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Role of filling medium of holes in the transmission and negative refractive index of metal–dielectric–metal sandwiched metamaterials

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The transmission and negative refractive index (NRI) of metal–dielectric–metal sandwiched metamaterials perforated with different filling media of holes are numerically studied. Results indicate that filling the appropriate medium in rectangular holes can enhance transmission. The NRI and frequency bandwidth of NRI decrease with increased relative permittivity of the filling medium. A stronger magnetic response that contributes to the dual NRI metamaterials is found.

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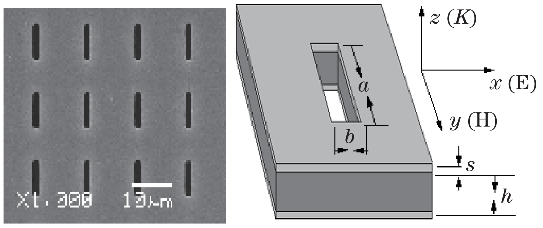
The transmission properties of metamatrials perforated with two-dimensional (2D) subwavelength hole arrays have become an active research area in electromagnetism since extraordinary optical transmission (EOT) is reported by Ebbesen *et al.*[1]. Over the past decade, the EOT or negative refractive index (NRI) of metamaterials have been widely investigated[1−6]. Recently, many experiments have been performed to study the influence of hole shape on the optical transmission properties of 2D hole arrays[7,8]. These studies indicate that transmission through a rectangular hole has strong polarization dependencies. Research has shown that the filling medium can influence the optical properties of metamaterials[9]. However, the influence of filing medium on the NRI of 2D rectangular hole arrays of sandwiched metamaterials has not been considered. To gain deeper insight into the influence of filing medium of holes on the transmission and NRI of sandwiched metamaterials, these two properties are studied as a function of filling medium.

A scanning electron microscopy (SEM)(JSM-5610LV, JEOL, Japan) is used to characterize the sample. The SEM image of the sample is shown in Fig. 1(a), which shows a rectangular hole with sides $a = 6$ μm and $b = 2$ μm perforated on sandwiched metamaterials. The lattice constant in the x-y plane is $P = 12$ μm. The sample consists of three layers, i.e., two layers of silver and one layer of SU-8. The thicknesses of the silver film and SU-8 layer are $s = 0.05$ μm and $h = 2$ μm, respectively. The sample in Fig. 1(a) is fabricated by optical lithography and has an area of around 5×5 (mm). In a typical procedure, the freestanding SU-8 layer with a rectangular hole is initially fabricated by optical lithography. Then, two silver layers are deposited onto surface of the SU-8 layer by thermal evaporation. Numerical calculation is performed based on the SEM image in Fig. 1(a). The scheme of the one-unit cell of the metal-dielectric-metal (MDM) structure is shown in Fig. 1(b).

The simulated spectra of the MDM (black curve) and metal-metal-metal (MMM; red curve) structures are shown in Fig. 2. Three transmission peaks are found in the 10–25 THz region for the MDM sample, as shown in Fig. 2 (black curve). To determine the origin of these transmission peaks, the SU-8 layer of the hole in Fig. 1 is changed to a silver layer to obtain a MMM structure. We further test the transmission of the MMM structure, and the transmission spectrum of the MMM structure is also shown in Fig. 2 (red curve). Two high-frequency transmission peaks still exist in the MMM structure, but the low-frequency transmission peak disappears. These simulated results indicate that the two high-frequency transmission peaks originate from the excitation of external surface plasmon polaritons (SPPs) and the waveguide modes of holes. The low-frequency transmission peak disappears in the MMM structure, which means that the low-frequency transmission peak originates from the excitation of the internal SPPs. To gain deeper insight into the influence of the filling medium of holes on the transmission and NRI of MDM sandwiched metamaterials, the relative permittivity of filling medium is changed from $\varepsilon = 1$ to $\varepsilon = 2$, $\varepsilon = 3$, $\varepsilon = 4$, and $\varepsilon = 5$ while fixing the other parameters. In the simulation, we use 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[10]. The entire model is tested in air, and light incident from air to our structure propagates along the z-axis. We use the



(a) (b)

Fig. 1. (a) SEM image of the sample; (b) scheme of the one-unit cell of the MDM structure.

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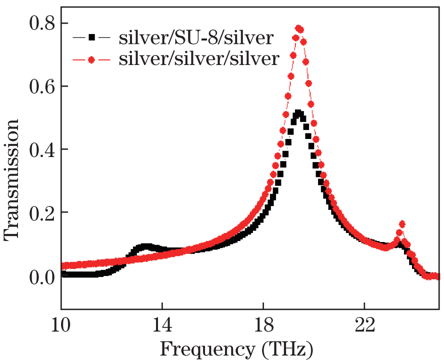

Fig. 2. (Color online) Simulated spectra of the MDM (black curve) and MMM (red curve) structures.

