Dual-Circularly-Polarized Dual-Beam Microstrip Patch Antenna Arrays at Ka-Band

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Abstract-In this work, the design of array antennas for producing dual-circularly-polarized dual-beam radiation via element rotation and phasing is presented. In the pattern synthesis of an antenna array, by exploiting both radiator rotation and phased feeding for all the array elements, the beamforming for left- and right-handed circularly-polarized (LHCP and RHCP) radiated waves can be independent controlled, thus resulting in dual-circularly-polarized high-gain beams each pointing at an arbitrary direction. To verify the proposed technique, a linear array with 16-elements and a planar array containing 4×4 elements are designed and simulated. The proposed antenna arrays have a simple structure, a wide bandwidth, and high polarization purity.

I. INTRODUCTION

With the development of satellite, radar tracking, and mobile communication systems, the application of circularly-polarized (CP) antenna has become increasingly important. Unlike linearly-polarized (LP) antennas, CP antennas are ideal for addressing challenges associated with mobility, adverse weather conditions, and non-line-of-sight applications [1]-[3]. In particular, CP antennas can deliver better connectivity for both fixed and mobile devices and ultimately lead to a more robust wireless link.

The sequential element rotation technique is one of the main methods for synthesizing CP antenna arrays with either LP or CP elements [4]-[6]. It can readily obtain a wide impedance and axial ratio bandwidth, with decent polarization purity. Recently, random sequential rotation arrays have also been reported, which can suppress both the side lobes and cross-polarization level [7]. However, these sequential rotation arrays can only generate beams with a single handedness at a time.

In this work, we propose dual-circularly-polarized antenna arrays with independent beamforming for both left- and right-handed circularly-polarized radiated beams. To verify the proposed technique, a linear 16-elements array and a 4×4 elements planar array were designed and numerically simulated. The proposed arrays have simple structures and wide bandwidth, which can be promising candidates for satellite communication, millimeter-wave radars, mobile communications, and so on.

II. ANTENNA ARRAY DESIGN

A. Element Design

Figure 1(a) shows the configuration of the radiating element of the dual-CP array. The antenna element is composed of a circle patch, a microstrip feedline, a ground plane with an H-shaped aperture. The two dielectric substrate layers are integrated by a bonding film. The upper and lower dielectric substrate are both Rogers RT5880 with \( \varepsilon_r = 2.2 \) and \( \delta = 0.0009 \), while the bonding film is Rogers RO4450B with \( \varepsilon_r = 3.52 \) and \( \delta = 0.004 \). Compared with directly fed microstrip antennas, the aperture-coupled microstrip patch has a wider bandwidth with the spurious radiation from the feed-lines.
being isolated [8]. Optimized by a 3D electromagnetic full-wave solver HFSS, the parameters of the antenna are \( a = 1.8 \), \( h_1 = 0.787 \), \( h_2 = 0.254 \), \( h_3 = 0.101 \), \( SL = 1.82 \), \( SW = 0.24 \), \( SH = 0.92 \), \( Ls = 0.86 \), and \( Wf = 0.38 \), all in millimeters. The simulated \( S_{11} \) of the array element is shown in Fig. 1(b). It can be observed that from 23.1 GHz to 25.4 GHz simulated \( S_{11} \) is below -10 dB, indicating a -10 dB impedance bandwidth of 9.58%.

B. Linear Array Design

The geometry of the linear dual-CP array with \( N \) elements is depicted in Fig. 2. All the elements have equal amplitude excitations with an inter-element spacing of \( d = 6.5 \text{ mm} \) (about 0.52\( \lambda_0 \), \( \lambda_0 \) is the free-space wavelength at 24 GHz). Along the \( x \)-axis, the elements are gradually rotated in the transverse plane with a rotation angle of \( \phi_i \), where \( i = 1, \ldots, N \). In addition, the excitation phase for each element is \( \beta_i \). In order to independently steer the left-handed and right-handed CP (LHCP and RHCP) beams to angles of \( (\phi_L, \theta_L) \) and \( (\phi_R, \theta_R) \), respectively, the following equations need to be satisfied, where \( k_0 \) is the wave number in free space.

\[
\psi_x = k_0 d \sin \theta_L \cos \phi_x + \left( \beta_{i+1} - \beta_i \right) \pm (\phi_{i+1} - \phi_i) = 0 \quad (3)
\]

\[
\psi_y = k_0 d \sin \theta_L \cos \phi_y + \left( \beta_{i+1} - \beta_i \right) \pm (\phi_{i+1} - \phi_i) = 0 \quad (4)
\]

\[
(\phi_{i+1} - \phi_i) = \left( \beta_{i+1} - \beta_i \right) = \frac{k_0 d \sin \theta_L}{2} \approx 32.01^\circ \quad (5)
\]

\[
(\phi_{i+1} - \phi_i) = \left( \beta_{i+1} - \beta_i \right) = \frac{k_0 d \sin \theta_R}{2} \approx 46.80^\circ \quad (6)
\]

