Multi-band Microwave Metamaterial Perfect Absorber Based on Mie Resonance Theory

Jun-Feng Chen[1], **Guo-Dong Wang**[1], **Zhao-Quan Chen**[2,3], **Ming-Hai Liu**[1], **and Xi-Wei Hu**[1]

[1]State Key Laboratory of Advanced Electromagnetic Engineering and Technology
School of Electrical and Electronic Engineering
Huazhong University of Science and Technology
Wuhan 430074, China
[2]University ITMO, Kronverkskiy pr. 49, St. Petersburg 197101, Russia
[3]College of Electrical and Information Engineering
Anhui University of Science and Technology
Huainan 232001, China

Abstract— A multi-band metamaterial absorber (MA) with near-unity absorption based on Mie resonance theory is proposed in the microwave region. It is composed of an array of dielectric cubes with different geometric parameters and a metallic ground plane. The simulated results show that four absorption peaks at 7.31 GHz, 7.58 GHz, 7.90 GHz and 8.19 GHz with the corresponding absorption rates of 99.05%, 99.37%, 99.65% and 99.16%, respectively. In addition, the composite MA is polarization-insensitive at the normal incidence and maintains high absorption rates at wide angles of incidence for both TE and TM wave. The influences of the permittivity and the side length of the dielectric cubes on its absorption characteristics are also investigated. This MA would be a promising candidate as absorbing elements in scientific and technical applications, such as cloaks, perfect lens and filters.

1. INTRODUCTION

Metamaterials (MMs) are artifical, effectively homogeneous electromagnetic (EM) structures consisting of dielectrics and highly conducting metals, which are periodically arranged. MMs research has always been popular because of its superior properties than natural materials. However, the metamaterials with perfect absorption have attracted plenty of attention from scientists over the past several years. Periodic dielectric or metallic structures have been a subject of continuing interest for applications to frequency selective or polarization selective devices in microwaves and optical waves. In 2008, Landy et al. [1] first demonstrated a perfect MM absorber (MA) in a narrow-band which was made of a sub-wavelength structure of electric ring resonators and metal cut wires separated by a dielectric substrate. The idea is that by adjusting the electric and magnetic resonances independently, it is possible to realize the impedance of the MM matching to the free space so as to minimize the reflection. Meanwhile, the transmission wave is completely consumed in the lossy substrate and two metallic layers. As a result, perfect absorption is achieved at the resonance frequency. Since then, the type of MAs excite a new wave of research such as fishnet structures [2], square Loops [3] and coplanar Jerusalem crosses [4].

Recently, an isotropic Mie resonance-based metamaterial perfect absorber with near unity absorbance at the microwave frequencies was reported by Liu et al. [5]. The metamaterial is constructed with an array of dielectric cubes and a metallic ground plane. The new type of absorber was fabricated successfully, which achieved a single band absorption at 9.96 GHz and the absorptivity was 98%. Indeed, Lewin [6] derived an expression based on Mie Resonance Theory [7] for the effective properties of an array of spherical particles embedded in a background matrix. A medium composed of periodically placed scatterers generates polarization and magnetization densities. The densities are related to the distribution of the scatterers and their polarizabilities. As a result, a wave propagating through an array of these scatterers will see the material as an effective medium. The problem of effective-medium theory and modeling the electromagnetic response of inclusions embedded in a host material has a long history going back to Maxwell and Rayleigh [8, 9]. Many other authors [6, 10] studied the properties and applications of the metamaterials in detail.

In this paper, we propose a four band polarization-insensitive MA based on a structure of periodic array of dielectric cubes with different geometric parameters and a metallic ground plane. The permittivity of the dielectric cube is $115 + 0.92i$, and the metallic ground plane is made of copper as reported in [5]. Simulation results show that the proposed MA has four distinct absorption peaks and their absorptivity is over 99%. Distributions of surface current density on the dielectric cubes and back metallic layers are illustrated. The loss contributions of dielectric cubes and ground plane are also discussed. Moreover, the simulation results exhibit that the MA is polarization-insensitive and could operate well at different angles of incidence for both transverse electric (TE) and transverse magnetic (TM) waves, which is potential to be used in devices such as detection of explosives, stealth technology and bolometer.

