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Terahertz transmission resonances in complementary multilayered metamaterial with deep subwavelength interlayer spacing

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We introduce a flexible multilayered THz metamaterial designed by using the Babinet's principle with the functionality of narrow band-pass filter. The metamaterial gives us systematic way to design frequency selective surfaces working on intended frequencies and bandwidths. It shows highly enhanced transmission of 80% for the normal incident THz waves due to the strong coupling of the two layers of metamaterial complementary to each other. *Published by AIP Publishing.*
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Research on devices operating in the terahertz (THz) frequency domain has grown significantly during the last decade, owing to the unique applications of these devices in medical imaging, security and manufacturing inspection as a substitute for X-rays, molecular spectroscopy, and ultra-fast communication.^{1–4} Despite the broad scientific and industrial needs, THz-range devices are relatively limited compared with optical and microwave devices, owing to the difficulties associated with the generation, detection, and control of THz electromagnetic (EM) waves. Recently, rapid advance has been made in the field of metamaterials, which are composed of subwavelength scale artificial atoms (meta-atoms) with unattainable properties from natural materials. This relatively new paradigm of metamaterial has created new application possibilities for THz-range devices because the meta-atoms in THz regime can be designed to exhibit novel properties which are not found in conventional THz devices and easily fabricated using various microfabrication technologies due to their micro-meter order size.^{5–10} Specifically, the transmission enhancement in the deep subwavelength scale metallic slit has attracted broad attention both for its potential applications in THz devices and for the scientific interest in the field enhancement mechanism in the deep subwavelength scale.^{11–16}

In this paper, we explore a novel class of flexible multilayered THz-range metamaterials based on the Babinet's principle with a narrow band-pass filter functionality. By changing the distance between the metamaterial layers and the metamaterial unit cell size, one can easily design the operating bandwidth in addition to the working frequency. It exhibits high transmission enhancement, reaching 80%, at the THz working frequency although the spacing between the two complementary metamaterial surfaces is almost 1/100 of the wavelength of the incident light. The resulting metamaterial provides us with a systematic method for designing frequency-selective surfaces (FSSs) with a preset frequency

and bandwidth and the clue to understand the mechanism of the transmission enhancement in subwavelength metallic structures.

The proposed metamaterial consists of a combination of two or three metallic layers filled with a polyimide substrate with transmission characterized by Babinet's principle as depicted in Fig. 1(a) and Fig. 1(b). In the three layer metamaterial, the top and bottom layers are square-shaped metallic patch arrays and the middle layer structure is complementary to those of the outer layers. According to Babinet's principle, if $\{E_1, H_1\}$ is a solution of Maxwell's equation for a given

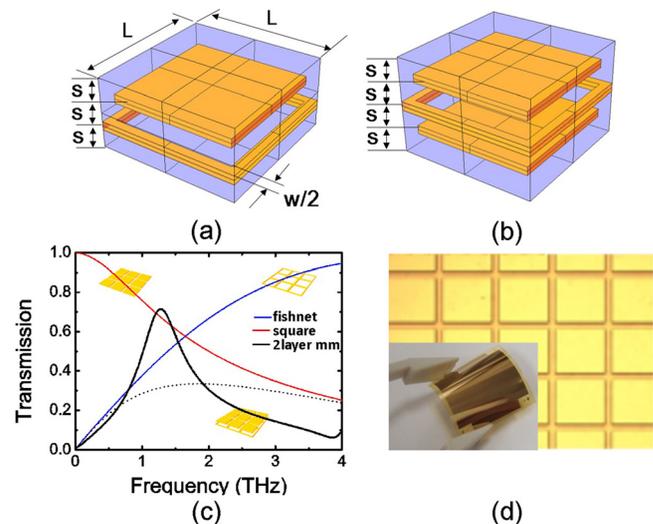


FIG. 1. The schematics of the unit cell structure of (a) two and (b) three layered complementary metamaterials; the unit cell size (L) and the metallic linewidth of the fishnet layer (w) is set to $40\ \mu\text{m}$ and $5\ \mu\text{m}$, respectively. (c) The simulated transmission spectra of a single fishnet layer with interlayer spacing $s = 1\ \mu\text{m}$ (blue solid line), a square array layer (complementary to the fishnet structure, red solid line), a simple product of the two spectra (black dotted line), and the resultant composite two layer metamaterial with high transmission resonance are plotted (black solid line). (d) Microscopy image of the fabricated flexible complementary multilayered metamaterial.

