Millimeter-Wave, Spiral Phase Plates for Orbital Angular Momentum Wave Generation

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***Abstract*—The design goal of this paper is to observe and evaluate the formation of orbital angular momentum (OAM) waves from a fundamental Laguerre-Gaussian (LG) beam using a millimeter-wave optical device known as a spiral phase plate (SPP). From the simulated and experimental data presented in this document, it can be concluded that the proposed design for a millimeter-wave SPP achieves its goal of forming an OAM wave from a fundamental LG beam. The results of the simulation and experiment show the characteristic annular shape of the intensity pattern of an OAM wave with an azimuthal mode number of plus or minus one.**

***Keywords*—Orbital Angular Momentum, Laguerre-Gaussian, Millimeter-wave, Quasi-optics**

I. Introduction

Laguerre-Gaussian (LG) beams are electromagnetic waves of energy. The Poynting vector is used to determine the magnitude and direction of the LG beam. Fundamental LG beams have planar phase fronts which can be influenced by a device, such as a spiral phase plate (SPP), to transform the beam and create a helical phase front. This is done by creating an azimuthal component to the fundamental LG beam [1]. This process effectively creates an electromagnetic wave with orbital angular momentum (OAM). The purpose of this paper is to pursue the formation of LG beams which carry non-zero orbital angular momentum in the V-band frequency range, which is 57 GHz to 67 GHz, which falls within the V-band. Two different phase plates were fabricated from high density polyethylene (HDPE) with the purpose of producing different OAM beams. One SPP was designed to yield the lowest mode of right-handed chirality (having an azimuthal modal index of +1), and the other SPP was designed to yield the lowest mode of left-handed chirality (having an azimuthal modal index of -1). The wave front of an OAM beam can be analyzed from the phase part of the complex amplitude equation for the LG beam [2]. An example of the helical phase front can be seen in Fig. 1.

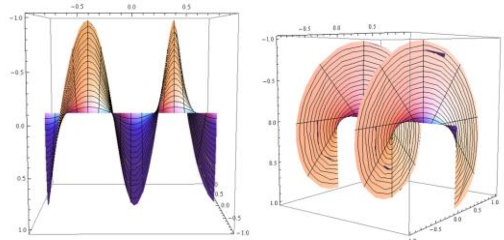

Fig. 1. OAM beam wave front with azimuthal mode number $\ell = 1$.

II. Spiral Phase Plate (SPP) Design

The diameter of the SPP was designed to capture most of the incident beams intensity. The diameter was determined to be 160 mm to allow coverage of incident beam waists ranging from 10 mm to 80 mm that provides compatibility with multiple beam waists. The equation for determining the step height of the SPP is given by [3]:

$$h = \frac{(\ell_2 - \ell_1)\lambda}{(n_2 - n_1)}. \quad (1)$$

The variables in (1) represent the following parameters. The desired azimuthal mode number is ℓ_2. The incident azimuthal mode number of the beam illuminating the SPP is ℓ_1, which in this case is 0. The SPP index of refraction is n_2. The medium index of refraction of the incident beam is n_1, which for this case air was estimated to have an index of 1. The wavelength of the incident LG beam is λ. The calculated SPP height was determined to be 9.1 mm by choosing an operating frequency of 61.25 GHz and an index of refraction of 1.54 for the SPP. A 3D model of the SPP can be seen in Fig. 2.

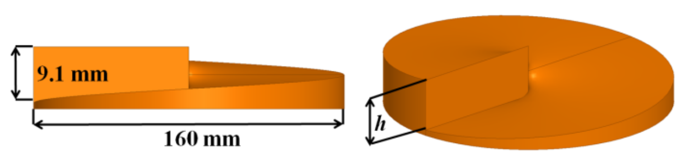

Fig. 2. Counter-clockwise spiral phase plate with design specifications.

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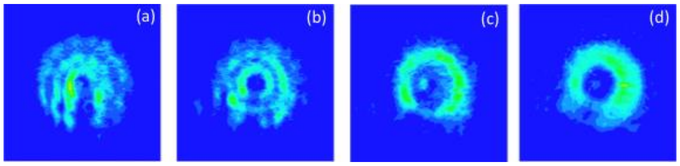

Fig. 3. Cross-sectional intensity plots (a), (b), (c), and (d). The annular intensity pattern can be seen forming in the progression from (a) to (d), (d) being the farthest away from the SPP.

