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Performance Enhancement of Substrate Integrated Waveguide Antenna for Wi-Fi Applications

Srisudharshan Manikandan, Anbazhagan V. Linkkesh,
Shankaragouda M. Patil, and Rajeshkumar Venkatesan*

Department of Communication Engineering, School of Electronics Engineering
Vellore Institute of Technology, Vellore, Tamilnadu, India

ABSTRACT: A single-band, linearly polarized Substrate Integrated Waveguide (SIW) antenna is designed specifically for WLAN 802.11a applications. The SIW design consists of four rectangular slots adjacent to each other through the SIW wall, with appropriate rectangular patch elements inserted in the two vertical slots for bandwidth enhancement. The structure is optimized to radiate at a frequency of 5.22 GHz, resulting in linear polarization caused by the excitation of the fundamental mode (likely TE_{120} mode). The simulated design offers a gain of 7.275 dBi and a bandwidth of 47 MHz. The radiation pattern of the proposed fabricated antenna is measured in test environments where it is found to be unidirectional. The proposed design is compact and minimal in complexity, offering a higher gain.

1. INTRODUCTION

The advancements in wireless communication systems have demanded the development of low-profile, high-frequency devices for efficient communication. Antenna is an essential component in this network that ensures the efficient linking between the devices. There is a need for high-gain antennas offering maximum bandwidth to overcome interference resulting from the signal traffic in the environment. In Wireless Local Area Networks (WLAN), antennas with linear polarization emerge as a suitable option as they are simple in design and less prone to multipath interferences between transmitters and receivers [1, 2]. However, antenna designers prefer using microstrip patch antennas citing their wider bandwidth and smaller profile [3–5].

Such antennas operating at higher frequencies exhibit problems such as unwanted radiation and crosstalk enhancements. While waveguides are efficient at higher frequencies, they are complex and expensive to manufacture to support planar devices [6]. To address such challenges, cavity-backed antennas emerge as a reliable option offering a higher gain, Q-factor, density design, and directionality for smaller dimensions [7].

SIW technology has been developed rapidly in recent years and is replacing microwave passive components mainly in cellular communication networks and other sub-6 GHz applications with economical options such as printed circuit board (PCB) technology. They are fabricated by sandwiching the substrate with top and bottom layers of suitable materials with a series of vias punched in from top to bottom, have properties as rectangular waveguides, and behave similarly to dielectric-filled waveguides with vias [8]. The vias are of suitable dimensions from highly conductive materials such as copper. The radiation losses in SIW cavity antennas are lowered by adjusting the spacing between these vias [4, 9]. For WLAN applications, antennas with high gain are essential for better coverage, improved signal-to-noise ratios, and reduced signal interference.

Numerous SIW antennas have been proposed for WLAN applications. In [10], a SIW cavity-backed antenna using nested cavities is described, where the antenna radiates at 5.2 and 5.8 GHz. It is 42×45 mm in dimensions, is circularly polarized, and offers a peak gain of 6.25 dBi and 6.8 dBi, respectively. It is well suited for Wi-Fi applications with enhanced bandwidth; however, the gain is comparatively smaller for its dimensions and design complexity. The researchers in [11] have designed a 37×45.5 mm microstrip patch antenna employing SIW technology, which radiates at 5.2 GHz. The antenna offers a gain of 6.6 dBi and a narrow bandwidth for its dimensions. In [12], a self-triplexing SIW cavity antenna is developed using hexagonal slots radiating at 5.23, 7.5, and 10.82 GHz. It is 29×29 mm in dimensions and offers a peak gain of 7.33, 6.66, and 6.28 dBi, respectively.

The literature review shows that it is the first triplexing antenna suitable for Wi-Fi applications. Still, it offers a limited bandwidth in the sub-6 GHz range and a relatively lower gain for its design complexity. In [13], a dual-band circular Half-Mode Substrate Integrated Waveguide (HMSIW) antenna is designed by the researchers. Built on a 25.6×25.6 mm substrate, it radiates at 5.2 GHz, offering a max gain of 4.97 dBi, a lower gain value for its design employing HMSIW. In [14], a reference microstrip patch antenna of dimensions 17.6×13.2 mm is designed, offering a gain of 4.48 dBi and a bandwidth of 70 MHz. The proposed antenna is designed by embedding a cylindrical post to the reference, producing a bandwidth of 120 MHz. Though the patch dimensions are smaller, the substrate dimensions are large, making it bulky while offering a lower gain for its dimensions. In [15], a reference

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* Corresponding author: Venkatesan Rajeshkumar (rajeshkumar.v@vit.ac.in).

