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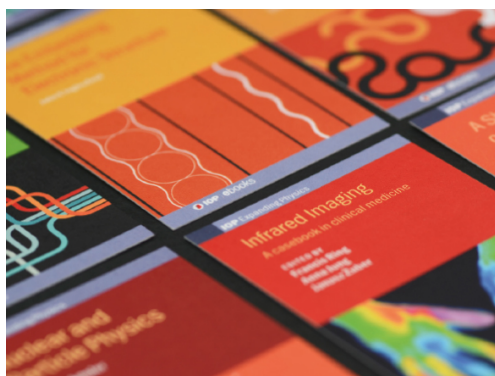
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High-efficiency ultra-broadband orbital angular momentum beam generators enabled by arrow-based fractal metasurface

Yiting Liu¹ , Rensheng Xie¹, Xu Chen², Hualiang Zhang³ and Jun Ding^{1,*}

¹ Key Laboratory of Polar Materials and Devices, Department of Electronic Sciences, School of Physics and Electronic Sciences, East China Normal University, Shanghai 200241, People's Republic of China

² Shanghai Radio Equipment Research Institute, Shanghai 200090, People's Republic of China

³ Department of Electrical and Computer Engineering, The University of Massachusetts Lowell, Lowell, MA 01854, United States of America

E-mail: jding@ee.ecnu.edu.cn

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Abstract

Vortex beams carrying orbital angular momentum (OAM) are of great importance owing to the capacity to expand channel capacity of communication systems from microwave to optical regimes. In this work, a single-layer ultra-broadband meta-atom is designed by using the method of fractal. The reflected co-polarization amplitude of the arrow-based fractal meta-atom can exceed 0.9 in a frequency range from 6 to 19.7 GHz and the complete 2π phase control can be achieved by rotating the structure. Based on the proposed meta-atom, metasurface-based vortex beam generators are designed. As an illustrative example, a metasurface-based OAM beam generator with a mode of $+1$ is designed, fabricated, and measured. Both the experimental and simulated results match well with each other, proving the practicability of the proposed high-efficiency ultra-broadband metasurface.

Keywords: fractal, metasurface, ultra-broadband, high-efficiency, OAM beam generator

(Some figures may appear in colour only in the online journal)

1. Introduction

Vortex beams carrying orbital angular momentum (OAM) have attracted considerable attentions for their promising applications in modern wireless communication systems [1–5]. A vortex beam with the phase factor of $e^{il\theta}$ carries the OAM of $l\hbar$ per photon, where θ is the azimuthal angle and l represents the OAM mode number. The orthogonality of different OAM modes could provide an additional degree of freedom for the signal modulation [1, 6], enhancing data capacity in different frequency regimes [7–11]. Therefore, a number of traditional methods to generate OAM beams have

been proposed in the past decades [12], such as spiral phase plates [13–17], spatial light modulators [18–21], vortex lasers [22, 23] and uniform circular antenna arrays [24, 25], which typically suffer from the issues such as bulky configurations, low efficiencies as well as narrow bandwidths.

Metasurfaces, the two-dimensional counterparts of the metamaterials, have sparked enormous interest in recent years [26–35] due to their superior capabilities for wave-front modulations. Metasurfaces are composed of low-profile artificially periodic subwavelength structures, demonstrating strong capabilities to manipulate electromagnetic (EM) wave-front [36–39]. Very recently, several metasurfaces have been reported to realize broadband OAM beams, showing broader bandwidth and higher efficiency than the traditional methods [40–45]. An effective approach is based on transmission-type

* Author to whom any correspondence should be addressed.

metasurface with metallic grating layers [40], which could realize high transmission efficiency in the entire operation band. Moreover, a bilayer reflection-type OAM metasurface is proposed to function in a broad bandwidth from 6.95 to 18 GHz (a fractional bandwidth of 82%, $r_{co} > 0.89$) [41]. Nevertheless, the multilayer structures of the metasurface increase the profile thickness and fabrication complexity. Therefore, single-layer broadband OAM metasurfaces have been reported to tackle these issues, such as the rectangular-hole metasurface [42], the reflection-type brick-shaped metasurface [43], the ultra-thin z-shaped metasurface [44], and the H-shaped metasurface [45]. Moreover, a novel square-loop-shaped metasurface has achieved the balance between high efficiency and broad bandwidth, with the fractional bandwidth of 105.6% ($r_{co} > 0.9$) [46–48]. Furthermore, the fractal topology provides a novel and efficient method to meet the growing requirement of high-efficiency broadband OAM generation [49], which deserves further research.

