IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 28, 2019, accepted July 8, 2019, date of publication July 11, 2019, date of current version August 1, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2928357

All Dielectric Terahertz Left-Handed Metamaterial Based on Mie Resonance Coupling Effects

JU GAO, YIMING ZHANG, AND QIANG WU, (Member, IEEE)
Faculty of Information Technology, Beijing University of Technology, Beijing 100124, China

Corresponding author: Qiang Wu (wuqiang@bjut.edu.cn)

This work was supported in part by the National Science Foundation for Post-doctoral Scientists of China under Grant 2019M650406.

ABSTRACT Precise control of a coupling effect is critical for space-limited communication system applications. Dielectric metamaterials, which derive their electromagnetic properties from subwavelength structures, have emerged as a promising way to tune coupling effect due to their complex resonant modes. However, it has not yet achieved quantitative control of coupling effects in metamaterial designs, which is important for advanced engineering applications such as artificial intelligence antenna and reconfigurable camouflage. In this paper, all dielectric left-handed metamaterial operating in THz band based on the deep coupling of higher mode Mie resonance is presented. Distinguished from those designs published before, this left-handed metamaterial is composed only by one same structure, not two separated parts providing negative permittivity and permeability, respectively. By utilizing different Mie resonant modes, negative permittivity and permeability are accomplished via high order Mie resonant modes and the coupling between cubes. This work opens a gate to highly control of electromagnetic wave in dielectric metamaterial by using the coupling between the unit cells.

INDEX TERMS Coupled mode theory, dielectric metamaterial, left-handed metamaterial, terahertz structure.

I. INTRODUCTION

Dynamically manipulation on wavefront has always been an important issue in modern electromagnetic engineering technology [1]–[3]. It requires more integrated and miniaturized electromagnetic devices in new generation communication systems, and each component in the system needs to implement more functions in a limited space. Shrinking space will affect the mutual coupling between the electromagnetic devices [4]–[7]. This coupling effect will bring problems in two stages: the first stage is the couple between each component just affect the performance in bad ways and it needs to be eliminated; the second stage is the coupling effect can play a role in a range of performances, but meanwhile needs to be under completely control.

Dielectric metamaterial, artificially electromagnetic dielectric media structured on subwavelength scale, is now being great candidate for engineering electromagnetic space and light propagation control [8]–[13]. It has been a hot topic since its introduction, and has achieved remarkable achievements, such as energy harvesting, [14]–[16] chemical sensing, [17], [18] and heat management [19]–[21]. Since the relative permittivity of the dielectric resonator is generally high, there are more resonant modes and coupling effect between the structures [22]–[25]. However, the quantitative description of the coupling effect in the dielectric resonant structure has not yet been considered [26]–[29]. Therefore, this study focuses on the internal principle of coupling effect and proposes the combination of Mie scattering theory and coupled mode theory to quantitatively describe the complex coupling effect in dielectric metamaterials at the resonant frequencies.

In this paper, the coupling effect generated during the resonance of dielectric structure is studied. Distinguished from the metal structures which can be studied by equivalent circuit method, the resonant modes in the dielectric cube are much more complicated. Hence we propose a novel method that combines coupled mode theory and Mie scattering theory to analyze the coupling effect in the dielectric structures. This idea is simple and intuitive because this method regards each resonance mode as a whole and analyzes the structure directly from the energy point of view. By taking advantage of the

---

The associate editor coordinating the review of this manuscript and approving it for publication was Wanchen Yang.

quantitatively coupling effect, a novel left-handed metamaterial (LHM) is proposed by introducing only one structure to realize it. Deep coupling between each cubes are introduced to play an important role in regulating the higher Mie resonance mode, and by controlling the cube diameters and distance between each other, the first higher electric mode and magnetic mode are combined to achieve a left-handed metamaterial. Deep coupling effect can make the effective permittivity and permeability tuning more flexible, and also improve the freedom of electromagnetic energy manipulation.

