# Coding Anisotropic Metasurface with Integrated Broadband Tunable Radiation and Low-Scattering Performance

Li Li Cong<sup>\*</sup>, Xiang Yu Cao<sup>\*</sup>, Huanhuan Yang<sup>†</sup>, Jun Gao<sup>†</sup> and Tao Song<sup>†</sup>

## Abstract

In this paper, we propose a coding electromagnetic metasurface (EMMS) with integrated broadband tunable radiation and low-scattering performance. Anisotropic elements demonstrating opposite phases under *x*- and *y*-polarized incidence are investigated and coded as "0" and "1" basic elements. These elements are then arranged in an optimized layout using a simulated annealing algorithm to perform the EMMS. By this means, diffusion scattering is realized in a broadband. Meanwhile, when "0" and "1" are fed properly, the coding EMMS displays wideband linearly or circularly polarized radiation with symmetric profiles. Simulated and experimental results verify that our method offers a simple and ingenious way to integrate broadband radiation and low scattering into one single-coding EMMS.

Keywords: Coding metasurface, Diffusion, Radar cross section, Polarization reconfigurable, Array antenna

## Background

Electromagnetic (EM) metasurfaces (EMMSs), artificially constructed by periodic or quasi-periodic sub-wavelength particles, are denoted as a surface version of three-dimensional metamaterials [1, 2]. By virtue of compact structures, low profile, good conformal shape, low cost, and easy fabrication, the EMMSs have been extensively investigated and engineered to manipulate EM waves [3–9], such as polarization, amplitude, and phase.

Especially, anisotropic EMMSs are more ready to achieve a number of interesting characteristics not possible with isotropic ones in some occasions. For polarization engineering, by employing anisotropic particles to construct reflective or transmissive polarization conversion EMMSs, one can almost realize arbitrary polarizations from one specific polarization, such as linear polarization to linear polarization [10–13], linear polarization to circular polarization [14-16], circular polarization to circular polarization [17, 18], and so on. Circularly polarized antennas, polarization-controlling devices, and radar cross section reduction (RCSR) can be further accomplished based on polarization

\* Correspondence: 1183068955@qq.com; xiangyucaokdy@163.com

<sup>†</sup>Huanhuan Yang, Jun Gao, and Tao Song contributed equally to this work. Air Force Engineering University, Xi'an 710077, China manipulation. Absorption is a common fashion for amplitude manipulation. Through changing relative gap orientations or neighboring center offsets of multilayered anisotropic split-ring resonators [19–21], one can tune the near-field interactions between them. By this means, low reflection and transmission can be simultaneously obtained to achieve perfect absorption. As for phase manipulation, by delicately designing the geometry of sub-wavelength particles of the EMMS, phase discontinuities imparted across the reflected or transmitted surface can be achieved. Thus, many fascinating EM devices, such as metasurface lens [22, 23], metasurface holograms [24, 25], invisible cloaking [6], spin-orbit manipulation [26, 27], and some other functional interfaces [28–31], can be then realized.

Recently, coding EMMSs have gained intensive attention as another paradigm for manipulating EM wave propagation [32–35]. The "coded bits" are represented by constitutive particles with different phase responses. Take 1-bit EMMS as an example, coded "0" and "1" elements are mimicked by constitutive structures with 0° and 180° phase shift, respectively. Through a certain spatial mixture of these coded elements, 2-bit, 3-bit, and multi-bit EMMSs can be subsequently accomplished [36–38]. With multifunction and tunability demands of

© The Author(s). 2019 **Open Access** This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.







EM devices, switchable components and field-programm able gate array hardware are included in coding EMMS design. Hence, reconfigurable [39] and programmable [40] EMMSs are then obtained. Based on the aforementioned "coding" concept, 0-bit EMMS, consisting of only one kind of anisotropic elements, can be used to achieve polarization conversion [39], while multi-bit EMMSs coded by optimization algorithms can be used to manipulate diffusion scattering performance, thus achieving RCSR [39].

