A Design of OAM Metal-only Transmitarray Antenna Using High-Transmission Slot-Type Jerusalem Elements

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Abstract **─** In this paper, an orbital angular momentum transmitarray antenna based on high-transmission slot-type Jerusalem elements is proposed. The equivalent circuit model of the proposed element is analyzed by the transmission line theory. Theoretical results calculated by MATLAB show that a four-layer element with non-identical layers can realize a similar phase range and a much higher transmission efficiency as that with identical layers. Using this method, the transmission magnitude is greater than −0.45 dB within a 360° transmission phase range. Based on the proposed element, a round aperture orbital angular momentum transmitarray composed of 648 elements is designed and simulated by HFSS. The results confirm that orbital angular momentum waves with l=+1 are successfully generated. The divergence angle and maximum gain are about 6° and 19.2 dBic, respectively. And the aperture efficiency with l=+1 is 11.3%.

Index Terms **─** High-transmission, metal-only, orbital angular momentum (OAM), transmitarray, transmission line theory.

I. INTRODUCTION

In recent years, wireless communication technology has been developed rapidly, which poses unprecedented challenges to the limited spectrum resources. As a new method to improve the spectrum efficiency, orbital angular momentum (OAM) [1-3] has aroused extensive attention, which has infinite eigen modes with transmission orthogonality.

To date, fruitful methods for generating OAM waves have been continuously proposed, such as spiral phase plates [4], parabolic antennas [3], and circular array antennas [5]. However, due to the disadvantages such as large size, complex structure, high cost, and narrow bandwidth, their further development and application are restricted. Recently, transmitarray antennas [6] have gradually become a hot candidate for OAM generation, which combine optical theory and array synthesis theory. By adjusting the transmission phase of each element in the array, the spherical waves radiated by the feed source can be converted into OAM waves in a specific direction.

In [7], a planar spiral phase plate composed of double-layer split-ring transmitarray elements was proposed to generating OAM waves with l=+1. In [8], a transmitarray was designed to generated dual-mode OAM beam waves, which implemented the elements formed by two dual-polarized wideband microstrip antennas. In [9], a transmitarray for generating OAM beam waves was proposed by employing three-layer elements. Although these transmitarray antennas have successfully produced OAM waves, the element transmission loss of these transmitarray is up to 1 dB, even 3.9 dB, which may deteriorate the antenna radiation performance. Thus, it is necessary to design an OAM transmitarray with ultralow transmission loss.

In this paper, an OAM meta-only transmitarray antenna is presented by employing high-transmission slot-type Jerusalem elements with non-identical layers. The impedance matching condition based on the transmission line theory is applied to the element design, and hence a complete 360° transmission phase range with low transmission loss is obtained. An antenna prototype is designed, and simulated. The results confirm that OAM waves with l=+1 is successfully generated.

II. HIGH-TRANSMISSION ELEMENT DESIGN

A. Design principle

Inspired by [10], a general model of the four-layer element with non-identical layers which is described as

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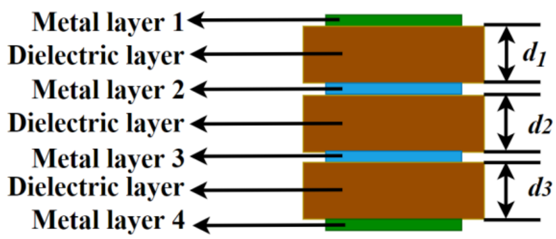
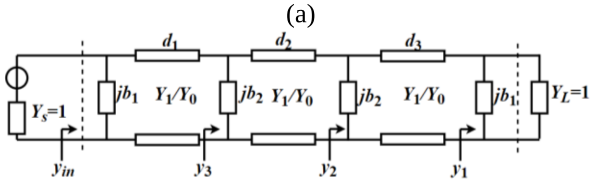
a combination of four metal layers and three dielectric layers with dielectric constant of ε_r, as shown in Fig. 1 (a). Metal layer 1 and 4 are the same, while metal layer 2 and 3 are the same. To simplify analysis, metal layers 1, 4 and 2, 3 are modelled as normalized pure susceptance jb_1 and jb_2, respectively. And the dielectric layers between two metal layers are modelled as the transmission line with the characteristic admittance of Y_1/Y_0 and the length of d_1, d_2 and d_3, respectively, as presented in Fig. 1 (b). Y_0 and Y_1 are the normalized characteristic admittance of free space and the dielectric layer, respectively. In addition, the air on the top and bottom sides of the four-layer element are equivalent to normalized susceptance Y_s and Y_L, respectively, and $Y_s = Y_L = 1$.



