Extraordinary optical transmission
by interference of diffracted wavelets

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The phenomenon of extraordinary optical transmission is drawing much attention of researchers because of its potential applications in diverse emerging areas. In the present work, experimental observations on diffraction-Lloyd-mirror interferometer are reported, where two diffracted wavefronts are superimposed using Lloyd's mirror. These observations provide direct experimental evidence in support of the idea that one of the main reasons of enhanced transmission through subwavelength apertures is the coherent superposition of diffracted wavelets originating from diffractive scattering at the apertures.

1. Introduction

The discovery of extraordinary optical transmission [1] through subwavelength apertures gave rise to an explosion of experimental and theoretical research in this direction. This research is motivated by both the brilliance and fundamental character of this phenomenon and because of its tremendous potential applications in the newly emerging areas such as subwavelength optics, opto-electronic devices, wavelength--tunable filters, optical modulators [2–5]. Although the photon tunneling effect has long been well known, the attenuation of evanescent waves, involved in the photon--tunneling process, shows that this phenomenon is not the actual source of extraordinary optical transmission. Several other mechanisms such as excitation of delocalized surface plasmon Bloch modes, interference between incident and surface waves and localized coupling between adjacent structures, waveguide resonances, *etc*., have been proposed as the possible origins of this phenomenon [2–10]. It is well known that to excite surface plasmon polaritons a transverse-magnetic (TM) polarized light, *i.e.*, the magnetic field parallel to the slits, should be incident on the subwavelength apertures [1–5, 11] because the surface plasmon polaritons have a TM wave-like character. Recently it has been demonstrated that the extraordinary transmission is independent of polarization of incident light [12] and can also be achieved with

transverse-electric (TE) polarized light. Besides it has been reported that enhanced transmission can also be observed in marginally metallic Cr [13] and the non-metallic tungsten hole arrays [14]. These observations show that extraordinary transmission is also possible without exciting the surface plasmon polaritons. It is also argued that the quoted enhancement factor of 1000 for optical transmission through subwavelength hole arrays is misleading, and that in fact placing a hole in an array leads to enhancement of its transmission coefficient by a factor of 7 at most at selected wavelengths [15]. Those authors have suggested that enhanced transmission is due to interference of light incident on the aperture and the composite diffracted evanescent wave. Recently, another model is reported that says that enhancement and suppression in transmission is due to constructive and destructive interference of diffracted waves generated by the subwavelength apertures, and classical as well as quantum mechanical theory of this process has been developed [16, 17].

In the present paper, based on the newly reported concept of superposition of boundary diffraction waves using a Lloyd's mirror [18, 19], we present experimental observations which support the above idea. We have used for the first time the physical appealing boundary diffraction wave theory [20, 21] to explain the phenomenon of extraordinary optical transmission. These investigations indicate that apart from other possible processes, mutual interference of diffracted waves originating from diffractive scattering at the apertures is the main source for enhanced transmission through subwavelength apertures.

2. Experimental details

Experimental arrangement of the setup proposed is schematically shown in Fig. 1. A photograph of the experimental setup is shown in Fig. 2**a**, and Fig. 2**b** shows a close view of the arrangement of knife-edge and Lloyd's mirror used to generate interference fringes due to superposition of diffracted waves. A transverse electric (vertical) polarized He-Ne laser L (Coherent Inc. Model No. 31-2140-000, 35 mW output at 632.8 nm) is expanded and spatially filtered using spatial filtering (SF) assembly. A telescopic system of lenses L_1 and L_2 is used to generate the diffraction limited focus spot S. A knife-edge K (good quality razor blade) is positioned vertically in proximity of the focus such that a single diffraction fringe covers the field of view, as shown in
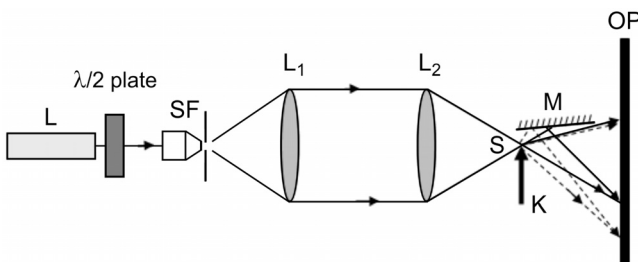

