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A High-Performance, Thin, Circularly Polarized Microstrip Antenna for Compact Radar Systems

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ABSTRACT: This paper presents a novel, thin, circularly polarized microstrip antenna optimized for radar applications, designed to operate within the 7.5–7.7 GHz frequency band. The antenna is compact, with overall dimensions of $1.97\lambda \times 1.08\lambda \times 0.0025\lambda$ (where λ is wavelength calculated at 7.5 GHz) printed on a flexible polyimide substrate, offering advantages in terms of mechanical flexibility and integration into conformal systems. Circular polarization is achieved with an axial ratio of less than 3 dB across the operating bandwidth, while a peak gain of 6.25 dBi ensures adequate signal strength for radar detection and communication. Performance improvements are realized by introducing inverted C-shaped slots in the radiating element, effectively manipulating the surface current distribution and enhancing polarization purity and radiation efficiency. A prototype of the antenna was fabricated and tested, with experimental results closely matching simulation data, confirming the reliability of the design methodology. The results demonstrate that the proposed antenna is highly suitable for compact radar systems, offering an optimal balance among size, performance, and fabrication simplicity.

1. INTRODUCTION

Thin antennas have gained significant attention in recent years due to their advantages in compactness and efficiency, making them essential for modern communication systems, including mobile devices, Internet of Things (IoT) applications, and automotive technologies. Recent studies focus on various designs of thin antennas to achieve multi-band and broadband capabilities, which are critical for the increasing demands of wireless communication. For instance, Barik and Koziel present a miniaturized broadband-multiband planar monopole antenna designed for autonomous vehicles, demonstrating the potential for integrating multiple communication protocols in a single compact device [1]. Chung and Yang review advancements in millimeter-wave antennas tailored for5G communications, highlighting the importance of miniaturization to fit into sleek device profiles while maintaining performance [2]. Furthermore, Lee et al. (2020) provide a comprehensive survey on the evolution of antenna technologies from 5G to beyond, underscoring the critical role that thin antennas will play in future wireless communications [3]. The application of thin antennas in the IoT and automotive sectors is particularly noteworthy. Sufyan et al. (2023) introduce an ultra-compact self-triplexing antenna that achieves high isolation, suitable for IoT applications where multiple communication channels are needed simultaneously [4]. Kishore et al. emphasize the growing need for reliable communication in vehicular networks, suggesting that thin antennas integrated into vehicle designs can enhance connectivity and performance [5]. Moreover, [6] emphasizes the suitability of these antennas for aerospace applications, highlighting their efficiency in environments where weight reduction and space optimization are essential, thereby demonstrating their remarkable adaptability [6]. Performance characteristics such as gain, efficiency, and bandwidth are crucial for the practical application of thin antennas. Pearson et al. discuss a wideband antenna design that balances size with efficiency, achieving significant improvements in performance metrics essential for mobile and IoT applications [7]. De Cos Gómez et al. focus on a flexible thin antenna design specifically for IoT applications, highlighting the need for antennas that can conform to different shapes and surfaces [8]. Additionally, De Cos Gómez et al. provide insights into the challenges of maintaining high performance in miniaturized antennas, discussing various techniques to optimize antenna gain and bandwidth while minimizing size [8]. The literature indicates a trend toward the use of flexible substrates and novel materials in the development of thin antennas, which allows for more adaptable designs suitable for various applications. Genovesi et al. propose innovative designs that leverage new materials to enhance the performance of thin antennas, making them suitable for emerging wireless standards [9]. Moreover, the design aspects are necessary for optimizing antenna performance while adhering to size constraints, thus addressing the challenges of modern communication requirements [10–14].