II. ANALYTICAL MODEL OF COUPLING EFFECT

The advantage of coupled-mode theory is that its mathematical model is very simple, and it can intuitively describe the physical process of coupling from the perspective of energy. Because small particle embedded in the background is a precondition of Mie scattering theory, the coupling effect analytical model needs to be based on small particles as well. For the adaptability concern, the analytical model is set by the simplest basic cubes and the effect of coupling effect on resonance characteristics is studied. The coupling model during the resonance process is shown in Fig. 1. When two dielectric cubes are placed close to each other, their internal resonant modes will interfere, affecting the inherent resonant frequency and resonant intensity of the dielectric cube itself. The Mie resonance mode in this case can be analyzed by the coupled mode theory.

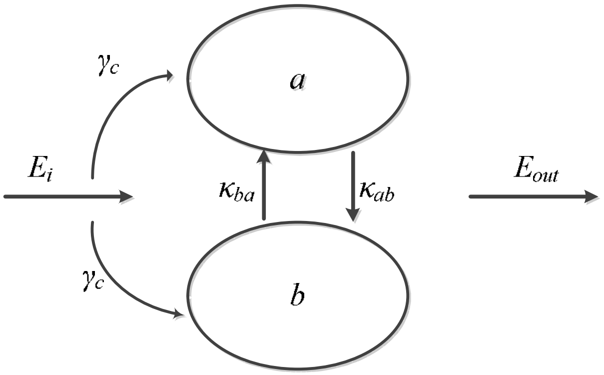


FIGURE 1. **Schematic diagram of dielectric cube coupling model of coupled mode theory.**

Figure 1 shows the coupling model in coupled mode theory for two particles case. In Figure 1, a and b respectively represent the resonance modes inside the two dielectric cubes placed adjacently, that is, the actual field distribution in the dielectric cube when the electromagnetic waves are incident. κ_{ab} represents the coupling effect of the dielectric cube a on the dielectric cube b and vice versa. Once $\kappa_{ab} = \kappa_{ba} = 0$, that means there is no mutual coupling effect between the two dielectric cubes. γ_c represents the coupling loss between the dielectric cube and the incident wave. E_i represents the amplitude of the incident wave. E_{out} represents the magnitude of the outgoing wave.

When two dielectric cubes are simultaneously irradiated by incident electromagnetic waves, the energy transfer equation with the influence of coupling effect can be expressed as follows:

$$\frac{da}{dt} = (j\omega_a - \gamma_a)a + \sqrt{\gamma_c}E_i - j\kappa_{ab}b \tag{1}$$

$$\frac{db}{dt} = (j\omega_b - \gamma_b)b + \sqrt{\gamma_c}E_i - j\kappa_{ba}a \tag{2}$$

ω_a and ω_b represent the resonant frequencies of the two dielectric cubes themselves, respectively. The left side of the equation represents the field distribution over time. The first term on the right represents its own excitation and loss, the second term represents the incident energy after loss, and the third term represents the scatter energy delivered to b by the dielectric cube a. The dielectric cube can be considered as a standing wave system at resonant frequency. Based on microstrip transmission line theory, the energy transfer equation can be rewritten as:

$$\frac{a}{E_i} = \frac{-j\sqrt{\gamma_c}}{\delta_a - j\gamma_a + \kappa_{ab}\frac{\delta_a - j\gamma_a - \kappa_{ba}}{\delta_b - j\gamma_b - \kappa_{ab}}} \tag{3}$$

$$\frac{b}{E_i} = \frac{-j\sqrt{\gamma_c}}{\delta_b - j\gamma_b + \kappa_{ba}\frac{\delta_b - j\gamma_b - \kappa_{ab}}{\delta_a - j\gamma_a - \kappa_{ba}}} \tag{4}$$

The electrical resonance mode and the magnetic resonance mode in the dielectric structure can be expressed by the following formula by Mie scattering theory:

$$m = \frac{n\Psi(nx)\Psi'(x) - \Psi(x)\Psi'(nx)}{n\Psi(nx)\xi'(x) - \xi(x)\Psi'(nx)} \tag{5}$$

$$e = \frac{\Psi(nx)\Psi'(x) - n\Psi(x)\Psi'(nx)}{\Psi(nx)\xi'(x) - n\xi(x)\Psi'(nx)} \tag{6}$$

$x = k_0 r_0$ is the parameter defining the dielectric particles, when $k_0 = \omega/c$ is the wave vector in vacuum. The distribution $\Psi(x)$ and $\xi(x)$ represent the Bessel function and the Hankel function.

