Experimental studies of extraordinary light transmission through periodic arrays of subwavelength square and rectangular holes in metal films*

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We fabricate a series of periodic arrays of subwavelength square and rectangular air holes on gold films, and measure the transmission spectra of these metallic nanostructures. By changing some geometrical and physical parameters, such as array period, air hole size and shape, and the incident light polarization, we verify that both global surface plasmon resonance and localized waveguide mode resonance are influential on enhancing the transmission of light through nanostructured metal films. These two resonances induce different behaviours of transmission peak shift. The transmission through the rectangular air-hole structures exhibits an obvious polarization effect dependent on the morphology. Numerical simulations are also made by a plane-wave transfer-matrix method and in good consistency with the experimental results.

Keywords: surface plasmon, extraordinary light transmission, metal film

PACC: 7360D, 7865E, 4270Y

1. Introduction

Extraordinary optical transmission (EOT) through subwavelength apertures in opaque metal thin film was first reported by Ebbesen *et al.* in 1998.[1] The intensity of light transmitting through an opaque metal slab, which is patterned with periodic air hole arrays, is much stronger than that expected from classical diffraction theory for subwavelength apertures. There are a lot of potential applications based on this EOT structure, such as subwavelength optics,[2−6] optoelectronics[7,8] and biosensing.[9] Since then, a lot of theoretical and experimental work has been done.[10−15] Many researchers have proposed that the enhanced transmission is caused by the excitation and coupling of surface plasmon modes,[16] which are bound modes that can exist only on metal surfaces. These modes can enhance the electromagnetic field intensity dramatically on the metal surfaces and enhance light transmission. However, it was found that the shape and the size of the hole also had an effect on the transmission spectrum.[17] This phenomenon cannot be explained by the surface plasmon theory. It was suggested that this shape-depending effect was caused by the localized surface plasmon (LSP) resonance.[18,19] Ruan and Qiu have made a theoretical investigation of this problem and suggested that the waveguide mode together with the surface plasmon mode on a metal surface might contribute to the shape-depending effect, therefore leading to the enhanced transmission.[12]

In the present paper we study EOT on patterned metal film experimentally and validate Ruan and Qiu's theory. We fabricate a series of samples with periodic subwavelength air hole arrays in different geometries and measure their transmission spectra. We also calculate the transmission spectra by using a plane-wave transfer-matrix method.[20−23] The simulation and the experimental results are in good agreement with each other.

2. Experimental setups

Our samples are fabricated on a 120 nm-thick (optically thick) gold film which is deposited on a quartz

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substrate (refractive index 1.55). We make the metallic nanostructures by using a Raith 150-electron beam lithography system. The samples consist of rectangular holes with different sizes. The lengths of the two sides can be equal, equivalent to a square hole, or have different ratios, equivalent to an ordinary rectangular hole. The periods of the arrays vary among three values, i.e. 1.0, 1.1, and 1.2 μm. The overall size of the whole sample is about 100 μm by 100 μm, so the total number of the rectangular holes is about 10000. A scanning electron microscope (SEM) image of a typical rectangular-hole sample is shown in Fig. 1. We can see that the shape of the rectangle, which is critical to the property of localized waveguide mode, is pretty good. Furthermore, the sample has quite a good periodicity and uniformity in a large area. All of these will facilitate good optical characterization through the accurate measurement of the transmission spectrum.

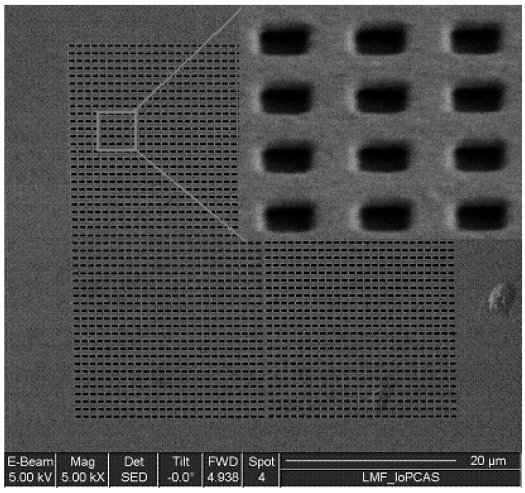


Fig. 1. SEM image of a typical metallic nanostructured sample composed of a square-lattice periodic array of rectangular holes in gold film. The hole has a size of 400 nm by 150 nm, and the period of the array is 900 nm.