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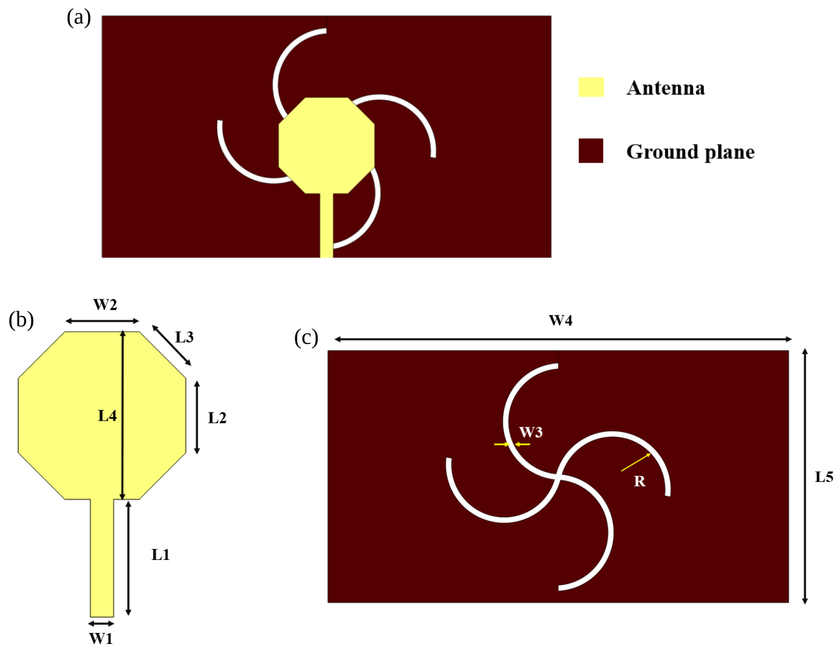

FIGURE 1. (a) Overall structure of proposed antenna, (b) front View, (c) back view.

The literature review highlights extensive research on thin antennas, particularly focusing on achieving multi-band and broadband capabilities for mobile, IoT, automotive, and aerospace applications. Various advancements in miniaturization, gain, bandwidth, and flexibility are discussed, with a trend toward using flexible substrates and novel materials to optimize performance while adhering to size constraints. However, despite the growing importance of thin antennas in a wide range of communication systems, there is limited research specifically targeting the development of thin, compact antennas for radar applications. The current studies mainly focus on wireless communication protocols (such as IoT, 5G, and automotive communications) and do not fully address the specific needs of radar systems, particularly in terms of circular polarization, high gain, and mechanical flexibility.

To address this gap, a novel thin, circularly polarized microstrip antenna is specifically designed for radar applications. This antenna operates within the 7.5–7.7 GHz frequency band, offering compactness and flexibility due to its polyimide substrate. The design achieves circular polarization with an axial ratio of less than 3 dB, ensuring reliable radar communication and detection, and features a peak gain of 6.25 dBi, which is critical for radar system performance. The introduction of inverted C-shaped slots enhances radiation efficiency and polarization purity, overcoming performance challenges previously identified in miniaturized antennas. By focusing on radar-specific requirements, such as polarization and gain, this paper fills the identified gap in research, providing an optimized solution for compact radar systems.

2. THIN ANTENNA DESIGN AND DISCUSSIONS

Figures 1(a)–(c) illustrate the design structure of a novel antenna with three distinct views: In Figure 1(a), the antenna features a central octagonal shape which is printed on the front side of a 0.1 mm thick polyimide substrate. The 50-Ω feed line is attached to the bottom of the structure, connecting the octagonal element to the substrate. Figure 1(b) presents the front view, showing the dimensions of the octagonal structure. Parameters $L1$, $L2$, $L3$, $L4$, $W1$, and $W2$ represent dimensions influencing the antenna's resonant frequencies and overall impedance matching. Figure 1(c), the back view, shows three circular arms or slots etched into the ground plane. These arms, marked with width $W3$ and radius R, appear as part of the design to achieve desired radiation patterns and polarization performance. The slots on the ground plane suggest the use of a defected ground structure (DGS), which helps improve bandwidth and gain by manipulating surface currents. Overall, this design appears to be a unique approach aimed at achieving specific operational characteristics, possibly for applications requiring circular polarization above sub-6 GHz frequency communications.

Figure 2 compares the reflection coefficient S_{11} results for the proposed antenna, derived from ADS and CST simulations, focusing on precision in the 7.4 to 7.8 GHz range. The ADS simulation reveals a sharp resonance with a minimum S_{11} below -25 dB around 7.65 GHz, demonstrating a deeper response than the CST, which indicates a slightly shifted peak at around -20 dB. This variation suggests minor discrepancies likely tied to differences in electromagnetic solver algorithms or meshing strategies, with both methods confirming effective impedance matching across the primary band of interest, particularly between 7.5 and 7.7 GHz. The reflection behaviour underscores the antenna's optimal tuning, validating its robust design within the specified X-band segment. Various parameters of the propose antenna are listed in Table 1.

