Microstrip Reflectarray for Generation of Electromagnetic Waves with Beam Vorticity

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Abstract ─ One type of orbital angular momentum (OAM) reflectarray antenna is presented to radiate the electromagnetic wave with beam vorticity. Microstrip double square loops are adopted as the element for the proposed reflectarray. Reflect phase of the elements with various sizes are analyzed by HFSS software with periodic boundary condition and Floquet mode. Then massive elements with different sizes are arranged helically to form the reflectarray, transforming the incident spherical wave into a vortex phase front. Several OAM reflectarray examples with different OAM mode and different feed mode are designed and fabricated. The phase patterns of far-zone field are simulated by FEKO software and measured by near-field scanning system, which demonstrates the phase singularity and vortex.

Index Terms ─ Orbital angular momentum, reflectarray antenna, vortex electromagnetic wave.

I. INTRODUCTION

Recently, much attention has been focused on vortex electromagnetic waves. Vortex electromagnetic waves have helical phase wavefronts and can carry orbital angular momentum (OAM) [1], [2]. The OAM is related to beam vorticity and phase singularity, which contains infinity eigenstates theoretically. The eigenstates of OAM are mutually orthogonal to each other, so the OAM can be used to add communication channels without increasing the frequency bandwidth.

For vortex electromagnetic waves application, various antennas have been presented in literatures, such as the twisted parabolic antenna [2], circular antenna array [3], [4], open cylinder resonant cavity [5], planar-spiral phase plate (planar-SPP) [6], and so on. The planar-SPP proposed in [6] can be seen as transmit array to transform the incoming phase front into a desired outputting phase front, in which air holes in substrate are adopted as the unit cell to provide the phase shift.

Different from the planar-SPP presented in [6], another quasi-periodic planar structure based on the reflectarray theory can also be used to generate vortex electromagnetic wave. The reflectarray antenna can be seen as a hybrid of reflectors and arrays, which have been widely discussed and in-depth [7-9]. Recently, a reconfigurable graphene reflectarray has been proposed in [10] for the generation of vortex waves in THz band, in which graphene reflect units are adopted.

In this paper, the design of an OAM microstrip reflectarray is presented. The proposed reflectarray antennas adopt double square loops printed on the grounded substrate as the element and the linear polarization horn is adopted to provide an incident spherical wave as a primary source. Massive elements with different sizes are arranged quasi-periodically to transform the spherical wave to waves with OAM in different states.

For the OAM reflectarray, the key parameter are the phase response provided by the elements arranged in array lattice, which are specifically designed to compensate for the differential spatial phase delays from the feed and form a helical phase front on the reflectarray aperture. Double square loops are adopted as the element and analyzed in Section II. Several OAM reflectarray examples are presented and simulated in Section III, including with prime focus feed and offset feed. Some experimental results are shown in Section IV, and Section V is the conclusion.

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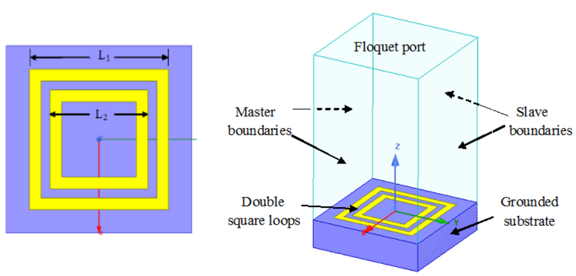
II. ELEMENT DESIGN

The OAM reflectarray antenna, presented in this paper is a quasi-periodic array illuminated by a horn. Double square loops, as shown in Fig. 1, are adopted as the element in view of its wide scope of phase response. The double square loops include an outer loop with edge length L_1 and an inner loop with edge length L_2. Different reflect phase response can be obtained by changing the edge length of the outer loop and inner loop. In order to create the anticipation aperture phase distribution to generate OAM, the scale of the element shall be varied according to its position.

Reflect phase of the element is analyzed by HFSS software with periodic boundary condition and Floquet mode, as shown in Fig. 1 (b). The simulated results are shown in Fig. 2, in which different ratio of the edge length between L_1 and L_2 are chosen. Other parameters of the double square loop are chosen as follows: width of the outer loop and inner loop are both 0.5mm, the substrate Rogers RT5880 and height 2mm, plus the periodic size 8mm and the frequency being 12.5GHz. It can be seen from the results shown in Fig. 2 that the wider scope of phase shift can be obtained if L_2 is more closed to L_1, and the slope of the curve will become steeper at the same time. According to the results, L_2 is chosen as L_2=0.7L_1 in this paper and then a phase shift range approach to 360 degrees is obtained by adjusting the edge-length of the outer square loop L_1 from 5.0mm to 7.5mm, which is enough to realize the arbitrary required phase distribution on the reflectarray.



