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The influence of hole shape on enhancing transmission through subwavelength hole arrays*

Sun Mei(孙 梅)[a], Liu Rong-Juan(刘荣鹃)[a], Li Zhi-Yuan(李志远)[a]†,
Cheng Bing-Ying(程丙英)[a], Zhang Dao-Zhong(张道中)[a],
Yang Hai-Fang(杨海方)[b], and Jin Ai-Zi(金爱子)[b]

[a] *Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing* 100080, *China*
[b] *Laboratory of Micro Fabrication, Institute of Physics, Chinese Academy of Sciences, Beijing* 100080, *China*

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The extraordinary light transmission through a 200-nm thick gold film when passing through different subwavelength hole arrays is observed experimentally. The sample is fabricated by electron beam lithography and reactive ion etching system. A comparison between light transmissions shows that the hole shape changing from rectangular to diamond strongly affects the transmission intensity although both structures possess the same lattice constant of 600 nm. Moreover, the position of the transmission maximum undergoes a spectral red-shift of about 63 nm. Numerical simulations by using a transfer matrix method reproduce the observed transmission spectrum quite well.

Keywords: subwavelength holes, surface plasmons, localized surface plasmon
PACC: 7320M, 7360D

1. Introduction

Surface plasmons (SPs) originate from the collective excitation of surface electrons (or charge density wave), which describe a special case in which the charges are confined to the surface of the metal.[1] Their electromagnetic fields decay exponentially into the space perpendicular to the surface and have their maxima on the surface as shown in Fig.1(a). It is well known that light with the wavelength in the visible- to near-infrared range does not couple with surface plasmons on a smooth metal–air interface, because the surface plasmons have a larger wave vector than light waves at this range, which can be seen from Fig.1(b). However, a metal film perforated with a periodic array of subwavelength holes has been shown to be able to enhance the transmission of light.[2−7] The grating momentum associated with the periodic structure of the array allows momentum conservation when the surface plasmons interact with the incident light. In other words, the periodicity gives rise to zone folding and the formation of a well-defined surface plasmon band structure, analogous to the electronic band structures found in crystalline solids. In 1998, Ebbesen *et al*[2] published a very interesting paper showing extraordinary light transmission through subwavelength hole arrays in a metallic film. That paper aroused considerable interest in this subject. Much experimental and theoretical work has been done to test the dependence of the extraordinary optical transmission on the structure parameters, such as the lattice constant, the thickness of metal film, the incident angle of light and the dielectric constant of substrate.[8−10] Although the exact mechanisms for this phenomenon are still under discussion, it has been proved by several groups that SPs can contribute to the enhancement of transmission through metallic holes arrays.

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†Corresponding author. E-mail: lizy@aphy.iphy.ac.cn

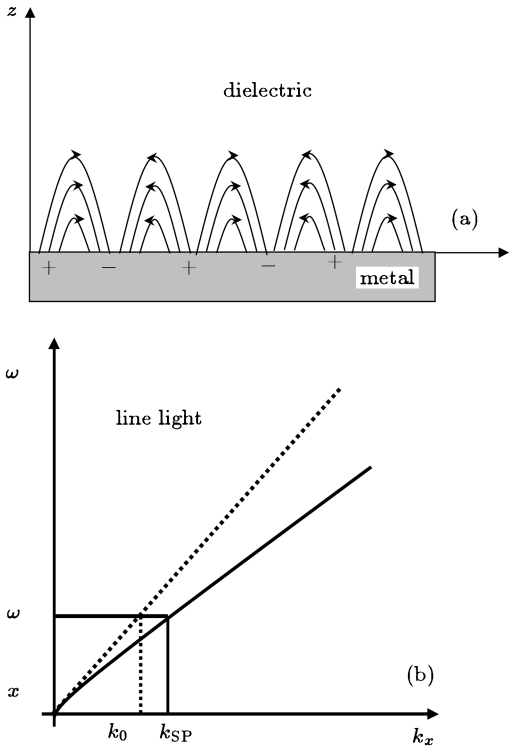


Fig.1. (a) Schematic diagram for the SPs at the interface between a metal and a dielectric material. (b) The dispersion curve for SPs (solid line) and light in free space (dotted line).

