light rays deflect on both sides of the initial propagation direction, thereby producing the major portion of the edge light flux. To elucidate conditions of formation of the edge wave in optically denser homogeneous media, the slit S_b of the experimental setup shown in Fig. 1 of Ref. 1 was replaced by a rectangular prism with a polished face AB (see Fig. 1*a*). The prism was fabricated from K8 optical glass and was 6.2 mm high. The face width t was equal to 114 μm. It matched the plane of the image S' of a linear light source. The distance from S' to a photomultiplier input L was equal to 118 mm, S' was 23 μm wide, angular half–width of a light beam coming from S' was $\gamma_{inc} = 1.4–1.6°$, the width of the beam projection onto the plane of photomultiplier input was 6–6.6 mm. The image S' of the light source is shown in the figure in the form of approximate distribution of the light intensity over its width.

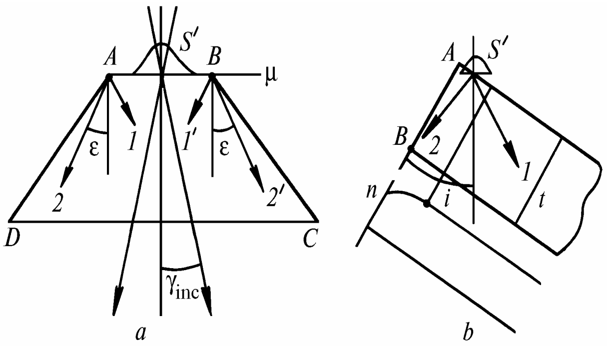

FIG. 1. Scheme of investigation of the factors engendering the edge light in optically denser media.

As the prism moves from the position in which S' is in the middle of the face and the incident beam is undistorted so as S' approaches the edge A, after a while horizontal bands B_1 and B_2 appear in the field of view on both sides of the incident beam projection that are formed by the edge rays *1* and *2* and are analogous to the bands from S_b. As S' approaches the edge B, $B_{1'}$ and $B_{2'}$ appear that are mirror symmetrical to B_1 and B_2.

In accordance with Ref. 1, the flux of edge rays *1* and *1'* is produced by the rays coming from the center of S' at the original parts of B_1 and B_2 5.5 mm wide (Φ_{B11} and $\Phi_{B1'1}$).

The experiments have shown that displacement of the prism $\Delta\mu_1$ from the position with maximum Φ_{B11} to that with maximum $\Phi_{B1'1}$ was equal to 106 μm, that is, Φ_{B11} and $\Phi_{B1'1}$ reach their maxima at the instant when the center of S' was at the distance $h_{z.1} = (t - \Delta\mu_1)/2 = 4$ μm from the edges rather than matched the edges. Thus, a zone is also formed in optically denser medium (prism) above the interface $AD(BC)$ between glass and air, in which incident rays deflect on both sides from the initial propagation direction and hence form the edge rays. This value of $h_{z.1}$ is approximately equal to $h_{z.1}$ in air.[1]

As S' approaches the edges, $\Phi_{B11(B1'1)}$ reaches its maximum when the center of S' is at the distance from the edge being 2.7 μm larger than the corresponding distance at the instant of maximum $\Phi_{B21(2'1)}$.

Table I gives the intensity of the edge rays *1*(*1'*) and *2*(*2'*) as a function of $H(\varepsilon)$ recorded with a laser light source at $\lambda = 0.6328$ μm when the electric wave vector is in the plane of incidence (P–component). (Here, H is the distance from the incident beam axis to the centers of the intervals 5.5 mm wide arranged consecutively along the bands in the input plane of the photomultiplier.) These data indicate that the edge light coming from optically denser medium exhibits sharply pronounced asymmetry. This effect intensifies with increasing H; therefore, the band $B_{1'1}$ is long and bright, whereas $B_{2'2}$ is short and weak. The ratio of Φ_{B11P} (the edge light with prism) to Φ_{B11S} (the edge light with slit formed by blades) is equal to 1.18, and the ratio of Φ_{B21P} to Φ_{B21S} is equal to 0.77. A comparison with the edge light from blade shows that here the P–component of the edge rays *1*(*1'*) is stronger than the S–component, while the P–component of the edge rays *2*(*2'*) is weaker than the S–component, therefore, $\Phi_{B11P}/\Phi_{B21P} = 6.8$ and $\Phi_{B11S}/\Phi_{B21S} = 4.4$.