TABLE 1. Design parameters of the proposed antenna.

Parameter	**L**	**W**	**L$_{\text{eff}}$**	**W$_{\text{eff}}$**	**p**	**d**	**L1**	**W1**	**L2**	**W2**
Value (mm)	26	35	24.05	33	1.5	1	21	1.5	1.7	23
Parameter	**L3**	**W3**	**X**	**Y**	**r2**	**r1**	**LW1**	**LL1**	**LW2**	**LL2**
Value (mm)	1.7	1	10	10.947	2.7	0.75	0.5	6.3	2	0.5

hexagonal cavity-backed self-hexaplexing antenna is proposed for sub-6 GHz applications and offers a gain of 5.68 dBi at 5.17 GHz with port isolation of 29 dB. The gain is relatively lower for the design complexities used. In [16], a quarter mode SIW (QMSIW) based self-diplexing Multiple-Input Multiple-Output (MIMO) antenna of dimensions 22 × 22 mm is proposed for Internet of Things (IoT) applications operating at 5.8 GHz, offering a gain of 5.83 dBi. In [17], a self-diplexing 28 × 28 mm SIW cavity with liquid-filled pockets is proposed, offering a gain of 5.76 dBi at 5.53 GHz.

This manuscript describes a single-band, high-gain SIW antenna designed to operate at 5.22 GHz. It consists of two L-shaped slots in the ground plane opposite each other. Four slots are in the top layer of the SIW, where opposite pairs of slots are equal in dimensions. Unlike the other works that use metal-filled vias to disturb current distributions within the radiating patch [17, 18], the proposed work fully utilizes the slots etched in the structure to enhance the average bandwidth, higher gain and achieve the unidirectional radiation pattern behavior with the help of the coaxial feeding method located at the top right corner. The performance of the cavity-backed antenna was evaluated using simulated and measured characteristics. Moreover, the designed antenna's surface current distribution and front-to-back ratio are examined. A compact cavity-backed slot antenna has been developed for Wi-Fi applications.

2. ANTENNA CONFIGURATION

The SIW cavity is constructed by embedding a chain of posts filled with a perfect electric conductor (PEC) to realize the cavity sidewalls. To preserve the loss of energy from the gap between the vias, the diameter (d) and the distance between the vias (p) are selected to be $\frac{d}{p} \geq 0.5$ and $\frac{d}{\lambda_o} \leq 0.1$ [19–21]. The structure consists of two copper plates of thickness 0.035 mm, length 26 mm, and width 35 mm sandwiched with 1.575 mm thick Rogers 5880 RT Duroid material of dielectric constant 2.2 and a loss tangent of 0.0009. Each via is 1 mm in diameter and is separated by a distance of 1.5 mm. Here, L_{eff} is the length of the SIW, and W_{eff} is the width of the SIW cavity. The performance results are examined by an electromagnetic simulator using the CST Microwave studio suite.

The punched metallic vias that make up the SIW structure are crucial in ensuring that the energy does not leak outward from the radiating patch by reducing the diffraction of the transmitted waves. The gap between these vias should be large enough to minimize these losses [6]. The antenna is coaxially fed to ensure the perfect impedance matching and to minimize the return losses. In addition, using coaxial feeding allows the designer to place the probe in multiple locations where the impedance is perfectly matched [22].

2.1. Mathematical Expressions

The dimensions of the given antenna resonating with TE110 modes are estimated using the formulae in [26]:

$$L_{\text{eff}} = L - 1.08\left(\frac{d^2}{p}\right) + 0.1\left(\frac{d^2}{L}\right) \tag{1}$$

$$W_{\text{eff}} = W - 1.08\left(\frac{d^2}{p}\right) + 0.1\left(\frac{d^2}{W}\right) \tag{2}$$

Here, L is the antenna length; W is its width; p is the distance between the vias; and d is the diameter of the vias. L_{eff} is the length of the SIW cavity while W_{eff} is its width. The frequency of operation for the antenna is estimated using the formula in [26]:

$$f_{mno} = \frac{1}{2\pi\sqrt{\mu\epsilon}}\sqrt{\left(\frac{m\pi}{L_{\text{eff}}}\right)^2 + \left(\frac{n\pi}{W_{\text{eff}}}\right)^2} \tag{3}$$

