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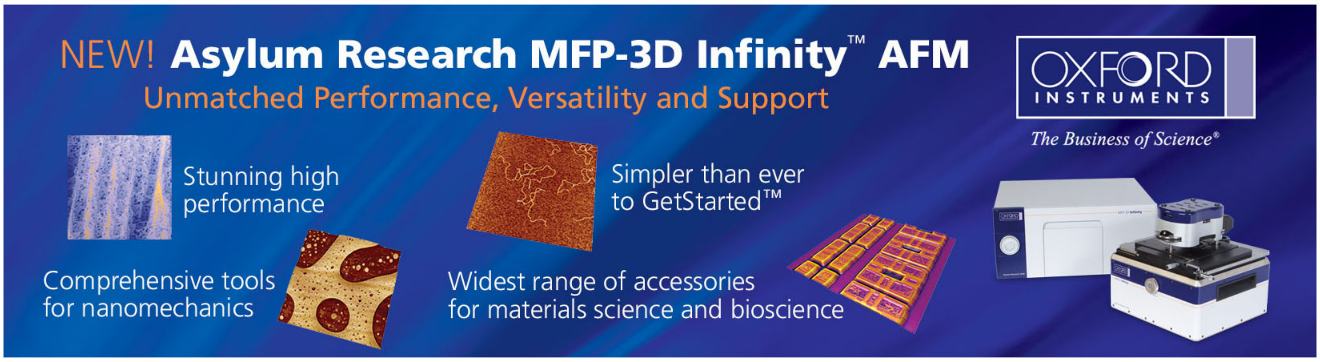

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Fano resonance in a metamaterial consisting of two identical arrays of square metallic patch elements separated by a dielectric spacer

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We report studies of Fano resonance in a double layer metamaterial consisting of two identical metallic square patch arrays separated by a dielectric spacer. The metallic patch arrays are arranged in mirror symmetry with respect to the dielectric spacer. It is shown that such a metamaterial can exhibit sharp Fano resonances. A good agreement is obtained between the experimental and simulation results for such a metamaterial fabricated on an FR4 substrate. The square patch based design is less sensitive to polarization due to its higher degree of symmetry than the metallic elements based on split rings in the previous work. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4812189]

Fano resonance is associated with the well-known exotic property of the electromagnetically induced transparency (EIT) in the optical wavelength region[1–3] and is characterised by an asymmetric line-shape in transmission and reflection of the atomic medium. In recent years, it has been found that metamaterials based on dielectric-metal composite media[4] and nanophotonic structures and devices also exhibit Fano resonance like characteristics.[5] This has generated a significant interest in the studies of physics and application of such materials.[3,4] In addition to the well known applications of metamaterials as filters and absorbers for electromagnetic radiation, recently a single layer metamaterial based on "X" shaped resonators has been studied for bio-sensing applications.[6] Fano resonance was first observed in metamaterials based on an array of asymmetric split rings on a dielectric substrate.[7–12] The Fano resonance behaviour originated from the effect of trapped mode resonance, in which anti-symmetric current modes are established under the excitation of the incident electromagnetic radiation. Fano resonances have been shown in modified split ring and other unit cell designs with a broken symmetry on dielectric substrates.[13,14] In double layer metamaterials, Papasimakis *et al.*[15] demonstrated EIT in a metamaterial consisting of two layers of continuous fish-scale metallic patterns separated by a dielectric substrate. Other studies of metamaterials consisting of two or more layers of periodic metallic patterns have concentrated on the properties of negative refractive index and the coupling effects based on fishnet,[16] short cut wire,[17–19] overlapped split ring and strip design,[20] and chiral structures,[21–23] respectively. Recently trapped mode resonances have been observed in a double layer metamaterial based on symmetrically arranged arrays of electric ring resonator (ERR) patterns separated by a dielectric insert.[24] A review of Fano resonance in metamaterials and plasmonic structures can be found in Ref. 25. In this paper, we report sharp Fano resonances in a metamaterial design based on double layers of square metallic patch arrays. The square metal patch based metamaterial offers design simplicity and ease of fabrication and is less sensitive to polarization. It will be shown that the double layer material exhibits sharp resonances in transmission and reflection with distinct characteristics of the classical Fano resonance.

