Tunable and polarization-selective THz range transmission properties of metallic rectangular array with a varying hole channel shape

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Abstract: This paper proposes a metallic hole array of a rectangular converging-diverging channel (RCDC) shape with extraordinary transmission. We use a three-dimensional (3D) finite element method to analyze the transmission characteristics of two-dimensional metallic hole arrays (2D-MHA) with RCDC. For a straight channel MHA, when the aperture size is reduced, the transmission peaks have a blue-shift. The same result is observed for a smaller gap throat for the RCDC structure. For the rectangular holes with a high length-width ratio, a similar blue-shift in the transmission peaks as well as a narrower full width at half maximum (FWHM) are observed. The asymmetry from the rectangular shape gives this structure high selectivity for light with different polarizations. Furthermore, the RCDC shape gives extra degrees of geometrical variables to 2D-MHA for tuning the location of the transmission peak and the FWHM. The tunable transmission property of this structure shows promise for applications in tunable filters, photonic circuits, and biosensors .

OCIS codes: (050.1220) Apertures; (050.0050) Diffraction and gratings; (120.2440) Filters; (240.6680) Surface plasmons; (040.2235) Far infrared or terahertz; (120.7000) Transmission; (230.5440) Polarization-selective devices.

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1. Introduction

In 1998, extraordinary optical transmission (EOT) phenomenon was reported by T. W. Ebbesen and his coworkers. EOT was achieved through subwavelength metallic hole arrays (MHAs) milled in an opaque metal screen [1]. This work generated considerable interest and led to the development of a new family of optical devices based on subwavelength hole arrays with tunable transmission spectrums via adjustable array properties (periodicity, thickness of the film, etc.). There have been arguments about the main cause of this high transmission through subwavelength holes [2-4]; however, more and more researchers in this area are beginning to believe that enhanced transmission through subwavelength MHA can be divided into three steps: the coupling of light to SPPs on the incident surface, the transmission through the holes and the re-emission from the second surface. EOT in the terahertz (THz) region has been observed recently in both metallic [5-8] and semiconductor hole arrays [9-11]. Although metal surfaces in this frequency region act as perfect conductors and the SPPs excitation cannot be expected, it has been proven both experimentally [12] and theoretically [13] that the resonantly-excited SPP-like mode plays an important role in high transmission in the THz region.

Photonic structures have several geometric variables, such as film thickness, interface media, periodicity, hole shape, aperture size, etc., that can be used to manipulate the light propagation at the subwavelength scale. As mentioned above, the high transmission is caused by the coupling interaction of the SPPs on both the incident and the transmitted surfaces and is strongly affected by the thickness of the metal film. The transmission decreases exponentially with increasing depth [14], and the SPPs on the two surfaces are uncoupled when the hole depth is large. It is observed in the THz region that the EOT can be achieved at an array thickness of only one third of the skin depth [15]. It has also been shown that the peak transmission has a red-shift as the index of refraction inside the metallic hole arrays undergoes an increase [16]. Similarly, when the surrounding dielectric constant increases, a red-shift along with a reduction in the transmission magnitude is observed [9]. In addition to

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the parameters that have already been discussed, periodicity is also very important. It has been reported that a planar circular grating with the period of the rings matching the SPP wavelength can have enhanced intensity at the focal point of the plasmonic lens [17]. Different hole shapes have also been studied. A circular hole shape has an order of magnitude higher normalized transmission than a rectangular shape, along with a large blue-shift spectrum [18]. Also, the different influence of the hole shape in the THz region from that in the optical region has been studied [5, 6].

The hole size along with the channel shape will have significant impact on the transmission efficiency because the holes are expected to mediate the SPP coupling between both surfaces of the metal film. Recently we have proposed a subwavelength hole array having a converging diverging channel (CDC) with a circular hole shape [19]. This CDC-shaped hole array offers similar EOT effects, yet has an extra degree of freedom in a geometric variable, the converging angle, to tune the transmission spectrum. The converging angle determines the slope of the sidewall and the area at the throat of the CDC channels (Fig. 1). The transmission spectrum was studied for a 2D-MHA with variable throat and aperture size and was compared with a straight channel array. The results show that when the channel shape is changed to CDC the transmittance peaks become narrower and there is a blue-shift. The blue-shift becomes larger as the throat area decreases.