Obviously, abovementioned EMMS designs mainly devote to investigate scattering performance for incoming EM wave. Actually, if fed appropriately, the EMMSs themselves can act as antennas to radiate EM wave [41-46]. Furthermore, to the best of the authors' knowledge, the "coding" concepts mainly focus on scattering evaluation, but not included in radiation performance. In this paper, the proposed EMMS involves broadband radiation and low-scattering performance simultaneously. The EMMS is composed of anisotropic elements, which possesses opposite phases under x- and y-polarized incidence. These anisotropic elements are coded as "0" and "1" and then arranged in a certain sequence optimized by the simulated annealing algorithm (SAA). Based on the antenna array theory [47], appropriate feeding structures are added to coding "0" and "1" elements to realize desired radiation performance. If "0" and "1" elements are fed with the same amplitude and phase, linearly polarized (LP) radiation can be achieved. While if "0" and "1" elements are fed with the same amplitude but with 90° phase difference, left- or right-hand circular polarization (L/RHCP) radiation can be achieved. Meanwhile, the optimized layout of EMMS results in broadband diffusion scattering performance for incoming EM wave, which is to the advantage of bistatic RCSR. Both simulation and measurement prove that our method offers a simple, flexible, and ingenious strategy for EMMS design with integrated broadband radiation and low scattering performance.

## Methods

Figure 1 depicts the detailed geometry of the coding EMMS and the constitutive anisotropic elements. Two FR2 dielectric layers (dielectric constant of 2.65, loss tangent of 0.002) are employed as substrates, denoted as substrate1 and substrate2. The two dielectric layers are tightly and flatly stacked together without any air space between them. The thicknesses of the substrates from top to bottom are 3 mm and 0.5 mm, respectively.  $4 \times 4$  bowtie-shaped metallic patches are etched on the top surface of substrate1 measuring  $36 \times 36 \text{ mm}^2$  (equal to  $0.66\lambda_0 \times 0.66\lambda_0$  at 5.5 GHz). The metallic ground plate with a slot as thin as possible (length of 15.5 mm, width of 0.2 mm) is etched on

the bottom surface of substrate2 to ensure absolute reflection. Apparently, the EM properties of such anisotropic element lie in its physical arrangement. Based on the "coding" concept, the anisotropic element shown in Fig. 1b is nominated as "1", while its counterpart (90° rotation around z-axis) is denoted as "0". The layout of finally proposed EMMS is optimized by SAA, which is a method for local searching. Figure 1d shows the flow chart of the SAA for achieving the optimal coding matrix. It begins with an initial solution which is randomly modified in an iterative process. The main parameters of SAA involve the initial temperature  $T_i$  the decreasing rate  $\alpha$ of each iteration process, the final temperature Tf, the number of iterations I, and the merit function. In our model, we define an initial coding matrix with equal number of "0" and "1". It is then upgraded by changing positions of an arbitrary pair of "0" and "1". The parameters T,  $\alpha$ , Tf, and I are set as 100, 0.9, 0, and 1000, respectively. For low RCS performance, good diffusion scattering is expected. Thus, our goal is to find the optimal coding matrix  $(M_{\text{best}})$  leading to a desired scattering pattern with the smallest maximum value. Thus, the issue is a min-max problem in which the merit function can be expressed as  $F(M_{\text{best}}) =$  $min(AF_{max})$ , where  $AF_{max}$  is the maximum value of AF corresponding to a given coding matrix. The optimal coding matrix corresponds to the minimum  $AF_{max}$ , which would lead to a perfect diffusion scattering performance. Generally, the bigger the array size is, the better diffusion scattering we obtain. Here, we choose an array consisting of  $4 \times 4$  elements (M = N = 4). Finally, the optimal coding matrix is shown in Fig. 1a. All simulations in the following analysis unless otherwise stated are carried out with aid of the commercial simulation software Ansoft HFSS v.14.0.