2. EFFECTIVE DIELECTRIC AND MAGNETIC PROPERTIES OF A CUBICAL-PARTICLE COMPOSITE

As mentioned above, in 1947, Lewin [6] derived an expression based on Mie resonance theory for the effective permittivity and permeability of a composite material which was constituted of an array of lossless magneto dielectric spherical particles with the permittivity ε_2 and permeability μ_2 embedded in a background matrix with the permittivity ε_1 and permeability μ_1. The effective permittivity ε_{re} and permeability μ_{re} of the composite shown in Fig. 1(a) are given by [6]

$$\varepsilon_{re} = \varepsilon_1 \left[1 + \frac{3f}{\frac{F(\theta)+2K_e}{F(\theta)-K_e} - \upsilon_f} \right] \tag{1}$$

and

$$\mu_{re} = \mu_1 \left[1 + \frac{3f}{\frac{F(\theta)+2K_m}{F(\theta)-K_m} - \upsilon_f} \right] \tag{2}$$

In these expressions,

$$K_e = \frac{\varepsilon_1}{\varepsilon_2} \qquad K_m = \frac{\mu_1}{\mu_2} \tag{3}$$

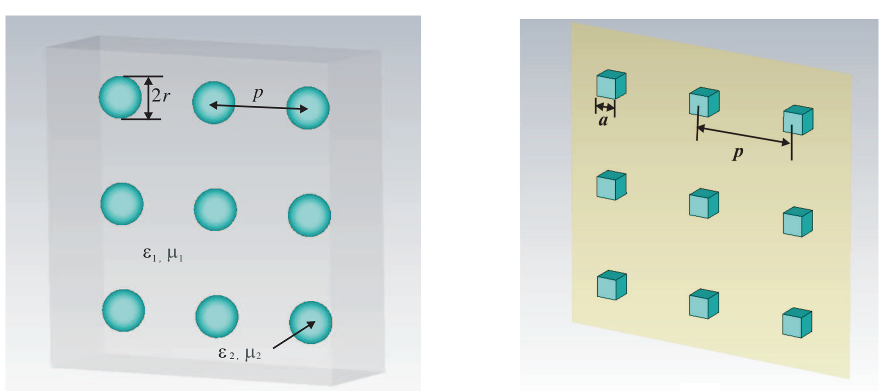
The volume fraction υ_f of the spherical inclusions is given by

$$\upsilon_f = \frac{4\pi r^3}{3p^3} \tag{4}$$

where r is the particle radius and p is the particle spacing. The function $F(\theta)$ is

$$F(\theta) = \frac{2(\sin\theta - \theta\cos\theta)}{(\theta^2 - 1)\sin\theta + \theta\cos\theta} \tag{5}$$

where $\theta = k_0 r\sqrt{\varepsilon_2\mu_2}$, and the free-space wavenumber is $k_0 = \frac{2\pi}{\lambda}$, λ is the free-space wavelength. $F(\theta)$ is a resonant function and becomes infinite at some values of θ, which results in the magnetic and electric resonances. Among all the resonances, the first Mie resonance mode is the most intense and leads to the magnetic resonance of the spheres. We add a copper ground plane with the thickness of 0.1 mm under the dielectric particles to form a Mie resonance-based MA. Besides



(a) (b)

Figure 1: (a) Structure of the composite material in Lewins model. (b) Structure of the Mie resonance-based MA constituted of cubes and a metallic ground plane

spherical particles, other geometric shapes of particles have the same property [11]. For simplicity, we use cubes rather than spheres as the scattering objects shown in Fig. 1(b).

