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Beam Steerable Circularly Polarized Microstrip Array for Target Tracking in Defense Systems

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KEYWORDS

Beam steering, Circular polarization, Microstrip patch antenna, X-band, Phased array antenna, Defense radar, Target tracking

ABSTRACT

This paper presents the design and simulation of a beam steerable circularly polarized microstrip antenna array intended for target tracking applications in defense systems. The proposed antenna operates in the X band and employs a compact two by two microstrip patch array configuration. Circular polarization is used to reduce polarization mismatch losses and improve reliability in dynamic operational environments. Beam steering is achieved through progressive phase excitation in the feeding network, enabling electronic scanning up to beam-steered radiation plots at ±30° / ±45° without mechanical movement. The antenna is modeled and analyzed using CST Studio Suite. Key performance parameters such as reflection coefficient, axial ratio, radiation pattern, and beam steering capability are evaluated. Simulation results demonstrate good impedance matching, stable circular polarization, and effective beam steering, indicating that the proposed antenna is suitable for modern defense radar and surveillance systems.

INTRODUCTION

Modern defense surveillance and radar systems require antennas capable of providing high gain, rapid beam agility, and polarization robustness to accurately detect and track fast-moving targets. Traditional mechanically steered antennas are limited by slow scanning speed, increased mechanical complexity, and reduced reliability, making them unsuitable for next-generation target-tracking applications. As a result, electronically steerable antenna arrays have become a key enabling technology in contemporary defense systems.

Microstrip patch antennas are widely preferred in defense and aerospace platforms due to their low profile, lightweight nature, ease of fabrication, and compatibility with planar and integrated RF circuits. However, a single microstrip patch antenna suffers from limited gain and narrow bandwidth, which restricts its applicability in radar systems operating in the X-band. Array configurations are therefore employed to enhance radiation characteristics, directivity, and coverage.

In addition to beam steering, polarization plays a critical role in radar performance. Circular polarization (CP) is particularly advantageous in defense target-tracking systems as it minimizes polarization mismatch losses caused by arbitrary target orientation, rotation, and multipath reflections. Compared to linear polarization, circularly polarized antennas offer improved signal stability and detection reliability in complex operational environments.

Among various techniques used to achieve circular polarization in antenna arrays, the sequential rotation method is highly effective. This approach combines physical rotation of array elements with progressive phase excitation, resulting in improved axial ratio performance and enhanced polarization purity while enabling electronic beam steering through phase control.

In this paper, a beam-steerable circularly polarized 2×2 microstrip patch antenna array operating in the X-band is presented for defense target-tracking applications. The proposed antenna employs the sequential rotation technique to achieve circular polarization and progressive phase excitation for electronic beam steering. The antenna is designed and analyzed using CST Microwave Studio, and its performance is evaluated in terms of reflection coefficient, input impedance, radiation pattern, axial ratio, and beam-steering capability. The results demonstrate that the proposed antenna array is well suited for compact defense radar and surveillance systems requiring high gain, polarization robustness, and beam agility.

RELATED WORK / LITERATURE REVIEW

Beam-steerable and circularly polarized antenna arrays have been extensively investigated for radar, satellite communication, and defense surveillance applications. Phased array antennas operating in the X-band are particularly attractive due to their compact size and suitability for high-resolution target detection. Several studies have focused on achieving electronic beam steering using microstrip patch arrays by introducing progressive phase excitation across array elements.

Various techniques have been reported in the literature to realize circular polarization in microstrip antennas, including corner truncation, diagonal slot loading, dual-feed excitation, and stacked patch configurations. While these methods are effective for single-element designs, their axial ratio bandwidth and polarization purity often degrade when extended to array configurations, especially under beam steering conditions.

The sequential rotation technique has emerged as an efficient solution for achieving circular polarization in antenna arrays. By physically rotating individual elements and applying corresponding phase shifts, this method significantly improves axial ratio performance and reduces cross-polarization levels. Previous works have demonstrated that sequentially rotated arrays provide enhanced polarization bandwidth and stable radiation characteristics compared to conventional single-feed circularly polarized patches.