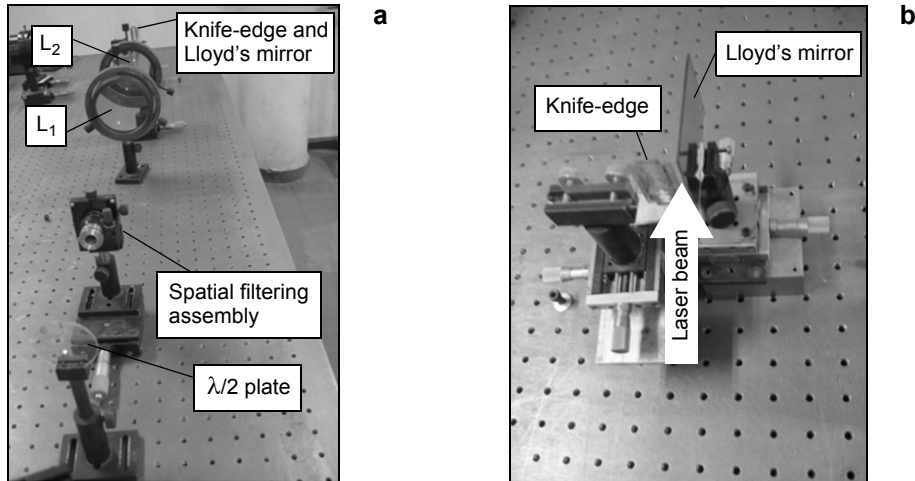Fig. 1. Schematic experimental arrangement of diffraction Lloyd's mirror interferometer.

Fig. 2. Photograph of the experimental arrangement of diffraction Lloyd's mirror interferometer (**a**) and close view of the knife-edge and Lloyd's mirror arrangement (**b**).
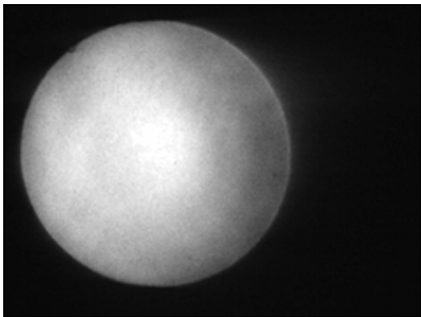

Fig. 3. A typical photograph of knife-edge diffraction pattern where single diffraction fringe covers the field of view.

Fig. 3. At this position knife-edge diffracts light from the Airy disk [22] and thereby diffracted light has maximum amplitude. In order to demonstrate that two diffracted wavefronts could interfere, a Lloyd's mirror M (20 mm × 50 mm × 1 mm, SiO_2 protected front surface silver coated, reflectivity ∼94%) is positioned near the knife-edge. Lloyd's mirror and the knife-edge were mounted on precise translation stages for fine control. A $\lambda/2$ plate with its axis making an angle of 45° with the vertical was used in the thin beam to change the state of polarization of initially vertically polarized light into horizontally polarized light. Experimental results have been captured with a Canon S-50 Power Shot digital camera with 1024 × 768 pixel resolution settings.

3. Results and discussion

It is well known that in a conventional Lloyd's mirror interferometer a geometrical wavefront in divided into two parts which are subsequently superimposed to generate
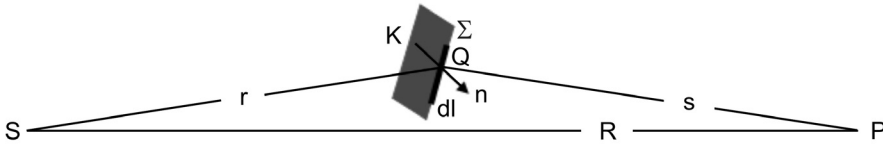
Fig. 4. Schematic representation of diffraction from a knife-edge.

the interference fringes. In our case the Lloyd's mirror configuration is used on a diffracted wavefront (known as boundary diffraction wave), generated by diffraction of geometrical light at the knife-edge, to generate equi-spaced and straight interference fringes analogous to those obtained with a conventional Lloyd's mirror interferometer.

Formation of these fringes due to superposition of two diffracted wavefronts can be explained with the physically appealing boundary diffraction wave theory [20, 21] which relates diffraction to the true cause of its origin, *i.e.*, existence of the boundary of diffracting aperture. According to this theory the diffracted field in the observation plane at point P is given by

$$U(P) = U^g(P) + U^d(P) \tag{1}$$

where

$$U^g(P) = \begin{cases} \dfrac{A}{R} \exp(jkR) & \text{when } P \text{ is in the direct beam} \\[2mm] 0 & \text{when } P \text{ is in geometrical shadow} \end{cases} \tag{2}$$

and

$$U^d(P) = \frac{A}{4\pi} \int_{\Sigma} \frac{\exp\left[jk(r+s)\right]}{rs} \frac{\cos(n,s)}{1+\cos(s,r)} \sin(r, \mathrm{d}l)\mathrm{d}l \tag{3}$$

