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A Modified Bow-Tie Slot Loaded Cavity Backed Antenna Based on SIW

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Abstract—A design of a modified bow-tie slot loaded wideband antenna using a Substrate Integrated Waveguide (SIW) cavity is proposed in this paper. The simple bow-tie slot perturbs the current distribution of the TE_{120} mode, which generates two hybrid modes, namely odd TE_{120} and even TE_{120} modes at 9.6 GHz and 10.8 GHz, respectively, but the achieved bandwidth is only 500 MHz (5.2%). To increase the bandwidth, a short rectangular slot is incorporated at the middle of the bow-tie slot, which moves the hybrid odd TE_{120} mode to 10.2 GHz, near even TE_{120}, which helps to achieve a wide bandwidth of 1.1 GHz ranging 9.9 GHz–11 GHz (10.5%), and also it exhibits a unidirectional radiation pattern. The proposed antenna is fabricated for experimental validation of the modified bow-tie slot antenna. The measured value of bandwidth is 1.1 GHz from 10.1 GHz to 11.2 GHz (10.3%) with a consistent gain of 6.25 dBi, and the variation between co-pol and cross-pol is maximal. Because of the wide bandwidth, high gain, and compactness, the suggested antenna is suitable for satellite, radar, and all practical wireless applications of X-band frequencies.

1. INTRODUCTION

Low-profile antennas with high bandwidth and gain are in exceptionally high demand in the millimeter and microwave frequency range due to the widespread use of wireless communication technologies. Planar slot antennas are a popular choice for various wireless applications. However, these antennas exhibit bi-directional radiation, which is undesirable in many real-time wireless applications. A metallic cavity must be positioned behind the radiating slot to block the backside radiation [1–3], but the antenna's volume is significantly increased. Additionally, it makes the integration with planar circuits quite challenging. Hence, the Substrate Integrated Waveguide (SIW) technology evolved as a potential solution [4–6], overcoming the problems mentioned above.

Various techniques for increasing the bandwidth of SIW based antennas have been suggested in the literature. The SIW cavity with a rectangular slot for enhancing bandwidth has been first introduced in [7], which realizes a bandwidth of 1.7% using TE_{120} mode. In [8], dual slots are employed to generate two resonant frequencies. Two resonant frequencies can be moved closer to realize the wide bandwidth by changing the length of slots. The removal of substrate technique has been proposed for bandwidth enhancement in [9], by lowering the quality factor (Q) of the cavity and slot, which is achieved by removing the substrate behind the slot. However, removing substrate is difficult in practice, resulting in more expensive and complex designs. In [10], a small circular hole engraved on the rectangular slot generates an extra resonant frequency, which increases the bandwidth but is limited to 3.34% only. Bandwidth enhancement is obtained in [11], by concurrently generating two hybrid modes in the SIW cavity and combining them in the desired band of frequencies. Bandwidth is improved in [12, 13], by splitting the resonant frequency of the degenerate modes TE_{210} and TE_{120}, exhibiting dual resonances,

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where a perturbation technique using a single corner cut is used in [12], and two corner cuts are used in [13]. In order to couple higher order modes and increase impedance matching, the antenna in [14] uses the offset feeding method. Compared to the center feeding approach (1.7%), it demonstrates a considerable increase in bandwidth, although it is limited to 4.2%. Impedance bandwidth is improved in [15] using a SIW slot antenna supported by two cavities, one substrate above another substrate, which are coupled through a slot. A circular cavity is placed inside the rectangular cavity with separate excitations as demonstrated in [16], and circular ring slots are engraved on both the cavities to support the radiation. Each cavity is excited individually, producing two frequency bands with bandwidths of 6% and 3.4%. A 3×3 array of rectangular slots backed by a SIW cavity has been proposed in [17] to be operated in X-band. The slots are placed alternately, maintaining a spacing of half of the wavelength, which generates constructive radiation in the desired direction, but the volume of the cavity is large. Enhancement of bandwidth using bilateral slots backed by a SIW cavity is proposed in [18]. The SIW cavity's quality factor (Q) decreases with the placement of bilateral slots, which increases the antenna's bandwidth significantly by using two closely spaced hybrid modes. The half mode SIW hexagonal cavity backed slot antenna [19] is developed using TM_{010} and TM_{110} modes to achieve dual resonances in C-band. The resonant frequency of TM_{110} mode of the structure is brought closer to the fundamental mode with the help of the slot.