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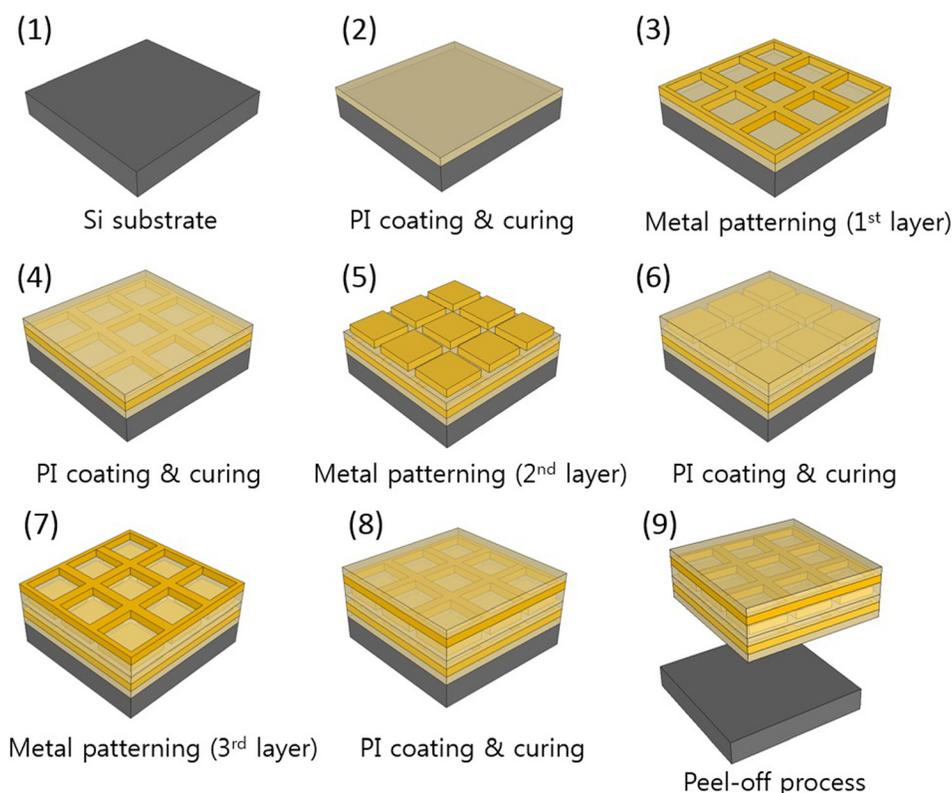


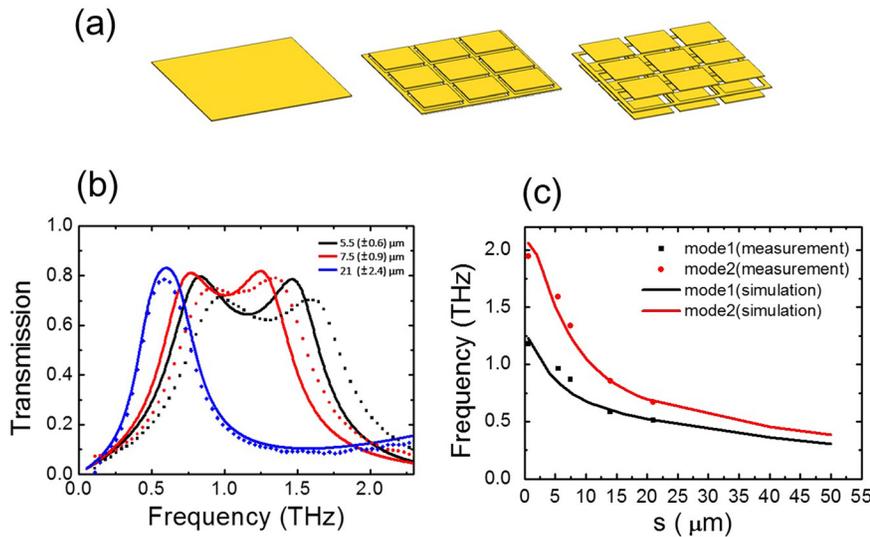
FIG. 2. Schematic of the metamaterial fabrication process.