The approximate positions of the feeding points were calculated using as in [22]:

$$X = \frac{L}{2\sqrt{\epsilon_{\text{reff}}}} \tag{4}$$

$$Y = \frac{L}{3\sqrt{\epsilon_{\text{reff}}}} \tag{5}$$

The design parameters for operating the antenna at 5.22 GHz are in Table 1. The proposed design has a length of 25 mm and a width of 35 mm using (1) and (2). The coaxial feeding points are estimated from (4) and (5). The inner radius ($r1$) and outer radius ($r2$) are calculated to be 0.35 mm and 1.35 mm using CST's inbuilt line impedance calculator. The ideal feeding point for this design was obtained through simulations where varying the y-coordinate alone provided perfect impedance matching.

2.2. Proposed Antenna Design Workflow

To reach the design goal as in Figure 1, the following design changes are introduced to the resonating SIW cavity:

1. Rectangular slots: The rectangular slots of suitable dimensions are etched in the top layer along the vertices of the antenna, and their dimensions are varied based on the enhancement of the parameters [23].

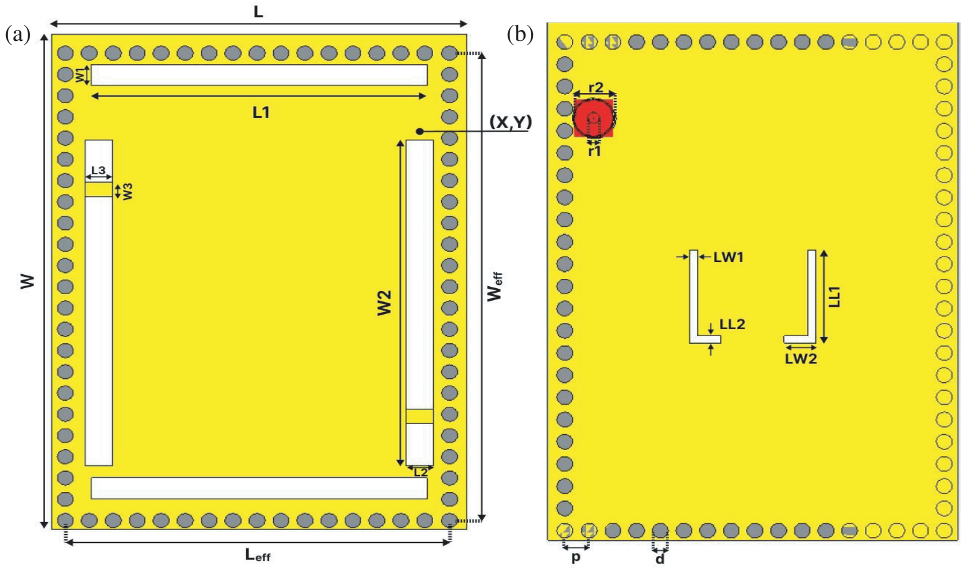

FIGURE 1. Proposed antenna's (a) top view, (b) bottom view.