This paper presents a cavity backed antenna based on SIW with a modified bow-tie slot. The suggested antenna provides a bandwidth of 10.3% and a gain of 6.25 dBi with a unidirectional radiation pattern. The combination of a rectangular slot and a bow-tie slot enables the cavity to resonate at two closely located hybrid modes, resulting in a wide bandwidth response. The suggested antenna is excited by using a simple grounded coplanar waveguide (GCPW) feeding technique, which makes the design simpler. The suggested antenna exhibits a consistent gain in the desired bandwidth while keeping its planar structure. The experimental results are compared with the earlier designs [9–16] for a thorough investigation. Section 2 presents the structure of the antenna, and its operating principle is described in Section 3. A study of parameters is presented in Section 4 to observe their influence on bandwidth. Section 5 presents a comparison of the measured results with the earlier designs, and Section 6 concludes.

2. ANTENNA STRUCTURE

Dielectric substrate Rogers RT/Duroid 5880 (dielectric constant-2.2) of height 1.57 mm, which is approximately $0.05\lambda_o$, is employed to realize the proposed wideband operation. Fig. 1 illustrates the three phases of the suggested antenna's design evolution. Placing metallic cylinders (or vias) equally along the edges of the substrate shorting the top and bottom conductors forms the SIW cavity, as shown in Fig. 1(a). Diameter of the via 'd' and pitch 'p' (separation between two adjacent vias) are chosen carefully, $p \leq 2d$ and $d \leq 0.1\lambda_o$, to ensure minimum energy leakage from the SIW cavity's sidewalls (where λ_o is the free space wavelength).

The initial dimensions of the SIW cavity can be estimated using the resonant frequency formula in Equation (1):

$$f_{mpp'} = \left(\frac{1}{2\sqrt{\mu\epsilon_0\epsilon_r}}\right)\sqrt{\left(\frac{m}{W_{eff}}\right)^2 + \left(\frac{n}{L_{eff}}\right)^2 + \left(\frac{p'}{h}\right)^2} \tag{1}$$

where ϵ_r is the relative permittivity; μ is the relative permeability of the substrate; m, n, and p' represent the half wave sinusoidal variations in x, y, and z directions, respectively; and h is the thickness of the substrate.

The effective width of the cavity,

$$W_{eff} = W_{cav} - \frac{d^2}{0.95 * p} \tag{2}$$

The effective length of the cavity,

$$L_{eff} = L_{cav} - \frac{d^2}{0.95 * p} \tag{3}$$

and W_{cav} and L_{cav} are the cavity width and length, respectively.

The main objective of stage-II is to disturb the conventional cavity modes by using a bow-tie slot. Fig. 1(b) depicts the implementation of the bow-tie slot. The slot length is 15.5 mm, approximately $\lambda_o/2$, and the width of bow (W_{bow}) is 7.52 mm, approximately $\lambda_o/4$, where $\lambda_o = 31.25$ mm at resonant frequency 9.6 GHz. Stage-III is aimed to accomplish a wide impedance bandwidth by placing a short rectangular slot, as shown in Fig. 1(c). The modified bow-tie slot serves as a radiator and is etched on the substrate's bottom metal laminate. It is situated at a distance of d_{su} from the top wall formed by the vias in x-direction, as shown in Fig. 2. The rectangular slot is placed in the middle of the bow-tie slot having a length of 2.6 mm and width of 1.6 mm. To excite the suggested structure, a grounded coplanar waveguide (GCPW) feeding method is used at the SIW cavity's bottom sidewall. For the measurement convenience, one end of the 50 Ω micro-strip line is attached to the center conductor of GCPW of the same width. In addition, it encourages planar integration.

