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Multi-Band Cavity Backed SIW Based X-Shaped Slot Antenna for Ku and K Bands

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ABSTRACT: In this manuscript, a well-designed multiband cavity-backed X-shaped slot antenna is presented using substrate-integrated waveguide (SIW) technology. Its performance is optimized for the K and Ku bands to suit various advanced communication scenarios. Including X-shaped slot in this design leads to significant advantages, such as better impedance matching, broadside radiation pattern, and multiband operation. In addition, it shows decent gain values of 6.89 dB at 15.02 GHz, 6.91 dB at 15.90 GHz, and 7.12 dB at frequency 19.58 GHz. This is accomplished by the innovative application of X slots on the substrate-integrated waveguide (SIW) cavity. Simulated and experimental results validate multiband antenna operation and exceptional performance, highlighting its potentially high suitability for state-of-the-art millimeter-wave applications, such as satellite communications and radar systems. This compact structure, along with the proposed antenna performance metrics, confirms its feasibility for future wireless communication systems. This progress enables further developments in SIW-based antenna technology.

1. INTRODUCTION

In light of fast-paced technology developments in wireless communication, antennas that can work across multiple bands have become a crucial requirement. Such antennas are essential for next-generation applications, such as satellite communications, medical applications, and security systems. Nevertheless, it is challenging for traditional antenna designs to obtain compact size, high performance dual-band operation, and perfect integration [1]. This paper addresses such challenges by investigating the design and implementation of a novel SIW cavity-backed multiband antenna. With distinctive benefits of SIW technology, including compactness and seamless integration with other electronic components, this proposed antenna provides enhanced performance at its designed bands.

SIW technology has been introduced as a promising development in high-frequency antenna designs, providing a plethora of compelling benefits, including very low loss, ultra-high quality factor, and compatibility with planar circuits. SIW structures limit electromagnetic waves in a dielectric substrate using metallic vias meticulously arranged in rows. This innovative design effectively emulates robust conventional waveguides while minimizing antenna dimensions drastically. It follows that this methodology not only improves overall efficiency but also makes SIW-based antennas highly suitable for a wide variety of advanced communication systems, thereby improving reliability and effectiveness in the new era of connectivity [2].

In this context, SIW has been used as a promising technological platform for antenna and microwave devices, including filters and phase shifters [3]. In particular, SIW antennas have been extensively investigated due to their easy integration as modules within a broader system [4]. Because of the relatively compact nature of SIW technology, numerous single- and multilayered SIW antennas have been created. Multiple researchers [5, 6] have devised multilayer SIW progressive aperture antennas, which simultaneously enhance bandwidth and gain by drilling holes in the substrate. Additionally, a notable 60 GHz antenna array is reported in [7], verifying the feasibility of applying SIW layers on low-temperature co-fired ceramic (LTCC). For this purpose, the radiating element consists of a cavity backed aperture. Additionally, various antenna types have been developed employing different layers. For instance, in [8], a microstrip feed layer was proposed, and in [9], an antenna array was implemented using a metallic plate for radiating elements. For a single-layer SIW antenna, the design example can be found in [10, 11]. Ref. [10] used a corporate feeding network, while [11] takes a different approach without using a corporate feeding network. Additionally, SIW antennas discussed in the literature feature distinct geometrical configurations to enable different methods of radiating electric fields at antenna units. Slot antennas, owing to their unique structural properties, possess core application advantages that enable adaptation to a wide range of scenarios in the wireless communication field. In another research direction, the impedance bandwidth of a cavity-backed slot antenna was improved by incorporating a via-hole, as discussed in [12]. However, this antenna operates at low frequencies and is a single-element design with low gain. Slot antennas, which are often implemented in arrays, are typically backed by a cavity. It is noteworthy that there are instances in which higher-order modes have been effectively excited within the backed cavity to achieve operation in distinct frequency bands [13, 14]. On the other hand, there are scenar-

