Role of shape of hole in transmission and negative refractive index of sandwiched metamaterials*

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(Received 12 March 2013; revised manuscript received 16 April 2013; published online 10 December 2013)

Transmission and negative refractive index (NRI) of metal–dielectric–metal (MDM) sandwiched metamaterial perforated with four kinds of shapes of holes are numerically studied. Results indicate that positions of all transmission peaks of these kinds of holes are sensitive to the shape of the hole. Under the same conditions, the circular hole can obtain the maximum NRI and the rectangular hole can obtain the maximum frequency bandwidth of NRI. Moreover, the figure of merit (FOM) of the circular hole is the maximum too. As a result, we can obtain a higher NRI and FOM metamaterial by drilling circular hole arrays on MDM metamaterial.

Keywords: metamaterials, negative refractive index (NRI), transmission

PACS: 41.20.Jb, 78.20.Cj, 73.20.Mf, 42.25.Bs **DOI:** 10.1088/1674-1056/23/2/024101

1. Introduction

The transmission properties of two-dimensional (2D) hole arrays perforated in metal–dielectric–metal (MDM) metamaterials of subwavelength apertures have become a very active research area in electromagnetism since extraordinary optical transmission (EOT) was reported by Ebbesen *et al.*[1] Over the past decade, the EOT and negative refractive index (NRI) of 2D hole arrays of sandwiched metamaterials have been widely investigated because of their remarkable properties.[2–9] Very recently, many experiments have been conducted to study the influence of hole shape on the optical transmission properties of 2D hole arrays.[10–12] But unfortunately in these experimental studies, the role of shape in determining the NRI of 2D hole arrays of sandwiched metamaterials was not taken into consideration, nor was what shape of hole should be used to obtain better transmittance and NRI. In order to have a deeper insight into the influence of the shape of hole on the properties of transmission and NRI of sandwiched metamaterials, transmission spectra and negative refractive spectra of the cross hole, circular hole, rectangular hole and square hole are studied, respectively.

In this paper, we study the influences of the shape of hole on transmittance and NRI. It is found that, on the one hand, the NRI of a circular hole is larger than those of a cross hole, rectangular hole and square hole significantly under the same conditions, i.e. the same lattice periodicity, thickness of the silver film and the SU-8 layer and the same material; on the other hand, the frequency bandwidth of the NRI of the rectangular hole is higher than those of the other three hole shapes.

2. Model and method

Figure 1(a) shows a unit cell of our model under study, which is made of a sandwiched metamaterial with a rectangular hole of sides $a = 6$ μm and $b = 2$ μm. Scanning electron microscopy (SEM) images of samples are shown in Fig. 1(b). The periodicity in the x–y plane is $T = 12$ μm. The lattice consists of three layers of media, two layers of silver and the middle layer are both SU-8 layers. The thickness values of the silver film and the SU-8 layer are $s = 0.05$ μm and $h = 2$ μm, respectively. In the simulation, we utilize two ideal magnetic conductor planes on the boundary normal to the x axis and two ideal electric conductor planes on the boundary normal to the y axis.[13] The whole model is tested in air and light that is incident from air to our structure and propagates along the z axis.

We use commercial software Ansoft HFSS10 to perform the simulation. The dielectric constant of the SU-8 layer is assumed to be $2.56 + 0.035$i.[14] The dielectric constant of the silver layer is obtained using the Drude model:

$$\varepsilon(\omega) = 1 - \frac{\omega_{\mathrm{p}}^2}{\omega^2 - \mathrm{i}\omega\gamma_{\mathrm{D}}}, \tag{1}$$

where $\gamma_{\mathrm{D}} = 9 \times 10^{13}$ s^{-1} is the collision frequency, $\omega_{\mathrm{p}} = 1.37 \times 10^{16}$ s^{-1} is the plasma frequency[15] and ω is the circle frequency. We can obtain the transmittance, the refractive index and s parameters using the unit cell.[16]

*Project supported partially by the National Natural Science Foundation of China (Grant No. 60778041) and the Natural Science Foundation of the Jiangsu Higher Education Institutions, China (Grant No. 07KJA51001).