(a)



(b)

Fig. 1. The four-layer element: (a) the general model, and (b) the equivalent circuit model.

In the above design, according to the transmission line theory, it can be obtained:

$$y_1 = 1 + jb_1, \tag{1}$$

$$y_2 = (Y_1/Y_0) * \frac{y_1 + j(Y_1/Y_0)tan(\beta d_3)}{(Y_1/Y_0) + jy_1 tan(\beta d_3)} + jb_2, \tag{2}$$

$$y_3 = (Y_1/Y_0) * \frac{y_2 + j(Y_1/Y_0)tan(\beta d_2)}{(Y_1/Y_0) + jy_2 tan(\beta d_2)} + jb_2, \tag{3}$$

$$y_{\text{in}} = (Y_1/Y_0) * \frac{y_3 + j(Y_1/Y_0)tan(\beta d_1)}{(Y_1/Y_0) + jy_3 tan(\beta d_1)} + jb_1, \tag{4}$$

$$\beta = \omega\sqrt{\mu_0 \varepsilon_0 \varepsilon_r}, \tag{5}$$

$$Y_1 = \sqrt{\mu_0/\varepsilon_0 \varepsilon_r}, \tag{6}$$

$$Y_0 = \sqrt{\mu_0/\varepsilon_0}. \tag{7}$$

Where μ_0 and ε_0 are the dielectric constant and permeability in the free space. When $y_{in} = y_s = 1$, the impedance matching condition is satisfied. Assume that $d_1 = d_2 = d_3 = \lambda_0/4$ and ε_r=1 (λ_0 is the wavelength at center frequency), i.e., the dielectric layer is filled with air, then the relationship between b_2 and b_1 can be obtained:

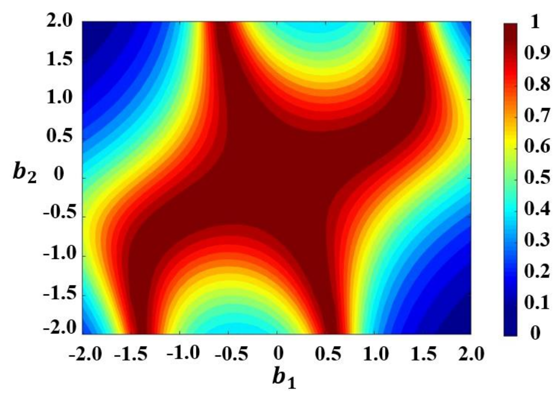
$$b_2 = \left\{ {Y_1}^2 b_1 \pm jY_1 \left[-\left({Y_1}^2 - \left(Y_0 {b_1}^2 + Y_0 \right) \right)^{1/2} \right] \right\} / \left({Y_0}^2 {b_1}^2 + {Y_0}^2 \right). \tag{8}$$

The transmission matrix of the normalized equivalent circuit between the dashed line in Fig. 1 (b) can be written as a cascade form of transmission matrices of a plurality of two-port networks, as follows:

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ jb_1 & 1 \end{bmatrix}^2 \begin{bmatrix} 1 & 0 \\ jb_2 & 1 \end{bmatrix}^2 \begin{bmatrix} 0 & j\frac{Y_1}{Y_0} \\ j\frac{Y_0}{Y_1} & 0 \end{bmatrix}^3, \tag{9}$$

$$S_{21} = \frac{2}{a + b + c + d}. \tag{10}$$

Then the transmission magnitude and the corresponding transmission phase are calculated by equation (9) and (10) in MATLAB, as shown in Fig. 2. Since there is no linear relationship between b_1 and b_2, there are two matching trajectories. One matching trajectory is with $|b_1|$ lower than 2 and $|b_2|$ lower than 0.58 and another is with $|b_1|$ lower than 2 and $|b_2|$ lower than 1.5, which form the red area in Fig. 2 (a). Seen from Fig. 2 (c), a 360° phase range with transmission magnitude greater than −0.45 dB is achieved. Thus, it is necessary to design a one-layer structure whose equivalent susceptance b can cover the variation range from -2 to 2.



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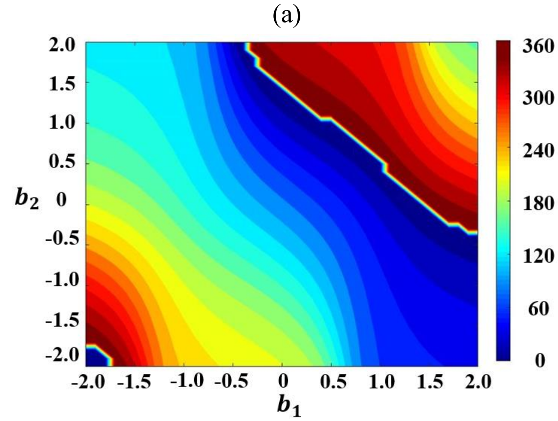

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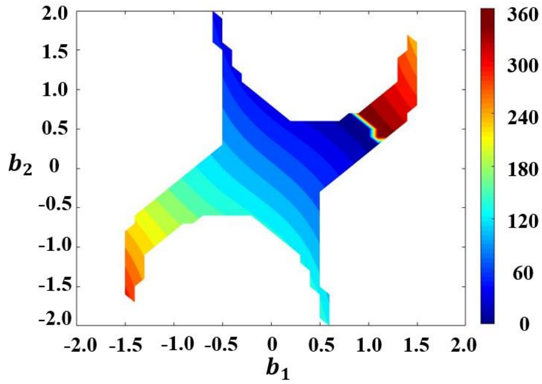


(c)

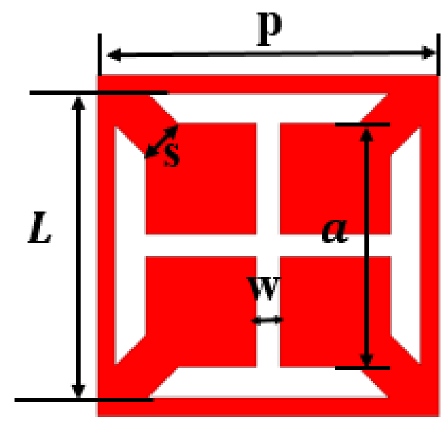
Fig. 2. The transmission characteristic of four-layer elements calculated by MATLAB: (a) transmission magnitude, (b) transmission phase, and (c) transmission phase for magnitude > - 0.45 dB.

B. Element design

Due the advantages of the metal-only structure [11], such as low cost and low loss, a metal-only slot-type Jerusalem metal layer etched on the 0.2 mm aluminum plate is designed, as shown in Fig. 3 (a). The operation frequency is 6 GHz and the period are 15 mm ($0.3\lambda_0$). Full wave electromagnetic simulation software (HFSS) is used to analyze the proposed metal layer which is surrounded by the periodic boundary conditions and illuminated by Floquet port. The capacitive and inductive equivalent susceptance can be realized by changing the size of the designed metal layer. As plotted in Fig. 3 (b), it can be seen that the equivalent susceptance changes from -3.3 to 2.3 when L varies from 11 mm to 14.5 mm, which meet the design requirements of the metal layer.

