Millimeter-Wave Quarter-Wave Plate for Diffusion Bonded Slot Array Antennas

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***Abstract*—A single-layered quarter-wave plate (QWP) is proposed and demonstrated for linear-to-circular polarization (LP-to-CP) conversion in the near-field of a slot array antenna. The QWP is based on a square unit cell with five elliptically shaped air holes - four on the edges and one in the center. The central ellipse is rotated by $45°$ which decomposes the incoming linear polarization into two orthogonally polarized components with $90°$ phase difference. The LP-to-CP conversion is demonstrated by simulating the proposed QWP in the near-field of an LP slot array antenna with a 3 dB axial ratio and -10 dB matching bandwidths of 5.1% and 8.9%, respectively, around 60 GHz.**

***Index Terms*—quarter-wave plate, linear-to-circular polarization conversion, near-field engineering, metasurfaces.**

I. INTRODUCTION

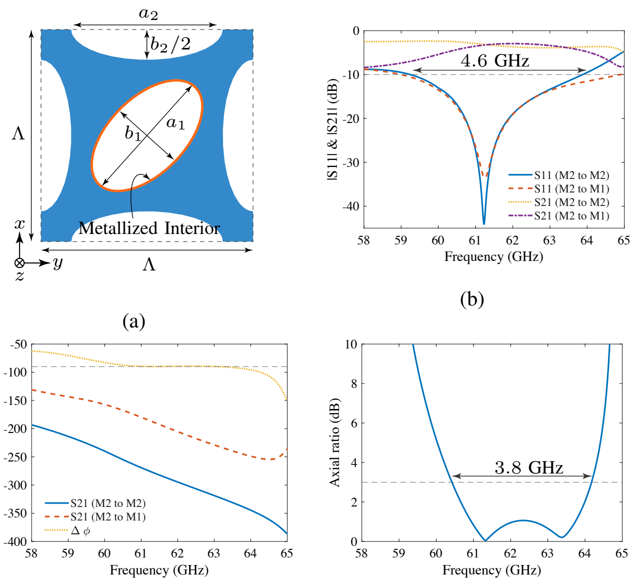
Polarization of an electromagnetic (EM) wave refers to the path traced by the electric field and is an important characteristic to consider in antenna design. The electric field generally traces an ellipse (elliptical polarization, EP) with special cases being a line (linear polarization, LP) and a circle (circular polarization, CP) [1]. CP is preferred when the orientation of the receiver with respect to the transmitter is unknown, in which case LP may suffer from significant polarization loss. While having considerable advantages, CP antennas are more challenging to design than LP antennas due to feeding complexity.

This problem is more prevalent in the millimeter-wave band and can be exemplified using the diffusion bonded slot array antenna configuration [2]. These antennas are corporate-fed 2D slot arrays, which are realized by diffusion bonding several patterned metal layers to achieve the desired 3D profile. Since the structures are air-filled, as compared to dielectric based designs, they offer superior radiation efficiencies. Utilizing various patterns and shapes of the metallic layers, different radiation characteristics can be achieved. To achieve CP radiation, an additional metal stack layer is used to convert LP to CP. This additional stack adds significant weight and thickness to the overall antenna, in addition to increased fabrication costs and uncertainties in fabrication tolerances.

Quarter-wave plates (QWPs) are conventionally implemented using metallic patterns on a dielectric. For instance, QWPs operating as reflect-arrays were recently proposed based on an array of modified square patches [3], and on ellipse-shaped rings [4]. QWPs can also operate as transmit-arrays, such as a double-layered QWP based on split ring resonators [5] and a single-layered QWP based on cross backed metal strips [6]. In this paper, a single-layered QWP is proposed. The contributions of this work are twofold. First, a novel QWP unit cell based on simple elliptical holes and metallization is presented. The unit cell is subsequently demonstrated for LP-to-CP conversion in the near-field of an LP diffusion bonded slot array antenna, hence eliminating the need for the additional stack to convert LP-to-CP. The unit cell is demonstrated in the millimeter-wave band around 60 GHz, where metallic based designs such as [5], [6] would be unfeasible due to unachievably small copper line widths. In addition, while previous designs have been demonstrated in the far-field, the proposed unit cell operates in the near-field of the antenna.

II. PROPOSED QUARTER-WAVE PLATE (QWP)

The unit cell of the proposed QWP is shown in Fig. 1(a). It is a $\Lambda \times \Lambda$ square with five elliptical holes - four on the



(a) (b)

(c) (d)

Fig. 1. a) Illustration of the proposed unit cell implemented on Rogers' RO3006 ($\epsilon_r = 6.15$, $\tan\delta = 0.0025$, and height, $h = 50$ mil). Simulation results for an infinite array of the unit cell: b) reflection and transmission magnitude, c) transmission phase, and d) axial ratio. Mode 1 (M1) is $y-$polarized and Mode 2 (M2) is $x-$polarized. The dimensions are as follows: $\Lambda = 4.2$ mm. $a_1 = 2.7$ mm, $b_1 = 1.5$ mm. $a_2 = 3$ mm, $b_2 = 0.6$ mm.

