Electronically Beam-Steered Dielectric Resonator Antenna Array for Millimeter-Wave Applications

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***Abstract*—This paper presents a compact 2×2 dielectric resonator antenna (DRA) array with two-dimensional beam-steering capabilities for modern wireless communication systems. The design employs high-permittivity materials ($\varepsilon = 9.9$ for the DRA and $\varepsilon_s = 3.66$ for the substrate) and a four-way microstrip feed network with integrated phase shifters to enable directional beam control in both the X- and Y-planes. The proposed array achieves beam steering up to ±15° while maintaining circular polarization (CP) across the steering range. The DRA dimensions are optimized using the dielectric waveguide model (DWM) and validated through CST eigenmode simulations. Experimental results demonstrate efficient beam steering with low insertion loss, stable impedance matching, and robust polarization performance, making the proposed array well-suited for millimeter-wave 5G and beyond-5G applications.**

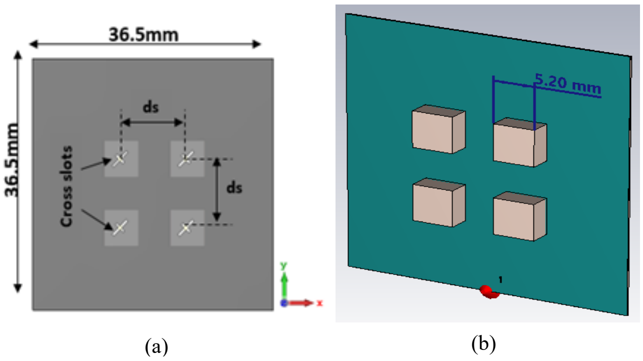
Keywords—Dielectric resonator antenna, array, Beam steering, 5G.

I. INTRODUCTION

Beam steering is a key capability in modern communication systems, particularly for millimeter-wave (mmWave) applications, wearable antennas, and high-speed wireless networks, as it enhances directional communication, reduces interference, and improves gain. Dielectric resonator antenna (DRA) arrays are especially attractive due to their high radiation efficiency, low profile, and design flexibility, making them strong candidates for 5G/6G systems [1]. Electronic beam control can be achieved by integrating phase-shifting mechanisms into microstrip feed networks, thereby eliminating the need for mechanical movement and enabling compact, reconfigurable implementations.

Various approaches have been investigated for efficient beam steering in DRAs and related antenna arrays. Low-loss, planar, substrate-compatible SIW phase shifters were demonstrated in [2], while a single-layer frequency selective surface (FSS) approach enabled simplified beam control [3]. Compact Ka-band feed networks with intermediate phase control were reported in [4], and 2D beam-steerable metasurfaces using phase gradients were introduced in [5]. Microstrip phase shifters for directive control [6], scalable E-band phased arrays [7], and low-cost 3D-printed dielectric lens antennas [8] have also been proposed. A four-arm circularly polarized high-gain, high-tilt beam curl antenna for beam steering applications was presented in [9]. Mechanical solutions such as rotating dielectric slabs in slotted waveguide antennas [10,17], as well as hybrid analog–digital beamforming [11], nonreciprocal phased arrays [12], near-field body-centric beam shaping [13], and active partially reflective surfaces for 2D control [14] have been explored. The use of time-delay transmission lines has also proven effective in circularly polarized mmWave phased array designs [15]. Classical fixed-angle beamforming using the Butler matrix remains relevant [16].

In this work, we propose a 2 × 2 rectangular DRA (RDRA) array fed by a microstrip network with integrated phase shifts. By introducing a progressive phase difference across the input ports, the array achieves directional electronic beam steering without mechanical movement, supporting compact, low-profile configurations suitable for mmWave, wearable, and space-constrained applications.

