URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Multi-functional metasurfaces and their applications

Ke Chen(1), Yijun Feng(1), Junming Zhao(1), and Tian Jiang(1)
(1) School of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China

Abstract

This paper presents a summary of recent development of multi-functional metasurfaces at microwave frequencies, including direction-controlled, helicity-selective, and tunable metasurfaces. The design and experimental results of several illustrative multi-functional metasurfaces and their applications in focusing, beam shaping, and antenna designing are shown. These metasurfaces combine two or more wave functionalities into a single device, thus providing more flexibility in electromagnetic wave control, which is quite promising for many real-world applications.

1 Introduction

Engineering non-planar surface to manipulate the electromagnetic (EM) wavefront for conventional devices inevitably brings inherent inconveniences due to the weight, volume, etc. Such drawbacks could be possibly overcome by the metasurfaces, a recently developed concept composed of subwavelength-sized elements to introduce desired phase discontinuities on the interface [1-2]. To date, metasurfaces have been used for many intriguing EM devices and applications such as meta-lenses, beam shapers, and antennas [3-4].

The rapid development of wireless and optical communication technologies has continuously required high communication speed/quality, large data storage capacity, etc. Integrating several concurrent tasks or wave functionalities into a single device recently emerges as an efficient route for solving this problem. An ultimate goal pursued by scientists and engineers is to make devices as miniaturized as possible, yet integrated with wave functionalities as many as possible. Hence, there is an increased interest in metasurface multiplexing technique that can significantly enhance the information capacity of devices in terms of manipulating the electromagnetic waves over such as spin, polarization, and wavelength [5].

Here, a series of metasurface multiplexing techniques are presented, empowering a single metasurface device to perform different wave functionalities that are dependent on the incident direction, circular polarization, and external bias voltage. Beam shaping, focusing, and dynamic wave control are demonstrated both in simulations and experiments.

2 Direction-controlled metasurface

To realize direction-controlled passive metasurface for tailoring the wavefront, asymmetric modulation of transmission phase should be excited. The meta-atom is designed as cascaded structures with a rotational twist in the geometry, as shown in Fig. 1a. The overall performance of the meta-atom can be theoretically calculated from the impedance sheets and their geometric relationship, see detailed derivation in [6]. Here, the meta-atom is realized by identical split-ring structures rotated sequentially with an in-plane rotational angle of 45° and a dielectric spacer between consecutive planes. Such structure naturally has a chiral response that leads to asymmetric transmission of EM wave. By parameter optimization, unidirectional meta-atom (+z) operating for x-linearly polarized (x-LP) forward transmission can be realized, namely forward x-LP wave can pass through the meta-atom with desired transmission phase while the backward x-LP wave is blocked.

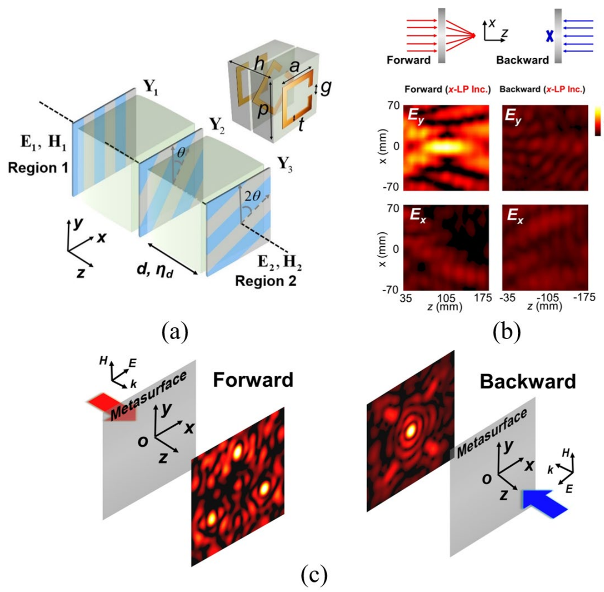


Figure 1. (a) Schematic of the meta-atom and its theoretical model. (b) One-way meta-lens for x-LP incidence and the distribution of output electric fields. (c) The x-LP components of the output for asymmetric meta-lens. The y-LP components are very weak and not shown here.