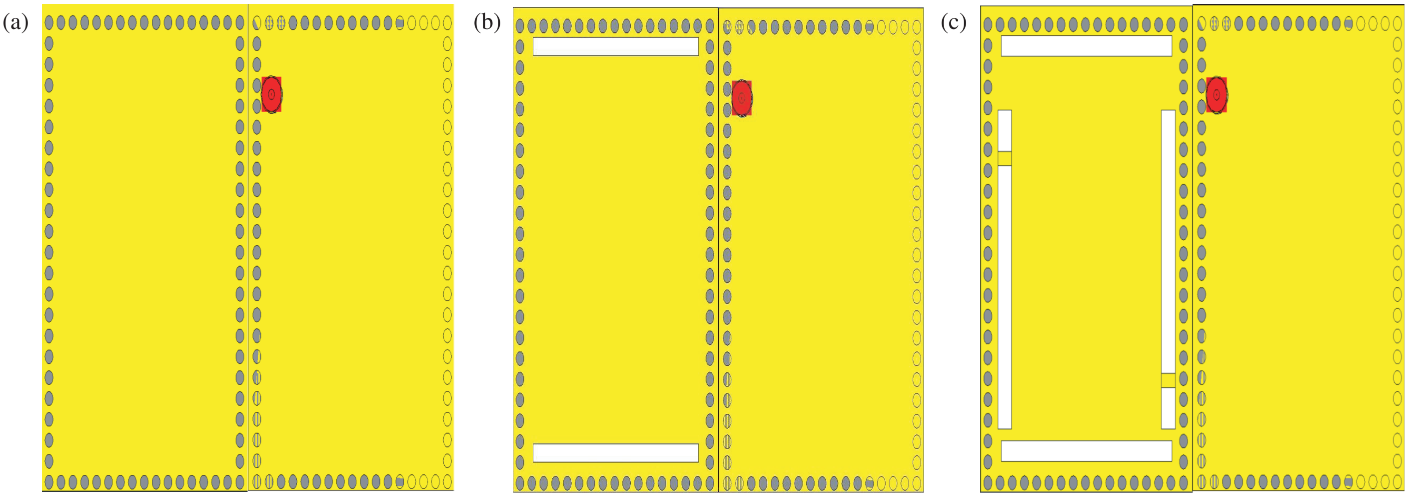

FIGURE 2. The design evolution. (a) Stage-1 design of SIW cavity. (b) Stage-2 design with horizontal slots. (c) Stage-3 design with vertical, horizontal slots and patch elements.

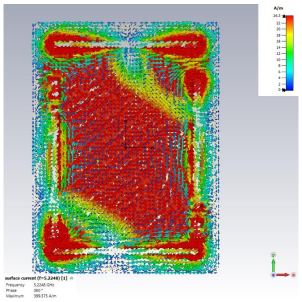

FIGURE 3. Current distribution of the proposed antenna.

2. Rectangular patch elements: Small elements of suitable dimensions are inserted within the vertical rectangular slots, with their sizes varied to enhance the parameters further.
3. L-shaped slots: The slots of suitable dimensions are etched in the ground plane and are varied in their area to enhance the parameters to the maximum [24].

Figure 2 shows various stages of the design evolution process. In each design stage, enhancing the performance is focused solely on disturbing surface current distributions [17] as in Figure 3. Figure 4 depicts the step-by-step design process for enhancing the antenna's performance.

3. PARAMETRIC ANALYSIS

3.1. Adding Horizontal Rectangular Slots

In Stage-1, the SIW cavity radiates at a frequency of 5.3 GHz, resulting in a bandwidth of 10 MHz and a gain of 2.83 dBi. Further, a horizontal rectangular slot nearly half the substrate

