PHYSICS

Special Topic: Metamaterials

Microwave metamaterials

Tie Jun Cui

Metamaterials are artificial structures with tailored meta-atoms at subwavelength scales to control electromagnetic waves at will. Usually, metamaterials are described by effective medium parameters (e.g. index of refraction, permittivity and permeability) due to the subwavelength nature of meta-atoms. When the meta-atom is comparable to the wavelength, the effective medium description is sometimes still valid but the effective medium parameters become dependent on the wave vector, i.e. non-local. The flexible designs of meta-atoms and their overall arrangements make it possible to achieve medium parameters with extreme values such as zero and negative, which do not exist in nature, and high anisotropies and inhomogeneities, which are difficult to realize in nature. Working in the range from MHz to 100 GHz, microwave metamaterials are important metamaterials. Most unusual physical phenomena were first demonstrated at microwave frequencies, including negative refraction [1], invisibility cloaking and optical illusion. The proposal of non-resonant meta-atoms [2] enables microwave metamaterials to be broadband and low-loss, resulting in many applications like meta-lens antennae (see Fig. 1(a)) [3], reduction of radar cross section, and antenna radomes, etc. [4]. It is expected that more fantastic physical phenomena will be discovered by using microwave metamaterials due to their easier realization of complicated medium parameters. Only having been discovered in the last 20 years, metamaterials must find practical applications in engineering

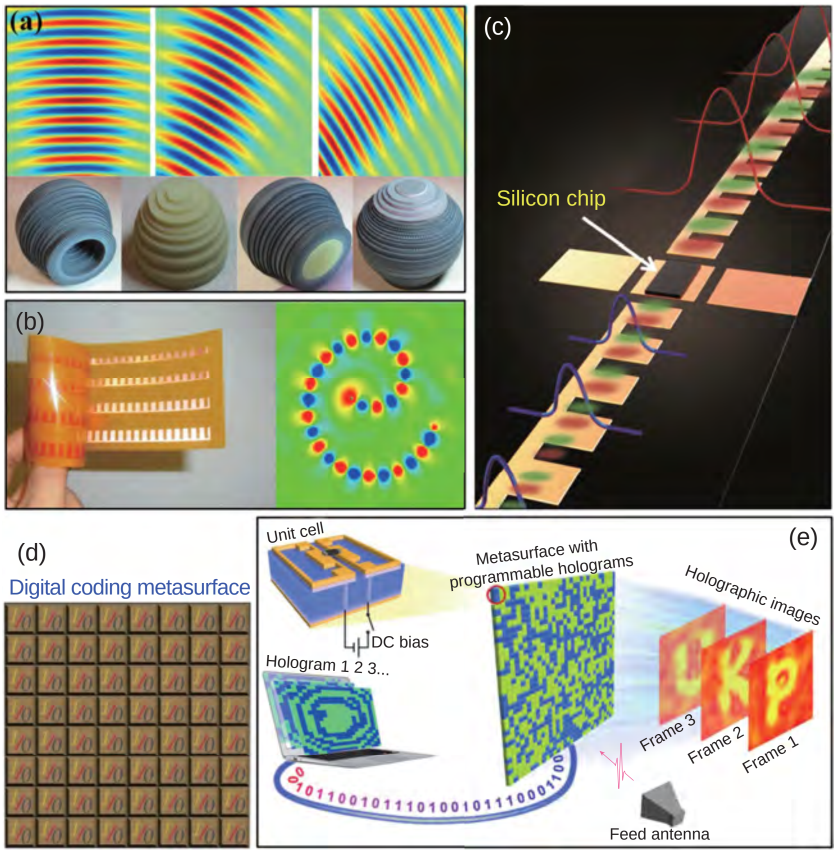

Figure 1. (a) Fabricated sample of a three-dimensional flattened Luneburg lens and measured near electric-field distributions, showing good beam-scanning properties in the Ku band (12–18 GHz). Adapted from [3] with the permission of Nature Publishing Group. (b) Fabricated samples of narrow, ultrathin and flexible spoof SPP transmission lines, which can support conformal SPPs on curved surfaces. Adapted from [7] with the permission of PNAS. (c) SPP amplifier in the microwave frequency based on a subwavelength-scale silicon chip. Reprinted with permission from [10]. Copyright (2017) American Chemical Society. (d) Digital coding metamaterials composed of '0' and '1' meta-atoms with opposite phases, which can control electromagnetic waves by changing the coding sequences. Adapted from [14] with the permission of Nature Publishing Group. (e) Reprogrammable microwave holographic imaging, in which a computer digitally controls the programmable metasurface by dynamically changing the phase distribution. Under the illumination of a feeding antenna, the metasurface hologram can successively project different holographic images. Adapted from [18] with the permission of Nature Publishing Group.