0235-6880/95/06 419-04 $02.00

TABLE I.

H, mm	Φ_{B1i}, rel. units	Φ_{B2i}, rel.units	$\dfrac{\Phi_{B1i}}{\Phi_{B2i}}$
5.8	122.4	18.6	6.6
11.6	23.2	3.8	6.2
17.4	11.1	1.36	8.2
23.2	7.3	0.7	10.3

When the electric wave vector is perpendicular to the plane of incidence, Φ_{B11} with prism is 2.11 times stronger than with blade. When the electric wave vector is in the plane of incidence, Φ_{B11} with prism is 2.34 times greater than Φ_{B11} with blade. When the electric wave vector is perpendicular to the plane of incidence, Φ_{B21} with prism is 1.34 times weaker than Φ_{B21} with blade. When the electric wave vector is in the plane of incidence, Φ_{B21} with prism is 2.8 times weaker than Φ_{B21} with blade.

When a source of the edge light is the refraction zone of blade, $\Phi_{B11}/\Phi_{B21} = 5.6$ and $\Phi_{B21}/\Phi_{B22} = 5$. In the case of the edge light coming from the zone in prism, these ratios are equal to 5.3 and 4.9, correspondingly.

As is seen, the edge light coming from prism and blade obeys the same law as a function of $H(\varepsilon)$.

Table II summarizes the data on the edge light asymmetry in plane–parallel plates (Fig. 1*b*) fabricated from different materials and tilted at the angle $i = 14°$ with respect to the incident beam axis (natural light).

TABLE II.

Plate material	$\dfrac{\Phi_{\mathrm{B}1i}}{\Phi_{\mathrm{B}2i}}$	t, mm
Quartz crystal	1.52	3.5
Fused quartz	3.1	2.1
K8 glass	3.56	2.2
PS14 glass	6.7	3

Proceeding from the lowest degree of asymmetry of the edge light formed in a quartz crystal plate and a lower degree of asymmetry of the edge rays coming from a plate fabricated from K8 glass (in comparison with the asymmetry of the edge flux coming from a prism), we may suggest that it is caused by the formation of a transition layer[2] in plates and prisms in which the refractive index decreases from that of the material down to a fixed value in the direction toward their surfaces. In this case, the transition layer will impede deflection of rays *2* toward the face *AB* and will promote the deflection of rays *1* off the face.

Figures 2*a* and *b* show the light intensity distribution in the input plane of the photomultiplier over the incident beam width for the case of the edge ray formation in the region of the blade edge and near the edge *A* of the prism. Curves *1* characterize *J* in undistorted incident beam, curves *2* – when the center of *S'* is in the diffraction zone of the blade and prism, halfway between its positions with maximum Φ_{B11} and Φ_{B21}. Curve *2* in Fig. 2*a* is nearly symmetrical about the undistorted beam axis, whereas curve *2* in Fig. 2*b* is shifted to the right, that is, the transition layer pulls more intense edge rays *2*, forming *B*2, in the region of projection of the undistorted incident beam, and pulls out more intensive rays *1*.