(a) (b)

Fig. 1. Double square loops on a grounded substrate and its HFSS model: (a) double square loops, and (b) HFSS model with periodic boundary condition and Floquet mode excitation.

For designing the reflectarray, we shall seek the size of the elements according to the requested phase shift. So the curve of the reflect phase shift against the element size is fitted piecewise by the 2-order polynomial, as shown in Fig. 3. It's convenient for building the geometry model of the massive quasi-periodic array, and the edge length of the outer loop L_1 of the nth element can be calculated directly as:

$$L_1 = \begin{cases} -0.000015\beta_n^2 - 0.00093\beta_n + 7.5 & 0 \le \beta_n < 180 \\ 0.000062\beta_n^2 - 0.043\beta_n + 12.7 & 180 \le \beta_n < 360 \end{cases}, \quad (1)$$

where β_n is the requested phase shift (deg.) of the nth element.

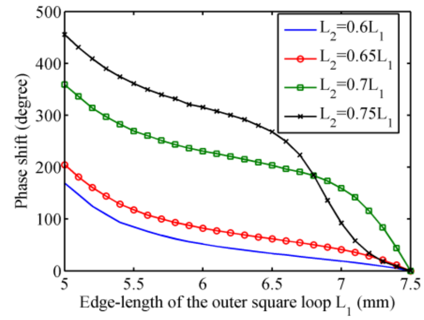


Fig. 2. Reflect phase shift of the double square loops element with different ratio between the outer loop edge length L_1 and the inner loop edge length L_2. The results are simulated by HFSS.

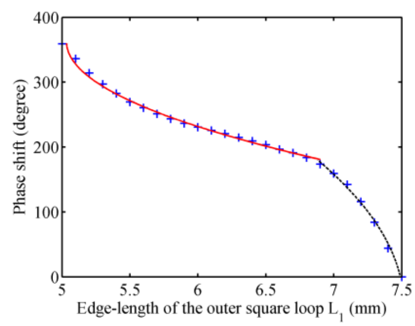


Fig. 3. Reflect phase shift of the elements with various sizes. The cross line is obtained from HFSS, while the red solid line and black dash line are fitting results.

III. THE ARRAY LAYOUT AND SIMULATED RESULTS

As shown in Fig. 4, a reflectarray is placed on the xy-plane. The reflectarray is illuminated by a y-polarization horn located at (x_f, y_f, F), where F is the distance between the aperture of the horn and the surface of the reflectarray elements.

The electromagnetic wave excited by the feed horn can be approximated as a spherical wave which originates from the center of the horn aperture. When the feed horn is adopted to illuminate the reflectarray, there are some non-uniform phase distributions for the incident wave on the aperture of the reflectarray. Then the phase shift of each element is designed to compensate for the spatial delay of the incident wave, and provide a vortex phase distribution on the aperture that generates a wave with beam vorticity at the specific direction

Assume the beam direction is perpendicular to the aperture of the proposed reflectarray. In order to create vortex phase front, the requested phase shift for the element located at (x_n, y_n) can be written as:

$$\beta_n = l\varphi_n + k_0\left(\sqrt{(x_n - x_f)^2 + (y_n - y_f)^2 + F^2} - \sqrt{x_f^2 + y_f^2 + F^2}\right), \quad (2)$$

where l is the OAM mode number, φ_n is the azimuthal angle of the element position. In the right of Equation (2), the second part represent compensating for the differential spatial phase delays from the feed, and the first part is used to form the request vortex phase front.

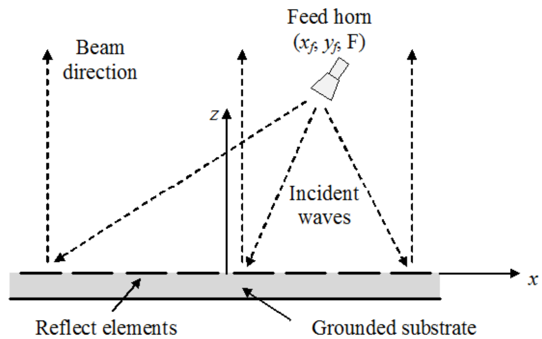


Fig. 4. Configuration of the reflectarray illuminated by a horn located at (x_f, y_f, F). The beam direction is perpendicular to the reflect elements surface.