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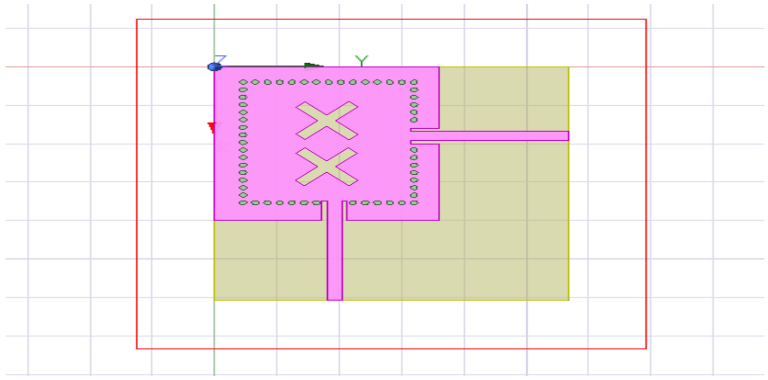

FIGURE 1. SIW structure with double X slot configuration.

ios in which the excited modes are positioned closely enough to facilitate a broad operating bandwidth [15, 16]. Additionally, relative orientations of the slots can be fine-tuned to achieve the desired polarization [17].

In this work, an antenna is proposed with two slots on the radiating elements of a cavity-backed antenna at millimeter-wave frequencies. Our analysis indicates that including a dual-slot configuration in the cavity-backed antenna offers increased design flexibility across the operational frequency range of antenna arrays. Ref. [18] discusses a cavity-backed antenna that employs two slots solely for tuning narrow bands around the center frequency of 10 GHz, with backed cavities supplied by cascade power dividers. In contrast, we report a Ku- and K-band double X-slot waveguide antenna design. Moreover, the dual-slot configuration excites multiple resonant modes to improve the antenna gain. The reflection coefficient simulations show that prominent resonance dips appear at 15.02 GHz, 15.90 GHz, and 19.58 GHz, which confirms that the impedance matching of corresponding frequency bands is effective and that the excitation of multiple resonant modes is successfully achieved. Further, peak gains of the designed antenna are 6.89 dB at 15.02 GHz, 6.91 dB at 15.90 GHz, and 7.12 dB at 19.58 GHz, respectively. These findings highlight the performance potential of the proposed design for high-gain operation, regarding potential satellite communication applications at Ku and K bands.

2. PROPOSED ANTENNA DESIGN AND ANALYSIS

Figure 1 illustrates the configuration and design of the proposed antenna. The SIW cavity ($L_s \times W_s$) is realized on a Rogers RT Duroid 5880 substrate ($\varepsilon_r = 2.2$, $\tan\delta = 0.0009$, and substrate thickness $= 0.508$ mm). Material selection and dimensions are also critical to antenna performance for successful signal transmission or reception. Further, this square SIW cavity is designed with four rows of metallic vias and incorporates two metallic plates secured to both the top and bottom of the substrate. This cavity-backed slot antenna, based on SIW technology, incorporates a cavity backing situated beneath the slot. The use of a low-loss substrate contributes to unidirectional radiation characteristics. Figure 1 provides a comprehensive overview of parameters associated with the proposed antenna, including details on positioning components, electrical connections between them, and overall design layout.

TABLE 1. Antenna dimensions.

Length of the ground plane	28.4 mm
Width of the ground plane	30.4 mm
Diameter of the vias	0.55 mm
Pitch of the vias	0.98 mm
Width of the feedline	1.2 mm
Length of the feedline	12.7 mm
Slot length	6 mm
Slot width	1 mm
Substrate height	0.508 mm
Substrate width	30.4 mm
Substrate length	28.4 mm
Distance between the slots	4.5 mm

Length, width, and height specifications of the designed antenna are listed in Table 1. The substrate-integrated waveguide (SIW) antenna designed in this study uses two orthogonally arranged microstrip feedlines to couple electromagnetic energy into the SIW cavity. Dimensions of the SIW cavity are designed to support the dominant TE_{10} mode within the operating frequency band. Further, the effective SIW width is determined from the dominant-mode cutoff frequency, which is given by

$$f_c\,(TE_{10}) = \frac{c}{2W_{eff}\sqrt{\varepsilon_r}} \quad (1)$$

$$W_{eff} = W - \frac{d^2}{0.95p} \quad (2)$$

where c represents the velocity of light in vacuum, and ε_r stands for the substrate's relative permittivity. To effectively reduce the radiation loss between vias in high-frequency circuits, it is imperative to accurately calculate and measure via dimensions. Selecting appropriate diameters, spacing, and depths for vias can greatly reduce electromagnetic radiation and improve the circuit's signal integrity.

