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Citation: Appl. Phys. Lett. **112**, 234102 (2018); doi: 10.1063/1.5029307
View online: https://doi.org/10.1063/1.5029307
View Table of Contents: http://aip.scitation.org/toc/apl/112/23
Published by the American Institute of Physics

APPLIED PHYSICS LETTERS **112**, 234102 (2018)

Electromagnetically induced transparency in sinusoidal modulated ring resonator

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(Received 13 March 2018; accepted 18 May 2018; published online 6 June 2018)

In the present work, we demonstrate controlling the excitation of bright mode (continuum mode) resonance and dark mode (discrete mode) resonance in a planar metasurface made of sinusoidal modulation inside a closed rectangular metallic ring placed over a dielectric substrate. Unlike asymmetrical breaking of a meta-atom (often referred to as the unit cell) to achieve the dark mode response in regular metamaterials, in the present structure, the bright or dark mode resonance is achieved using even or odd half cycle modulation. The achieved dark-mode shows a sharp resonance for a particular polarization of the incident electric field, which results in an electromagnetically induced transparency like spectrum. The electromagnetic behavior of the proposed meta-atom has been investigated in the frequency domain using commercially available software and validated through experiments in the gigahertz regime. *Published by AIP Publishing.*
https://doi.org/10.1063/1.5029307

The last few years witnessed tremendous research interest in metamaterials due to their ability to support resonances in subwavelength space. The possibility of controlled and tailored electromagnetic near field within these metamaterials is well explored in various artificial engineered structures. The intrinsic electromagnetic behavior of metamaterials is inherited from the structure of their individual meta-atoms otherwise known as unit cell. Metamaterials are periodic arrangements of crystalline-like sub-wavelength electromagnetic resonators which can exhibit exotic properties, e.g., extraordinary transmission,[1] magnetic mirror,[2,3] invisible cloaking,[4] slow wave, negative refraction, super directivity, and many more.[5,6] These unusual properties are seldom found in naturally available materials and media. This thrives the electromagnetic research community to develop a variety of devices with enhanced and unconventional functionalities. More recently, manipulating near-field interference effects in metamaterial arrays reveals designs with a sharp low-loss resonance with a high Q factor in a planar 2D metamaterial sheet with the thickness (h) much smaller than the free space wavelength ($h \ll \lambda_0$). Frequency dependent transmission and reflection of these patterned metal layers on regular dielectric materials show strong dispersive behavior and improved radiation leakage suppression at the resonance. In a broad sense, the methods to achieve these high-Q resonances can be categorized based on two different physical mechanisms. The first approach is to introduce structural asymmetry such that two slightly detuned eigenmodes are created, and consequently, a trapped mode with high Q factor resonance is achieved. It was first reported by Fedotov *et al.* in asymmetric split rings (ASRs).[7] They demonstrated a high Q resonance with an electromagnetically induced transparency (EIT) like spectral response in a planar metasurface made of an ASR unit cell based on the trapped mode in the microwave regime. The anti-phased current oscillation in the ASR unit cell at the trapped mode resonance greatly suppresses radiation leakage and hence less free space coupling. The second approach is to establish a coupling mechanism between a radiative element and a quasi-radiative element to achieve high Q resonance. The composite structure has the ability to support bright mode and dark mode resonance depending on the polarization of the applied field. Often, the achieved high-Q resonance mimics the EIT phenomena. The EIT-like resonances in these artificial structures arise due to the near-field coupling between the bright mode and dark mode resonators. The energy exchange (destructive interference) between the two states results in a Fano type resonance which is quite sensitive to the local dielectric environment.

Electromagnetically induced transparency (EIT) is a coherent interference phenomenon generally observed in a three-level atomic system, which often requires sophisticated experimental conditions, e.g., cryogenic temperatures and high intensity optical pump.[8] It opens up a transparent window (narrow band) within a broad absorption spectrum with a high transmission index. However, the EIT-like behaviour in planar artificial structures is relatively easy to control without the requirement of a much needed complex setup. The spectral response can be tuned by altering the geometry, which only makes it more popular and finds a range of applications from the *microwave* to *terahertz* regime.[9–21]

Potential applications of EIT have been demonstrated for slow light behavior in the terahertz regime with a mechanism to control coupling between bright and dark modes and hence controllable transmission strength.[22] Lattice-induced transparency (LIT) is also reported in Ref. 23, where control of EIT behavior by changing the periodicity of the asymmetric split ring resonator has been demonstrated in the terahertz regime. The photo-active EIT effect is also demonstrated in the symmetric unit cell having a tunable bandwidth.[24] Active control and switching of transmission strength are achieved using the external pump of the near-infrared light beam.