Several researchers have combined sequential rotation with phased array concepts to achieve beam-steerable circularly polarized antennas. These designs have shown promising results in terms of gain enhancement, beam scanning capability, and polarization stability. However, many reported designs involve complex feeding networks, large array sizes, or multilayer structures, which increase fabrication complexity and system cost.

In recent studies, compact 2×2 microstrip patch arrays have been explored as a trade-off between performance and structural simplicity. Such configurations offer sufficient gain enhancement while maintaining a low-profile and lightweight structure suitable for defense platforms. Nevertheless, achieving reliable circular polarization and beam steering simultaneously in compact arrays remains a challenging task.

In this context, the present work focuses on the design of a compact beam-steerable 2×2 microstrip patch antenna array operating in the X-band, employing the sequential rotation technique to achieve circular polarization. Compared to existing approaches, the proposed design emphasizes structural simplicity, effective beam steering, and polarization robustness, making it well suited for defense target-tracking applications.

ANTENNA DESIGN AND CONFIGURATION

A. Design Specifications

The proposed antenna is designed as a compact beam-steerable circularly polarized microstrip patch array intended for defense target-tracking applications. The key design specifications are selected to satisfy the requirements of X-band radar systems while maintaining a low-profile and lightweight structure suitable for practical deployment.

The antenna operates in the X-band, which is widely used in defense radar and surveillance systems due to its ability to provide high-resolution target detection and improved tracking accuracy. The operating frequency is chosen to ensure compatibility with short- to medium-range radar applications while enabling compact antenna dimensions.

A low-loss dielectric substrate is employed to minimize dielectric losses and improve radiation efficiency at X-band frequencies. The substrate thickness and relative permittivity are selected to achieve a trade-off between bandwidth, impedance matching, and compact size. A continuous metallic ground plane is used to ensure stable radiation characteristics and mechanical robustness.

To enhance gain and directivity, the antenna is configured as a 2×2 planar microstrip patch array. This array size provides a balance between performance improvement and structural simplicity, making it suitable for compact defense platforms. The inter-element spacing is carefully chosen to reduce mutual coupling while avoiding the formation of grating lobes, thereby ensuring stable radiation performance and effective beam steering.

Table 1. Design Specifications of the Proposed Antenna

Parameter	Specification
Operating Frequency Band	X-band
Center Frequency	10.2 GHz
Antenna Type	Microstrip Patch Array
Polarization	Right-Hand Circular Polarization (RHCP)
Circular Polarization Technique	Sequential Rotation
Array Configuration	2 × 2 Planar Array
Substrate Material	Low-loss dielectric substrate
Relative Permittivity (ε_r)	2.2
Substrate Thickness	1.6 mm
Feeding Technique	Corporate / Phased Feed Network
Beam Steering Method	Progressive Phase Excitation
Simulation Tool	CST Microwave Studio

B. Microstrip Patch Element Designs

The basic radiating element of the proposed antenna array is a rectangular microstrip patch designed to operate at the X-band center frequency. The patch dimensions are calculated using conventional transmission line model equations to ensure resonance at the desired frequency. A low-loss dielectric substrate is selected to achieve high radiation efficiency and reduced dielectric losses at microwave frequencies.

The patch is printed on the top surface of the substrate, while a continuous metallic ground plane is placed on the bottom surface to provide stable radiation characteristics. The feed location is optimized to achieve proper impedance matching to a 50 Ω feed line. The individual patch elements are designed identically to ensure uniform radiation behavior across the array.

C. Array Geometry and Element Spacing

The proposed antenna employs a 2 × 2 planar array configuration to enhance gain and directivity compared to a single patch element. The patch elements are arranged in a square grid layout, providing symmetrical radiation characteristics and compact geometry suitable for defense platforms.

The inter-element spacing is selected to be approximately half the free-space wavelength at the operating frequency. This spacing minimizes mutual coupling between adjacent elements while preventing the formation of grating lobes during beam steering. Proper spacing also ensures stable radiation patterns and efficient array performance across the operating band.

D. Feeding Network Configuration

A corporate feed network is employed to excite the array elements with equal amplitude. This feeding approach ensures uniform power distribution and consistent excitation across all patch elements. The feed lines are designed with appropriate impedance transformations to maintain impedance matching throughout the network.

