Metamaterials - Beyond Crystals, Noncrystals, and Quasicrystals: Microwave Applications

Tie Jun Cui

State Key Laboratory of Millimetre Waves
Department of Radio Engineering, School of Information Science and Engineering
Southeast University, Nanjing 210096, China
Fax: + 86 25 83790295; email: tjcui@seu.edu.cn

Abstract

In this presentation, I will focus on microwave metamaterials and introduce their counterparts to crystals, noncrystals, and quasicrystals, which are homogeneous metamaterials, random metamaterials, and inhomogeneous metamaterials. For all three cases, I will introduce the important experiments and applications in microwave frequencies conducted at Southeast University, China, including the invisibility cloaks, electromagnetic black hole, radar illusion devices, planar gradient-index lenses, flattened Luneburg lens, Maxwell fisheye lens, high-gain Vivaldi antennas, and decoupling device for MIMO system.

1. Introduction

For a long time, the natural materials have been classified into two types: crystals and noncrystals, until Daniel Shechtman discovered quasicrystals in 1982, who won the Nobel chemistry prize in 2011 for this work. In fact, crystals and noncrystals are composed of periodically-distributed and randomly-distributed atoms, while quasicrystals have a third material state between crystals and noncrystals: which are non-periodic structures of atoms with certain rules instead of random. Hence the two factors to affect natural material properties are the atoms themselves and the spatial arrangements of atoms. Quasicrystals have brought a lot of new features of materials and found applications in steel armour, non-stick frying pans, and devices in cars for recycling waste heat into electricity. However, it is very hard to control atoms themselves and their spatial arrangements to get more material properties. Metamaterials provide us a freedom to tailor the material properties, both for electric and magnetic. Metamaterials are composed of periodic or non-periodic structures of artificial “atoms” or “particles”, which have a size of subwavelength scale. The flexible design of single artificial particles, the feasible arrangements of such particles, and the high anisotropy make it possible to control the material properties as desired: metamaterials can be used to realize the effective permittivity and/or permeability which cannot be achieved in nature. Hence they have either unique features with unusual physical phenomena (such as negative refraction, invisibility cloak, optical illusion, etc.) or superior performance than the natural materials. In this presentation, I will focus on microwave metamaterials and introduce their counterparts to crystals, noncrystals, and quasicrystals, which are homogeneous metamaterials, random metamaterials, and inhomogeneous metamaterials.

2. Homogeneous Metamaterials – Beyond Crystals

Metamaterials were first known as the left-handed materials composed of periodic structures with both electric and magnetic resonances. In the past decades, homogeneous metamaterials constructed by the periodic structures have been well investigated. In the microwave region, an effective medium theory was proposed based on the discrete Maxwell’s equations [1], which sets up an analytical link between the effective medium parameters and the geometry of periodic structure. Based on the effective medium theory, we experimentally demonstrated a novel feature of zero-index material – the tunnelling effect – that is, the electromagnetic waves can tunnel through a very narrow channel filled with zero-index material [2]. We also built up an anisotropic metamaterial (or indefinite metamaterial) with one component of permittivity tensor being negative to realize a planar partial focusing lens [3]. For the applications of homogeneous metamaterials, we give three examples: Small devices for wireless communications [4-6], Metamaterial polarizers [7,8], and high-directivity antennas based on Anisotropic zero-index materials [9-11].

3. Random Metamaterials – Beyond Noncrystals

Metamaterials have been mostly investigated when the artificial particles are periodically packed (homogeneous) or distributed non-periodically in certain rules (inhomogeneous). However, the random arrangements of particles, named as random metamaterials, can realize some special features. We have shown that a thin planar sheet of metamaterial with randomly distributed index gradients will generate diffuse reflections, instead of mirror reflections, when it is placed in front of a conducting plate [12]. Here, the randomly gradient index metamaterial is designed and realized using crossed-I-shaped array whose unit cells vary randomly in space. The new features of random metamaterial have been verified experimentally [12].

4. Inhomogeneous Metamaterials – Beyond Quasicrystals

Due to the flexibility in designing the unit particles and their spatial arrangements, inhomogeneous metamaterials have more capabilities to control electromagnetic waves, producing many exciting new physical phenomena and real applications. The new experiments include the two-dimensional (2D) ground-plane invisibility cloak [13], compact 2D ground-plane cloak [14], three-dimensional (3D) ground-plane cloak [15], the electromagnetic black hole [16], illusion optics devices [17-21], the 2D planar gradient-index (GRIN) metamaterial lens [22], 3D GRIN lens [23], 2D Luneburg lens [24] and Maxwell fisheye lens [25], and transformation-optics lenses (2D focusing lens [26] and 3D flattened Luneburg lens [27]).

5. Conclusions

The flexible design of single artificial particles, the feasible arrangements of such particles, and the high anisotropy make microwave metamaterials possible to control the material properties as desired. Hence such metamaterials can be used to realize the effective permittivity and/or permeability which cannot be achieved in nature, providing novel functional microwave devices and antennas.

References

[1] R. Liu, T. J. Cui, D. Huang, B. Zhao, and D. R. Smith, “Description and explanation of electromagnetic behaviors in artificial metamaterials based on effective medium theory,” *Physical Review E*, vol. 76, 026606, 2007.

[2] R. Liu, Q. Cheng, T. Hand, J. J. Mock, T. J. Cui, S. A. Cummer, and D. R. Smith, “Experimental demonstration of electromagnetic tunneling through an epsilon near zero metamaterial at microwave frequencies,” *Physics Review Letters*, vol. 100, 023903, 2008.

[3] Q. Cheng, R. Liu, J. J. Mock, T. J. Cui, and D. R. Smith, “Partial focusing by indefinite complementary metamaterials,” *Physical Review B (Rapid Communications)*, vol. 78, 121102(R), 2008.