In this work, a novel ultra-broadband high-efficiency OAM generator based on a fractal metasurface is proposed. Numerical analysis of the proposed arrow-based fractal meta-atom is carried out, and the co-polarization reflection coefficients under the circularly polarized incidence can exceed 0.9 in an ultra-broad working range from 6 to 19.7 GHz with a fractional bandwidth of 107%. The meta-atom is then utilized to design metasurface-based OAM generators based on the Pancharatnam–Berry principle [50, 51]. High-efficiency ultra-broadband OAM beam generators with different topological charges are designed and numerically studied, validating the performance of the designed meta-atom. In addition, an OAM beam generator with a topological charge of +1 is fabricated and characterized, featuring high efficiency and ultra-broad bandwidth. The proposed OAM metasurfaces with high efficiency and broad frequency band could pave the way to enhance the data capacity for wireless communication systems.

2. Design of the ultrabroadband meta-atom

Figures 1(a) and (b) plot the top and side views of the proposed reflective meta-atom, which is composed of single-layer metallic structures and a dielectric spacer backed by a ground plane. The top metallic layer of the meta-atom is an arrow-based fractal structure, which is generated from a rectangle bar in the design process of the fractal design. With the rotation angle of the metallic fractal structure θ_r modified, the full 2π geometric phase control can be achieved with high efficiency under the circular polarization (CP) incidence. The dielectric spacer is made of F4B, with a relative dielectric constant of 2.2 and a loss tangent of 0.002. In the simulations, the thickness of metallic layer is 0.035 mm, the thickness of F4B substrate is $h_{sub} = 4$ mm, and the period of the meta-atom is $p = 8$ mm. The arrow-based fractal consists of rectangle bars with different geometric parameters. The shaft length of the arrow-based fractal is $l_1 = 7$ mm and the arm lengths are $l_2 = 3.5$ mm and $l_3 = 0.85$ mm. The widths of the rectangle bars are $w_1 = 0.5$ mm, $w_2 = 0.2$ mm, and $w_3 = 0.3$ mm.

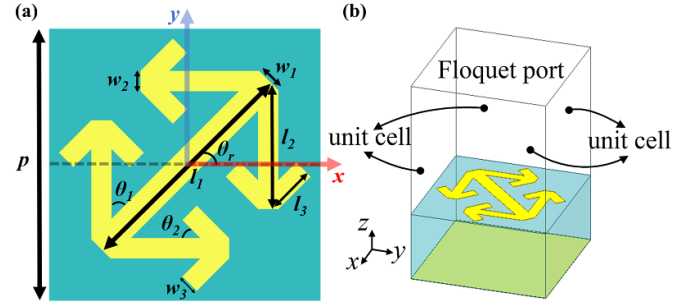


Figure 1. The layouts of the proposed meta-atom. (a) Top view. (b) Perspective view.

These rectangle bars are connected at angles $\theta_1 = 60^\circ$ and $\theta_2 = 30^\circ$.

To analyse the reflected fields for the proposed meta-atom, the reflected Jones matrix can be employed. Reflection coefficients in the Jones matrix under CP incidences are defined as follows [41]:

$$r_{--} = \frac{1}{2}[(r_{xx} - r_{yy}) + j(r_{xy} + r_{yx})]e^{-j2\theta} \quad (1)$$

$$r_{++} = \frac{1}{2}[(r_{xx} + r_{yy}) + j(r_{yx} - r_{xy})]e^{j2\theta} \quad (2)$$

$$r_{-+} = \frac{1}{2}[(r_{xx} + r_{yy}) + j(r_{yx} - r_{xy})] \quad (3)$$

$$r_{+-} = \frac{1}{2}[(r_{xx} + r_{yy}) - j(r_{yx} - r_{xy})] \quad (4)$$

where r_{--} and r_{++} denote the amplitudes of the co-polarized and cross-polarized reflection coefficients of the EM propagation under the left-handed CP (LHCP, $-$) incidence, respectively, while r_{++} and r_{-+} represent the amplitudes of the co-polarized and cross-polarized reflection coefficients under the right-handed CP (RHCP, $+$) incidence, respectively. Besides, r_{xx} and r_{yy} are the amplitudes of the co-polarized reflection coefficients under the x - and y -polarization incidences, respectively. It can be seen from equations (1) and (2) that an abrupt phase change $e^{-j2\theta}$ ($e^{j2\theta}$) could be introduced in by rotating the meta-atom with an angle of θ . Meanwhile, the polarization conversion rate (PCR) of the co-polarization reflection for the LHCP incidence could be used to show the polarization conversion efficiency of the proposed meta-atom. The PCR is defined as

