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RESEARCH ARTICLE

Circularly polarized wave beamforming using one-dimensional Fresnel zone plate

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Abstract

This letter entails a methodology to steer circularly polarized (CP) wave main beam in the near-field region. The letter first demonstrates a planar circular polarizer which can convert an incoming linearly polarized wave into a CP wave from 24.0 to 40.0 GHz. Afterwards a one-dimensional Fresnel zone plate consisting of electrically opaque and transparent regions is devised to formulate constructive interference for CP near-field beamsteering at 22°. Measurement ascertains that the axial ratio and TE/TM phase difference at the aforementioned angle is 0.36 dB and 87.1°.

KEYWORDS

circular polarization, frequency selective surface, Fresnel zone plate, near-field

1 | INTRODUCTION

Circularly polarized (CP) waves are instrumental for maintaining robust wireless links under propagation channel conditions such as fading, multi-reflections, Faraday rotations, and atmospheric influences. Consequently, CP configuration is widely preferred in modern radar and satellite communication systems as the receiver power can be enhanced without continuous alignment between the transmitting and receiving antennas.[1] Symmetric radiating structure such as square patch, circle slot, and helix with passive feeding network[2–4] have been reported to be effective methods for generating CP waves. Circular polarization converter based on frequency selective surfaces (FSSs) is also applicable.[5,6]

Up to present, CP beamforming is confined in the far-field region in which beam synthetizing methods such as phased array and circular polarization converter array consisting of gradient unit cells are used. However, these methods are subject to mutual coupling between adjacent antenna elements and unit cells,[7] which severely deteriorate the beam properties such as axial ratio, phase difference, and gain.

This letter proposes a CP wave beamforming methodology in the near-field region using a Fresnel Zone plate. The total CP beamforming system consists of a planar circular polarizer to first convert a linearly polarized wave into CP wave and a one-dimensional Fresnel zone plate for steering the generated CP wave in the near-field region. Experimental results demonstrate 22° beam steering at 28.0 GHz while maintaining 3-dB axial ratio.

2 | DESIGN OF CIRCULAR POLARIZATION CONVERTER

The geometry of the devised circular polarization converter illustrated in Figure 1A uses bisected ring structures[8] for wide transmission bandwidth from 24.0 to 40.0 GHz. Asymmetric vertical and horizontal gaps along with the metallic strip pattern in the bottom face is devised to create the desired phased difference between the Transverse Electric; Vertical polarization (TE) and Transverse Magnetic; Horizontal polarization (TM) modes. This circular polarization converter is cascaded to four-layers with 2.5 mm separations to maximize the transmission bandwidth and phase difference using Fabry–Perot resonance.

The unit cell of the circular polarization converter is designed using full-wave commercial solver ANSYS HFSS under an infinite periodic boundary condition. Equivalent circuit analysis[7,9,10] is conducted based on transmission line theory.[11] The aforementioned four-layer circular polarization converter is fabricated on a Taconic TLY substrate (ε_r = 2.20, h = 0.128 mm, t = 0.017 mm). Each layer contains 324 cells with total lateral dimension of 90 × 90 mm^2 and detailed dimensions of the unit cell and equivalent circuit