C. Planar Array Design

Such a design method can be extended from designing a linear array to synthesizing a dual-CP planar array. As the geometry shown in Fig. 3, the elements of the planar array have equal amplitude excitations with an element spacing of \( d_x = d_y = 6.5 \text{ mm} \). The \((i,j)\)th element has a rotation angle of \( \phi_{ij} \) and the excitation phase of \( \beta_{ij} \), where \( i = 1, \ldots, N \) and \( j = 1, \ldots, N \). In order to steer the LHCP beam to the angle of \( \phi_L=0^\circ, \theta_L=20^\circ \) and direct the RHCP beam at \( \phi_R=0^\circ, \theta_R=-30^\circ \), the following equations need to be satisfied.

\[
\psi_x = k_0 d_x \sin \theta_L \cos \phi_x \pm \left( \beta_{i+1} - \beta_i \right) \pm (\phi_{i+1} - \phi_i) = 0 \quad (3)
\]

\[
\psi_y = k_0 d_y \sin \theta_L \cos \phi_y \pm \left( \beta_{i+1} - \beta_i \right) \pm (\phi_{i+1} - \phi_i) = 0 \quad (4)
\]

\[
(\phi_{i+1} - \phi_i) = \left( \beta_{i+1} - \beta_i \right) \approx \frac{k_0 d_x \sin \theta_L}{2} \approx 32.01^\circ \quad (5)
\]

\[
(\phi_{i+1} - \phi_i) = \left( \beta_{i+1} - \beta_i \right) \approx \frac{k_0 d_y \sin \theta_R}{2} \approx 46.80^\circ \quad (6)
\]

III. SIMULATION RESULTS

A. Linear Array

As a proof-of-concept example, a linear array was first designed to have the RHCP and LHCP beams pointing at \((\phi_x=0^\circ, \theta_x=20^\circ)\) and \((\phi_y=0^\circ, \theta_y=-30^\circ)\), respectively. Figure 4 shows the simulated normalized LHCP and RHCP patterns in the \(x-z\) plane for the proposed linear array at 24 GHz. It can be seen that the LHCP and RHCP components are separated and are steered in the desired directions. The simulated axial ratio
(AR) and gain for the LHCP and RHCP beams as a function of frequency is displayed in Fig. 5. It can be seen that the AR is below 3 dB from 22.4 to 27 GHz, meaning a wide AR < 3 dB bandwidth of 19.2%. Simultaneously, the 1-dB gain bandwidth is 2.9 and 3.8 GHz, for the LHCP and RHCP beams, respectively, which are 12.1% and 15.8%.

B. Planar Array

Figure 6 exhibits the simulated normalized LHCP and RHCP patterns in the (a) y-z and (a) x-z planes for the proposed planar array at 24 GHz. The LHCP beam and RHCP beam are steering towards two angles of $\phi_L=0^\circ$, $\theta_L=20^\circ$ and $\phi_R=0^\circ$, $\theta_R=-29^\circ$, respectively. Figure 7 reports the simulated AR and gain curves for the two beams. From 22 to 27 GHz, the AR is below 2 dB. Therefore, 2 dB AR bandwidth is 5 GHz, i.e. 20.8%, while the 1-dB gain bandwidth is 3.2 GHz, i.e. 13.3%.

IV. DISCUSSION

From the results above, it can be seen that the proposed technique can realize independent beamforming of LHCP and RHCP radiated waves, resulting in dual-CP high-gain beams each pointing at an arbitrary direction. Furthermore, the proposed antennas have a simple structure, a wide bandwidth, and high polarization purity. An 8 × 8 planar array with a corporate feeding network was designed and fabricated, currently being characterized. The photographs of the array prototype are exhibited in Fig. 8.

![Fig. 8. Photographs of the top and bottom layer of the 8×8 planar array prototype](image)

V. CONCLUSION

The novel dual-CP beam steering microstrip linear and planar array using a sequential rotation technique is studied in this paper, which achieves independent control of LHCP and RHCP components. The proposed antennas have a simple structure, a wide bandwidth, and high polarization purity. The simulated results show the minimal -10 dB impedance bandwidth is 10%, the minimal -1 dB gain bandwidth is 12.1% and axial ratio <3 dB is above 19.2%.

ACKNOWLEDGMENT

This work is supported by National Natural Science Foundation of China (NSFC) under Grant 61801109 and 61627801. The authors would like to thank T.Y.Huo for his assistance during the antenna fabrication.

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