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Performance Evaluation of a Millimeter-Wave Phased Array Antenna Using Circularly Polarized Elements

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***Abstract*—**This paper is focused on the design of an mm-wave phased array. To date, linear polarization is adapted in the reported designs of phased arrays. However, linear polarization faces several well-known challenges. As such, an advanced design for phased array antennas is required that offers circularly polarized (CP) radiation. A feasible solution for achieving CP phased array antennas is proposed using open-circular loop antennas. To this end, a 3-element circular loop phased array antenna is designed to operate at 28 GHz. In addition, the array ability to control the direction of the main lobe is investigated. The results show that the highest achievable field of view (FOV) is 100°, i.e. 50° to the left and 50° to the right-hand side directions. The results are achieved with a CP bandwidth of 15%. Furthermore, the results demonstrate that a high broadside gain of circa 11 dBi can be achieved for the steered beam. Besides, radiation efficiency of 97% can also be achieved based on the proposed design.

***Keywords*—**Loop antenna, phased array, beam steering, wide bandwidth, circular polarization, CST.

I. Introduction

THE demands data traffic has witnessed explosive growth over the past few years. Data traffic is expected to continue straining the capacity of future communication networks [1]. Millimetre-wave phased arrays play an essential role in the next generation of wireless communications systems. Specifically, the phased array facilitates main beam steering in different angular directions [2], [3]. Furthermore, the phased array would help to enhance the capacity of cellular networks by improving the signal to interference ratio (SIR), which can be achieved by targeting the desired users and mitigating the interference caused by other users [4]. However, various external factors in outdoor environments still limit the applications of mm-wave bands in mobile communication systems [5]. In particular, there are some key fundamental differences between the mm-wave communications and the existing communication systems, which adopt lower frequencies. These differences are raised, mainly due to the sensitivity of mm-wave communications to attenuation factors such as reflectivity, absorption, Faraday rotation and orientation [6]. Therefore, to overcome the limitation of mm-wave signal propagation, the linearly polarized elements can be replaced by CP counterparts [7], [8].

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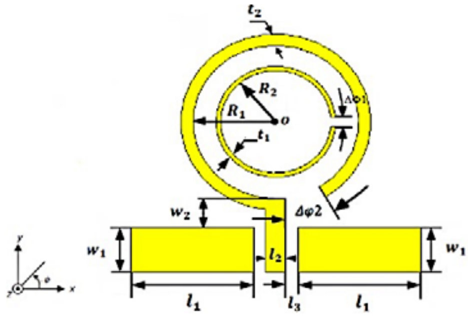


Fig. 1 Geometry of circular loop antenna

The research carried out on loop antennas can be classified into two categories. The first is focused on enhancing the radiation characteristics of one element such as gain, efficiency, circular polarization bandwidth and radiation pattern. On the other hand, the second category is focused on designing an array antenna in order to achieve the highest field of view (FOV) of beam steering with efficient utilization of the CP technique [9].

In this paper, a one-element CP loop antenna has been designed initially at 28 GHz, and thus a wideband performance is achieved by introducing a parasitic loop inside the original loop [10], [11], where the axial ratio bandwidth has increased by approximately 15%, while the gain has decreased by approximately 1.1 dBi.

To that end, a three-elements array antenna is designed to achieve high gain and directivity as well as steering the beam in different directions.

The highest value that can be achieved for the FOV of a phased array antenna is 100°, i.e., 50° to each side with left hand CP radiation during the beam steering. Furthermore, the array antenna achieves a wide impedance matching bandwidth of circa 25% with a gain of 11 dBi. Parameters observed include return losses, gain, CP bandwidth, radiation pattern and main lobe direction.

II. Antenna Configuration

A. Design of Single-Element Loop Antenna

Circular polarization can be obtained using a single-feed technique. However, the technique may require the perturbation of the element's shape [12].

When the circumference of a normal loop antenna is approximately one wavelength, the maximum linear polarization radiation appears in the broadside direction. However, the broadside linear polarization radiation can be changed to a circular polarization wave by perturbing the loop element with insertion an air gap along the loop circumference [13]. Furthermore, in this structure, the CP bandwidth can be significantly increased by using a parasitic inner loop. Since the additional parasitic element is placed inside the original loop without a direct electrical connection, there is no significant increase in the size and complexity of the antenna structure as illustrated in Fig. 1.