Based on the Clausius-Mossoti equation, for several particles embedded in the host medium case, we can calculate the magnetic resonance mode and electric resonance mode as follows:

$$a_m = \mathrm{j}\frac{2}{3}(k_0^2\mu_0\varepsilon_0)^{3/2}\frac{\varepsilon_0 - \varepsilon_i F(\theta_m)}{2\varepsilon_0 + \varepsilon_i F(\theta_m)}r^3 \tag{7}$$

$$b_m = \mathrm{j}\frac{2}{3}(k_0^2\mu_0\varepsilon_0)^{3/2}\frac{\mu_0 - \mu_i F(\theta_m)}{2\mu_0 + \mu_i F(\theta_m)}r^3 \tag{8}$$

where a_m and b_m represent the actual magnetic and electric mode inside the dielectric cube, which means this equation is calculated under coupling effect. In this way, through the combination of the above formulas, it is possible to quantitatively solve the coupling effect of κ_{ij}, the coupling effect between two dielectric structures, and finally obtains the expression of the coupling effect on the parameters of the dielectric unit itself and the period size.

III. UNIT CELL DESIGN AND SIMULATION RESULTS

Based on the controllable coupling effect, a left-handed metamaterial with single structure is proposed and explained. As one could know from the transmission line theory, series inductance and shunt capacitor on the incident wave propagating direction are the key point to achieve LHMs. The easier to get the series inductance and shunt capacitor at the same time, the wider LHM working band will be. So via this theory, we demonstrate a single structure LHM shown in Fig.2. As we can see in Fig.2, the unit cell is composed by a simple cube and arranged periodically in *xoy* plane. This simple structure guaranteed the field distribution is not that complex at lower Mie resonance mode, which means if there is left-handed effect, the working band is assured to be wide. Meanwhile, the compact formation makes it possible to achieve isotropic material by utilizing both the Mie resonance in the cube and the coupling between each cubes together to enrich the methods in obtaining isotropic material, such as 3D left-handed metamaterial. The parameters in Fig.2 are as follows: the length of the cube a is 10um and the distance between each cube l is 2um. Gaps between the cubes can be regarded as capacitances. There is no essential difference whether the gaps between the cubes are wide or narrow. It only affects the coupling capacitance strength. So, in the coupled mode theory, this kind of coupling effect can also be solved through the perspective of energy.

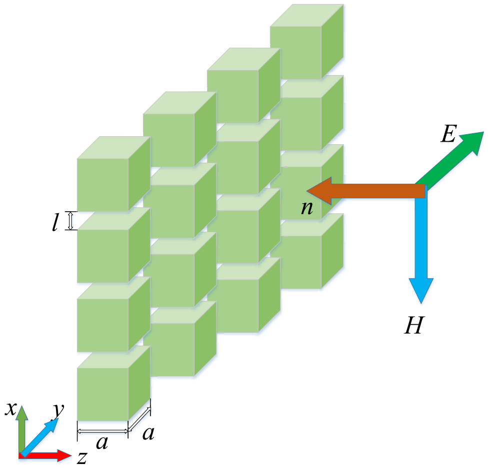
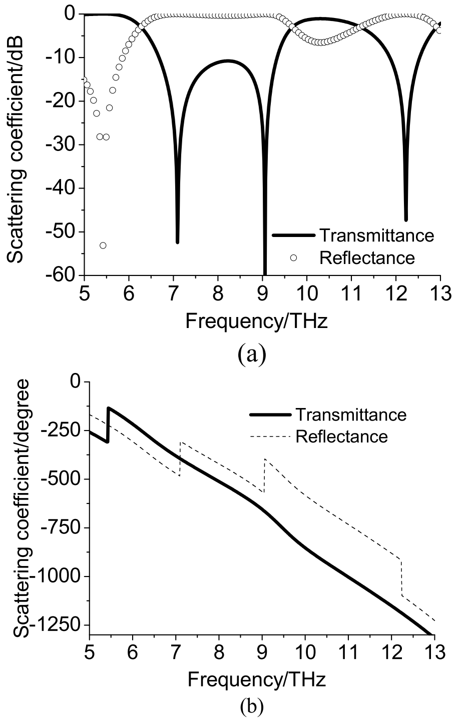


FIGURE 2. **Schematic diagram of LHM array.**

The distance between cubes is much smaller to the cube diameter, so the coupling effect cannot be ignored. The traditional Mie scattering theory is to embed dielectric particles in the background material, and assumes that the distance between the particles is much larger than the volume of the particles themselves, so the coupling effect between the particles can be neglected. In this paper, the left-hand metamaterial crystalline silicon cube is close to each other, so the coupling effect is very obvious. Through the coupling between the dielectric cubes, the resonance strength of the magnetic field in the Mie resonance effect is enhanced, thereby achieving the purpose of forming a single structured left-handed metamaterial.