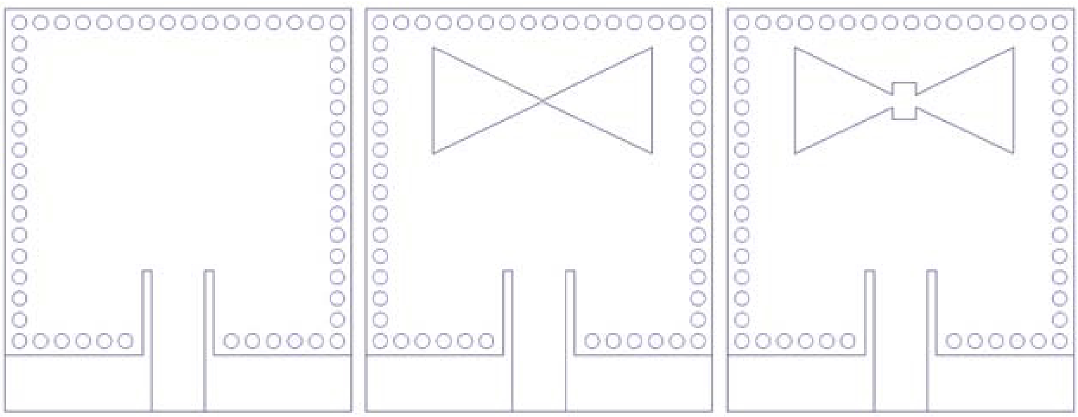

Figure 1. Design evolution stages: (a) SIW cavity (Stage-I); (b) Bow-tie slot antenna (Stage-II); (c) SIW cavity backed antenna with a bow-tie slot and a short rectangular slot (Stage-III).

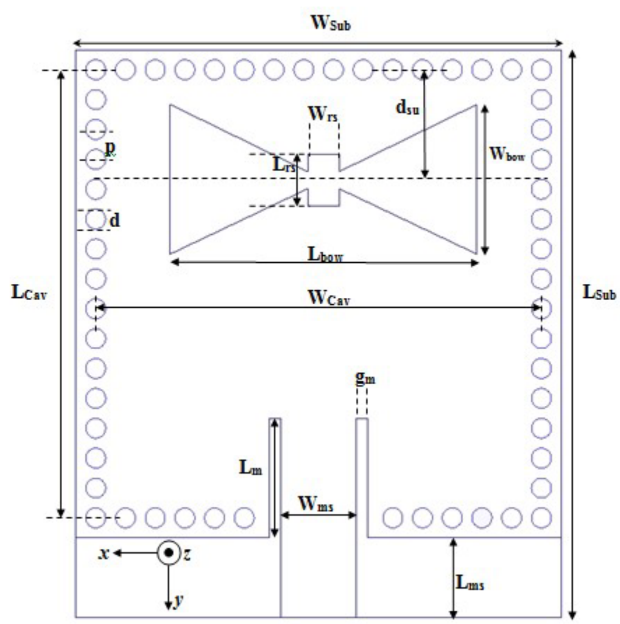

Figure 2. Dimensions of the proposed antenna (Stage-III) [$L_{Sub} = 28.5$, $W_{Sub} = 24.5$, $L_{Cav} = 22.5$, $W_{Cav} = 22.5$, $L_{bow} = 15.5$, $W_{bow} = 7.52$, $L_{rs} = 2.6$, $W_{rs} = 1.6$, $L_{ms} = 4$, $W_{ms} = 3.8$, $L_m = 6$, $g_m = 0.6$, $h = 1.57$, $p = 1.5$, $d = 1$] (All units are in mm).