The antenna has been fed using a coplanar waveguide port (CWP) connected to the outer loop at φ=0. The width of the feed l_2 and the distance l_3 between feed and grounded rectangular pads are optimized to be 0.21 mm and 0.16 mm for 50 Ω matching, respectively. By adjusting the width and the positions of the two-loop gaps (φ_1, φ_2) the required axial ratio (AR) can be achieved. The configuration parameters are summarized in Table I: The circumference of the outer loop can be calculated at the operation frequency of 28 GHz in terms of the effective wavelength [14] by calculating, the effective permittivity as:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} \tag{1}$$

As such, the effective wavelength can be expressed as:

$$\lambda_{eff} = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \tag{2}$$

where λ_0 is the free-space wavelength Finally, the circumference of the outer loop should be approximately equal λ_{eff} in order to get the main beam in the broadside direction, i.e.,

$$2\pi R_1 \simeq \lambda_{eff} \tag{3}$$

TABLE I
DIMENSIONS PARAMETERS OF THE ANTENNA

Symbol	Quantity	Value
R_1	outer loop radius	1.34 mm
R_2	parasitic loop radius	0.9 mm
t_1	outer loop width	0.065 mm
t_2	parasitic loop width	0.17 mm
l_1	pads length	1.84 mm
l_2	transmission line width	0.21 mm
l_3	the gap between the transmission line & pads	0.16 mm
w_1	pads width	0.74 mm
w_2	the width between the pads & outer loop	0.3 mm
a_0	antenna thickness	0.035 mm
h	thickness of the substrate	1.524 mm
t	reflector thickness	0.04 mm
Subx	substrate length	9.2 mm
Suby	substrate width	7.75 mm
$\Delta\varphi_1$	outer loop gap	35 deg
$\Delta\varphi_2$	parasitic loop gap	5 deg

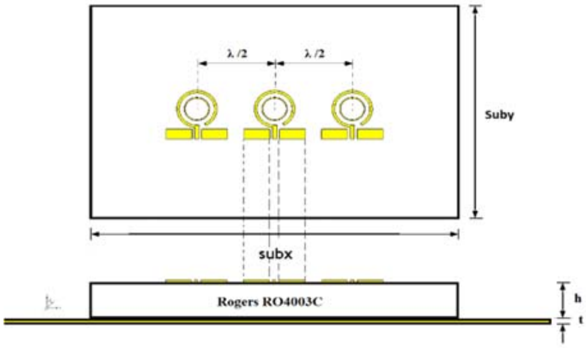


Fig. 2 The geometric configuration of 3-elements circular loop antenna array

B. Design of 3-Elements Array Antenna

To achieve a high gain and electronic beam steering with circular polarization, a phased array is considered. Fig. 2 demonstrates a uniform linear array of three identical elements, and the spacing between the elements is chosen as λ/2. The proposed array is placed on a Rogers RO4003C substrate having a size of 20.9×29 mm^2, with a thickness of 1.524 mm and dielectric constant of 3.55. The printed circular loops and substrate are mounted above a square copper plate that acts as a reflecting ground plane with a thickness of 0.04 mm. In this study, we also aim to minimize the mutual coupling between the elements and decrease the side lobes level. These factors can be considered as a source of impairments that affects the wireless system performance considerably. In addition, the required phase excitation of each element is obtained from the array factor. A waveguide port for each individual element is designed using the CST Microwave Studio. As such, the phase shift is changed from 0^0 to 360^0 in order to obtain the desired beam direction.

III. RESULTS AND DISCUSSION

Fig. 3 presents the simulated axial ratio and the gain of the wideband CP loop antenna with and without the parasitic inner loop. The axial ratio bandwidth is defined when AR≤3 dB and has been increased from 7% to 14.5% when the inner loop is incorporated. The gain of is decreased by approximately 1.1 dBi for the coupling loss between two loops. The results indicate that the parasitic loop plays an essential role in utilizing the bandwidth efficiently. This can be attributed to the outer loop that creates one minimum axial ratio point. On the other, the inner loop produces an additional minimum AR point. The suitable combination of the two minimum axial ratio points results in a significant improvement in the CP bandwidth.

Fig. 4 illustrates the simulated return losses, where it can be observed that the operating frequency range of S11≤−10 dB extends from 24 GHz to 31 GHz, which indicates that the proposed antenna offers a wide impedance matching bandwidth of circa 25%.