The measurement system uses a halogen lamp, which is a white-light broad band continuum source. The incident light is focused onto a tiny spot, which is less than 100 μm in diameter, smaller than the dimension of the array area. The transmission light is then collected by a microscope objective, and projected onto a monochrometer, which is equipped with a PbS infrared photoelectric detector. A chopper and a lock-in amplifier are used to reduce noise and extract a reliable signal. The range of wavelength in our experiment is 800–2000 nm. All data are recorded and processed by a computer. Finally, by comparing the transmission intensity of the measured rectangular hole array samples with that of a reference large square hole which is 100 μm by 100 μm and made on the same gold thin film, we obtain the experimental transmission spectra in the infrared region.

3. Results and discussion

We first investigate the effect of surface plasmon mode on EOT. We start with measuring the transmission spectra of square-hole samples with different array periods. The measured transmission spectra are shown in Fig. 2, where the periods of the arrays are 1.0, 1.1, and 1.2 μm separately, and the square hole has a size of 400 nm by 400 nm. For each sample, we can see that there are three peaks in the 800–2000 nm region. The positions of the first peaks on all the curves are almost the same, appearing around 800 nm, which is twice the size of the square-hole. We believe that this peak is caused by the local waveguide mode, which is determined by the hole size. It is known that the fundamental mode of a rectangle waveguide has a cutoff wavelength that is twice as long as the length of the rectangle. In the current samples, the rectangles are, in fact, squares, so the wavelength of the fundamental mode is twice the side length. We can also see that the longer the period of arrays is, the lower the peak in magnitude will be. This can be easily explained by the fact that the larger the array period is, the smaller the filling ratio of the rectangle waveguides on the overall structure will be.

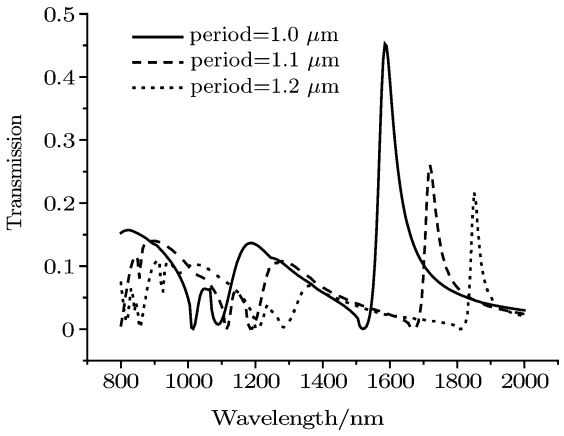


Fig. 2. Measured transmission spectra of three samples with three different array periods: 1.0, 1.1, and 1.2 micrometres. Their square hole sizes are the same, and are all 400 nm by 400 nm.

The second peak on each spectrum curve, which is caused by the surface plasmon resonance, might be the most important one. Surface plasmons are a collective excitation of surface electrons by external electromagnetic (EM) radiations. They describe a special

case in which the charges and the field are confined to the surface of metals. We can see from the spectra that the transmission peaks are at positions which are a little longer than the array periods. Take the sample with 1.0 μm period as an example. Its transmission spectrum is shown by a solid line in Fig. 2. The transmission maximum appears at a wavelength of 1.15 μm, which is a little longer than the array period. This phenomenon has been elaborated by Liu and Lalanne.[24] In short, the surface plasmon mode on the patterned metal surface is different from that of a flat metal slab. The surface wave is scattered by the holes, and there is a phase shift of the surface plasmon on the border of the hole. This phase shift could change the dispersion relation a little. Liu and Lalanne pointed out that the transmission maximum appeared at the wavelength which is a little longer than the period of the array structure, and the degree of difference between the transmission maximum wavelength and the array period depends on air-hole size and period.

It is obvious in Fig. 2 that the transmission minimum shifts toward longer wavelengths gradually when the array period increases from 1.0 μm to 1.2 μm. According to the model discussed in Ref. [24], the transmission minimum is directly related to the array period as it is caused by Wood's anomaly. In the infrared range, it is almost equal to the array period. Excitation of the surface plasmon mode will result in enhanced transmission, and the peaks are located on the long-wavelength side of the transmission minimum. As a result, the transmission peaks also shift with respect to the array period as shown in Fig. 2.