3. PRINCIPLE OF OPERATION

The three conventional cavity modes, TE_{110}, TE_{120}, and TE_{130}, are generated at 6.8 GHz, 10.3 GHz, and 14.1 GHz, respectively in Stage-I (SIW Cavity without slots) of the design. The generation of several cavity modes can be observed from the maximum values of the real part of input impedance plot, as shown in Fig. 3. The electric field intensities of the aforementioned cavity modes are shown in Fig. 4(a) through (c). The bow-tie slot (Stage-II) is etched on the ground plane of the SIW cavity. Fig. 3 makes it evident that the slot perturbs the conventional cavity modes in this stage. Because of the loading effect of the slot, the dominant mode of the cavity TE_{110} is moved from 6.8 GHz to 5.9 GHz. Similarly, TE_{120} mode is split into two hybrid modes and radiates the field at 9.6 GHz (odd TE_{120}) and 10.8 GHz (even TE_{120}), which can be examined using the field distributions of the corresponding modes as shown in Fig. 5. However, the bandwidth is limited to a narrow band of 500 MHz from 9.4 GHz to 9.9 GHz, which is a fractional bandwidth of 5.2%, as shown in Fig. 7. A short rectangular slot is placed at the center of the bow-tie slot which forms the proposed design (modified bow-tie slot named as Stage-III). The structure of the proposed antenna is shown in Fig. 2. The hybrid odd TE_{120} mode is shifted from 9.6 GHz to 10.2 GHz, with the help of introducing a rectangular slot at the center of the bow-tie slot, which results in two closely spaced hybrid modes resulting in a wide impedance bandwidth. The modes in stage-II are almost unaffected by the placement of the rectangular slot, as shown in Fig. 6. The rectangular slot does not create any additional resonances, but the bandwidth is increased significantly

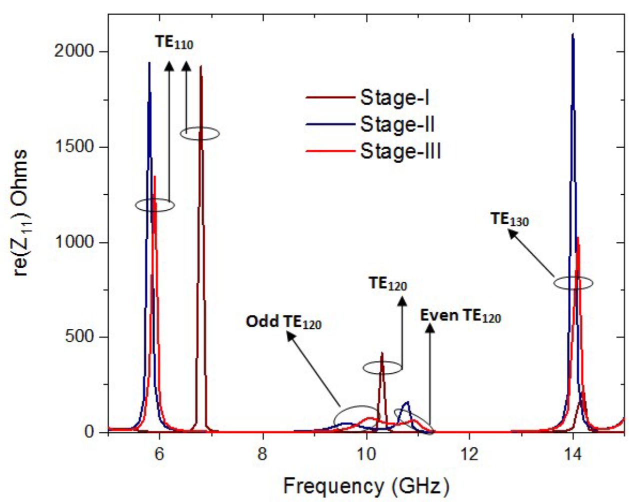

Figure 3. Input resistance ($\mathrm{re}(Z_{11})$) plot.

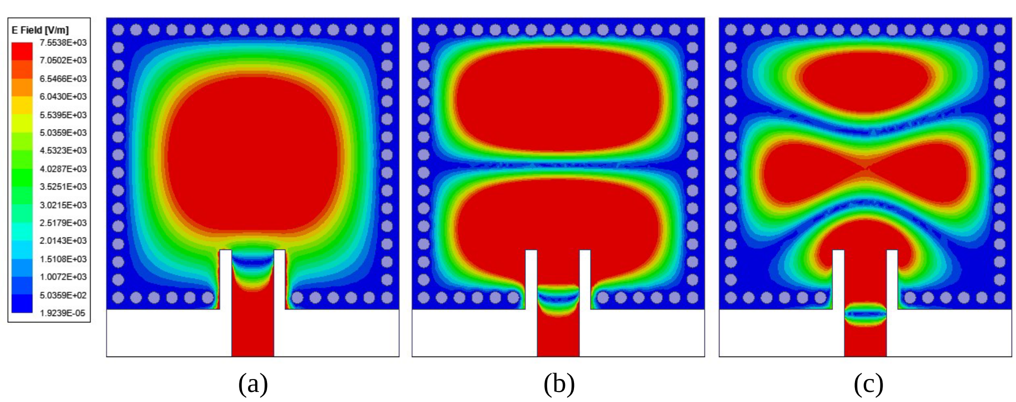

Figure 4. Electric field intensities of SIW cavity (Stage-I) at (a) 6.8 GHz, (b) 10.3 GHz, (c) 14.1 GHz.

