Transmission of doughnut light through a bull’s eye structure

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We experimentally investigate the extraordinary optical transmission of doughnut light through a bull’s eye structure. Since the intensity is vanished in the center of the beam, almost all the energy reaches the circular corrugations (not on the hole), and excites surface plasmons which propagate through the hole and reradiate photons. The transmitted energy is about 32 times of the energy input on the hole area. It is also interesting that the transmitted light has a similar spatial shape with the input light even though the diameter of the hole is much smaller than the wavelength of light.

PACS numbers: 78.66.Bz,73.20.MF, 71.36.+c

The phenomenon of extraordinary optical transmission (EOT) through metallic films which were perforated by nanohole arrays was first observed a decade ago[1]. It is generally believed that surface plasmons (SPs) in metal surface play a crucial role in this process, during which photons first transform into SPs and then back to photons again[2,3]. Such SPs are involved in a wide range of applications[4,5]. The report of EOT phenomenon attracts considerable attention because it shows that more light than Bethe’s prediction could be transmitted through the holes[6]. This stimulates much fundamental research and promotes subwavelength apertures as a core element of new optical devices. For EOT in periodic hole arrays, not only the polarization properties[7,8,9] but also the spatial mode properties[10,11] are widely discussed. Even for a single aperture surrounded by circular corrugations, we can also get high transmission efficiencies and a well-defined spectrum since the periodic corrugations act as an antenna to couple the incident light into SPs[12,13].

Usually, the light transmitted through the subwavelength holes can be divided into two parts: one is the directly transmitted light and the other comes from the surface plasmon assisted transmission process. Here we present a new method to eliminate the influence of the first part in EOT phenomenon by using a doughnut input light and a bull’s eye structure. Since the intensity is null in the center of the beam, there is no light illuminating on the single hole directly. Almost all the energy reaches the circular corrugations, and excites SPs which propagate through the hole and reradiate photons (as shown in Fig.1). It is also interesting that the transmitted light has a similar spatial shape with the input light even though the diameter of the hole is much smaller than the wavelength of light.

Inset of Fig. 2 is a scanning electron microscope picture of our bull’s eye structure. The thickness of the gold layer is 135 nm. The cylindrical hole(250 nm diameter) and the grooves are produced by a Focused Ion Beam Etching system (FIB, DB235 of FEB Co.). The grooves have a period of 500nm with the depth 60nm and width 250nm. Transmission spectra of the hole array are recorded by a Silicon avalanche photodiode (APD) single photon detector coupled with a monochromator through a fiber. White light from a stabilized tungsten-halogen source passes through a single mode fiber and a polarizer (only vertical polarized light can pass), then illuminates on the sample. The hole array is set between two lenses with the focus of 35nm. The light exiting from the hole array is launched into the monochromator. The transmission spectra are shown in Fig. 2(Black square dots), in which the transmission efficiency is determined by normalizing the intensity of transmitted light over the intensity before the sample. At the resonant frequency (632.8 nm in the experiment), the transmission efficiency is about 2.55%, much higher than that of the non-resonant case. To verify the phenomenon does not come from the direct transmitted light, we use another sample as a comparison. The new sample also has a Bull’s eye geometry, but without hole in center. The transmission efficiencies are all about 1.0% and there is no transmission peak as shown in Fig. 2(Black round dots), which verify that the transmission peak for bull’s eye structure come from the surface plasmons assisted transmission process. In the following experiments, we use the bull’s eye structure with a hole in center to investigate the extraordinary optical transmission of doughnut light.

The typical doughnut light is produced by changing its or-

![Image](FIG. 1: Sketch map of our protocol. The typical doughnut light has an intensity null on the beam axis. Almost all the energy reaches the circular corrugations, excite surface plasmons which propagate through the hole and reradiate photons.)

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bital angular momentum (OAM), which is associated with the transverse phase front of a light beam. Light field of photons with OAM can be described by means of Laguerre-Gaussian (\(LG_p^m\)) modes with two mode indices \(p\) and \(m\)\(^{[14]}\). The \(p\) index gives the number of radial nodes and the \(m\) index represents the number of the \(2\pi\)-phase shifts along a closed path around the beam center. Light with an azimuthal phase dependence \(e^{im\phi}\) carries a well-defined OAM of \(\hbar m\) per photon\(^{[14]}\). When \(l = 0\), the light is in the general Gaussian mode, while when \(l \neq 0\), the associated phase discontinuity produces an intensity null on the beam axis. If the mode function is not a pure LG mode, each photon of this light is in a superposition state, with the weights dictated by the contributions of the comprised different \(l\)th angular harmonics. For the sake of simplification, we can consider only LG modes with the index \(p = 0\). Computer generated holograms (CGHs)\(^{[15,16]}\), a kind of transmission holograms, are used to change the winding number \(l\) of LG mode light. Inset of Fig. 3 shows part of a typical CGH \((n = 1)\) with a fork in the center. Corresponding to the diffraction order \(m\), the \(n\) fork hologram can change the winding number \(l\) of the input beam by \(\Delta \omega = m \times n\). In our experiment, we use the first order diffraction light \((m = 1)\) and the efficiency of our CGHs is about 30\%. Superposition mode is produced using a displaced hologram\(^{[16]}\), which is particularly suitable for producing superposition states of \(LG^0_0\) mode with the Gaussian mode beam.