As to the third peak, we can see that the wavelength of the third peak is about 1.5 times that of the second one. Similar to the second peak, a transmission minimum is also accompanied by a transmission maximum. This could be explained by the surface plasmon resonance on the gold–quartz interface, instead of on the air–gold interface as for the second peak. The quartz has a refractive index of 1.55. Since the hole has only a slight effect on the surface plasmon, the wavelength of the gold–quartz interface surface plasmon mode could be regarded as 1.55 times that of the air–gold interface surface plasmon mode. So the shapes of the second peak and the third peak are almost the same, and the third peak, similar to the second one, red shifts as the array period increases. We note that the third peak for the sample with an array period of 1.2 μm cannot be seen in Fig. 2. This is because the third peak of the sample is too low to be detected due to the low spectrum intensity of the light source and the low efficiency of the detector on this long wavelength side.

In order to check the experimental results, we use the plane-wave transfer-matrix method to calculate the transmission spectra of the samples. The practical dispersion data of gold[25] are adopted in the calculations. The calculated results are shown in Fig. 3. The parameters are the same as those of the samples we made. We can see that the calculated results fit the measured results very well. The positions of the peaks and the dips in two figures are almost the same, but the width and height of the peaks are a little bit different. This might be caused by the inaccuracy of the measurement and the quality of the sample. When we calculate the transmission spectrum, we assume that the incident light is a plane wave perpendicular to the sample surface. But when we measure the spectrum, the light shining on the sample is a focused light, which is composed of light rays from different directions. The transmission peak of the light shifts a little if the light impinging on a sample is not strictly perpendicular to the sample surface. As the light rays impinging on the sample come from various directions, the transmission peak is a superposition of peaks of light rays from different directions. So the transmission peak is broadened, as can be seen by comparing Fig. 2 with Fig. 3. On the other hand, the gold film that we made is not perfect. The film surface is roughened by gold grains with various nanometre sizes. This roughness of the gold surface can influence the surface plasmon on it and has an effect on the transmission spectrum as well. Although the measured spectrum is

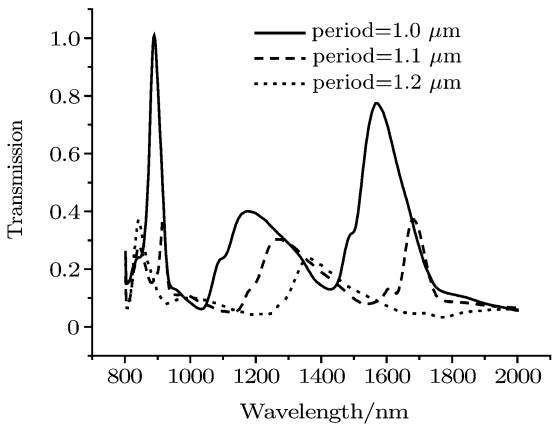


Fig. 3. Calculated transmission spectra of the three samples discussed in Fig. 2.

a little bit different from the calculation, the main features can still be seen. The positions of the peaks and

the shift of the peaks as the array period changes suggest that the explanation of the EOT effect is pretty cogent by using the surface plasmon model.

Then we proceed to investigate the role of hole shape and size in EOT. To do this, we make samples with rectangular holes of different sizes. The holes are also arranged in a square lattice with a fixed period of 0.9 μm. The holes are 0.35, 0.42, and 0.5 μm in length, separately, and they all have a width of 0.15 μm. For rectangular holes, the polarization of the incident light is vital to the transmission, so we measure the transmission spectra with light of two different polarizations. The measured spectra with using light polarized in the direction perpendicular to the long side of the rectangle are shown in Fig. 4 for several samples. The corresponding calculated spectra are displayed in Fig. 5. The measured and calculated spectra with the incident light polarized in the direction parallel to the long side of the rectangle are shown in Fig. 6. In Figs. 4 and 5, two main peaks can be observed. The first peak starting from 900 nm, which is equal to the array period, could be caused by the surface plasmon. Because the samples have identical periods, the positions of the first peak are the same, and this is also verified by the simulation. As the hole sizes get larger, the second peaks of the spectra all become higher and wider. This is because larger holes can accept more EM waves and turn them into waveguide modes. Consequently, more energy is transmitted and so the transmission is enhanced. More importantly, as the holes get larger, the positions of the peaks all have

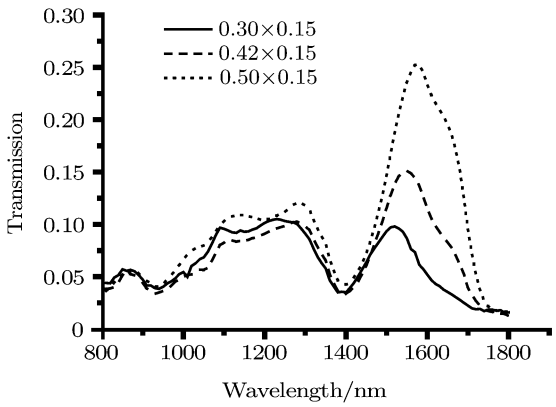


Fig. 4. Measured transmission spectra of three samples with rectangular hole arrays of different hole sizes. The rectangular hole sizes are 0.35, 0.42 and 0.5 μm in length, and 0.15 μm in width. The polarization is perpendicular to the long side of the rectangle.

a slight red shift. This is predicated by the simulation and observed in experiment. For this reason, the second peak is attributed to the excitation of local surface plasmon mode associated with the waveguide mode of the rectangular holes.

