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Planar circularly polarized antennas fed by substrate integrated waveguide with asymmetric feeding and modal perturbation

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In this study, a compact circularly polarized (CP) antenna based on substrate integrated waveguide (SIW) technology is proposed and investigated. By integrating a square patch rotated at 45° with a side-fed SIW structure, circular polarization is achieved through an effective phase delay introduced by asymmetrical current paths, thus avoiding the use of conventional microstrip phase-shifting networks. Trapezoidal extensions and geometric perturbations, such as via cutbacks and patch corner chamfers, are employed to enhance impedance matching and axial ratio performance. Parametric simulations confirm that optimal coupling and polarization characteristics are obtained when the via extension is shortened and the patch geometry is finely tuned. The antenna is fabricated and tested, and measurement results show good agreement with simulations. The −10 dB impedance bandwidth is 2% (2.43-2.48 GHz), and the axial ratio bandwidth reaches 1.6% (2.44-2.46 GHz), validating successful right-hand circular polarization (RHCP) operation. Unlike prior SIW-based CP designs that often rely on multilayer stacking or extended slot arrangements, the proposed single-layer, side-fed structure achieves circular polarization with a compact footprint and simplified fabrication. These results highlight the potential of SIW-fed CP antennas as practical solutions for narrowband ISM and IoT wireless communication systems where frequency stability, integration capability, and electromagnetic compatibility are prioritized over wideband operation.

Keywords: circular polarization, edge feeding, modal perturbation, patch antenna, substrate integrated waveguide (SIW)

1 Introduction

In recent years, the rapid advancement of wireless communication systems and the growing demand for compact electronic devices have underscored the importance of space-efficient designs. Among the critical components in such systems, compact and high-performance antennas play a vital role in maintaining reliable wireless connectivity. Portable wireless communication devices, in particular, represent a significant market segment. However, due to their unpredictable orientation during operation, these devices are more susceptible to multipath delay spread and polarization mismatch, which can degrade signal reception quality [1, 2]. As a result, ensuring stable signal reception regardless of incident angle has become a key consideration in antenna design. To address these challenges, the integration of polarization diversity and circular polarization (CP) techniques offers a promising solution, enabling robust and orientation-independent signal reception [3].

Unlike traditional microstrip-fed patch antennas, this work proposes a circularly polarized antenna design utilizing substrate integrated waveguide (SIW) technology. SIW is chosen for its lower radiation loss and higher immunity to external interference, providing an efficient means of energy transmission and integration [4]. Compared with corner-truncated microstrip CP patches, which are simple but suffer from feed-line radiation, surface-wave leakage, and limited integration, SIW offers unique advantages. The via-walled SIW structure confines the electromagnetic fields, suppressing spurious feed radiation and enhancing electromagnetic compatibility in densely integrated RF-digital systems. Moreover, SIW inherently exhibits high-pass filtering characteristics, providing out-of-band suppression and reducing the need for additional filtering. Importantly, SIW enables seamless integration with other planar SIW components, such as filters and power dividers, facilitating system-on-substrate implementation. These merits justify the adoption of SIW feeding beyond the classical corner-truncation method and highlight its potential for designs requiring compactness and integration rather than wideband operation. Conventional CP designs that rely on microstrip phase delay face limitations within SIW-oriented implementations, since achieving sufficient delay by simply increasing microstrip length often results in a disproportionately large footprint [5]. Therefore, it becomes essential to leverage the modal properties of SIW to achieve CP in a compact manner. By exploiting SIW's ability to support multiple modes,

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novel configurations that deviate from conventional microstrip-fed architectures can be realized [6].

It is anticipated that polarization diversity will become increasingly critical for next-generation antennas, particularly with the proliferation of 5G communication systems and advanced wireless positioning technologies [7]. In this context, the development of CP antennas capable of polarization reconfiguration is expected to play a pivotal role in future wireless applications [8]. Numerous CP designs have been proposed in recent years, which can be broadly categorized into two main excitation approaches: (1) exciting orthogonal modes (e.g., TM_{01} and TM_{10}) by modifying the boundary conditions of the radiating structure, and (2) introducing a 90-degree phase difference through feeding networks or power dividers [9]. The most common implementation involves using asymmetric microstrip lines to create the required phase delay. This is typically achieved by extending one branch of the feedline to increase the electrical path length while adjusting the line width to ensure impedance matching and equal amplitude excitation on both sides. Although this approach is straightforward for tuning, it becomes problematic as antenna dimensions shrink, due to potential strong coupling effects and the additional area required to realize the phase shift [10]. Alternative designs avoid direct feeding by employing electromagnetic coupling, a technique frequently used in slot antennas. When two orthogonal slots generate fields with a 90-degree phase and polarization difference, circular polarization can be achieved [11]. Another method involves perturbing patch geometry, such as trimming corners, to generate rotating surface currents [12]. Compared to trimmed patch designs, rectangular patch configurations relying on geometry-induced phase delays are less common. While such methods reduce reliance on microstrip area, they often present challenges in implementation and tuning, especially under strict size constraints [13].