© The Author(s) 2017. Published by Oxford University Press on behalf of China Science Publishing & Media Ltd. All rights reserved. For permissions, please e-mail: journals.permissions@oup.com

Downloaded from https://academic.oup.com/nsr/article-abstract/5/2/134/4590046 by guest on 26 March 2020

that cannot be replaced by traditional approaches, and microwave metamaterials will be the first candidate.

Besides controlling spatial electromagnetic fields, microwave metamaterials can also be used to manipulate spoof surface plasmon polaritons (SPPs) and localized surface plasmons (LSPs) at lower frequencies [5], which mimic the highly confined SPPs and LSPs in the optical regime. Constructed by metal surfaces decorated with periodic arrays of subwavelength grooves, holes, dimples and wires, the plasmonic metamaterials can tailor the dispersion properties, generate field enhancements and multipolar resonances, and even reproduce topological isolators for directional transmissions of spoof SPPs [6]. Despite the attractive physical phenomena, such plasmonic metamaterials are impractical due to their non-planar layouts with vertical dimensions of decorations. For engineering applications, transmission line-like plasmonic metamaterials are required.

In fact, in traditional microwave technologies, there are two basic elements: a transmission line (such as a microstrip, a narrow metal strip with ground) and an active chip, which are the foundations of all passive and active devices, respectively. However, the spatial mode distributions of traditional transmission lines may result in signal integrity problems when they are tightly packed. To solve the problem via basic physics, a transmission line-like plasmonic metamaterial, i.e. an ultrathin, narrow, and flexible corrugated metal strip emerged [7], as shown in Fig. 1(b), which can guide spoof SPPs for long distances on flat and curved surfaces with small bending and radiation loss. Nearly perfect conversions from spatial to SPP modes on the ultrathin corrugated metal strip are then presented by designing gradient corrugations for momentum matching and impedance matching [8], which help develop a series of SPP passive devices at microwave frequencies, including power dividers, bends, couplers, filters, resonators and SPP antennas. On the other hand, a closed ultrathin corrugated metal disk at the subwavelength scale can support plentiful spoof LSP resonances [9], in which the dipole, quadrupole, hexapole, octopole and decapole modes are experimentally observed, enriching high Q-factor SPP passive devices. The effective medium theory well explains the spoof LSP resonance and plasmon hybridization [10].

A breakthrough in microwave plasmonic metamaterials is the incorporation of the spoof SPP transmission line to semiconductor chips, which directly results in two core SPP active devices with high performance: an SPP amplifier (see Fig. 1(c)) and an SPP frequency multiplier [11,12]. The availability of passive and active SPP devices makes it possible for fully SPP-based microwave systems (e.g. wireless communication systems) to be produced in the near future. Such systems may have significant advantages over traditional microwave systems, because it has been shown that the mutual coupling between two closely adjacent SPP transmission lines is much smaller than that of traditional transmission lines with the same geometry, solving the signal integrity problem [13]. Recent progress on controllable transmissions and rejections of SPP signals in multilayered substrates will accelerate the birth of SPP silicon-integrated circuits based on SPP theory and technology.

Microwave metamaterials described by effective medium parameters exhibit strong capabilities in controlling electromagnetic fields, in both spatial and SPP modes. However, once a metamaterial is fabricated its functionality is fixed. To dynamically manipulate the electromagnetic waves in real time, digital coding and programmable metamaterials appear in the microwave frequency [14], in which the meta-atoms are represented by digital codes '0' and '1' with the opposite phases, as shown in Fig. 1(d). Then, the functionality of a metamaterial can be controlled in large dynamics by changing the coding sequences of '0' and '1'. The coding metamaterial has been extended from microwave to terahertz frequencies [15], from isotropic to anisotropic [16] and even with full tensor, from reflection type to transmission type, from single band to dual band, and from spatial coding to frequency coding [17], demonstrating the powerful ability and large potential of coding metamaterials in manipulating the wave fronts, polarization states, numbers and directions of scattering beams, diffusions, and conversions from spatial waves to surface waves.

