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Bandpass Filter Based On Parallel Cascaded Multiple Microring Resonators
An ultrabroad terahertz bandpass filter based on multiple-resonance excitation of a composite metamaterial

Yi-Ju Chiang,1 Chan-Shan Yang,2 Yu-Hang Yang,1 Ci-Ling Pan,2 and Ta-Jen Yen1,a)

1Department of Materials Science and Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan
2Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan

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We experimentally present an ultrabroad terahertz (THz) bandpass filter based on a composite metamaterial (CMM) by exciting its multiple resonances. This metamaterial-based filter, consisting of a metal-dielectric-metal sandwiched structure, possesses a notable spectral-filtering capability with a 0.5-THz-broad bandwidth and excellent band-edge transitions of 140% THz and 182% THz in the THz-gap region. Furthermore, we manifest the mechanism for each of the resonances and the coupling within the composite metamaterial. This realization enables the capacity for engineering the electromagnetic properties to develop other complex optical functionalities. An example of a high-profile dualband THz bandpass filter is also proposed theoretically in this work. © 2011 American Institute of Physics. [doi:10.1063/1.3660273]

Metamaterials attract much attention owing to their notable electric or magnetic properties, which originated from their specially designed architecture rather than their constitutive compositions.1–5 A significant breakthrough via metamaterials is to tailor the desired electromagnetic properties and to realize the practical optical devices in the special terahertz (THz)-gap region, a band between 0.3 THz to 10 THz that is rarely explored than radio and optical bands. Some studies have shown that metamaterials provide an effective approach to improving THz-based systems by exciting different modes of metamaterials.5–12 In addition, metamaterials with multiple resonances possess considerable potential for complex and powerful optical devices.

In this work, we present an ultrabroad bandpass filter based on a composite metamaterial (CMM) that possesses multiple resonances in the THz-gap region. This CMM consists of a metal-dielectric-metal (MDM) sandwiched structure of 4-fold rotational symmetry, as shown in Fig. 1(a), and can be decomposed into two component structures: the MDM cross-wire arrays (MDM-C) as shown in Fig. 1(b) and the MDM cross-slot arrays (MDM-S) as shown in Fig. 1(c).13 The dimensional parameters are all shown in Figs. 1(a)–1(c). To materialize the CMM-based THz filter, first, we simulated the CMM by employing three-dimensional full-wave simulation software CST MICROWAVE STUDIO™. In the simulation process, we inputted the unit cell of the CMM with the boundary condition of PEC and PMC along the x and y directions, respectively, to ensure a normally incident plane wave with the polarization as shown in Fig. 1(a). Next, for real-sample fabrication, we applied a UV-lithography technique and an e-gun deposition to patterning 200-nm-thick copper with 10-nm-thick chromium as an adhesion layer on a 38-μm-thick flexible Teijin® Tetoron® PET film with dielectric constant of 2.89.11 Since strict alignment of the metallic layers of the CMM is necessary to ensure the functionality of the structure, we used alignment marks providing 2-μm accuracy. The finished sample without any additional substrate is shown in Fig. 1(d). Afterward, we measured the THz beam transmitted from the sample under normal incidence by THz time-domain spectroscopy (THz-TDS) from 0.2 THz to 2.0 THz with a resolution of 0.03 THz.14,15 During the experiment, the chamber was purged with dry nitrogen to avoid noises from water absorption, and the measurement result would be normalized by air. Meanwhile, we also measured and simulated a bare PET film and estimated its intrinsic dielectric loss tangent at about 0.05 accordingly. Through inspecting the transmissions of the CMM derived from the measurement and the simulation involving the loss tangent of 0.05 of the PET film, as shown in Fig. 2, the encouraging results indicate that the CMM-based THz filter possessed a 0.5-THz-broad bandwidth defined by the full width at half maximum of the transmitted power (equal to about 0.5 in the transmission coefficient) and, furthermore, sharp band-edge transitions of 140% THz and 182% THz in the THz-gap region. Compared with traditional frequency-selective surfaces (FSSs) that acquire multi-layered structures to achieve high-profile passbands,16 this CMM-based filter only consists of a single sandwiched MDM structure. Hence, the fabrication process can be largely facilitated. We have noticed that a little deviation between the simulation and measurement results arose from the imperfect fabrication process.

To elucidate the electromagnetic properties of the CMM, we simulated not only the CMM but also its component structures, i.e., MDM-S and MDM-C, and scrutinized their respective resonant modes and coupled behavior between them. Here, we applied d = 10 μm instead of 38 μm and lossless PET films to these simulations to differentiate the resonant characteristics. Figure 3(a) shows the simulated transmission and reflection properties attributable to the component MDM-C, exhibiting an antisymmetric mode at \( f_m = 1.73 \) THz and a symmetric mode at \( f_s = 2.03 \) THz.17–19 In addition, the other component, MDM-S, possessed two pronounced passbands at \( f_{s1} = 1.29 \) THz and \( f_{s2} = 2.12 \) THz respectively, as shown in Fig. 3(b), due to standing-wave-like resonance of FSSs.13,16 In comparison with the spectra of these component structures, Figure 3(c) indicates that the...
combined CMM yielded two responses \((f_m'\) and \(f_{s1}'\)) corresponding to the resonances \(f_m\) and \(f_{s1}\) in MDM-C and MDM-S, respectively. This phenomenon suggests that the electromagnetic properties of the CMM originated from the superposition of the individual component structures. Furthermore, it is intriguing to observe that the CMM did not inherit any of the responses from MDM-S or MDM-C at higher frequencies from \(1.9\) THz to \(2.2\) THz but possessed an additional passband at \(f_c = 1.15\) THz, which was absent from both the component structures. One can also observe that a tiny magnetic response occurred at \(1.02\) THz in both the CMM and MDM-S due to the fact that MDM-S is a kind of fishnet structures.\(^{20,21}\)

