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Visualization of propagation of boundary diffraction wave

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Abstract. Experimental evidence of the existence of the boundary diffraction wave is presented. The secondary wave occurring at the boundary of a sharp knife edge, interacts with each other while crosses the primary wave. This interaction and its path have been experimentally observed and recorded using a CCD sensor array. The observed diffraction profile of the composite wave has been discussed and briefly compared with the existing model of diffraction.

1 Introduction

Even though there are several models to explain the transportation of energy in space, the wave theory is the most widely accepted model so far. One of the dominating factors of the wave model is that it explains most of the experimental observations and also predicts solutions within practically acceptable accuracy. Most of the inventions related to energy spectrum based on electromagnetic theory and its allied rules and techniques are known to everybody. The visible part of the energy spectrum being easily recognized by the naked eye gets most of our attention.

Diffraction in light is one of the most common observances of nature. Its history originates far ahead of the latest development of science. The effects of diffraction of light were first carefully documented [1] by Italian scientist Grimaldi (1613–1663). He also named the term *diffraction*, from the Latin *diffringere*, 'to break into pieces', referring to light breaking up into different directions. He was one of the earliest physicists to suggest that light was wavelike in nature. Later many physicists contributed to the development of theories related to the concept of the diffraction. Huygens (1629–1695) [2], Gregory (1638–1675) [3], Young (1773–1829) [4,5] and Fresnel (1788–1827) [6,7], are some of these pioneers in developing the model of diffraction.

In order to explain the diffraction phenomena, there are two main theories, forwarded by Young [4] and Fresnel-Kirchhoff [6]. Fresnel claimed that the essential features of diffraction phenomena can be explained by Huygens' principle. The principle states that the propagation of a light wave can be predicted by assuming that each point of the wave front acts as the source of a secondary wave with a regular sequence of spreading disturbances out in all directions. The envelop of all secondary waves is the new wave front. The mathematical treatment of Huygens's

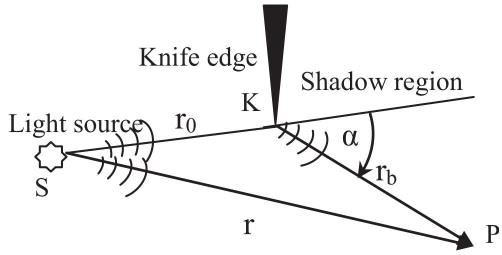

Fig. 1. Schematic diagram of the hypothesis of how diffraction occur due to boundary diffraction wave initiated in a disturbed light beam by a sharp metal edge. S is the source of light, K is the knife edge, and P is the observation point. where r is the direct distance from light source, S to the point of observation P, r_0 is the distance between S and knife edge, r_b is the distance between knife edge and point P. α is the angle between SK and KP.

principle is given by Fresnel-Kirchhoff formula which is derived fundamentally by Green's theorem and regular wave equation with the introduction of some basic simplifying assumptions. Even though that there is a mathematical treatment, diffraction is customarily distinguished between two general cases, known as Fresnel diffraction and Fraunhofer diffraction [8]. These two diffraction regions are also considered as near field and far field diffraction. Different assumptions had to be applied in treating these two types of diffraction. Later in 1883, Fresnel's argument was strengthened by Helmholtz and Kirchhoff integral formula [9] and this classical description of Fourier optics can be found in textbooks on optics [10].

The generation of a secondary boundary wave in the presence of a diffracting body which happened to interact with a light beam was first introduced by Young [4]. According to the model of boundary diffraction wave (BDW), the edge of the body which causes the diffraction by interacting/intersecting the wave (SK), see Figure 1, produces

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secondary wave (KP), called boundary diffraction wave, (BDW) and this wave interacts with the original wave (SP, also called geometrical wave) to produce the resultant diffraction pattern behind the point P.