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Theoretical and experimental analyses of eigenmodes using classical perturbation theory are discussed for double identical gap split ring resonators.[25] The dark mode is basically even-odd or odd-even eigenmodes for orthogonal symmetry, which are natural to symmetric structures and are difficult to excite, unless one breaks the symmetry in the structure. However, in the present work, we proposed even or odd sinusoidal modulation inside the ring resonator. This basically results in an in-phase or out-of-phase coupling of induced current, which in-turn controls the excitation of the dark mode.

In the present letter, we report the observation of sharp trapped mode resonance in a meta-atom made of sinusoidal modulation inside a rectangular ring. Depending on the incident polarization with the odd number of half cycle modulation, the achieved trapped mode resonance is the analog of electromagnetic induced transparency (EIT). We studied the spectral behavior of the rectangular ring and our proposed sinusoidal modulation inside the regular rectangular ring to control bright or dark mode resonance.

The design principle for the proposed metamaterial unit cell starts with the design of a regular frequency selective surface (FSS) having a band-stop response to free space propagation. The FSS is composed of a periodic arrangement of identical subwavelength metallic "inclusions" in the form of rectangular rings over a FR-4 dielectric substrate in a 2-dimensional fashion (Fig. 1). The substrate is a lossy dielectric ($\epsilon = 4.3 + i0.017$) material with a thickness of 0.8 mm. The metallic part is modeled as perfect electric conductors (PECs) in simulation.

The unit cell is modelled and simulated using commercial full wave simulator (CST Microwave Studio) package for its scattering parameters. The spectral response of the unit cell is investigated for two possible polarization states of the electric field of incident electromagnetic radiation with a planar wave front. Considering the dimension of the unit cell, such a periodic structure does not diffract normally incident electromagnetic radiation for the frequency spectrum lying below 15 GHz. Figure 1 shows the reflection and transmission profiles of the unit cell for two orthogonal electric polarizations. It is observed that the unit cell behaves as a band stop FSS with maximum reflection and minimum transmission around 2.45 GHz for both polarizations of incident EM radiation. The Q factor of this kind of resonator can be calculated as the ratio of resonance frequency (reflection peak) to the full width at half of peak reflection. It can be seen that the resonator is a low Q factor resonator. As the second step, a sinusoidal modulation is incorporated inside the rectangular ring unit cell as depicted in Fig. 2.

$$X(t) = A1 * t, \quad Y(t) = A2 * \sin(2 * pi * A3 * t), \qquad (1)$$

where A1 = 12, A2 = 6.7, A3 = 3.5, and t = (0, 1). Here, we have defined the modulation index as parameter "A3." The total number of half cycles [defined as the analytical equation in Eq. (1)] incorporated inside the rectangular ring structure is twice the value of the modulation index. If the modulation index is 3, there are 6 half cycles inside the rectangular ring, whereas a modulation index of 3.5 means that 7 half cycles are incorporated inside the ring.

The transmission and reflection properties of the proposed structure have strong dependency on the polarization state of incident electromagnetic waves and on the modulation index.

Figures 3 and 4 show the frequency domain transmission and reflection behavior for modulation indices of 3.0 and 4.0, respectively. It can be observed that the structure has a similar response to the ring FSS structure with no modulation.

However, the interesting behavior of the structure appears with a modulation index of 3.5 (Fig. 5). The spectral behavior of the structure dramatically changes when the electric field is parallel to the sinusoidal curve (here, it is the Y-polarization state of the incident electromagnetic wave) with an even or odd number of half cycle modulation inside the rectangular ring. For the orthogonal polarization state of incident electromagnetic radiation (here X-polarization), the spectral behavior is similar to that of the original rectangular ring and does not depend on the modulation. It means that the modulated ring shows a band stop like FSS similar to the original rectangular ring alone for X-polarization state of the