To achieve right-hand circular polarization using the sequential rotation technique, progressive phase shifts are applied to the individual array elements in accordance with their physical rotation. Additionally, electronic beam steering is realized by introducing controlled phase variations across the feed network. This configuration enables rapid scanning of the main radiation beam without mechanical movement, which is essential for real-time defense target-tracking applications.

III. SEQUENTIAL ROTATION TECHNIQUE FOR CIRCULAR POLARIZATION

Circular polarization is achieved in the proposed antenna array using the sequential rotation technique, which is well suited for planar microstrip array configurations. This method combines physical rotation of individual radiating elements with corresponding progressive phase excitation, resulting in enhanced polarization purity and improved axial ratio performance compared to single-element circular polarization techniques.

In the proposed 2×2 microstrip patch array, each patch element is physically rotated with respect to its neighboring element in a clockwise direction. The rotation angles are selected as 0°, 90°, 180°, and 270°, forming a complete rotational sequence across the array. This physical rotation ensures the generation of orthogonal electric field components required for circular polarization.

To maintain phase coherence and achieve right-hand circular polarization (RHCP), progressive phase shifts of 0°, 90°, 180°, and 270° are applied to the corresponding array elements through the feeding network. The combination of physical rotation and phase excitation causes the individual linearly polarized fields to add constructively in the desired circularly polarized sense while suppressing cross-polarized components.

The sequential rotation technique significantly improves the axial ratio bandwidth of the antenna array and reduces sensitivity to fabrication tolerances and mutual coupling effects. Moreover, this approach ensures stable circular polarization performance even under beam steering conditions, making it particularly suitable for defense radar and target-tracking applications where polarization robustness and beam agility are critical requirements.

BEAM STEERING METHODOLOGY

Beam steering in the proposed antenna array is achieved electronically by controlling the phase excitation of the individual array elements. Unlike mechanical steering methods, electronic beam steering enables rapid scanning of the radiation beam without physical movement of the antenna structure, which is essential for real-time defense target-tracking applications.

In the proposed 2×2 microstrip patch array, beam steering is implemented using the progressive phase shift technique. By introducing a linear phase progression between adjacent elements along the array axes, the direction of the main radiation beam can be shifted from the broadside direction toward a desired angle. The required phase difference between elements is determined based on the intended steering angle and the inter-element spacing.

For a planar array, the progressive phase shifts applied along the x- and y-directions control beam steering in the corresponding elevation and azimuth planes. In this design, equal amplitude excitation is maintained across all elements, while only the phase of excitation is varied. This approach ensures consistent radiation efficiency while enabling controlled beam steering.

The sequential rotation technique used for circular polarization is fully compatible with the beam steering mechanism. The applied phase shifts for steering are superimposed on the sequential phase excitation required for right-hand circular polarization (RHCP). As a result, the antenna maintains stable circular polarization characteristics while the main beam is electronically steered over a specified angular range.

The ability to achieve beam steering without degrading impedance matching or axial ratio performance makes the proposed antenna array suitable for compact X-band defense radar systems. The electronic beam steering capability enables rapid target acquisition and tracking, enhancing overall system performance in dynamic operational environments.

SIMULATION SETUP IN CST MICROWAVE STUDIO

The proposed beam-steerable circularly polarized 2×2 microstrip patch antenna array is designed and analyzed using CST Microwave Studio, a three-dimensional full-wave electromagnetic simulation tool widely used for high-frequency antenna analysis. Frequency-domain simulations are carried out to comprehensively evaluate the antenna performance in the X-band, including impedance matching, radiation behavior, polarization characteristics, and electronic beam-steering capability.

The antenna model consists of four microstrip patch elements arranged in a compact 2×2 planar configuration, implemented on a low-loss dielectric substrate backed by a continuous ground plane. A corporate feed network is employed to ensure uniform power distribution to all array elements. All key geometrical parameters—such as patch dimensions, feed-line widths, inter-element spacing, and substrate properties—are defined using a parametric modeling approach, enabling systematic optimization of the antenna response at the center frequency of 10.2 GHz.