Parameter optimization plays a key role in improving the performance and reliability of all types of electronic designs.

Under the design context of substrate-integrated waveguides (SIWs), its core structural parameter, effective width W_{eff}, is jointly determined by the vias' size and arrangement, which are fundamental components that guide electromagnetic waves.

This paper identifies two core design variables for substrate-integrated waveguide (SIW). The first is structural diameter, which affects impedance matching and insertion loss. Appropriate selection of this parameter can improve coupling efficiency between the waveguide and external circuits and suppress signal reflection. The second is via spacing 'p', that is, the spacing between through-holes, which can reduce electromagnetic interference and crosstalk, and guarantee clear signal transmission. The vias' optimal spacing in a Substrate Integrated Waveguide (SIW) must be adjusted according to its operating frequency and target bandwidth. A reasonable spacing can suppress higher-order modes that degrade device's performance. In addition, the SIW's rectangular waveguide width parameter W determines the waveguide's cutoff frequency, which in turn produces a cascading effect on the SIW's effective bandwidth and guided-wave characteristics. The waveguide proposed in this study can support a wider range of frequency bands and adapt to multiple types of application scenarios to improve versatility. The core goal of waveguide size selection is to minimize radiation loss in order to ensure that

$$p/\lambda_c < 0.25 \tag{3}$$

$$d < \lambda_g/5 \tag{4}$$

$$d < p < 2d \tag{5}$$

where λ_c and λ_g are the cut-off wavelength and guided wavelength, respectively. Equations (3)–(5) are adopted from the established SIW design methodology reported in [2].

This design relies on orthogonal feeding technology to maintain low return loss within the specified frequency band, optimize signal transmission, and comprehensively improve the antenna's overall performance. In the optimization scheme for the cavity-backed antenna proposed in this paper, the newly added X-shaped slot acts as an additional radiating element. It not only supports the main radiation mode, but also introduces a complementary coupling mechanism to improve efficiency and signal distribution across bandwidth. When paired with the strategic slot arrangement presented in Figure 1, this design further regulates resonant characteristics, precisely controls the operating frequency band, and enhances design flexibility.

Based on results presented in Figure 2, the antenna for millimeter-wave communication proposed in this study resonates in three frequency bands: 15.02 GHz, 15.90 GHz, and 19.58 GHz. The corresponding impedance bandwidths at these frequencies are 50 MHz, 50 MHz, and 60 MHz, respectively. The reflection coefficient of each mode is lower than -10 dB, and mode interaction improves both impedance matching and gain. These outcomes verify this design's effectiveness for compatibility with millimeter-wave communication systems.

Figure 3 illustrates the simulated electric-field distribution at all three resonant frequencies. At the first resonance (15.02 GHz), the electric field is predominantly concentrated around the feed region and lower X-shaped slot, while the remaining cavity exhibits relatively weaker field intensity. It

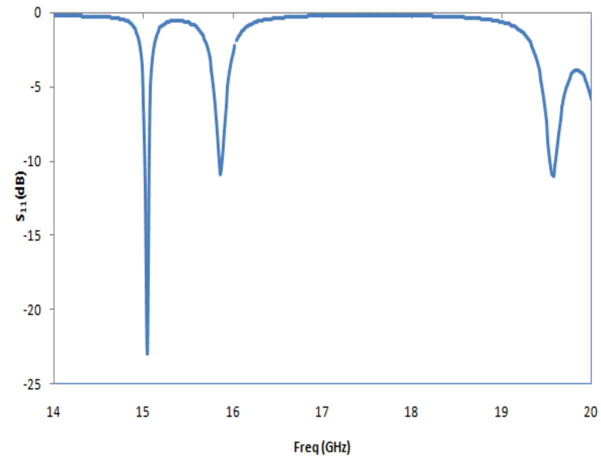

FIGURE 2. S parameter graph for SIW structure with double X slot configuration.