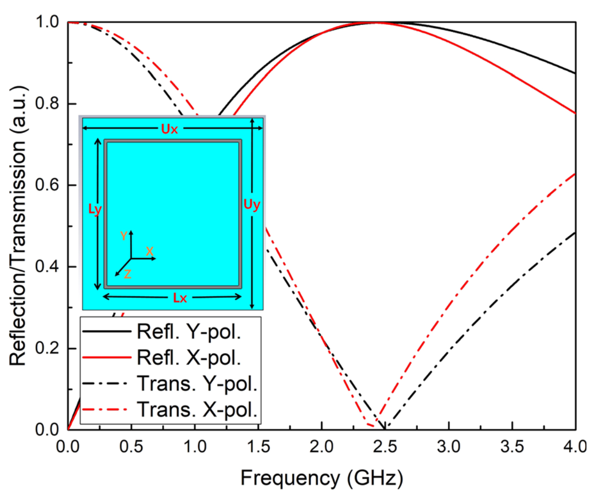

FIG. 1. Schematic view of the rectangular ring unit cell structure and simulated reflection and transmission spectrum of the unit cell for two orthogonal polarization states.

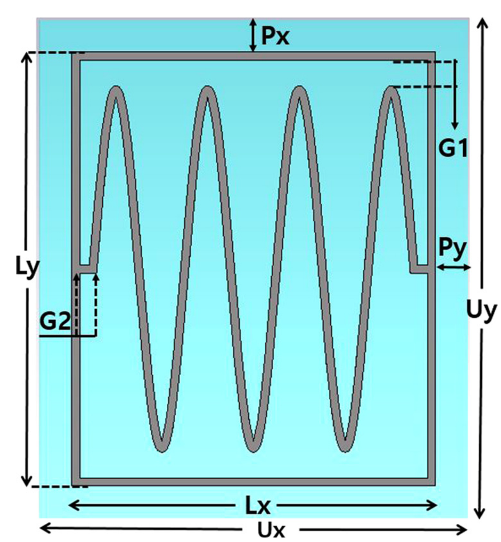

FIG. 2. Schematic view of the rectangular ring unit cell with the sinusoidal modulation index as 3.5 (Lx = 13.6, Ly = 16.2, Ux = 14, Uy = 16.6, Px = 0.2, Py = 0.2, G1 = 1, and G2 = 0.5) (all units in mm).

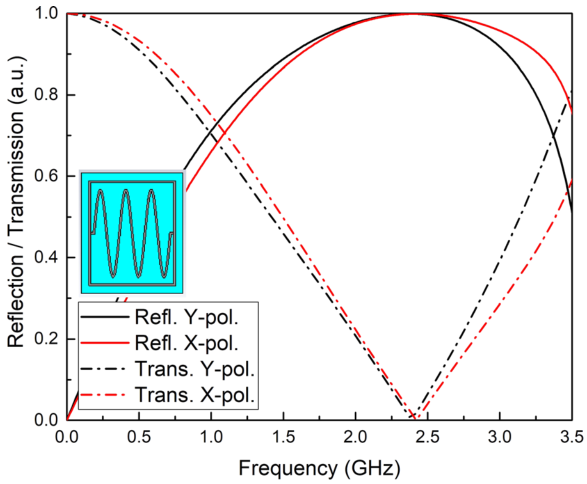

FIG. 3. Simulated reflection and transmission of the unit cell for two orthogonal polarization states for mod = 3.0.

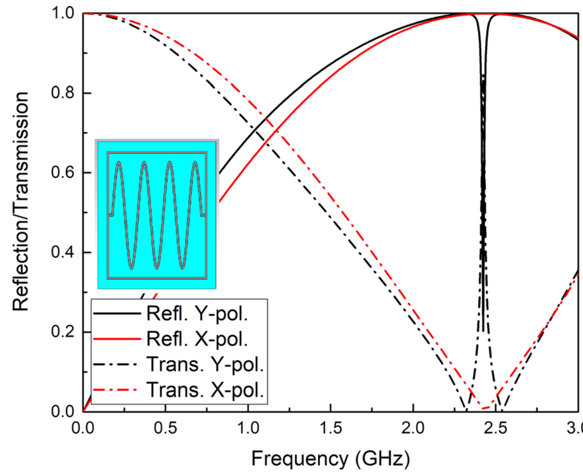

FIG. 5. Simulated reflection and transmission of the unit cell for two orthogonal polarization states for mod = 3.5.

incident electromagnetic radiation, and the spectral response is the same irrespective of the modulation index.