Later Maggi [11] and Rubinowicz [12] both showed that this diffraction pattern can be obtained by superposition of two waves, one from direct wave and other originating from the edge. They independently showed that Helmholts and Kirchhoff integral can be converted in to a line integral [13] representing the diffraction and this boundary diffraction is given by the expression

$$U(P) = U_g(P) + U_d(P) \tag{1}$$

where $U_g(P) = \dfrac{\exp(jkr)}{r}$

and $U_d(P) = -\dfrac{1}{4\pi}\int_c \dfrac{\exp[-jk(r_0+r_b)]}{r_0 r_b}\dfrac{\sin(r_0, dl)}{\sin(\alpha/2)}dl.$

U_g is the geometrical contribution which includes incident, reflected and directly transmitted waves from the light source S (see Fig. 1) and U_d (line integral along the edge contour of C) is the boundary diffraction wave contribution originating from the knife edge K of the diffracting object to the point P where observation is being made. The resultant $U(P)$ is then the superposition of two components $U_g(P)$ and $U_d(P)$. Where r is the direct distance from light source, S to the point of observation P, r_0 is the distance between S and K, r_b is the distance between K and point P and is the angle between SK and KP.

$U_g(P) = \exp(jkr)/r$ shows the amplitude and phase at P when exposed to the geometrical wave and $U_g(P) = 0$ when P is in a point where there is no contribution from the geometrical wave. $U_d(P)$ is the key component that produces the diffraction phenomenon. However at the shadow boundary where α equals zero, the line integral approaches infinity and a discontinuity occurs. For this, the reason uniform theory of BDW has been proposed and details can be found elsewhere [13,14].

The existence of the BDW is theoretically discussed in literature [9,12–18] by many researchers. The need to exhibit the physical existence of the BDW is becoming more and more relevant [19–21] with the ongoing treatment of theoretical discussion. The results reported in this work is another attempt to show physical evidence towards it, to prove the said phenomenon in a very simple manner. The observed properties of BDW are also briefly discussed showing how they fit with existing theories of diffraction.

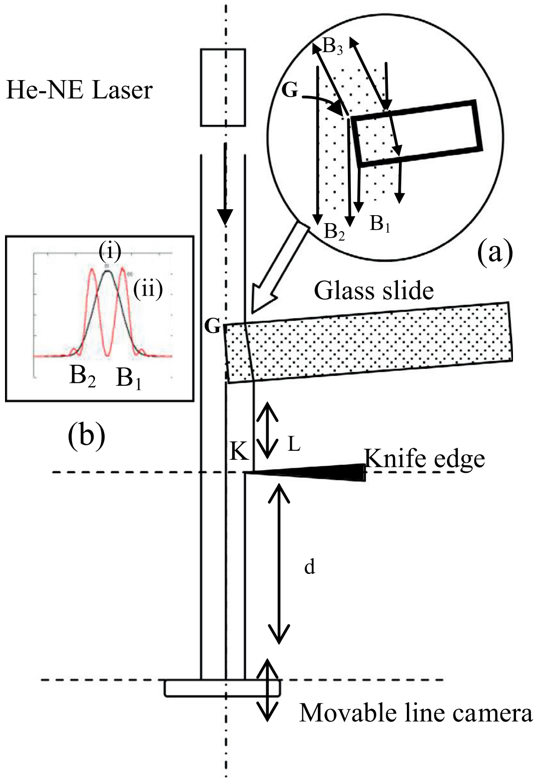

Fig. 2. (Color online) The experimental arrangement. A laser beam (Thorlabs HRR050.1 He-Ne laser, 632.8) is divided in to two nearly identical beams using a glass slide. Beam splitting at the glass slide is shown in (a). Two splitted (B_1 and B_2) and one reflected (B_3) beam were initiated at the glass edge, G. The distance L between glass slide to knife edge was kept well apart until the diffraction pattern get distinctly settled. Vertical metal knife edge K was inserted about one forth (1/4) of the beam width from the right side as shown in the Figure. A movable line camera (Thorlabs, LC1-USB, 3000 pixels in 24.5 mm length, 7 μm pixel) was placed behind the knife edge and recorded the intensity profile in the plane of CCD sensor for different distances, d. The distance d varied from 0 mm to 1500 mm. Twenty six (26) measurements were recorded within that distance. (b) beam profile at a distance point (i) undisturbed Gaussian beam emanating from the laser (ii) splitted beam: two nearly identical beams were formed by the glass slide.