In this work, we propose to use a rectangular converging-diverging channel (RCDC) to study the EOT properties for light with different polarizations. The proposed structure has another geometric variable, the length-width ratio of the rectangle that can be used to tune the transmission properties. More importantly, this structure has a strong selectivity for different polarizations.

2. Computational considerations

Figure 1 shows a side view of the structure used for the simulation where the incident light goes through a thin film of silver. The thickness of the film is t, and there is a rectangular RCDC hole array with a converging angle θ in it. The transmission vs. wavelength curve was calculated for different geometric variables. Figure 2 shows the top surface of the silver film. The rectangular hole array is periodic in both the x and y directions, and the periodicity for the two directions are the same (22μm). The inset shows the top view of a single rectangular hole, with a and b defined as the long and short sides. The lengths of the two sides are not identical, resulting in an asymmetric structure along the x and y directions. Transmissions are expected to change with different polarizations of the incident light. In fact, we will show that such a structure has a very high selectivity of transmission with different polarizations and can be used as a polarization-selective filter.

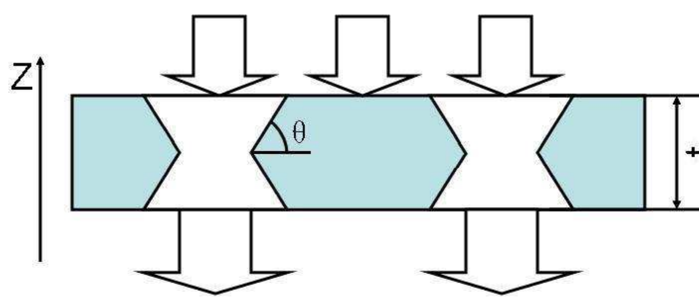

Fig. 1. Side view of the structure. The thickness of the film is t, and there is a rectangular RCDC hole array with a converging angle θ in it.

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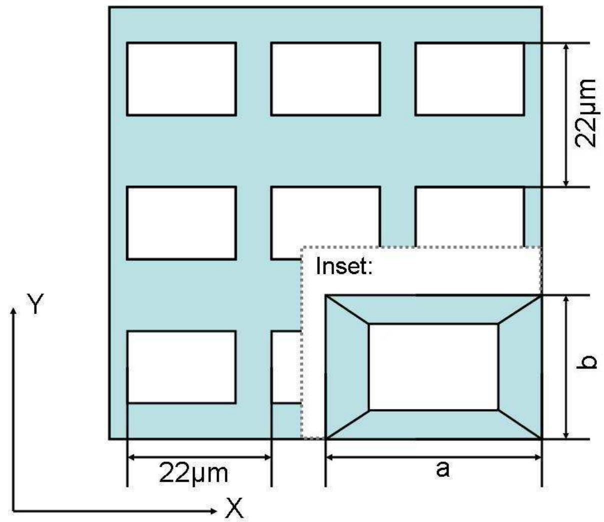

Fig. 2. Top surface of the structure. The rectangular hole array is periodic in both the x and y directions, and the periodicity for the two directions are the same (22µm). The inset shows the top view of a single rectangular hole, with a and b defined as the long and short sides. The lengths of the two sides are not identical, resulting in an asymmetric structure along the x and y directions.

In this paper, we will change the length-width ratio (a/b), the converging angle θ, and the metal film thickness t, while keeping the other parameters unchanged to study the effect of these parameters on the relationship between transmission and wavelength.

For this study we considered the frequency to be around 15 THz or 20µm wavelength. The dielectric constant of silver used in the simulation was described by the Drude model $\varepsilon = \varepsilon_\infty - \omega_p^2 / (\omega^2 + i\gamma\omega)$, where $\varepsilon_\infty = -175.0$, $\omega_p = 1.1 \times 10^{16}\ \mathrm{s}^{-1}$, and $\gamma = 10.51 \times 10^{13}\ \mathrm{s}^{-1}$ [20]. The electromagnetic fields were assumed to be time harmonic and the resulting governing equations for the steady-state distribution was solved using a commercially available 3-dimensional (3D) finite element software (COMSOL 3.3) [21]. The computational domain considered is a single unit cell surrounded either by periodic boundary conditions or by perfectly matching layers (PML) [22].