is indicated that the first operating band is mainly produced by excitation of fundamental SIW cavity mode coupled with lower slot resonance. At the second resonance (15.90 GHz), strong electric-field concentration is observed around both X-shaped slots, with a more symmetric distribution inside the cavity. This demonstrates enhanced electromagnetic coupling between the two slots and the SIW cavity, leading to the excitation of a coupled resonant mode responsible for the second operating band. At the third resonance (19.58 GHz), the electric field becomes more uniformly distributed over the cavity with stronger localization around the edges of both X-shaped slots, indicating the excitation of a higher-order coupled cavity-slot mode. The evolution of the field distributions confirms that tri-band response is not generated by three independent slot resonances but by the interaction between SIW cavity modes and dual X-shaped slot resonators. This multi-mode coupling mechanism enables the antenna to achieve three well-defined resonant frequencies while maintaining efficient impedance matching and radiation performance.

The cavity-backed antenna proposed in this paper has its excellent radiation characteristics verified via Figure 4. Results show that the antenna exhibits a gain of 6.89 dB at 15.02 GHz, 6.91 dB at 15.90 GHz, and 7.12 dB at 19.58 GHz. The highest gain is obtained at 19.58 GHz because the corresponding resonant mode exhibits stronger coupling between the SIW cavity and dual X-shaped slots. Additionally, at 19.58 GHz, a greater portion of the SIW cavity participates in radiation, leading to more efficient aperture excitation and improved radiation efficiency.

Further, conventional SIW slot antennas only use a single radiating slot or multiple independent slots. The novel X-shaped SIW slot antenna proposed in this paper integrates a pair of X-shaped slots within a single SIW cavity to achieve controllable electromagnetic coupling between cavity modes and slot resonances. This design can excite three closely spaced resonant modes, while maintaining a compact single-layer structure and simple feeding scheme. It eliminates the need for adding extra resonators, multi-layer substrates, defected ground structures, or matching circuits, and strikes a balance among compactness, radiation performance, and manufacturing simplicity.