A. Prime focus feed OAM reflectarray

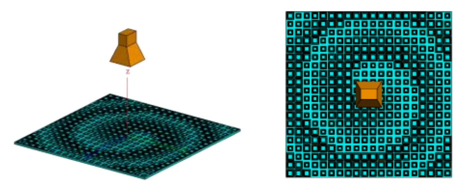
The design examples of prime focus feed OAM reflectarray are presented firstly. The mode number of the OAM is chosen as “1” and “2” respectively. The scale of the reflectarray D×D is 160mm×160mm and the number of the elements is 20×20. The feed horn is located at (0, 0, F), and F is chosen as 80mm, which means F/D=0.5. By using Equation (2), size of each element can be calculated

Because of electrically large size, combined with massive elements and thin dielectric layer, the full-wave simulation is a challenging task for the reflectarray. The surface meshing approach will be more appropriate than the volume meshing method for this problem [11]. As such, the multi-level fast multipole method (MLFMM) based on integral equation and method of moment (MoM) technique is more effective than other numerical techniques such as finite element method or finite difference method. Then the commercial MLFMM software FEKO v.7.1 is adopted here for full-wave simulation of the reflectarray. The reflectarray modeled in FEKO with OAM mode l=1 is shown in Fig. 5. The simulated gain pattern and phase pattern is shown in Fig. 6, in which the phase pattern is obtained on a plane $50\lambda_0$ away from the reflectarray. The observation distance $50\lambda_0$ is only an example, and arbitrary distance which is much large than wavelength can be chosen.

For the simulation of this example, FEKO uses 1348 metallic triangles in free space, 56,486 metallic triangles that coincide with the surface of a dielectric, and 28,552 triangles for the surface of a dielectric to mesh the model. 232,916 unknown basis functions need to be calculated by the FEKO MLFMM solver. The peak memory usage during the whole solution is 13.31GB and the CPU time is 1854 seconds on a 4 core 2.80GHz Intel(R) Xeon(R) Dell Precision 7710 computer.

It can be seen in Fig. 6 that there is a radiation null at the beam direction and the phase varied from 0° to 360° around the center singularity point, which conforms to the vortex wave with “1” order OAM.

The FEKO model of the reflectarray with OAM mode l=2 is shown in Fig. 7, and the simulated results are shown in Fig. 8. The phase pattern is also obtained on a plane $50\lambda_0$ away from the reflectarray. It can be seen that the phase varied from 0° to 720° around the center singularity point, which conforms to the vortex wave with “2” order OAM.



(a) (b)

Fig. 5. FEKO model of the reflectarray with OAM mode l=1: (a) perspective view and (b) top view.

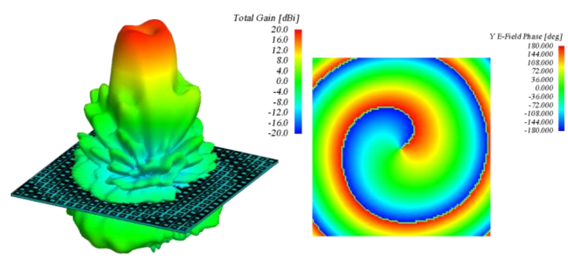
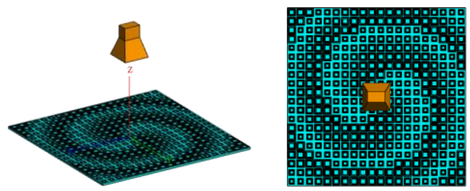


Fig. 6. Simulated results for the 1 order OAM reflectarray: (a) gain pattern and (b) phase pattern.