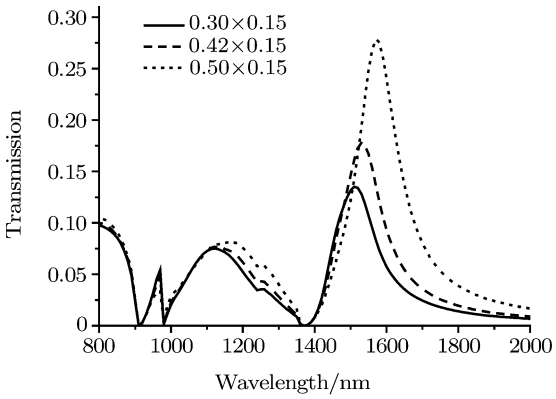


Fig. 5. Calculated transmission spectra of the three samples discussed in Fig. 4.

Both the experimental and calculation results (Fig. 6) clearly show that when the incident light is polarized in the direction parallel to the long side of the rectangular hole, the transmission magnitude is very low. As one can see in Fig. 6, the maximum

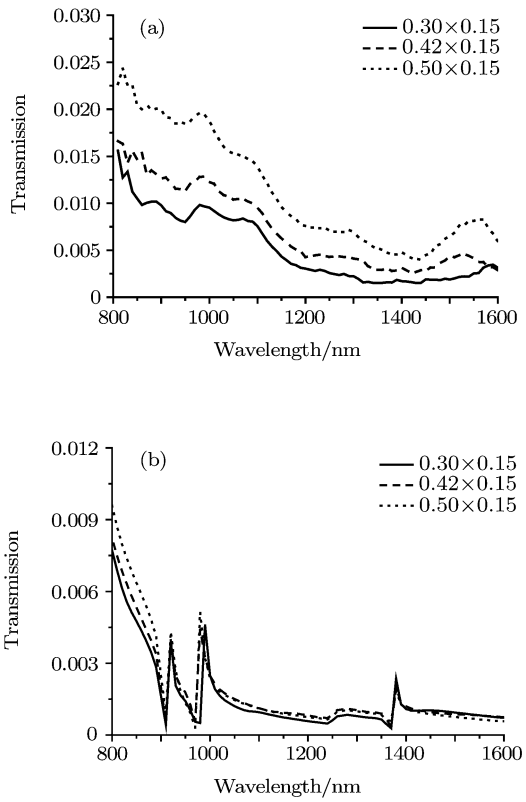


Fig. 6. Measured (a) and calculated (b) transmission spectra of samples with rectangular holes, where polarization of light is parallel to the long side of the rectangle.

transmission is less than 0.03. This is easy to understand. The cutoff frequency of this polarization is

much higher than that in the perpendicular polarization situation. Light at a wavelength range of 800–1600 nm adopted in our experiment cannot transmit through this waveguide, so the transmission is relatively low.

4. Conclusions

We designed and fabricated a series of samples composed of periodic arrays of subwavelength air holes with different periods, hole shapes and sizes in metal thin film. We measured the optical transmission spectra of these samples and investigated the phenomena of extraordinary optical transmission. The experimental and theoretical results both indicate that such an extraordinary transmission property is dependent on two factors. One is local surface plasmon resonance associated with the waveguide mode, which is mainly determined by both the size and shape of the air hole. The other is the global surface plasmon resonance, which is mainly affected by the array period and the environment around the metal film. Our experiments are designed deliberately so that we can separate these two factors. By changing the period of the array, some of the transmission peaks shift. This demonstrates that the surface plasmon resonance plays a key role in the formation of these transmission peaks. When the size and the shape of holes change, some of the transmission peaks apparently shift, indicating that the local plasmon resonance is the major determinant for these peaks. Our experimental and theoretical studies explicitly show the polarization effect on samples with rectangular air holes, which again supports the model of local plasmon resonance.

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