3. Results and discussions

3.1 Results for different a/b ratios

Figure 3 (a-c) shows the transmission spectrums for Ag MHAs having different a/b ratios. For all the cases, the hole area, the converging angle (30°) and the metal film thickness (2µm) are kept the same. The solid and dashed lines show the transmissions for different polarizations (solid line: E-field parallel to the short side; dash line: E-field parallel to the long side). Since these 2D structures are asymmetric along their short and long sides, the polarization becomes a very crucial parameter for the transmission peak. In the case of polarization (i.e., E-field) parallel to the long sides of the rectangles, there is negligible transmission. When the incident polarization is rotated 90° to point along the rectangles' minor sides, the aperture transmits a substantial fraction of the incident light, in agreement with the result reported previously [23].

The transmission spectrum changes as the a/b ratio increases, but the magnitude of the transmission peak remains the same and is much larger than $(A/\lambda)^4$, the Bethe-Bouwkamp power law model. In this model, 'A' is the aperture size and 'λ' is the wavelength of the light. By changing the a/b ratio, we can tune the position of the band and the full width at half maximum (FWHM). For example, decreasing the a/b ratio causes an increase in the FWHM of the transmission peaks accompanied by a red-shift. At the frequencies below the cutoff frequency ω_c (the frequencies at which the transmission reaches half maximum of the peak),

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the curves are very sharp and the transmissions rapidly drop to 0.1. This means the RCDC structures with different a/b ratios are all very good filters for low frequencies.