Then, unidirectional metasurfaces lens by employing the proposed method is demonstrated at 8.6 GHz, as shown in Fig. 1b. The measured results show that for forward x-LP incidence (left panels), the electric fields are converted to *y*-LP output and form a focused spot. For backward *x*-LP incidence (right panels), the output field is very weak, revealing that the backward wave cannot pass through the metasurface. Furthermore, metasurface lens multiplexed for different propagation directions is demonstrated as an example of its ability in asymmetrically structuring the wavefront. To realize this, the unidirectional meta-atom working for backward *x*-LP wave is designed, and these two kinds of elements working respectively for backward and forward unidirectional transmission are distributed in an interleaved manner to realize the desired spatial phase profiles focusing the incidence. As shown in Fig. 1c, single-spot focusing for forward wave and three-foci focusing for backward wave are simultaneously obtained. More details of the unidirectional and asymmetric meta-lens for *x*-LP incidence can be found in [6]. The achievable functionalities are not limited to those presented, and in general, versatile functionalities could be combined by the proposed directional metasurface.

3 Helicity-selective metasurface

To realize independent control of right-handed and left-handed circularly polarized (RHCP and LHCP) wave, the metasurface should simultaneously contain resonant phase and geometric phase. The resonant phase is originated from the resonant behavior of the meta-atom that are closely dependent on the structure sizes and shapes, while the geometric phase is determined by the structure orientation [7]. Therefore, the meta-atom is elaborately optimized with change of both physical sizes and structure orientations, as shown in Fig. 2a, where the meta-atom can provide independent phases for LHCP and RHCP incidence with an interval of 45°. To demonstrate its capability in controlling the wavefront, such metasurface is used for generating orbital angular momentum (OAM) beams. When the incidence is a LHCP wave, vortex beams with OAM mode of $l = 2$ and $l = 0$ are generated. However, when the incidence is switched to RHCP wave, the output vortex beams are shaped with OAM mode of $l = 1$ and $l = -1$. Moreover, superimposing of multi OAM beams and complex wavefront multiplexing can be independently realized in each helicity channel, enabling helicity-selective metasurface devices. More details of simulated and measured results can be found in [7].

The helicity-selective metasurface can be applied to engineering fields, for example, achieving multiplexing reflector antenna supporting independent far-field radiations for RHCP and LHCP feed source. As shown in Fig. 2b and 2c, highly directive beam is observed in *xoz* plane for LHCP source while in *yoz* plane for RHCP source. The middle panels show the phase distributions imparted on the antenna aperture, and then the two phase maps are realized by quasi-I-shaped metasurface. Finally, the reflector antenna realizes a peak gain of 29.5 dBic, with 3 dB gain variation bandwidth of 13.2-20.2 GHz (41.9%) and 3 dB axial ratio bandwidth of 11.8-21 GHz for LHCP channel. As for RHCP, the peak gain if 29.6 dBic, 3 dB gain band is 13.4-20.2 GHz, and 3 dB axial ratio band is 11.5-22 GHz. More details of the design method and antenna performances can be found in [8]. Such kind of metasurface is also applied for reducing the side-lobes of reflector antenna [9].

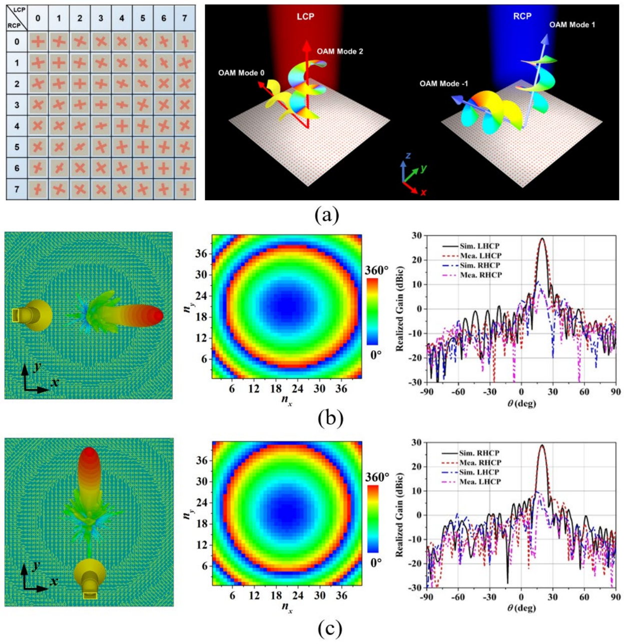
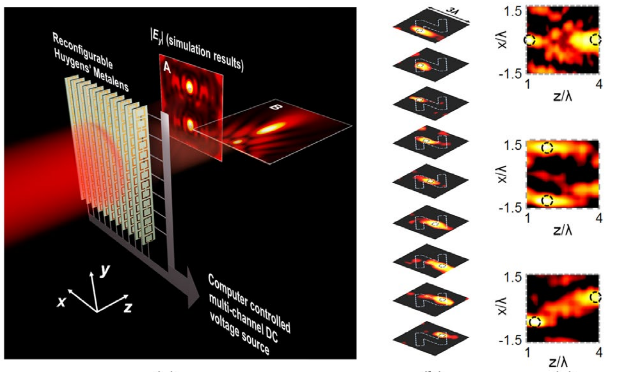


Figure 2. (a) The elements for realizing full phase coverage with an interval of 45° independent for LHCP and RHCP channel, and the schematic of bi-functional metasurface dependent on the helicity. Results of dual-polarized reflector antenna for (b) LHCP feed source and (c) RHCP feed source. Left panels are the schematics, middle panels are the phase distributions on the antenna aperture, and right panels are the results at 15 GHz.