The manipulation of light on a subwavelength scale with artificial photonic structure can rely on two ingredients: shape and periodicity. As has been demonstrated,[11−12] the shape of structure has a strong influence on the extraordinary transmission. The "shape resonance" is used to explain the difference between transmission spectra passing through the circular and rectangular hole arrays. In this paper, we show experimentally and theoretically that the transmission spectrum of periodic rectangular hole arrays is also different from that of the sub-wavelength diamond hole arrays. In particular, the position of the transmission peak shifts toward the longer wavelengths. Theoretical simulations based on the transfer matrix method (TMM) confirm our experiment results.

2. Experiment and simulation

A 200-nm-thick Au film and a 5-nm-thick chromium adhesion layer are deposited on a 0.5-mm-thick quartz substrate. A Raith 150 electron beam lithography system (EBL) is used to convert the subwavelength structure onto the 160-nm-thick 495 Polymethylmethacrylate (PMMA) that is overlaid on an Au film by using the spin coating method. Then the 80 Plus Reactive Ion Etching System (RIE) is used to etch the PMMA with Ar gas for about ten minutes. Finally the desired structure is formed on the optically thick Au film. The scanning electron microscopy (SEM) images of the square-lattice rectangular and diamond hole arrays are shown in Fig.2. The overall size of the samples that was measured in our experiment is about $20\times20\mu m^2$, which is composed of 30×30 periodic subwavelength hole arrays. Figure 2(a) depicts an array of rectangular holes ($290\times200\,nm^2$), while Fig.2(b) shows an array consisting of diamond holes each with a side-length of 240 nm. The periods of the two samples are both 600 nm and the fractions of the area occupied by the holes are both $f=14\%$. The transmission spectra of the rectangular and the diamond hole array structures are measured by a spectrometer in combination with a photomultiplier tube (PMT). The range of wavelength in our experiment is

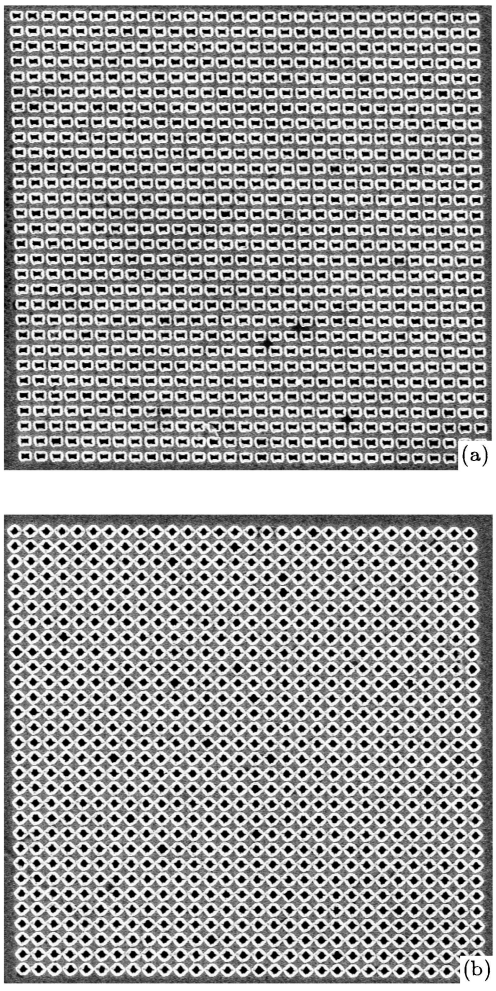


Fig.2. SEM images of two kinds of hole arrays fabricated in a 200-nm-thick gold film. (a) Rectangular and (b) diamond hole arrays.

400–900 nm. A light beam from a 50W broadband light source passes through a pinhole with a diameter of 200μm. An object lens ($\times$40) is used to focus the incoming beam, producing a 100 μm diameter light spot normally incident upon the Au film of the sample. Another object lens ($\times$25) behind the sample collects the transmitted light. A model 650 light chopper is used to provide a reference signal for the lock-in amplifier. All data are recorded and processed by a computer.