For the radiation case, lumped port excitation and radiation boundary are applied on the anisotropic element. A 50- $\Omega$  SMA is connected to the extremely thin rectangular patch (length of 13 mm, width of 1.3 mm) through a small hole in substrate2 for impedance matching. The slot in the metallic ground then takes effect by coupling energy to the top anisotropic EMMS to radiate LP EM wave. The reflection coefficient  $S_{11}$  and radiation patterns are plotted in Fig. 2. As clearly observed, the bandwidth for -10 dB impedance matching is achieved from 5 GHz to 6 GHz, implying a relative bandwidth of 18.2%. A stable boresight gain varying from 6.97 dBi to 7.86 dBi is obtained over the impedance bandwidth. Meanwhile, a normal and symmetric radiation profiles are observed in broadside direction for both xoz- (E-) and yoz- (H-) planes, as clearly shown in Fig. 2b-d.

To give a physical insight into the working mechanism, the modal surface current of the anisotropic element at



5.35 GHz and 5.75 GHz is plotted in Fig. 3a and b. Note that the simulations performed in this section were carried out by using FEKO 7.0. As clearly shown, the surface current of mode 1 and mode 2 mainly distributes on the middle patches which may result in broadside radiation, while that of unwanted mode 3 and mode 4 mainly distributes on the edge patches, which may result in radiation nulls in the broadside. Furthermore, the surface current of mode 1 and mode 3 flows along the y-axis, while that of mode 2 and mode 4 flows along the x-axis. Besides, the calculated modal significances of the first four characteristic modes of the anisotropic element with and without metasurface are illustrated in Fig. 4a and b. We can tell from Fig. 4b that when the metasurface is applied on the element, mode 1 and mode 2 are resonant at 5.32 GHz and 5.72 GHz in the desired operation band, with either of their modal significances approaching unity. Thus, mode 1 and mode 2 are the fundamental orthogonal mode pairs to generate the wideband and broadside radiation patterns.

For the scattering case, floquet port excitation and master/slave boundaries are implemented on the anisotropic element to exploit the reflection characteristics. As plotted in Fig. 5, only one 0° reflection phase point arises at 9.38 GHz for "1" element, while dual 0° reflection phase points appear at 4.75 GHz and 17.52 GHz for "0" element. Thus, an effective reflection phase difference is created between "0" and "1" elements, as indicated in the dark grey part in Fig. 5a. Meanwhile, the reflection magnitudes shown in Fig. 5b maintain close to 1 in  $2\sim18$  GHz for both elements. It is worth noting that a hollow zone for

reflection magnitude response is observed around the working band  $(5\sim 6 \text{ GHz})$  of "0" element. This is attributed that part of the co-polarized energy is absorbed by the feeding structure. Still and all, energy cancellation [47] can be well obtained in a broadband. Consequently, broadband RCSR can be expected.

## **Results and Discussion**

In some sense, the scattering process can be understood by transforming EM wave reflection to re-radiation process. Therefore, for an  $M \times N$  EMMS array, the working principle for both radiation and scattering cases can be interpreted by the standard array theory [47]:

$$E_{\text{total}} = \text{EP} \cdot AF = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} \text{EP}_{(m,n)} \cdot e^{j[km\Delta x \sin\theta \cos\phi + kn\Delta y \sin\theta \sin\phi + \phi(m,n)]}$$
(1)

where EP is the pattern function of a single element, *AF* is the array factor, *k* is the wavenumber,  $\Delta x$  and  $\Delta y$ 

are the distance between adjacent elements along *x*- and *y*-directions, respectively,  $\phi(m, n)$  is the phase of the (m, n) element, and  $\theta$  and  $\phi$  are the elevation and azimuth angle of an incidence. For simplicity, the subscripts of  $E_{\text{rtotal}}$  and  $E_{\text{stotal}}$  in the following analysis indicate cases of radiation and scattering, respectively.

For the radiation case, all anisotropic elements act as radiators when fed appropriately. Naturally, the "0" and "1" elements would produce two orthogonally polarized electric fields, namely  $EP_{0} \perp EP_{1}$ . Then, the polarization of radiated EM wave from EMMS depends on the amplitude and phase of the feed sources. Assuming that the input power of each element is equal, one would have  $|EP_{0'}| = |EP_{1'}|$ .  $\phi(m, n)$  would represent the input phase from feed sources. Hence, along the normal direction with  $(\theta, \phi) = (0^{\circ}, 0^{\circ})$ , Eq. (1) would be simplified as  $E_{\text{rtotal}}$  $= 8(EP_{0'}e^{j\phi_{0'}} + EP_{1'}e^{j\phi_{1'}})$  for the proposed EMMS. If  $\phi_{0'} - \phi_{1'} = 0$  or  $\pm 180$ , the total radiation would be LP within the diagonal planes. If  $\phi_{0'}$  is 90°ahead of  $\phi_{1'}$ , the total radiated field would be RHCP. Otherwise, if  $\phi_{0'}$  falls 90°behind  $\phi_{1'}$ , LHCP radiation