SIW technology has been widely adopted in antenna designs due to its advantages of low loss, high integration, and compatibility with planar circuits. It has been applied in leaky-wave antennas, cavity-backed patches, and SIW horn antennas [4, 6]. Several studies have explored CP antenna structures based on SIW, primarily by extending the SIW length to introduce phase shift or by employing multilayer coupling structures [8, 14, 15]. While effective, these methods often increase complexity or require multilayer fabrication. In contrast, the present study proposes a compact single-layer, side-fed SIW patch antenna that generates CP through asymmetric current paths and modal perturbations, thereby eliminating the need for extended SIW slots, multilayer stacking, or external phase-shifting networks. This highlights a novel use of SIW as a direct side-feeding mechanism for CP excitation, a configuration that has received limited attention in prior work. To further develop SIW-fed CP patch antennas, it is essential to investigate whether phase delay can be generated through SIW characteristics alone, as an alternative to microstrip-based designs. Reference [5] demonstrated that phase delay could be introduced by varying the SIW width, confirming the feasibility of generating the necessary phase difference within the waveguide. However, a key challenge lies in the limited number of existing studies on side-fed CP patch antennas using SIW. Most prior works treat SIW as a resonant cavity or waveguide layer rather than a direct side-feed. To address this gap, the present study proposes a novel SIW-based design and systematically analyzes its performance through simulation and experimental validation.

From a system-level perspective, the bandwidth requirements of typical ISM-band IoT applications are inherently narrow. For instance, the IEEE 802.11ah (Wi-Fi HaLow) standard, which is explicitly designed for large-scale IoT and machine-type communications, defines channel bandwidths of 1, 2, 4, 8, and 16 MHz, all well below 20 MHz [16, 17]. Similarly, widely adopted short-range low-power standards such as IEEE 802.15.4 (Zigbee/Thread) and Bluetooth Low Energy (BLE) employ channel bandwidths on the order of 2 MHz [18, 19]. For long-range low-power wide-area network (LPWAN) technologies, the bandwidth requirement is even more stringent, with NB-IoT operating at 180 kHz and LoRaWAN typically utilizing bandwidths between 125 kHz and 500 kHz [20, 21]. These quantitative specifications clearly indicate that a bandwidth on the order of several megahertz to tens of megahertz is sufficient for the vast majority of ISM-band IoT systems. Therefore, a narrowband antenna design targeting a bandwidth within 20 MHz represents a practical and conservative choice, aligned with realistic system requirements rather than a design limitation.

2 Antenna design

Waveguides are a well-established signal transmission medium that guide electromagnetic fields through enclosed metallic structures. Unlike microstrip lines, metallic waveguides support TE and TM modes independently but cannot maintain TEM modes. They offer several advantages, such as low loss, high power-handling capability, minimal radiation leakage, and ease of fabrication. Additionally, since waveguides only support frequencies above their cutoff frequency, they inherently act as high-pass filters. Due to their enclosed structure, the guided fields are less susceptible to external interference [22].

Substrate Integrated Waveguide (SIW), a relatively recent development, replicates the characteristics of rectangular metallic waveguides in planar form using dielectric substrates [23]. As shown in Fig. 1, SIW is formed by metallizing the top and bottom surfaces of a dielectric substrate and inserting periodic rows of vias along the sides to emulate the waveguide walls. SIW combines the benefits of microstrip lines and hollow waveguides: compact size, light weight, ease of integration, low radiation loss, and high quality factor. SIW is widely used in planar structures such as filters, couplers, power dividers, and antennas – primarily serving as feed networks, resonant cavities, or even the radiating aperture itself [24].