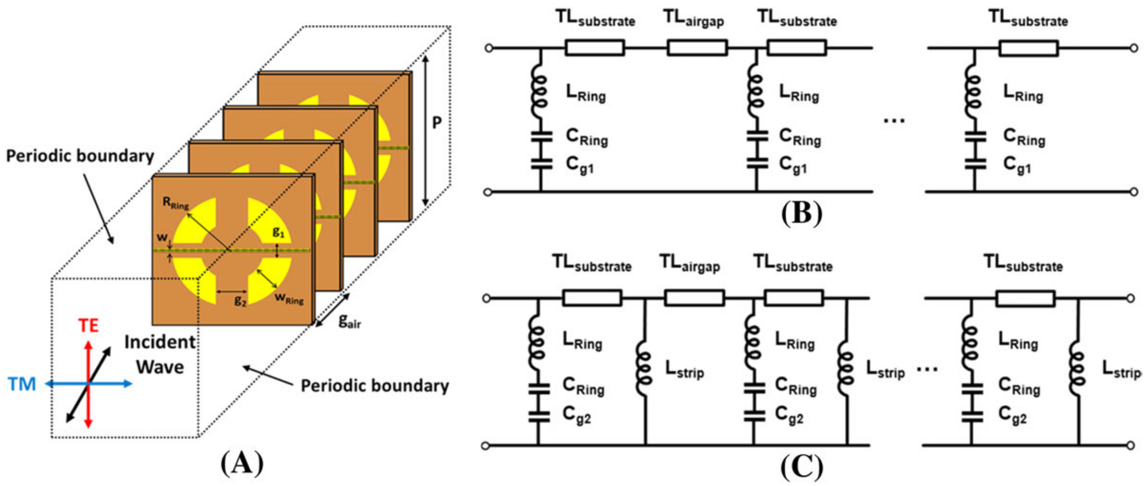

FIGURE 1 (A) Schematic of circular polarization converter unit cell (P, period of circular polarization converter unit cell; R_{Ring}, radius of ring on the top face; W_{Ring}, width of ring on the top face; W, width of metal strip on the bottom face; g_1, vertical gap of ring on the top face; g_2, horizontal gap of ring on the top face; g_{air}, gap between layers), (B) equivalent circuit model in TE ($\text{TL}_{\text{substrate}}$, transmission line substrate; $\text{TL}_{\text{airgap}}$, transmission line airgap; L_{Ring}, inductance of the ring on the top face, C_{Ring}, capacitance of ring on the top face; C_{g1}, capacitance of the vertical gap on the top face), (C) equivalent circuit model in TM (C_{g2}, capacitance of the horizontal gap on the top face; L_{strip}, inductance of the metal strip on the bottom face) [Color figure can be viewed at wileyonlinelibrary.com]

parameters are presented in Tables 1 and 2. The transmitted waves through circular polarization converter were measured in two directions for TE and TM. In Figure 2, simulated and measured results demonstrate wide transmission and polarization conversion bandwidth with good agreements in the Ka-band.

3 | VERIFICATION OF CP WAVE NEAR-FIELD BEAMFORMING

$$\Psi_{Feed}(x) = k\left[\sqrt{x^2+F^2}-F\right] \quad (1)$$

$$\Psi_D(x) = kx\sin\varphi_0 \quad (2)$$

$$\Psi_{FZP}(x) = \Psi_D(x) - \Psi_{Feed}(x) \quad (3)$$

A one-dimensional Fresnel zone plate consists of a series of parallel strips where electrically transparent and electrically opaque zone is repeatedly arranged as illustrated in Figure 3A. The locations of transparent and opaque zones are determined by the operating frequency, the total plate size (D), beam steering angle (φ_0), and the distance (F) between feed antenna and Fresnel zone plate.[12] Assuming the cylindrical wave is radiated from the feed antenna on the $Z = -F$ plane, Fresnel zone plate compensates the difference (Ψ_{FZP}) between the phase on the $Z = 0$ plane (Ψ_{Feed}) and the desired phase (Ψ_D) for steering far-field radiation along the azimuth angle of φ_0 in Equation 1-3.

Fresnel zone plate is designed for steering 28.0 GHz CP wave main beam peak situated at 25° as illustrated in Figure 3B where the total plate size is 110 × 110 mm^2 and the distance between feed antenna and Fresnel zone plate is 50 mm.

The measurement setup illustrated in Figure 4 consists of two Ka-band standard gain horn antennas (A-INFO LB-28-20) which are connected a vector network analyzer (Keysight N5247A PNA-X) and used as transmitting and receiving (TRX) antenna. Circular polarization converter is used in transmitting antenna for feeding CP wave on the Fresnel zone plate.

4 | RESULTS

Simulated peak radiation intensity features 17.7 dB at 24.7° when the CP wave is incident on the Fresnel zone plate at a distance of 50 mm. This distance between the circular polarization feed and the Fresnel zone plate is within the near-field region at 28.0 GHz. Radiation intensity of the TE and TM waves is, respectively, measured by the RX antenna with revolving arms in the far-field region. The maximum value of measured radiation intensity for the TE wave is

TABLE 1 Dimensions of the circular polarization converter unit cell

Variable	Values (mm)	Variable	Values (mm)
P	5	g_1	0.5
R_{Ring}	1.9	g_2	1.0
W_{Ring}	0.9	g_{air}	2.5
W	0.1		

TABLE 2 Parameters of the equivalent circuit model

Parameters	Values	Parameters	Values
$\text{TL}_{\text{substrate}}$	266.57 Ω	C_{g1}	47.46 fF
$\text{TL}_{\text{airgap}}$	377 Ω	C_{g2}	52.24 fF
L_{Ring}	0.4 nH	L_{strip}	0.35 nH
C_{Ring}	30 fF		

