3D Printed Metasurface for Terahertz Orbital Angular Momentum (OAM) Generation and Multi-Dimensional Multiplexing

Xiaoyuan He, *Student Member, IEEE,* Yang Yang, *Senior Member, IEEE*

***Abstract*— Terahertz (THz) vortex waves, which feature different orbital angular momentum (OAM) modes and polarization states, hold tremendous potential in addressing the capacity crunch in future ultra-fast wireless communication systems. In this project, we propose a scheme to achieve multi-dimensional multiplexing of polarization and OAM domains using a single metasurface. Specifically, polarization-division multiplexing is achieved based on the Pancharatnam-Berry (PB) phase mechanism while OAM multiplexing is realized using an off-axis technique. In this way, different incidences featuring different incident angles and polarization states can be transformed into coaxial THz-vortex waves carrying different OAM modes, providing an effective approach of multi-dimensional multiplexing of polarization and OAM domains in the THz region.**

***Index Terms*— Orbital angular momentum (OAM), multi-dimensional multiplexing, metasurface**

I. Introduction

TERAHERTZ (THz) vortex waves carrying orbital angular momentum (OAM) have gained much interest owing to the ultrawide-band resources of terahertz waves [1] and the inherent orthogonality of OAM waves [2]. However, as the OAM mode increases, the beam divergence becomes problematic, which limits the number of OAM waves available for THz wireless communication. While approaches have been proposed to mitigate the diffraction of THz OAM waves [3], achieving OAM multiplexing while suppressing the divergence of multiple OAM waves remains challenging.

This project proposes a scheme for multi-dimensional multiplexing of polarization and OAM domains through a single metasurface. Specifically, the Pancharatnam-Berry (PB) phase mechanism is employed for polarization-division multiplexing of left-hand- and right-hand-circularly-polarized (LHCP and RHCP) waves, which doubles the number of THz-OAM waves for wireless communications without increasing the OAM mode. Meanwhile, an off-axis technique is adopted to identify different incidences, transforming them into orthogonal THz-vortex waves coaxially. For demonstration, a 3D-printed metasurface was designed to generate eight orthogonal THz-vortex waves at 140 GHz, demonstrating the efficiency of the proposed strategy.

This work was supported by the IEEE MTT-S Undergraduate/Pre-graduate Scholarship. Xiaoyuan He was with Beijing Laboratory of Advanced Information and Convergence, Beijing University of Posts and Telecommunications, Beijing, 100876, China, and also with the School of Electrical and Data Engineering, University of Technology Sydney, Ultimo, NSW, 2007, Australia. Yang Yang is with the School of Electrical and Data Engineering, University of Technology Sydney, Ultimo, NSW, 2007, Australia.

II. Design Theory

The proposed strategy for multi-dimensional multiplexing of polarization and OAM domains via a transmissive metasurface is shown in Fig. 1. The key to it is achieving polarization-division and OAM multiplexing.

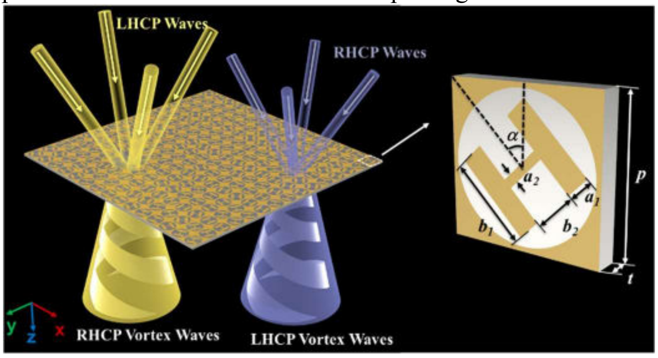

Fig. 1. Schematic illustration of multi-dimensional multiplexing of polarization and OAM domains via a transmissive metasurface. (a_1 = 96 μm, b_1 = 341.3μm, a_2 = 37.3μm, b_2 = 170.6μm, p = 597.3μm, t =90μm)