would be generated. To summarize, the polarization of radiated field from the EMMS can be adjusted at will by controlling input phases of "0" and "1" elements.

For briefness of the paper, only two representative cases are involved in the following analysis. All "0" and "1" elements are fed with equal power in both cases. On one hand, in terms of  $\phi_{0'} = \phi_{1'} = 0$ , LP radiation performances are obtained as depicted in Fig. 6. Good impedance matching is achieved from 4.97 GHz to 6.05 GHz

(19.6% relative bandwidth), while the gain in normal direction varies from 12.6 dBi to 17.38 dBi in the operation band. Symmetrical radiation patterns are observed in the broadside direction for both E- and H-planes, as clearly shown in Fig. 6b. On the other hand, when  $\phi_{1'} - \phi_{0'} = 90^{\circ}$ , RHCP radiation is observed as expected. As shown in Fig. 7, the bandwidth for S<sub>11</sub> < – 10 dB and 3 dB axial ratio bandwidth (ARBW) is 4.97~6 GHz and 5.22~6 GHz, respectively. The common bandwidth for S<sub>11</sub> < – 10 dB and 3 dB ARBW is from 5.22 GHz to 6 GHz





(13.9% relative bandwidth), with boresight gain varying from 13.16 dBi to 15.8 dBi. Likewise, symmetric, broadside, and normal radiation profiles are observed in the 3D radiation patterns at 5.35, 5.5, and 5.75 GHz.

From the aforementioned analysis, it can be verified that the proposed EMMS can perform as a good antenna and radiate in linear polarization and circular polarization modes alternatively by controlling the input magnitudes and phases. Meanwhile, the simulated results indicate that the working bandwidth of proposed EMMS maintains well compared with a single anisotropic element, which verifies the effectiveness of our proposed method. To get an intuitive insight into the working mechanisms of the EMMS for different radiation modes, the electric field distributions at 5.35 GHz with different time variants are investigated. It is clearly shown in Fig. 8a that the resonant E-field distributes evenly across "0" and "1" elements all along as time changes for LP radiation. However, for CP radiation, "1" elements exhibit stronger field density at the phase of 0°, while "0" elements prevail over "1" ones at the phase of 90°. Thus, two orthogonal modes with a 0° or 90° phase difference are excited to perform LP or CP radiation.

For the scattering case, all of "0" and "1" elements act as passive devices. The aperiodic layout of "0" and "1" elements optimized by SAA aims at achieving diffusion scattering performance. Here, for Eq. (1),  $\phi(m, n)$  represents the phase compensation of reflected wave from the (m, n) element. In terms of our proposed design,  $\phi(m, n)$ evaluates 0° and 180° in correspondence to "0" and "1" elements, respectively. In order to give an intuitive demonstration of the low-scattering property of proposed EMMS, the simulated RCS result versus frequency is demonstrated compared with a same-sized metallic





board. As clearly shown in Fig. 9, obvious reflection suppression is achieved in a broadband ranging from 5 GHz to 18 GHz. A continuous 6-dB RCSR is achieved nearly from 5 GHz to 18 GHz (113.04% relative bandwidth). Two RCS hollow dips appear around 5.9 GHz and 10.4

GHz with a maximum RCSR reaching up to 31.8 dB. One can tell from Fig. 9e that the scattering field of the EMMS splits into eight main small beams, which is in adequate agreement with the result obtained by the mathematical calculation in Fig. 9c. Compared with





traditional chessboard configuration (four main reflected lobes), more reflected lobes contribute to each beam significantly suppressed based on energy conservation. Fig. 9f reveals the working mechanism of the EMMS. It can be observed that different elements resonate discrepantly, which yields the necessary discontinuous phase shift and finally results in diffusion reflection. The scattering properties of EMMS under oblique incidence were also investigated as shown in Fig. 10. Likewise, instead of strong specular reflection for a same-sized metal board, diffusion scattering is consecutively observed for EMMS with different incident angles. Meanwhile, as shown in Fig. 11, the normalized scattering patterns at 6 GHz with incident angles from 0° to 60° are also provided to give an intuitive demonstration of diffusion reflection. To conclude, the proposed EMMS demonstrates diffusion scattering performance in a broadband as expected.