The patch based frequency selective surface (FSS) is initially known as a two-dimensional planar periodic structure that can function as a partially reflective surface possessing a capacitive response in microwave filters and reflectors.[26] Such FSS structures have been incorporated in planar antenna devices to increase their directivity.[27,28] Recently, a metamaterial structure consisting of a pair of patch arrays each on an FR4 substrate has been studied for sensing applications.[29] The FR4 substrates were separated by a gap for the placement of the material of interest for measurements. Although a weak Fano resonance was present in the obtained transmission characteristics, it was not investigated and instead another resonance was used to study the sensing properties of the slab-pair based structure. In this paper, we have studied Fano resonance in a pair of identical patch arrays separated by a thin dielectric spacer. The square patch based double layer metamaterial possesses a strong coupling effect resulting in a sharp resonant transmission over a narrow band of frequency. The configuration of a unit cell for the double layer metamaterial is shown in the inset of Fig. 1(a). The two patch arrays are separated by a dielectric medium with a dielectric constant of ε_r. In the simulation work, the dielectric medium is assumed to be a lossless material with unity dielectric constant. An infinite array size is used in all of the simulation work described in the paper.[4] The dimensions of the unit cell are 15 × 15 mm corresponding to the half wavelength at 10 GHz. The dimensions of the copper patches are 14 × 14 mm. The two arrays are aligned such that the corresponding metallic patch arrays are facing each other in mirror symmetry. The transmission response of the double layer FSS based metamaterial was studied by numerical simulation using the ANSOFT HFSS software tool. Fig. 1(a) shows the results of the transmission responses of the double layer metamaterial as a function of frequency. As can be seen, Fano resonance characteristics are obtained over a

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range of spacer thicknesses from 0.1 mm to 1 mm corresponding to 1/300 to 1/30 of the design wavelength. For the smallest spacer thickness of 0.1 mm, the transmission resonance is much sharper due to the strong electromagnetic coupling between the two patches with a corresponding Q-factor of 95. As the spacer thickness increases, the transmission resonance becomes broader due to the reduced electromagnetic coupling between the pair of patches. The results show a much higher throughput in transmission with a peak value of near unity than in the ERR based design.[24] The results demonstrate that much thinner structures can be used to obtain sharp electromagnetic transition based on the Fano resonance effect as compared to the conventional resonator structures with cavity length of typically about half-wavelength. For comparison, the results for a single array are also included in Fig. 1(a). However, there is no resonant behaviour as expected. It is interesting to observe that the behaviour of the double layer material resembles to that of the single layer at frequencies beyond the resonance region especially in the lower frequency region. At higher frequencies, the effect is more evident for the thin spacer (0.1 mm) as a result of the sharp resonance.

To determine the effects of the spacer thickness (*t*) and the dimensions (*L*) of the square patch element on the resonance frequency, the results of normalised resonant frequency (f/f_0) as a function of the ratio t/P and L/P are obtained and shown in Figs. 1(b) and 1(c), respectively. *P* is the period of the unit cell and its value is 15 mm; *P*, *t*, and *L* are defined in the insets in Fig. 1(a). f_0 is the initial design frequency at 10 GHz. As can be seen in Fig. 1(b), the resonant frequency can be tuned over a wide range from approximately 0.3f_0 to 0.95f_0 by changing the spacer thickness between the two patch arrays. Equally the resonant frequency can also be tuned over a wide range as shown in Fig. 1(c) by varying the dimensions of the square patch.