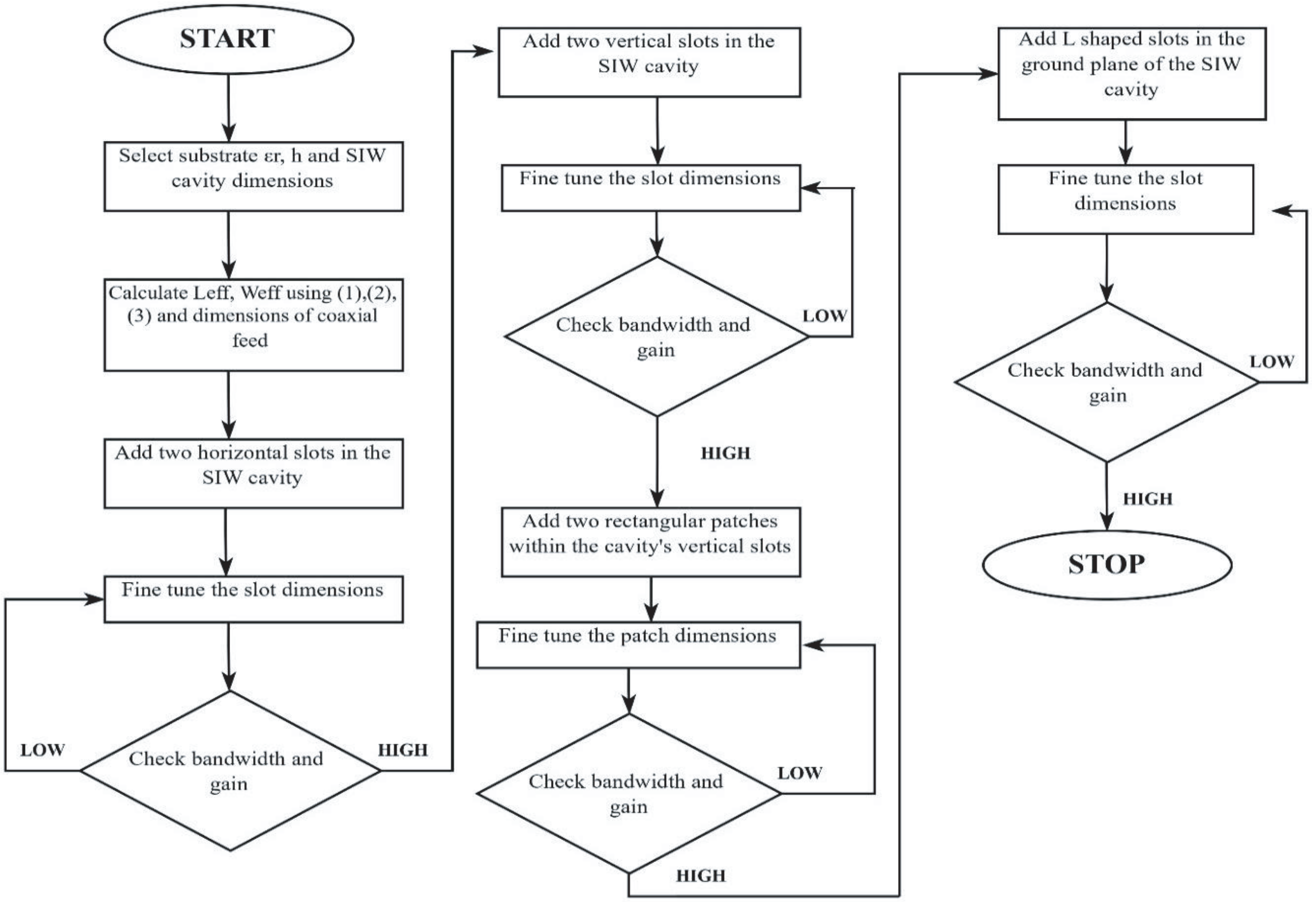

FIGURE 4. Flowchart for the proposed antenna.

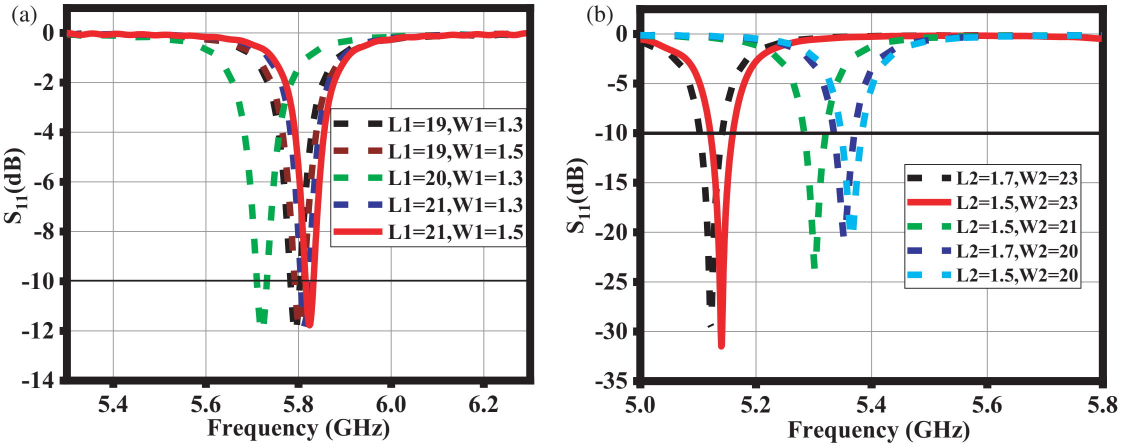

FIGURE 5. Changes in reflection coefficient S_{11} for different (a) $L1$ and $W1$, (b) $L2$ and $W2$.

length and 1 mm in width was etched to the cavity, which did not radiate effectively. Another horizontal slot of the exact dimensions was added just opposite the first slot along the y-axis at the bottom of the structure, as shown in Stage 2.

The added slot improved radiation efficiency as there was a disturbance of the surface currents effectively, resulting in enhanced gain. Figure 5(a) shows the S-parameter variation, and Table 2 shows the gain and bandwidth recorded for the given slot dimensions. The ideal results were produced when the two horizontal slots had a length of 21 mm and a width of 1.5 mm. As shown in the other measurements, the gain was less than 3.259 as a result of improper impedance matching and fewer disturbances in the currents. This analysis also yielded