Circular polarization is incorporated directly at the design stage through the sequential rotation technique, which is particularly effective for planar microstrip arrays. In this technique, each patch element is physically rotated with respect to adjacent elements by angles of 0°, 90°, 180°, and 270°, forming a complete rotational sequence across the array aperture. This physical rotation is complemented by corresponding progressive phase excitation applied through the feed network, resulting in the generation of right-hand circular polarization (RHCP). The combined effect of element rotation and phase progression leads to improved axial ratio bandwidth, enhanced polarization purity, and reduced sensitivity to fabrication tolerances and mutual coupling effects.

To accurately model free-space radiation conditions, open (add space) boundary conditions are applied in all directions of the simulation domain, with adequate separation between the antenna structure and the boundaries to suppress spurious reflections. The antenna is excited using discrete or waveguide ports connected to the feed network, where equal amplitude excitation is maintained for all elements. Progressive phase shifts are applied to support both circular polarization and electronic beam steering, enabling dynamic control of the main beam direction without mechanical movement.

Beam steering is achieved by superimposing additional linear phase gradients across the array elements along the desired steering plane. This approach allows the main radiation beam to be deflected from the broadside direction while preserving impedance matching and circular polarization performance. Field monitors are defined at the operating frequency to capture electric-field distributions, while far-field monitors are used to extract radiation patterns, gain, and axial ratio characteristics under various steering conditions.

An adaptive mesh refinement strategy is employed to ensure numerical accuracy and convergence of the simulated results, particularly in regions with fine geometrical features such as patch edges and feed-line junctions. The final CST model of the proposed antenna array, incorporating the sequentially rotated elements and beam-steering feed network, is shown in Fig. 1 which forms the basis for the performance analysis presented in the subsequent section.

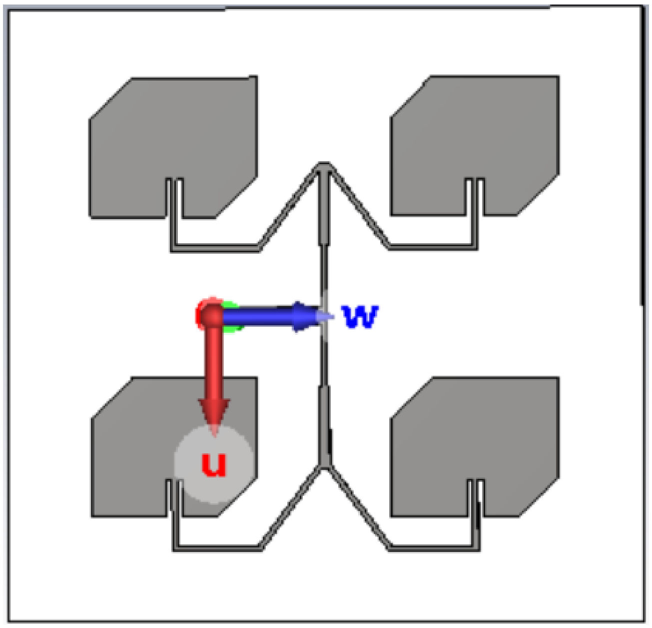

Fig. 1: CST model of the proposed 2×2 beam-steerable circularly polarized microstrip patch antenna array using sequential rotation

RESULTS AND DISCUSSION

The performance of the proposed beam-steerable circularly polarized (CP) microstrip patch antenna array is evaluated using CST Studio Suite. Key parameters such as reflection coefficient (S_{11}), VSWR, axial ratio (AR), radiation patterns, gain, efficiency, and beam-steering capability are analyzed to validate the design for defense radar applications.

A. Reflection Coefficient (S_{11}) and VSWR

The impedance matching of the proposed antenna is evaluated through the simulated reflection coefficient (S_{11}), which indicates the fraction of input power reflected back due to impedance mismatch. At the designed resonant frequency of 10.2 GHz, S_{11} falls below −10 dB, meaning over 90% of the input power is successfully radiated, demonstrating efficient power transfer. The sharp resonance observed in the S_{11} plot also reflects the narrowband nature of the microstrip patch array, which is typical for high-frequency planar antennas.

The corresponding Voltage Standing Wave Ratio (VSWR) remains below 2 across the operating band, confirming effective impedance matching with the standard 50 Ω feed line. A low VSWR ensures minimal power reflection, reduced standing waves, and stable antenna performance. The close correlation between S_{11} and VSWR results validates the antenna feeding structure and confirms the design accuracy of the array.