Figure 3 illustrates the phase response of the proposed antenna within the frequency range of 7.4 to 7.8 GHz. A notable phase transition is observed around the 7.6 GHz mark, where the phase abruptly shifts from approximately 140 degrees to about -140 degrees, indicating a resonance point. This rapid phase change is a clear indicator of a strong resonant behaviour, commonly associated with efficient

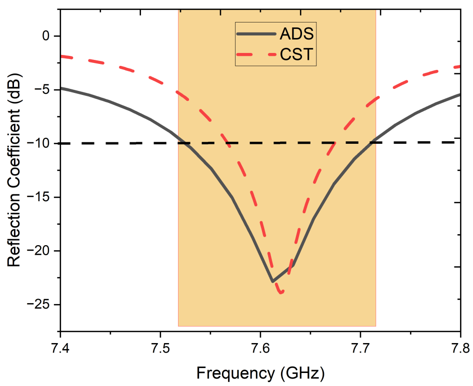

FIGURE 2. Reflection coefficient of the proposed antenna.

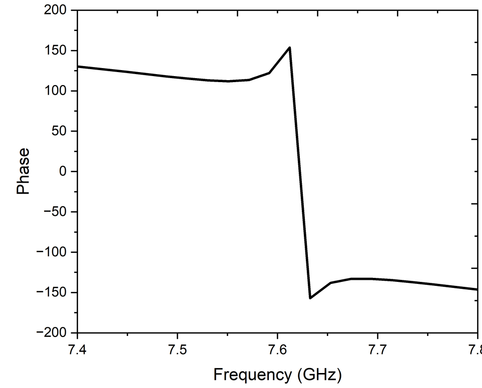

FIGURE 3. Frequency vs phase of the proposed antenna.

