URSI GASS 2020, Rome, Italy, 29 August - 5 Sep. 2020

Vortex Beam Generation and Mode Conversion using Spiral-phase Transmitarrays

Arash Valizade Shahmirzadi*[1], Ahmed A. Kishk[2]
Department of Electrical and Computer Engineering, Concordia University, Montreal, Canada
[1]arash.valizade@concordia.ca
[2]kishk@encs.concordia.ca

Abstract

This paper presents a concept to generate vortex beams and their inter-mode conversion into each other using transmitarrays (TAs) consisting of circularly polarized elements. The novel circularly polarized unit-cell operates between 22.5-23.5 GHz of the ka-band. The novel presented unit cell has a compact profile and composed of three identical metallic sections which are placed on top and between a double-layer dielectric substrate. The designed TAs are composed of 12 × 12 elements, in which each unit-cell is rotated individually in order to generate the related phase distribution of the desired vortex mode. Through rotation of the unit-cells a full 360-degree spiral phase progression on the TA can be obtained. Using several TAs with different phase distributions, the mode of the resultant propagating vortex wave can be changed in space. The simulated results for vortex beams of modes 1, 2, and 3 show desirable inter-mode conversion.

1 Introduction

Recently, tremendous attention has been focused on the vortex electromagnetic waves for their potential to increase the data transmission rate in modern communications. The spiral phase front of the vortex beam carries orbital angular momentum (OAM). Theoretically, OAM has an infinite number of eigenstates that are orthogonal to each other. This orthogonality of OAM modes can be used as a diversity resource for increasing the communication channel capacity [1]. Moreover, since the vortex beam is a localized wave that carries orbital angular momentum OAM, it is suitable for several other applications as well, such as small particle tweezing, and high accuracy short-range imaging.

Vortex beams have a progressive helical phase of $exp(il\phi)$, in which ϕ is the azimuthal transverse angle and l is the topological charge which is an unbounded positive or negative integer that determines the mode of the OAM [2].

Several techniques have been recently proposed for vortex beam generation, including circular phased-array antenna [3], open cylindrical resonant cavity [4], and spiral-phase plates [5]. The non-planar spiral phase-plate in [1] utilizes machined helical dielectric cylinders. The reflectarray presented in [2] has a planar structure and consists of two fully metallic plates but it suffers from the blockage problem which is a common issue in all center-fed reflectarray based designs. The perforated dielectric spiral-phase plate in [5] works as a TA in order to generate the desired spiral phase distribution. However, substrate perforation requires drilling holes with various diameters on dielectric materials which can be a challenging and time-demanding process.

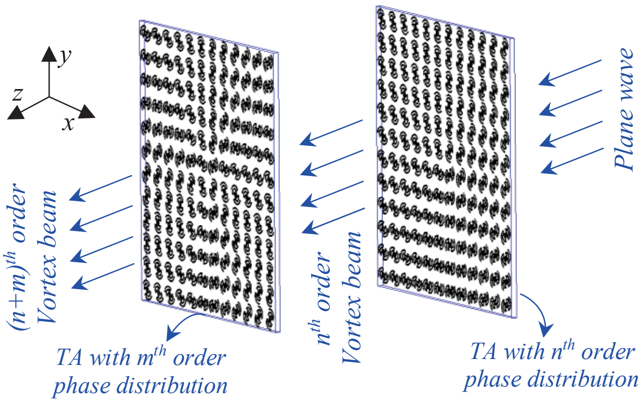


Figure 1. The concept of inter-mode conversion for vortex beams

In this paper, in order to generate vortex beams of various modes, planar TAs based on printed circuit board technology (PCB) are utilized. In the design of all TAs, a single unit-cell is used as the array element. The required phase distribution is obtained by rotating the individual unit-cells employed on the array. The designed TAs are capable of generating vortex beams with various OAM modes, while having a compact and planar structure. Then, the inter-mode conversion of the vortex beams in space is achieved by integrating and combining multiple TAs into the wave transmission system.