$$\text{PCR} = \frac{r_{--}^2}{r_{--}^2 + r_{+-}^2}. \quad (5)$$

The proposed meta-atom is numerically studied and analysed by using the commercial software CST Microwave Studio. The boundary conditions in both x - and y -directions are ‘unit cell’, and a Floquet port is adopted in the z -axis direction. The frequency domain solver is used in the simulation. Figures 2(a) and (b) plot the amplitudes of the reflection coefficients and co-polarized reflection phases with varied rotation angle θ_r . As

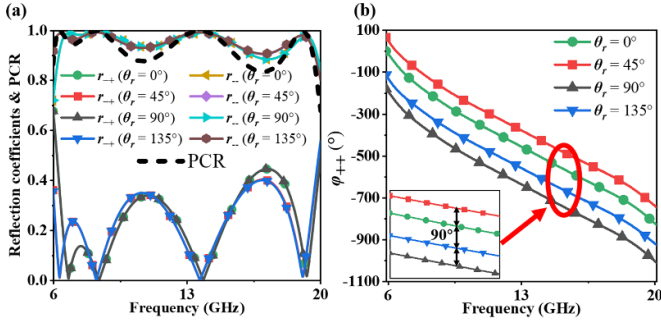


Figure 2. The amplitude and phase responses of the reflection coefficients of the proposed meta-atom with varied rotation angle θ_r under the RHCP incidence. (a) The amplitudes of the reflection coefficients. (b) The phases of the co-polarized reflection coefficients.

can be seen in figure 2(a), the amplitudes reveal polarization conversion for right-hand circularly polarized incidence in the frequency band ranging from 6 to 20 GHz. The amplitudes of co-polarized reflection coefficients keep higher than 0.9 within the ultrawide frequency range with a fractional bandwidth of 107.2%, and the cross-polarized ones are suppressed. The PCR value of the co-polarization reflection for the LHCP incidence is also shown in figure 2(a), which is higher than 0.8 in the working frequency band. Figure 2(b) exhibits the gradient phase variation by rotating the top metallic structure θ_r with an interval of 45° . It can be seen from figure 2(b) that the phase variation is almost twice the rotation angle θ_r in an ultrawide bandwidth from 6 to 20 GHz. Figure 2 indicates that the ultra-broadband phase manipulation with high efficiency can be achieved by simply rotating the proposed meta-atom under the CP incidences. In order to study the method of the fractal structure, figures 3(a)–(c) demonstrate the evolution progress of the original bar structure (stage 1) shown in figure 3(a). The arrow structure shown in figure 3(b) can be obtained by adding two parasitic bars at each end of the bar structure, and the adding operation can be repeated to spawn higher order iterations. Consequently, the reflection performances of the optimized three fractal stages are presented in figure 3(d). For the original structure (stage 1), the amplitude of the co-polarized reflection coefficient keeps higher than 0.9 in a relatively narrow range of 18.3–19.7 GHz with a fractional bandwidth of only 7.4%. The first-level arrow-based fractal structure (stage 2) could achieve an enlarged bandwidth, from 8.4 to 19 GHz with a fractional bandwidth of 77.4%. Finally, the ultra-wide bandwidth from 6 to 19.7 GHz with a fractional bandwidth of 107.2% can be obtained by the proposed meta-atom (stage 3). Compared with other stages, the fractal design of the stage 3 achieves a good balance between high amplitude and wide operating bandwidth.