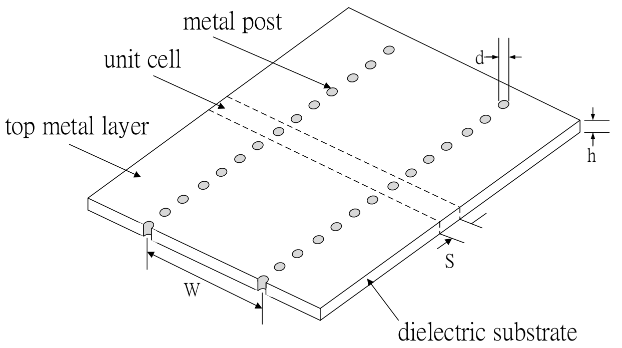


Fig. 1. Structure of the substrate integrated waveguide (SIW)

The SIW cutoff frequency is determined by the via diameter d, the spacing between adjacent vias S, and the total width W between the two via rows. To ensure sufficient bandwidth for a 2.45 GHz design, the SIW width W was extended to 55 mm, lowering the cutoff frequency below the operating band. The total length of the waveguide was set to 100 mm to clearly observe signal transmission characteristics, and a common substrate thickness of 1.6 mm was used. As shown in Fig. 2, the designed SIW layout enables full-wave simulation analysis. The corresponding simulated return loss and insertion loss are presented in Fig. 3, where the reflection coefficient dropped significantly above the cutoff frequency and S_{21} remained near 0 dB, indicating efficient energy transmission from Port 1 to Port 2 with minimal standing wave effects.

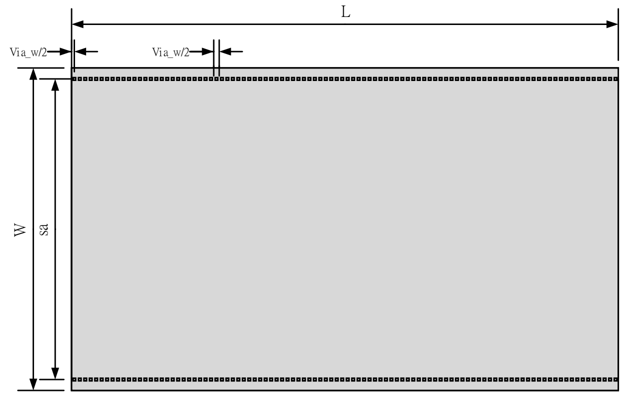


Fig. 2. Designed SIW configuration with dimensions: L=100 mm, W=59 mm, Sa=55 mm, and via width 1 mm

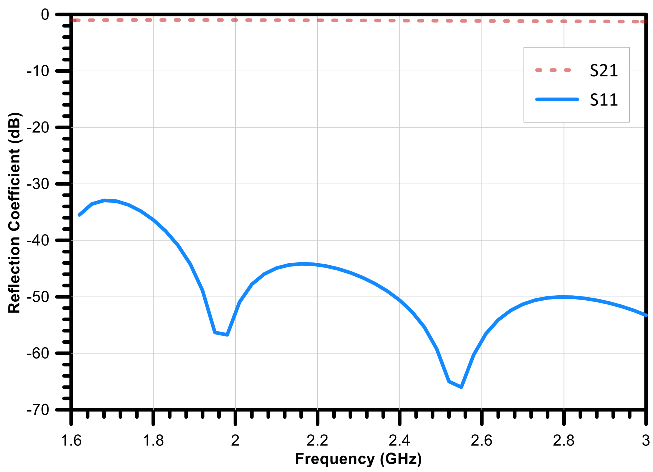


Fig. 3. Simulated return loss and insertion loss of the designed SIW structure

To simplify future simulations and reduce the computation time, a simplified SIW model was also created by replacing via rows with perfect electric conductor (PEC) walls. This structure is shown in Fig. 4, and the simplified model's return loss and insertion loss results are illustrated in Fig. 5 [25].