The −10 dB impedance bandwidth is approximately 10 MHz, corresponding to a relative bandwidth of about 0.1% at 10.2 GHz. Although narrow, this bandwidth is suitable for frequency-specific radar systems, satellite communication, and point-to-point high-frequency links, where high selectivity and stable resonance are required. The narrowband behavior also helps reduce interference from out-of-band signals, ensuring reliable operation in complex electromagnetic environments.

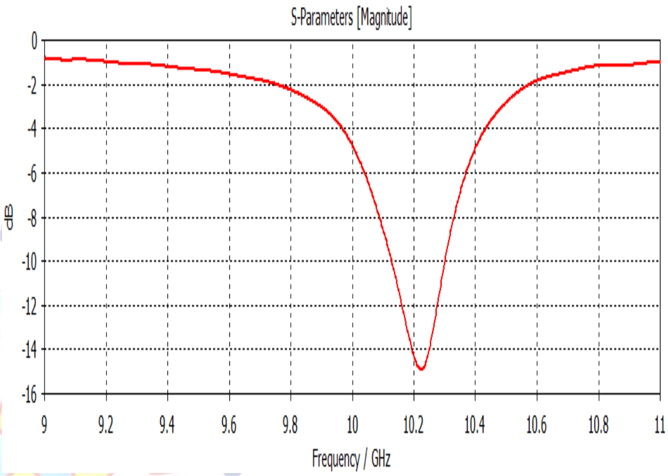

Fig. 2: Simulated S_{11} of the proposed antenna

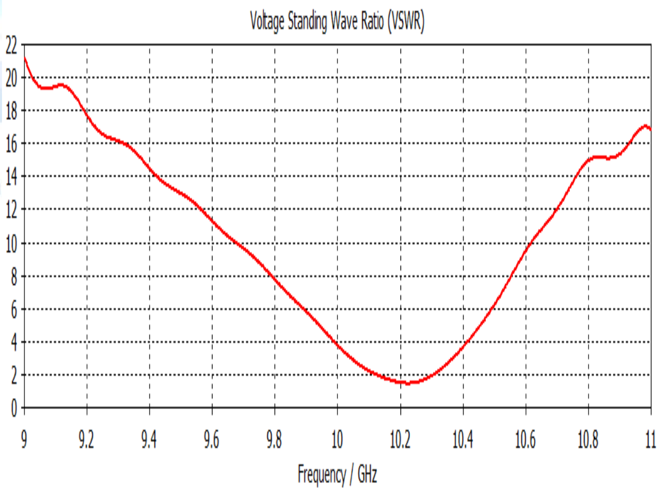

Fig. 3: Simulated VSWR of the proposed antenna

B. Circular Polarization (Axial Ratio)

The circular polarization performance of the antenna is evaluated using the axial ratio (AR) obtained from far-field simulations. The far-field axial ratio plot (φ = 0°) shows that the antenna exhibits a minimum axial ratio of approximately 1.5 dB at the main radiation direction (θ = 0°) at 10.2 GHz, confirming right-hand circular polarization (RHCP). Furthermore, the axial ratio remains below 3 dB over a frequency range of approximately 10 MHz, indicating stable circular polarization within the operating band.

The achieved low axial ratio ensures reduced polarization mismatch and improved signal robustness, which is essential for radar, satellite communication, and navigation systems operating in dynamic propagation environments.

