THz Pseudo-Bessel Beam Generation Base on Axicon-frustum Antenna Array

Han Huang1,2, Yongxi Zeng1,2, Weiyu Zhang1,2 and Yanzhong Yu1,2,*
1 College of Physics & Information Engineering, Quanzhou Normal University, Fujian, China
2 Key Lab of Information Functional Materials for Fujian Higher Education, Fujian, China

*Corresponding author email: yuyanzhong059368@163.com

Abstract. An axicon-frustum antenna array was designed. Circular microstrip antenna with coaxial feeding was taken as an element to place on concentric rings at equal intervals, constructing a phased axicon-frustum antenna array, which were then simulated and optimized by Ansoft HFSS. The results showed this antenna array can not only radiate a 0-order narrow beam with stable gain, but also generate a high-order radiation pattern with orbital angular momentum, which was demonstrated as an axicon-frustum antenna array which can generate pseudo-Bessel beams.

Keywords: Terahertz; Conical antenna array; Vortex beam; Pseudo-Bessel beam.

1. Introduction
A Bessel beam was firstly introduced into optics by Durnin et al. in 1987 [1], respectively. They are also named as non-diffracting beams and therefore possess some interesting properties. For example, the lateral size of it is very narrow, and the depth of field is excessively long. Many potential applications might be found in engineering. A new multiplexing method based on Orbit Angular Momentum (OAM) is of great interest to scientists due to the new degrees of freedom it brought about. L. Allen et al. [2] stated that each photon carrying OAM has an azimuthal angular dependence of $\exp(-il\phi)$, where $l$ is topological charge and $\phi$ is the azimuth angle, demonstrating that OAM is an attribute that can generate the beam with helical phase distribution. In 2007, Thide [3] generated electromagnetic waves with OAM eigenstates orthogonal to each other through array antennas, revealing that electromagnetic waves also have the characteristics of vortex-waves and promoting the research of vortex electromagnetic waves in wireless frequency band to a new era. In 2011, through OMA coding with a transceiver antenna, Tamburini [4] realized the transmission of multi-channel signals on the same frequency band without mutual interference due to the information carried by the angular momentum. In 2013, Bennis [5] generated vortex wave with topological charge number $l = 1$ by metasurface. Dr. Zelenchuk [6] realized circularly polarized vortex wave radiation by controlling the phase delay at different positions in each ring unit. In 2015, Dr. Zhou Shouli has successively published two papers [7][8] on vortex waves, which describe how to utilize antenna arrays to realize vortex waves in C and Ku bands independently. In terahertz band, Li Yao [9] implemented antenna array with metasurface to realize vortex wave beam. Lemaitre-Augur et al. [10] proposed that pseudo-Bessel beams with finite energy, limited lateral dimensions and eventual divergence can be realized through a regular hexagonal antenna array composed of 91 antenna elements, where the divergence starts from the outermost side lobe, followed by the divergence from the second outer side lobe and
eventual divergence from the main lobe. This paper designed an antenna array to generate pseudo-Bessel beam with spiral phase distribution. Circular microstrip antenna elements were simulated by Ansoft HFSS to obtain the antenna element size operating at about 102 GHz after global optimization, followed by a separate construction of planar and conical phased microstrip antenna arrays with ninety antenna elements designed previously.

2. Antenna Design

2.1. Antenna Element Design

Coaxial feeding was implemented to reduce the mutual interference among the large quantity of antenna array elements involved and circular microstrip antennas were selected for convenience of adjustment, with the structure as shown in Figure 1. The antennas elements, from top to bottom, are circular patch, dielectric substrate, coaxial feed and ground plate, respectively.

Figure 1. Circular microstrip antenna array element

Through the formula related to the microstrip antenna, the size of the circular microstrip antenna element was calculated and optimized by Ansoft HFSS to obtain the specific parameters of the array element satisfactory for the design, as shown in Table 1. In the table, \( a \) is the radius of the circular patch, \( L_D \) is the length of the square ground, \( L_s \) is the length of the substrate, \( H \) is the thickness of the dielectric substrate with FR4 as the material, \( F \) is the distance of the coaxial line from the origin, the inner diameter of the coaxial line is \( R \) with pec as its material. Figure 2 is the simulation result of an antenna array element. From the figure, the central working frequency of the antenna is \( f_c = 102 \text{GHz} \), the minimum return loss value is \( S_{11} = -29.27 \text{dB} \), where its \(-10\text{dB}\) bandwidth is about 3.96GHz, demonstrating that the antenna element has a good radiation function suitable for the construction of antenna array.