edges and one in the center. The central ellipse has metallized interior and is tilted by 45°. The unit cell was implemented on Rogers' RO3006 ($\epsilon_r = 6.15$, $\tan\delta = 0.0025$, and $h = 50$ mil) and simulated with Floquet ports and periodic boundaries on Ansys HFSS. The S-parameters, which are de-embedded to the center of the unit cell, are shown in Fig. 1(b) & (c). The curve labels "Mode 1 (M1)" and "Mode 2 (M2)" refer to $y-$ and $x-$polarized E-fields, respectively. As seen from the magnitude results in Fig. 1(b), an $x-$polarized incident E-field generates both $x-$ and $y-$polarized E-fields with similar magnitudes. In the same frequency range, low reflection is achieved where the -10 dB reflection bandwidth is ≈ 4.6 GHz. In the range where the magnitudes are similar, the phase difference between the two polarizations is $\Delta\phi \approx -90°$ as shown in Fig. 1(c), as is desirable for LP-to-CP conversion. Finally the axial ratio (AR) can be calculated as the ratio of the major and minor axes of the polarization ellipse [1]:

$$\mathrm{AR} = \frac{\sqrt{\frac{1}{2}\left(E_{xo}^2 + E_{yo}^2 + \sqrt{E_{xo}^4 + E_{yo}^4 + 2E_{xo}^2E_{yo}^2\cos(2\Delta\phi)}\right)}}{\sqrt{\frac{1}{2}\left(E_{xo}^2 + E_{yo}^2 - \sqrt{E_{xo}^4 + E_{yo}^4 + 2E_{xo}^2E_{yo}^2\cos(2\Delta\phi)}\right)}} \quad (1)$$

where E_{xo} and E_{yo} are the magnitudes of $x-$ and $y-$polarized E-fields, and $\Delta\phi$ is the phase difference. Axial ratio is shown in Fig. 1(d) where the 3 dB AR bandwidth is ≈ 3.8 GHz.

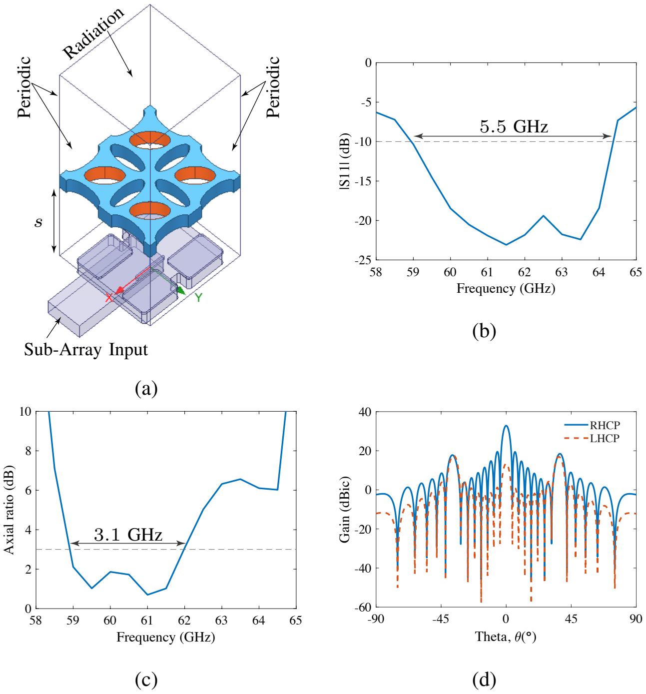
These results have demonstrated that the proposed unit cell can convert a single LP wave (polarized in x or y) to a CP wave. The sense of rotation of the output CP wave, right-hand circular polarization (RHCP) or left-hand circular polarization (LHCP), is determined by the polarization of the input LP wave and the direction of propagation. For the same direction of propagation, one polarization of the LP wave will generate RHCP while the other will generate LHCP.

III. QWP ON A 2D SLOT ARRAY

An application of the proposed QWP in achieving CP from an LP antenna is subsequently demonstrated to operate in the near-field of a slot array antenna that is linearly-polarized in the $y-$direction and radiates a main beam centered at broadside ($\theta = 0°$) [2]. Four unit cells of the quarter-wave plate above a unit cell sub-array of the slot array antenna were simulated, with periodic and radiation boundaries as shown in Fig. 2(a). Results are shown for the reflection [Fig. 2(b)], axial ratio [Fig. 2(c)], and RHCP & LHCP radiation patterns at 60 GHz [Fig. 2(d)]. The achieved -10 dB reflection bandwidth is ≈ 5.5 GHz and the 3 dB axial ratio bandwidth is ≈ 3.1 GHz. A frequency shift and bandwidth narrowing is observed between the unit cell axial ratio [Fig. 1(d)] and the antenna axial ratio which can be attributed to the near-field interaction between the antenna and the unit cell. These results have demonstrated that the proposed unit cell converts LP to CP in the near-field of the slot array antenna.

IV. CONCLUSION

A novel single-layered QWP was proposed and demonstrated to operate in the near-field region of a 2D slot array antenna. The LP-to-CP conversion in the near-field of an LP slot array antenna was demonstrated where a 3 dB AR bandwidth of 3.1 GHz (5.1% fractional bandwidth) and -10 dB matching bandwidth of 5.5 GHz (8.9% fractional bandwidth) were achieved. The proposed QWP therefore represents a simple solution to converting an LP slot array antenna into a CP one with low profile and weight, while maintaining wide AR and matching bandwidths. Future work will involve analysis of the operating principle behind the unit cell as well as experimental demonstration.



(a)

(b)

(c)

(d)

Fig. 2. Simulation results for an infinite array of the proposed unit cell and a linearly-polarized slot array antenna with a separation $s = 9$ mm. a) Illustration of 2×2 unit cells and the slot antenna sub-array unit cell, b) reflection coefficient, c) axial ratio, and d) RHCP and LHCP gain in the $yz-$plane ($\phi = 90°$) at 60 GHz.

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