To validate the radiation and scattering performance mentioned above, a  $4 \times 4$  coding EMMS sample was





fabricated using standard printed circuit board (PCB) technology. The measurement was conducted in an anechoic chamber to minimize the noise interference. For the radiation case, one RS2W2080-S and two RS8 W2080-S power dividers are connected in sequence to equally distribute the signal into 16 ports, while coaxial cables with different lengths are utilized to provide 90° phase shifting between "0" and "1" elements, as shown in Fig. 12. The measured bandwidths for  $S_{11} \leq -10 \text{ dB}$ and 3 dB ARBW shown in Fig. 13a are 4.96~6.02 GHz and 5.22~6.02 GHz, respectively. The common bandwidth is from 5.22 GHz to 6.02 GHz (14.2% relative bandwidth), which is in satisfactory accordance with the simulated results. The normalized radiation patterns at 5.35 GHz and 5.75 GHz are depicted in Fig. 13b and c. Corresponding to the prediction of simulation, sym metric, normal-directed, and RHCP radiation is observed in broadside direction. The measured side lobe levels are at least 10 dB lower than the main lobe levels. In addition, the fields of RHCP are always stronger than that of LHCP by over 18.6 dB in the boresight direction. Thus, it can be concluded that the EMMS achieves good RHCP radiation performance as expected.

For the scattering case, the EMMS sample was placed vertically on the center of a foam platform, while two identical LP pyramidal horn antennas working at 1~18 GHz were placed adjacently as transmitter and receiver, respectively. A piece of absorbing material is set between the two horns to reduce undesired coupling. The centers of the sample and two horns are in the same height, and the distance between them is far enough to satisfy far-field test conditions. Gate-reflect-line calibration was





also employed to further eliminate undesirable signals in the environment. The two horn antennas are connected to the two ports of VNA Agilent N5230C to evaluate reflected power on transmission coefficients. As plotted in Fig. 13d, a considerable 6-dB RCSR compared with a same-sized metal board is achieved from 5 GHz to 18 GHz (113% relative bandwidth), while over 10-dB RCSR is achieved in the band of 5.6~6.5 GHz (14.9% relative bandwidth), 9.2~13.5 GHz (37.9% relative bandwidth) and 15.9~18 GHz (12.4% relative bandwidth). Two RCSR peaks appear around 6.1 GHz and 10.2 GHz valuing 25.9 dB and 30.6 dB, respectively. The measured results agree well with the simulated ones, which verify broadband low-scattering performance of the EMMS. Comparisons between the proposed design and former metasurface-based antenna design have been made in Table 1. In particular, [42, 45] demonstrate the performance of antenna array, while others of the single antenna. As clearly shown, the proposed EMMS yields an ultrawideband RCSR involving in-band and out-of-band while achieving broadband tunable radiation simul taneously.

### Conclusions

This paper presents a novel coding EMMS with integrated broadband tunable radiation and low-scattering performance. An anisotropic element with intrinsically opposite phases under different polarized incidence is adopted as the constituent element. Appropriate feeding

Table 1 Measured comparisons between the proposed design and former metasurface-based antenna design