3. Designs of metasurface-based OAM generators

OAM beam generators based on the arrow-based fractal metasurface are studied in this part. The phase distribution of the OAM metasurface can be expressed as [52]

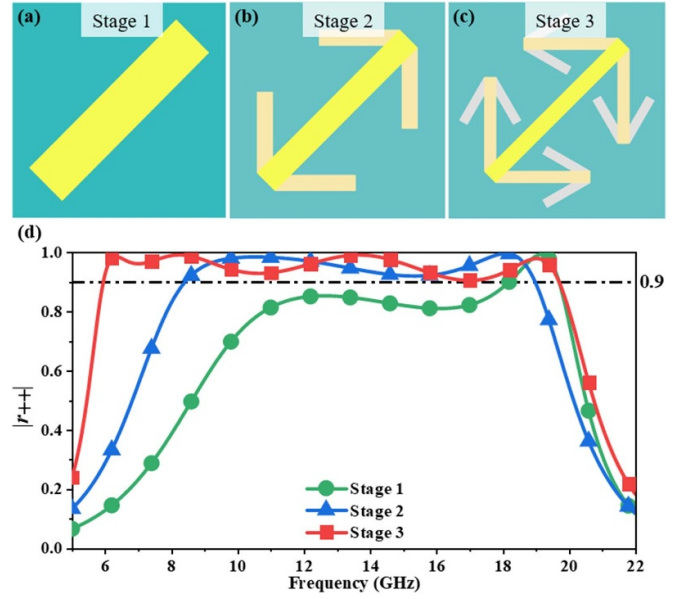


Figure 3. The design process of the fractal structure. (a)–(c) The schematic views of stage 1–3. The added rectangles in every stage are painted in different colors. (d) The simulated amplitude of co-polarized reflection coefficients in stage 1–3.

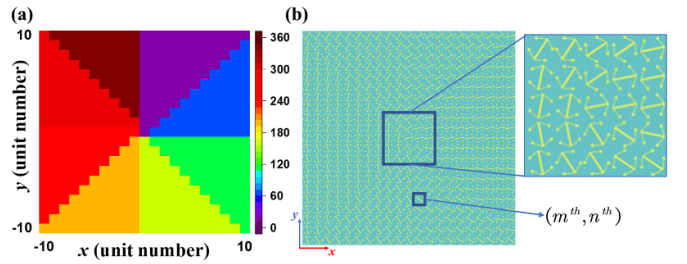


Figure 4. (a) The calculated phase distribution and (b) the layouts of the OAM metasurface (21×21) with $l = +1$.

$$\varphi(m, n) = l \tan^{-1} \left(\frac{n}{m} \right) \quad (6)$$

where l denotes the topological charge of the vortex beam, m and n represent the position coordinates of the (m th, n th) meta-atom in the x - and y -directions, respectively. Figure 4(a) demonstrates the phase distribution of the proposed OAM metasurface with a topological charge of $+1$ and an array of 21×21 meta-atoms. As can be seen from figure 4(a) that the phase distribution changes by 360° for a full turn circling the propagation axis. The metasurface is composed of 21×21 meta-atoms covering a total area of $168 \times 168 \text{ mm}^2$, which is shown in figure 4(b). Figure 4(b) also shows an enlarged part of the centre 5×5 meta-atoms.

Then, the full-wave simulations by CST Studio Suite are conducted to investigate the proposed OAM metasurface in the frequency range from 6 to 20 GHz. Figure 5 plots the simulated intensity and the phase distributions of the RHCP field (E_R) at 6, 10, 12, 14, 16, 18, and 20 GHz under RHCP plane wave excitation. The incident plane waves are sampled at a distance $z = 300 \text{ mm}$ from the vortex beam generator.