The measured transmission spectra of the two samples are shown in Fig.3. A bare quartz plate is used as reference for the calibration of measured transmission spectra. For the rectangular hole arrays (solid line), there is a broad peak centred at 763 nm with a maximum transmission of about 12%. An incoherent white light source is used to illuminate the sample from the gold side. Its spectral range is between 400 nm and 900 nm and the intensity maximum occurs at 525 nm. The results show that the maximum transmission coefficient can exceed unity when normalized to the area of air opening of the rectangular hole arrays in the gold film. For the diamond hole arrays, there is also a peak with a maximum transmissions of about 8%, but it is centred at 700 nm. A comparison between optical transmission clearly shows that the hole shape varying from rectangular to diamond strongly affects the transmission intensity although both structures possess the same lattice constant 600 nm and the same area fraction f. Moreover, the position of the transmission maximum undergoes a spectral red-shift of about 63 nm. The "shape resonance" in the rectangular holes is used to explain the difference in the optical spectrum from the diamond holes structure, and the resonance is believed to originate from the localized surface plasmon (LSP) mode. Our experiments confirm again the role of the LSP mode. Although the SPs play a dominant role in enhancing the transmission, the LSP can strongly affect the position of the transmission peaks. Therefore, the contribution of the LSP must be taken into account in analysing the enhanced transmission phenomenon.

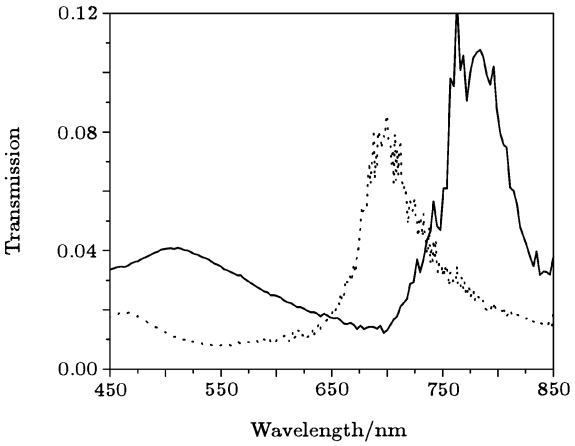


Fig.3. The measured transmission spectra of the two kinds of structures: the rectangular (solid line) and diamond (dotted line) hole arrays.

In order to further verify the measurements, the plane-wave-based TMM is used to simulate the spectra of the diamond structure in the optical region.[13] The two-fold mirror reflection symmetry involved in the structure has been taken into account in order to save large amounts of memory space and computational time.[14] The simulated (dotted line) spectrum of the diamond-hole structure is shown in Fig.4. The simulation transmission spectrum shows a peak at 710 nm with a transmittance of 13%. The theoretical curve slightly (solid line) shifts about 10 nm toward the longer wavelengths and which is much higher. We attribute this discrepancy to the slight difference between the fabrication parameters and the theoretical ones. In principle, there exists to some extent the ambiguity in determining the structural parameters merely from the SEM image. Besides, the theoretical simulation did not take into account the very thin chromium layer (5 nm thick) that is used to improve the adhesion of the gold film to the quartz substrate. On the other hand, the sample has always some structural nonuniformities, such as surface roughness, and this will increase the scattering effect, leading to a much lower magnitude of the peak transmittance than predicted by the theory.

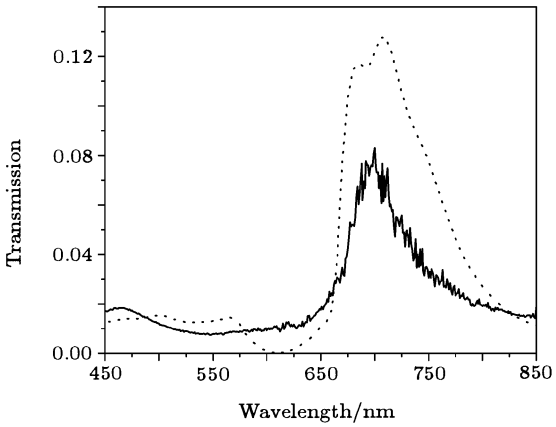


Fig.4. The measured (solid line) and simulated (dotted line) transmission spectra of the diamond hole arrays.

3. Conclusion

In conclusion, we have presented experimentally the enhanced transmission through metallic rectangular and diamond hole arrays in the optical region. A TMM simulation reproduces the experimental results quite well. The position of the peaks has a blue shift of about 61nm when the hole shape changes from rectangular to diamond, and this confirms the important role of LSP in enhancing transmission through a periodic subwavelength structure. Our results can offer a valuable reference for better understanding the enhanced transmission phenomena. It has been found that these subwavelength microstructured metallic materials possess some promising applications in the near-field optical microscopy, surface-enhanced Raman scattering, and biochemical sensing, and so on.

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