Influence of unsymmetrical periodicity on extraordinary transmission through periodic arrays of subwavelength holes

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Quadrate hole array is explored to study the influence of unsymmetrical periodicity on extraordinary optical transmission through periodic arrays of subwavelength holes. It is found that the transmission efficiency of light and the ratio between transmission efficiencies of horizontal and vertical polarized light can be continuously tuned by rotating the quadrate hole array. We can calculate out the transmission spectra (including the heights and locations of peaks) for any rotation angle $\theta$ with a simple theoretical model.

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The extraordinary optical transmission (EOT) through periodic arrays of subwavelength holes has attracted much attention since it was first reported in 1998 [1]. Generally, it is believed that metal surface plays a crucial role and the phenomenon is mediated by surface plasmons and there is a process of transforming photon to surface plasmon and back to photon [2, 3, 4]. The polarization of the incident light determines the mode of excited surface plasmon which is also related to the periodic structure. This phenomenon can be used in various applications, for example, sensors, opto electronic device, etc [5, 6, 7, 8, 9]. Polarization properties of nanohole arrays have been studied in many works [10, 11, 12]. Recently, orbital angular momentum of photons were explored to investigate the spatial mode properties of surface plasmon assisted transmission [13, 14]. The shape distortion of single wavepacket during photon to plasmon and back to photon process was also discussed [15].

In 2002, E. Altewischer et al. [16] also showed that quantum entanglement of photon pairs can be preserved when they respectively travel through a hole array. Therefore, the macroscopic surface plasmon polarizations, a collective excitation wave involving typically $10^{10}$ free electrons propagating at the surface of conducting matter, have a true quantum nature. However, the increasing use of EOT requires further understanding of the phenomenon.

For the manipulation of light at a subwavelength scale with periodic arrays of holes, two ingredients exist: shape and periodicity [2, 3, 4, 17, 18, 19]. In this work, we used a quadrature hole array to investigate the influence of unsymmetrical periodicity on EOT. It was found that the optical transmission spectra were changed when we rotated the hole array. The transmission spectra strongly depends on the rotation angle, in other words, the angle between polarization of incident light and axis of hole array. We also gave a simple model to explain the results. Using this feature, we can continuously tune the transmission efficiency of light with certain polarization by rotating the quadrature hole array. The ratio between transmission efficiencies of horizontal polarized and vertical polarized light can also be modified.

Fig. 1 shows sketch maps of our hole arrays. (a) is a square hole array. It is produced as follows: after subsequently evaporating a 3-\textit{nm} titanium bonding layer and a 135-\textit{nm} gold layer onto a 0.5-\textit{mm}-thick silica glass substrate, a Electron Beam Lithography System (EBL) is used to produce cylindrical holes (200\textit{nm} diameter) arranged as a square lattice (600\textit{nm} period). The area of the hole array is 300\mu\textit{m} × 300\mu\textit{m}. (b) is a quadrature hole array. It is produced by a Focused Ion Beam Etching system (FIB). Periods in two axes are 600\textit{nm}
and 540 nm respectively. The area of the hole array is $42\mu m \times 44\mu m$.

Transmission spectra of the hole arrays were recorded by a Silicon avalanche photodiode (APD) single photon counter couple with a spectrograph through a fiber. White light from a stabilized tungsten-halogen source passed through a single mode fiber and a polarizer (only vertical polarized light can pass), then illuminated the sample. The hole arrays were set between two lenses of 35 mm focal length, so that the light was normally incident on the hole array with a cross sectional diameter about 20$\mu m$ and covered hundreds of holes. The light exiting from the hole array was launched into the spectrograph.

In our experiment, the hole arrays were rotated anti-clockwise in the plane perpendicular to the illuminating light, as shown in Fig. 1 (c). First, we used the square sample and recorded the transmission spectra with rotation angle $\theta = 0^\circ, 30^\circ, 60^\circ, 90^\circ$ respectively. The results were shown in Fig. 2. We can see that there is no obvious change among the spectra of four cases.

Then we used the quadrate hole array and recorded the transmission spectra with rotation angle $\theta = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ$ respectively. The results were shown in Fig. 3. Much different from the case of square sample, the spectra had a large change in both the heights and the locations of peaks. For $\theta = 0^\circ$, the wavelengths at two peaks were about 555 nm and 700 nm with transmission efficiencies 1.21% and 6.30%. While for $\theta = 90^\circ$, the wavelengths at two peaks were about 570 nm and 680 nm with transmission efficiencies 1.53% and 3.99%. For other rotation angles, the heights and the locations were located between the upper two cases. The transmission spectra were more close to the case of $\theta = 90^\circ$ with increasing of $\theta$.