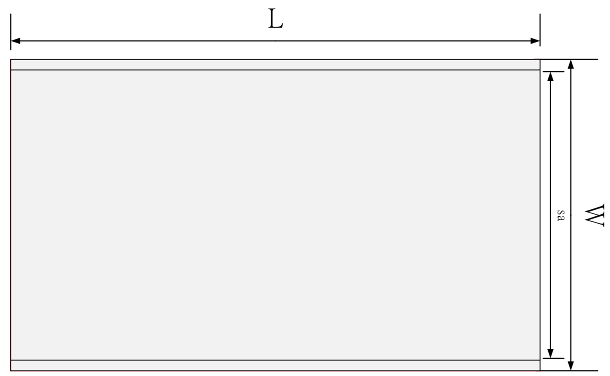


Fig. 4. Simplified SIW model with PEC walls replacing via rows. Dimensions L=100 mm, W=59 mm, Sa=55 mm

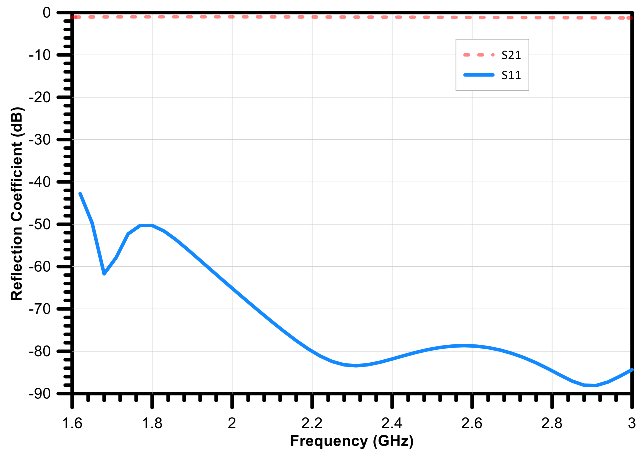


Fig. 5. Return loss and insertion loss of the simplified SIW model

The circularly polarized (CP) antenna was designed using a square patch rotated 45° and placed at the end of the SIW structure, forming a diamond-shaped configuration. The patch was dimensioned such that its diagonal matched the intended resonant condition at 2.45 GHz. The original side length of 27.5 mm results in a diagonal length of approximately 38.89 mm. To improve capacitive coupling between the SIW and the patch, trapezoidal extensions were added to both sides of the SIW, as illustrated in Fig. 6.

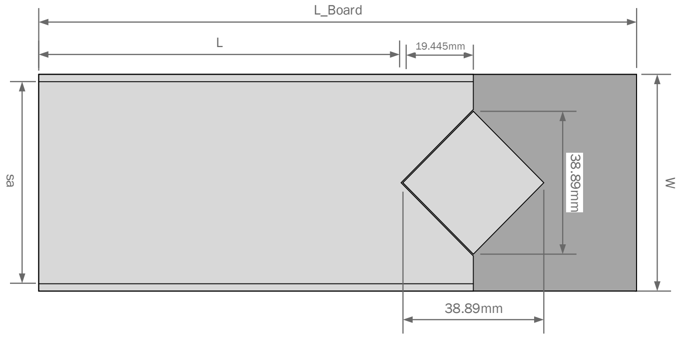


Fig. 6. Capacitively coupled SIW-fed patch antenna with dual-side coupling; spacing between SIW and patch 0.5 mm

Simulation results showed that reducing the gap between the SIW and the patch improves coupling and impedance matching, although it also causes a downward shift in resonant frequency due to increased parasitic capacitance. This trend is summarized in Fig. 7. Additional parametric studies, such as via extension length ("ViaCut") and edge chamfering ("TriCut"), further optimized the impedance performance. The definition of the ViaCut parameter is illustrated in Fig. 8, and its impact on reflection coefficient is shown in Fig. 8. Similarly, the geometry of the TriCut modification is provided in Fig. 9, and the corresponding reflection coefficient analysis is shown in Fig. 9.

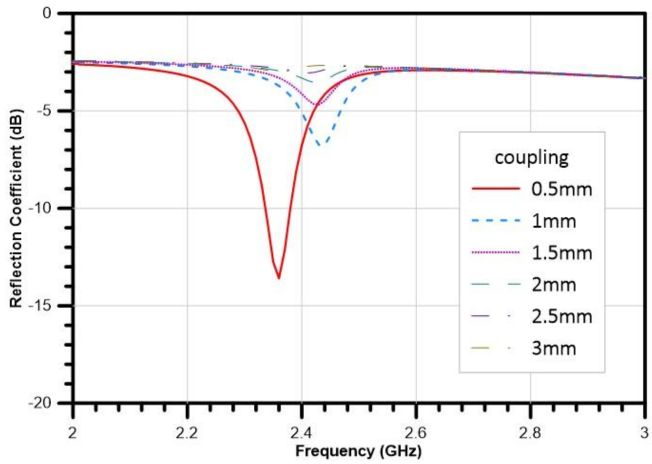


Fig. 7. Impact of coupling gap on the reflection coefficient of the capacitively coupled antenna