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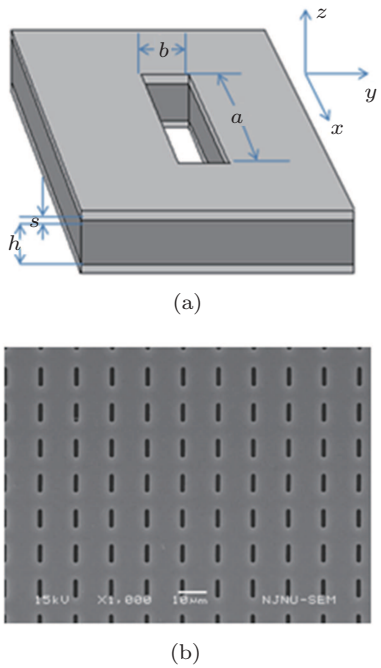


Fig. 1. (color online) (a) Schematic diagrams of one unit cell of our design and (b) scanning electron microscopy (SEM) image of the sample.

3. Result and discussion

Our simulated and measured transmission spectrum are shown in Fig. 2. There are two low-intensity transmission peaks and one high-intensity transmission peak in the midinfrared region. The low-frequency transmission peak comes from the internal surface plasmon polaritons (SPPs).[17] Two high-frequency transmission peaks come from external SPPs.[17] There exists a NRI around the low-frequency transmission peak.[5,18] In order to have a deeper insight into the influence of hole shape on the properties of transmission and NRI of MDM sandwiched metamaterials, the hole in Fig. 1(a) is changed into a cross hole, circular hole and square hole separately in simulation, with other parameters kept unchanged. The arm length of the cross hole is 6 μm and the arm width of the cross hole is 2 μm. The radius of the circular hole is 3 μm. The side length of the square hole is 6 μm. Transmissions of these kinds of holes are shown in Fig. 3.

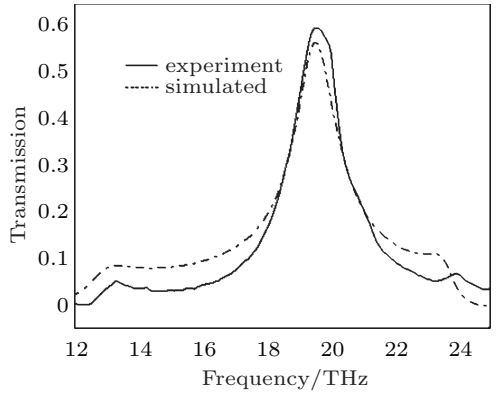


Fig. 2. Simulated and measured transmission spectrums.

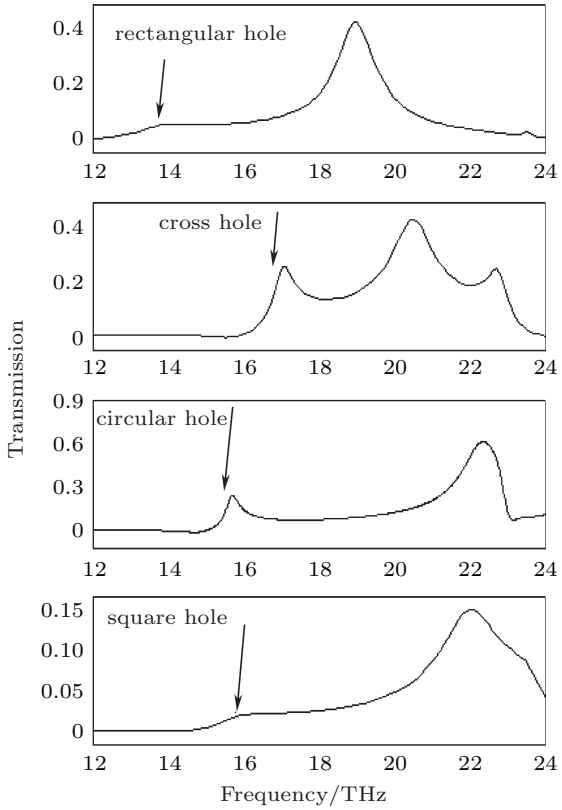


Fig. 3. Transmission spectra corresponding to rectangular hole, cross hole, circular hole and square hole, respectively.