The cubes couple strongly to the incident magnetic field and the metallic ground plane couples to the incident electric field at the first Mie resonance mode [5]. It is possible to match the impedance of the MA to free space, thus minimizing the reflectance at the first Mie resonance mode. We design the MA structure of an array of dielectric cubes with different geometric parameters, which leads to a four-band MA with near unity absorbance based on the Mie resonance mode. Furthermore, from Eq. (5) we know that

$$f = \frac{\theta c}{2\pi r\sqrt{\varepsilon_2 \mu_2}} \tag{6}$$

and the lowest order resonant mode frequency, magnetic resonance, of a cubic dielectric resonator can be given by

$$f = \frac{\theta_1 c}{2\pi r\sqrt{\varepsilon_2 \mu_2}} = \frac{c}{2r\sqrt{\varepsilon_2}} \tag{7}$$

θ_1 is a constant which is approximately equal to π and μ is 1 for dielectric particles. Obviously, the first resonance frequency (f_1) of these dielectric particles is completely determined by ε_2 and r. As a result, the peak of the Mie resonance-based MA will change when we change the permittivity or size of the dielectric particles. By simply assembling four dielectric cubes with slightly different geometric parameters next to each other into a unit cell, a perfect four-band absorption can be effectively obtained.

3. DESIGN AND SIMULATION

The designed four-band MA is inspired by the narrow-band perfect absorber structure in Ref. [5] which is composed of an array of dielectric cubes and a continuous copper ground plane. The proposed MA is designed and optimized by CST Microwave Studio, which is based on the commercial finite difference time domain (FDTD) solver. The periodic boundary condition is set along the lateral directions of the MA and open boundary condition is set along the wave propagating direction. The unit cell of designed MA structure is displayed in Fig. 2(a). The metallic ground plane is copper with 0.1 mm in thickness and frequency independent conductivity $\sigma = 5.8 \times 10^7$ S/m. In order to achieve a four-band perfect absorption, four cubes with different geometrical parameters are positioned on the ground plane in a unit cell. The final optimized geometry of the unit cell is given by: $l = 17.6$ mm, $a_1 = 2.7$ mm, $a_2 = 2.6$ mm, $a_3 = 2.5$ mm, $a_4 = 2.4$ mm, and $t = 0.1$ mm. The absorption rate is calculated by $A(w) = 1 - R(w) = 1 - |S_{11}|^2$ in our design because the transmission of the MA is zero due to the metallic ground plane is thicker than the penetration depth of light in the microwave range.

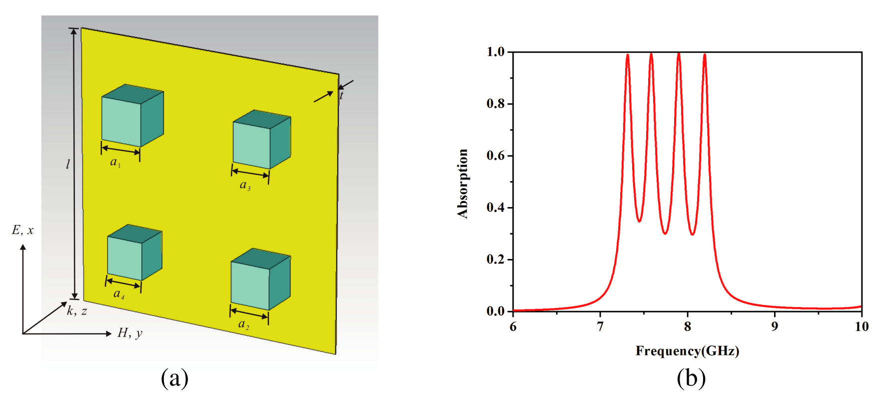


Figure 2: (a) The simulated unit cell. (b) The simulated absorption rate of the proposed MA.