To study the Fano resonance behaviour in detail, both transmission and reflection characteristics and the associated current distribution in the pair of patches in the unit cell are investigated. Fig. 2 shows the results of transmission and reflection resonances and the surface current distribution at the resonance frequencies for the double layer metamaterial with a spacer thickness of 0.5 mm. A sharp resonance in reflection can be seen in Fig. 2(a) corresponding to that of the transmission resonance and also showing the typical attribute of Fano resonance with an asymmetric line shape. Figs. 2(b)–2(d) show the results of the studies of current distribution at the resonance frequencies as indicated in Fig. 2(a). It should be noted that for clarity different scales are used for the density of the surface current in each case. Figs. 2(b) and 2(d) show the current distributions for the two weak resonances (I and III). The common characteristic of these two resonances is that the surface currents in the corresponding pair of patches are unequal and much weaker than that shown in Fig. 2(c) at the frequency of the main resonance. The currents in the two patches flow in the same direction at the lower resonance frequency of 7.8 GHz, but in opposite directions at the higher resonance frequency of 10.6 GHz. The current distribution in Fig. 2(c) shows the characteristic signature of trapped mode resonance, in which anti-symmetric currents with equal magnitude but in anti-phase are established in the pair of patches in the unit cell under the excitation of the incident electromagnetic wave.[12] The magnitude of the surface currents is much higher than that for the other two resonances as shown in Figs. 2(b) and 2(d). This current behaviour is a manifestation of the trapped electromagnetic fields between the pair of patches. It is this strong near field coupling between the two patches in the unit cell, which results in a sharp resonance peak in transmission and the corresponding dip in reflection.