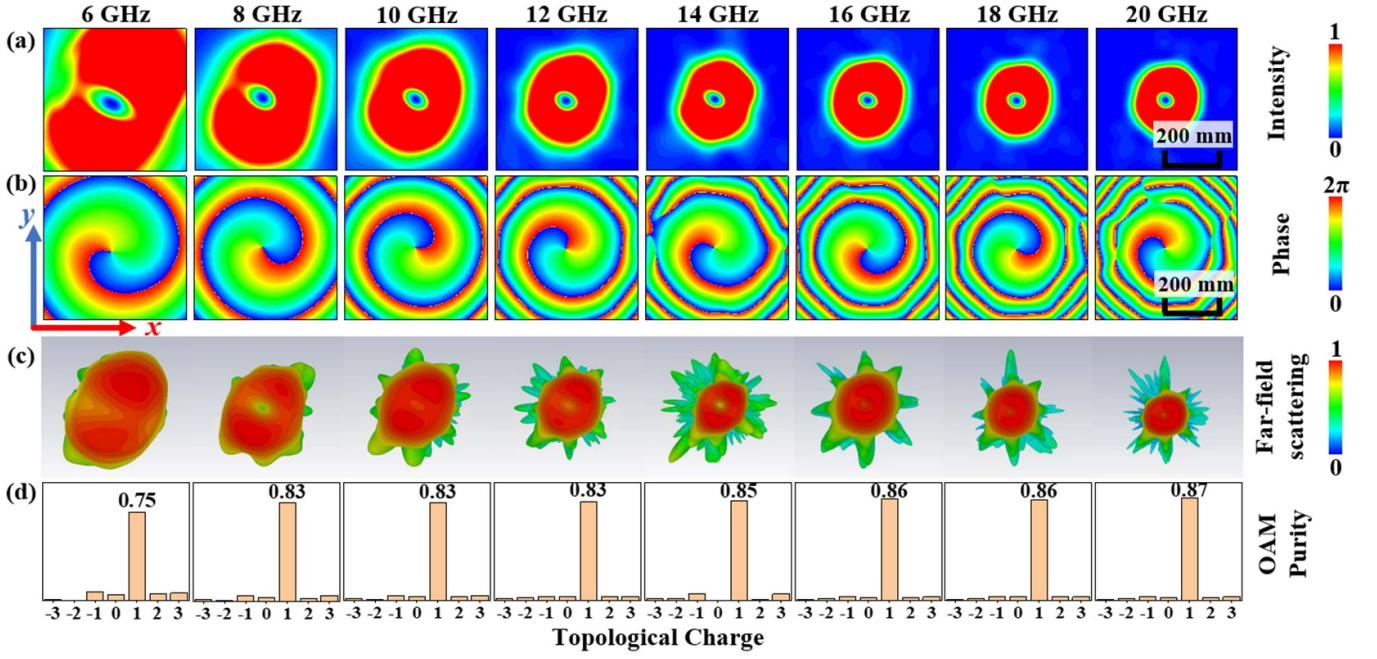


Figure 5. The simulated results of the OAM metasurface with $l = +1$ from 6 to 20 GHz with a step of 2 GHz. (a) Intensity, (b) phase distributions, (c) far-field scattering patterns, and (d) the calculated OAM purities.