ID	Transverse profile (mm)	Polarization mode	Operation bandwidth (GHz)	6-dB RCSR bandwidth (GHz)	Additional structure for RCSF
Ref. [41]	3.25 (0.06λ <sub>0</sub> )	LP	4.71~6.37 (29.96%)	Not investigated	-
Ref. [42]	2.3368 (0.047λ <sub>0</sub> )	LHCP	4.75–7.25 (41.67%)	Not investigated	-
Ref. [43]	3.5 (0.06λ <sub>0</sub> )	LP	4.72~6.04 (24.5%)	4.72~6.04 (24.5%)	Yes
Ref. [44]	2.4 (0.035λ <sub>0</sub> )	LHCP/RHCP/LP	4.3~4.44 for LHCP (3.2%)	4~4.65 (15%)	No
Ref. [45]	3.5 (0.058λ <sub>0</sub> )	LHCP	4.22~5.46 (25.6%)	4.53~6.7 (38.6%)	No
This paper	3.5 (0.06λ <sub>0</sub> )	LHCP/RHCP/LP	4.97~6.05 for LP (19.6%) 5.22~6 for BHCP (13.9%)	5~18 (113.04%)	No

 $\lambda_0$  is the free-space wavelength corresponding to the center frequency of the operation bandwidth

structures enable the anisotropic element to act as radiator. By controlling the input amplitudes and phases based on antenna array theory, LP, LHCP, or RHCP radiation can be achieved at will. In addition, the optimized layout of EMMS contributes to broadband diffusion scattering performance, which results RCSR in a broadband. Thus, broadband radiation and low-scattering performance can be simultaneously achieved in the proposed EMMS, which offers a simple, flexible, and effective strategy to solve the confliction between radiation and scattering. It is worth mentioning that the EMMS could be made up of other alternative anisotropic elements. Some application value can be expected in polarization reconfigurable antennas, target stealth, and so on.

#### Abbreviations

ARBW: Axial ratio bandwidth; EM: Electromagnetic; EMMS: Electromagnetic metasurfaces; L/RHCP: Left- or right-hand circular polarization; LP: Linearly polarized; PCB: Printed circuit board; RCSR: Radar cross section reduction; SAA: Simulated annealing algorithm

#### Funding

This work was supported by National Natural Science Foundation of China (Grant No. 61671464, 61471389, 61701523, 61801508); Natural Science Foundation of Shannxi Province (Grant No. 2018JM6040).

#### Availability of Data and Materials

All data are fully available without restriction.

#### **Author Details**

<sup>1</sup>Air Force Engineering University, Xi'an 710077, China

#### Authors' Contributions

LLC and XYC conceived the idea, did the simulations, interpreted the experiments, and wrote the manuscript. HHY and JG suggested the numerical simulations. TS contributed to the sample fabrication and measurement. All authors read and approved the final manuscript.

#### **Competing Interests**

The authors declare that they have no competing interests.

#### **Publisher's Note**

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

#### Received: 29 November 2018 Accepted: 15 March 2019 Published online: 29 March 2019

#### References

- Kuester EF, Mohamed MA, Piket-May M, Holloway CL (2003) Averaged transition conditions for electromagnetic fields at a metafilm. IEEE Trans Antenn Propag AP-51:2641–2651
- Yu N, Capasso F (2014) Flat optics with designer metasurfaces. Nat Mater 13:139–150
- Chen HT, Padilla WJ, Zide JMO, Gossard AC, Taylor AJ, Averitt RD (2006) Active terahertz metamaterial devices. Nature 444:597–600
- Pendry JB, Schurig D, Smith DR (2006) Controlling electromagnetic fields. Science 312:1780–1782
- Highstrete C, Lee M, Padilla W (2007) Complementary planar terahertz metamaterials. Opt Express 15:1084–1095
- Schurig D, Mock JJ, Justice BJ, Cummer SA, Pendry JB, Starr AF, Smith DR (2006) Metamaterial electromagnetic cloak at microwave frequencies. Science 314:977–980
- Alù A, Salandrino A, Engheta N (2006) Negative effective permeability and left-handed materials at optical frequencies. Opt Express 14:1557–1567