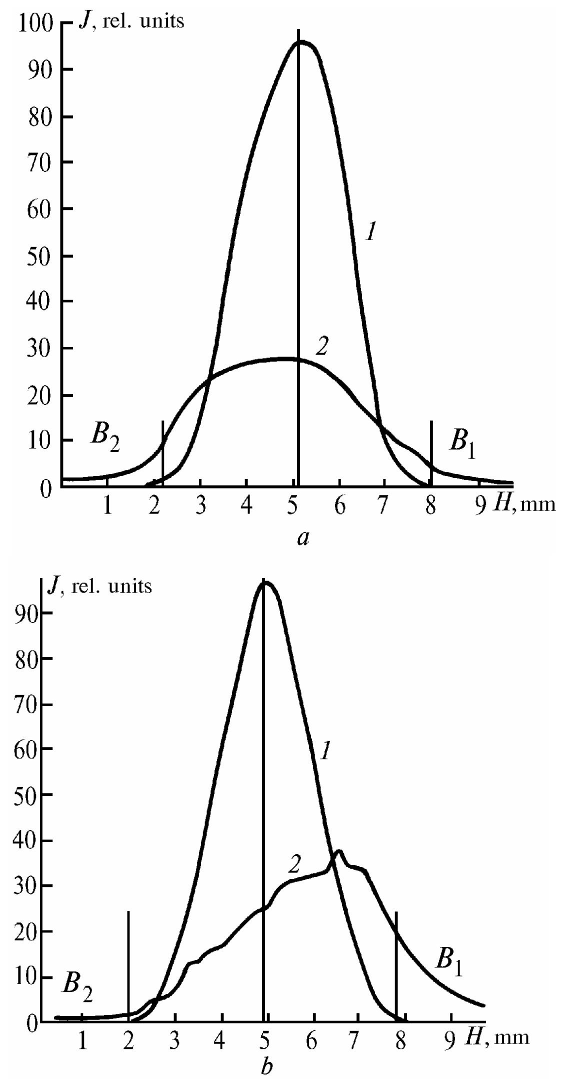

FIG. 2. Distribution of the intensity of the edge light coming from blade and optically denser medium.

As a result beyond the beam projection only weak part of B_2 remains, whereas the brightness of B_1 increases.

The experiments with a prism discussed above were carried out within three month after manufacture of the face *AB*. In the experiments performed within three days after manufacture of the face, $h_{z.1}$ was equal to 4.2 μm, that is, the same as in the subsequent experiments, but $\Phi_{B11}/\Phi_{B21} = 2$, that is, a few times less than its value given in Table I. This fact testifies that n in the transition layer varies with time elapsed from the edge fabrication. In the first experiments Φ_{B21} reached its maximum when the center of *S'* was at a distance of 2.4 μm from the edge *A* rather than at nearest approach to the edge *A* with $\Phi_{B11\max}$. This fact together with small value of the ratio Φ_{B11}/Φ_{B21} suggests that initially n varied in the way shown in Fig. 3.

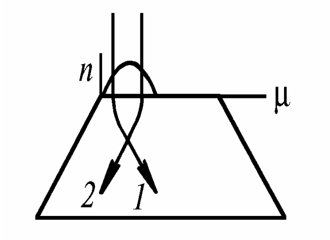

FIG. 3. Assumed behavior of the refractive index in the subsurface layer of the face of a prism fabricated from K8 glass.

When the window 0.5 mm wide (placed in the input plane of the photomultiplier instead of window 5.5 mm wide), $\Phi_{B1.\max}$ was recorded at the origin of B_1 when the distance from the center of S' to the edge A was 3.7 μm greater than that with maximum Φ_{B1i} recorded on the periphery of B_1 at the distance H = 17.5 mm from the incident beam projection. It is evident that this displacement is approximately equal to the thickness of the layer with positive refractive index gradient.

In experiments with prism, $\Phi_{B11} + \Phi_{B21}$ = 11.2 rel units. With blade instead of prism in the plane of S', $\Phi_{B11} + \Phi_{B21}$ = 9.9 rel. units. Approximately equal values of total flux indicate that the transition layer is within the refraction zone. As is seen from the foregoing, experiments with the edge light coming from optically denser medium allow transition layers to be detected and their thickness to be estimated, together with its variation in time.

The glancing light, in line with the existing notion, does not refract, but in reality this phenomenon is observed.[3,4]

Figure 4*a* shows two plates fabricated from PS14 and K8 glass and glued together with Canada balsam. The PS14 plate is 5.45 mm long, and the K8 plate is 5.3 mm long. The front faces of the plates are in the same plane. Their back faces are shifted by 150 μm because their lengths are different. The K8 plate is a denser medium in comparison with the PS14 plate. When a parallel light beam, for example, green light, propagates along the interface, the refracted light comes from the K8 plate, leaving the face DC. Due to the formation of the refraction zone established experimentally, it becomes obvious that this refraction is caused by the deflection of a portion of glancing rays *2* toward the interface in the refraction zone of the PS14 plate, and subsequent ordinary refraction of this portion of rays. Curve *1* in Fig. 5 gives an idea of the distribution of the intensity J_r over the refracted beam width at the distance λ = 101 mm from plates. The portion *bc* of the curve corresponds to the rays refracted at fixed angle determined by the expression $\sin\beta_r = 1/n_3$, where n_3 is the relative refractive index at the interface, being equal to 1.025 for the green light with λ = 0.53 μm. These rays were caused by deflection of glancing rays in less efficient region of the zone and hence sinus of their angle of incidence on the interface *BC* was equal or close to unity. The glancing rays that enter the zone closer to the edge *B* deflect in the efficient region of the zone, with the efficiency of their deflection rapidly increasing toward the edge.[1] As a result they refracted at different angles β_i. The range of variation of these angles and the intensity of the refracted rays are characterized by the portion *ab* of curve *1*.