2 Discussion

The OAM carrying vortex beam has unique properties that can be used in various applications. However, vorticity generation using a compact and small size device can be a challenging task, especially for higher-order modes. The mode state of the helical phase front of vortex beams which is determined by l in $exp(il\phi)$, is corresponding to the number of times that the wave experiences full 360° phase rotation on a plane transverse to the direction of propagation, for example, a vortex beam of mode 2 shows two 360° rotations at any transverse plane of observation. This means that in order to generate higher-order vortex beams with acceptable phase alteration resolution by a single spiral-phase device, larger apertures with denser elements distribution on the device must be employed. However, other techniques and measures can be employed and investigated in order to mitigate this drawback.

In this paper, we propose and discuss the multi-stage in space inter-mode conversion of vortex beams in order to achieve higher-order mode distributions. The concept of this method is illustrated in Fig. 1. As can be observed in this figure, at the first stage, a spiral-phase alteration of n^{th} mode is imposed to the plane wave by passing it through a TA with the required phased distribution on its aperture. Then at the next stage, the resultant n^{th} order vortex beam is passed through another TA of m^{th} mode, which in turn changes the spiral-phase distribution of the propagating wave and consequently the wave leaving the second TA will be a vortex beam of $(n+m)^{th}$ mode. This procedure can be continued and performed several times in order to generate any desirable inter-mode conversion of a vortex beam. The design procedure and the achieved results for the proposed technique are presented and discussed in the next sections.

3 Designs and Results

The phase of a wave passing through a unit-cell can be controlled by rotating the unit cell about its origin, if two criteria are satisfied. First, the unit-cell must be illuminated by a circularly polarized (CP) wave, and second, the hand of the polarization must change while passing through the unit cell. Then according to the calculus in [2] it can be shown that through rotating the unit cell about its origin by an angle of θ_r a phase shift of $\varphi = 2\times\theta_r$ will occur in the phase of the transmitted wave.

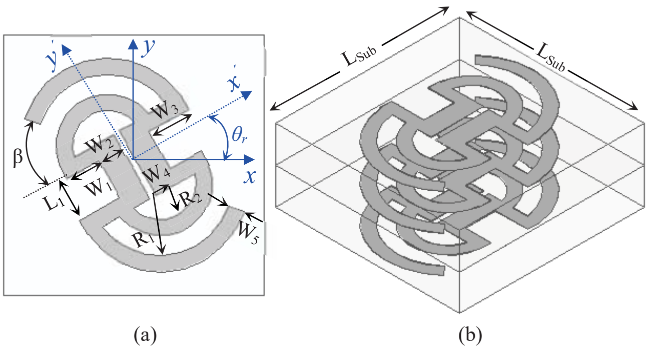
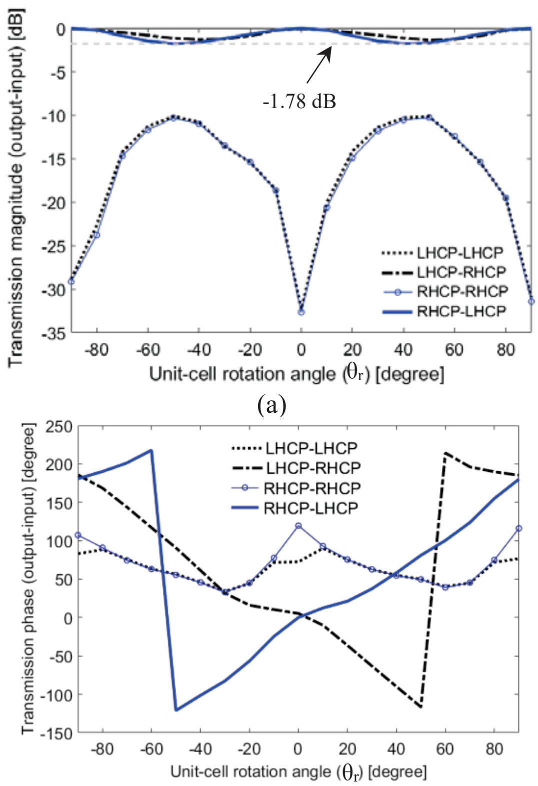