2 Experimental

The experimental arrangement is shown in Figure 2. A laser beam (Thorlabs HRR050.1 He-Ne laser, 632.8) is divided in to two nearly identical (Fig. 3) coherent beams using a glass slide. Beam splitting at the glass slide is shown in Figure 2a. Once the beam splits (null region between two beams, B_1 and B_2, occurs due to the interference caused by path difference of two beams through two different media, air and glass respectively), two side lobs (curve (ii) in Fig. 2b) are seen in both sides of the dual peak B_1 and B_2. This is also due to boundary diffracted waves originating at the glass/air edge at "G". The distance L between glass slide to knife edge is kept well apart until the diffraction pattern gets distinctly settled. In practice the double edge diffraction due to edge of the glass slide appear negligible in the disturbance through the knife edge. A vertical knife edge (metal-brass) K is inserted around one forth (1/4) of the beam-width from

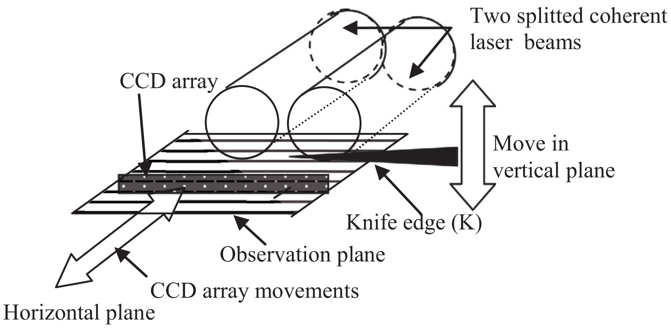

Fig. 3. Charged coupled device (CCD) linear array and knife edge arrangement to measure intensity profiles of dual coherent beam at different distances, d. Although any measurement taken at the beam cross section vertically gives the same beam profile CCD array was placed middle of the dual beam in order to get the maximum intensity profile. CCD can be moved in Horizontal plane to capture intensity variations at different distances, d. Knife edge, K can be moved in order to produce disturbed and undisturbed light beams in vertical plane.

the right side as shown in Figure 2. A movable line camera, equipped with a linear charged coupled device (CCD) as a light sensor (Thorlabs, LC1-USB, 3000 pixels in 24.5 mm length, 7 μm pixel) is placed behind the knife edge and the intensity profile of the region where both the GW and BDW co-exist is recorded in the plane of CCD sensor. See Figure 3. CCD array lies in the plane of observation. The distance d is varied from 0 mm to 1500 mm. Twenty six (26) measurements are recorded within this distance. For each point, three measurements are taken. Firstly, the knife edge is inserted as shown in Figure 2, secondly the knife edge is vertically moved out (Fig. 3) from the beam area in order to obtain the undisturbed beam profile at the observer plane. Third measurement is taken when the knife edge moves back to its original position. Measurement one and three are compared in order to verify the exact return of the knife edge to previous position. Any measurement taken at the beam cross section vertically gives the same beam profile but with different intensities. All measurements are taken at the middle of the beam cross section where intensity is maximum.

Same experiment is performed without the glass slide. This new arrangement produces only single beam which has a Gaussian intensity distribution as in curve (i) in Figure 2b. Knife edge is inserted till the middle of the laser beam and the beam profile is imaged by a line camera as in the previous experiment. The distance between knife edge and the line camera is varied from 0 mm to 2600 mm with smaller intervals.