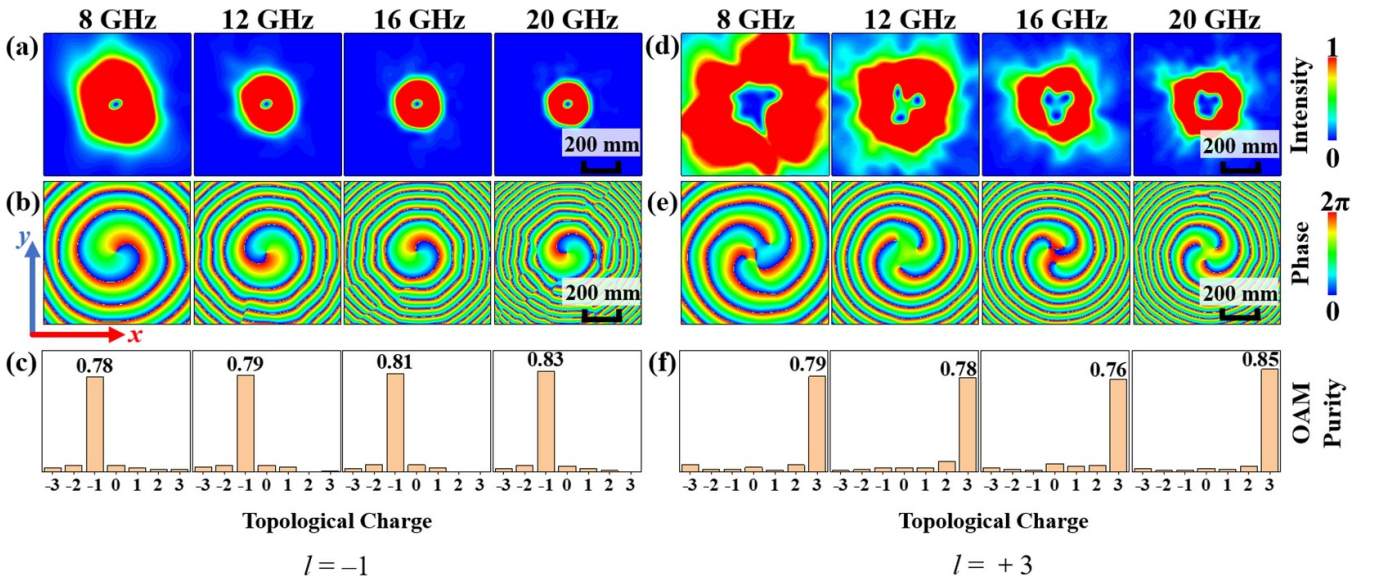


Figure 6. The simulated results of the OAM metasurfaces with $l = -1$ from 8 to 20 GHz with a step of 4 GHz. (a) Intensity, (b) phase distributions, and (c) OAM purities in the xoy plane. The simulated results of the OAM metasurfaces with $l = +3$ from 8 to 20 GHz with a step of 4 GHz: (d) intensity, (e) phase distributions, and (f) OAM purities in the xoy plane.

All the patterns in figures 5(a) and (c) are normalized values. Figure 5(a) shows the intensity distributions of the E_R and the characteristic amplitude nulls resulted from the phase singularity exist at the central regions, which can be also observed in the far-field patterns shown in figure 5(c). In figure 5(b), it is found that the major feature of the spiral phase distributions is obtained, and its phase characteristics of topological charge $l = +1$ can be well recognized. Furthermore, the concept of OAM spectrum could be introduced

for numerically quantitative exploration of the OAM mode purity. The fast Fourier transform algorithm is adopted in the calculation of OAM spectrum and the Fourier transform analysis of OAM mode purity A_l can be calculated as [53]

$$A_l = \frac{1}{2\pi} \int_0^{2\pi} \psi(\varphi) e^{-jl\varphi} d\varphi, \quad (7)$$

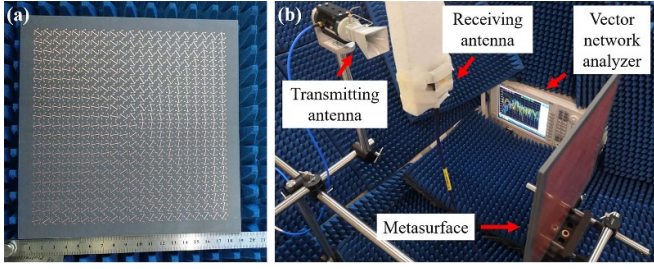


Figure 7. (a) The photograph of the fabricated ultra-broadband metasurface (21×21) with $l = 1$ and (b) the experimental setup.

where φ represents the azimuth angle and ψ is the value of the sampling phase. The calculated OAM purities from figure 5(b) depicted in figure 5(d) are higher than 0.75, which shows that the designed OAM mode $l = +1$ is the dominant part in the RHCP component of the reflected field at each frequency.

To further investigate the performance of the proposed method, two ultra-broadband OAM generators with different OAM mode numbers ($l = -1$ and $+3$) are also designed and simulated. The simulated intensity distributions, phase distributions and the calculated OAM purities are illustrated in figure 6. Amplitude nulls caused by the phase singularity can be clearly observed in figures 6(a) and (d) for the OAM generators. The rotation direction and spiral phase changes are determined by the topological charge, as shown in figures 6(b) and (e), respectively. For the spectral analysis of the generated vortex beam shown in figure 6(b) and (e), a high OAM mode purity of the dominant mode $l = -1$ ($l = 3$) shown in figure 6(c) and (f) can be obtained.

4. Experiments

For experimental verification, the metasurface-based vortex beam generator with $l = +1$ is fabricated and measured. The front view of the fabricated metasurface and the setup of experimental system are shown in figures 7(a) and (b), respectively. The transmitting antenna is a horn antenna (A-info LB-SJ-60180) operating from 6 to 18 GHz, which is connected to Keysight PNA Microwave Network Analyzer (N5227A) along with the receiving antenna. The distance between the transmitting antenna and the metasurface is 700 mm, and the receiving antenna could scan along x - and y -axes with a distance of 350 mm away from the metasurface.