4 Tunable and reconfigurable metasurface

Passive metasurfaces only empower one or a few functions once fabricated, which may limit their practical impact. To overcome this problem, metasurface can be designed with active components controlled by the external stimulations to realize tunable EM responses. Here, by co-designing the varactors and electric/magnetic polarizabilities of the meta-atoms, tunable Huygens' metasurface metalens is demonstrated at microwave frequencies. As shown in fig. 3a, since the transmission phase of the meta-atoms are individually controlled by the direct current (DC) voltage, the meta-lens can dynamically tailor the output wavefront into desired focal patterns just by changing the input bias voltages. As an experimental verification, the focusing spot is dynamically and continuously moved long a predesigned trace of the letter "N", by successively switching the bias-voltage profile from one distribution to another, as seen by the electric field amplitude distribution in Fig. 3b. The control speed can reach 10 μs or 10^5 switches per second. Furthermore, the metalens can reshape the incidence into two focal spots at will that are in front of each other, symmetrically displaced, or any other positions, as shown in Fig. 3c. More details of the design principle and focusing performances can be found in [10].

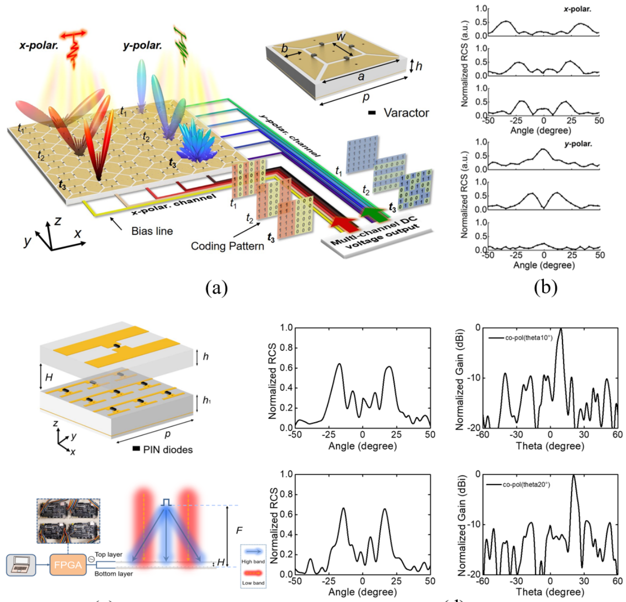


(a) (b) (c)

Figure 3. (a) The schematic of the active Huygens' metalens. (b) Measured results of the electric field amplitude distribution, where the focal spot is moved along the trace of "N". (c) Two foci with distinct positions.

To further improve the capability of tunable metasurfaces, polarization-multiplexing technique are introduced to provide more degrees of freedom in dynamic wavefront control. As shown in Fig. 4a, the anisotropic metasurface works independently for differently linear-polarized (LP) incidence with dynamic wavefront manipulations. In particular, the meta-atom is parametrically tailored for anisotropic objective: two voltage-controlled varactors are placed on both *x*-axis and *y*-axis that are independently connected to two DC bias voltage source. Therefore, distinct spatial phase patterns can be encoded onto the metasurface simultaneously to trigger distinct wave functionalities for *x*-LP and *y*-LP excitations. As the design example, fig. 4b shows that symmetric beams are gradually changed with the input voltages, achieving a dynamic beam-scanning functions for *x*-LP incidence. Meanwhile, single beam, symmetric beams, and random beams are successively obtained for *y*-LP incidence. See more details in [11]

To realize wavelength-multiplexing tunable metasurface, double-layered I-shaped meta-atom loaded with PIN diodes is employed for dual-band dynamic phase tuning, as shown in fig. 4c. Independent1-bit tunable phase can be obtained at 6 GHz and 9.8 GHz, and for all cases, the reflection amplitude is larger than 0.95, indicating a high-efficiency tunable metasurface. As the proof of concept, distinct wave functionalities controlled by field-programmable gate arrays (FPGA) hardware system are experimentally measured. At low frequencies, twin-beam-scanning is demonstrated, and at the same time, single-beam-scanning reflector antenna is achieved by successively changing the spatial bias voltage sequences. More results can be found in [12].