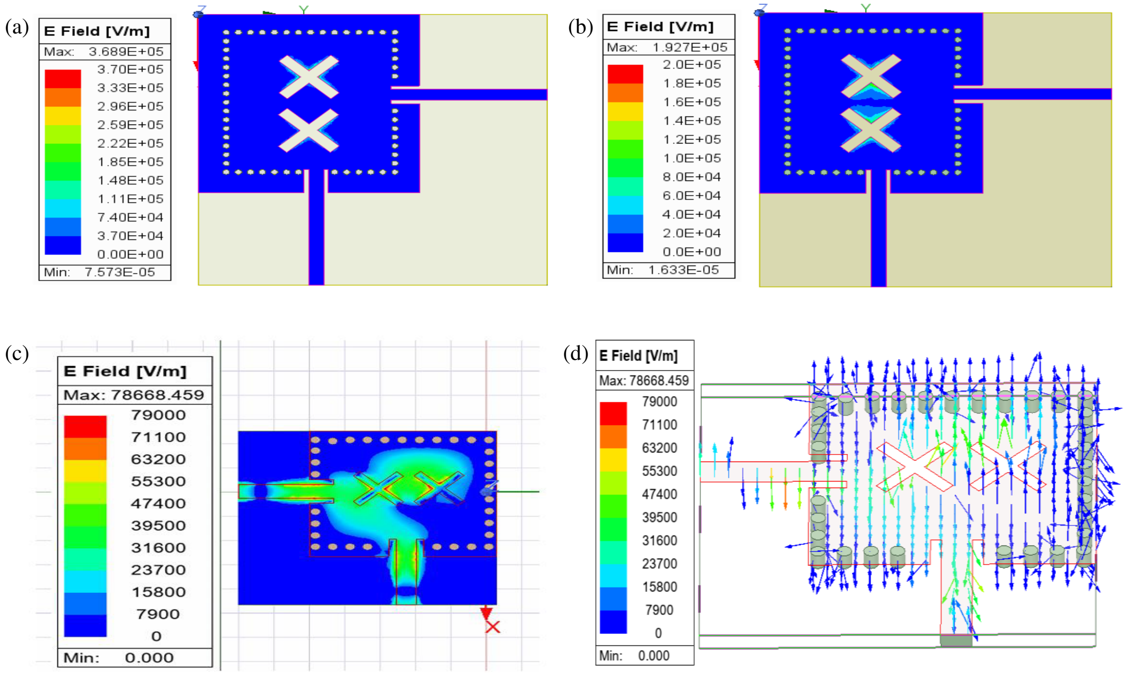

FIGURE 3. Electric field distribution of the structure. (a) 15.02 GHz, (b) 15.98 GHz, (c) 19.58 GHz, and (d) 19.58 GHz.

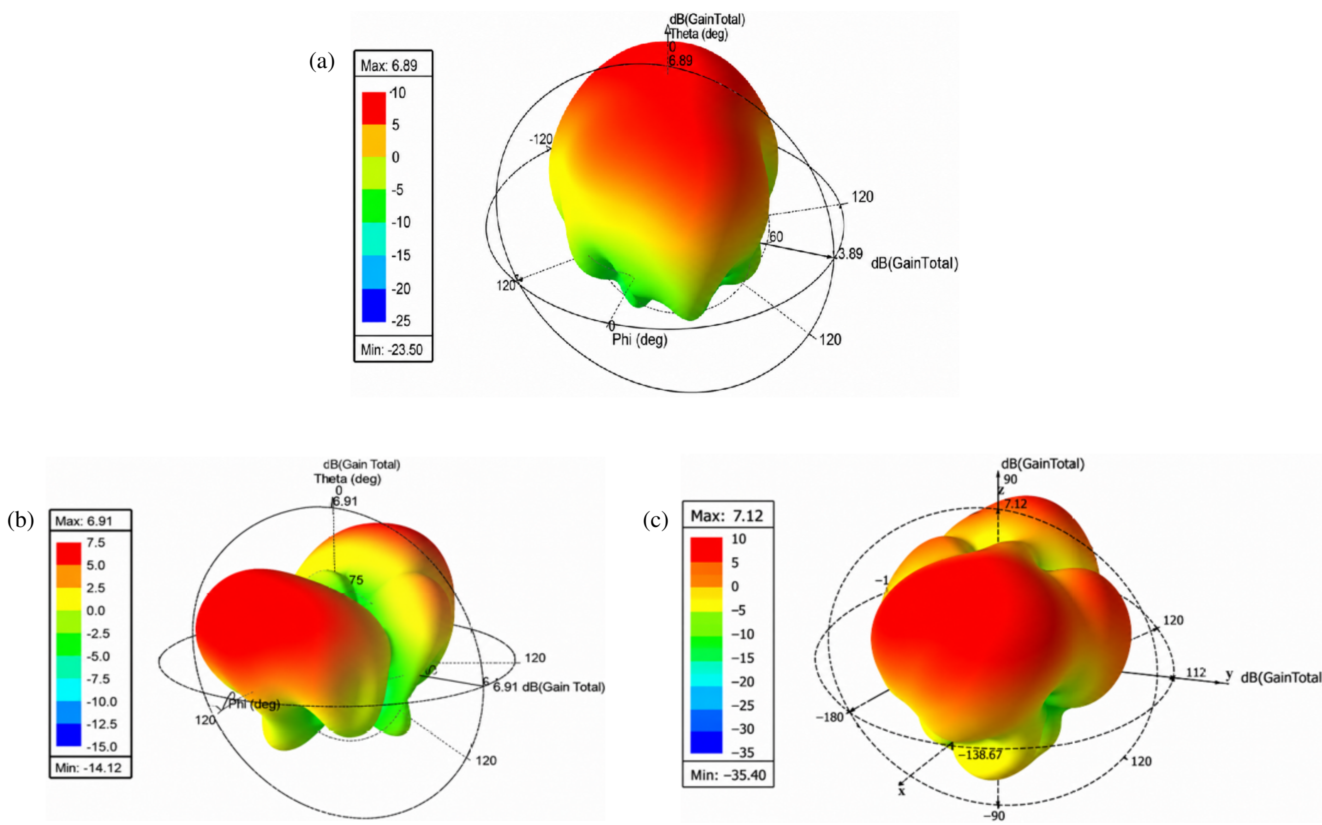

FIGURE 4. Gain plots of proposed structure. (a) 3D gain plot at 15.02 GHz, (b) 3D gain plot at 15.90 GHz, and (c) 3D gain plot at 19.58 GHz.