The near-field experimental results at frequencies from 6 to 18 GHz with a step of 2 GHz are illustrated in figure 8, which can be compared with the numerical results in figure 5. Due to the limited working frequency bandwidth of the transmitting horn, the experimental results exclude results at 20 GHz. It can be seen from figures 5(a), (b) and 8(a), (b) that the numerically simulated results and experimental ones are in good

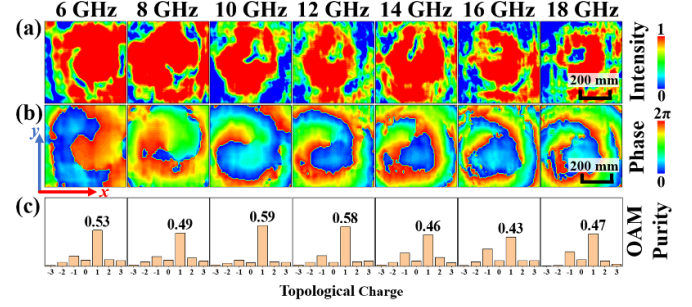


Figure 8. The experimental results of the fabricated metasurface with $l = +1$ from 6 to 18 GHz with a step of 2 GHz.

(a) Experimental intensity, (b) phase distributions, and (c) OAM purities in the xy plane.

agreement with each other. The donuts-like intensity profile and the spiral phase distribution can be observed in figures 8(a) and (b), respectively, validating the OAM performance of the fabricated metasurface. Moreover, the calculated OAM purities for $l = +1$ are around 0.5 for all the observation frequencies. Although the OAM purities are a little less than that in the simulations, the designed OAM mode still occupies the dominant part of the vortex beams as seen in figure 8(c). The discrepancy between the experiments and simulations could be caused by the fabrication tolerance and measurement precision.

5. Comparison with other works

To show advantages of the proposed arrow-based fractal metasurface, the comparison with other reported broadband metasurfaces is presented in table 1. Two reported representative works to design multilayer broadband OAM metasurfaces are numbered as [40, 41] for comparisons. As seen, the OAM metasurface in [40] is well optimized to feature a fractional bandwidth of 66.7%, but still with three layers and a large profile. The bilayer metasurface in [41] is designed with the dispersion engineering method for broadband operation with a fractional bandwidth of 86%. Owing to the fact that multilayer broadband OAM metasurfaces are bulky and require complex fabrication processes, several single-layer designs are also proposed. The fractional bandwidths of the rectangular-hole metasurfaces in [42] and the brick-shaped design in [43] are lower than 50%. The ultra-thin single layer metasurface reported in [44] could operate at both transmission and reflection modes simultaneously in a broad fractional band of 112% with a transmission/reflection efficiency of around 0.45. As for the square loop metasurface in [46], the achieved fractional bandwidth is 105% and the efficiency of the meta-atoms is higher than 0.8. In comparison, most of the reported designs are limited either by the bandwidth or the efficiency, and the proposed reflection-type meta-atom in this work features an improved performance with higher efficiency and broader bandwidth, as well as the easy implementation of the single-layer structure.

Table 1. Comparison for wideband efficient metasurfaces proposed recently.

Design	Layers	Operating frequency range	Meta-atom efficiency	Fractional bandwidth	Mode of operation
[40]	3	40–80 GHz	>90%	66.7%	Transmission
[41]	2	6.95–17.6 GHz	>89%	86%	Reflection
[42]	1	300–500 THz	>50%	50%	Transmission
[43]	1	18–28 GHz	>90%	43.5%	Reflection
[44]	1	9.3–32.5 GHz	~45%	112%	Transmission/Reflection
[45]	1	7.3–21 GHz	>92%	96.8%	Reflection
[46]	1	6.75–21.85 GHz	>80%	105%	Reflection
This work	1	6–19.7 GHz	>90%	107%	Reflection

6. Conclusion

In summary, an arrow-based fractal metasurface has been proposed to realize high-efficiency ultra-broadband OAM generators. The proposed reflection-type meta-atom could achieve the co-polarization reflection amplitudes higher than 0.9 under the CP illumination with a fractional bandwidth of 107.2% from 6 to 19.7 GHz. Based on the proposed meta-atom, high-performance OAM generating metasurface arrays with different topological charges are designed and numerically studied. Moreover, to verify the proposed arrow-based fractal meta-atom, the OAM metasurface with $l = +1$ is fabricated and measured. The experimental results agree well with the simulated results. The proposed method features low cost, easy integration to optical or wireless communication systems, and flexible extension to other frequency regimes. However, due to the fabrication tolerance, the evolving process could be limited to the first several stages. In addition, as other passive devices, the functionality of the metasurface could not be altered after design and fabrication. Nevertheless, the proposed method can be a promising candidate for high capacity data rate communication systems and other fields.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iD

Yiting Liu  <https://orcid.org/0000-0003-1046-6763>

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