A. Polarization-Division Multiplexing

The geometry of the proposed anisotropic element is shown in Fig. 1. It is composed of an H-shaped resonator, a square ring and a dielectric layer made from ultraviolet curable acrylates ink (ε_{eff}=2.8, tanδ=0.013). To describe its working mechanism, a Jones matrix is introduced to describe the transmissive characteristics of the proposed element located at (x, y), which can be expressed by

$$J_{linear}(x,y)=R(-\alpha(x,y))\begin{bmatrix} j_x(x,y) & 0 \\ 0 & j_y(x,y)\end{bmatrix}R(\alpha(x,y)) \quad (1)$$

where $j_x(x,y)$ and $j_y(x,y)$ are the transmission coefficients in x- and y-axes, $\alpha(x,y)$ refers to the rotation angle of the proposed element, $R(\alpha(x,y))=\begin{bmatrix} \cos\alpha(x,y) & \sin\alpha(x,y) \\ -\sin\alpha(x,y) & \cos\alpha(x,y)\end{bmatrix}$. Therefore, the transmission coefficients for circularly polarized waves can be obtained by performing a liner-circular transformation:

$$J_{circle}(x,y)=C^{-1}R(-\alpha(x,y))\begin{bmatrix} j_x(x,y) & 0 \\ 0 & j_y(x,y)\end{bmatrix}R(\alpha(x,y))C \quad (2)$$

where $C=\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ -i & i\end{bmatrix}$. After some mathematical works, (2) can be simplified as

$$J_{circle}(x,y)=\begin{bmatrix} j_{LL}(x,y) & j_{LR}(x,y)\\ j_{RL}(x,y) & j_{RR}(x,y)\end{bmatrix}$$
$$=\begin{bmatrix} j_x(x,y)+j_y(x,y) & \left(j_x(x,y)-j_y(x,y)\right)e^{i2\alpha(x,y)}\\ \left(j_x(x,y)-j_y(x,y)\right)e^{-i2\alpha(x,y)} & j_x(x,y)+j_y(x,y)\end{bmatrix} \quad (3)$$

where $j_{LL}(x,y)$, $j_{LR}(x,y)$, $j_{RL}(x,y)$ and $j_{RR}(x,y)$ denote the transmission coefficients for circularly polarized waves. It can be learned from (3) that both incident LHCP and RHCP waves can be converted into their cross-polarization component with the same amplitude but opposite phase. Moreover, the transmission phases for RHCP and LHCP waves are $2\alpha(x,y)$ and $-2\alpha(x,y)$, respectively. The simulated transmissive characteristics of the proposed elements shown in Fig. 2 agree well with the theoretical results.

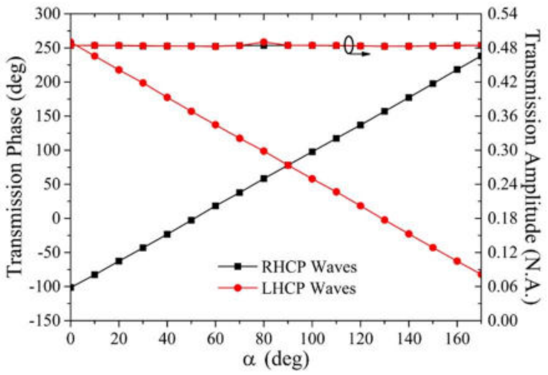

Fig. 2. Transmissive characteristics of the proposed element.

B. OAM Multiplexing

For OAM multiplexing, an off-axis technique is employed to isolate the input information in the spatial domain, as shown in Fig. 1. Assuming that the proposed metasurface is illuminated by n RHCP waves at (θ_i, φ_i), the desired phase pattern to convert them into coaxial OAM wave propagating towards the +z axis can be calculated as follows:

$$\phi_R(x,y)=2\alpha=\arg\left[\sum_{i=1}^{n}e^{jl_i\delta}e^{-jk(x\sin\theta_i\cos\varphi_i+y\sin\theta_i\sin\varphi_i)}\right] \quad (4)$$

where δ is the azimuthal angle, l_i refers to the OAM mode of the transmitted waves of the i^{th} RHCP incidences, and k denotes the wavenumber at 140 GHz. Therefore, the corresponding phase pattern for LHCP incidences is given by

$$\phi_L(x,y)=-2\alpha=\arg\left[\sum_{i=1}^{n}e^{-jl_i\delta}e^{-jk\left(x\sin(-\theta_i)\cos\varphi_i+y\sin(-\theta_i)\sin\varphi_i\right)}\right] \quad (5)$$