The original rectangular ring structure shows a larger bandwidth and hence a lower Q factor which is referred to as the bright mode resonance, whereas the modulated ring structure (with odd half cycle modulation) shows an ultra-sharp resonance for Y-polarized incident radiation which is referred to as the dark-mode resonance. Depending on the nature of modulation, even or odd, the excitation of the dark-mode can be controlled. The excitation of this narrow and strong resonance in the spectral response is the so-called "trapped modes," which is basically the reason for electromagnetic induced transparency (EIT) in the proposed sinusoidal modulated rectangular structure. This makes the original FSS/metasurface with the band stop spectra response (opaque) transparent to incident electromagnetic radiation with a particular polarization. It is the property of the trapped modes that allows in principal to achieve high-quality resonances in very thin structures. These modes are weakly coupled to the free space and hence superior radiation suppression.

For a deeper understanding of resonant nature of the proposed structure, the induced surface current in the metal pattern by the incident electromagnetic wave has been analyzed in the full wave simulator. Figure 6 shows the induced surface current in the unit cell with a modulation index of 3.5. Surface current is induced in the metallic trace along the incident polarization. The direction and strength of the surface current are along the arrow. It can be observed that the in-phase coupling between the two opposite branches of the ring restores the original current distribution (when even number of half cycle inside the ring), and hence, the scattering response is similar to the ring alone (without modulation). We can see that the induced current strength is very weak for Y-polarized radiation incident in the trapped mode (Fig. 6). The out of phase coupling between the opposite branches of the ring leads to the suppression of net induced current in the trapped mode. The scattered field strength by such current is weak that significantly reduces free space coupling and hence reduces radiation losses. For X-polarized incident, it can be understood that the metallic trace of the modulation is orthogonal to the incident electric field. Hence, the induced electric field on the ring is not affected by the modulation.

The fabricated sample is having 10×10 unit cells arranged in a planar form. The overall size of the sample is $140\,\text{mm} \times 166\,\text{mm}$. Transmission and reflection of a single sheet metamaterial are measured inside an anechoic chamber using broadband horn antennas with normal incidence along the principal plane. We observed a sharp transmission window within a broad stop band. Figure 7 shows the transmission

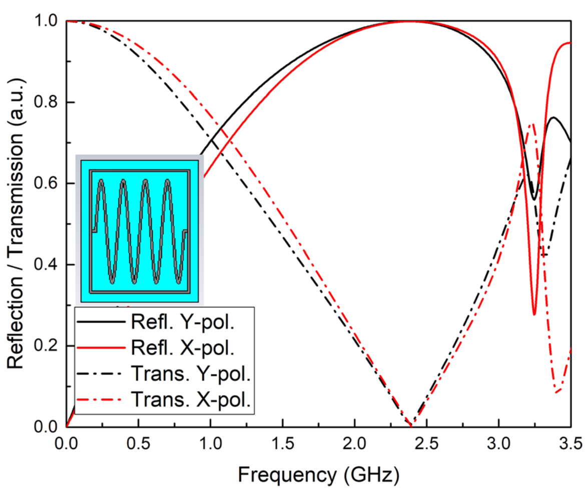

FIG. 4. Simulated reflection and transmission of the unit cell for two orthogonal polarization states for mod = 4.0.

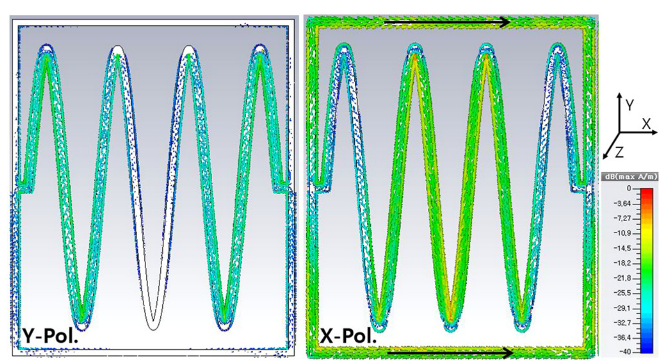

FIG. 6. Simulated surface current on the unit cell with a modulation index of 3.5 for (a) Y-polarization (b) X-polarization of the electric field.