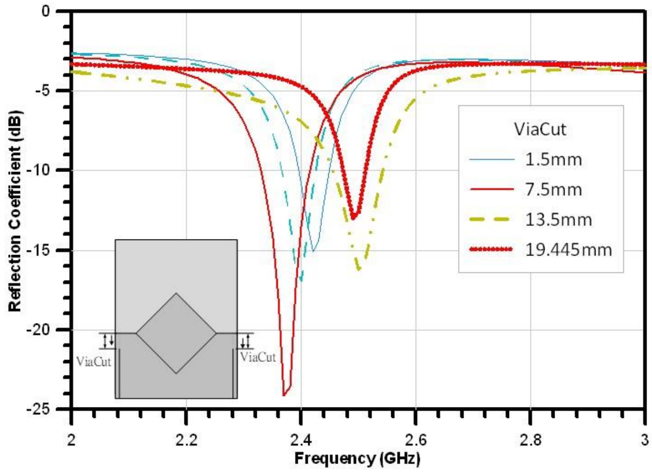


Fig. 8. Parametric analysis of the reflection coefficient with varying ViaCut lengths, together with the illustration of via wall shortening at the SIW end (parameter: ViaCut)

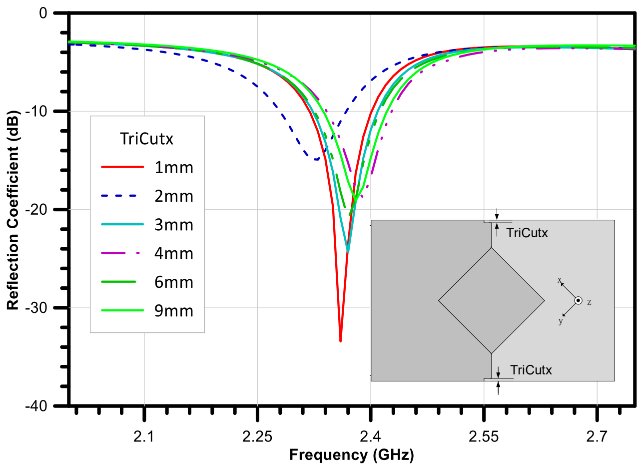


Fig. 9. Reflection coefficient variation with different TriCutx values, along with the illustration of partial recess in the ungrounded SIW side wall (parameter: TriCutx)

Due to the symmetric current distribution in the x and y directions, the original patch fed by SIW only supports linear polarization at an angle of φ=135°. To achieve circular polarization, a 90° phase difference between the x- and y-directed currents is required. This was accomplished by directly connecting one patch corner to the SIW, allowing current in the y-direction to travel a longer path than that in the x-direction, effectively introducing a phase delay and producing right-hand circular polarization (RHCP). Additionally, the patch corners were trimmed to improve axial ratio performance [26]. The final antenna structure including a tapered microstrip-to-SIW transition is shown in Fig. 10, and the simulated S_{11} and axial ratio performance are presented in Fig. 11.

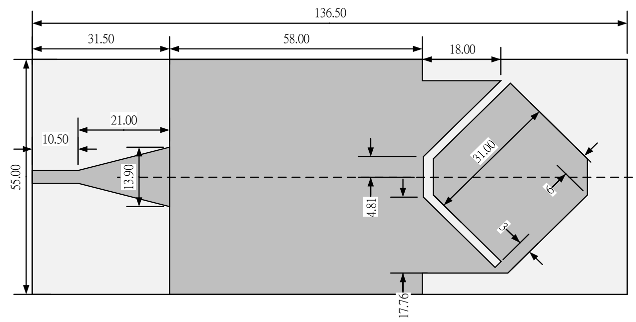


Fig. 10. Geometry of the RHCP antenna with microstrip feed (all dimensions in mm)