where R is the distance from source to the point of observation P; s is the distance between point P and a typical point Q situated on the illuminated boundary Σ of knife-edge K and r is the distance from source to point Q (Fig. 4). Here, $\mathrm{d}l$ is an infinitesimal element situated on Σ, n is a unit vector outward normal to the plane of diffracting aperture and $j = \sqrt{-1}$. Here, U^g propagates according to the laws of geometrical optics and is known as the geometrical wave while U^d is generated from every point of the illuminated boundary of the diffracting element and is called the boundary diffraction wave. The geometrical wave and the boundary diffraction wave are shown in Fig. 1 by solid and dotted lines, respectively. The intensity distribution due to superposition of two boundary diffraction waves and a geometrical wave at the observation plane may be represented as:

$$I(P) = (U^g + U^{d1} + U^{d2}) (U^g + U^{d1} + U^{d2})^* \tag{4}$$

where U^{d1} is the boundary diffraction wave starting from illuminated part of the knife-edge; U^{d2} is the boundary diffraction wave starting from mirror image of the knife-edge which works as a virtual source for this wave. It is known that the amplitude of boundary diffraction wave is maximum near the geometrically illuminated to geometrically shadowed transition boundary where its value is approximately equal to half of the incident light [20]. For subwavelength apertures the spacing between the edges is small and thus amplitude of interfering beams is maximum $\sim U^g/2$. Solving Eq. (4) and taking $U^{d1} = U^{d2} = U^g/2$ for the case of subwavelength apertures, gives

$$I(P) \; = \; I_0 \left[\frac{3}{2} + 2\cos\psi\cos\phi + \frac{1}{2}\cos(2\psi) \right] \tag{5}$$

where I_0 represents intensity of the geometrical wave impinging on the aperture, ϕ is the phase difference between the geometrical wave and the two boundary diffraction waves, and ψ represents phase difference between the two boundary diffraction waves reaching the observation point P. The fringes generated due to interference of two boundary diffraction waves are superimposed on the geometrical wave present in observation plane as background light, as demonstrated in reference [19].

The fringe width of these fringes formed due to interference of two boundary diffraction waves is given by

$$\beta \; \sim \; \frac{\lambda D}{a} \tag{6}$$

where λ is the wavelength of light used, D is the distance between the plane of the two-point sources (knife-edge and its virtual image) and the observation plane *OP*, and a is the distance between two-point sources. Equation (6) shows that the fringe width β could become infinite when distance between the two-point sources approaches zero. Experimentally, change in the fringe width was observed by changing the distance between the knife-edge and Lloyd's mirror, and two interferograms with different fringe widths obtained using this system are shown in Fig. 5. These fringes
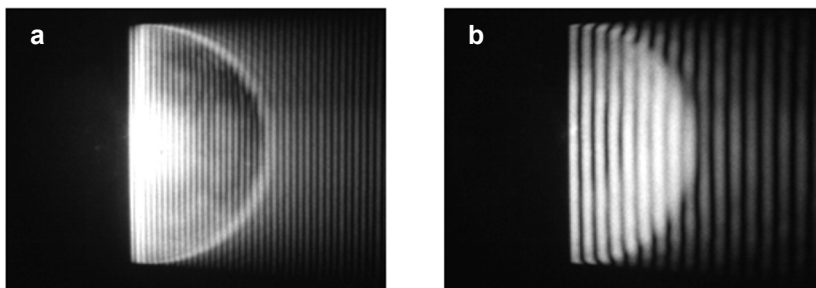

Fig. 5. Photographs of experimental results showing interferograms of different fringe widths obtained by superposition of two boundary diffraction waves using a Lloyd's mirror.
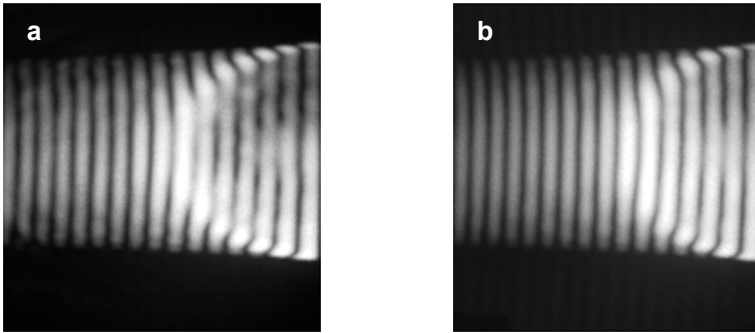
Fig. 6. Photographs of experimental results showing interferograms with different polarization states of the incident laser beam; with vertical polarization (**a**) and with horizontal polarization (**b**).