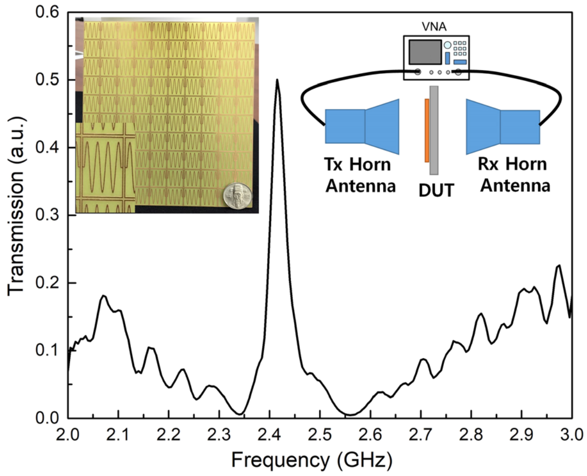

FIG. 7. Measured transmission in the anechoic chamber (photograph of the sample in the inset).

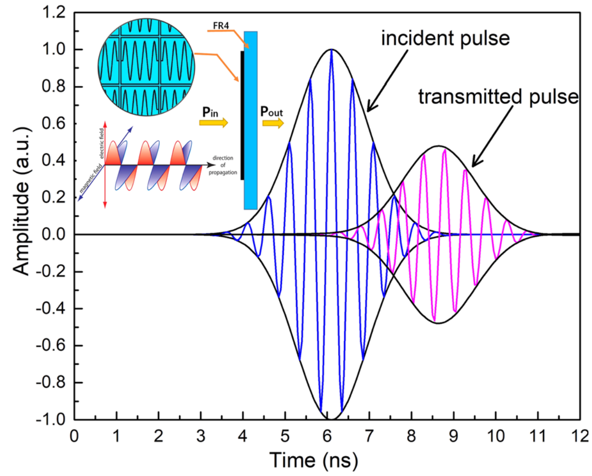

FIG. 8. Experimentally measured time domain behavior (polarization is along the vertical axis, here Y-axis).

performance of the sheet for Y-polarization of the incident electromagnetic field. It can be seen that the transmission is quite good at the trapped resonance with a little broadening of the bandwidth. Still, the bandwidth measured at half maxima is quite narrow which confirms a high Q-resonance.

The Q factor is obtained from the transmission profile, calculated as the ratio of resonance frequency f_0 (transmission peak) to bandwidth Δf. The bandwidth is qualitatively calculated as full width at half transmission maximum. The calculated Q factor from simulation and measured transmission profile is 122 and 88, respectively.

In the present case, the dispersive behavior of the proposed structure is investigated for a propagating electromagnetic pulse with a planar wave front. For the same, a unit amplitude Gaussian modulated sinusoidal pulse is considered with the center frequency the same as the frequency at which the proposed structure shows EIT like behavior. The transmission response of the system (S21) using the network analyzer with the horn antenna is measured. The principal E-plane is kept aligned along the desired orientation for which the structure shows EIT behavior. Applying Hermitian processing, the frequency domain system impulse response is calculated. Thereafter, inverse fast Fourier transform (IFFT) is used to retrieve the time domain impulse response. Then, the impulse response is convolved with the incident pulse signal to obtain the received signal envelope.[26] From Fig. 8, it is observed that the received signal essentially retains the Gaussian shape with a small delay time of 2.5 ns. The transmission magnitude is reasonably high for a single layer of sheet.

In summary, we numerically and experimentally showed EIT resonance in the planar metasurface composed of a periodic arrangement of a unit cell structured in the form of a sinusoidal modulated rectangular ring. Depending on the nature of modulation (even or odd), an extremely sharp resonance can be achieved, the so called trapped mode. The generation of the trapped mode transforms the metasurface from opaque to transparent at the resonance band for a particular polarization of the incident electromagnetic radiation. This electromagnetic induced transparency shows a high polarization selectivity. With the odd number of half cycle modulation inside a regular rectangular ring shows the EIT like behavior, whereas with an even number of half cycle modulation the spectral response of the modulated ring is the same as the regular ring. The proposed approach of sinusoidal modulation is scalable to higher frequency by selecting materials (both conductive traces and substrate) with suitable electromagnetic properties.

This research was supported by the MSIT (Ministry of Science and ICT), Korea, under the ITRC (Information Technology Research Center) support program (IITP-2017-2017-0-01635) supervised by the IITP (Institute for Information and Communications Technology Promotion) and also supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (NRF-2017R1A5A1015596).