In periodical structures, dielectric metamaterials can be regarded as electric dipole and magnetic dipole over the resonant frequencies. So the coupling effect can also be understood as the dipole-dipole interaction between neighboring particles. It is correct to study the coupling effect in dielectric metamaterials by both periodical structures and waveguide. This is a big difference between the metal-based metamaterials [30]–[32]. The whole simulation progresses are finished by CST Microwave Studio 2015 frequency domain solver. The cubes are arranged in *xoy* plane periodically and the boundary condition in z direction is open add space. The material of the cube is silicon which is well developed in optical and microwave band fabrication. The simulation results of the silicon cube array are shown in Fig.3. The operating band is settled from 5THz to 13THz and we could clearly find 3 resonant gaps which refer to the magnetic Mie resonant mode (TE_{10}), the electric resonant mode (TM_{10}) and the first high order magnetic Mie resonant mode (TE_{20}). These first two Mie resonant modes could provide negative permeability and negative permittivity at each resonant frequency, respectively. The whole cube array behaves as a reflector over this frequency band. By using the Nicolson-Ross-Weir (NRW) and S-parameter retrieve algorithm [33], the effective permittivity and permeability are calculated based on the amplitude and phase of the S parameters.



(a)

(b)

FIGURE 3. **Electromagnetic response of the LHM (a) amplitude (b) phase.**

Dielectric resonators based on silicon cubes are good substitute for THz metasurfaces since they are far less lossy and exhibit strong resonances. These resonances provide large field enhancement along the operating axis, which can be analogous to an actively tunable material. This allows tuning of the resonator without changing any region of the surrounding environment, but only related to the incident frequency. What makes this design interesting is the frequency band between 9THz and 12THz, there is a clearly transparency band in Fig.3 which means the electromagnetic wave is passed through this frequency. However, we could find that this transmittance is not that simple as the frequency before 7THz, this band is between two Mie resonant modes, but it is between the first electric resonant mode and the high magnetic resonant mode. So, while we keep moving the electric resonant frequency and the high magnetic resonance frequency together, things goes different from what happened between the first two Mie resonant modes. No resonant mode disappeared, and there is a coincidence frequency band while moving these two bands together. So a LHM by only introducing one same structure is achieved since both permittivity and permeability are negative over these frequency bands.

The calculated results are shown in Fig.4. It is clear that before the first resonant frequency, 7THz, both the permittivity and permeability are positive. That means there is no resonance and no negative index over these frequency bands. And then around 7THz and 9THz, the magnetic resonance and electric resonance appear, the effective permeability and permittivity become negative, respectively. What we need to mention is the frequency between 9THz and 12THz, here we keep it at a high reflectance coefficient by selecting proper cube dimensions and distance between each other to make the Mie magnetic resonant mode and Mie electric resonant mode connected. However, it is not possible to combine these first two resonant modes together, it is only possible to separate them far away or make them closer. If we keep optimizing them together, the electric mode will disappear. By using this connection part, both effective permittivity and permeability from 9.9THz to 10.9THz are negative, so double negative medium is generated in the single dielectric cube. The relative bandwidth of double negative medium is 9.1%.

