Reprinted from Nature, Vol. 350, No. 6319, pp. 594–595, 18th April, 1991

Observation of the optical analogue of quantized conductance of a point contact

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DIFFRACTION of light by an aperture is a well-known manifestation of the wave nature of light. The most familiar case is that of an incident plane wave, which is diffracted into a spatial pattern that is sensitive to the properties of the aperture: the ratio of transmitted power to incident flux (the transmission cross-section σ) depends in a complicated way on the aperture area A (refs 1–3). For diffuse (that is, isotropic rather than plane-wave) illumination, however, the situation is much simpler[4]: in three dimensions, σ increases with A in a series of steps of equal height $\lambda^2/2\pi$ (where λ is the wavelength of the light), and is thus independent of the detailed aperture shape. A similar simplification occurs for two-dimensional diffuse illumination of a slit: the transmission cross-section per unit slit length increases in stepwise fashion as a function of the slit width W, with steps of height $\lambda/2$ occurring whenever $W = n\lambda/2$ ($n = 1, 2, 3, \ldots$)—that is, whenever a new mode is enabled in the slit. Although the optical transmission characteristics of slits have been studied extensively for plane-wave illumination[5–8], we know of no investigation of this predicted staircase dependence for diffuse illumination. Here we report the observation of such an effect, and suggest that it may play a part in any process of wave propagation through a constriction.

The argument of ref. 4 is based on the analogy with the recently discovered quantization of conductance in ballistic electron transport[9,10]. The conductance of a point contact in a two-dimensional electron gas increases in steps of $2e^2/h$ as its width is increased (e is the charge on an electron). The origin of this effect is the quantization of the electrons' transverse momentum owing to lateral confinement within the point contact. This leads to the formation of one-dimensional sub-bands in the conduction band (analogous to the formation of transverse modes in a waveguide), each occupied sub-band contributing $2e^2/h$ to the conductance. Planck's constant h appears in the step height as a result of the application of Fermi statistics to a degenerate electron gas. Obviously, this consideration does not carry over to the optical case. But the staircase dependence of conductance on the width of the constriction is not directly related to the fermionic nature of electrons, and has its optical analogue in the predicted stepwise increase of the transmission cross-section of a diffusely illuminated slit[4]. The diffuse illumination is analogous to the isotropic velocity distribution of the incoherent electron waves incident on a point contact.

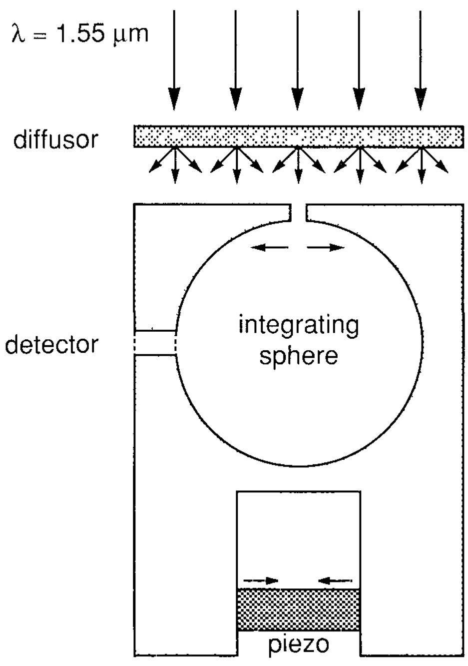

FIG. 1 Schematic illustration of the apparatus.

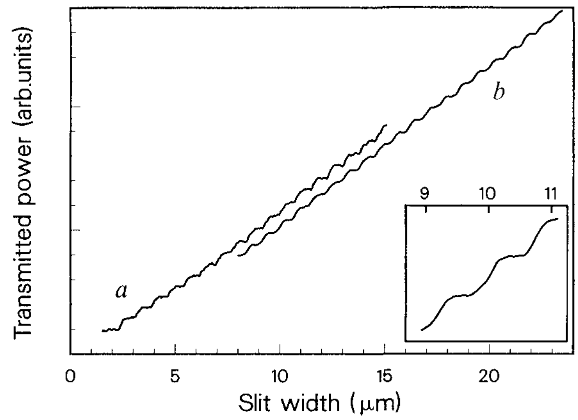

FIG. 2 Transmitted power as a function of the slit width, using a paper diffuser (*a*) and a glass-fibre diffuser (*b*); trace *b* is scaled and shifted vertically for clarity. The inset shows an enlarged part of trace *b*.

We performed our experiments at a wavelength of 1.55 μm. This value of λ is sufficiently large to allow fabrication of a slit with tolerances of $\lambda/10$, while enabling the use of a semiconductor laser and a sensitive Ge diode detector. The set-up is shown schematically in Fig. 1. The body of the device consists of two halves of an integrating sphere (40 mm diameter) made of aluminium and coated with diffusively scattering barium sulphate. The slit is situated in a region of the sphere at which the metal is only 25 μm thick. The length of the slit is 200 μm. Inside the slit, the aluminium is covered with silver to obtain a high reflection coefficient (0.98). This, and a small thickness, are required to avoid destruction of the transmission staircase by excessive absorption at the walls of the slit. The radiation transmitted through the slit in all directions is collected by the integrating sphere and detected by a Ge diode. The slit width is varied by separating the two halves of the sphere using a piezo-electric transducer, which allows a 15-μm scan in width (added to a manual offset). The variation of the slit width is monitored by a Michelson interferometer operating at 633 nm, with one of the mirrors attached to the device.