The simulation of the proposed element composed of four non-identical slot-type Jerusalem metal layers is also conducted in HFSS. The element is divided in two groups, the middle two layers form a group, and the other two layers form another group, as shown in Fig. 4. The structures in two group are exactly the same, but the sizes are different. In this design, d=$\lambda_0/4$, p = 15 mm, $a_1 = 0.8 \times L_1$, $a_2 = 0.8 \times L_2$, s = 2 mm, w = 1 mm. And L_1 and L_2 range from 12 to 14 mm with a step size of 0.1 mm. The transmission coefficient distribution when L_1 and L_2 change from 12 to 14 mm is shown in Fig. 5, it can be concluded that the proposed element is able to cover the transmission phase range of 360° with transmission amplitude greater than -0.45 dB.

To investigate the difference between the transmission characteristics of elements obtained by equivalent circuit model in MATLAB and that obtained by full wave simulation in HFSS, some elements with different sizes are picked out, as shown in Table 1. Obviously, the transmission magnitude and phase obtained by full wave simulation in HFSS are slightly different from that obtained by equivalent circuit model in MATLAB. This is because the input impedance of the one-layer slot-type Jerusalem element may not be ideal pure susceptance, and the existence of conductance will lead to the increase in transmission loss.



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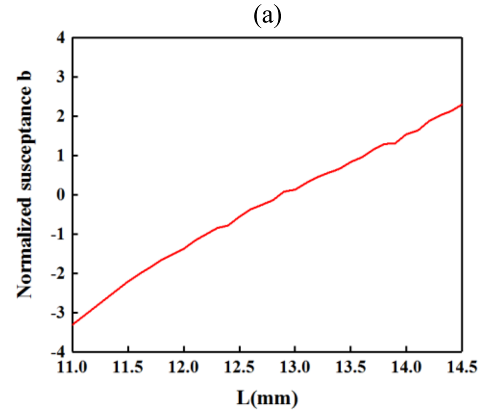


(b)

Fig. 3. The slot-type Jerusalem metal layer: (a) the model and (b) the equivalent susceptance b versus L.

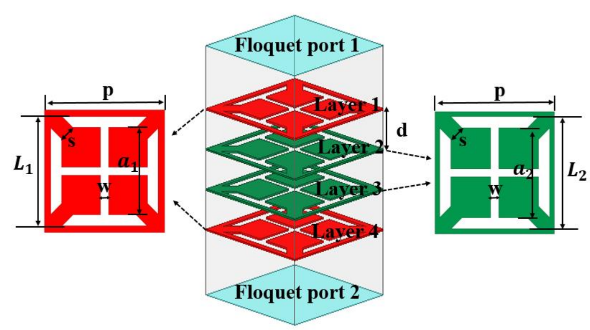


Fig. 4. The structure of the designed element.