3 Results and discussion

For dual beam experiment, only five recorded images (Fig. 4) for distances d (0 mm, 8 mm, 70 mm, 500 mm and 1500 mm) are given for convenience. Undisturbed (black curve) and disturbed (red curve) profiles were given in the

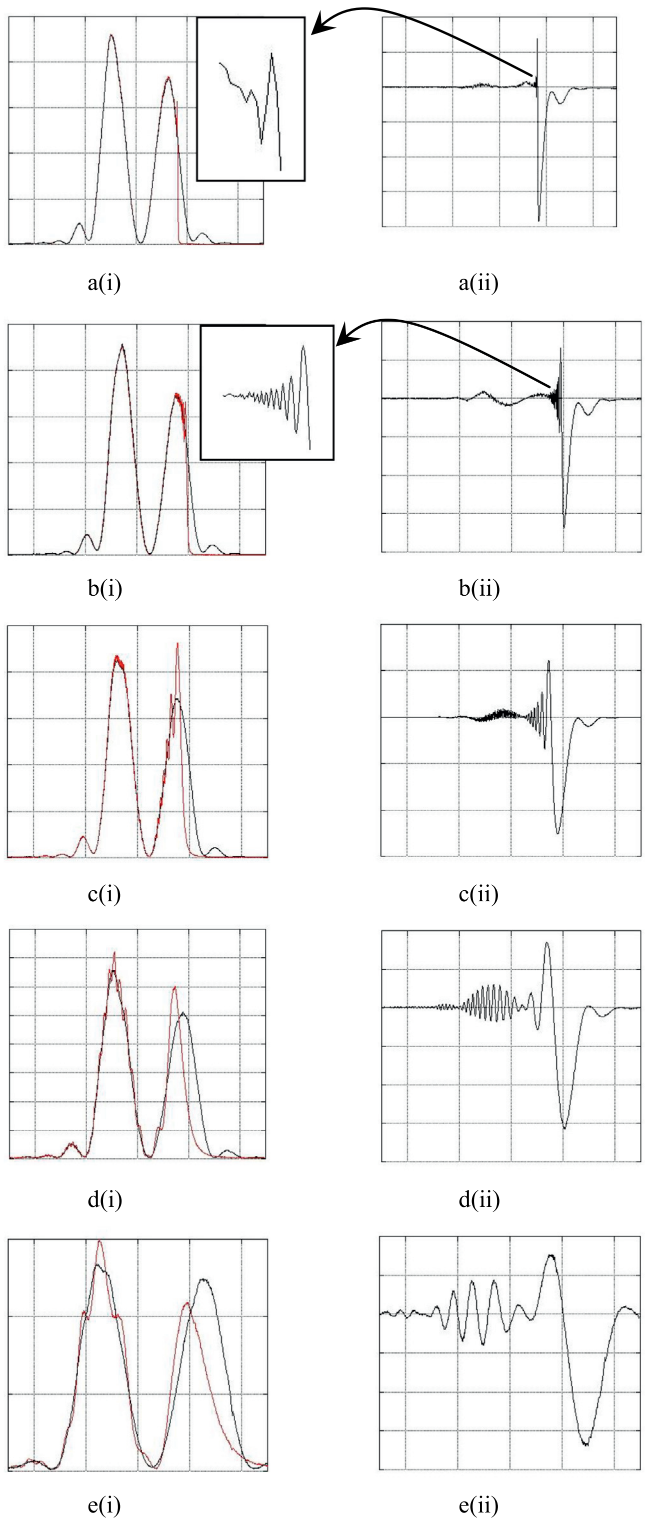

Fig. 4. (Color online) Intensity profiles recorded by the line camera at distances, d from the knife edge, K. a(i)–e(i) depict the undisturbed (black) and disturbed (red) intensity profiles at distances 0 mm, 8 mm, 70 mm, 500 mm and 1500 mm. Notice that B_2 is not effected by the BDW at distances 0 mm and 8 mm. a(ii)–e(ii) are shows the magnitude difference in intensity of disturbed and undisturbed curves respectively. Enlarged view of magnitude differences at distances 0 mm and 8 mm are showed in the top right corner of a(i) and b(i).

Table 1. Visible span (d_1) of the diffraction over the observation plane with the distance d, distance to the observer plane from the knife edge.