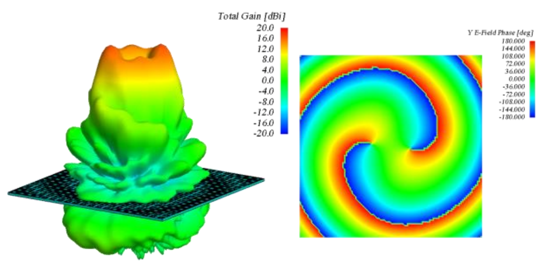
B. Offset feed OAM reflectarray

The OAM reflectarray can also be designed as offset feed configuration. Assuming the feed horn is located at (0, -D/2, F), substitute the y_f in Equation (2) with -D/2 and build the layout of the reflect elements for the vortex beam with OAM mode l=1, as shown in Fig. 9. The beam direction is assumed perpendicular to the reflectarray surface. It can be seen that the layout of elements for offset feed is much different to the case of prime focus feed. The elements are not arranged helically but more complicated.



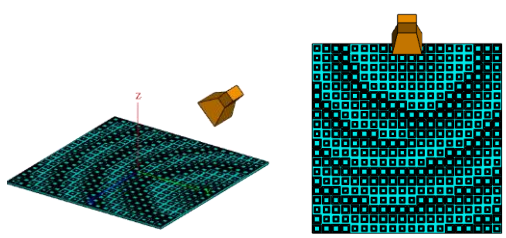
(a) (b)

Fig. 7. FEKO model of the reflectarray with OAM mode *l*=2: (a) perspective view and (b) top view.



(a) (b)

Fig. 8. Simulated results for the 2 order OAM reflectarray: (a) gain pattern and (b) phase pattern.



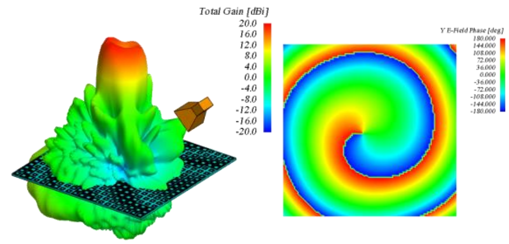
(a) (b)

Fig. 9. FEKO model of the 1 order OAM with offset feed: (a) perspective view and (b) top view.

The radiation pattern and phase pattern of the offset feed OAM reflectarray are shown in Fig. 10, which is obtained on a plane 50λ_0 away from the reflectarray and demonstrate the helical phase front and field singularity along the beam direction, which is in line with the radio vorticity well.

C. Discussion of the aperture efficiency

Because of the radiation null at the beam direction, it's ambiguous for evaluating the gain or efficiency of the OAM antenna as conventional antenna. A conversion efficiency for the OAM metasurface was considered in [12] as the ratio of the energy carried by the OAM wave to the total energy of the transmitted wave. This conversion efficiency can be seen as an OAM mode efficiency. In order to evaluate the gain of the OAM reflectarray, we introduce a relative efficiency here which is defined as the aperture efficiency relative to the twisted parabolic antenna [2] with same area and same feed source.



(a) (b)

Fig. 10. Simulated results for the 1 order OAM reflectarray with offset feed: (a) gain pattern and (b) phase pattern.

As example, the relative efficiency of the 1 order OAM reflectarray proposed in Part A is invetsgated. A twisted parabolic antenna with radius 90mm is established and modeled in FEKO. The twisted parabolic antenna has same aperture area and is fed by the same horn as that of the OAM reflectarray.

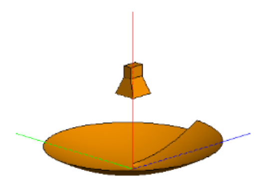
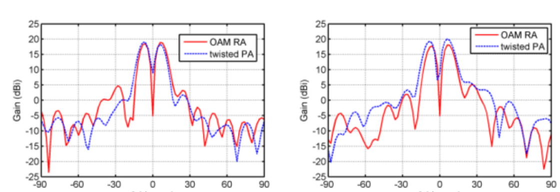


Fig. 11. FEKO model of the twisted parabolic antenna which is used as a referenced antenna to evaluate the aperture efficiency of the proposed reflectarray.

The FEKO model of the twisted parabolic antenna is shown in Fig. 11, and the simulated results of gain pattern are shown in Fig. 12, in which simulated results of the OAM reflectarray are also given. It can be seen that the gain patterns of the OAM reflectarray are approached to that of the twisted parabolic antenna and have about 1.8dB descrease than the latter in E-plane when θ is near to the beam direction. It means that the relative aperture effciency of the OAM reflectarray is about 66% relative to the twisted parabolic antenna. The decrease of the aperture efficiency can be attributed to the aperture shape and phase distortion.