(a) (b)

(c) (d)

Figure 4. (a) Schematic of active anisotropic metasurface for dual-polarized independent wave control. Inset shows the meta-atom. (b) Measured results of scattering patterns for *x*-LP wave (upper) and *y*-LP wave (bottom). (c) Schematic of the dual-band tunable metasurface (bottom) and the meta-atom (upper). (d) Measured results of scattering patterns for low frequency band (left) and high frequency band (right).

5 Conclusion

In conclusion, several methods to realize multi-functional metasurface including functionalities determined by the propagation direction, polarization, and external bias voltages have been summarized. In general, the proposed multi-functional metasurface can provide more degrees of freedom in controlling the EM wave, which may boost integration with other device component, providing opportunities for developing a variety of real-world applications.

6 Acknowledgements

This work is supported by National Key Research and Development Program of China (2017YFA0700201) and National Natural Science Foundation of China (NSFC) (91963128, 62071215, and 61801207).

7 References

1. N. Yu et al., "Light propagation with phase discontinuities: generalized laws of reflection and refraction," *Science*, **334**, 6054, February 2011, pp. 333-337, doi: 10.1126/science.1210713.

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 Antennas Propag. Mag.*, **54**, 2, April 2012, pp. 10-35, doi: 10.1109/MAP. 2012.6230714.

3. D. González-Ovejero, G. Minatti, G. Chattopadhyay, and S. Maci, "Multibeam by metasurface antennas," *IEEE Trans. Antennas Propag.*, **65**, 6, June 2017, pp. 2923-2930, doi: 10.1109/TAP.2017.2670622.

4. E. Abdo-Sánchez, M. Chen, A. Epstein, and G. V Eleftheriades, "A leaky-wave antenna with controlled radiation using a bianisotropic Huygens' metasurface," *IEEE Trans. Antennas Propag.*, **67**, 1, January 2018, pp. 108-120, doi: 10.1109/TAP.2018.2878082.

5. S. Chen, W. Liu, Z. Li, H. Cheng, and J. Tian, "Metasurfaces: Metasurface-Empowered Optical Multiplexing and Multifunction," *Adv. Mater.*, **32**, 3, January 2020, p. 2070022, doi: 10.1002/adma.20180591 2.

6. K. Chen et al., "Directional Janus metasurface," *Adv. Mater.*, **32**, 2, November 2020, p. 1906352, doi: 10.1002/adma.201906352.

7. G. Ding, K. Chen, X. Luo, J. Zhao, T. Jiang, and Y. Feng, "Dual-helicity decoupled coding metasurface for independent spin-to-orbital angular momentum conversion," *Phys. Rev. Appl.*, **11**, 4, April 2019, p. 44043, doi: 10.1103/PhysRevApplied.11.044043.

8. W.-L. Guo, G.-M. Wang, W.-Y. Ji, Y.-L. Zheng, K. Chen, and Y. Feng, "Broadband spin-decoupled metasurface for dual-circularly polarized reflector antenna design," *IEEE Trans. Antennas Propag.*, **68**, 5, May 2020, pp. 3534–3543, doi: 10.1109/TAP.2020.2963945.

9. W.-L. Guo, G.-M. Wang, X.-Y. Luo, K. Chen, H.-P. Li, and Y. Feng, "Dual-Phase Hybrid Metasurface for Independent Amplitude and Phase Control of Circularly Polarized Wave," *IEEE Trans. Antennas Propag.*, **68**, 11, November 2020, pp. 7705-7710, doi: 10.1109/TAP.2020. 2996818.

10. K. Chen, N. Zhang, G. Ding, J. Zhao, T. Jiang, and Y. Feng, "Active Anisotropic Coding Metasurface with Independent Real-Time Reconfigurability for Dual Polarized Waves," *Adv. Mater. Technol.*, vol. 5, no. 2, p. 1900930, 2020.

11. K. Chen et al., "A reconfigurable active Huygens' metalens," *Adv. Mater.*, **29**, 17, May 2017, p. 1606422, doi: 10.1002/adma.201606422.

12. N. Zhang *et al.*, "Programmable Coding Metasurface for Dual-Band Independent Real-Time Beam Control," *IEEE J. Emerg. Sel. Top. Circuits Syst.*, **10**, 1, March 2020, pp. 20-28, doi: 0.1109/JETCAS.2020.2973310.