To discuss these aforesaid facts in greater detail, we compared the behavior of surface currents at the frequencies of interest designated in Fig. 3 in the following. Figure 4(a) shows the surface currents on MDM-C as its antisymmetric or symmetric modes were excited, turning out two distinct responses: the magnetic dipolar resonance at \(f_m\) and the electric dipolar resonance at \(f_e\).\(^{17,18}\) Meanwhile, as shown in Fig. 4(b), the surface currents on MDM-S oscillated in the form of standing waves along the circumjacent or central cross-slots provided that the incident wavelength had matched the corresponding perimeters of these cross-slots in MDM-S.\(^{13,16}\)

Combining MDM-S and MDM-C together to form the CMM led to the complex electromagnetic properties. Figure 4(c) shows distinct contours of surface-current distributions on the CMM at the three respective resonant frequencies. First, at the resonance \(f_m'\) of the CMM, the current contours reveal the same behavior with the resonance \(f_m\) of MDM-S where the surface currents oscillated antisymmetrically on the cross-wires, demonstrating that this resonance \(f_m'\) originated from MDM-C. Second, at another resonance \(f_{s1}'\) of the CMM, the surface currents induced along the circumjacent cross-slots instead. This behavior consistent to the resonance \(f_{s1}\) of MDM-S also demonstrates that the resonance \(f_{s1}'\) originated from MDM-S. For the last prominent response \(f_c\), the corresponding current contours show a striking occurrence: the surface currents on the two distinct components definitely oscillated in counter direction to each other with almost identical magnitude. In other words, these surface
currents induced on the CMM interfered destructively, leading to so-called “trapped-mode resonance.”\textsuperscript{9,22,23} In fact, the trapped-mode resonance of the CMM was a result of coupling between the symmetry mode \( f_s \) from MDM-C and the standing-wave-like mode \( f_{s2} \) from MDM-S. This can be traced by their corresponding surface-current distributions shown in Fig. 4.

The capacity to engineer electromagnetic properties is one of the fascinating advantages of metamaterials. Herein, we organized the resonant modes of the CMM-based broadband bandpass filter shown in Fig. 1 to develop a high-profile dualband THz bandpass filter by modulating the dimensions \((d, h, l, w)\) individually based on simulations where the PET films were assumed lossless. Figure 5 shows the process flow of the structural modulation of the CMM. As shown in Fig. 5(a), decreasing the thickness \(d\) raised the resonant frequency of the standing-wave-like resonance \((f_{s1})\) due to more repulsive electric force between the surface currents on the top and bottom layers of the CMM [see Fig. 4(c)], and it also changed the quality factor of the magnetic resonance \( f_m \) due to the greater inductance and smaller capacitance.\textsuperscript{19} In Fig. 5(b), the standing-wave-like resonance \((f_{s1})\) had strong dependence on the parameter \(h\) because it decides the perimeter of the circumjacent cross-slots.\textsuperscript{13} In Fig. 5(c), the length \(l\) affects both the geometry of the cross-wires and the cross-slots in the center of the CMM and, hence, could shift the resonant frequencies of the magnetic resonance \((f_m)\) and the trapped-mode resonances \((f_s)\).\textsuperscript{18} However, the parameter \(w\) only influenced on the quality factors of these two modes \( f_m \) and \( f_s \),\textsuperscript{19} as shown in Fig. 5(d). By precisely adjusting the dimensions of the CMM according to the revised parameters (in microns): \(a = 95\), \(b = 2.5\), \(h = 15\), \(l = 65\), \(w = 25\), \(g = 4\), and \(d = 10\), the CMM possessed a new functionality of a dualband bandpass filter based on the simulation, which was shown in Fig. 5(d).

In conclusion, we here realized an ultrabroad THz bandpass filter based on the multiple-resonance excitation in the unique composite metamaterial. The corresponding simulation and measurement results agree excellently with each other, even though the inevitable dielectric loss of the PET films depressed the transmission efficiency of this THz filters. More importantly, this work provides the approach of employing composite metamaterials with multiple resonances to enable complex optical functionalities. Resting on this concept, another example of a high-profile dualband THz bandpass filter was also theoretically proposed and numerically verified in this work.

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\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure5.png}
\caption{(Color online) Transmissions of the CMM as adjusting the individual dimensional parameters from \(a\) to \(w\) [\(a\) to \(d\)] accordingly. In each step, the adjusted parameter referred to the black solid line would be substituted into the next generation to develop a high-profile dualband THz bandpass filter. The final result is shown in the black curve in Fig. 5(d).}
\end{figure}

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