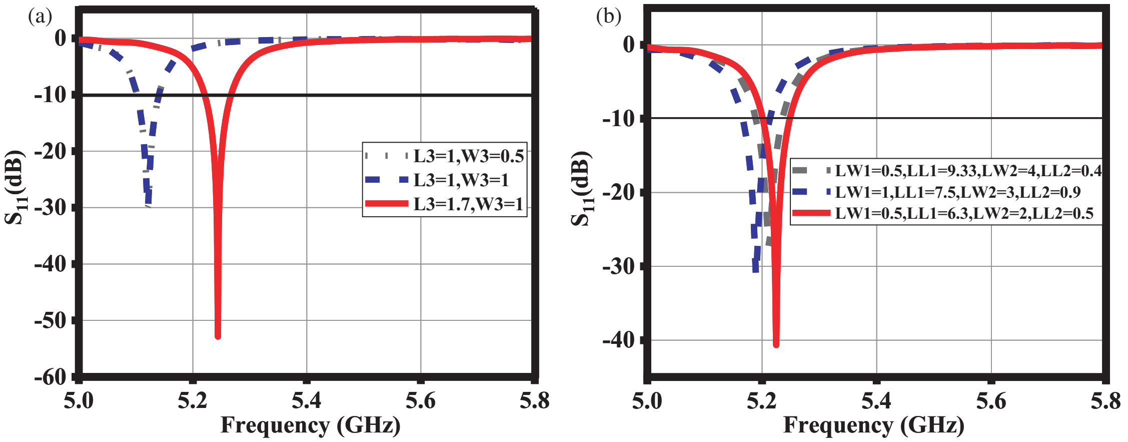

FIGURE 6. Changes in reflection coefficient S_{11} for different (a) $L3$ and $W3$, (b) $LW1$, $LL1$, $LW2$ and $LL2$.

TABLE 2. Analysis with 5 different horizontal slot dimensions.

S.N.	Slot length (mm)	Slot width (mm)	Center frequency	Max gain (dBi)	Bandwidth (MHz)
1	19	1.3	5.79	3.259	19.6
2	21	1.3	5.67	6.398	22.7
3	21	1.5	5.68	6.736	22.6
4	19	1.5	5.8	4.73	19.0
5	20	1.3	5.72	2.583	22.1

TABLE 3. Analysis with 5 different vertical slot dimensions.

S.N.	Slot length (mm)	Slot width (mm)	Center frequency	Max gain (dBi)	Bandwidth (MHz)
1	20	1.5	5.36	6.751	35.9
2	20	1.7	5.35	5.116	35.4
3	21	1.5	5.30	6.733	37
4	23	1.7	5.12	7.877	38.5
5	23	1.5	5.14	7.491	38.9

TABLE 4. Analysis with 3 different patch element dimensions.

S.N.	Element length (mm)	Element width (mm)	Center frequency (GHz)	Max gain (dBi)	Bandwidth (MHz)
1	1	0.5	5.12	7.852	38.5
2	1	1	5.12	7.842	38.5
3	1.7	1	5.24	7.15	46.4

enhanced gain and bandwidth with the closeness of the slots toward the SIW walls

3.2. Adding Vertical Rectangular Slots

Two vertical slots were etched below the coaxial feed pin to the stage-2 design alongside the SIW cavity's width. Figure 5(b) shows the variation in the S-parameters, and Table 3 shows the parameters recorded for the vertical slot dimensions. The optimal results were recorded when the two slots had a length of 23 mm and a width of 1.7 mm, respectively. Adding slots maintained design symmetry and disturbed surface currents evenly to obtain enhanced gain and bandwidth.

3.3. Adding Two Rectangular Patch Elements within Slots

In the stage-3 design, enhancing bandwidth was the focus, as the gain rapidly increased with the addition of slots. Two congruent and rectangular patch elements were added inside vertical rectangular slots of the previous design to enhance bandwidth. They were positioned at opposite locations in both the horizontal and vertical planes and effectively enhanced bandwidth. Figure 6(a) shows the S-parameter variation, and Table 4 shows the gain and bandwidth recorded for the given patch dimensions. The most considerable bandwidth for the design was recorded when these patches had a length of 1.7 mm and a width of 1 mm. When being placed in the horizontal slots, the patches did not enhance the parameters as effectively as placing them inside the vertical slots. The location of these elements within the slot was obtained through a series of parametric analyses that yielded the ideal results.

3.4. Etching L-Shaped Slots in the Ground Plane

For stage-3 design, differently-shaped slots were etched in the ground plane to enhance gain and bandwidth. Initially, a pair of congruent H-shaped and inverted T-shaped slots were chosen for the design changes in the ground plane, but they were ineffective in disturbing the surface currents.