The laser beam, modulated at 1 kHz to enable phase-locked detection, is expanded by a microscope objective lens and scattered by a diffusor. Diffuse illumination in two dimensions only (no propagation in the direction parallel to the slit) is crucial, because we use a slit rather than an aperture. We obtained two-dimensional diffuse illumination in two different ways. In the first, a piece of white plotting paper was used as a three-dimensional diffuser. To eliminate divergence parallel to the slit, two narrow slit-shaped diaphragms were placed between the diffuser and the slit. This resulted in an unpolarized, two-dimensionally diffuse light source. Alternatively a random array of parallel glass fibres was used as an intrinsically two-dimensional diffuser[11], giving polarized diffuse illumination with the electric field parallel to the slit. In both methods, two-dimensionally diffuse illumination of the slit was achieved in an opening angle from 0° to 85° normal to the slit. The construction of our device did not allow illumination from −85° to 0°, nor illumination at grazing angles (in excess of 85°). Neither of these omissions affects the results. Because of the large band-width of the laser (15 nm), the illumination is essentially incoherent.

The experimental results are presented in Fig. 2, which shows the transmitted power as a function of the slit width. The two curves *a* and *b* show the results obtained using the paper diffuser and the glass-fibre diffuser respectively. The latter method produces a higher illumination intensity and thus a better signal-to-noise ratio. A stepwise increase of the transmitted power is clearly observed in both cases. The steps occur at width intervals of $\lambda/2$, as predicted[4]. The first two steps were not observed, because the slit could not be closed completely for mechanical reasons. The transmitted power is equal to the transmission cross-section per unit length, σ', multiplied by a normalization factor. For large slit widths ($W/\lambda \to \infty$), σ' is equal to W; it therefore follows that the height of the steps in σ' must be equal to the size of the intervals in W, that is, $\lambda/2$.

The steps in the transmission cross-section are not abrupt. This is caused partly by non-uniformities in the slit width, and partly by the slight absorption of radiation at the walls of the slit, which occurs in spite of the use of a silver coating. The resulting damping of the propagating modes[11] causes a rounding of the steps and a slight curvature of the staircase for the first few steps, as seen in Fig. 2*a*. Rounding of the steps is also partly due to non-adiabatic coupling (with inter-mode scattering) between the narrow slit and the infinite exterior space[12].

Our choice of the slit geometry was motivated partly by a desire to make the analogy with the two-dimensional electron gas, and partly by experimental considerations: a diaphragm of variable area of the order of λ^2 is rather difficult to fabricate, and in addition the total transmitted power is much smaller than that for a slit. Nevertheless, the extension of the experiment to three-dimensional illumination is of interest because it brings the vector character of light into the problem in a non-trivial way (two-dimensional diffraction being essentially a scalar problem[1]).

To conclude, we find it remarkable that this optical phenomenon, with its distinctly nineteenth century flavour, was not discovered before its electronic counterpart. □

Received 21 January accepted 7 March 1991

1 Bouwkamp C J *Rep Progr Phys* **17**, 35–100 (1954)
2 Bowman J J Senior T B A & Uslenghi P L E *Electromagnetic and Acoustic Scattering by Simple Shapes* (North Holland Amsterdam 1969)
3 Jackson J D *Classical Electrodynamics* 2nd edn (Wiley New York 1975)
4 Van Houten H & Beenakker C W J in *Analogies in Optics and Microelectronics* (eds Van Haeringen W & Lenstra D) 203 225 (Kluwer Dordrecht 1990)
5 Kashyap S C & Hamid M A K *IEEE Trans on Antennas and Propagation* **19**, 499 507 (1971)
6 Neerhoff F L & Mur G *Appl Sci Res* **28**, 73–88 (1973)
7 Elsherbeni A Z & Hamid M *Can J Phys* **65**, 16–22 (1987)
8 Lightbody M T & Fiddy M A *Adv in Electronics and Electron Physics* **19**, 61–67 (1987)
9 Van Wees B J *et al Phys Rev Lett* **60**, 848–850 (1988)
10 Wharam D A *et al J Phys* **C21**, L209–L214 (1988)
11 Van der Mark M B thesis Univ Amsterdam (1990)
12 Szafer A & Stone A D *Phys Rev Lett* **62**, 300–303 (1989)

ACKNOWLEDGEMENTS We thank G J J Geboers and A W Sleutjes for fabrication of the slit Q H F Vrehen and H van Houten for discussion and P J A Thijs for a high-power semiconductor laser