4. RESULTS AND ANALYSES

The simulated absorption rate of the four-band MA is shown in Fig. 2(b). The results exhibit that there are four absorption peaks at 7.31 GHz, 7.58 GHz, 7.90 GHz and 8.19 GHz with the corresponding absorption rates of 99.05%, 99.37%, 99.65% and 99.16%, respectively. The proposed MA is not geometrical symmetry owing to the four dielectric cubes with small differences in geometric parameters. So the polarization-insensitive feature is characterized by setting the polarization angles at 45° and 90°, as shown in Fig. 3. The result proves that the Mie resonance-based MA is polarization-insensitive at the normal incidence. The full width at half-maximum (FWHM) of each absorption peak is 0.14 GHz, 0.15 GHz, 0.15 GHz and 0.13 GHz, respectively.

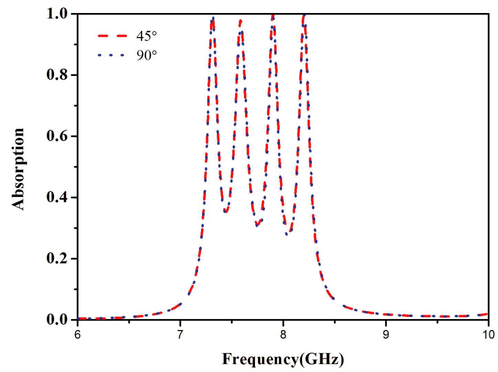


Figure 3: Simulated absorption rates of the four-band MA at an polarization angles of 45° and 90° under the normal incidence.

To get a better understand the intrinsic mechanism of the four bands MA, the surface current distributions and the power loss density distribution of the four resonances are monitored as shown in Fig. 4 and Fig. 5.

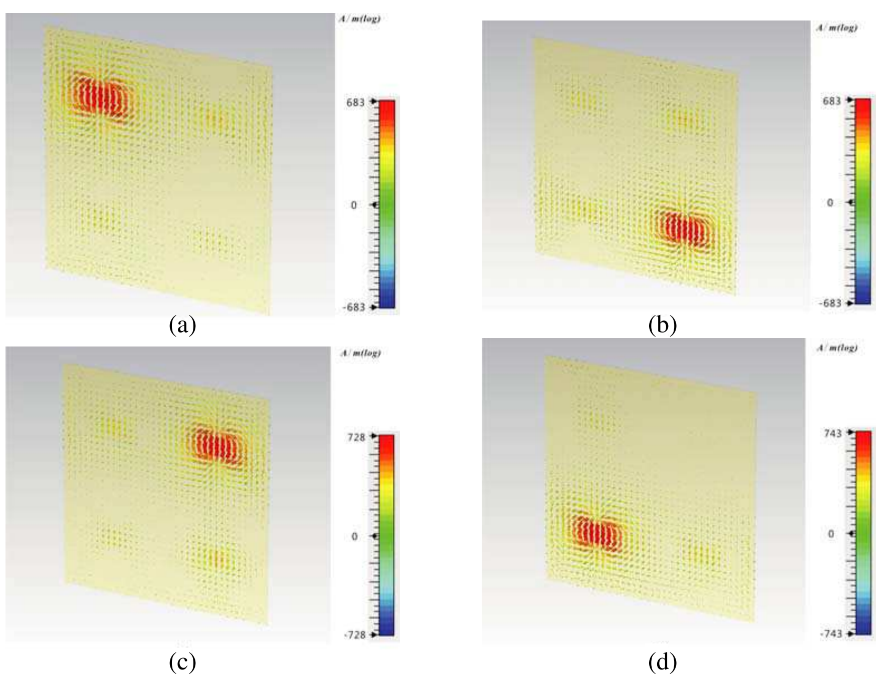


Figure 4: Surface current distributions of the MA at resonance frequencies corresponding to the four different geometrical parameters: (a) at 7.31 GHz, $a = 2.7$ mm; (b) at 7.58 GHz, $a = 2.6$ mm; (c) at 7.90 GHz, $a = 2.5$ mm; (d) at 8.19 GHz, $a = 2.4$ mm.