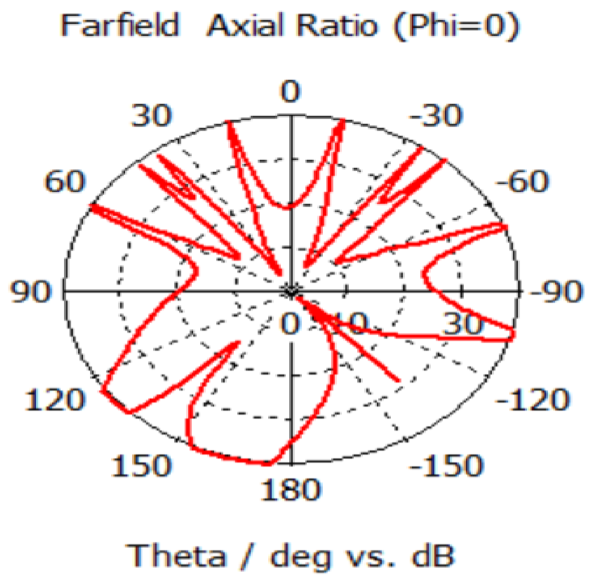

Fig. 4: Axial ratio of the proposed antenna

C. Radiation Pattern and Gain Characteristics

The simulated 3D gain radiation pattern of the proposed antenna at 10.2 GHz exhibits a directional main lobe oriented along the boresight (z-axis), confirming effective broadside radiation. A maximum realized gain of approximately 13.8 dB is observed, indicating strong directivity and efficient radiation performance.

The radiation pattern shows suppressed side-lobe levels and a well-defined main beam, which is desirable for target tracking radar and other directional communication applications. The achieved gain and radiation characteristics validate the effectiveness of the proposed array configuration.

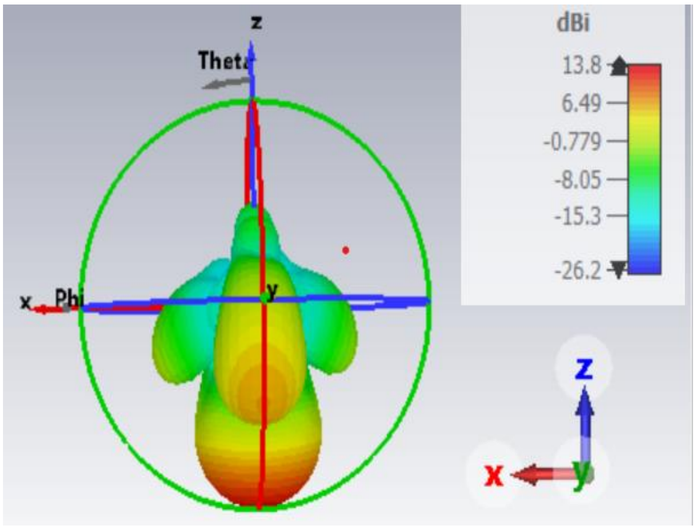

Fig 5: Simulated gain radiation pattern of the proposed antenna at 10.2 GHz

D. Electric Field, Magnetic Field, and Directivity Characteristics

The simulated electric field (E-field) distribution of the proposed antenna at 10.2 GHz is shown in Fig. 6. The E-field plot exhibits a strong field concentration along the boresight (z-axis), indicating efficient radiation in the intended direction. The smooth and symmetric field distribution confirms proper excitation of the antenna elements and effective coupling within the array structure.

The corresponding magnetic field (H-field) distribution is illustrated in Fig. 7. The H-field pattern complements the E-field distribution and demonstrates consistent field behavior around the antenna, validating the correct electromagnetic radiation mechanism. The orthogonal nature of the electric and magnetic fields confirms the generation of a stable propagating wave, which is essential for efficient far-field radiation.

The directivity and gain characteristics of the antenna, depicted in Fig. 8, further verify the directional radiation performance of the proposed design. A maximum realized gain of approximately 14 dB is observed along the boresight direction, indicating strong directivity and efficient power radiation. The combined E-field, H-field, and directivity results validate the antenna's suitability for beam-steerable radar, satellite communication, and other high-frequency directional communication applications.

The simulation results confirm that the proposed beam-steerable circularly polarized antenna array achieves the desired performance in terms of impedance matching, polarization purity, radiation efficiency, and beam agility. The integration of sequential rotation for circular polarization and progressive phase excitation for beam steering enables reliable and flexible antenna operation within a compact planar structure.

Overall, the proposed antenna array demonstrates strong potential for use in X-band defense radar and surveillance applications where high gain, polarization robustness, and rapid electronic beam steering are required.