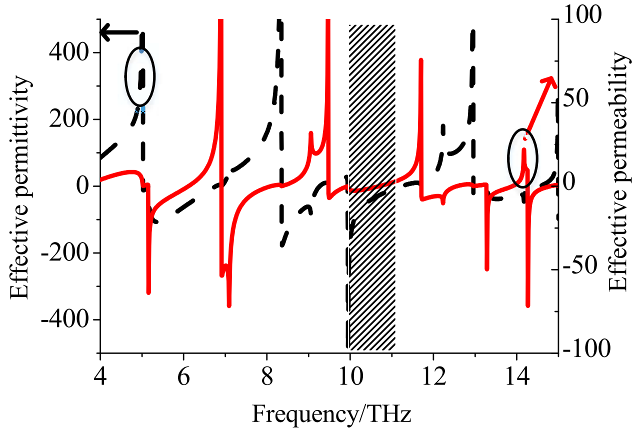


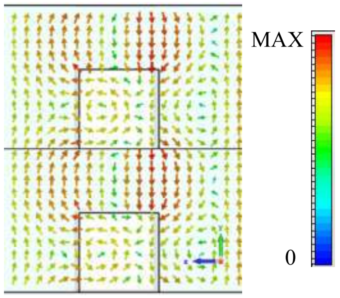
FIGURE 4. Calculated effective permittivity and permeability by NRW algorithm.

The double negative bandwidth is not wide because the left-handed metamaterial proposed in this paper is generated by the overlap of two different resonance modes, it is reasonable that this work is not wideband. The dielectric metamaterials based on Mie resonance theory are narrow band in theory. This can also be found in figure.6, the theoretical calculated results are both narrow-bandwidth.

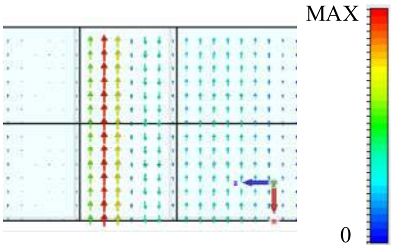
This work shows a novel method to calculate the coupling effect in dielectric metamaterials, by designing a simple simulation model, the analysis method proves correct. Fig.3 successfully verifies that coupling effect can generate another resonance mode and Fig.4 verifies that the negative permittivity and permeability can overlap with each other.

IV. FIELD DISTRIBUTION ANALYSIS

The electric field distributions are also shown to illustrate the physical inside the cubes. Fig.5 shows the electric field distribution of the LHM at 10.375THz. In Fig.5, the edges between each cube form two electric dipoles, and each edge also has the opposite polar. That means the adjacent cube could be regarded as an electric dipole and presents a negative effective permittivity in whole cube array. Additionally, an electric loop also shows inside the silicon cube, which is relatively weak compared to the electric resonance between the cubes. However, no matter how weak the magnetic resonance is, this magnetic resonance is the reason for that the cube array presents a passing band over this frequency band and also provides the negative permeability for LHM. There is no specific structure to generate extra negative permittivity and permeability, therefore, it's not easy to simultaneously adjust the transmittance efficient to reach100% while realizing a wider passband for the lack of enough magnetic resonance.



(a) Electric field distribution



(b) Magnetic field distribution

FIGURE 5. Schematic of the field distribution at the left-handed resonant frequency (a) Electric field distribution (b) Magnetic field distribution.

Our design provides a new method to design LHM with only one structure by combining the effects of Mie resonant modes.

It's clear that the distance between tubes is crucial for the LHM generation through the further investigation of the electric field distribution. A loop electric field generates around the inner edges of the cube as well as a relatively weak one in front of it. These two electric-field loops could further enhance the abovementioned weak magnetic resonance to the same level of the electric mode resonance, which can provide more negative permeability at the resonant frequency. Moreover, since the cubes are placed near with each other, their adjacent edges can operate as an electric dipole. For the above-discussed field distribution, both electric dipole and magnetic dipole excite at the operating frequency band, which make this structure behave as a LHM.

In order to prove the correctness of the proposed coupling effect calculation method, a comparison is made between the single cube case and the cubes placed with coupling effect case. The calculated cube model is silicon cube. The side length is 10μm and the relative permittivity is 11.9. In the case with coupling effect, the distance of the cubes is 2μm to make sure the coupling effect is strong enough. The comparison result is shown in Figure 6.