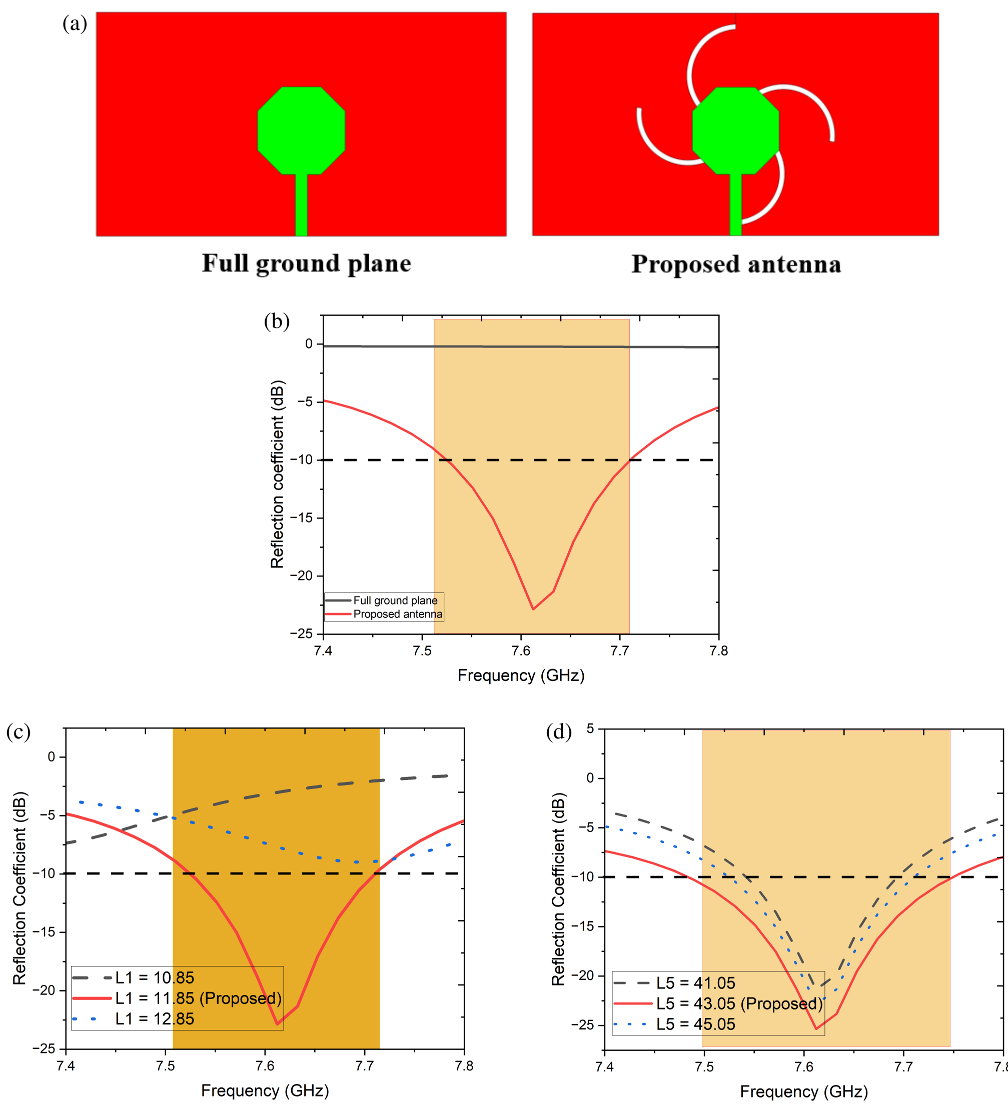

FIGURE 4. (a) Proposed antenna with full ground plane and defected ground plane and their (b) reflection coefficient, parametric analysis when altering (c) feed length ($L1$), (d) ground plane length ($L5$).

radiation and good impedance matching. The relatively stable phase behaviour before and after the sharp transition suggests consistent performance across the non-resonant regions. This phase shift is crucial for achieving the desired circular polarization, ensuring that the antenna maintains stable electromagnetic characteristics within the target band, reinforcing its suitability for X-band applications.

Figure 4(a) compares an antenna with a full ground plane and a proposed antenna design with a defective ground structure. Figure 4(a) depicts the traditional configuration featuring a solid ground plane and

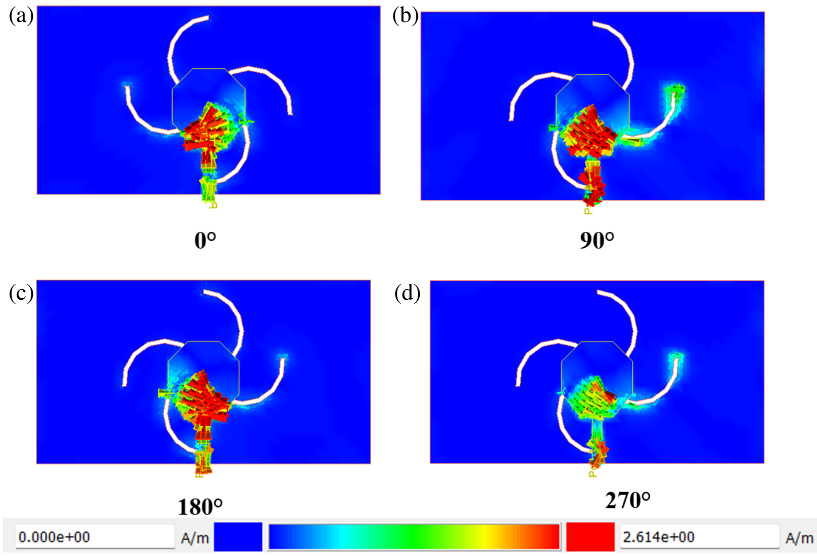

FIGURE 5. Surface current distribution of the proposed antenna at 7.6 GHz.

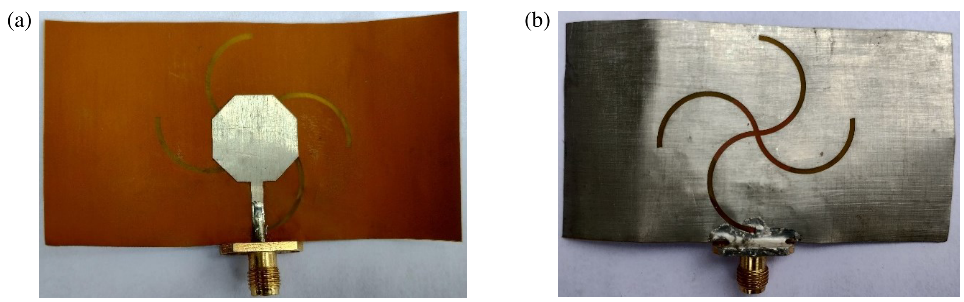

FIGURE 6. Fabricated prototype of the proposed antenna, (a) front view, (b) back view.

TABLE 1. Various parameters of the proposed antenna.