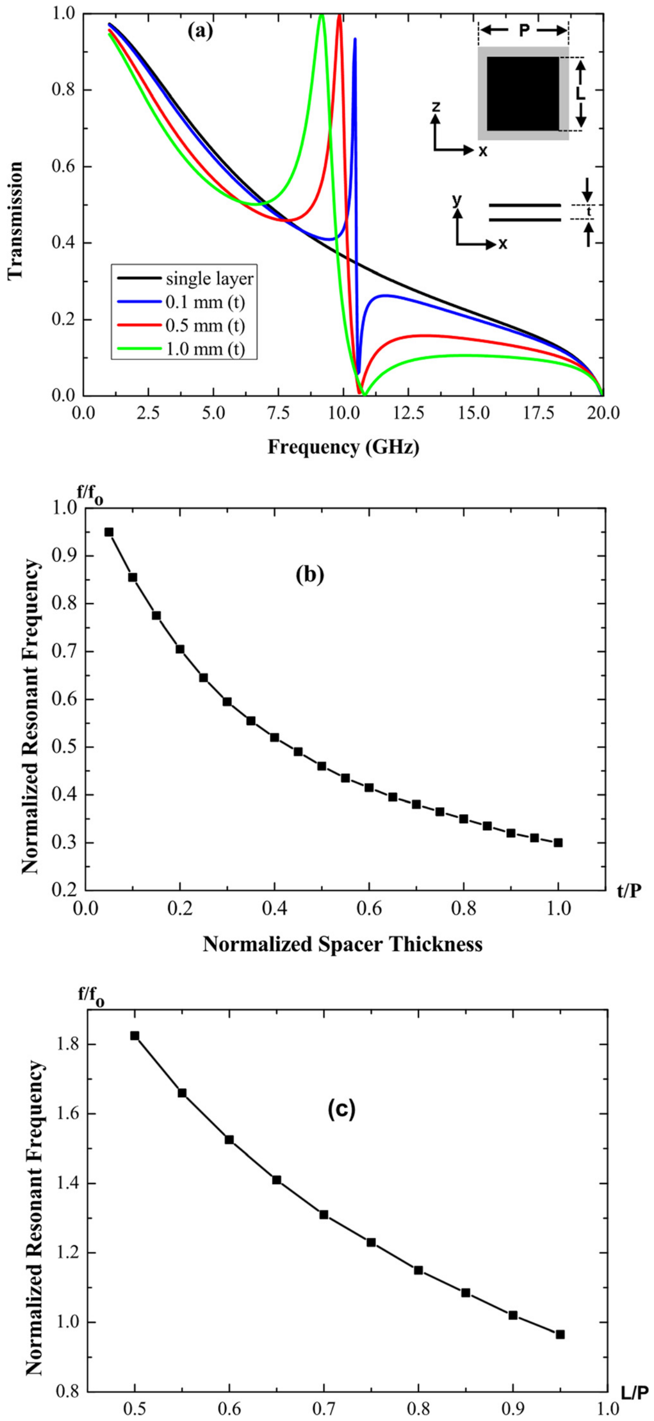

FIG. 1. (a) Simulation results of transmission spectra for a double layer metamaterial, (b) dependence of resonance frequency on the thickness of the dielectric spacer, and (c) effect of patch dimensions on resonance frequency.

For ease of fabrication, we have implemented the proposed metamaterial design using an FR4 substrate. This