The experimental setup is shown in Fig. 3. The OAM of the laser light (632.8 nm wavelength) is changed by a CGH, while the polarization is controlled by a polarization beam splitter (PBS, working wavelength 632.8 nm) followed by a half wave plate (HWP, working wavelength 632.8 nm). The polarized laser beam is directed into the microscope and focused on the metal plate using a 100X objective lens (Nikon, NA=0.90) with a diameter about 3.8 \(\mu m\). The CCD camera before the objective lens is used to adjust the position of the hole structure. Transmitted light is collected by another 100X objective lens (Nikon, NA=0.80) and recorded by another CCD camera. The relative position of the beam center to the hole is estimated as follows: We detect the transmission of the Gaussian beam with the sample moved by a three-dimensional stage (Suruga Seiki Co., Ltd. B71-80A). When the center of beam is coincided with the center of hole, the maximum transmission is achieved. A CCD camera is also used as an assistant to observe the picture directly. Since the doughnut light is produced via the movement of hologram which does not affect the optical path, we can realize the protocol that the position of zero electric field coincides with the center of the hole.

Transmission efficiencies are measured for light with Gaussian mode \((l = 0)\), the first order mode \((l = 1)\) and a typical superposition mode \((a|0\rangle + b|1\rangle)/\sqrt{a^2 + b^2}\), where \(a\) and \(b\) are real numbers. When the hologram is placed in the beam center, the OAM of the first diffraction order light is 1, while for hologram in the beam edge, the OAM is 0. In the middle part, the output light is in the superposition mode of 0 and 1. The results for 0 and 1 order mode light are 2.55\%, and 2.82\% respectively. The transmission efficiency for the superposition mode light is between the upper two cases and can be changed with the ratio of \(a\) and \(b\) when we move the hologram. In all the cases, transmission efficiency is much larger than the value obtained from the classical theory\(^{[6]}\). The reason is that the interaction of the incident light and surface plasmon is made allowed by coupling through the grating momentum and obeys conservation of the momentum

\[
\vec{k}_{sp} = \vec{k}_0 \pm i\vec{G}_x \pm j\vec{G}_y, \tag{1}
\]

where \(\vec{k}_{sp}\) is the surface plasmon wave vector, \(\vec{k}_0\) is the component of the incident wave vector that lies in the plane of

![FIG. 2: (Color online) Transmission efficiency as a function of wavelength for bull’s eye structure (Black square dots) and similar structure without hole in center (Red round dots). Inset is a scanning electron microscope picture of our bull’s eye structure (groove periodicity, 500 nm; groove depth, 60 nm; hole diameter, 250nm; film thickness, 135 nm).](Image 191x236 to 260x296)

![FIG. 3: Experimental setup. A computer generated hologram (CGH) is used to change the OAM of the laser beam. The polarized laser beam is directed into the microscope and focused on the metal plate using a 100X objective lens (Nikon, NA=0.90). Transmitted light is collected by another 100X objective lens (Nikon, NA=0.80). Inset, pictures of part of a typical CGH (n = 1) and produced light with the first order mode.](Image 494x204 to 524x233)
the sample, \( \overrightarrow{G}_x \) and \( \overrightarrow{G}_y \) are the reciprocal lattice vectors, and i, j are integers. \( \overrightarrow{G}_{x,y} = 2\pi / d_{x,y} \) are the lattice vectors in the \( x,y \) directions respectively, and \( d_{x,y} \) are the periodicity of the structure in the \( x,y \) direction. While in the practical experiments, the Eq.1 can not be satisfied simply, because many parameters can influence the resonant frequency, for example, the thickness of the metal film, the width of the grooves, as mentioned in [17].

Due to the symmetry of the Bull’s eye structure, the polarization of the light has no influence on the whole process. We can see that the transmission efficiency for Gaussian mode light is larger than that of the first order mode light. Although it is hard to give a precise explanation, the possible factors may be that the additional transmissions of Gaussian mode light from directly passing light, SPs excited from the hole edge by scattering, and lower propagating loss in the hole. This lower loss comes from the waveguide property of the hole in which the Gaussian mode light has a higher transmission efficiency than that of other modes as shown in [2, 18].

Calculation shows that the energy in the beam center (250 nm diameter) is only about 0.04% of the whole doughnut light. Comparing with the SPs assisted transmission efficiency 1.28%, we can find that the transmitted energy is about 32 times of the directly illuminating light on the hole area. This can be the evidence that the transmitted light in the case of doughnut mode results from the surface plasmon assisted transmission process.

CCD pictures are also taken for the three cases as shown in Fig. 4. The light power is decreased to give clear pictures. It is interesting that the spatial shape of the light was still preserved after the plasmon assisted transmission process, even though the hole diameter (250 nm) is much smaller than the light wavelength (632.8 nm). Since the spatial shape of the light is determined by its OAM, which is associated with the transverse phase front of a light beam, we can conclude that the OAM of the photons are not influenced in this process. It has been proven in many works that the phase of the photons can be preserved in the surface plasmons assisted transmission process, here we show that the helical wavefront of photons can also be transferred to SPs and carried by them [10].

In conclusion, we investigate the extraordinary optical transmission phenomenon through a subwavelength aperture surrounded by circular corrugations when the light is in the doughnut shape. Since all the energy reaches the circular corrugations but not on the hole, the directly transmitted light can be ignored. The present experiment could provide intriguing prospects for both the exploiting of the surface plasmon based devices and the study of fundamental physics issues.

This work was funded by the National Basic Research Programme of China (Grants No.2009CB929600 and No. 2006CB921900), the Innovation Funds from Chinese Academy of Sciences, and the National Natural Science Foundation of China (Grants No.10604052 and No.10874163).

FIG. 4: CCD pictures of light beam before (upper) and after (lower) the bull’s eye structure. The light power is decreased to give clear pictures. A, B, C are the cases for light with Gaussian mode \( l = 0 \), the first order mode \( l = 1 \) and a typical superposition mode \( (a|0\rangle + b|1\rangle)/\sqrt{a^2 + b^2} \) (where \( a \) and \( b \) are real numbers) respectively.

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