III. Realization of Multi-Dimensional Multiplexing

For proof-of-concept, a 3D-printed meatsurface was designed to generate eight orthogonal THz-vortex waves coaxially. In the design, four LHCP and four RHCP incidences impinge the proposed metasurface at ($\theta_1 = 30°$, $\varphi_1 = 0°$), ($\theta_2 = 30°$, $\varphi_2 = 180°$), ($\theta_3 = 30°$, $\varphi_3 = 90°$) and ($\theta_4 = 30°$, $\varphi_4 = 270°$). The corresponding transmitted waves for these four LHCP incidences carry OAM modes of l_1=0, l_2=+1, l_3=+2, and l_4=+3. According to (5), the OAM modes of transmitted waves for the four RHCP incidences are l_2=-1, l_1=0, l_4=-3, and l_3=-2.

Fig. 3 shows the performance of the proposed metasurface under the illumination of the pre-designed RHCP and LHCP waves at 140 GHz. Apparently, broadside OAM waves with anti-clockwise phase profiles are generated, indicating that the four RHCP and LHCP waves are converted to OAM waves with OAM modes of 0, +1, +2, +3 and -1, 0, -3, -2, respectively.

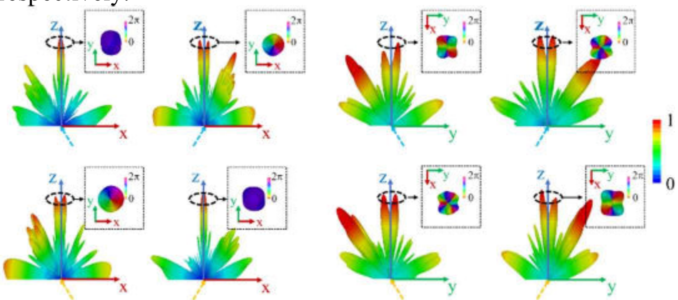

Fig. 3. Simulated radiation patterns and phase profiles of the proposed metasurface under the illumination of RHCP (blue dashed arrow) and LHCP (orange dashed arrow).

IV. Conclusion

In this project, an efficient strategy for multi-dimensional multiplexing of polarization and OAM domains via a single metasurface was proposed. Specifically, anisotropic elements were designed for polarization-division multiplexing based on the PB phase method. Meanwhile, an off-axis technique is for OAM multiplexing. In this way, different incidences featuring different incident angles and polarization states can be transformed into coaxial THz-vortex waves carrying different OAM modes. For proof-of-concept, a 3D-printed metasurface was designed for the generation of eight coaxial THz-vortex waves featuring different OAM modes and polarization states, demonstrating the efficiency of the proposed strategy.

V. Acknowledgements

The IEEE MTT-S Undergraduate/Pre-graduate Scholarship has not only given me the opportunity to pursue research in the terahertz frequency range but has also been a driving force for me to continue my research. In addition, I would like to express my appreciation to Prof. Yang Yang. His mentorship has been invaluable to my growth as a researcher and has inspired me to pursue further research in this field.

References

[1] Y. S. Lee, et al., "Low-Loss Polytetrafluoroethylene Hexagonal Porous Fiber for Terahertz Pulse Transmission in the 6G Mobile Communication Window," *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 11, pp. 4623-4630, 2021.

[2] Geng-Bo Wu, et al. "Millimeter-wave holographic flat lens antenna for orbital angular momentum multiplexing." *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 8 pp. 4289-4303, 2021.

[3] Xiaoyuan He, et al. "3D printed sub-terahertz all-dielectric lens for arbitrary manipulation of quasi-nondiffractive orbital angular momentum waves." *ACS applied materials & interfaces*, vol. 13, no. 17 pp. 20770-20778, 2021.