From Fig. 3 it follows that the maximum transmission peaks are 0.44 (rectangular hole), 0.48 (cross hole), 0.61 (circular hole) and 0.15 (square hole). Positions of these maximum transmission peaks are at 18.9 THz (rectangular hole), 20.5 THz (cross hole), 22.34 THz (circular hole) and 22 THz (square hole). The transmission spectrum peak of the circular hole is obviously bigger than those of the other holes. These results indicate that the second transmission peak is high and its position is sensitive to the hole shape. The position and the value of the low-frequency transmission peak are also sensitive to the hole shape, as indicated by arrows in Fig. 3. Each kind of hole shape exhibits an EOT phenomenon, as indicated by arrows in Fig. 3. It is interesting that the low-frequency transmission peak of the cross hole is most significant, which mainly results from the internal SPPs.[17] The refractive indices of these kinds of holes are shown in Fig. 4.

As shown in Fig. 4, each shape of hole exhibits an NRI phenomenon. The values of NRI and the frequency bandwidth of NRI are −1.74 THz and 5.16 THz (rectangular hole), −1.42 THz and 4.87 THz (cross hole), −2.39 THz and 3.12 THz (circular hole), and −0.64 THz and 2.31 THz (square hole). The NRI of the circular hole is bigger than those of other holes. But the frequency bandwidth of the NRI of the rectangular hole is bigger than those of other holes, obviously. By comparing, we can find that the frequency bandwidth of the NRI of the hole is reduced with the increase of the hole area, as shown in Table 1.

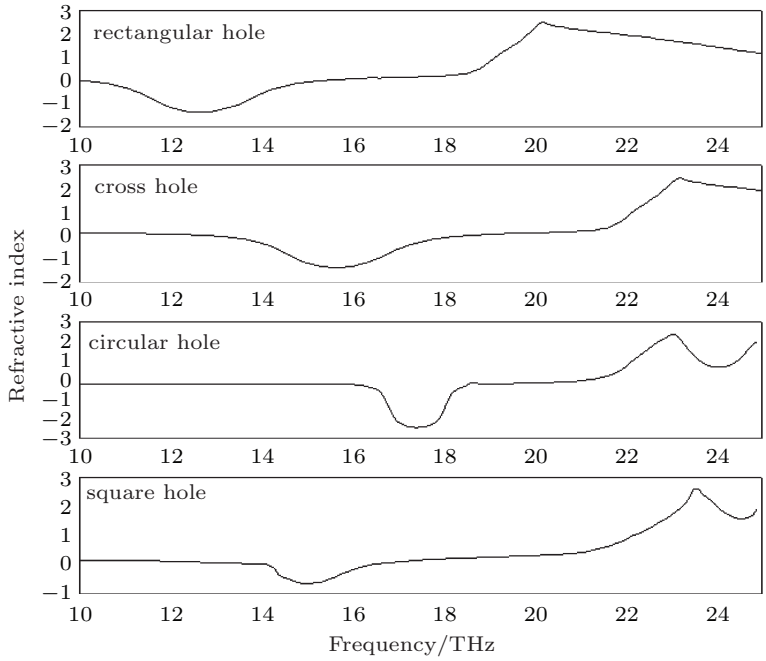


Fig. 4. Refractive index spectra corresponding to rectangular hole, cross hole, circular hole and square hole, respectively.

Table 1. Values of area and the frequency bandwidth of the NRI of each kind of hole.

	Rectangular hole	Cross hole	Circular hole	Square hole
Area of hole/μm^2	12	20	28.26	36
Frequency bandwidth of NRI/THz	5.16	4.87	3.12	2.31

At the same time, we used Origin8.0 software for numerical fitting to obtain a linear formula as follows:

$$y = a + b * x. \tag{2}$$

In Eq. (2), x denotes the hole area and y the NRI. The result of fitting is the solid line, as shown in Fig. 5.