According to the previous study [12], the scattered field of dielectric particles can be decomposed into a multipole series. For the lowest resonant frequency, the cube particle is equivalent to a magnetic dipole resonance. It is observed from Figs. 4(a) $\sim$ (d), the current flows on the copper plane along the incident electric field, which generates the absorption of the MA. It is observed that near the lowest resonant frequency, the cube is equivalent to a magnetic dipole. In general, the magnetic dipole response is usually weak. This can be driven into resonance, however, by using materials with a large permittivity. In addition, the cubes couple strongly to the incident magnetic

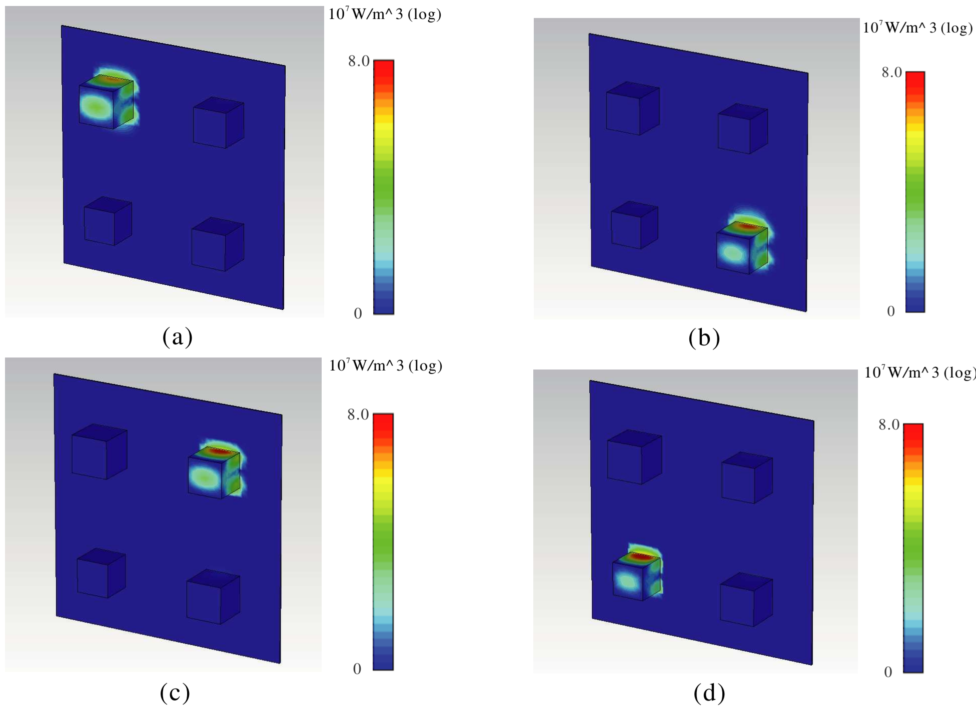


Figure 5: The distribution of the power loss density of the MA at resonance frequencies corresponding to the four different geometrical parameters: (a) at 7.31 GHz, $a = 2.7$ mm; (b) at 7.58 GHz, $a = 2.6$ mm; (c) at 7.90 GHz, $a = 2.5$ mm; (d) at 8.19 GHz, $a = 2.4$ mm.

field and the metallic ground plane couples to the incident electric field at the first Mie resonance mode. As shown in Fig. 5, the power loss densities distributions with the four different resonant frequencies are explored on the cubes and copper ground plane. It indicates that nearly all of the EM radiation is absorbed by the dielectric particles. In addition, we concluded that the MA can concentrate EM waves in some specified locations, where the energy is significantly reinforced and subsequently converted into thermal energy, leading to strong absorption [13].