In order to reduce mutual coupling between adjacent radiating elements, the distance between the elements has been chosen to be $\mathbf{0.5\lambda}$. Fig. 5 indicating the return losses of the mutual coupling parameters for the proposal array, where it can be noted that the mutual coupling at the operating frequency is approximate -25 dB.

Fig. 6 demonstrates the axial ratio and the radiation efficiency with an AR bandwidth of 15%. The results also demonstrate a radiation efficiency of circa 97%. The highest achieved FOV value is 100°, i.e., 50° to the left and 50° to the right. In addition, LHCP is achieved during the beam steering as illustrated in Figs. 7 and 8.

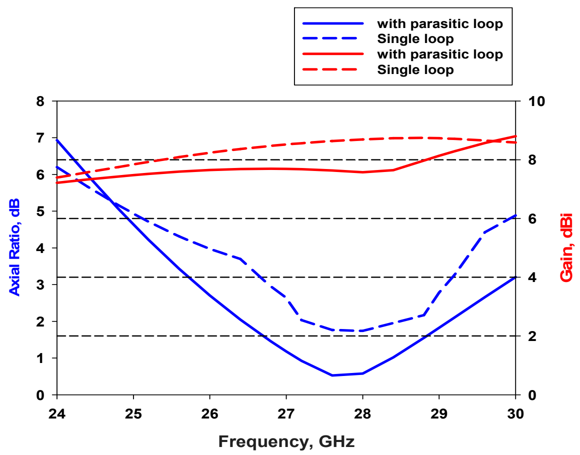


Fig. 3 Gain and the axial ratio of a single element with and without parasitic loop