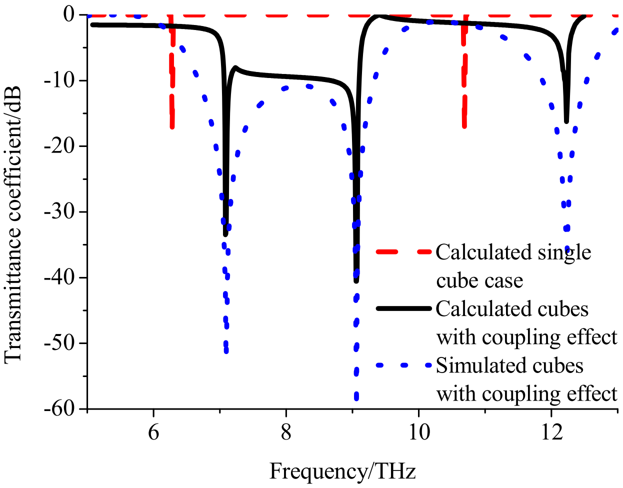


FIGURE 6. **Transmittance coefficient comparison of cubes with coupling effects case and single cube case.**

As it can be seen from figure 6, the coupling effect has a great influence on both calculated and simulated transmittance coefficient results. The calculated result shows that there are two resonant modes excited in the dielectric cube around 6.28THz and 10.69THz in the single cube case. The calculation is based on the Mie scattering theory which focuses on each resonant mode, so this result only shows the resonant frequency. The resonance intensity is 0dB over nonresonant frequencies in this calculation. In the coupling effect case, the calculation model is set up by two cubes placed nearby and analyzed by coupled mode theory. The results indicate that coupling effects have a great influence on the resonant frequency. The magnetic and electric resonant modes have been shifted to 7.01THz and 9.02THz, respectively. Meanwhile, the first high order resonance around 12.3THz is also calculated in this case. Because this calculation result is based on the energy transmission, the nonresonant frequency bands are also involved in this calculation method. For convincing and logic integrity concern, the simulation result with coupling effect is added here to compare with the calculated result. It can be seen from the comparison results that the resonant frequencies of the theoretical deduction in good agree with the simulation calculation. This shows that the method of using the coupled mode theory and the Mie scattering theory to calculate the coupling effect on the overall scattering characteristics of the structure is practicable.

V. CONCLUSION

Aiming at solving the problem that the existing Mie resonance theory does not fully consider the coupling between dielectric cubes, this paper studies the coupling effect of dense arrangement between dielectric cubes, and quantitatively discusses the influences of coupling effect on the resonant mode. According to the proposed analysis method, the influence of coupling effect on the overall scattering mode and frequency of the structure is deduced and simulated. By verifying the method with simple dielectric cubes, the quantitative coupling effect is excited between the cubes gap to provide negative permittivity performance and the negative permeability is generated inside the dielectric cube. The full control over coupling effect enriches the wave manipulation methods in terahertz band and will play a guiding role in the comprehensive application of terahertz devices in the future.

REFERENCES

[1] P. Genevet, F. Capasso, F. Aieta, M. Khorasaninejad, and R. J. O. Devlin, "Recent advances in planar optics: From plasmonic to dielectric metasurfaces," *Optica*, vol. 4, no. 1, pp. 139–152, 2017.

[2] C. L. Holloway, E. F. Kuester, J. A. Gordon, J. O'Hara, J. Booth, and D. R. Smith, "An Overview of the theory and applications of metasurfaces: The two-dimensional equivalents of metamaterials," *IEEE Antenn. Propag. Mag.*, vol. 54, no. 4, pp. 10–35, Jul. 2012.

[3] N. Yu and F. Capasso, "Flat optics with designer metasurfaces," *Nature Mater.*, vol. 13, pp. 139–150, Jan. 2014.

[4] F. Bayatpur and K. Sarabandi, "Multi-layer miniaturized-element frequency selective surfaces," in *Proc. Antennas Propag. Soc. Int. Symp.*, Jul. 2008, pp. 1–4.

[5] F. Bayatpur and K. Sarabandi, "Single-layer high-order miniaturized-element frequency-selective surfaces," *IEEE Trans. Antennas Propag.*, vol. 56, no. 4, pp. 774–781, Apr. 2008.

[6] F. Bayatpur and K. Sarabandi, "Multipole spatial filters using metamaterial-based miniaturized-element frequency-selective surfaces," *IEEE Trans. Microw. Theory Techn.*, vol. 56, no. 12, pp. 2742–2747, Dec. 2008.

[7] S. M. A. M. H. Abadi and N. Behdad, "Wideband linear-to-circular polarization converters based on miniaturized-element frequency selective surfaces," *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp. 525–534, Feb. 2016.