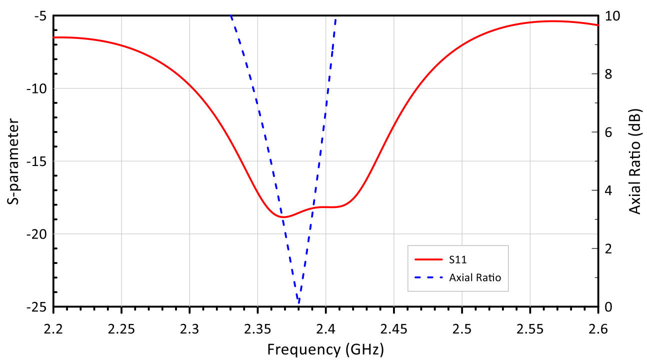


Fig. 11. Simulated reflection coefficient and axial ratio of the RHCP antenna

3 Circular polarization excitation by perturbing the electric field distribution in SIW

In SIW structures, the fundamental propagating mode is the TE_{10} mode. In the previous section, circular polarization was achieved by feeding the patch from the SIW end using asymmetric coupling and feeding,such that energy was coupled into two orthogonal sides of the patch with a 90° phase difference. This enabled excitation of CP by exciting orthogonal patch modes with the required phase quadrature.

In this section, we present an alternative approach that does not require physical connection of the patch and SIW. Instead, circular polarization is excited by perturbing the electromagnetic field distribution inside the SIW. Specifically, a metallic via is introduced at one side of the SIW end, creating an asymmetric boundary condition: a short-circuited termination on one side and an open-ended condition on the other. This asymmetry distorts the TE_{10} field distribution within the SIW, resulting in unequal phase coupling to the two orthogonal patch sides and thereby generating circular polarization. As illustrated in Fig. 12, the perturbed field excites surface currents that rotate progressively with phase, confirming RHCP gene-ration.

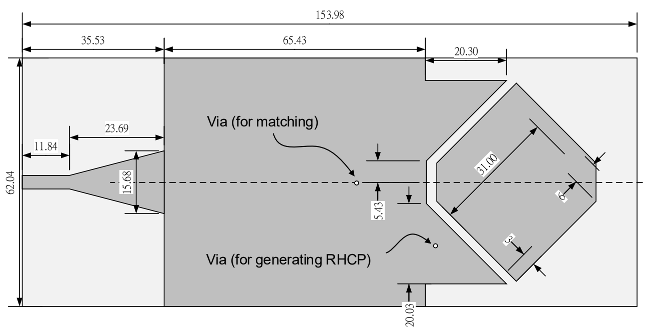


Fig. 12. Geometry of the RHCP antenna with mode perturbing

At 0° phase (Fig. 13a), the current flows along the x-direction; at 90° (Fig. 13b), it rotates towards the y-direction; at 180° (Fig. 13c), it reverses along the x-axis; and at 270° (Fig. 13d), it continues along the negative y-direction. This full-cycle rotation confirms the right-handed circular polarization behavior of the proposed configuration. However, the insertion of the metallic via strongly impacts impedance matching. To restore performance, additional shorting vias were introduced at the center of the SIW region. A para-metric study on the distance between this central shorting via (referred to as mid_post) and the patch coupling edge is shown in Fig. 14. The optimal mid_post value of 15.5 mm provided the best return loss performance at 2.45 GHz.