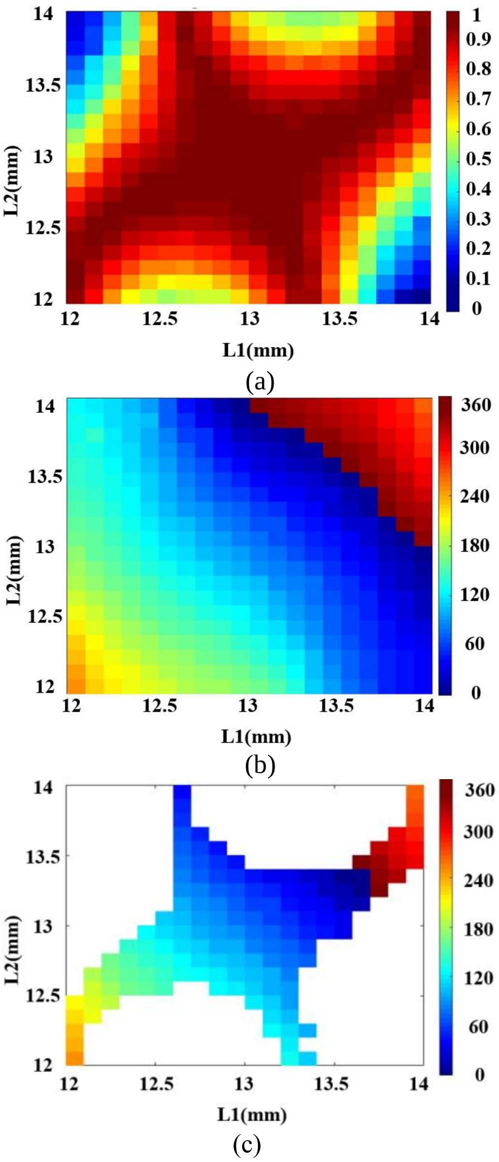


Fig. 5. The transmission coefficient of the proposed element when L_1 and L_2 change from 12 to 14 mm: (a) transmission amplitude distribution, (b) transmission phase distribution, and (c) transmission amplitude > -0.45 dB.

In particular, for OAM transmitarray antenna, because the far field radiation pattern of 3-bit quantization transmitarray is very close to the continuous ones [12], these eight elements in Table 1 are sufficient to form a transmitarray. Thus, to reduce the simulation time, in actual design, the theoretical dimension values L_1 and L_2 to achieve desired phase can be obtained by the corresponding relationship between dimension size and equivalent susceptance value in Fig. 3 (b), where the equivalent susceptance value is calculated by equivalent circuit model in MATLAB. Then the full wave simulation analysis of the designed element is carried out in HFSS.

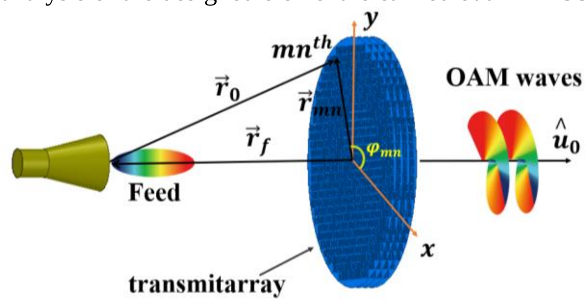


Fig. 6. The schematic of OAM transmitarray antenna.

Table 1: The transmission characteristics of some elements

	Circuit Model				Full-wave Simulation	
	b_1	b_2	$\lvert S_{21}\rvert$ (dB)	Phase (deg)	$\lvert S_{21}\rvert$ (dB)	Phase (deg)
1	0.5	1.0	0	0	-0.12	3.1
2	0.1	0.6	-0.09	48.8	-0.15	49.4
3	0	0	0	90	-0.09	90.2
4	-0.3	-0.5	0	136.4	-0.11	140.4
5	-0.5	-1	0	180	-0.12	178.4
6	-1	-1.2	0	222.6	-0.45	222.2
7	-1.5	-1.4	0	272.3	-0.23	272.2
8	0.9	1.3	0	312.7	-0.19	301.6

III. OAM TRANSMITARRAY DESIGN

Consider a planar circular aperture transmitarray that are illuminated by a horn at position vector $\vec{r}_f$, as shown in Fig. 6. $\vec{r}_{mn}$ is the position vector of the mn^{th} element, l is the desired OAM mode number which can be an arbitrary integer, and $\varphi(x_{mn}, y_{mn})$ is the azimuth angle of the mn^{th} element. To generate OAM beam waves, the phase compensation can be accomplished by varying the transmission phase $\phi(x_{mn}, y_{mn})$ of each element, which can be calculated as follows:

$$\phi(x_{mn}, y_{mn}) = k_0\left[\left|\vec{r}_{mn} - \vec{r}_f\right| - \vec{r}_{mn} \cdot \hat{u}_0\right] + l\varphi(x_{mn}, y_{mn}). \tag{11}$$