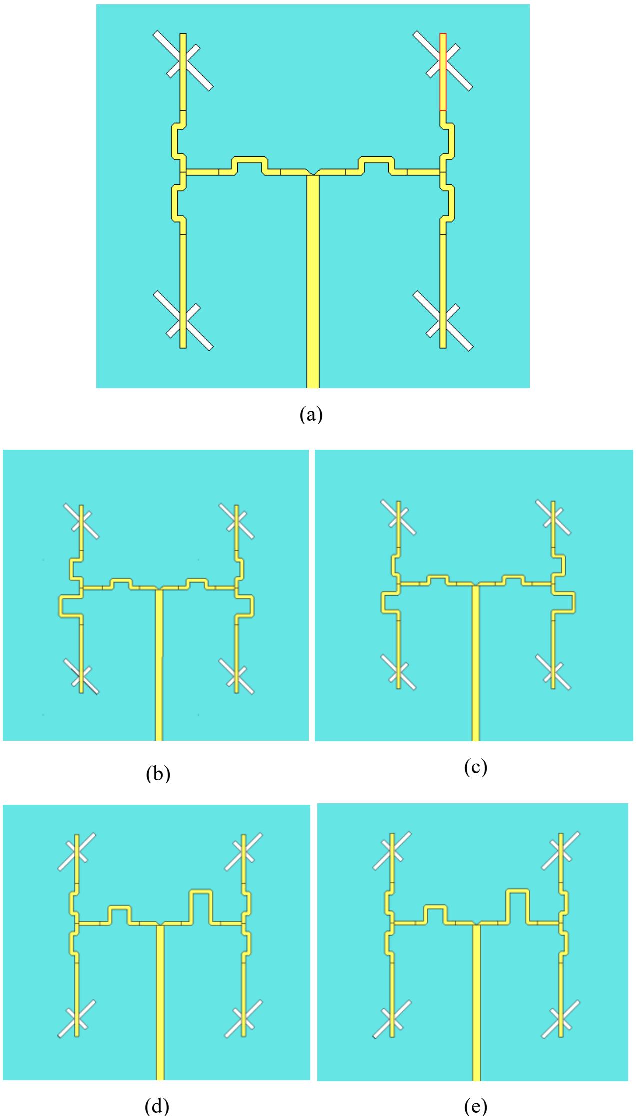


(a) (b)

Fig. 1. Proposed DRA array: (a) Top view, (b) Bottom view.

II. ANTENNA CONFIGURATION

Figure 1 illustrates the proposed RDRA array, which consists of a dielectric resonator antenna (DRA) and a substrate separated by a ground plane with etched feeding slots. The DRA is fabricated using a material with a relative permittivity of $\varepsilon = 9.9$ and a loss tangent $\tan\delta < 0.0001$, while the substrate has $\varepsilon = 3.66$ with $\tan\delta < 0.0027$. The DRA dimensions were optimized using the dielectric waveguide model (DWM), and the resonant modes were validated through eigenmode analysis in CST Microwave Studio to ensure operation at the target frequency. The feeding network employs a four-way microstrip line configuration incorporating progressively varied transmission line lengths to introduce controlled phase shifts, thereby enabling beam steering. The cross slot was chosen to be 3.2 mm × 1.7 mm in order to achieve circular polarization, ensuring that the radiated field has the desired handedness for polarization-sensitive applications. This configuration ensures impedance matching and uniform amplitude distribution across all ports while minimizing insertion loss. To validate the beam-steering performance, five excitation scenarios were investigated: (i) equal-phase feeding for broadside radiation (0°), (ii) progressive delays along the X-plane to steer the beam to −15° in X, (iii) reversed delays along the X-plane to steer to +15° in X, (iv) progressive delays in the Y-plane for −15° in Y, and (v) reversed delays in the Y-plane for +15° in Y. These tailored phase distributions provide precise directional control of the main beam without relying on active circuitry, demonstrating the suitability of the proposed array for compact and low-complexity beam-steering applications in emerging 5G/6G mm-wave systems.


(a)

(b)

(c)

(d)

(e)

Fig. 2. Transmission line feed network configurations for the proposed 2×2 RDRA array, illustrating five excitation cases: (a) 0° broadside radiation, (b) −15° beam steering in the X-plane, (c) +15° beam steering in the X-plane, (d) −15° beam steering in the Y-plane, and (e) +15° beam steering in the Y-plane.

III. RESULTS

For phased array antennas, maintaining good impedance matching across all beam steering angles is essential. To verify this, simulations of the return loss were conducted at steering angles of 0°, +15°, and −15° in both the X- and Y-planes, as shown in Figure 3. The results demonstrate a wide operating bandwidth from 25 GHz to 31 GHz, corresponding to 21.4%, indicating that all three antenna arrays operate within the same frequency range throughout the beam steering process.

The simulated axial ratios (AR) of the antenna arrays across all scanning angles within the operating band are shown in Figure 4. The corresponding simulated 3 dB AR bandwidths are approximately 15.8%, 12.1%, 12.2%, 10.8%, and 10.8% for the scanning angles of 0°, −15°X, +15°X, −15°Y, and +15°Y, respectively. These results indicate that the arrays maintain good right-hand circular polarization (RHCP) performance across the entire beam-steering range.