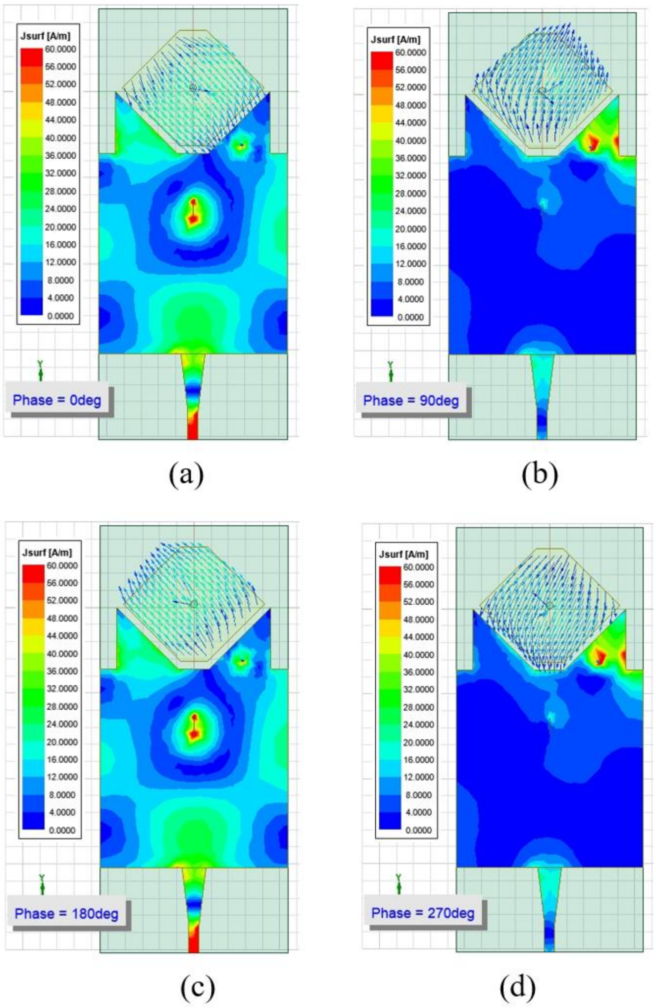


Fig. 13. Surface current distributions with shorting via, showing RHCP rotation behavior: (a) phase 0°, (b) 90°, (c) 180°, (d) 270°

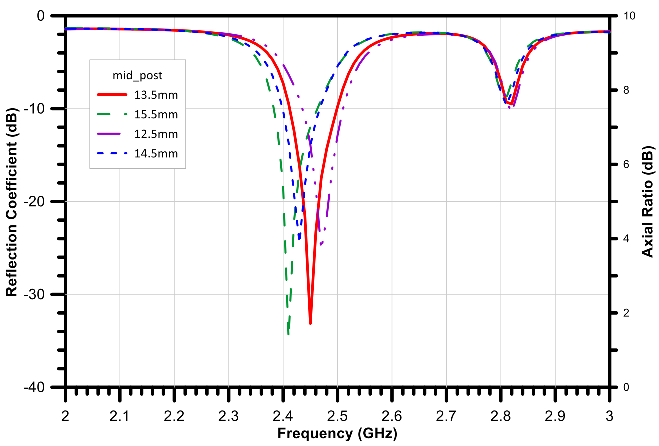


Fig. 14. Effect of mid_post (distance between central shorting post and SIW end) on the reflection coefficient

4 Experimental results

To validate the simulation results, the mode-tuned SIW CP antenna was fabricated and experimentally tested. Photographs of the fabricated prototype are shown in Fig. 15. The radiation characteristics, including gain, axial ratio (AR), and radiation patterns, were characterized in a microwave anechoic chamber with dimensions of 7 m × 5 m × 3 m. In this setup, the proposed antenna served as the transmitter, while a dual-polarized Vivaldi antenna was employed as the receiver. The system was calibrated using a standard gain horn antenna via the gain-substitution method. Data acquisition, specifically S_{21} for gain extraction, was performed using an HP 8753D vector network analyzer, while the reflection coefficient S_{11} was measured using an Anritsu MS46122B.

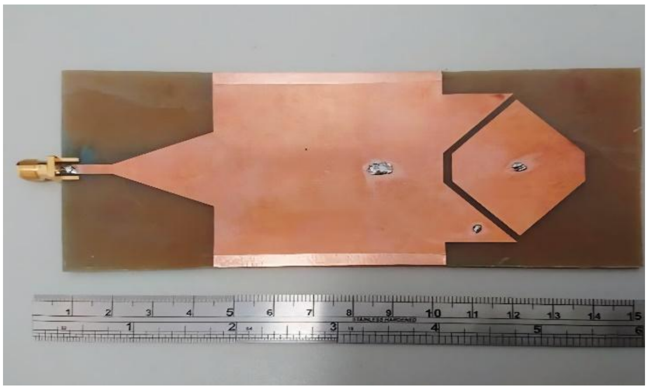


Fig. 15. Circularly polarized SIW antenna with mode tuning capability

The measured and simulated reflection coefficients are compared in Fig. 16, indicating good impedance matching at 2.45 GHz. The same figure also includes a photograph of the measurement setup in the anechoic chamber and presents the measured AR, which confirms the successful excitation of circular polarization.