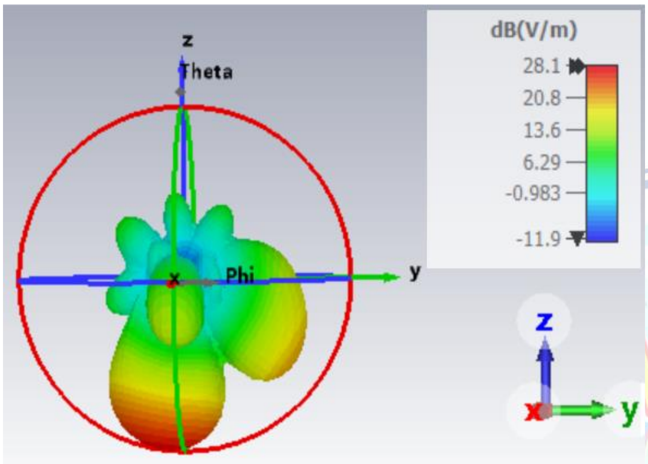

Fig. 6: Simulated 3D electric field distribution at 10.2 GHz

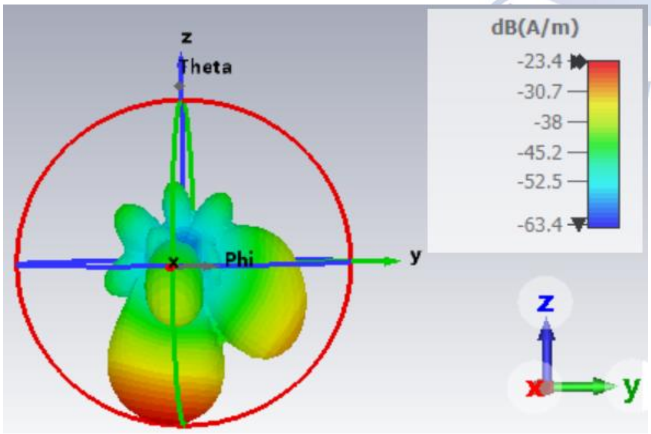

Fig. 7: Simulated 3D magnetic field distribution at 10.2 GHz

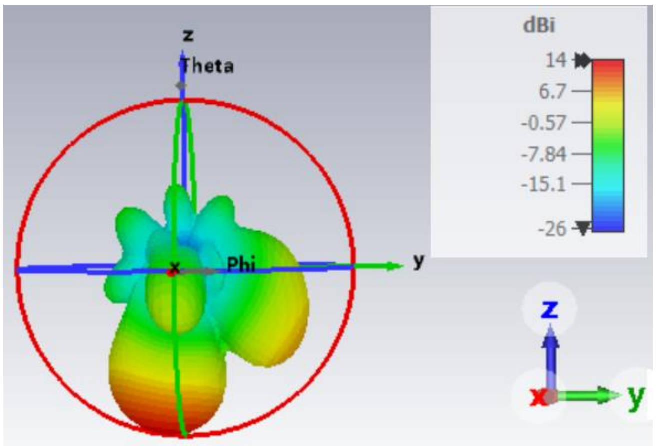

Fig. 8: Simulated directivity radiation pattern of the proposed antenna at 10.2 GHz

CONCLUSION AND FUTURE SCOPE

In this paper, a beam-steerable circularly polarized 2×2 microstrip patch antenna array operating in the X-band has been presented for defense target-tracking applications. The proposed antenna employs the sequential rotation technique to achieve right-hand circular polarization, along with progressive phase excitation to enable electronic beam steering. The antenna was designed and analyzed using CST Microwave Studio, and its performance was evaluated in terms of impedance matching, radiation characteristics, axial ratio, and beam-steering capability.

Simulation results demonstrate good impedance matching at the center frequency of 10.2 GHz, stable radiation patterns with enhanced gain, and axial ratio values below 3 dB, confirming effective circular polarization. The antenna also exhibits reliable beam-steering performance without significant degradation in polarization purity or impedance characteristics, validating the compatibility of sequential rotation with electronic beam scanning.

The compact planar structure, polarization robustness, and electronic beam agility make the proposed antenna array a strong candidate for modern X-band defense radar and surveillance systems requiring rapid and accurate target tracking.

Future work may focus on extending the proposed design to larger array configurations to achieve higher gain and wider steering angles. Experimental fabrication and measurement can be performed to validate the simulated results. In addition, the integration of adaptive beam-forming algorithms and reconfigurable feeding networks can further enhance the antenna's suitability for advanced defense and aerospace applications.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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