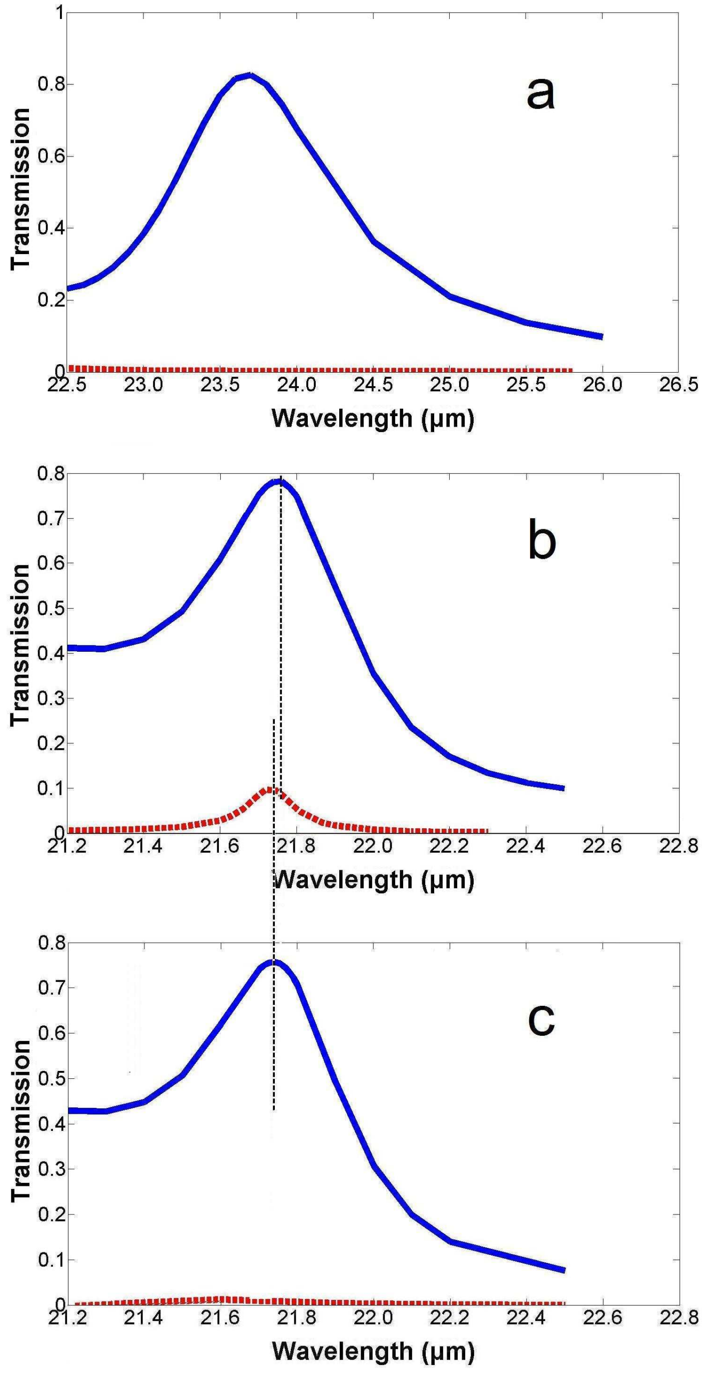

Fig. 3. Transmittance spectrum with the same hole area and converging angle θ=30°, but different a/b ratios (a) a=16μm, b=12μm, (b) a=18μm, b=10.7μm, and (c) a=20μm, b=9.6μm. The solid and dashed lines represent the transmissions for different polarizations. The vertical dashed lines denote the wavelength of each peak.

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3.2 Results for different converging angles

Figure 4 shows the transmission spectrum for Ag MHAs with different converging angles while keeping the same hole area, a/b ratio (16μm/12μm) and film thickness (2μm). The two sets of simulation data show a high-selectivity for different polarizations. Similar to the results in section 3.1, the transmission spectra for an E-field perpendicular to the long side has a strong peak for each converging angle in this wavelength range, while there is no peak in the range of our interest for the case of an E-field parallel to the long side. The position of the peaks and the FWHM can be tuned by changing the converging angle. Figure 4 shows that the location of the peak blue shifts nearly linearly as the converging angle decreases. Moreover, since the throat size varies as the converging angle changes, the magnitudes of the transmission peak and the FWHM increase as the angle increases. Interestingly, the change of magnitude with respect to the angle is nearly linear. For frequencies beyond the cut off frequency ω_c, the transmissions drop rapidly, indicating the potential application as band-pass filters.

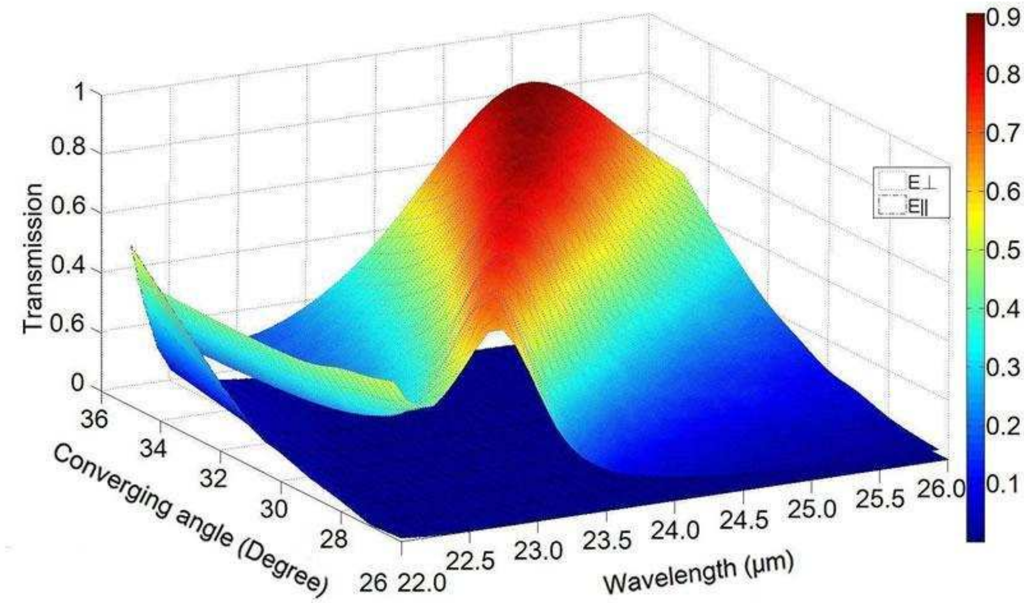

Fig. 4. Transmissions for different converging angles. The hole area, film thickness and a/b ratio (16μm/12μm) remain the same in all cases.