Figure 2. Proposed circular polarization converter unit-cell

CST Microwave Studio software is used for simulation studies. Fig. 1 illustrates the geometry of the proposed circular polarization converter unit-cell and its design parameters are provided in Table 1. The unit cell consists of two dielectric substrates (thickness of 1.575 mm and dielectric constant of 2.2) and three metallic sections are placed symmetrically above the substrates and between them. The simulation results at 23 GHz for amplitude and phase of the transmitted wave as a function of the unit-cell rotation angle when it is illuminated by normal circularly polarized waves are depicted in Figs. 2a and 2b, respectively. According to these results, the unit-cell is able to change the hand of circular polarization of the incident wave and also by its rotation, a full range of 360° phase shift is achievable. The insertion loss for all rotation angles of unit cell is less than 1.78 dB which is acceptable.

Table 1. Design parameters for unit-cell

Parameter	Value	Parameter	Value
L_{Sub}	8 mm	R1	2.2 mm
R_2	1.1 mm	W_1	1.1 mm
W_2	0.8 mm	W_3	1.4 mm
W_4	0.2 mm	W_5	0.5 mm
β	47°		



(b)

Figure 3. Simulated results for unit-cell with the rotation of the unit-cell for normal incidence of CP waves ("output" and "input" indicate the polarization of the transmitted and incident waves, respectively), (a) transmission amplitude, and (b) transmission phase.

Several TAs consisting of 12 × 12 elements for the generation of vortex beam with various OAM modes are designed based on the proposed unit-cell. For the generation of a vortex beam with a topological charge of l = 1, the unit cells were rotated along with their origin based on Equation (1) [2]:

$$\varphi(x,y)=\begin{cases} arctg\dfrac{y}{x}, & x>0,\ y>0 \\ arctg\dfrac{y}{x}+\pi, & x<0 \\ arctg\dfrac{y}{x}+2\pi, & x>0,\ y\le 0 \end{cases} \tag{1}$$