PEC (perfect electric conductor) boundary condition, then $\{E_2, H_2\}$, given by $E_2 = \mp \sqrt{\frac{\epsilon}{\mu}} H_1, H_2 = \pm \sqrt{\frac{\mu}{\epsilon}} E_1$, is also a solution of Maxwell's equations. Consequently, the complementary structure yields the same interference pattern and the inverse transmission spectrum of the original one.^{10,18–21} Based on this principle, one can expect that if a metamaterial layer is designed to have a capacitive frequency response, working as a high-pass FSS, the complementary layer will exhibit an inductive frequency response, working as a low-pass FSS. If the two complementary metamaterial layers are closely stacked, ensuring sufficiently strong electromagnetic coupling, the resultant metamaterial yields highly enhanced THz transmission which is a generic resonance behavior as in an LC circuit.^{22–24} The idea is shown schematically in Fig. 1(c), in which the simulated transmission spectra of a single fishnet layer, a square array layer (complementary to the fishnet structure), a simple product of the two spectra (dotted line), and the resultant composite two layer metamaterial with high transmission resonance are plotted. (In reality, the fabricated metamaterial has three layers for achieving structural symmetry as shown in Fig. 1(d).)

One of the interesting features of the proposed metamaterial is that it is possible to investigate the terahertz response change by varying the interlayer spacing between the layers, which determines interlayer coupling. If the interlayer spacing (parameter s) is zero, the metamaterial is reduced to a simple gold thin plate shown in Fig. 3(a), so that most of the incident light is reflected and the transmission is nearly zero. However, if the spacing is slightly opened, the transmission dramatically increases, more than 70%, even though the gap owing to the spacing is less than 1/100 of the wavelength of the incident light, as shown in Figs. 1(c) and 3(b). This

feature seems quite similar with the previous results exhibiting the transmission enhancement in THz and microwave frequency regimes.^{12,14,15,17} However, our work is distinguished from the previous reports in the following points. Transmission resonance in the previous works has been achieved in the metasurface with the deep subwavelength slits or holes, whereas in our work, the interlayer spacing between the two complementary layers, instead of slits, opens the subwavelength scale gap and plays an essential role to control EM resonances of the metamaterial. By the same token, the opened gap is unobservable as viewed from the front of samples since the orientation of the gap is orthogonal to the direction of incident terahertz wave.

The fabrication process of flexible multilayered metamaterials is shown schematically in Fig. 2. The process was started on a bare silicon substrate as a sacrificial wafer. A polyimide solution (PI-2610, HD MicroSystems) was spin-coated onto the substrate, and the substrate was baked at 180 °C in a convection oven for 30 min to obtain a flexible metamaterial substrate. A negative photoresistor (AZnLOF2035, AZ Electronic Materials) was spin-coated and patterned by using conventional photolithography. Au/Cr (90 nm/10 nm) was then evaporated and patterned as square- and fishnet-shaped metallic structures via the lift-off technique. Single-layer metamaterials were fabricated by repeating the polyimide coating and curing processes. Multi-layer metamaterials on the silicon substrate were obtained by repeating the above single-layer processes until stacking the desired number of metamaterial layers. Finally, the flexible THz-range metamaterials were obtained by peeling off the metamaterial layers from the silicon substrate. The dimensions of these micrometer-gap metamaterials were estimated by using optical microscopy, a stylus profiler, and a 3D profiler.



Different from the 2-layer case, in 3-layer metamaterials, we observed two resonance peaks within the working frequency window. Figure 3(b) shows both simulation (solid line) and experimental results (dotted line) of the transmission spectra for inter-layer spacing of $5.5 \mu\text{m}$, $7.5 \mu\text{m}$, and $21 \mu\text{m}$. The mismatch in detail between simulation and experimental data is due to the error of measured thickness (parameters) of dielectric polymer. As the interlayer distance decreases, the difference between the two resonance frequencies increases. This behavior is very similar to the phenomenon of degenerate modes splitting that is caused by mutual coupling.²⁶ Figure 3(c) shows the simulation results and the measurement results for the two resonance peak frequencies, plotted against the interlayer spacing; the peaks were extracted by fitting the data with two Lorentzian functions. If the spacing is sufficiently large enough to ignore the inter-layer interaction, the splitting of peaks disappears, and the overall transmission spectrum can be approximately described as a simple product of transmission spectra of the individual layers, as shown in Fig. 1(c).