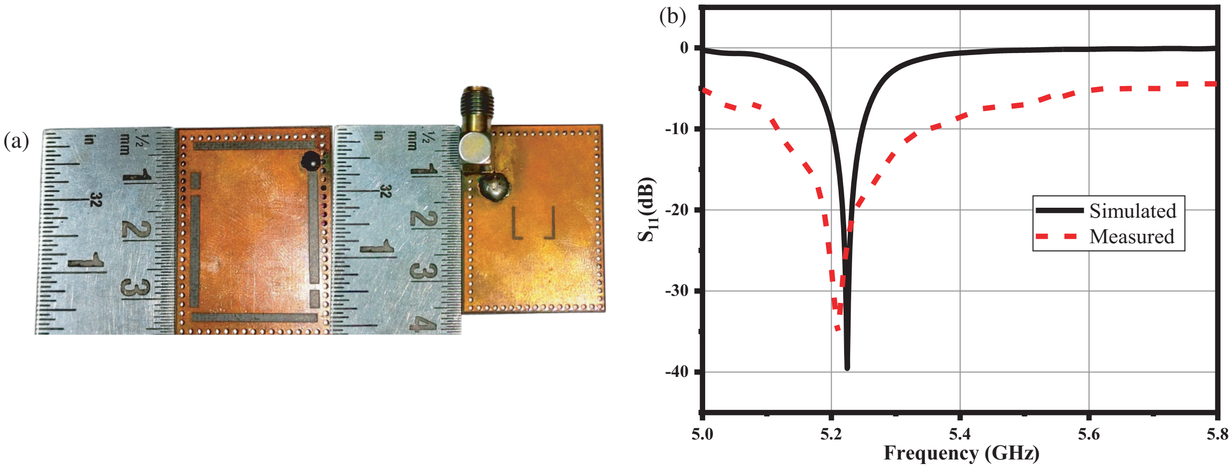

FIGURE 7. (a) Photograph of fabricated prototype. (b) Simulated and measured S_{11} values.

TABLE 5. Analysis with 3 different L-shaped slot dimensions.

S.N.	$LW1$ (mm)	$LL1$ (mm)	$LW2$ (mm)	$LL2$ (mm)	Center frequency (GHz)	Max gain (dBi)	Bandwidth (MHz)
1	1	7.5	0.9	3	5.19	6.157	47.3
2	0.5	6.3	0.5	2	5.22	8.407	47.1
3	0.5	9.33	0.4	4	5.21	7.515	46.4

TABLE 6. Evaluating the simulated antenna to the previously reported antennas.

References	Dimensions (mm)	Simulated Gain (dBi)	Techniques
[10]	42 × 45	6.25	Nested cavity
[11]	37 × 45.5	6.6	Antenna array
[12]	29 × 29	7.33	Self diplexing SIW cavity
[13]	25.6 × 25.6	4.16	HMSIW, self diplexing cavity
[14]	17.6 × 13.2	4.48	Microstrip patch with cylindrical rods
[15]	-	5.68	Self-Hexaplexing cavity
[16]	22 × 22	5.83	QMSIW, Self-diplexing MIMO
Proposed Design	26 × 35	7.27	Rectangular SIW cavity

A pair of congruent L-shaped slots were etched in the ground plane of the stage-3 design to enhance the gain further. Figure 6(b) shows the S-parameter variation, and Table 5 shows the gain and bandwidth recorded for the given L-shaped slot dimensions. The maximum gain and bandwidth resulted when $LW1 = 0.5$ mm, $LL1 = 6.3$ mm, $LW2 = 0.5$ mm, and $LL2 = 2$ mm. Other cases of parametric analysis involving variations in the slot dimensions showed no further enhancements in bandwidth and offered a less gain than the tabulated values. The above simulations showed that the antenna radiated in the TE_{110} mode. Various gain enhancement techniques have been compared in [25]. Table 6 compares our proposed design with the previously reported works.

4. MEASUREMENT AND DISCUSSION

Figure 7(a) depicts the proposed antenna, built on a 1.6 mm thick Rogers RT Duroid 5880 substrate with a dielectric constant of 2.2. When the proposed antenna is simulated, a resonance peak at 5.22 GHz with a -10 dB impedance bandwidth of 47 MHz is observed. Figure 7(b) shows variations in the results due to fabrication mismatches. A photograph of the measurement setup for the proposed compact SIW antenna is shown in Figure 8(b). The reflection coefficient S_{11} results were obtained using an Anritsu VNA (MS20227C), and a radiation pattern was measured in the anechoic chamber. The simulated bandwidth covers nearly two complete bands from the list of bands in 5 GHz 802.11a/h/n/ac/ax/be. It covers the band with a center frequency of 5.22 GHz, covers 99.7% of the band with a center frequency of 5.24 GHz, and covers 0.0435% of the band with a center frequency of 5.2 GHz. It offered a gain of 7.275 dBi at the center frequency.