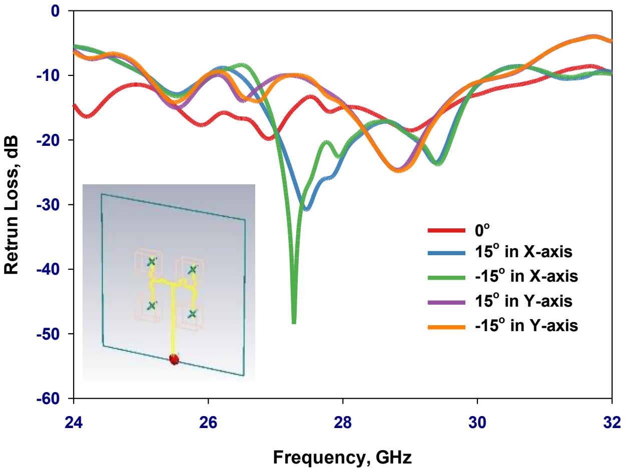


Fig. 3. Simulated return loss of the phased array at beam steering angles of 0°, ±15° in the X- and Y-planes.

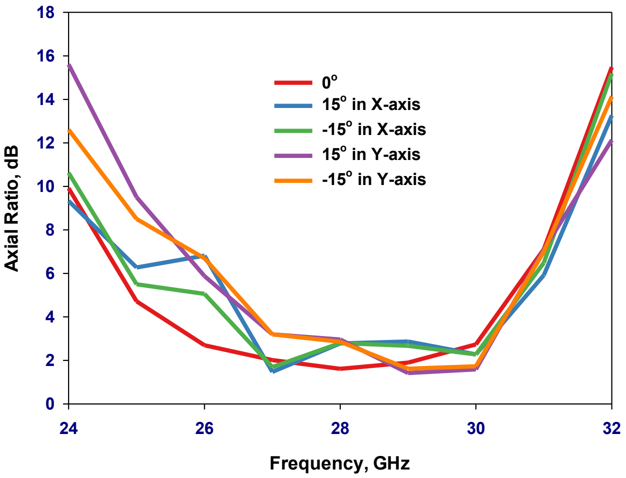


Fig. 4. Simulated axial ratio of the antenna arrays across all scanning angles within the operating band.

The maximum gains of the antenna arrays cases are presented in Figure 5. The simulated broadside gain reaches approximately 13.9 dBic at 0°. As the beam steering angle increases, a gradual reduction in antenna gain is observed; for example, at −15° and +15° scanning angles, the gain decreases to around 13.5 dBic. This reduction is attributed to the element pattern tapering and increased phase errors associated with off-broadside steering. Moreover, the results show a rise in side-lobe levels with larger steering angles, which is a common characteristic of phased arrays.

Figure 6 illustrates the radiation efficiency of all antenna configurations. The simulations show a consistently high efficiency of approximately 82% across the X-axis beam-steering angles at 28 GHz, with a slight reduction to about 79% along the Y-axis. These results indicate that the array effectively radiates power even under off-broadside scanning conditions.

Figure 7 shows the radiation patterns of the 28 GHz antenna array at ϕ = 0°. Patterns are presented for the X-plane at 0°, −15°, and +15° (Fig. 7(a)) and for the Y-plane at −15° and +15° (Fig. 7(b)). The results illustrate the array's directional characteristics and beam-steering performance, demonstrating consistent radiation behavior across the scanned angles in both planes.

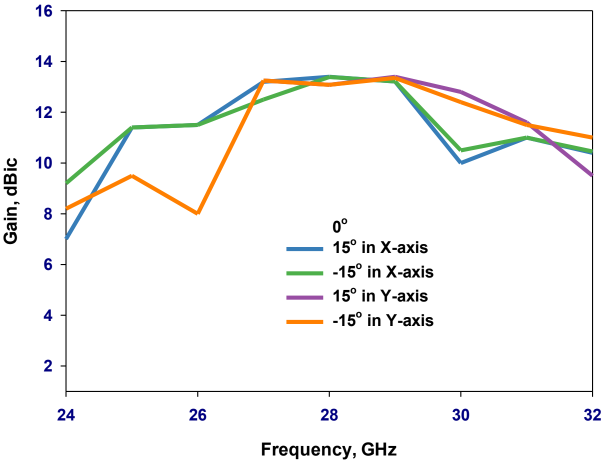


Fig. 5. Main beam gain for the all-beam steering angles.