The proposed antenna is simulated using Ansys HFSS 2022 R2. Full-wave electromagnetic analysis is implemented based on the finite element method. An adaptive mesh refinement technique is adopted to optimize meshes in high field-strength regions, including dual X-shaped slots, SIW via array, and feed structure. Simulations run iteratively until they meet the convergence criteria specified in [19], which ensures the accuracy and stability of core performance indicators such as S-parameters and gain.

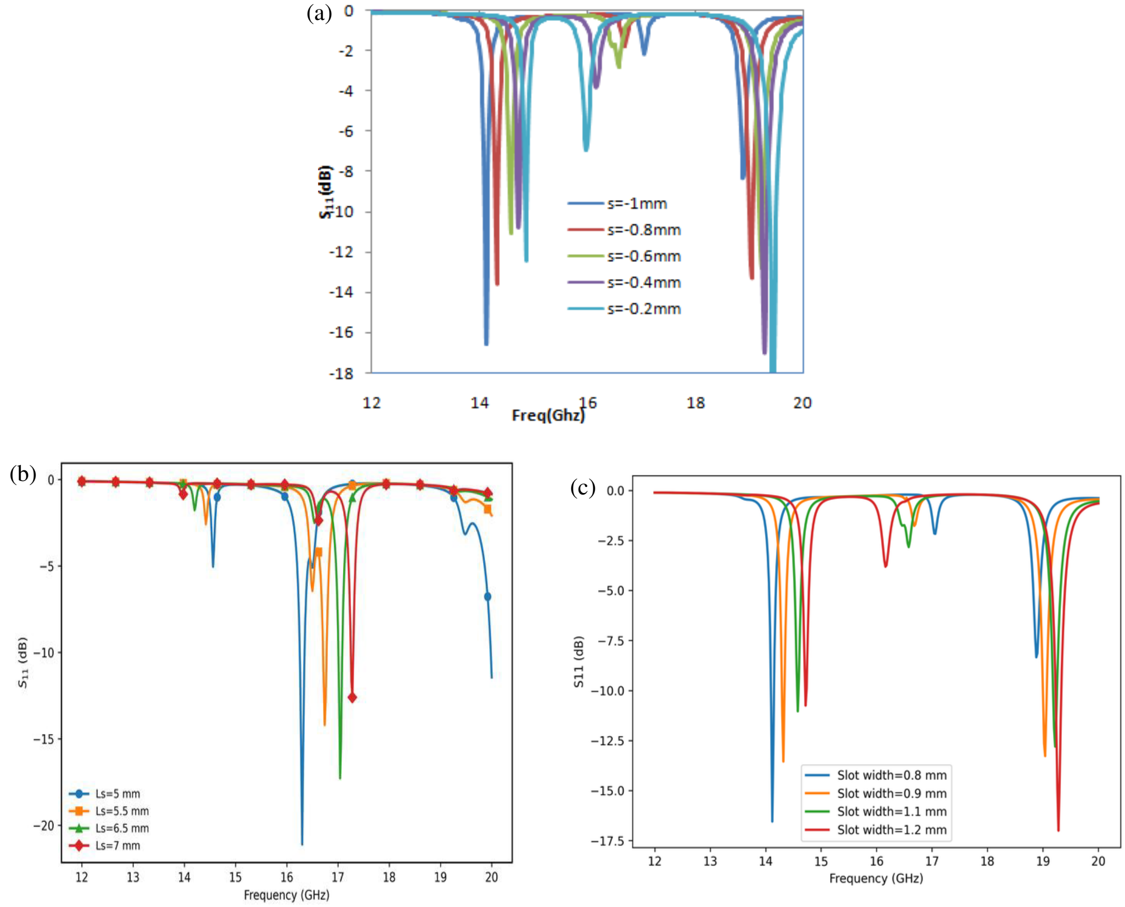

FIGURE 5. Parametric analysis on (a) position of slot, (b) slot length, and (c) slot width.