[8] A. N. Grigorenko, A. K. Geim, H. F. Gleeson, Y. Zhang, A. A. Firsov, I. Y. Khrushchev, and J. Petrovic, "Nanofabricated media with negative permeability at visible frequencies," *Nature*, vol. 438, no. 7066, pp. 335–338, 2005.

[9] X. Zhang, "Optical negative index metamaterials," *Nature Photon.*, vol. 1, no. 1, pp. 41–48, 2011.

[10] M. Silveirinha and N. Engheta, "Design of matched zero-index metamaterials using nonmagnetic inclusions in epsilon-near-zero media," *Phys. Rev. B, Condens. Matter*, vol. 75, no. 7, pp. 794–802, 2007.

[11] M. Hentschel, M. Schäferling, T. Weiss, N. Liu, and H. Giessen, "Three-dimensional chiral plasmonic oligomers," *Nano Lett.*, vol. 12, no. 5, pp. 2542–2547, 2012.

[12] E. Plum, J. Zhou, J. Dong, V. A. Fedotov, T. Koschny, C. M. Soukoulis, and N. I. Zheludev, "Metamaterial with negative index due to chirality," *Phys. Rev. B, Condens. Matter*, vol. 79, no. 3, 2009, Art. no. 035407.

[13] H. N. S. Krishnamoorthy, Z. Jacob, E. Narimanov, I. Kretzschmar, and V. M. Menon, "Topological transitions in metamaterials," *Science*, vol. 336, no. 6078, pp. 205–209, 2011.

[14] R. Jiang, B. Li, C. Fang, and J. Wang, "Metal/semiconductor hybrid nanostructures for plasmon-enhanced applications," *Adv. Mater.*, vol. 26, no. 31, pp. 5274–5309, 2015.

[15] Z. J. Coppens, I. I. Kravchenko, and J. G. Valentine, "Lithography-free large-area metamaterials for stable thermophotovoltaic energy conversion," *Adv. Opt. Mater.*, vol. 4, no. 5, pp. 671–676, 2016.

[16] P. Li, B. Liu, Y. Ni, K. K. Liew, J. Sze, S. Chen, and S. Shen, "Large-scale nanophotonic solar selective absorbers for high-efficiency solar thermal energy conversion," *Adv. Mater.*, vol. 27, no. 31, pp. 4585–4591, 2015.

[17] A. Tittl, A.-K. U. Michel, M. Schäferling, X. Yin, B. Gholipour, L. Cui, M. Wuttig, T. Taubner, F. Neubrech, and H. Giessen, "A switchable mid-infrared plasmonic perfect absorber with multispectral thermal imaging capability," *Adv. Mater.*, vol. 27, no. 31, pp. 4597–4603, 2015.

[18] K.-J. Kim, X. Chong, P. B. Kreider, G. Ma, P. R. Ohodnicki, J. P. Baltrus, A. X. Wang, and C.-H. Chang, "Plasmonics-enhanced metal–organic framework nanoporous films for highly sensitive near-infrared absorption," *J. Mater. Chem. C*, vol. 3, no. 12, pp. 2763–2767, 2015.

[19] M. M. Hossain, B. Jia, and M. Gu, "Metamaterials: A metamaterial emitter for highly efficient radiative cooling (advanced optical materials 8/2015)," *Adv. Opt. Mater.*, vol. 3, no. 8, p. 980, 2015.

[20] G. Smith, A. Gentle, M. Arnold, and M. Cortie, "Nanophotonics-enabled smart windows, buildings and wearables," *Nanophotonics*, vol. 5, no. 1, pp. 55–73, 2016.

[21] I. E. Khodasevych, L. Wang, A. Mitchell, and G. Rosengarten, "Micro- and nanostructured surfaces for selective solar absorption," *Adv. Opt. Mater.*, vol. 3, no. 7, pp. 852–881, 2015.

[22] F. Bayatpur and K. Sarabandi, "Tuning performance of metamaterial-based frequency selective surfaces," *IEEE Trans. Antennas Propag.*, vol. 57, no. 2, pp. 590–592, Feb. 2009.

[23] F. Bayatpur and K. Sarabandi, "A tunable metamaterial frequency-selective surface with variable modes of operation," *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 6, pp. 1433–1438, Jun. 2009.