To explain this phenomenon, we gave a simple model. Since the surface plasmons were excited in the directions of long (L) and short (S) axes of quadrate hole array, we can suspect that this two directions were eigenmode-directions for our sample. The polarization of illuminating light was projected into the two eigenmode-directions to excite surface plasmons. After that, the two kinds of surface plasmons transmitted the holes and irritated light with transmission efficiencies $T_L$ and $T_S$ respectively. So for light whose polarization had an angle $\theta$ with the L axis, the transmission efficiency $T_\theta$ will be

$$T_\theta = T_L \cos^2(\theta) + T_S \sin^2(\theta).$$

This equation was appropriate for any wavelength. So if we know the transmission spectra for enginmode-directions (here L and S), we can calculate out the transmission spectra.
(including the heights and locations of peaks) for any $\theta$. Fig. 4 gave the comparison between the calculations (lines) and experimental results (dots) for $\theta = 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ$. It can be seen that the experimental data fit the lines well, which sustains our model. The surface plasmon was highly polarization dependent, so the polarization of transmitted light was composed of two parts: directions along the L and S axes of quadrate hole array. For rotation angle $\theta$, polarization $V$ was changed to $(\sqrt{T_L} \cos^2(\theta) + \sqrt{T_S} \sin^2(\theta))|V\rangle + (\sqrt{T_S} - \sqrt{T_L}) \sin(\theta) \cos(\theta)|H\rangle$ (not normalized). Since the square hole array had the relation: $T_L = T_S$ for any wavelength, transmission efficiencies will always be $T_\theta = T_L = T_S$ and the transmission spectra will not be influenced, as shown in Fig. 2. Unlike the square hole array, not only the transmission efficiencies of light, but also the ratio of transmission efficiencies between vertical and horizontal polarized light were changed when we rotated the quadrate hole array. For rotation angle $\theta$, the ratio was

$$R_\theta = \frac{T_{V_\theta}}{T_{H_\theta}} = \frac{(T_L \cos^2(\theta) + T_S \sin^2(\theta))}{(T_L \sin^2(\theta) + T_S \cos^2(\theta))}.$$  \hspace{1cm} (2)

As an example, the case for 700nm wavelength light was shown in Fig. 5. Obviously, the ratio could be varied in a range by changing the rotation angle $\theta$. Of course, the polarization of transmitted light will be changed due to this unequal transmission efficiencies. Our model may also be extended to other structures, such as metal plate with subwavelength slits. While for different structures and materials, the eigenmode-directions might be different.

In conclusion, quadrate hole array was explored to study the influence of unsymmetrical periodicity on EOT. Because of the reduced symmetry of structure, the transmission spectra were changed when we rotated the hole array. A simple model was given to explain this phenomenon. Using this protocol, we could continuously tune the transmission efficiency of light with certain polarization by rotating the quadrate hole array. The ratio of transmission efficiencies between horizontal and vertical polarized light could also be modified. Our results may be useful in the further application of plasmonics.

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Fig. 1. Sketch picture of our hole arrays: (a) Square hole array. Period is 600nm. (b) Quadrate hole array. Periods are 600nm and 540nm in two directions respectively. (c) Rotation of our hole arrays. S (L) is the axis of short (long) period of quadrate hole array; H(V) is horizontal (vertical) axis.

Fig. 2. (Color online) Transmittance as a function of wavelength when we rotated the square hole array. The rotation angle are 0°(black square dots), 30°(red round dots), 60°(green triangle dots), 90°(blue inverse triangle dots) respectively.

Fig. 3. (Color online) Transmittance as a function of wavelength when we rotated the quadrate hole array. The rotation angle are 0°(black square dots), 15°(red round dots), 30°(green triangle dots), 45°(blue inverse triangle dots), 60°(cyan diamond dots), 75°(magenta pentagon dots), 90°(yellow hexagon dots) respectively.

Fig. 4. (Color online) Comparison between theoretical calculations (lines) and experimental results (dots). Rotation angle: (a) 15°, (b) 30°, (c) 45°, (d) 60°, (e) 75°. The individual spectra are offset vertically by 1.5% for clarity. In all the cases, experimental data fit theoretical calculations well.

Fig. 5. (Color online) Ratio of transmission efficiencies between vertical and horizontal polarized light (wavelength 700\,nm). Black dots are experimental results.