Distance (d)	Span of diff (d_l)
00	
01	10
02	19
03	29
04	31
05	36
08	53
10	64
15	90
20	110
25	128
30	130
40	135
50	290
55	293

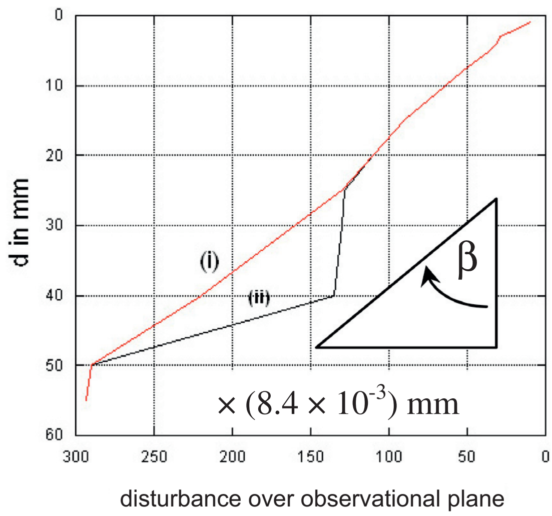

Fig. 5. (Color online) Graph drawn according to the values of Table 1. At d = 30 mm and 40 mm the disturbances are not seen due to the null region between two peaks. The angle of propagation of the disturbance of diffraction to the main beam is ∼2° 24′. Axis are interchanged in order to visualize the propagation geometry of BDW.

same graphs as shown in Figures 4a(i) to 4e(i) and differences in intensity between undisturbed and disturbed properties of each measurement are given in Figures 4a(ii) to 4e(ii).

There are several interesting features which are very clearly seen in this experiment. Initial disturbance/diffraction of the laser beam occurs at point "G" (Fig. 2a) where the incoming laser beam divides into three beams (direct, refracted and reflected) at the edge of glass slide. All three beams are disturbed/diffracted by the same boundary edge, G created by two different media, air and glass. The information provided by the measurements taken with B_1 and B_2 are used in this paper. Observation of diffraction in reflected wave, B_3 also provides information about BDW and it will be discussed in a separate article.

The disturbance that occurs in the first beam, B_1 (Fig. 4a(i)) gradually crosses over to second beam B_2 (see Figs. 4a(i)–4e(i)) with the increase of distance d. The intensity differences between undisturbed and disturbed beam profile (Figs. 4a(ii)–4e(ii)) show us how it travels and grows in magnitude with the increase of distance d. It is notice that B_2 is not affected by the BDW at distances 0 mm and 8 mm (Figs. 4a(i) and 4b(i)) but later BDW marches into the beam B_2 and changes its intensity profile (Figs. 4c(i)–4e(i)). Table 1 gives the length d_l of the disturbance of BDW at different distances of d. Figure 5 depicts the length of disturbance d_1 vs. distance d and that gives divergence angle β which is approximately 2° 24′ to the direction of main beam.

Experimental curves obtained with the single laser beam with Gaussian intensity profile are given in Figure 6. Intensity profiles of selected distances (0, 30, 200, 1300 mm) are depicted here to clearly visualize the propagation of BDW within the GW from knife edge to the other side of the beam, which finally makes a diffraction pattern similar to Fraunhofer diffraction at a distance point. Complete set of data for single beam are given in supplementary Figure file 8. In both experiments, existence and propagation of BDW across the GW are clearly demonstrated regardless of the beam types, dual or single.

The propagation geometry of BDW could also be given as a possible explanation for both Fresnel's and Fraunhofer (near field and far field) diffraction. BDW starting from the knife edge create a pattern (Figs. 7a(ii)/7b(ii)) similar to one end of Fresnel's diffraction pattern close to a slit (see Figs. 7a(i)/7b(i)) in a similar distance. With the increase of distance this disturbance travels to the other side of the beam and makes a pattern quite similar to the Fraunhofer diffraction (compare left side of Figs. 7c(i) and 7c(ii)).

