Electromagnetic wave transmission through subwavelength metallic meshes sandwiched between split rings

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We report the extraordinary enhanced transmission of microwaves through a subwavelength metallic mesh sandwiched between two identical split-ring arrays. Such *split-rings/metallic mesh/split-rings* structure demonstrates some unique electromagnetic (EM) characteristics. It is found that the transmittances of EM wave are significantly enhanced at some frequencies near the stop bands of the split rings. The theoretical simulation indicates that two different physical mechanisms dominate those transmissions: negative refractive index effect and electromagnetic wave tunneling when EM wave penetrates through negative permittivity media sandwiched between two high permittivity slabs. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2133915]

The phenomenon of transmissions of electromagnetic (EM) waves through structured materials has sparked great interest in recent years. Several kinds of extraordinary transmissions, governed by completely different physical mechanisms, have been discovered. For instance, the composite medium with simultaneously negative permittivity ε and permeability μ, called left-handed material (lhm), exhibits a pass band in the otherwise opaque EM spectrum of any single negative material due to the existence of negative refractive index n, which was theoretically investigated by Veselago[1] and experimentally realized by Smith *et al.*[2,4] and Shelby *et al.*[3,5] By tailoring the surface of a material, Ebbesen *et al.*[6] and Ghaemi *et al.*[7] reported the enhanced transmission of light through two-dimensional arrays of subwavelength holes perforated in an optically thick metal film, where surface plasmons were considered accountable. Furthermore, high transmissions through metal films with thin slits can be induced by Fabry-Pérot resonance of propagating waves inside the slits.[8–10] Very recently, another mechanism was proposed that enabled perfect transmission of a classically opaque flat slab (negative ε) by attaching two identical slabs of high ε on both sides to stimulate an enhancement of magnetic fields at the interfaces.[11] In this letter, we demonstrate that two types of transmissions of EM waves can be observed simultaneously for the layered metamaterials with configuration of "*split rings/metallic mesh/split rings,*" one of which corresponds to the negative n transmission, while the other is the transparency of opaque media sandwiched between high ε slabs.

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The sample was a three-layered structure *ABA*, where layer *A* was composed of split ring resonators (SRRs), while the layer *B* was the metallic mesh, as illustrated in Fig. 1(a). The unit of the SRRs was a single square ring with a side length of 12.0 mm and a split of 2.0 mm, and was replicated in the x and y directions at a constant of 20 mm apart. The metallic mesh was fabricated using metal strips, each with dimensions of 0.5 mm in width and 0.1 mm in thickness and a spacing of 4.5 mm in both the x and y directions. Then the mesh was sandwiched between two 0.25 mm thick substrates and became layer *B*. Two identical layers *A* were attached to both sides of layer *B* with a separation of distance s. The resultant structure *ABA* measured $12.5\times 12.5\ \mathrm{cm}^2$ in the xy plane. To measure microwave transmissions, the sample was mounted in the central window (with the same size as $12.5\times 12.5\ \mathrm{cm}^2$) of a 100×100 cm steel plate which stood between two identical microwave horns (HP11966E). The horns were set 100 cm apart and connected with the ports of a network analyzer (Agilent 8720ES) to generate and receive the signals.

Figure 1(b) shows the experimentally normal transmissions of layers *A* and *B* as well as the combined layers *ABA* measured within frequency range of 2–12 GHz. In the measurement, the frequency step is taken to be 0.02 GHz and the accuracy of the transmission is ±2.5%. The polarization of the EM wave is such that the electric field is along the x axis, while the magnetic field is along the y axis. Individually, layer *B* reflects most of the incident wave exhibiting the low transmission characteristic varying from $\sim$10 to $\sim$40% determined by the subwavelength cells of the metallic mesh, while layer *A* allows the microwave to pass through at most frequencies except for 3.35 and 10.25 GHz, showing two