Based on the proposed element and the phase compensation equation (11), a transmitarray with circular aperture composed of 648 elements is designed to generate OAM beam waves with l=+1. $\hat{u}_0 = (0°, 0°)$ and a left-hand circular polarization horn antenna whose E-plane pattern can be represented as $cos^{8.5}\theta$ at 6 GHz is used as a feeding source. Its maximum gain is 15.2 dBi. And the distance between the phase center of the horn and transmitarray is about 490 mm. The corresponding phase distribution of the designed transmitarry is shown in Fig. 7.

Table 2: The comparison of the proposed antenna with other published designs

Refs.	Frequency (GHz)	Element			Array			
		Phase Range	Maximum Transmission Loss (dB)	Dielectric Layers	Size	OAM Mode	Gain (dBic)	Aperture Efficiency with l=+1
[9]	10	360°	1.94	With	$21.7\lambda_0^2$	+1	14.8	11%
[14]	60	360°	1	With	$144\lambda_0^2$	+1	21.5	7.8%
[15]	13.58	360°	1.5	Without	$45.7\lambda_0^2$	0	23.9	——
This work	6	360°	0.45	Without	$58.32\lambda_0^2$	+1	19.2	11.3%

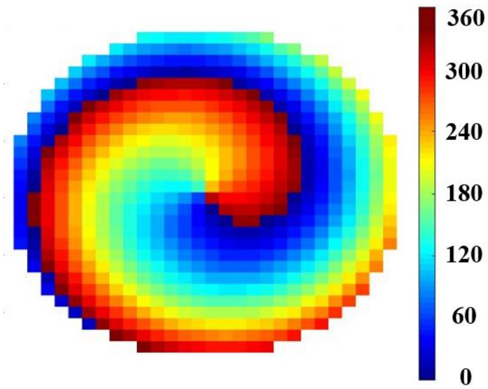


Fig. 7. The corresponding phase distributions of the designed transmitarray.

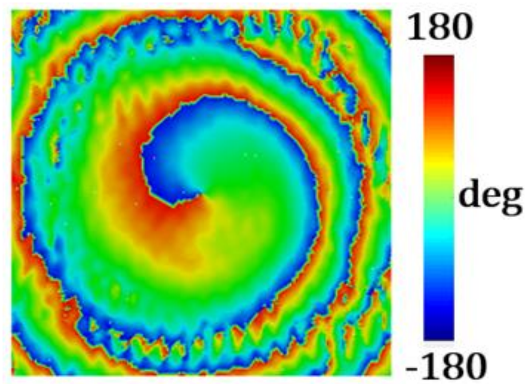
IV. SIMULATED RESULTS

The full-wave electromagnetic simulation software Ansys HFSS is used to analyze the proposed transmitarray antenna. To observe the characteristics of near-field *E*-field of the generated OAM beam waves, a test plane is set at a distance of 1 m in front of the transmitarray. The *E*-field characteristics of the OAM beam waves on the test plane is shown in Fig. 8. It is revealed that a doughnut-shaped magnitude is obtained in the generated OAM beam waves and a phase distribution varying from -180° to 180° is also observed, which is accord with the property of OAM waves of l=+1. The simulated two-dimensional (2-D) far-field radiation patterns at 6 GHz are plotted in Fig.9. It is clear that a zero-depth structure appears in the center of the beam which agrees well with the characteristics of OAM waves. The maximum gain is about 19.2 dBic and the divergence angle is 6°.