Parameters	$L1$	$L2$	$L3$	$L4$	$L5$	$W1$	$W2$	$W3$	$W4$	R
Values (mm)	11.85	7.53	4.68	16.87	43.05	2.34	7.5	1.2	78.8	9.5

modified design with curved slot-like cuts in the ground plane. This defective ground configuration aims to enhance performance by manipulating current distribution. Figure 4(b) illustrates the reflection coefficient (S_{11}) over the 7.5 to 7.72 GHz frequency range, highlighting the proposed antenna's superior impedance matching compared to the full ground plane. The proposed design significantly reduces the reflection coefficient, reaching below -20 dB around 7.6 GHz, indicating better resonance and more efficient power transfer. The shaded region emphasizes the operating bandwidth where the proposed antenna maintains an S_{11} below -10 dB, signalling effective performance improvements through the defected ground structure.

Figures 4(c) and (d) present a parametric analysis of the reflection coefficient (S_{11}) as a function of frequency when altering two key dimensions of the antenna: (c) the feed length ($L1$) and (d) the ground plane length ($L5$). In Figure 4(c), variations in $L1$ (10.85 mm, 11.85 mm, and 12.85 mm) show that the proposed feed length ($L1 = 11.85$ mm) achieves the best impedance matching, as evidenced by the lowest reflection coefficient (approximately -20 dB) at the central operating frequency of around 7.6 GHz. In Figure 4(d), adjustments to the ground plane length ($L5 = 41.05$ mm, 43.05 mm, and 45.05 mm) similarly indicate that the proposed length ($L5 = 43.05$ mm) yields optimal performance, minimizing the reflection coefficient near -22 dB within the same frequency range. These results highlight the critical impact of fine-tuning $L1$ and $L5$ on achieving efficient impedance matching, with the shaded region representing the target operating bandwidth where $S_{11} < -10$ dB is consistently maintained.

In Figure 5, the surface current distributions at different phases illustrate how the antenna generates a circularly polarized (CP) wave. In (a) and (c), the surface currents are the same but flow in opposite directions, showing a 180° phase rotation during half of a wave cycle. Similarly, (b) and (d) are the same but in opposite directions, representing the other 180° of the wave cycle. This alternating current direction across phases demonstrates the continuous rotation of the surface currents, which creates a circular motion of the radiated electric field. This consistent rotation confirms the generation of a circularly polarized wave.

3. MEASURED RESULTS AND DISCUSSIONS

Front and back views of the fabricated prototype of the proposed antenna are illustrated in Figures 6(a) and (b), respectively. Figure 7

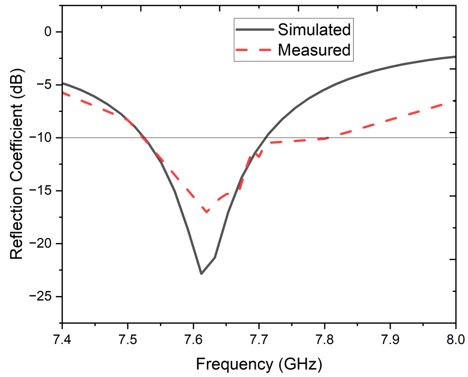

FIGURE 7. Simulated and measured reflection coefficients of the proposed antenna.

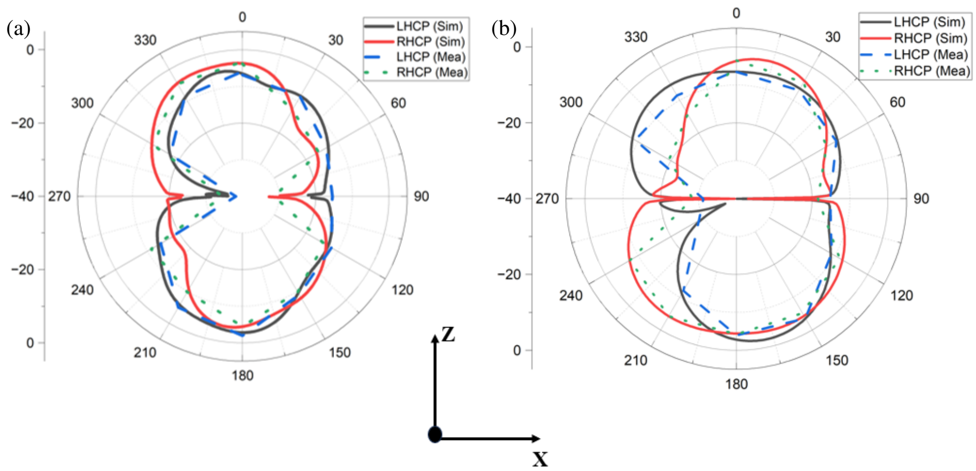

FIGURE 8. Simulated and measured far-field patterns, (a) E-plane, (b) H-plane.