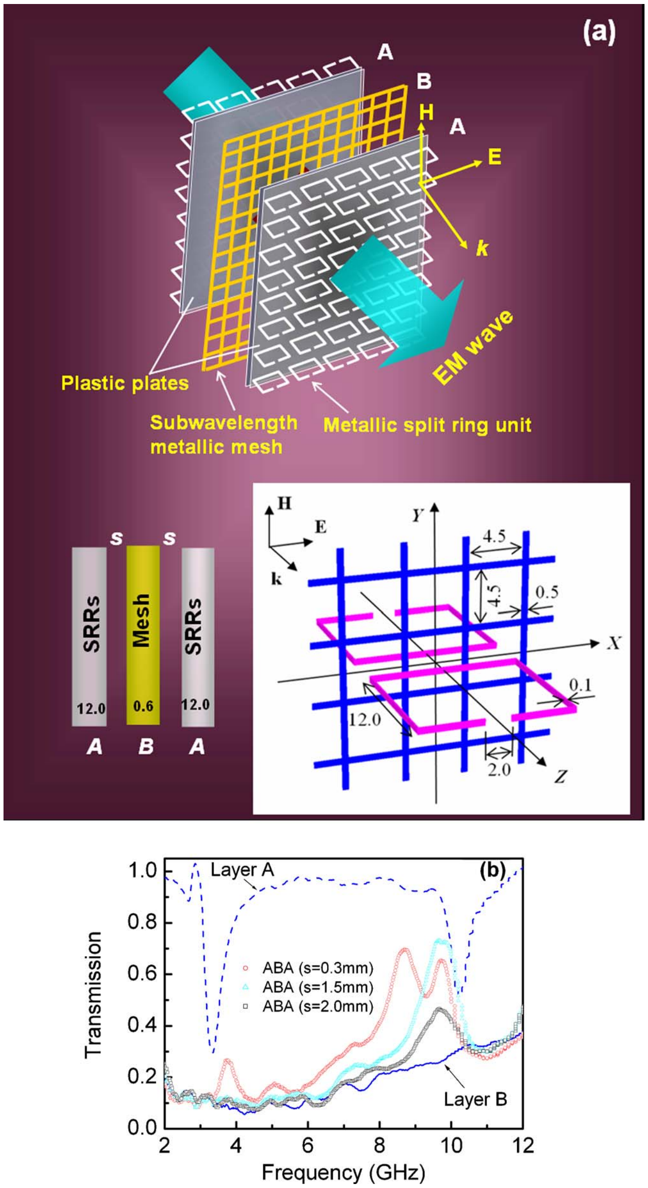

FIG. 1. (Color online) (a) Experimental setup; lower left: the side view and *s* denotes the distance separating the layers. The length unit is millimeters. Lower right: the perspective view of the split unit cell of the sample; (b) the measured normal transmissions of layers *A* and *B* as well as the *ABA* layers at various separations. The EM waves are incident along the *z* direction with the electric field polarized along the *x* axis and the magnetic field along the *y* axis.

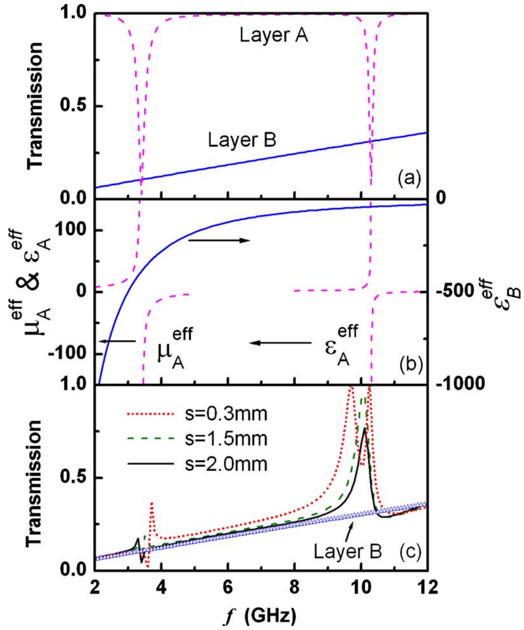

FIG. 2. (Color online) (a) Simulated transmission results for layers *A* and *B* alone; (b) the effective ε and μ for layers *A* and *B*; (c) the simulated transmissions of the *ABA* structure at various separations, and the simulated transmission of layer *B* is replotted for comparison.

stop bands. When combined with a separation *s* of 0.3 mm, the structured *ABA* layers give rise to a transmission peak ($\sim$30%) at 3.74 GHz and a twin peak ($\sim$70%) around 9.0–10.0 GHz. Compared to layer *B* alone, the introduction of the *A* layers significantly enhances the transmission of the opaque layer *B* at these frequencies. In particular, it is noted from the spectra that the first enhanced transmission peak occurs at the right side of the first stop dip (lower frequency) of layer *A*, while the next twin peak at the left side of the second stop dip (higher frequency). As the separation *s* between adjacent layers increases, the 3.74 GHz peak fades rapidly, while the twin peaks located near 10 GHz become merged to be one, remaining at the left side of the stop dip, and then diminish.

In order to understand the physical mechanisms for two enhanced transmission peaks, a numerical study for the *ABA* structure was carried out by employing a finite-difference time-domain (FDTD) simulation[12] and effective media theory (EMT), respectively, and the results are shown in Fig. 2. For the FDTD investigation, periodic boundary conditions were adopted and perfect conductor approximations, excellent for microwave frequencies, were applied to the metal/air interfaces. The simulation results for single *A* and *B* layers as well as *ABA* structure were depicted in Figs. 2(a) and 2(c), respectively, which are in good agreement with the experiments. However, some minor discrepancies, mainly the peak widths and the peak values, were possibly caused by (1) fluctuations of the parameters when fabricating the sample, (2) finite-size effects of the sample, or (3) absorptions.