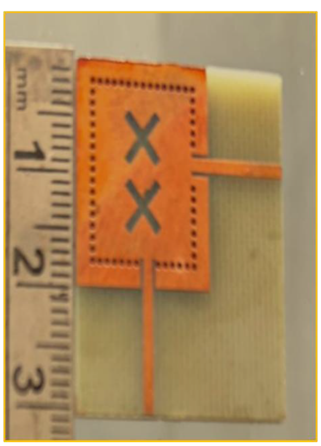

FIGURE 6. Photograph of the fabricated prototype.

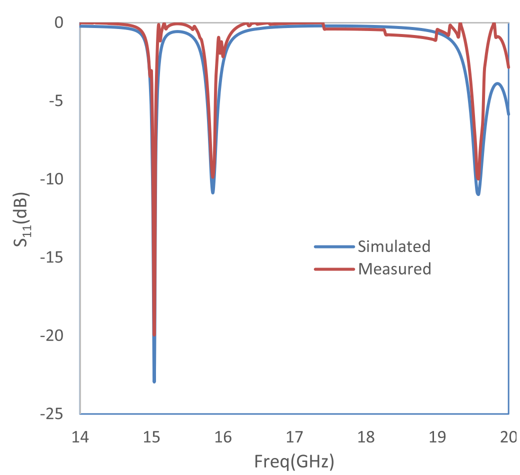

FIGURE 7. S parameter graph of the SIW structure.

3. PARAMETRIC ANALYSIS

3.1. Effect of Slot Position

A detailed parametric analysis is conducted to observe the impact of the X-slot's position and dimensions on the system's overall behavior. Simulation results show that adjusting slot position causes significant changes to the return loss at all three resonant frequencies, as illustrated in Figure 5(a). When the slot position is gradually adjusted from -1 mm to -0.2 mm, an observable increase in the return loss value occurs. The present observation indicates that this shift may result in degrading impedance matching, which is essential for effective energy transfer. In addition, the small yet noteworthy shift in the upper resonant frequency highlights the importance of slot positioning. Also, the central resonant frequency does not remain stable with fluctuations throughout the entire observation period. In Figure 5(b), when the slot length Ls varies from 5 mm to 7 mm, the effective current path lengthens, which

TABLE 2. Comparison of the performance between the designed and previously reported work.

Ref.	Size (mm^2)	Band	RL (dB)	Rad eff (%)	Gain (dBi)	Substrate Material	Feed Type
[20]	31.85×28	Ku	> 40 dB	86%	6.56	Rogers RT Duriod 5880	GCPW(Grounded coplanar feed type)
[21]	38×35	Ku	> 40 dB	NR	6.05	Epoxy FR-4	MSL(Microstrip feed line)
[22]	33×16	Ku	> 20 dB	85	4.7	Rogers RT Duriod 5880	MSL(Microstrip feed line)
[23]	24×25	Ku	> 20 dB	80	4.9	Rogers RT Duriod 5880	MSL(Microstrip feed line)
[24]	32.7×15.4	Ku	> 20 dB	97	6.4	Rogers RT Duriod 5880	MSL(Microstrip feed line)
Proposed	28.4×30.4	K and Ku	> 20 dB at 15.02 GHz and > 10 dB at 15.90 GHz and 19.58 GHz	76.20, 93.51, 95.18	6.89, 6.91 and 7.12	Rogers RT Duriod 5880	MSL(Microstrip feed line)

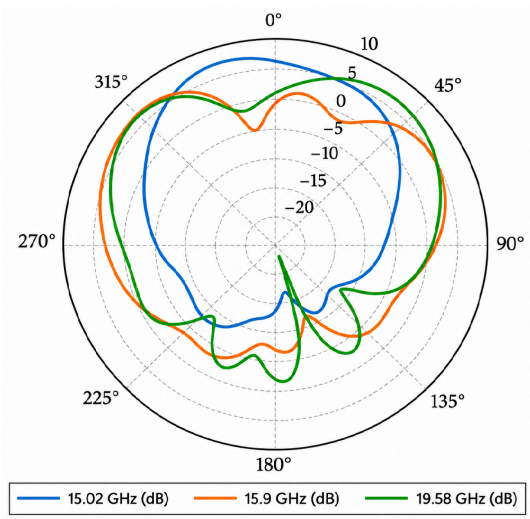

FIGURE 8. Simulated gain plot at all three frequencies.