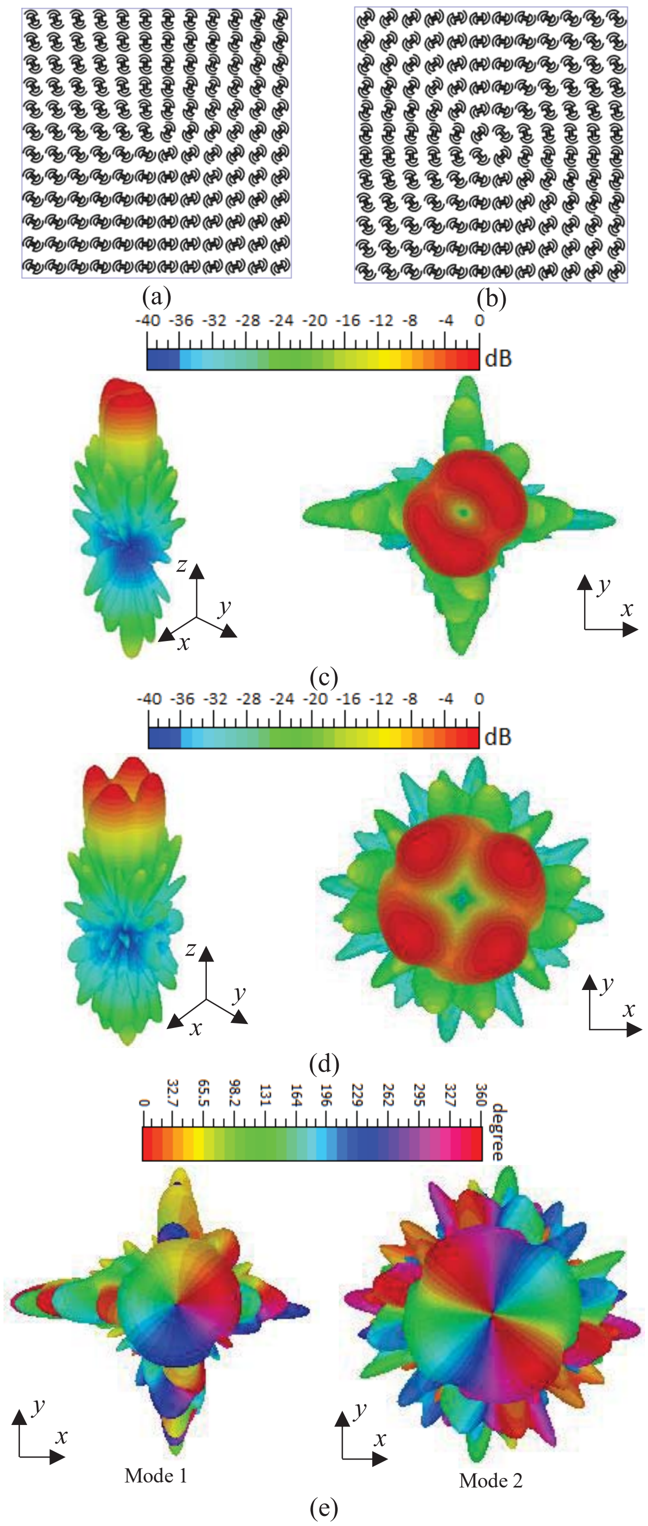


Figure 3. Designed vortex beam generator TAs based on the proposed unit-cell and simulated farfield results at 23 GHz: (a) mode 1 TA, (b) mode 2 TA, (c) 3D farfield radiation pattern for mode 1, (d) 3D farfield radiation pattern for mode 2, and (e) farfield radiation pattern phase distribution for modes 1 and 2.

The simulated farfield results for designed vortex beam generator TAs of mode 1 and 2 are depicted in Fig. 3. As can be observed in Fig. 3, the radiation pattern for mode 1 has a null at its center while the radiation pattern for mode 2 has 2 nulls in its center which are equal to the vortex beam. Moreover, as depicted in Fig. 3e, the phase of the radiation pattern for mode 1 experiences a single 360° variation on the transverse plane to the propagation direction, while the result for mode 2 reveals two full 360° phase rotation on the transverse plane.

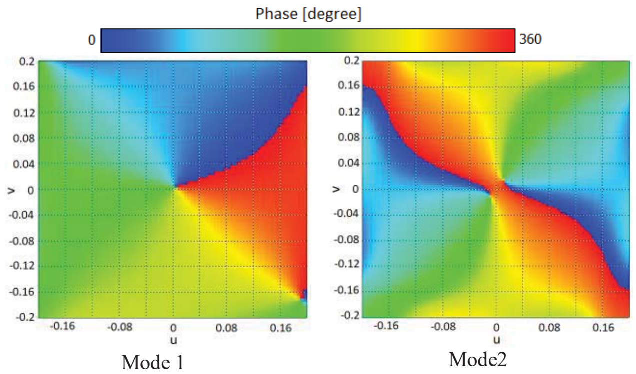


Figure 4. Simulated farfield phase distribution on the u-v plane for various TAs in Fig. 3.

This can be more clearly distinguished in Fig. 4, where the phase of the radiation patterns is plotted on the u-v plane. Consequently, it can be concluded that the designed TAs based on the proposed unit-cells are able to generate vertex beams of various modes by only changing the unit-cell elements rotation angles (θ_r).