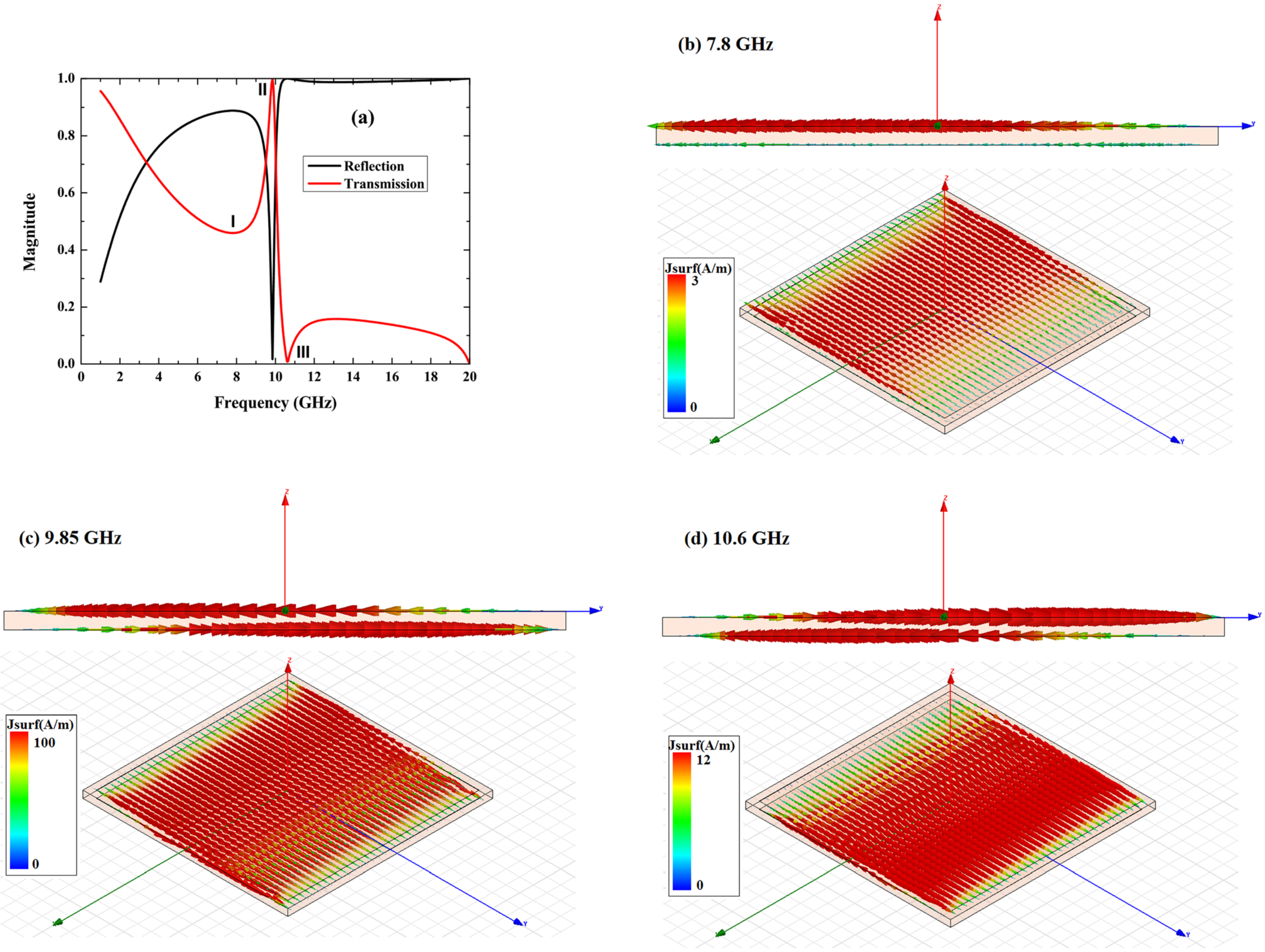

FIG. 2. Transmission, reflection, and current distribution for the double layer metamaterial with a spacer thickness of 0.5 mm. (a) Simulation results for transmission and reflection, (b)–(d) current distribution in the pair of patches in a unit cell for the three resonances marked as I, II, and III in (a) at frequencies of 7.8 GHz, 9.85 GHz, and 10.6 GHz, respectively.

substrate material is low cost and widely available with choice of thicknesses. Fig. 3 shows the simulation results for an FR4 based design for 3 commercially available material thicknesses of 0.2 mm, 0.8 mm, and 1.6 mm, respectively.

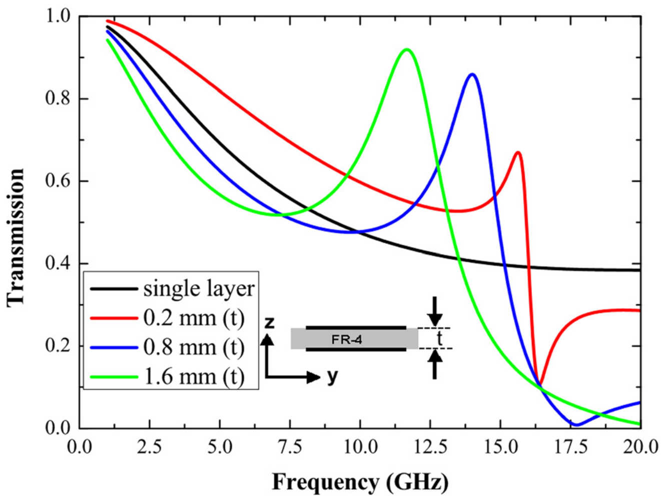

FIG. 3. Simulation results of transmission spectra for the FR4 based metamaterial consisting of two identical arrays of square metallic patches.

The corresponding resonant frequencies are 15.65 GHz, 14 GHz, and 11.6 GHz. The two patch arrays are arranged symmetrically one on each side of the FR4 substrate. The frequency response of a single layer array is also shown in Fig. 3. A dielectric constant of 4.1 was used in the simulation work and the corresponding loss tangent was 0.02.[30] The pitch of the cell and the patch dimension are 7 mm and 6 mm, respectively. The FR4 based design consists of an array of 21 × 21 patch elements on each side of the substrate. The corresponding size of the sample is about 105 × 105 mm.