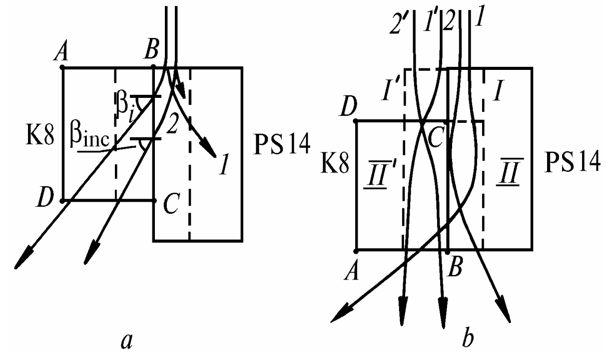

FIG. 4. Refraction of the glancing light in the region of the interface between the plates fabricated from K8 and PS14 optical glass. The plates are in optical contact.

If we turn the plates over so that their back faces become front faces (see Fig. 4*b*), the glancing rays, before their deflection in zone II of the PS14 plate located above the boundary of its optical contact with the K8 plate [in zone of optically less dense medium (OLDM)], will deflect in the zone of the plate *1* extended outward which is the zone of optically denser medium (ODM). After deflection of glancing rays subsequently in the ODM and OLDM, the refracted flux turns out to be formed only by the rays refracted at the critical angle (curve *2* of Fig. 5). The essence of this can be easily understood if it is granted that the rays deflected to the left in zone II were first deflected to the right in zone I. As a result they first enter less efficient region of zone II as compared with the case without zone I. Second, they were incident on the interface at small glancing angles at such distances from the edge *B* for which the zone is either equally efficient along the face or its efficiency varies only slightly, and these rays refracted at critical angle due to the fact that they change their direction of propagation from that off the interface to that forward it, that is, due to the need to compensate the effect of zone I by zone II.

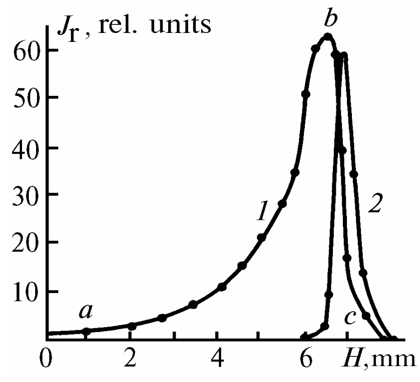

FIG. 5. Distribution of the light intensity, produced by refraction of glancing rays, over the refracted beam width.

The rays that must deflect from the interface in zone II, to the contrary, deflect toward the interface in zone I. As a result of joint but opposite effect of zones I and II, these rays either are incident on the refracting surface at small glancing angles beyond the efficient region of the zone, or propagate in the opposite direction forming the edge light (2) with considerably increased intensity as compared with the intensity recorded in the experiments based on the scheme shown in Fig. 4*a* due to smaller angles of refraction of rays.

Due to the opposite effect of the refraction zones in OLDM and ODM, the rays *1'* and *2'* of the incident light first propagating in the refraction zone in air (*1'*) and then in the zone of the K8 plate (II') deflect at the angles smaller than the deflection angles for one zone. Therefore, the band produced by these rays is short and its brightness is comparable to brightness of the undistorted incident beam.

When the refraction zones are formed in OLDM and ODM on both sides of the interface (Fig. 4*a*), the rays deflected toward the interface in the first zone will deflect from this interface in zone II, that is, in the direction of their deflection in zone I. As a result the refraction angles will be larger than the refraction angles for one zone.

If the deflection of light rays in the zone toward the interface (the screen) or in the opposite direction was random in nature, the light rays deflected at fixed angles within a certain range of variation of these angles from the initial direction of propagation in the first zone would scatter at larger angles in the next zone II. However, the edge light, the reverse, converges to the incident beam axis after passage of two consecutive zones having opposite effects. This suggests that light quanta propagating along the ray trajectories are in two if not three different states as far as the direction of deflection in the zone is concerned.