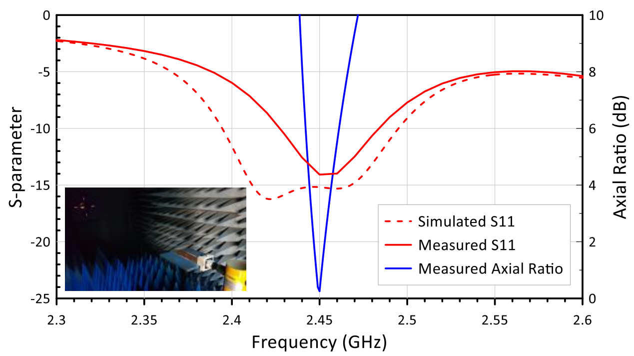
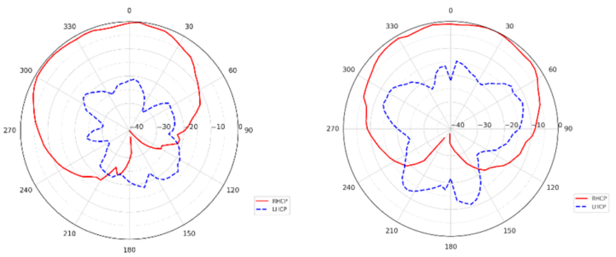


Fig. 16. Simulated and measured results of the mode-tuned circularly polarized SIW antenna

Figure 17 illustrates the normalized RHCP radiation patterns at 2.45 GHz in the XZ- and YZ-planes, with a measured RHCP gain of 2.08 dBi. The gain result is consistent with expectations for FR4-based SIW implementations, where dielectric and conductor losses may slightly limit radiation efficiency; nevertheless, higher gain can be achieved by employing lower-loss substrates or optimizing the SIW length. Overall, the close agreement between measurement and simulation validates the reliability of the models and confirms the effectiveness of the proposed polarization excitation strategy.



(a) (b)

Fig. 17. Measured radiation patterns: (a) XZ plane, (b) YZ plane

5 Conclusion

This paper has presented a compact single-layer circularly polarized patch antenna based on a side-fed substrate integrated waveguide (SIW) structure. Circular polarization is achieved using a structurally simple configuration that avoids extended microstrip phase-delay lines, multilayer stacking, or complex feeding networks. Compared with conventional microstrip-fed or cavity-backed SIW CP antennas, the proposed approach offers an integration-friendly solution that is well suited for space-constrained implementations.

A detailed comparison with previously reported circularly polarized antennas is summarized in Tab. 1. The comparison shows that many existing SIW-based CP antennas rely on cavity-backed configurations, extended SIW sections, or multilayer structures to realize circular polarization, which often results in increased antenna size and fabrication complexity. In contrast, the proposed antenna achieves a notably compact footprint using a single-layer structure and a straightforward side-fed excitation scheme, while maintaining stable circular polarization and reliable radiation characteristics within the intended application scope.

In summary, this work establishes an alternative design paradigm for circular polarization excitation in SIW-based antennas, demonstrating that circular polarization can be realized through intrinsic current asymmetry induced by a side-fed SIW configuration, rather than conventional phase-shifting or multi-path feeding schemes. The proposed antenna provides a balanced combination of compact size, structural simplicity, and practical radiation performance, making it a suitable candidate for wireless devices and integrated RF front-end systems.

Table 1. Performance comparison of the proposed circularly polarized antenna with prior works

Ref.	Center freq. (GHz)	−10 dB BW (%)	3-dB AR BW (%)	Peak gain (dBi)	Overall antenna size	Feed / CP mechanism
[27]	5.8	18.7	2.3	>2	0.83 $\lambda_0 \times 1.4\ \lambda_0$	SIW cavity, high-order mode
[28]	10	23.3	2.34	>2	1.50 $\lambda_0 \times 1.16\ \lambda_0$	SIW ring-slot
[29]	10	23.9	2.7	>2	0.86 $\lambda_0 \times 1.5\ \lambda_0$	SIW cavity-backed
[30]	10.25	6	0.7	>2	0.13 $\lambda_0 \times 0.5\ \lambda_0$	Microstrip cavity-backed
[31]	10	10	1	>2	0.6 $\lambda_0 \times 0.8\ \lambda_0$	HMSIW cavity
[32]	28	—	<2	>2	141 mm × 109 mm	SIW sequential rotation
This work	2.45	2	1.6	2.08	136 × 55 mm	Single-layer SIW, asymmetric perturbation

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