The absorptivity of the MA at different angles of incidence for TE and TM waves are displayed in Fig. 6. For the case of TE wave (see Fig. 6(a)), the absorption peaks are all over 99% at normal incidence. With the increasing angle of incidence the four peaks monotonically decrease, but the lowest absorption still has a value of 85.87% at an incident angle of 60°. When the incident angle continues to increase, the peaks decrease quickly, as the x-component of the incident magnetic field drops rapidly to zero and no longer effectively induces a strong magnetic resonance.

For the TM case (see Fig. 6(b)), the absorption rates still remain more than 70% at the four resonance frequencies. This is because the direction of the incident magnetic field remains un-

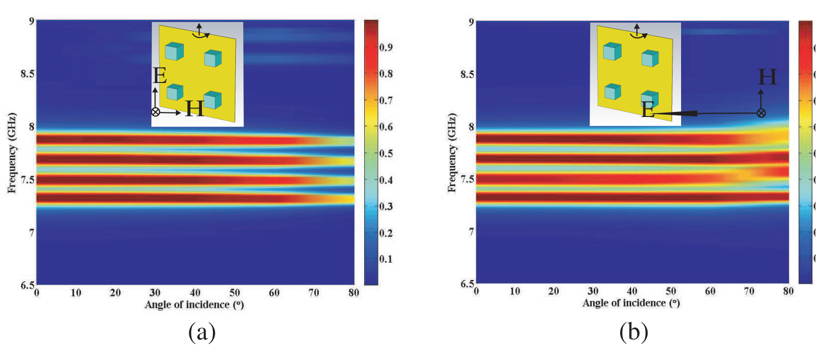


Figure 6: Simulated absorption rates of the four-band MA at different angles of incidence for (a) TE and (b) TM waves. The insets indicate the polarization and propagation directions of the incident wave.

changed at different angles of incidence and it can efficiently drive a strong magnetic resonance. It should be noted that the absorption peaks appear at the frequency of 7.31 GHz and 7.90 GHz are increased and the bandwidth are also slightly increased and frequency bands overlap in some degree. These results demonstrate that the Mie resonance-based MA could achieve high absorptivity at wide angles of incidence for both TE and TM waves.

According to Eq. (7), the absorption peak of the proposed MA will change if we change the permittivity or size of the dielectric particles. Fig. 7(a) showed that the simulated absorption peak frequency decreased from 8.60 GHz to 7.31 GHz as the side length (a) increased from 2.3 mm to 2.7 mm($\varepsilon = 115$), and Fig. 7(b) indicated that the simulated absorption peak frequency decreased from 8.26 GHz to 7.58 GHz as the permittivity (ε) increased from 105 to 125 ($a = 2.5$ mm). We found good agreement between the theoretical and simulated results.

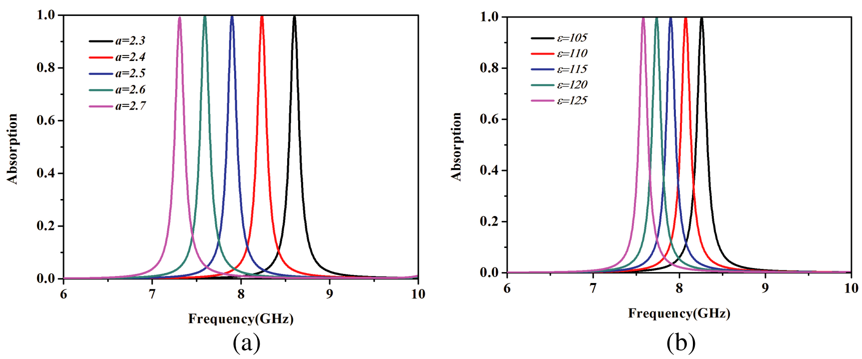


Figure 7: (a) The simulated absorption of the MA by different a (mm). (b) The simulated absorption of the MA by different ε.