- He XY, Xiao GN, Liu F, Lin FT, Shi WZ (2019) Flexible properties of THz graphene bowtie metamaterials structures. Opt Mater Express 9:44–55
- He XY, Liu F, Lin FT, Shi WZ (2018) Graphene patterns supported terahertz tunable plasmon induced transparency. Opt Express 26:9931–9944
- Sun HY, Gu CQ, Chen XL, Li Z, Liu LL, Martin F (2017) Ultra-wideband and broad-angle linear polarization conversion metasurface. J Appl Phys 121: 1304–1404
- Gao X, Han X, Cao WP, Li HO, Ma HF, Cui TJ (2015) Ultra-wideband and high-efficiency linear polarization converter based on double v-shaped metasurface. IEEE Trans Antenn Propag 63:3522–3530
- 12. Jia Y, Liu Y, Zhang W, Gong S (2016) Ultra-wideband and high-efficiency polarization rotator based on metasurface. Appl Phys Lett 109:051901
- Chen HY, Ma H, Wang J, Yuan H, Pang Y, Xu C (2016) Ultra-wideband transparent 90° polarization conversion metasurfaces. Appl Phys A 122:463
- Mutlu M, Akosman AE, Serebryannikov AE, Ozbay E (2011) Asymmetric chiral metamaterial circular polarizer based on four U-shaped split ring resonators. Opt Lett 36:1653–1655
- Ma X, Huang C, Pu M, Hu C, Feng Q, Luo X (2012) Multi-band circular polarizer using planar spiral metamaterial structure. Opt Express 20:16050– 16,058
- 16. Orr R, Goussetis G, Fusco V, Saenz E (2015) Linear-to-circular polarization reflector with transmission band. IEEE Trans Antenn Propag 63:1949–1956
- 17. Huang XJ, Yang D, Yang HL (2014) Multiple-band reflective polarization converter using U-shaped metamaterial. J Appl Phys 115:103505
- Han JF, Cao XY, Gao J, Wei J, Zhao Y, Li SJ, Zhang Z (2018) Broadband radar cross section reduction using dual-circular polarization diffusion metasurface. IEEE Antennas Wirel Propag Lett 17:969–973
- Ji L, Varadan V (2017) Gap orientation tuning in split ring resonator array for increased energy absorption. J Appl Phys 121:244504
- 20. Powell DA, Lapine M, Gorkunov MV, Shadrivov IV, Kivshar YS (2010) Metamaterial tuning by manipulation of near-field interaction. Phys Review B 82:155128
- 21. Gu S, Barrett JP, Hand TH, Popa BI, Cummer SA (2010) A broadband lowreflection metamaterial absorber. J Appl Phys 108:064913
- Wei ZY, Cao Y, Su XP, Gong ZJ, Long Y, Li HQ (2013) Highly efficient beam steering with a transparent metasurface. Opt Express 21:10739–10,745
- 23. Ni XJ, Emani NK, Kildishev AV, Boltasseva A, Shalaev VM (2012) Broadband light bending with plasmonic nanoantennas. Science 335:427
- 24. Lin J, Genevet P, Kats MA, Antoniou N, Capasso F (2013) Nanostructured holograms for broadband manipulation of vector beams. Nano Lett 13: 4269–4274
- Zheng J, Ye ZC, Sun NL, Zhang R, Sheng ZM, Shieh HPD, Zhang J (2014) Highly anisotropic metasurface: a polarized beam splitter and hologram. Sci Rep 4:6491
- Wang S, Wang XK, Kan Q, Ye JS, Feng SF, Sun WF, Han P, Qu SL, Zhang Y (2015) Spin-selected focusing and imaging based on metasurface lens. Opt Express 23:26434–26,441
- 27. Yin XB, Ye ZL, Rho J, Wang Y, Zhang X (2013) Photonic spin hall effect at metasurface. Science 339:1405–1407
- Yang F, Deng RY, Xu SH, Li MK (2018) Design and experiment of a nearzero-thickness high-gain transmit-reflect-array antenna using anisotropic metasurface. IEEE Trans Antenn Propag 66:2853–2861
- Cai T, Wang GM, Fu XL, Liang JG, Zhuang YQ (2018) High-efficiency metasurface with polarization-dependent transmission and reflection properties for both reflectarray and transmitarray. IEEE Trans Antenn Propag 66:3219–3224
- He XY, Liu F, Lin FT, Xiao GN, Shi WZ (2019) Tunable MoS<sub>2</sub> modified hybrid surface plasmon waveguides. Nanotechnology 30:125201
- Shi CYY, He XY, Peng J, Xiao GN, Zhang H (2019) Tunable terahertz hybrid graphene-metal patterns metamaterials. Optics and Laser Technology 114: 28–34
- 32. Giovampaola CD, Engheta N (2014) Digital metamaterials. Nat Mater 13: 1115–1121
- 33. Cui TJ, Qi MQ, Wan X, Zhao J, Cheng Q (2014) Coding metamaterials, digital metamaterials and programmable metamaterials. Light: Sci Appl 3:e218
- Liu S, Cheng Q, Xu Q, Wang TQ, Du LL, Luan K, Xu YH, Bao D, Fu XJ, Han JG, Zhang WL, Cui TJ (2016) Free-standing metasurfaces for high-efficiency transmitarrays for controlling terahertz waves. Adv Opt Mater 4:384
- Liu S, Cui TJ, Xu Q, Bao D, Du L, Wan X, Tang WX, Ouyang C, Zhou XY, Yuan H, Ma HF, Jiang WX, Han J, Zhang W, Cheng Q (2016) Anisotropic coding metamaterials and their powerful manipulation of differently polarized terahertz waves. Light: Sci. Appl 5:e16076