The '0' and '1' coding states can be realized by the same meta-atom containing a biased diode in a controlled manner with a digital pulse of biased voltage [14]. If the pulse voltage is '0' (0 V), the coding state is '0'; if the pulse voltage is '1' (2 V), the coding state is '1'. Thus, the coding state of each meta-atom on the metamaterial is fully controlled by the digital state of the biased network, producing a digital metamaterial. With the aid of a field programmable gate array (FPGA) to store all possible coding sequences, a programmable metamaterial has appeared [14]. This is a single metamaterial that has many different functions controlled by FPGA. By programming different coding sequences, the single metamaterial can generate a high-gain beam, multiple beams with designed numbers and directions with anomalous reflections, diffusion and random scattering, and beam scanning in large angle ranges, realizing dynamic manipulations to the electromagnetic waves in real time. Based on this principle, reprogrammable microwave holograms have been presented recently with high efficiency, high frame rate, and good image quality, as shown in Fig. 1(e) [18].

The digital coding representation of metamaterials builds up a bridge between the metamaterial physical and digital worlds, which enables information theorems and signal processing methods to be applicable to digital coding metamaterials. The first approach proposes to use Shannon entropy on metamaterials to measure the information contained in the coding pattern and far-field scattering pattern quantitatively [19]. It has been shown that the Shannon entropy of the coding pattern is proportional to that of the far-field pattern, which is very helpful in realizing new imaging systems and wireless communication systems. The other application is the digital convolution theorem on coding metamaterials, which can achieve arbitrary beam shifts in a direct and simple way [20]. Based on the convolution

Downloaded from https://academic.oup.com/nsr/article-abstract/5/2/134/4590046 by guest on 26 March 2020

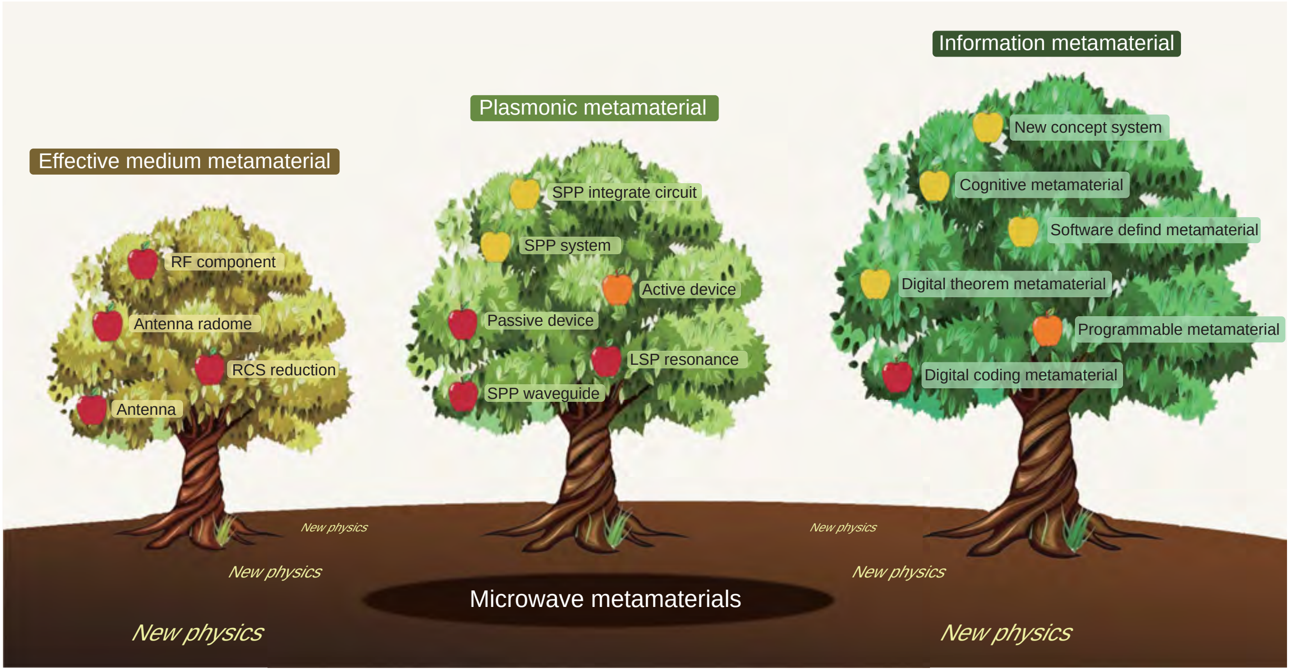

Figure 2. The trend of future microwave metamaterials.

theorem, one can generate arbitrarily anomalous reflections to pre-designed angles, which are hard to design using conventional methods. It is expected that more digital signal processing methods will be used on digital coding metamaterials to find enable the discovery of new applications.