5. CONCLUSION

In conclusion, we have presented a four-band metamaterial absorber (MA) with near-unity absorption based on Mie resonance theory in the microwave region. The MA is composed of periodic array of dielectric cubes with different geometric parameters and a metallic ground plane. The simulated results show that four absorption peaks at 7.31 GHz, 7.58 GHz, 7.90 GHz and 8.19 GHz with the corresponding absorption rates of 99.05%, 99.37%, 99.65% and 99.16%, respectively. The four-band MA is polarization-insensitive at the normal incidence. This absorber could operate well at different angles of incidence for both transverse electric (TE) and transverse magnetic (TM) waves. Finally, distributions of surface current density on the dielectric cubes and back metallic layers are illustrated. The loss contributions of dielectric cubes and ground plane are also discussed. Experiment of the Mie resonance-based MA will be conducted to validate the simulated results in the next work. The proposed multi-band MA has many potential applications such as the spectroscopic detection and phase imaging of hazardous materials and prohibited drugs which require distinct absorption features at multiple frequencies.

ACKNOWLEDGMENT

This work was supported by Graduates' Innovation Fund of Huazhong University of Science Technology (Grant No. HF-11-15-2013) and the special funds of State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology (Grant No. 2014ZZ001).

REFERENCES

1. Landy, N. I., S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, "Perfect metamaterial absorber," *Physical Review Letters*, Vol. 100, No. 20, 207402, 2008.
2. Shchegolkov, D. Y., A. K. Azad, J. F. O'Hara, et al., "Perfect subwavelength fishnetlike metamaterial-based film terahertz absorbers," *Physical Review B*, Vol. 82, No. 20, 205117, 2010.
3. Shen, X. P., T. J. Cui, J. M. Zhao, H. F. Ma, W. X. Jiang, and H. Li, "Polarization-independent wide-angle triple-band metamaterial absorber," *Optics Express*, Vol. 19, No. 10, 9401–9407, 2011.

4. Wang, G. D., M. H. Liu, X. W. Hu, L. H. Kong, L. L. Cheng, and Z. Q. Chen, "Multi-band microwave metamaterial absorber based on coplanar Jerusalem crosses," *Chinese Physics B*, Vol. 23, No. 1, 017802, 2014.
5. Liu, X. M., Q. Zhao, C. W. Lan, and J. Zhou, "Isotropic Mie resonance-based metamaterial perfect absorber," *Applied Physics Letters*, Vol. 103, No. 3, 031910, 2013.
6. Lewin, L., "The electrical constants of a material loaded with spherical particles," *Proceedings of the Institution of Electrical Engineers*, Vol. 94, No. 65, 65–68, 1947.
7. Mie, G., "Beiträge zur optik trüber medien, speziell kolloidaler metallösungen," *Annalen der Physik*, Vol. 330, No. 3, 377–445, 1908.
8. Maxwell, J. C., *A Treatise on Electricity and Magnetism Unabridged*, Dover, 1954.
9. Rayleigh, L. L., "On the influence of obstacles arranged in rectangular order upon the properties of a medium," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, Vol. 34, No. 211, 481–502, 1892.
10. Khizhniak, N. A., "Artificial anisotropic dielectrics: 2. Soviet physics-technical physics," Vol. 2, No. 9, 1865–1876, 1957.
11. Holloway, C. L., E. F. Kuester, J. Baker-Jarvis, et al., "A double negative (DNG) composite medium composed of magnetodielectric spherical particles embedded in a matrix," *IEEE Transactions on Antennas and Propagation*, Vol. 51, No. 10, 2596–2603, 2003.
12. Wheeler, M. S., J. S. Aitchison, and M. Mojahedi, "Three-dimensional array of dielectric spheres with an isotropic negative permeability at infrared frequencies," *Physical Review B*, Vol, 72, No. 19, 193103, 2005.
13. Tuong, P. V., V. D. Lam, J. W. Park, E. H. Choi, S. A. Nikitov, and Y. P. Lee, "Perfect-absorber metamaterial based on flower-shaped structure," *Photonics and Nanostructures-Fundamentals and Applications*, Vol. 11, No. 1, 89–94, 2013.