- Yan X, Liang L, Yang J, Liu W, Ding X, Xu D, Zhang Y, Cui T, Yao J (2015) Broadband, wide-angle, low scattering terahertz wave by a flexible 2-bit coding metasurface. Opt Express 23:29128–29,137
- Sui S, Ma H, Wang JF, Feng MD, Pang YQ, Xia S, Xu Z, Qu SB (2016) Symmetry-based coding method and synthesis topology optimization design of ultrawideband polarization conversion metasurfaces. Appl Phys Lett 109:014104
- Chen K, Feng Y, Yang Z, Cui L, Zhao J, Zhu B, Jiang T (2016) Geometric phase coded metasurface: from polarization dependent directive electromagnetic wave scattering to diffusion-like scattering. Sci Rep 6:35968
- Zhao Y, Cao X, Gao J, Liu X, Li S (2016) Jigsaw puzzle metasurface for multiple functions: polarization conversion, anomalous reflection and diffusion. Opt Express 24:11208–11,217
- Yang HH, Cao XY, Yang F, Gao J, Xu SH, Li MK, Chen XB, Zhao Y, Zheng YJ, Li SJ (2016) A programmable metasurface with dynamic polarization, scattering and focusing control. Sci Rep 6:35692
- 41. Liu W, Chen ZN, Qing XM, Shi J, Lin FH (2017) Miniaturized wideband metasurface antennas. IEEE Trans Antenn Propag 65:7345–7349
- 42. Son XT, Ikmo P (2017) Compact wideband circularly polarized patch antenna array using metasurface. IEEE Antennas Wirel Propag Lett 16:1932–1936
- Jia YT, Liu Y, Wang H, Li K, Gong SX (2015) Low RCS, high-gain and wideband mushroom antenna. IEEE Antennas Wirel Propag Lett 14:277–280
- Kandasamy K, Majumder B, Mukherjee J, Ray KP (2015) Low-RCS and polarization-reconfigurable antenna using cross-slot-based metasurface. IEEE Antennas Wirel Propag Lett 14:1638–1641
- Zhao Y, Cao XY, Gao J, Xu LM, Liu X, Cong LL (2017) Broadband low-RCS circular-polarized array using metasurface-based element. IEEE Antennas Wirel Propag Lett 6:1836–1839
- Cong LL, Cao XY, Gao J, Song T (2018) Ultra-wideband low-RCS circularlypolarized metasurface-based array antenna using tightly-coupled anisotropic element. IEEE Access 6:41738–41,744
- Paquay M, Iriate JC, Ederra I, Gonzalo R, de Maagt P (2007) Thin AMC structure for radar cross-section reduction. IEEE Trans Antenn Propag 55: 3630–3638

## Submit your manuscript to a SpringerOpen<sup>®</sup> journal and benefit from:

- Convenient online submission
- ► Rigorous peer review
- Open access: articles freely available online
- ► High visibility within the field
- Retaining the copyright to your article

Submit your next manuscript at **>** springeropen.com