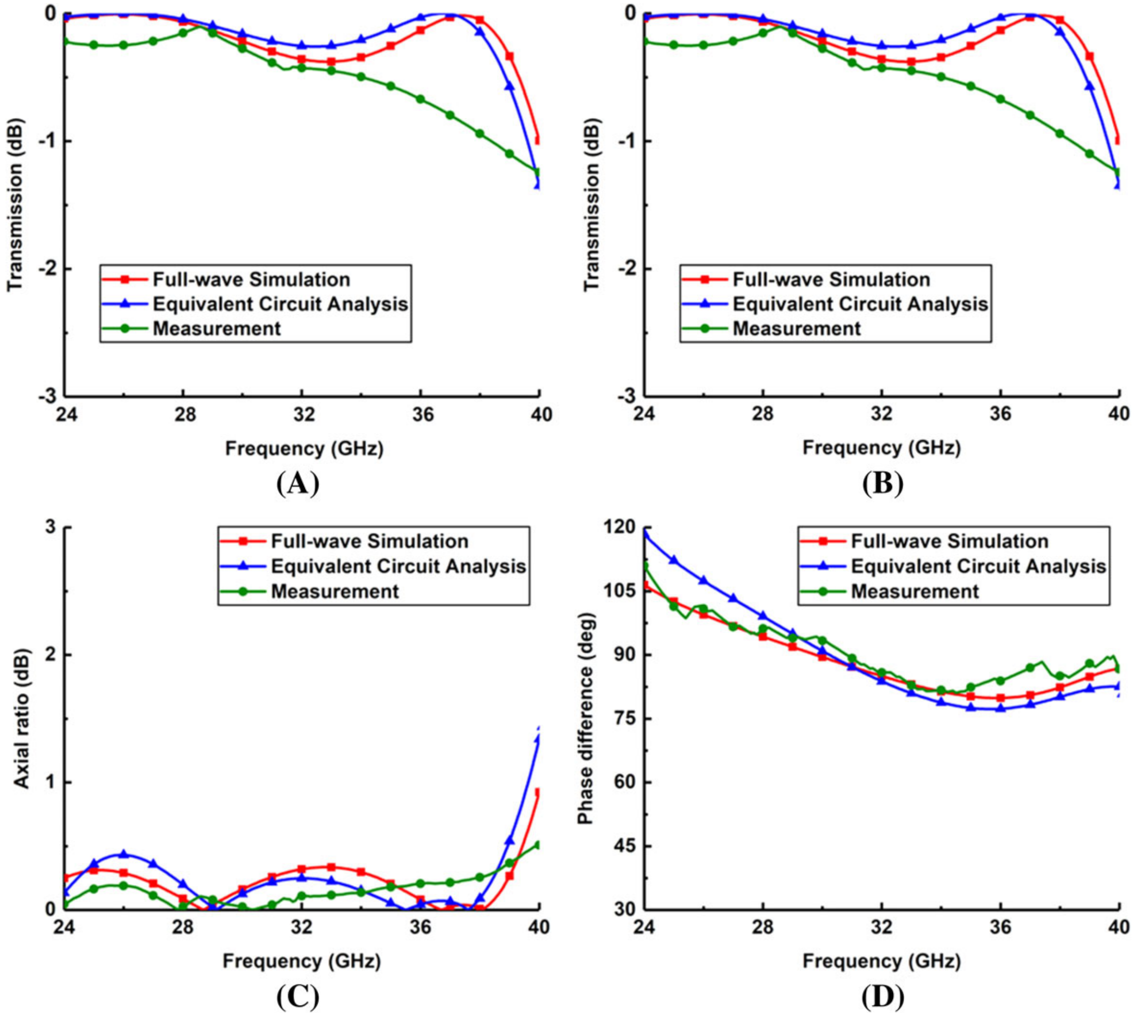

FIGURE 2 Simulated and measured results of (A) transmission magnitude in TE, (B) transmission magnitude in TM, (C) axial ratio, (D) phase difference between TE and TM [Color figure can be viewed at wileyonlinelibrary.com]

16.29 dB at 22° and 16.12 dB at 21° for the TM wave as illustrated in Figure 5A. The axial ratio is measured and calculated by the magnitude difference between the measured radiation intensities and the phase difference is extracted using transmission coefficients of the steered TE and TM wave in Figure 5B.