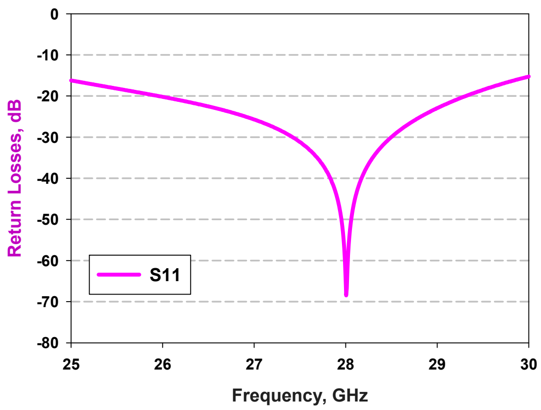


Fig. 4 Return losses of the proposed 3-elements array antenna

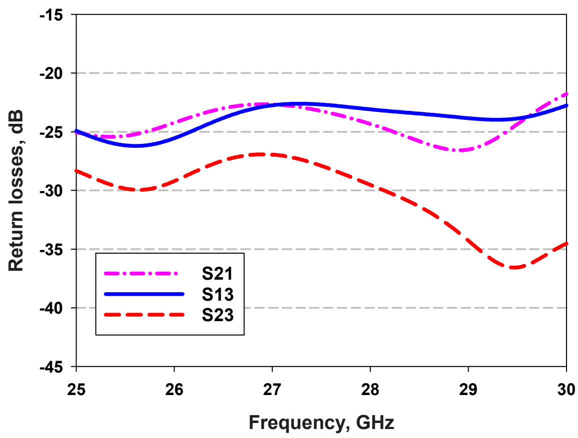


Fig. 5 Mutual coupling of the proposed array

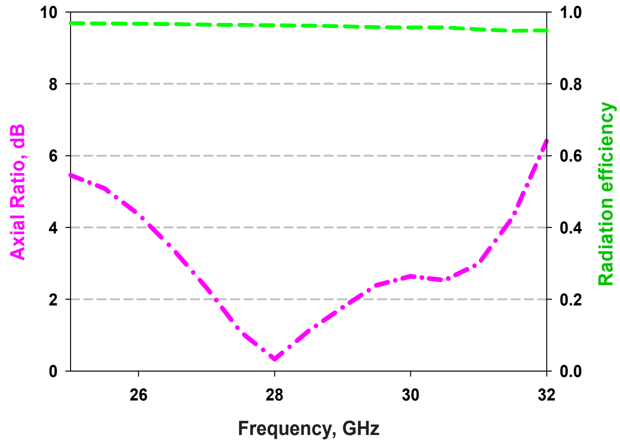
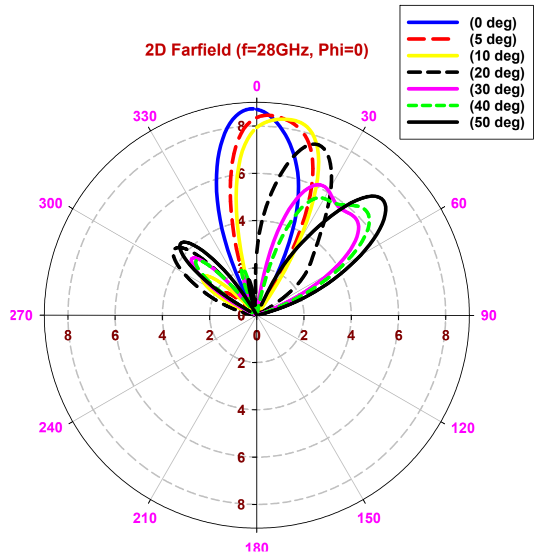
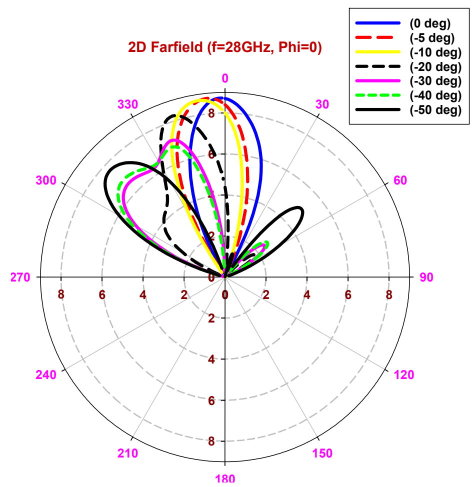


Fig. 6 Axial ratio and the radiation efficiency of 3-elements array antenna



(a)



(b)

Fig. 7 Beam steering of the 3-elements array antenna in E-plane from (a) 0^0 to $+50^0$ (b) 0^0 to -50^0

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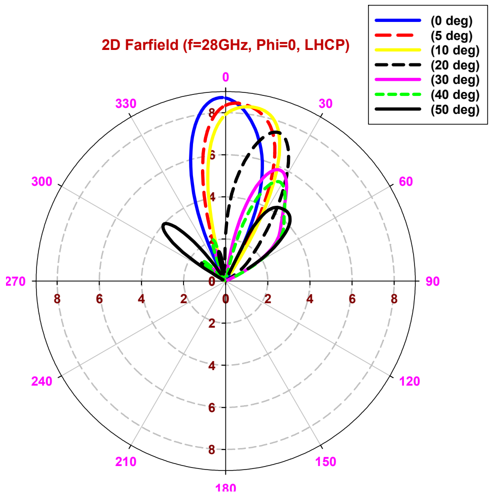
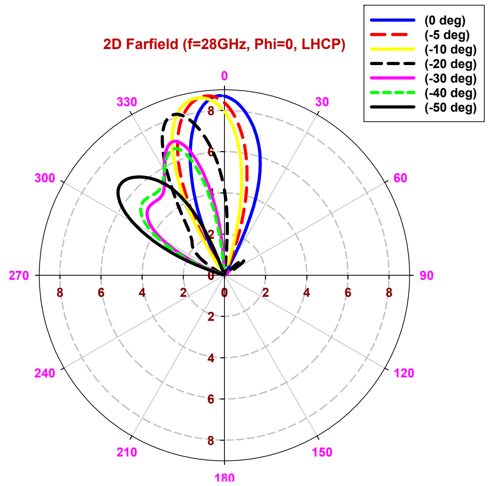


(a)



(b)

Fig. 8 CP of the 3-elements array antenna in E-plane from (a) 0^0 to $+50^0$ (b) 0^0 to -50^0

IV. Conclusion

The design of a 3-elements phased-array circular loop antenna has been proposed in this paper in order to achieve a CP radiation. The results demonstrated that the main beam can be efficiently controlled to steer the beam in a CP mode, where the scanning angle is up to $\pm 50^0$. This is achieved by changing the excitation of the elements. A LHCP radiation is obtained during the beam steering with an axial ratio bandwidth of circa 15%. The results demonstrate that the radiation efficiency of an array can achieve circa 97% with an antenna array gain of 11 dBi.

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