[4] X. M. Yang, Q. H. Sun, Y. Jing, Q. Cheng, X. Y. Zhou, H. W. Kong, and T. J. Cui, “Increasing the bandwidth of microstrip patch antenna by loading compact artificial magneto-dielectrics,” *IEEE Transactions on Antennas and Propagation*, vol. 59, pp. 373-378, 2011.

[5] M. Li, X. Q. Lin, J. Y. Chin, R. Liu, and T. J. Cui, “A novel miniaturized printed planar antenna using split-ring resonator,” *IEEE Antennas and Wireless Propagation Letters*, vol. 7, pp. 629-631, 2008.

[6] X. M. Yang, X. G. Liu, X. Y. Zhou, and T. J. Cui, “Reduction of mutual coupling between closely-packed patch antennas using waveguided metamaterials,” *IEEE Antennas and Wireless Propagation Letters*, accepted for publication, 2012.

[7] J. Y. Chin, M. Lu, and T. J. Cui, “Metamaterial polarizers by electric-field-coupled resonators,” *Applied Physics Letters*, vol. 93, 251903, 2008.

[8] J. Y. Chin, J. G. Gollub, J. J. Mock, R. Liu, C. Harrison, D. R. Smith, and T. J. Cui, “An efficient broadband metamaterial wave retarder,” *Optics Express*, vol. 17, pp. 7640-7647, 2009.

[9] Q. Cheng, W. X. Jiang, and T. J. Cui, “Radiation of planar electromagnetic waves by a line source in anisotropic metamaterials,” *Journal of Physics D: Applied Physics*, vol. 43, 335406, 2010.

[10] B. Zhou and T. J. Cui, "Directivity enhancement to Vivaldi antennas using compactly anisotropic zero-index metamaterials," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 326-329, 2011.

[11] B. Zhou, H. Li, X. Y. Zou, and T. J. Cui, “Broadband and high-gain planar Vivaldi antennas based on inhomogeneous anisotropic zero-index metamaterials,” *Progress in Electromagnetic Research*, vol. 120, pp. 235-247, 2011.

[12] X. M. Yang, X. Y. Zhou, Q. Cheng, H. F. Ma, and T. J. Cui, “Diffuse reflections by randomly gradient index metamaterials,” *Optics Letters*, vol. 35, pp. 808-810, 2010.

[13] R. Liu, C. Ji, J. J. Mock, J. Y. Chin, T. J. Cui, and D. R. Smith, “Experimental verification of a broadband ground-plane cloak,” *Science*, vol. 323, no. 5912, pp. 366-369, 2009.

[14] H. F. Ma, W. X. Jiang, X. M. Yang, X. Y. Zhou, and T. J. Cui, “Compact-sized and broadband carpet cloak and free-space cloak,” *Optical Express*, vol. 17, 19947-19959, 2009.

[15] H. F. Ma and T. J. Cui, “Three-dimensional broadband ground-plane cloak made of dielectrics,” *Nature Communications*, 1: 21, DOI: 10.1038/ncomms1023, 2010.

[16] Q. Cheng and T. J. Cui, “An electromagnetic black hole made of metamaterials,” *New Journal of Physics*, vol. 12, 063006, 2010.

[17] W. X. Jiang, H. F. Ma, Q. Cheng, and T. J. Cui, “Illusion media: Generating virtual objects using realizable metamaterials,” *Applied Physics Letters*, vol. 96, 121910, 2010.

[18] W. X. Jiang and T. J. Cui, “Moving targets virtually via composite optical transformation,” *Optics Express*, vol. 18, 5161, 2010.

[19] W. X. Jiang, H. F. Ma, Q. Cheng, and T. J. Cui, “Virtual conversion from metal to dielectric objects using metamaterials,” *Optics Express*, vol. 18, 11276, 2010.

[20] W. X. Jiang, T. J. Cui, H. F. Ma, X. M. Yang, and Q. Cheng, “Shrinking an arbitrarily-shaped object as desired using metamaterials,” *Applied Physics Letters*, vol. 98, 204101, 2011.

[21] W. X. Jiang and T. J. Cui, “Radar illusion via metamaterials,” *Physical Review E*, vol. 83, 026601, 2011.

[22] H. F. Ma, X. Chen, H. S. Xu, X. M. Yang, W. X. Jiang, and T. J. Cui, “Experiments on high-performance beam-scanning antennas made of gradient-index metamaterials,” *Applied Physics Letters*, vol. 95, 094107, 2009.

[23] X. Chen, H. F. Ma, X. Y. Zou, W. X. Jiang, and T. J. Cui, “Three-dimensional broadband and high-directivity lens antenna made of metamaterials,” *Journal of Applied Physics*, vol. 110, 044904, 2011.

[24] H. F. Ma, X. Chen, X. M. Yang, H. S. Xu, Q. Cheng, and T. J. Cui, “A broadband metamaterial cylindrical lens antenna,” *Chinese Science Bulletin*, vol. 55, no. 19, pp. 2066-2070, 2010.

[25] Z. L. Mei, J. Bai, T. M. Niu, and T. J. Cui, “A half Maxwell fish-eye lens antenna based on gradient-index metamaterials,” *IEEE Transactions on Antennas and Propagation*, vol. 60, pp. 398-401, 2012.

[26] Z. L. Mei, J. Bai, and T. J. Cui, “Experimental verification of a broadband planar focusing antenna based on transformation optics,” *New Journal of Physics*, vol. 13, 063028, 2011.

[27] H. F. Ma and T. J. Cui, “Three-dimensional broadband and broad-angle transformation-optics lens,” *Nature Communications*, 1: 24, DOI: 10.1038/ncomms1126, 2010.