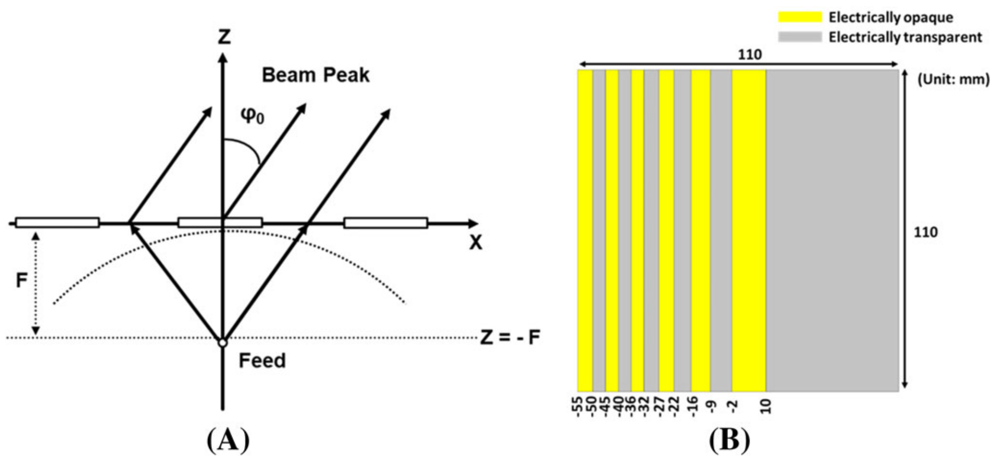

FIGURE 3 (A) Principle of one-dimensional Fresnel zone plate beamsteering, (B) detailed geometry of devised Fresnel zone plate (unit: mm) [Color figure can be viewed at wileyonlinelibrary.com]

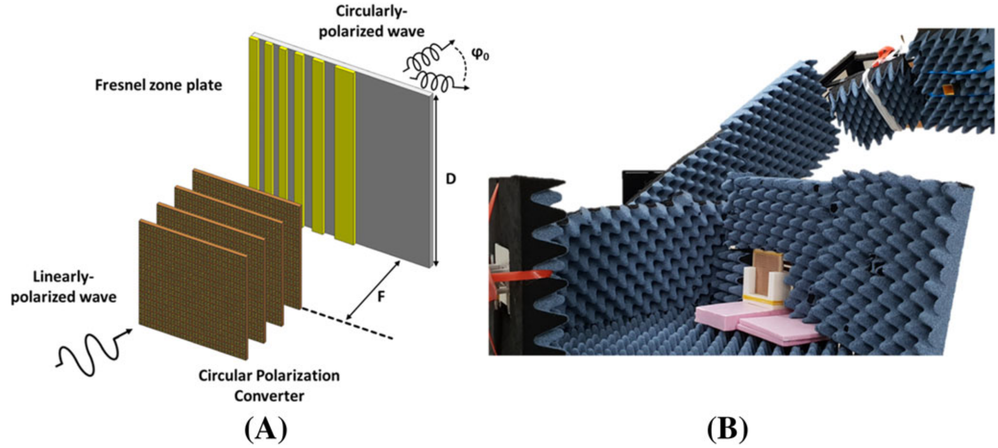

FIGURE 4 (A) Proposed circularly polarized wave beamforming system, (B) experimental setup [Color figure can be viewed at wileyonlinelibrary.com]

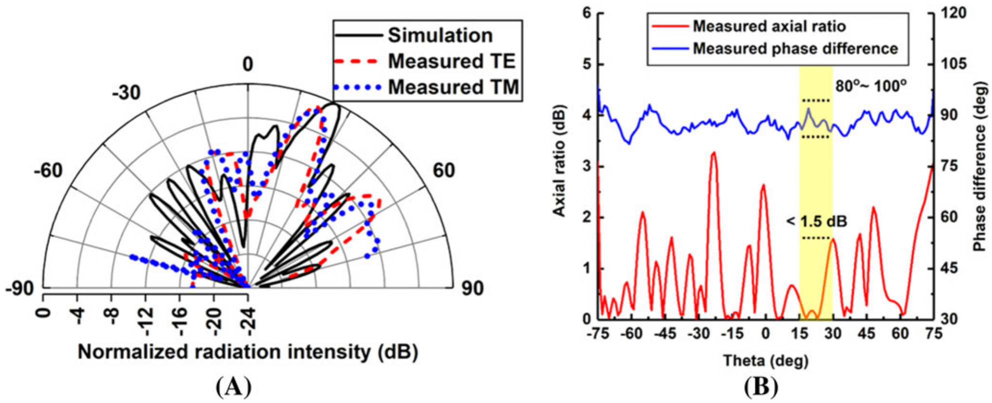

FIGURE 5 (A) Normalized radiation intensity, (B) axial ratio and phase difference between TE and TM [Color figure can be viewed at wileyonlinelibrary.com]

5 | CONCLUSION

For the first time to the authors' best knowledge, this letter introduces a CP wave beamforming system consisting of circular polarization converter and Fresnel zone plate. The proposed circular polarization converter is applicable in the entire Ka-band. Beamforming of CP wave in the near-field region using one-dimensional Fresnel zone plate is verified by simulation and measurements. This method enables diffraction in the near-field to formulate a CP constructive interference. This property is verified at 22° at 28.0 GHz.

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