The proposed antenna resonates at 5.21 GHz and offers a bandwidth of 230 MHz, which is 183 MHz more than the simulated antenna, due to possible fabrication and soldering tolerance, thermal effects, conductor loss, and dielectric losses. The

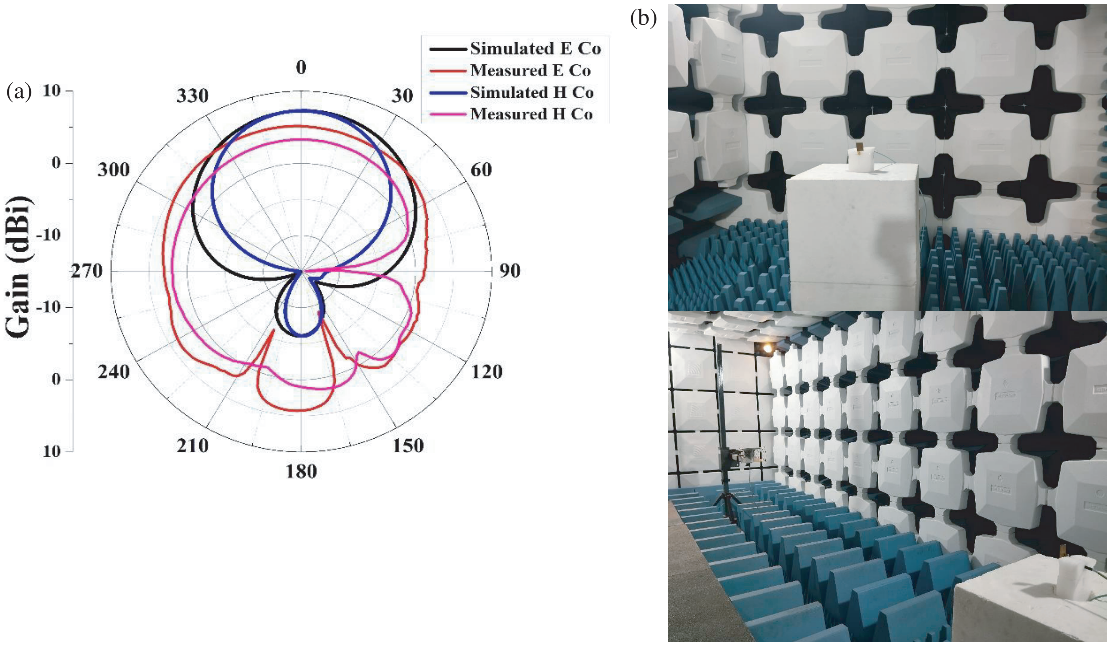

FIGURE 8. (a) Simulated and measured radiation patterns of proposed antenna at 5.2 GHz. (b) Radiation measurement setup in anechoic chamber.

measured peak gain of the proposed antenna is 5.85 dBi. Figure 8(a) shows the plot of the radiation pattern of the simulated antenna vs. measured one. It can be inferred from the E-plane's radiation pattern ($\phi = 0^\circ$) and the H-plane's radiation pattern ($\phi = 90^\circ$) that the antenna is highly unidirectional, offering maximum directivity and gain at the main lobes ($\theta = 0^\circ$) and minimum directivity at the back lobes ($\theta = 180^\circ$) while offering nearly no side lobe along with this proposed antenna having radiation and total efficiency of 86.67% and front-to-back ratio (FTBR) of 14.48 dB.

5. CONCLUSION

We design a substrate-integrated waveguide slotted antenna. Coaxial feeding ensures perfect impedance matching and minimizes radiation losses, parasitic effects, etc. To enhance gain and bandwidth effectively, rectangular slots, patch elements within the vertical slots, and L-shaped slots in the ground plane are used. A simulated antenna with a frequency of 5.22 GHz offers a bandwidth of 47 MHz and a peak gain of 8.406 dBi in the sub-6 GHz band. This design is ideal for Wi-Fi applications because it is entirely symmetrical. Compared to recent work on SIW antennas, this design involves minimal complexity.

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