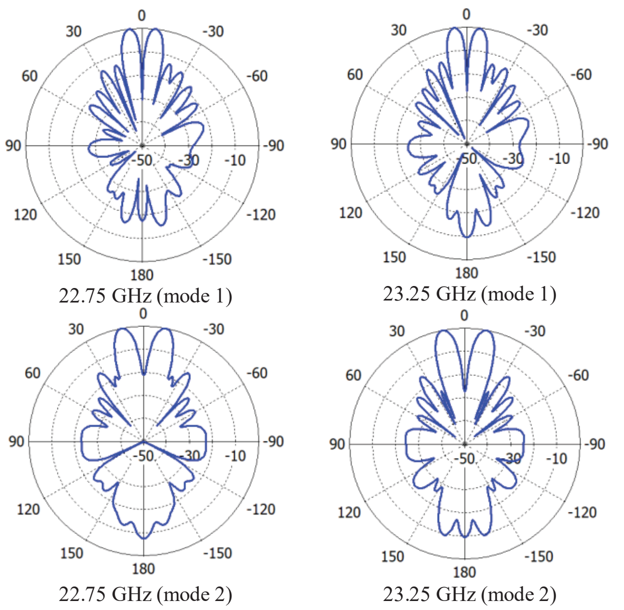


Figure 5. Polar radiation pattern for TAs in Fig. 3 at phi = 90°.

Additionally, the polar radiation pattern at two other frequencies for the TAs in Fig. 3 are presented in Fig. 5 and based on these results the designed TAs have consistent behavior through their frequency band of operation.

At the next step of this study, the integration of two TAs together and the possibility of generating a combined mode are investigated. Based on the configuration illustrated in Fig. 1, two different combinations are considered.