are shown to reach an infinite fringe mode condition for the case of mirror-edge diffraction, where mirror-edge diffracts light and mirror surface folds it back [23, 24]. This variation of fringe width with distance between the knife-edge and Lloyd's mirror confirms that the illuminated part of the diffracting aperture acts as a real source of light wherefrom boundary diffraction wave originates. In order to see the effect of polarization of the incident beam on these fringes the polarization of the beam was changed from vertical to horizontal one using a $\lambda/2$ plate, and interference fringes obtained with these polarization states are shown in Fig. 6 (with vertically polarized – 6**a** and with horizontally polarized light – 6**b**). These photographs show that formation of these fringes is independent of the state of polarization of incident beam and the intensity ratio for these fringes was also found to be the same, *i.e.*, $I/I_0 \sim 3.7$. These observations on polarization effect on fringe formation are in agreement with the results reported in reference [12] on extraordinary transmission of light through slit apertures.

It is known that one can achieve infinite fringe width condition only when two sources of light (knife-edge and its virtual image in our case) overlap each other or physically speaking, when distance between them is of the order of subwavelength. Thus the infinite fringe width condition is easily satisfied for the case of subwavelength apertures. As this is interference pattern of two waves originating from diffractive scattering at the apertures one would get a peak in the transmitted intensity when two interfering boundary diffraction waves are in phase with each other (constructive interference) and a valley will be detected when these interfering beams are out of phase (destructive interference). In the infinite fringe mode condition (bright field) all the three waves will travel along the same line and the same optical paths, *i.e.*, $\phi = \psi = 0$ which means a is of the order of subwavelength. In this situation, it becomes obvious from Eq. (5) that $I = 4I_0$, *i.e.*, light transmitted through a single subwavelength slit is four times more intense than light incident on the slit. Experimental measurements in our setup give a ratio of $I/I_0 \sim 3.7$. It may be noted that the theoretically calculated value of intensity $I/I_0 = 4$ is valid only for the case of

subwavelength apertures and the peak intensity will reduce with increase in slit width due to sharp decrease in amplitude of boundary diffraction wave away from the geometrically illuminated to geometrically shadowed transition boundary. Here we have considered a single diffraction only but, actually, the process of multiple diffractions in the slit (as explained by KELLER [25]) will take place, which could further increase the intensity of the transmitted beam. Due to subwavelength nature of the apertures, for the macroscopic point of view, the diffraction originates from the aperture as a whole entity and thus the transmitted light can be termed as originating from the process of diffractive scattering from the aperture.

In the case of a slit or hole arrays the transmission is determined by coherent addition of fields from all the diffracting apertures. The dependence of the fringe width on the ratio λ/a shows that infinite fringe mode condition will be obtained at different values of wavelengths for different slit widths. The infinite fringe mode maximum occurs when the interfering beams starting from edges of the apertures are in phase, *i.e.*, path difference between them is a multiple of the wavelength of incident light. For an array of, say, N slits, each slit having width a and period d, there will be total N waves of intensity given by Eq. (5) produced by these N independent slits. For such a system of slits KUKHLEVSKY [16] has demonstrated that in the transmitted spectrum intensity peaks will be observed at wavelengths that satisfy the condition $\lambda_n = d/n$, where $n = 1, 2, 3$, *etc.*, which is applicable for the present case also. The dependence on wavelength of the transmitted intensity for such a system is presented in Fig. 1 of reference [16]. Likewise, if the slit width is varied the wavelength corresponding to peak value will also be changed due to the condition of constructive interference of light waves. Further it may be noted that in the case of subwavelength slits the phases of the boundary diffracted waves from the apertures have nearly the same phase and thus adds constructively resulting an enhancement in the peak value of transmitted light that depends on the phases and amplitudes of the interfering beams where intensity scales as the number of light sources squared, *i.e.*, $I_N \sim N^2 I_1$ (I_1 is the intensity from a single slit) regardless of periodicity, which is a requirement for enhancement using equivalent circuit theory [26] and excitation of surface plasmons [1–5]. It may be noted that for large N experimental results may differ from the theoretical dependence of peak intensity as $N^2 I_1$. In addition to the process of interference of diffracted wavelets transmitted intensity can further be enhanced due to additional energy that could also be channeled through the slit by excitation of surface polaritons at periodic structures for resonant condition.

4. Conclusions

The phenomenon of extraordinary transmission through subwavelength apertures has been discussed in the light of experimental observations on the diffraction Lloyd's mirror interferometer and is explained using the boundary diffraction wave theory. It has been shown that for the case of subwavelength apertures our observations strongly

support the recently reported model of far-field multiple-beam interference [16, 17], which requires that in the case of subwavelength apertures the mutual constructive interference of these diffracted waves, originating from diffractive scattering at the apertures, is the main source for enhanced transmission.

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