III. Simulation of SPP

Before building a physical spiral phase plate for experimentation, the optical device was simulated using a finite element analysis tool, ANSYS HFSS. The purpose of the simulation was to analyze the behavior of the SPP with the calculated step height of 9.1 mm at an operating frequency of 61.25 GHz. The simulation was used to obtain the intensity pattern of the resultant beam after it passed through the spiral phase plate in the far field region. The far field region is any distance along the beams propagation path that is considered very large compared to the Rayleigh range. The Rayleigh range is the distance the waist radius increases by a factor of $\sqrt{2}$ compared to the waist radius of the incident beam at the source [2]. The far field region is important to analyze due to the azimuthal phase shift caused by the spiral phase plate which leads to destructive interference in the far field [3]. This interference forms an annular ring shape in the intensity pattern of the beam.

The SPP was created as a model and a fundamental LG beam was used as the source of excitation for the incident beam. The intensity patterns in Fig. 3 were captured at increasing distances away from the SPP in the far field region. The cross-sectional intensity patterns $I(z)$ are shown for increasing values of distance in Fig. 4. It can be seen from these intensity patterns that the annular ring shape of the OAM beam starts to form as the beam propagates further from the SPP into the far field region. The equation used in the simulation for calculating the optical intensity is:

$$I(z) = \frac{|E_0(z)|^2}{2\eta}. \quad (2)$$

Equation (2) relates the optical intensity I as a function of distance z to the magnitude of the electric field E_0 and the intrinsic impedance η.

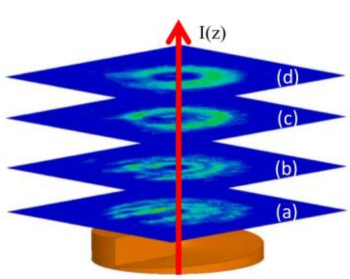

Fig. 4. SPP isometric view showing the progression of the intensity plots (a), (b), (c), and (d).

IV. OAM Experimental Setup and Results

To capture the cross-sectional intensity patterns of the resultant beam after passing through the spiral phase plate, a dual polarized horn antenna resonant at the operating frequency of 61.25 GHz was used to measure the intensity of the beam. The horn antenna was mounted to a movable XYZ stage. A signal generator sourcing the millimeter-wave gaussian beam guided by waveguide was focused using an ellipsoidal dish antenna. The focal point of the dish was the placement location for the spiral phase plate. The horn antenna is in the far field region to collect the measured intensity of the newly formed OAM beam. Absorbing material is placed behind the antenna to prevent any reflections of the beam to reduce any interference with the measurements.

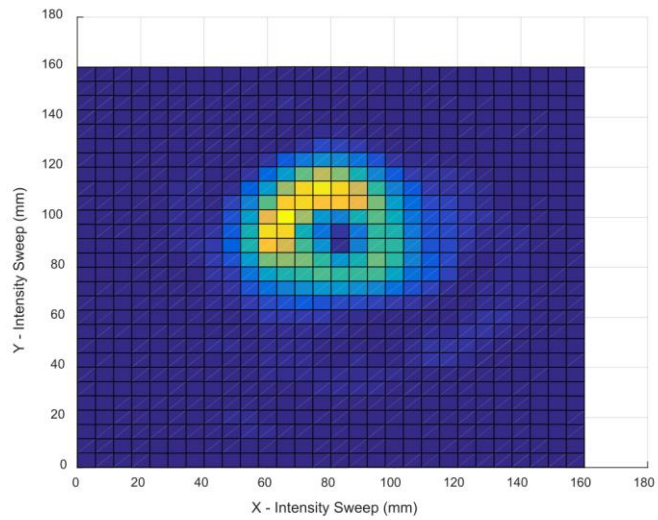

Fig. 6. Experimental OAM intensity plot.

V. Conclusion and Career Plans

The resultant OAM beam data obtained from the antenna was imported into MATLAB to analyze graphically. The cross-sectional cut of the intensity plot can be seen in Fig. 5. The spot size of the produced OAM beam was about 60 mm. This spot size matches the simulated spot size. The spot size and the distinct annular shape of the intensity pattern shows that the proposed design of the SPP can be used to transform millimeter-wave LG beams into OAM beams at 61.25 GHz.

The MTT-S scholarship allowed me to continue research as an undergraduate student at the University of Akron. I think the experience I gained while conducting research will be very useful as I begin working in industry as an electrical engineer.

References

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