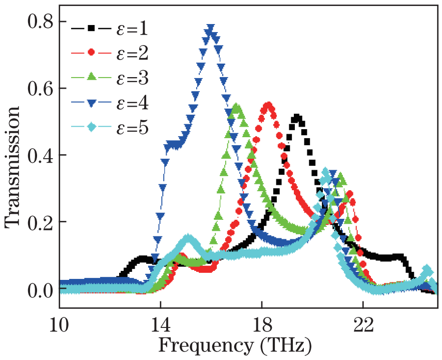

Fig. 3. Simulated spectra of the MDM structure with different filling media (relative permittivities $\varepsilon = 1$, $\varepsilon = 2$, $\varepsilon = 3$, $\varepsilon = 4$, and $\varepsilon = 5$).

commercial software Ansoft HFSS10 for the simulation. The dielectric constant of SU-8 is assumed to be $2.56 + 0.035\mathrm{i}$[11]. The silver layer uses the Drude model:

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

where the collision frequency $\gamma_D = 9 \times 10^{13} s^{-1}$, and the plasma frequency $\omega_{\mathrm{p}} = 1.37 \times 10^{16}\ \mathrm{s}^{-1}$[12,13].

We simulate the transmission spectra of the sample as a function of the relative permittivity, and the results are shown in Fig. 3. The transmittances of the low-frequency peak are 0.09, 0.10, 0.10, 0.43, and 0.13 for the samples with relative permittivities of $\varepsilon = 1$, $\varepsilon = 2$, $\varepsilon = 3$, $\varepsilon = 4$ and $\varepsilon = 5$, respectively. Interestingly, when the permittivity of filling media is $\varepsilon = 4$, the transmittance of the low-frequency peak markedly increases by almost 4.3 times of the $\varepsilon = 1$ sample (air). The transmittance of the low-frequency peak of the $\varepsilon = 4$ sample is obviously larger than those of other filling media. We consider that the enhanced transmission of the $\varepsilon = 4$ sample is due to the perfect impedance match. To further confirm our conjecture, we retrieve the effective impedances of the samples with different filling media, and the results are shown in Fig. 4.

The impedance of the $\varepsilon = 4$ sample is 0.64, which is significantly higher than the samples with other filling media. Comparison of Figs. 3 and 4 reveals that the transmission results are consistent with the retrieved impedances. This finding confirms our conjecture that high transmittance and perfect impedance match can be achieved by selecting the appropriate filling medium. Some studies suggest that NRI can be achieved at around the low-frequency transmission peak[5,14]. To identify the negative index response, the effective refractive index is retrieved through the S parameter retrieval procedure[10,12]. The refractive indices of the samples with different filling media are shown in Fig. 5.

Comparison of Figs. 3 and 5 reveals that the NRI bands are around the low-frequency transmission peaks. Moreover, the NRI and NRI band decrease with increased relative permittivity, as shown in Table 1.

Finally, to study the influence of filling medium on the electromagnetic properties of MDM sandwiched metamaterials, we retrieve the permittivity and permeability with different filling media. The results are shown in Fig. 6. The real part of the retrieved permeability at $\varepsilon = 4$ reaches –0.78 and exhibits a stronger magnetic response than other filling media, as well as a dual negative-index material ($\mathrm{Re}\ (\varepsilon) < 0$, $\mathrm{Re}(\mu) < 0$). This,

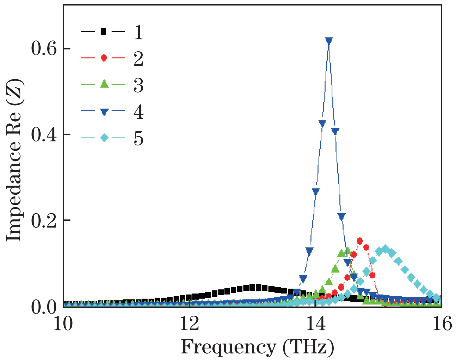

Fig. 4. Retrieved impedances of samples filled with different media and having different permittivities ($\varepsilon = 1$, $\varepsilon = 2$, $\varepsilon = 3$, $\varepsilon = 4$, and $\varepsilon = 5$).