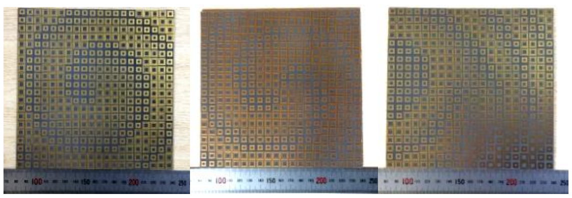


(a) (b)

Fig. 12. Gain pattern of the proposed OAM reflectarray and the twisted parabolic antenna: (a) H-plane (xoz-plane), and (b) E-plane (yoz-plane). In the label, OAM RA represents OAM reflectarry and twisted PA represents twisted parabolic antenna.

IV. PROTOTYPE AND EXPERIMENTAL RESULTS

The designed prototypes are fabricated using printed circuit board (PCB) technology and shown in Fig. 13, in which (a) is the 1-order OAM reflectarray with prime focus feed, (b) is the 2-order OAM reflectarray with prime focus feed and (c) is the 1-order reflectarray with offset feed.



(a) (b) (c)

Fig. 13. Photographs of the fabricated OAM reflectarrays: (a) OAM *l*=1 with prime focus feed, (b) OAM *l*=2 with prime focus feed, and (c) OAM *l*=1 with offset feed.

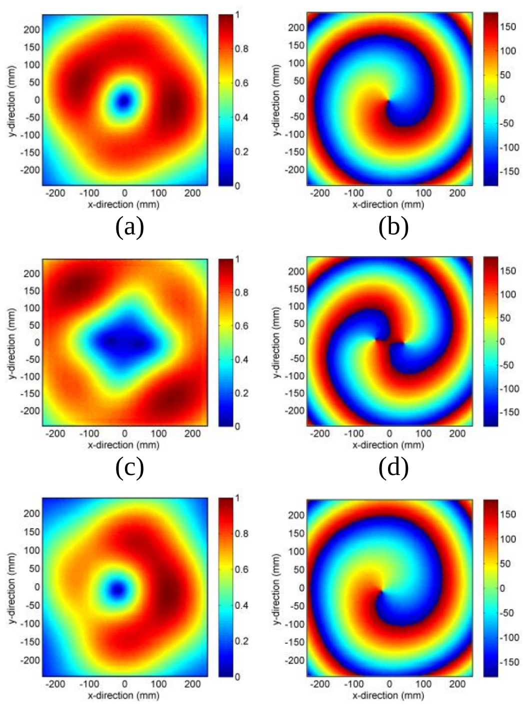


Fig. 14. The intensity patterns and the phase patterns of the OAM reflectarray propotypes. Those results are calculated from the measurement near-field data and plotted using Matlab code. The left-side figure (a), (c), (e) are the intensity patterns for the three prototypes shown in Fig. 13 respectively, and the right-side figure (b), (d), (f) are the phase patterns for those prototypes respectively.

The measure results of those prototypes are obtained by using a near-field scanning system in anechoic chamber. Electromagnetic fields near to the aperture of reflectarrays are measured and recorded. With aperture equivalence principle, a Matlab clode is developed to calculate the field patterns on the plane $50\lambda_0$ away from the reflectarray by using the near-field measurement data. The intensity patterns and the phase patterns of the three prototypes are shown in Fig. 14 and accord with thoe simulated results well.

V. CONCLUSIONS

Reflectarray technique is used to generate the vortex electromagnetic wave in this paper. Design of the reflectarray with different feed mode and different OAM mode has been demonstrated. The HFSS software is used to calculate the phase shift of the double square loops element and the FEKO software to simulate the OAM performance of the reflectarray. Prototypes and experimental results are introduced to validate the design. The proposed antenna in this paper can be used as a substitute for the twisted parabolic antenna to generate the electromagnetic wave with beam vorticity. The next step of our work is to develop an experimental transmit and receive system for radio vortex.

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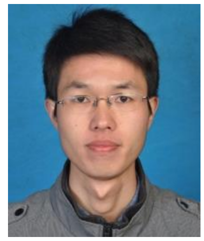

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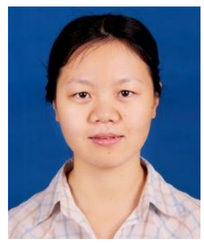

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