4 Conclusion

The propagation of BDW across GW is shown in two similar experiments, with single and dual coherent beams. In both situations diverging of BDW across GW was clearly seen from the edge of the diffracting object with an angle nearly 2.24° to the direction of propagation of main geometrical beam. The propagation of boundary diffraction wave generates a wave shape close to the edge and another far from the edge which are quite identical with the well known Fresnel's' (near field) and Fraunhofer (far field) diffraction patterns.

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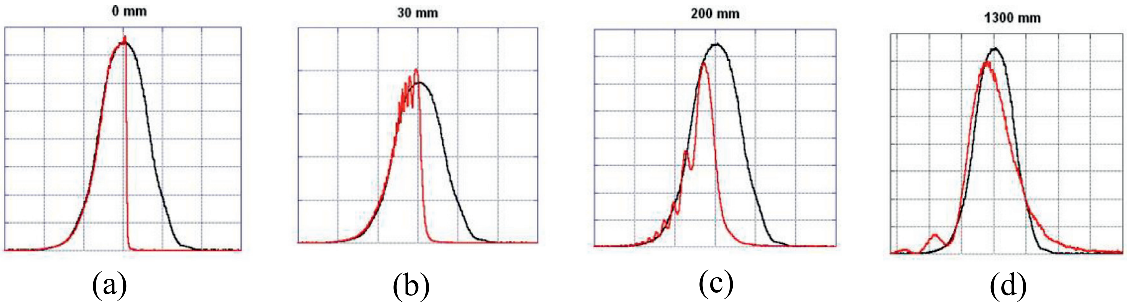

Fig. 6. (Color online) BDW in a Gaussian beam. Knife edge is intersected at the middle of the beam and intensity profiles at 0 mm, 30 mm, 200 mm and 1300 mm are depicted. Total 26 measurements were taken. 14 profiles are given as a supplementary figure.

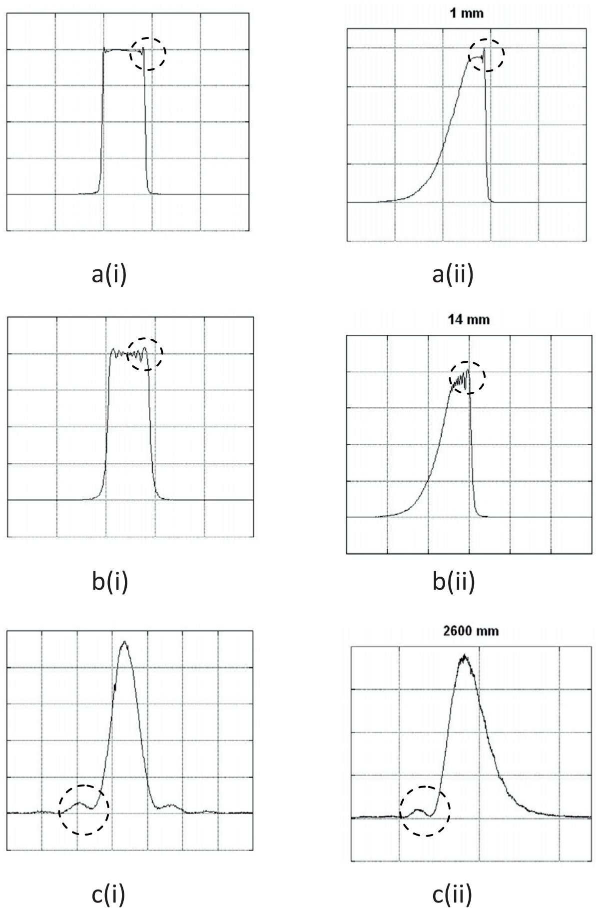

Fig. 7. Near field (Fresnel) and far field (Fraunhofer) diffraction observed in a slit and comparison with GW affected by BDW occurred due to a knife edge at similar distances. a(i) and b(i) are taken close to the slit and show near field diffraction profiles and the geometry (circled) are nearly identical to the intensity profile caused by the BDW (a(ii) and a(ii)) occurred in similar distances. c(i) – far field diffraction with a slit and c(ii) – GW affected by BDW are observed in a knife edge at a large distance.

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