The double layer metamaterial was fabricated on the FR4 substrate of thickness of 1.6 mm using a microfabrication method. A liquid photoresist (AZ9260) was deposited on each side of the substrate by spin-coating. The thickness of the photoresist layer was about 10 μm. After the photoresist film was patterned using a film based photomask, the exposed copper was etched away by wet chemical etching to obtain a patch array. The process is repeated for the other side to fabricate the second patch array. Fig. 4 shows the measured and simulation results for the transmission and reflection as well as a photograph of the fabricated sample. The experimental results were obtained using a vector network analyzer (HP 8510) and a pair of horn antennas in an

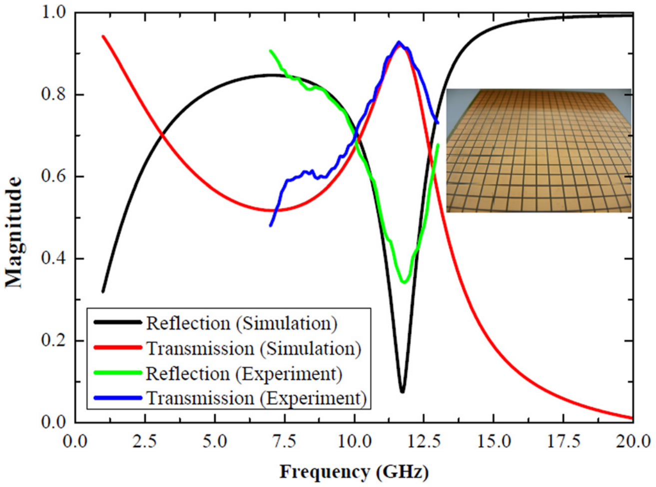

FIG. 4. Experimental and simulation results of transmission and reflection at normal incidence. The inset is an optical image of the fabricated sample.

anechoic environment. In transmission measurement, the transmitter and receiver horn antennas were aligned with a separation of 30 cm. The FR4 sample was placed in front of the receiver antenna. The reflection results were obtained by normalising the reflected signal from the FR4 sample to that of a copper sheet placed in the same position in front of the transmitter antenna. The reflectivity of the copper sheet is assumed to be unity. It can be seen that a good agreement between the simulation and measured results has been obtained. A Q-factor of about 5 can be determined from the simulation results of the transmission resonance. The frequency range of the experimental results was limited by the operational bandwidth of the horn antennas.

In summary, we have studied Fano resonance in a metamaterial consisting of two identical metallic square patch arrays separated by a dielectric spacer. The square patch based approach is easy to design and construct to produce a metamaterial exhibiting sharp Fano resonances. A Q-factor of 95 is predicted for a thin layer (0.1 mm) of a lossless dielectric medium. The dependence of resonant frequency on design parameters such as the patch dimension and the thickness of the dielectric spacer has been studied and it has been found that the resonant frequency can be tuned a wide range in both cases. The metamaterial was demonstrated using two patch arrays fabricated on an FR4 substrate. The results of the Fano resonance characteristics both in transmission and reflection are in good agreement with that of simulation work. The work shows that a planar metamaterial exhibiting sharp Fano resonances can be obtained using two identical arrays of square metallic elements.