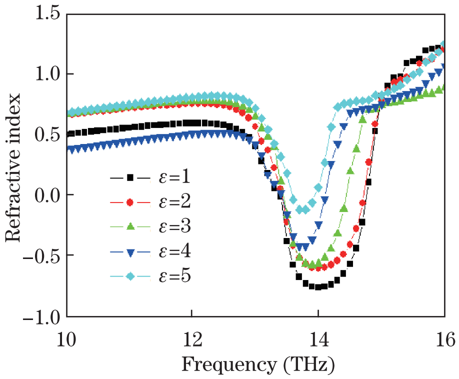

Fig. 5. Refractive index of MDM structures filled with different media and having different relative permittivities ($\varepsilon = 1$, $\varepsilon = 2$, $\varepsilon = 3$, $\varepsilon = 4$, and $\varepsilon = 5$).

Table 1. Refractive Index and Bandwidth of the NRI Band of the MDM Structure with Different Relative Permittivities (ε= 1, ε= 2, $\varepsilon = 3$, ε= 4, and ε= 5).

Permittivity	$\varepsilon = 1$	$\varepsilon = 2$	$\varepsilon = 3$	$\varepsilon = 4$	$\varepsilon = 5$
NRI	–0.75	–0.59	–0.56	–0.41	–0.11
Bandwidth (THz)	1.3	1.2	0.9	0.6	0.4

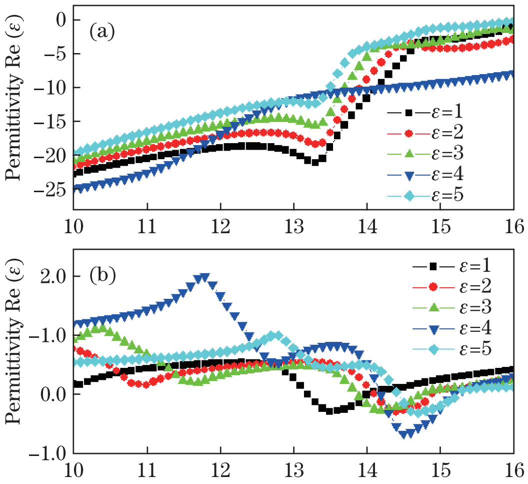

Fig. 6. (a) Retrieved permittivity of different filling media with permittivities of $\varepsilon = 1$, $\varepsilon = 2$, $\varepsilon = 3$, $\varepsilon = 4$, and $\varepsilon = 5$; (b) retrieved permeability of different filling media with permittivities of $\varepsilon = 1$, $\varepsilon = 2$, $\varepsilon = 3$, $\varepsilon = 4$, and $\varepsilon = 5$.

the real part of the retrieved permeability is useful in designing NRI metamaterials. In the negative-index band, $\mathrm{Re}(\varepsilon) < 0$ but $\mathrm{Re}(\mu)$ is positive or negative. For the samples with $\varepsilon = 1$, $\varepsilon = 2$, $\varepsilon = 3$, and $\varepsilon = 4$, $\mathrm{Re}(\varepsilon) < 0$ and $\mathrm{Re}(\mu) < 0$; thus, a double-negative NRI metamaterial is obtained. For the sample with $\varepsilon = 5$, $\mathrm{Re}(\varepsilon) < 0$ but $\mathrm{Re}(\mu) > 0$, i.e., single-negative NIMs can be obtained. Some studies indicate that NRI metamaterial with $\mathrm{Re}(n) < 0$ can be obtained either through the strong conditions of $\mathrm{Re}(\varepsilon) < 0$ and $\mathrm{Re}(\mu) < 0$ or through the general condition $\mathrm{Re}(\varepsilon)*\mathrm{Im}(\mu)+\mathrm{Re}(\mu)*\mathrm{Im}(\varepsilon) < 0$[3,15−17]. We can see that double-negative NRI metamaterials satisfy the condition $\mathrm{Re}(\varepsilon) < 0$ and $\mathrm{Re}(\mu) < 0$ and single-negative NRI metamaterials satisfy the condition $\mathrm{Re}(\varepsilon)*\mathrm{Im}(\mu)+\mathrm{Re}(\mu)*\mathrm{Im}(\varepsilon) < 0$. The results in Fig. 6 indicate that the filling medium significantly influences electric and magnetic responses.

In conclusion, we numerically study the transmission and NRI of MDM sandwiched metamaterials with rectangular perforated hole arrays and different filling media of holes. Results indicate that the perfect impedance match can lead to enhanced transmission. The NRI and frequency bandwidth of NRI of the rectangular holes decrease with increased relative permittivity. Moreover, a stronger magnetic response that contributes to the dual negative-index material is found. As a result, the desired NRI and frequency bandwidth of NRI can be obtained by adjusting the relative permittivity of filling media of rectangular holes of MDM metamaterials.

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