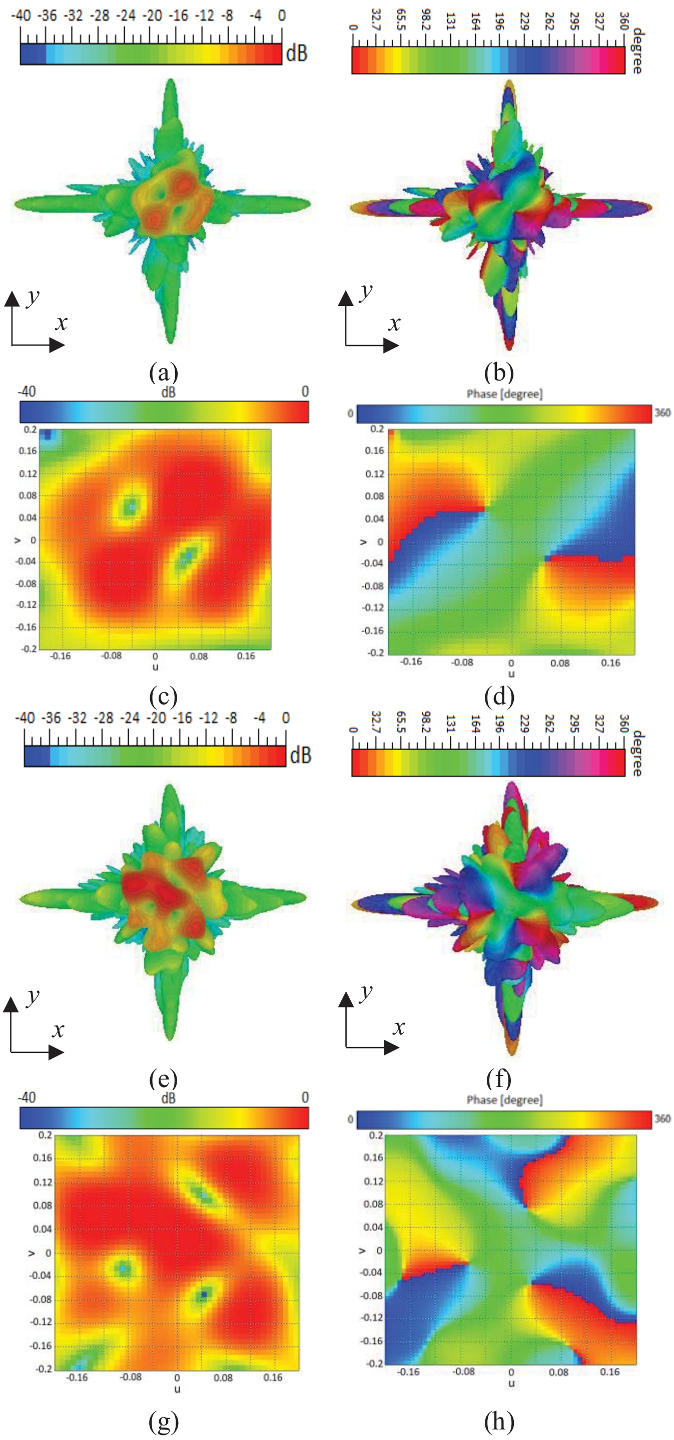


Figure 6. Simulated results for integrated TAs at 23GHz: (a-b) 3D magnitude and phase of the radiation pattern for mode 2 generated by two integrated TAs of mode 1, (c-d) magnitude and phase of the radiation pattern for mode 2 generated by two integrated TAs of mode 1 on the u-v plane, (e-f) 3D magnitude and phase of the radiation pattern for mode 3 generated by integration of TAs with modes 1 and 2, and (g-h) magnitude and phase of the radiation pattern for mode 3 generated by integration of TAs with modes 1 and 2 on the u-v plane.

Fig. 6 shows the obtained results for mode 2 (combining mode $l = 1$ spiral phase TAs twice) and mode 3 (combining a mode $l = 1$ and a mode $l = 2$ spiral phase TAs). The results in Figs. 6 a-d show that integrating two spiral TAs of mode $l = 1$, a vortex beam of mode $l = 2$, can be effectively generated in space.

The consequent beam characteristics depicted in Figs. 6 c-d show that the generated output beam has two nulls in its radiation pattern and also the phase variation experiences two fully covered 360º coverage which both verify the generation of vortex beam of mode 2. The corresponding results in Figs. 6 e-h verifies the generation of mode $l = 3$ OAM by combining a TA of mode 1 with a TA of mode 2. The results depicted in Figs. g-h show that there exist three nulls in the radiation pattern while the phase of the radiation pattern experiences three full 360º variation on the transverse plane to the direction of the propagation.

4 Conclusion

In this paper the generation of vortex beams using transmitarrays has been discussed. Moreover, a method based on the integration of multiple transmitarrays for the inter-mode conversion of vortex beams in space has been proposed. The performed simulations show that by utilizing the proposed method, various OAM modes can be generated and altered just by implementing various transmit arrays with different aperture phase distributions. Vortex beam carrying angular momentum can be a good and promising solution to several modern applications such as high data rate communication systems and high-resolution imaging systems

References

[1] G. A. Turnbull, D. A. Robertson, G. M. Smith, L. Allen, and M. J. Padgett, "The generation of free-space Laguerre-Gaussian modes at millimetre wave frequencies by use of a spiral phaseplate," Optics Communications, vol. 127, no. 6, June 1996, pp. 183–188, doi: 10.1016/0030-4018(96)00070-3.

[2] D. Zelenchuk, and V. Fusco, "Split-Ring FSS Spiral Phase Plate," IEEE Antennas aWireless Propagation Letters, vol. 12, February 2013, pp. 284–287, doi: 10.1109/LAWP.2013.2247735.

[3] T. Yuan, Y. Qin, Y. Cheng, and H. Wang, "Generation of OAM Radio Beams with Modified Uniform Circular Array Antenna," Electronics Letters, vol. 52, no. 11, May 2016, pp. 896-898, doi: 10.1049/el.2016.0269.

[4] Y. Chen, and S. Zheng, "Half-mode Substrate Integrated Waveguide Antenna for Generating Multiple Orbital Angular Momentum Modes," Electronics Letters, vol. 52, no. 9, February 2016, pp. 684-686, doi: 10.1049/el.2015.4416

[5] L. Cheng., W. Hong, and Z. Hao, "Generation of Electromagnetic Waves with Arbitrary Orbital Angular Momentum Modes," Nature Scientific Reports, no. 4, April 2015, pp. 1-5, doi: 10.1038/srep04814.