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[1] U. Fano, Phys. Rev. **124**, 1866 (1961).
[2] K. J. Boller, A. Imamolu, and S. E. Harris, Phys. Rev. Lett. **66**, 2593 (1991).
[3] Y. S. Joe, A. M. Satanin, and C. S. Kim, Phys. Scr. **74**, 259 (2006).
[4] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, Phys. Rev. Lett. **84**, 4184 (2000).
[5] A. E. Miroshnichenko, S. Flach, and Y. S. Kivshar, Rev. Mod. Phys. **82**, 2257 (2010).
[6] M. D. Rotaru and J. K. Sykulski, IEEE Trans. Magn. **47**, 1026 (2011).
[7] X. Jin, Y. Lu, J. Park, H. Zheng, F. Gao, Y. Lee, J. Y. Rhee, K. W. Kim, H. Cheong, and W. H. Jang, J. Appl. Phys. **111**, 073101 (2012).
[8] R. Singh, C. Rockstuhl, F. Lederer, and W. Zhang, Phys. Rev. B **79**, 085111 (2009).
[9] J. Zhang, S. Xiao, C. Jeppesen, A. Kristensen, and N. A. Mortensen, Opt. Express **18**, 17187 (2010).
[10] Z. Li, Y. Ma, R. Huang, R. Singh, J. Gu, Z. Tian, J. Han, and W. Zhang, Opt. Express **19**, 8912 (2011).
[11] X. Liu, J. Gu, R. Singh, Y. Ma, J. Zhu, Z. Tian, M. He, J. Han, and W. Zhang, Appl. Phys. Lett. **100**, 131101 (2012).
[12] V. A. Fedotov, M. Rose, S. L. Prosvirnin, N. Papasimakis, and N. I. Zheludev, Phys. Rev. Lett. **99**, 147401 (2007).
[13] R. Singh, I. A. I. Al-Naib, M. Koch, and W. Zhang, Opt. Express **19**, 6312 (2011).
[14] R. Singh, I. A. I. Al-Naib, Y. Yang, D. R. Chowdhury, W. Cao, C. Rockstuhl, T. Ozaki, R. Morandotti, and W. Zhang, Appl. Phys. Lett. **99**, 201107 (2011).
[15] N. Papasimakis, V. A. Fedotov, N. I. Zheludev, and S. L. Prosvirnin, Phys. Rev. Lett. **101**, 253903 (2008).
[16] K. Aydin, Z. Li, L. Sahin, and E. Ozbay, Opt. Express **16**, 8835 (2008).
[17] J. Zhou, L. Zhang, G. Tuttle, T. Koschny, and C. M. Soukoulis, Phys. Rev. B **73**, 041101 (2006).
[18] B. Kanté, S. N. Burokur, A. Sellier, A. de Lustrac, and J.-M. Lourtioz, Phys. Rev. B **79**, 075121 (2009).
[19] J. Zhou, T. Koschny, L. Zhang, G. Tuttle, and C. M. Soukoulis, Appl. Phys. Lett. **88**, 221103 (2006).
[20] N. Shen, L. Zhang, T. Koschny, B. Dastmalchi, M. Kafesaki, and C. M. Soukoulis, Appl. Phys. Lett. **101**, 081913 (2012).
[21] A. V. Rogacheva, V. A. Fedotov, A. S. Schwanecke, and N. I. Zheludev, Phys. Rev. Lett. **97**, 177401 (2006).
[22] Z. Li, R. Zhao, T. Koschny, M. Kafesaki, K. B. Alici, E. Colak, H. Caglayan, E. Ozbay, and C. M. Soukoulis, Appl. Phys. Lett. **97**, 081901 (2010).
[23] M. Mutlu, A. E. Akosman, A. E. Serebryannikov, and E. Ozbay, Opt. Lett. **36**, 1653 (2011).
[24] B. Seo, K. Kim, S. G. Kim, A. Kim, H. Cho, and E. Choi, J. Appl. Phys. **111**, 113106 (2012).
[25] B. Luk'yanchuk, N. I. Zheludev, S. A. Maier, N. J. Halas, P. Nordlander, H. Giessen, and C. T. Chong, Nature Mater. **9**, 707 (2010).
[26] B. A. Munk, *Frequency Selective Surfaces: Theory and Design* (Wiley, New York, 2000).
[27] S. Enoch, G. Tayeb, P. Sabouroux, N. Guerin, and P. Vincent, Phys. Rev. Lett. **89**, 213902 (2002).
[28] K. Komsan and C. H. Wang, in *Proceedings of the Loughborough Antennas and Propagation Conference (LAPC), Loughborough, UK*, 12–13 November, 2012, pp.1–4.
[29] G. Kenanakis, N.-H. Shen, C. Mavidis, N. Katsarakis, M. Kafesaki, C. M. Soukoulis, and E. N. Economou, Physica B **407**, 4070 (2012).
[30] E. L. Holzman, IEEE Trans. Microwave Theory Tech. **54**, 3127 (2006).