In addition, the OAM mode purity which can be calculated in [13] for the proposed transmitarray is shown in Fig. 10. It can be seen that OAM purity with l=+1 can reach up to around 90%. Besides, the maximum aperture efficiency of the antenna can be calculated by the following formula:

$$\eta = \frac{\lambda^2 G}{4\pi A}. \quad (12)$$

Where *G* represents the maximum gain of the antenna, and A represents the aperture area. Thus, the maximum aperture efficiency of the designed antenna is 11.3%, which is higher than that of 11% in [9] and 7.8% in [14].



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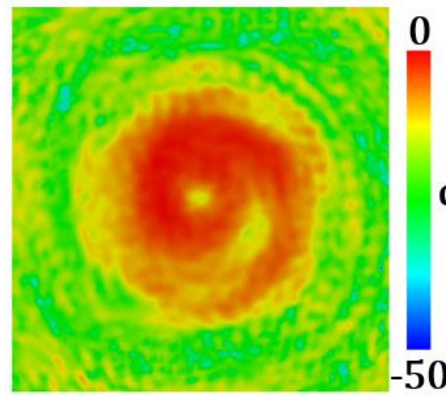

(b)

Fig. 8. The simulated *E*-field characteristics of the OAM beam on the test plane: (a) phase distribution and (b) magnitude distribution.

Finally, the element and array performances of the proposed transmitarray antenna are compared with other published designs, as summarized in Table 2. It can be clearly seen that the proposed element can achieve a 360° phase range with a much lower transmission loss.

Compared with [9] and [14], the proposed transmitarray antenna can generate OAM beam waves with much higher aperture efficiency.

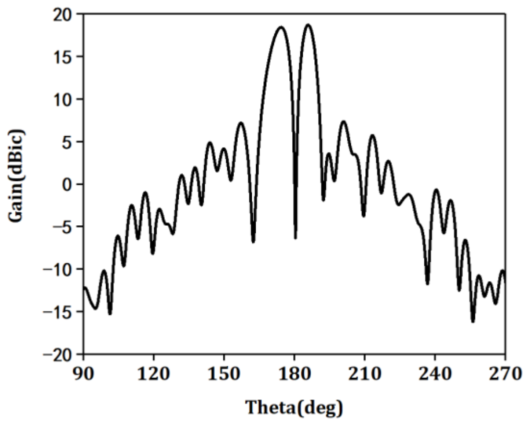

Fig. 9. The simulated 2-D far-field radiation patterns.

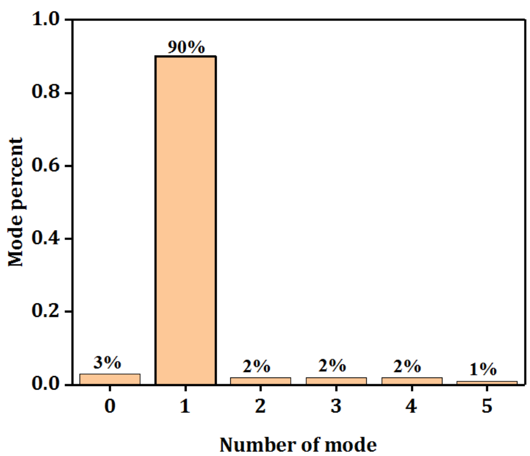

Fig. 10. The OAM mode purity for the proposed transmitarray.

V. CONCLUSION

In this paper, a transmitarray composed of 648 elements is designed to generate OAM beam waves with *l*=+1. A full 360° phase shift with transmission magnitude greater than -0.45 dB is obtained by using wavelength slot-type Jerusalem elements with non-identical layers. The full-wave electromagnetic simulation is used to analyze the proposed transmitarray and the simulated results confirm that OAM beam waves of *l*=+1 with high gain and small divergence angle have been successfully generated. The proposed design is an effective method to generate OAM beam waves for wireless communication applications.

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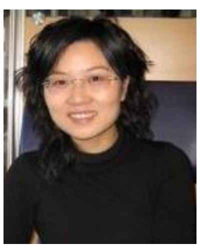

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