Table 1. Microstrip Antenna Sizes Working at 102GHz

| \( a \) | \( L_D \) | \( L_s \) | \( H \) | \( F \) | \( r \) |
|-------|-------|-------|------|------|------|
| 460nm | 1558nm| 1200nm| 75nm | 150nm| 12.0nm|

Figure 2. Return loss \( S_{11} \) of antenna array element
2.2. Antenna Array Design

A planar array and an axicon-frustum array are independently constructed through the aforementioned array elements, as shown in Figure 3. The center frequency $f_c = 102\,\text{GHz}$ corresponds to wavelength $\lambda = 2.941\,\text{mm}$, and the radius of the $i$-th circle of the circular ring array is $R_i = 3.0251 \times i$ with equal-interval distribution of antenna array elements on its circumference. Afterwards, the coordinate of element on the x axis is taken as $(R_i, 0)$ to form a 90-element planar antenna array, as shown in Figure 3(a). The axicon-frustum antenna array is constructed by setting the tilt angle as $\alpha = 5.2176^\circ$ so that the height of $i$-th layer (in the z propagation direction) is $h_i = R_i \times \sin \alpha \times \cos \alpha$, making the coordinate of element as $(R_i \times \cos \alpha, h_i)$. Therefore, a 90-element axicon-frustum antenna array is constructed by taking the radius of the $i$-th circle from the axis (i.e. z axis) as $R_i = R_c \times \cos \alpha \times i$ with equally spaced $6 \times i$ antenna array elements around the circumference, as shown in Figure 3(b). It is worth noting that the antenna element can be regarded as a point array element relative to far field, and the resulting antenna array can be treated as an axicon-like structure.

![Figure 3. Antenna arrays with two different structures. (a) 90-element planar antenna array; (b) 90-element axicon-frustum antenna array.](image)

3. Results and Discussion

The radiated electromagnetic wave, if fed with constant phase difference and equal amplitude on all elements of the uniform circular array antenna, will rotate around the array axis for one or multiple circles, generating vortex wave with spiral phase wavefront. Particularly, if all array elements of the antenna array are fed with the same amplitude and phase, the electromagnetic wave beam with OAM value $l = 0$ will be radiated. Otherwise, if following the setup aforementioned and prescribing the phase difference with equal amplitude as $\pm 60^\circ, \pm 30^\circ, \pm 20^\circ, \pm 15^\circ, \pm 12^\circ$ respectively (i.e. the innermost ring is $\pm 60^\circ$, the second ring is $\pm 30^\circ$, etc.), the electromagnetic wave beam with OAM value $l = \pm 1$ will be radiated. Besides, under the same condition but the phase difference is replaced with $\pm 120^\circ, \pm 60^\circ, \pm 40^\circ, \pm 30^\circ, \pm 24^\circ$, electromagnetic wave beam with OAM value $l = \pm 2$ will be radiated. Figure 4 and 5 shows the far-field 3D has more focused and stronger radiation of the axicon-frustum array as well as the planar array when $l = 0$. The first side lobe in convergence will be provided straight energy to main lobe. But it is not increased when the antenna elements is increase, almost remain the same. When the axicon-frustum antenna array of array is 60 elements, the electromagnetic wave radiated by the axicon-frustum antenna arrays is a pseudo-Bessel beam, which is a quasi-diffraction-free beam. In order to verify the higher-order electromagnetic wave is a kind of pseudo Bessel beam, We simulated vector field pattern in figure 6.
Figure 4. 3D and a gain diagram of planar and axicon-frustum antenna array when $l=0$ (a)(b) 60 elements planar antenna array; (c) (d) 60 elements axicon-frustum antenna array;