Figure 2(b) is the effective media approximations for layers *A* and *B*, respectively. Since the incident wavelength is much larger than the dimension of cell of the metallic mesh, we expected the very low transmission of the microwave through layer *B* [the solid line in Fig. 2(a)]. On the other hand, the structure may be modeled as a homogeneous slab of thickness 0.6 mm with an effective permittivity $\varepsilon_B^{\mathrm{eff}}=1.6-67^2/f^2$, f in gigahertz,[13] and the negative values of $\varepsilon_B^{\mathrm{eff}}$ [the solid line in Fig. 2(b)] spanning in measured frequencies imply the opaqueness. For layer *A*, there are two stop bands with maximum rejections at 3.40 and 10.30 GHz, respectively [the dash line in Fig. 2(a)]. It is investigated that the band at lower frequency corresponds to the magnetic resonance of the split square ring with the induced current being circular, while the higher one to the electric resonance where the current is three-sectioned.[14–16] Such localized resonances, either magnetic or electric, can be described by the response function of Lorentzian profile using the EMT.[17] Therefore, layer *A* may be modeled as a magnetic material of thickness 0.6 mm with an effective permeability $\mu_A^{\mathrm{eff}}=1.0+55/(3.40^2-f^2)$ only near the lower band and as a dielectric slab of the same thickness with only $\varepsilon_A^{\mathrm{eff}}=1.5+30/(10.30^2-f^2)$ near the higher band [the dash lines in Fig. 2(b)].[18]

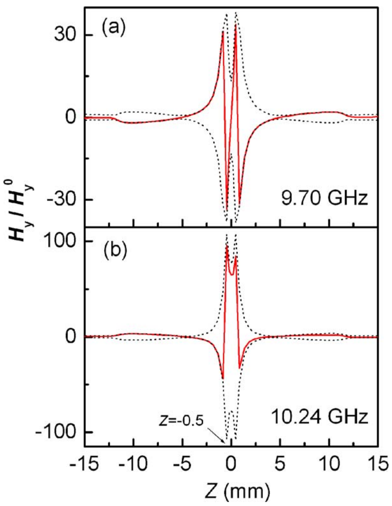

FIG. 3. (Color online) Distribution of H_y, normalized to the incident wave, on the z axis ($x=0$, $y=0$) at two perfect transmission peaks: (a) 9.70 GHz and (b) 10.24 GHz. The short dash lines denote the envelope; the solid lines denote the value at certain moment. The xy planes ($|z|=0.5$) are located inside the air gaps separating layers A and B.

The negative ε and μ coexist for the frequencies immediately higher than 3.40 GHz, where the negative branch of μ_A^{eff} appears, resulting in the 3.7 GHz transmission peak [the dot line in Fig. 2(c)] of the negative n nature.[2–5] On the other hand, the peaks around 10.0 GHz, as shown in Fig. 2(c), originate from the mechanism of transmission, the *ABA* structure,[11] where two high ε slabs facilitate the EM wave to tunnel through negative permittivity media. In this scenario, the SRRs act as the high ε slabs at the frequencies slightly lower than the electrical resonance frequency 10.3 GHz and assist the EM wave to propagate through layer B without attenuating the outputs. In fact, the early decay inside of layer B is compensated by the field growth afterward, showing no loss in the transmission. Otherwise, the wave would pass as the evanescent wave only, since layer B has the negative permittivity.

The FDTD simulation reveals two 100% transmissions at 9.70 and 10.24 GHz when $s=0.3$ mm, and the two peaks were found to correspond to two perfect transmission solutions for *ABA* structures through examining the field distribution.[11] In Fig. 3, we plotted the envelope of H_y along the z axis at $x=0$, $y=0$ for the two frequencies (the black lines in Fig. 3), and the significant enhancement of the field component appears in the air gaps separating layers A and B, which is the characteristic feature of perfect transmissions for such *ABA* structures. After the local field H_y distributed on the A/B or B/A interface is averaged, the enhancement factor, $|H_y/H_y^0|$, for the field at the interfaces is >2 at 9.7 GHz peak, and ~ 4 at 10.24 GHz peak, implying the nature of enhancement of EM wave through the *ABA* structure. The oscillation curves recorded at certain moment (the red lines in Fig. 3) show that the 9.7 GHz peak is the EMT-derived solution (magnetic field pattern being oddly symmetrical) and the 10.24 GHz peak is the second solution (evenly symmetrical).[11] From Fig. 2(c), the two peaks merge together at a larger separation, and the transmission then decreases with increased s, which reveals the tunneling nature of this kind of transmission. The rapid subsidence occurring to 3.7 GHz peak is considered as a result of the disappearance of negative n effect from decoupling of negative μ and ε at larger separations.

In conclusion, the normal transmissions of the microwave through the layered metamaterials (*split rings/metallic mesh/split rings*) were measured, and it was found that the transmission of the opaque metallic mesh was significantly enhanced near the stop bands of the split rings after adding the layers of split rings to both sides of the mesh. The transmission enhancements are characterized by two kinds of mechanisms: (1) the negative n effect and (2) the EM wave tunneling through negative ε media sandwiched between slabs with high permittivity. The present sample working at microwave frequencies may find applications in antenna design and radar detecting. The phenomena are also realizable in infrared or optical regimes with appropriate designs.

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