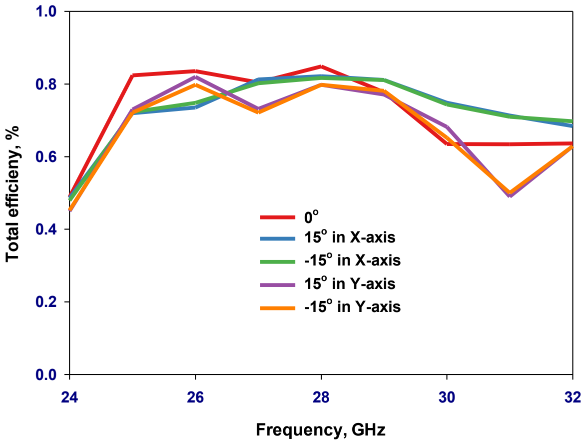
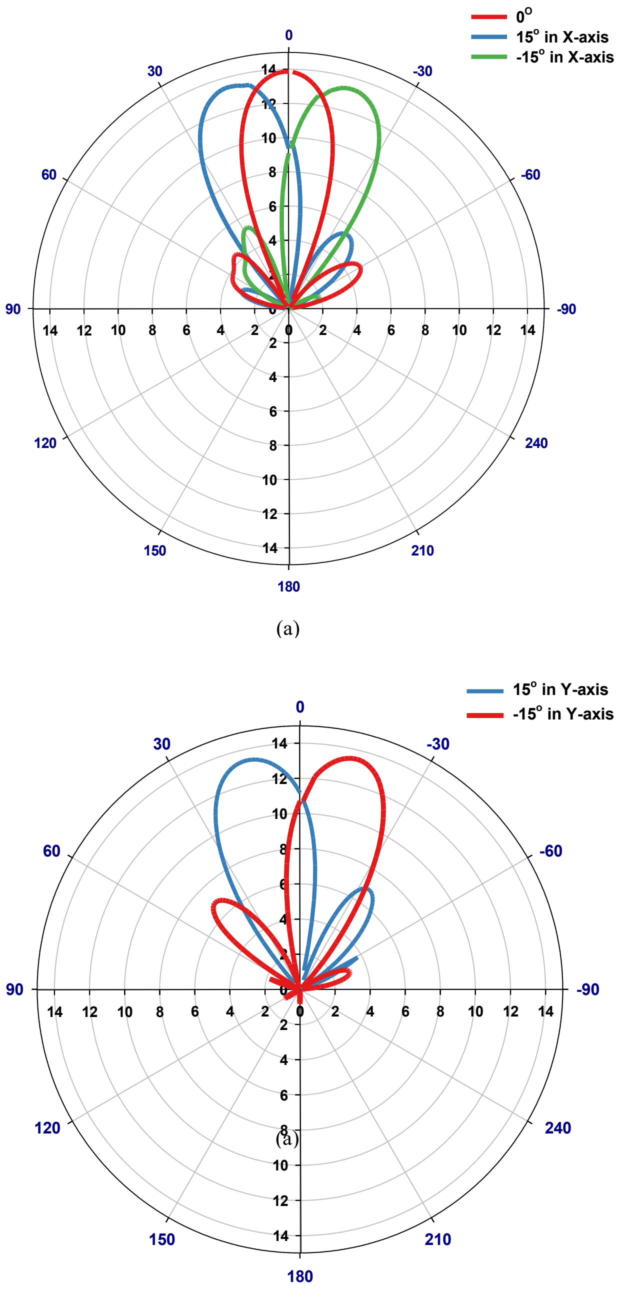


Fig. 6. Simulated total efficiency (η) for all different beam steering angles.



(a)

(b)

Fig. 7. Radiation patterns of the 28 GHz antenna array at ϕ = 0° for (a) X-plane angles of 0°, −15°, and +15° and (b) Y-plane angles of −15° and +15°.

IV. CONCLUSION

A compact 2 × 2 RDRA array with an integrated phase-shifting feed network has been successfully designed for mmWave beam-steering applications. Simulations show stable impedance matching, wide operating bandwidth (25–31 GHz), high radiation efficiency (~82%), and good right-hand circular polarization (RHCP) across all steering angles. The array maintains a broadside gain of ~13.9 dBic with minimal reduction at ±15° scanning, demonstrating effective beam control in both X- and Y-planes. These results confirm the array's suitability for dynamic and directional high-frequency wireless communication systems.

V. ACKNOWLEDGEMENT

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