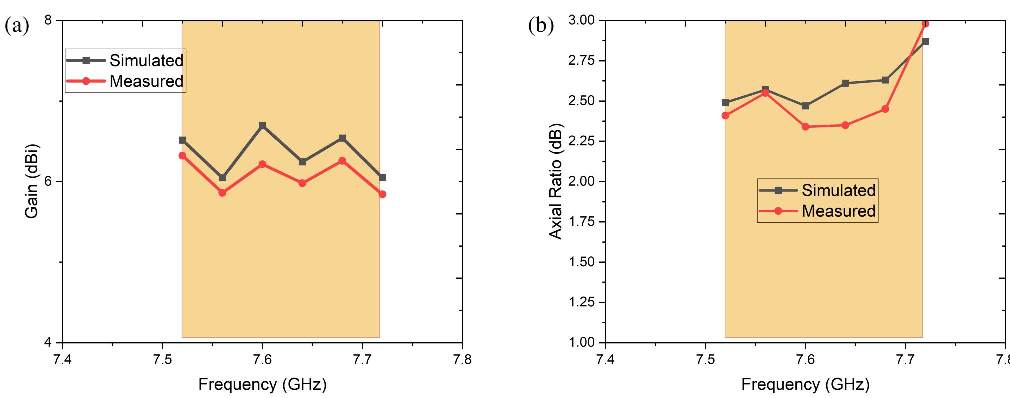

FIGURE 9. Simulated and measured (a) gain, (b) axial ratio.

presents the proposed antenna's reflection coefficient (S_{11}), comparing simulated and measured results. Both data sets show a distinct dip in the reflection coefficient around 7.6 GHz, corresponding to the antenna's resonant frequency, where the impedance is well matched. The simulated reflection coefficient drops below -20 dB, indicating excellent performance with minimal reflection, while the measured reflection coefficient reaches about -10 dB, which is still acceptable but highlights some discrepancies between the simulation and real-world performance. These variations could be attributed to factors such as manufacturing tolerances, measurement setup, or environmental influences on the antenna's behaviour.

Figures 8(a) and (b) compare the simulated and measured far-field radiation patterns of the proposed antenna in the E-plane and H-plane, respectively, displaying both Left-Hand Circular Polarization (LHCP) and Right-Hand Circular Polarization (RHCP) components. The patterns show good agreement between simulation and measurement, particularly in the main lobe regions, confirming the antenna's ability to generate circular polarization. However, some discrepancies are observed in the side lobes and nulls, likely due to fabrication imperfections, environmental factors, or measurement setup variances. The antenna demonstrates a dominant RHCP pattern, indicating its suitability for circularly polarized applications, while maintaining acceptable cross-polarization levels in both planes.

Figures 9(a) and (b) show a comparison between simulated and measured results for gain and axial ratio across an operating frequency range. The gain remains relatively stable, with the simulated results slightly higher than the measured ones, fluctuating between 5 and 8 dBi as shown in Figure 9(a). The axial ratio stays below 3 dB as illustrated in Figure 9(b), indicating good circular polarization within the operational bandwidth, though there is a sharp rise around 7.75 GHz, signalling a decrease in polarization quality.

4. CONCLUSION

A novel thin, circularly polarized microstrip antenna for radar applications has been successfully designed, fabricated, and tested. Operating in the 7.5–7.7 GHz frequency band, the antenna demonstrates compact dimensions with a flexible polyimide substrate that allows for mechanical adaptability and easy integration into conformal radar systems. Performance enhancements were achieved by incorporating inverted C-shaped slots into the radiating element, which optimized the surface current distribution and improved both polarization and radiation efficiency. The antenna consistently maintained an axial ratio below 3 dB, ensuring effective circular polarization, and delivered a peak gain of 6.25 dBi across the target frequency range, demonstrating sufficient signal strength for radar operations. Measurements from the fabricated prototype closely matched the simulation results, confirming the design's accuracy and reliability. Overall, the proposed antenna offers a practical solution for compact radar systems, combining a low-profile structure with robust performance, making it an ideal candidate for radar applications. Future work could focus on expanding the antenna's bandwidth, enhancing gain with advanced materials, being further miniaturized for use in drones or wearables, and testing performance under mechanical stress or on curved surfaces to validate its adaptability for real-world applications.

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