[24] M. Moallem and K. Sarabandi, "Miniaturized-element frequency selective surfaces for millimeter-wave to terahertz applications," *IEEE Trans. THz Sci. Technol.*, vol. 2, no. 3, pp. 333–339, May 2012.

[25] H. Haus and W. P. Huang, "Coupled-mode theory," *Proc. IEEE*, vol. 79, no. 10, pp. 1505–1518, Oct. 1991.

[26] Y. Zhang, B. J. Lester, Y. Y. Gao, L. Jiang, R. J. Schoelkopf, and S. M. Girvin, "Engineering bilinear mode coupling in circuit QED: Theory and experiment," *Phys. Rev. A, Gen. Phys.*, vol. 99, no. 1, 2018, Art. no. 012314.

[27] W. Götze, "Recent tests of the mode-coupling theory for glassy dynamics," *J. Phys. Condens. Matter*, vol. 11, no. 10A, p. A1, 1999.

[28] M. De Marzio, G. Camisasca, M. Rovere, and P. Gallo, "Mode coupling theory and fragile to strong transition in supercooled TIP4P/2005 water," *J. Chem. Phys.*, vol. 144, no. 7, 2016, Art. no. 094507.

[29] M. Feng and Z. Hou, "Mode coupling theory for nonequilibrium glassy dynamics of thermal self-propelled particles," *Soft Matter*, vol. 13, no. 25, pp. 4464–4481, 2017.

[30] F. Zhang, V. Sadaune, L. Kang, Q. Zhao, J. Zhou, and D. Lippens, "Coupling effect for dielectric metamaterial dimer," *Prog. Electromagn. Res.*, vol. 132, pp. 587–601, Oct. 2012.

[31] I. Sersic, M. Frimmer, E. Verhagen, and A. F. Koenderink, "Electric and magnetic dipole coupling in near-infrared split-ring metamaterial arrays," *Phys. Rev. Lett.*, vol. 103, no. 21, Nov. 2009, Art. no. 213902.

[32] F. Zhang, L. Kang, Q. Zhao, J. Zhou, and D. Lippens, "Magnetic and electric coupling effects of dielectric metamaterial," *New J. Phys.*, vol. 14, no. 3, 2012, Art. no. 033031.

[33] D. R. Smith, D. C. Vier, T. Koschny, and C. M. Soukoulis, "Electromagnetic parameter retrieval from inhomogeneous metamaterials," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 71, no. 3, Mar. 2005, Art. no. 036617.

JU GAO was born in Liaoning, China, in 1989. He received the B.S. degree in communication engineering, the M.S. degree in electronics and information engineering, and the Ph.D. degree in electronics science and technology from the Harbin Institute of Technology, Harbin, China, in 2011, 2013, and 2018, respectively.

He is currently holding the postdoctoral position with the Beijing University of Technology, Beijing, China, mainly focus on coupling effects in dielectric metamaterials and the electromagnetic device design in communication systems. His research interests include dielectric metamaterials, metasurfaces, and antennas.

YIMING ZHANG was born in Hubei, China, in 1964. He received the B.E. degree from the School of Electronic, Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China, in 1987, and the M.E. degree from the School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin, China, in 1992. From 2000 to 2006, he was a Senior Researcher with the Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China. Since 2007, he has been a Professor with the College of Electronic Information and Control Engineering, Beijing University of Technology, Beijing. His current research interests include intelligent power management, motor speed control, servo drivers, and motor energy conservation.

QIANG WU received the B.S. and M.S. degrees from the North University of China, Taiyuan, China, in 1995 and 1998, respectively, and the Ph.D. degree from the Beijing University of Technology, Beijing, China, in 2011. From 1998 to 2006, he was a Lecturer with the College of Electronic Information and Control Engineering, Beijing University of Technology. From 2006 to 2016, he was an Associate Professor with the College of Electronic Information and Control Engineering, Beijing University of Technology, where he has been a Professor with the School of Information and Communications Engineering, since 2016. His research interests include high performance, high-speed real-time system, multi-media information processing, DSP, and embedded systems. He currently leads a group on the researches of embedded system with projects supported by the National Natural Science Foundation of China, and National High Technology Research and Development Projects (863 Projects) of China.

• • •