The trend of future microwave metamaterials is summarized in Fig. 2. Discovering new physics is undoubtedly necessary for all kinds of metamaterials, but the major and emerging tasks for microwave metamaterials are engineering applications. For metamaterials based on the effective medium, some key devices/components that are unavailable using traditional techniques should be developed. For plasmonic metamaterials, a new SPP-based framework of microwave technology should be set up, from basic transmission lines to systems and integrated circuits, which not only compensate traditional microwave technology but will also produce new and irreplaceable applications. For digital coding metamaterials, huge potentials are expected. Naturally, digital coding metamaterials will evolve to be software-defined and even cognitive from being reprogrammable, leading to information metamaterials [21]. Information metamaterials will represent a link between physical science and information science, which will result in many new-concept information systems. In the future, microwave metamaterials will not only represent a material or device, but also an intelligent system or real-time information processor.

FUNDING

This work was supported by the National Natural Science Foundation of China (61571117 and 61631007) and the 111 Project (111-2-05).

Tie Jun Cui
State Key Laboratory of Millimeter Waves, Southeast University, China
E-mail: tjcui@seu.edu.cn

REFERENCES

1. Shelby RA, Smith DR and Schultz S. *Science* 2001; **292**: 77–9
2. Liu R, Ji C and Mock JJ *et al.* *Science* 2009; **323**: 366–9.
3. Ma HF and Cui TJ. *Nat Commun* 2010; **1**: 124.
4. Cui TJ. *Metamaterials - Beyond Crystals, Noncrystals, and Quasicrystals*. Boca Raton: CRC Press. 2016.
5. Pendry JB, Martin-Moreno L and Garcia-Vidal FJ. *Science* 2004; **305**: 847–8.
6. Gao F. *Nat Commun* 2016; **7**: 11619.
7. Shen X, Cui TJ and Martin-Cano D *et al.* *Proc Natl Acad Sci USA* 2013; **110**: 40–5.
8. Ma HF, Shen X and Cheng Q *et al.* *Laser Photonics Rev* 2014; **8**: 146–51.
9. Shen X and Cui TJ. *Laser Photonics Rev* 2014; **8**: 137–45.
10. Zhang J, Liao Z and Luo Y *et al.* *Laser Photonics Rev* 2017; **11**: 1600191.
11. Zhang HC, Liu S and Shen X *et al.* *Laser Photonics Rev* 2015; **9**: 83–90.
12. Zhang HC, Fan Y and Guo J *et al.* *ACS Photonics* 2016; **3**: 139–46.
13. Zhang HC, Cui TJ and Zhang Q *et al.* *ACS Photonics* 2015; **2**: 1333–40.
14. Cui TJ, Qi MQ and Wan X *et al.* *Light Sci Appl* 2014; **3**: e218.
15. Gao L, Cheng Q and Yang J *et al.* *Light Sci Appl* 2015; **4**: e324.
16. Liu S, Cui TJ and Xu Q *et al.* *Light Sci Appl* 2016; **5**: e16076.
17. Wu H, Liu S and Wan X *et al.* *Adv Sci* 2017; **4**: 1700098.
18. Li L, Cui TJ and Ji W *et al.* *Nat Commun* 2017; **8**: 197.
19. Cui TJ, Liu S and Li L. *Light Sci Appl* 2016; **5**: e16172.
20. Liu S, Cui TJ and Zhang L *et al.* *Adv Sci* 2016; **3**: 1600156.
21. Cui TJ, Liu S and Zhang L. *J Mater Chem C* 2017; **5**: 3644–68.

National Science Review
5: 134–136, 2018
doi: 10.1093/nsr/nwx133
Advance access publication 3 November 2017

Downloaded from https://academic.oup.com/nsr/article-abstract/5/2/134/4590046 by guest on 26 March 2020