[1]C. G. Meca, R. Ortuno, F. R. Fortuno, J. Marti, and A. Martinez, Opt. Express **17**, 6026 (2009).
[2]A. S. Schwanecke, V. A. Fedotov, V. V. Khardikov, S. L. Prosvirnin, Y. Chen, and N. I. Zheludev, J. Opt. A Pure Appl. Opt. **9**, L1 (2007).
[3]D. Sievenpiper, L. Zhang, R. Broas, N. Alexopolous, and E. Yablonovitch, IEEE Trans. Microwave Theory Tech. **47**, 2059 (1999).
[4]D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, Science **314**, 977 (2006).
[5]N. Engheta and R. W. Ziolkowski, *Electromagnetic Metamaterials: Physics and Engineering Explorations* (Wiley-IEEE Press, 2006).
[6]D. R. Smith and J. B. Pendry, J. Opt. Soc. **23**, 391 (2006).
[7]V. A. Fedotov, M. Rose, S. L. Prosvirnin, N. Papasimakis, and N. I. Zheludev, Phys. Rev. Lett. **99**, 147401 (2007).
[8]M. Fleischhauer, A. Imamoglu, and J. P. Marangos, Rev. Mod. Phys. **77**, 633 (2005).
[9]N. Papasimakis, Y. H. Fu, V. A. Fedotov, S. L. Prosvirnin, D. P. Tsai, and N. I. Zheludev, Appl. Phys. Lett. **94**, 211902 (2009).
[10]R. Singh, I. A. Al-Naib, Y. Yang, D. R. Chowdhury, W. Cao, C. Rockstuhl, T. Ozaki, R. Morandotti, and W. Zhang, Appl. Phys. Lett. **99**, 201107 (2011).
[11]C. Chen, Y. Lai, Y. Yang, C. Chen, and T. Yen, Opt. Express **17**, 15372 (2009).
[12]P. Tassin, L. Zhang, T. Koschny, E. N. Economou, and C. M. Soukoulis, Phys. Rev. Lett. **109**, 187401 (2012).
[13]Z. Y. Li, Y. F. Ma, R. Huang, R. Singh, J. Q. Gu, Z. Tian, J. G. Han, and W. L. Zhang, Opt. Express **19**, 8912 (2011).
[14]F. Zhang, Q. Zhao, C. W. Lan, X. He, W. H. Zhang, J. Zhou, and K. P. Qiu, Appl. Phys. Lett. **104**, 131907 (2014).
[15]C.-K. Chen, Y.-C. Lai, Y.-H. Yang, C.-Y. Chen, and T. Jen, Opt. Express **20**, 6952 (2012).

[16]F. Zhang, Q. Zhao, J. Zhou, and S. Wang, Opt. Express **21**, 19675 (2013).
[17]J. Q. Gu, R. Singh, X. J. Liu, X. Q. Zhang, Y. F. Ma, S. Zhang, S. A. Maier, Z. Tian, A. K. Azad, H. T. Chen, A. J. Taylor, J. G. Han, and W. L. Zhang, Nat. Commun. **3**, 1151 (2012).
[18]X. J. Liu, J. Q. Gu, R. Singh, Y. F. Ma, J. Zhu, Z. Tian, M. X. He, J. G. Han, and W. L. Zhang, Appl. Phys. Lett. **100**, 131101 (2012).
[19]L. Zhang, P. Tassin, T. Koschny, C. Kurter, S. M. Anlage, and C. M. Soukoulis, Appl. Phys. Lett. **97**, 241904 (2010).
[20]H. Ming Li, S. Bin Liu, S. Yuan Liu, S. Yun Wang, H. Feng Zhang, B. Rui Bian, and X. Kun Kong, Appl. Phys. Lett. **106**, 114101 (2015).
[21]S. Zhang, D. A. Genov, Y. Wang, M. Liu, and X. Zhang, Phys. Rev. Lett. **101**, 047401 (2008).
[22]M. Manjappa, S. Y. Chiam, L. Cong, A. A. Bettiol, W. Zhang, and R. Singh, Appl. Phys. Lett. **106**, 181101 (2015).
[23]M. Manjappa, Y. K. Srivastava, and R. Singh, Phys. Rev. B **94**, 161103 (2016).
[24]R. Yahiaoui, M. Manjappa, Y. K. Srivastava, and R. Singh, Appl. Phys. Lett. **111**, 021101 (2017).
[25]D. R. Chowdhury, X. Su, Y. Zeng, X. Chen, A. J. Taylor, and A. Azad, Opt. Express **22**, 19401 (2014).
[26]J. Malik, A. Patnaik, and M. V. Kartikeyan, *Compact Antennas for High Data Rate Communication* (Springer, 2018).