In the first state, they deflect toward the screen placed in air or toward the interface in the OLDM zone. In the second state, they deflect in the opposite direction, and in the third (intermediate) state they do not deflect.

Let the thin screen (blade) Sc_1 be positioned in the plane of *S'* (see Fig. 6). Let the thin screen Sc_2 be inserted into the edge light beam *1* (*2*) at the distance $l = 3$ mm from the first screen. In this case the edge rays *1'* and *2'* (*1''* and *2''*) come from the refraction zone of the second screen that propagate on both sides of the initial propagation direction.

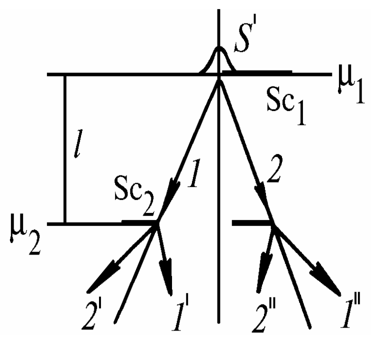

FIG. 6. Scheme of formation of the edge rays propagating in two different directions and engendered by the edge light having one direction of propagation.

Formation of secondary edge rays propagating along two opposite directions from the edge light propagating in one direction shows that the above–mentioned states of light quanta are unstable and can be transformed into the others at different time intervals less than l/c.

As a result light quanta of one state propagating along the ray trajectories *1* (*2*) from Sc_1 turn out to be in two states on their way to Sc_2 and hence deflect in the shadow and in the opposite direction in the zone of Sc_2.

The edge rays *2''* (see Fig. 7 of Ref. 1) coming from a cylindrical screen 30 mm in diameter deflect in the shadow at the angle being equal to that of the rays coming from the cylindrical screen 5.8 mm in diameter when they pass longer way in the diffraction zone due to lesser degree of curvature of the first screen. As they pass this way, the rays *2''* may change their state into the opposite one, and due to the change of the deflection direction, they penetrate the zone having the angles of incidence being smaller than the analogous rays coming from the screen having higher degree of curvature. Because of this fact, the rays *2* cease to attenuate beyond this region.

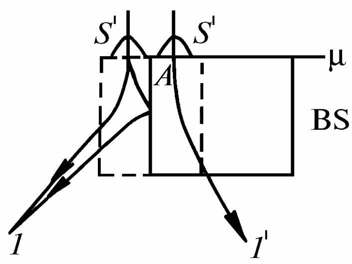

FIG. 7. Scheme of simultaneous study of the edge rays engendered in air and BS7 optical glass plate.

It seems likely that for this reason for $\mu > 0.3$ mm (Fig. 7 of Ref. 1) the intensity of the edge light in the shadow from the cylinder 30 mm in diameter becomes equal to that from the thin screen (curve *3* separates from curve *2* and merges with curve *1*).

When the front face of a plane–parallel plate fabricated from BS7 optical glass (Fig. 7) 6.5 mm high is placed in the plane of *S'* and is moved to the right along the μ axis from the position in which the undisturbed incident light beam is transmitted through the plate, the maximum of $\Phi_{B1'1}$ is achieved when the displacement is less by $\mu_{1-1'}$ of its value with maximum Φ_{B11}. In this case $\mu_{i-1'} = 8.7$ μm. This means that the values of flux of the edge rays coming from the plate (*1'*) and in air (*1*) reach their maxima when the center of *S'* is on both sides from the edge *A* rather than matches the edge *A*. This additionally supports the formation of a major portion of the edge light in the regions above the interface between media.

The sum of the values of $h_{z.1}$ in air and in ODM is equal to $\mu_{1-1'}$. Hence $\mu_{1-1'}$ is the sum of the distances from the edge *A* to the layers of the refraction zones in air and plate from which the incident light rays deflect at the angles larger or equal to 50' (see Ref. 1).

REFERENCES

1. Yu.I. Terent'ev, Atmos. Oceanic Opt. **8**, No. 4, 262–268 (1995).

2. V.A. Kizel', *Refraction of Light* (Nauka, Moscow, 1973), 351 pp.

3. Yu.I. Terent'ev, Atmos. Oceanic Opt. **7**, No. 3, 158–160 (1994).

4. Yu.I. Terent'ev, Atmos. Oceanic Opt. **7**, No. 3, 161–164 (1994).