To characterize the resonance properties and the corresponding transmission spectra of the metamaterial, we performed conventional THz time-domain spectroscopy (THz-

TDS) with the working frequency window in the 0.1–2.0 THz range. In the metamaterial transmission spectra in Fig. 3(b), two resonance peaks are observed in the 0–2.0 THz frequency range. Both peaks are enhanced to the same extent, but the underlying mechanisms are quite different. To clarify the mechanisms underlying the emergence of the resonant peaks, we employed the method of effective optical parameter retrieval.²⁵ Figure 4(a) shows the metamaterial parameters that were extracted by this method. The lower-frequency transmission peak exactly corresponds to a zero epsilon (ϵ) value and the metamaterial becomes a “nearly zero index” metamaterial, which means that the frequency is the plasma frequency and the electron in the metamaterial behave qualitatively much like a free electron gas. As a result, the currents induced in the two squared plates of the metamaterial unit cell are parallel with no phase difference and oscillate as shown in Fig. 4(b). Whereas the currents along the squared plates in the higher-frequency transmission peak are perfectly anti-parallel, yielding a strong net current circulation along the wave propagation direction, as shown in Fig. 4(c), which implies that the higher-frequency transmission peak is associated with magnetic resonance in accord with the fact that magnetic permeability (μ) exhibits a resonance at the peak frequency, as shown in Fig. 4(a).

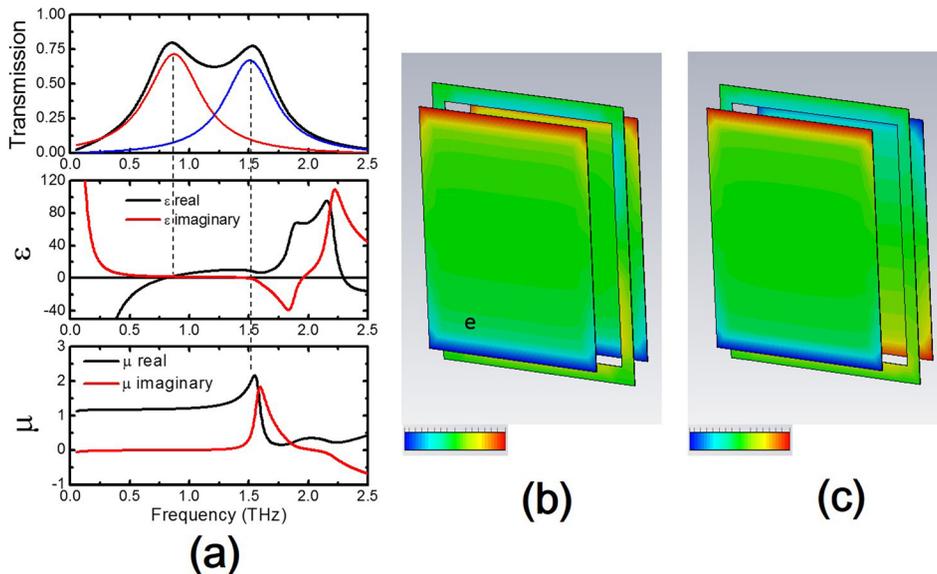


FIG. 4. (a) Electric permittivity and magnetic permeability retrieved for the simulated result with $s = 5 \mu\text{m}$. (b) Snapshot of numerically simulated current (z-component arbitrary scale) on the metal surface at the lower frequency peak in the transmission spectra in (a). (c) Snapshot of numerically simulated current (z-component, arbitrary scale) at the higher frequency peak in the transmission spectra in (a).

We proposed flexible multilayered metamaterials based on the Babinet's principle operating in the THz frequency regime. The metamaterial exhibits remarkably high transmission resonances due to the strong electromagnetic coupling between the two complementary metamaterial layers. The operating bandwidth and operation frequency of the metamaterial can be designed systematically by changing the spacing between the metamaterial layers. We also verified that the mechanism of the resonances in the layered metamaterial is due to two different kind of resonances which are associated with electric (ϵ) and magnetic (μ) resonance. We expect that the metamaterials proposed here can be applied in new functional EM filters and FSSs with various bandwidths and effective refractive indices.

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