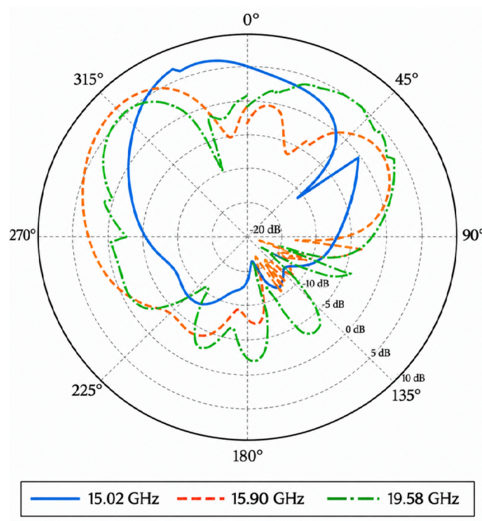

FIGURE 9. Measured gain plot at all three frequencies.

causes the resonant frequency to shift to lower frequencies, and the impedance matching at each resonant point is also affected, whereas in Figure 5(c), when the slot width varies from 0.8 mm to 1.2 mm, the resonant frequency only changes slightly, but the return loss varies, which allows the adjustment of electromagnetic coupling and impedance bandwidth. It can be seen that slot dimensions are an effective means to tune resonant frequencies, optimize impedance matching, and maintain stable operation of a multi-band system. Table 2 presents a comparative analysis of the proposed antenna and previously reported designs in terms of their key performance parameters.

4. EXPERIMENTAL VALIDATION

This paper proposes a novel radio-frequency (RF) antenna. The substrate material selected for the antenna is Rogers RT Duriod 5880, which has a dielectric constant of 2.2 and a thickness of 0.508 mm. Its prototype is shown in Figure 6. Simulations produce three bands at resonant frequencies of 15.02 GHz, 15.90 GHz, and 19.58 GHz, with corresponding gains of 6.89 dB, 6.91 dB, and 7.12 dB, as illustrated in Figure 4. In Figure 7, the red line of the measured reflection coefficient aligns closely with simulation results, which verifies the effectiveness of the proposed antenna design. The measured response of the self-developed antenna in this study exhibits robust tri-band operation capability. These bands can support multi-scenario applications for communication systems. As shown in Figures 8 and 9, measured results of the proposed antenna agree well with simulated ones in terms of main radiation direction and broadside radiation characteristics. Only minor deviations exist in the sidelobe level, null depth, beamwidth, and backlobe radiation, and all deviations are concentrated at two frequency points: 15.90 GHz and 19.58 GHz. Such discrepancies are normal in antenna measurements. Their root causes include manufacturing tolerances of X-shaped slot dimensions and via positions, as well as impacts of the SMA connector. As the proposed antenna operates relying on closely spaced coupled resonant modes, even tiny size deviations can change current distribution, which in turn causes deviations in the radiation pattern.

5. CONCLUSION

This paper proposes a cutting-edge X-slot antenna, developed using cavity-backed substrate integrated waveguide (SIW) technology. The antenna optimizes electromagnetic performance through a custom-designed X-shaped slot, uses a microstrip line feeding to achieve excellent impedance matching, boosts gain, and enhances signal quality, and its innovative structure can support operation across three independent frequency bands. The novel communication antenna developed in this paper adopts orthogonal feeding technology to further improve its performance. Fabricated on a single substrate using a standard printed circuit board (PCB) process, the antenna offers both reliable performance and high cost-effectiveness. The antenna proposed in this paper can be extended along three future research directions: operation in dynamic environments, frequency reconfigurability, and integration with advanced communication systems. Boasting tri-band operation capability within the Ku and K frequency bands, it is an ideal candidate for industrial sensing and monitoring.

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