Figure 5. 3D and a gain diagram of planar and axicon-frustum antenna array when $l=0$ (a)(b) 90 elements planar antenna array; (c) (d) 90 elements axicon-frustum antenna array;
Figure 6 show the diagrams of vectored field with OAM in different modes. When mode \( l = 0 \), the antenna array radiates electromagnetic waves without spiral phase wavefront. If \( l = +1, +2 \), a clockwise spiral phase wavefront is obtained. Similarly, if \( l = -1, -2 \), a counterclockwise spiral phase wavefront is obtained. Furthermore, there are 2 lobes in the vectored electric field when \( l = \pm 1 \), while there are 4 lobes in the vectored electric field diagram when \( l = \pm 2 \). It is worth noting that, as shown in these figures, the aperture of the antenna array becomes larger with the increase of the number of array elements, leading to larger distribution area and easier outward divergence of the vectored electric field. That is, it's a quasi Bessel beam.

![Figure 6. Vectored electric field diagram of 60-element axicon-frustum antenna array. (a) \( l = 0 \); (b) \( l = \pm 1 \); (c) \( l = \pm 2 \).](image)

4. Conclusion

In this paper, an axicon-frustum antenna array working at terahertz frequency with circular microstrip antennas as its elements was designed, which is similar to an axicon and can radiate pseudo-Bessel electromagnetic wave beams with diffraction-free characteristics. In particular, axicon-frustum antenna array radiates electromagnetic wave without spiral phase distribution when \( l = 0 \) and it, otherwise, radiates vortex wave with \( 2 \) lobes. Vortex wave radiated by this antenna array is expected to be implemented in terahertz communication, terahertz imaging as well as measurement, and other fields.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 61571271), the Natural Science Foundation of Fujian Province of China (No. 2018J01646; No. 2016J01760), and the Quanzhou Normal University Project of Innovative Entrepreneurship Undergraduate (No. 201810399080).

References

[1] Durnin J 1987 Exact solutions for nondiffracting beams. I. The scalar theory, J. Opt. Soc. Am. A, vol 4, No. 4, pp 651–654.

[2] Thidé B, Then H, Sjoholm J, Palmer K, Bergman J, Carozzi T D, Istomin Y N, Ibragimov N H, and Khamitova R 2007 Utilization of photon orbital angular momentum in the low-frequency radio domain, Physical Review Letters, vol. 99, No. 8, pp. 087701.

[3] Tamburini F, Mari E, Sponselli A, Romanato F, Thidé B, Bianchini A, Palmieri L, and Someda C G 2012 Encoding many channels on the same frequency through radio vorticity: first experimental test New Journal of Physics, vol. 14, No. 3, pp. 033001.

[4] Bennis A, Niemicr R, Brousseau C, Mahdjoubi K, and Emile O 2013 Flat plate for OAM generation in the milli-meter band Antennas and Propagation (EuCAP) 7th European Conference on. IEEE.

[5] Zelenchuk D, and Fusco V, 2013 Double split ring slot fss reflectarray for difference pattern generation Electronics Letter vol. 49, No. 1, pp. 10-11.
[6] Zhou S L, Yu Q, Lian X f, and An J S, 2015 Design of microstrip antenna array with electromagnetic radiation carrying orbital angular momentum(oam) at c-band, High Power Laser and Particle Beams, vol. 27, No. 6, pp. 188-191.

[7] Zhou S L, Gu Y F, Zao W L, Lian X f, and An J S 2017 Design of phased antenna array for gene-rating electromagnetic vortex in ku band Journal of Harbin Institute of Technology, vol. 49, No. 10, pp. 106-111.

[8] Li Y, Mo W C, Yang Z G, Lu J S, and Wang K J , 2017 “Generation of terahertz vortex beams base on metasurface antenna array,” Laser Technology, vol.41, No. 5, pp. 644-648.

[9] Y.A. Chen, 2017 Generation, Reception of Electromagnetic Vortex and its Applications in Imaging Beijing: University of Chinese Academy of Sciences , pp. 50-58.

[10] P Lemaitre-Augé, S Abielmona and C Caloz 2013 Generation of bessel beams by two-dimensional antenna arrays using sub-sampled distributions, IEEE Transactions on Antennas and Propagation, vol 61, No. 4, pp 1838-1849.