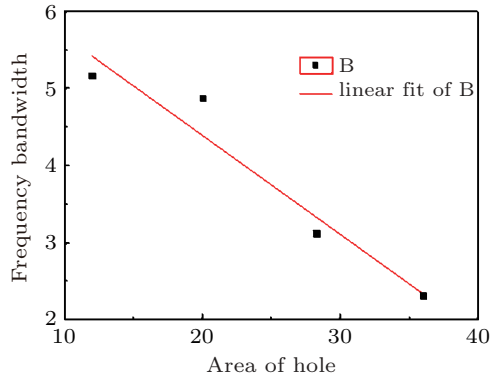


Fig. 5. (color online) Frequency bandwidths of NRI spectra corresponding to hole areas of 12, 20, 28.26 and 36 μm^2. The solid line represents the numerical fitting results.

We can see in Fig. 5 that the intercept is $a = 6.96$ and the slope is $b = -0.129$. The formula (2) indicates that the variation of frequency bandwidth of NRI with hole area follows a linear law, which means that an appropriate hole area on MDM metamaterial arrays can be chosen to obtain the desired frequency bandwidth of NRI.

Now we calculate the loss of MDM sandwiched metamaterial for electromagnetic waves with figure of merit (FOM):

$$\text{FOM} = -\text{Re}(n)/\text{Im}(n). \tag{3}$$

In the above formula, $\text{Re}(n)$ denotes the real part of the refractive index and $\text{Im}(n)$ represents the imaginary part of the refractive index. The higher the value of FOM, the lower the loss of MDM sandwiched metamaterial for electromagnetic wave is. The FOM spectra corresponding to a rectangular hole, cross hole, circular hole and square hole are shown in Fig. 6.

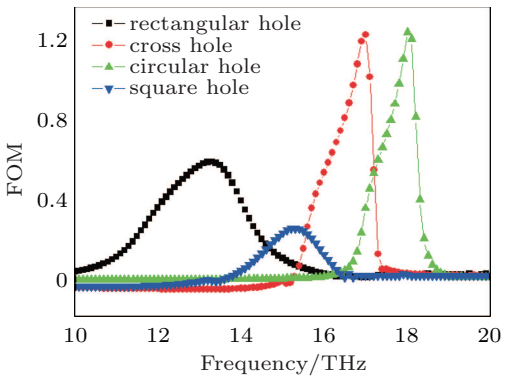


Fig. 6. (color online) FOM spectra corresponding to rectangular hole, cross hole, circular hole and square hole, respectively.

The FOMs of the rectangular hole, cross hole, circular

hole and square hole are 0.59, 1.25, 1.26, and 0.25, respectively. FOMs of the cross hole and the circular hole are much greater than those of the rectangular hole and the square hole. These results suggest that the loss of the cross hole and the circular hole for the electromagnetic wave is significantly smaller than those of the rectangular hole and the square hole. The values of FOM and NRI of each kind of hole are listed in Table 2.

Table 2. The FOM and NRI of each kind of holes.

	Rectangular hole	Cross hole	Circular hole	Square hole
FOM	0.59	1.25	1.26	0.25
NRI	−1.74	−1.42	−2.39	−0.64

By comparing FOMs and NRI of each kind of hole as shown in Table 2, it can be found that FOMs of the circular hole and the cross hole are similar, but the NRI of a circular hole is greater than that of a cross hole, obviously, with other conditions kept unchanged. It means that on the one hand, cross holes or circular holes may be drilled on an MDM metamaterial to obtain a higher FOM; on the other hand, circular holes may be drilled on an MDM metamaterial to obtain a higher NRI. In other words, circular hole arrays of 2D MDM sandwiched metamaterial can give both higher NRI and larger FOM.

4. Conclusions

Transmission, NRI and FOM of a MDM sandwiched metamaterial perforated with a rectangular hole, cross hole, circular hole and square hole are separately numerically studied under the same conditions. Our results indicate that positions and values of transmission peaks of the rectangular hole, cross hole, circular hole and square hole are sensitive to the shape of the hole. The NRI of a circular hole is the maximum. Moreover, the FOM of the circular hole is maximum too. As a result, we can obtain a higher NRI and FOM metamaterial by drilling circular holes arrays on MDM metamateriral.

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