3.3 Results for different metal film thickness

Figure 5 shows the transmission spectrum for Ag MHAs with different metal film thicknesses while keeping the same hole area, a/b ratio (16μm/12μm) and converging angle (30^{o}). The solid and the dashed lines are for different polarizations. Similar to the results in sections 3.1 and 3.2, the transmissions are highly selective—there are strong transmission peaks only for the cases of E-field perpendicular to the long side. But the difference is that, since we extend our study to shorter wavelengths, there are two transmission peaks for some cases. As the thickness increases, one of the peaks stays almost at the same location (~21.8μm), yet the location of the other peak blue shifts. The behavior of these two peaks may be due to the excitation of two types of electromagnetic modes as mentioned previously [24]: coupled SPPs and waveguide resonances. The nearly fixed peaks are excited by coupled SPPs whose

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locations are not sensitive to the film thickness, whereas the other peaks are caused by the waveguide resonances.

From t=2.0μm to 2.5μm, the transmission peaks due to the waveguide resonances blue shift and both the magnitude and the FWHM of the peaks decrease resulting from the reduced throat area. However, the magnitudes of the peaks related to SPPs increase as the thickness increases. One possible reason is as the waveguide resonances peak blue shifts, the two peaks come closer and the interaction between them becomes stronger. When t=2.5μm, the interactions are so strong that the location of the SPPs peak red shifts a little. For the case of t=3.0μm, however, only the SPPs peak is left and it is relatively small (<0.5). This shows that without the contribution of the waveguide resonance, the magnitude of the SPPs peak will decrease with an increasing film thickness.

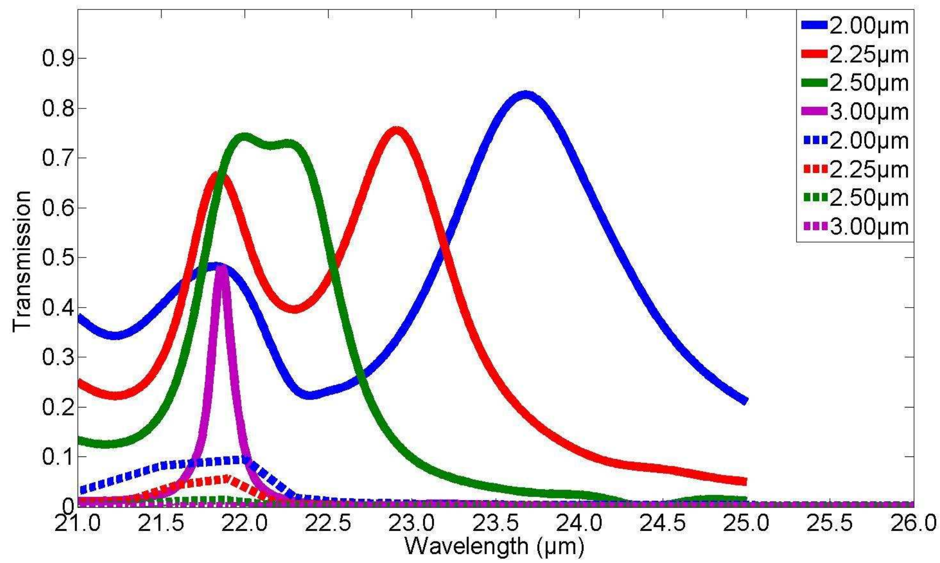

Fig. 5. Transmissions for different metal film thickness. The hole area, converging angle (30^o) and a/b ratio remain the same in all cases. The solid and dashed lines represent the transmissions for different polarizations.

4. Conclusion

The transmission spectrums of metallic hole arrays with different converging-diverging channels have been discussed in this paper. Since the structure is asymmetric along the x and y directions, it is highly selective for different polarizations, providing a potential application as a polarized optical filter. Meanwhile, by changing the a/b ratio, the converging angle and the metal film thickness, the transmission properties can be changed. As a result, this proposed RCDC shape in MHAs could lead to extraordinary transmission at different wavelengths and can be used to develop THz polarized filters. This could lead to a wide range of applications in tunable filters, photonic circuits, nanopatterning, and biosensors.

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