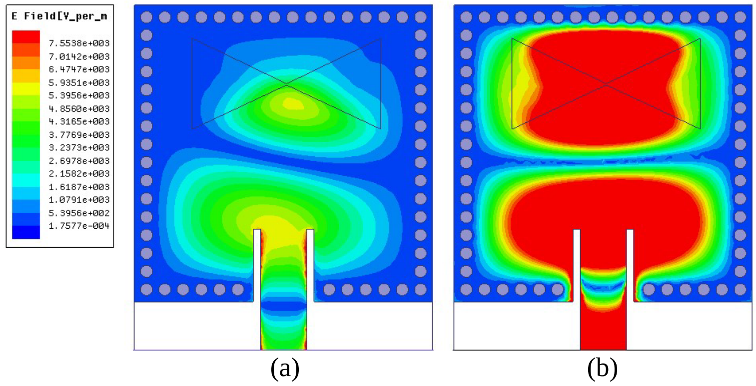

Figure 5. Electric field intensities of bow-tie slot (Stage-II) at (a) 9.6 GHz, (b) 10.8 GHz.

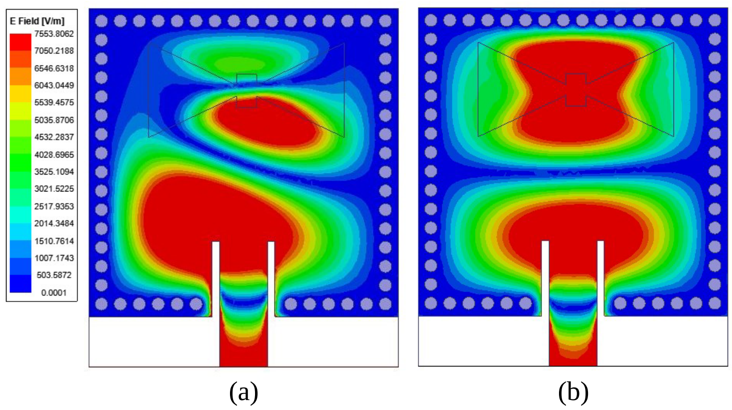

Figure 6. Electric field intensities of modified bow-tie slot (Stage-III) at (a) 10.2 GHz (b) 10.8 GHz.

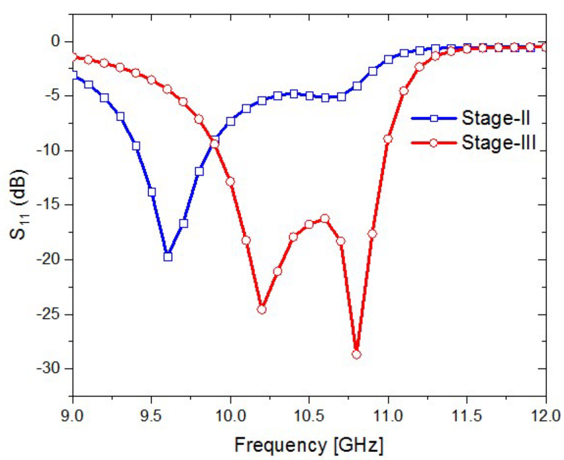

Figure 7. Reflection coefficient (S_{11}) of Stage-II versus Stage-III.

compared with stage-II, as shown in Fig. 7. Also, a good impedance matching is achieved in the desired band ranging from 9.9 GHz to 11 GHz. Here the bow-tie slot and a short rectangular slot are engraved in the ground plane to avoid the spurious radiation effects. Since the strength of the electric fields on either side of the modified bow-tie slot is different in magnitude and phase, the slot is better able to radiate the electromagnetic waves into free space. The TE_{130} mode is minimally perturbed; however, this mode is not employed to increase the bandwidth.

4. STUDY OF PARAMETERS

To recognize the impact of geometrical parameters on bandwidth, a study of optimization of parameters is conducted using High Frequency Structure Simulator (HFSS) tool. The variations of S_{11} with various parameters are plotted in Fig. 8 and Fig. 9. By increasing bow length (L_{bow}), the impedance matching at upper resonant frequency is greatly affected, but with proper tuning of length L_{bow}, we achieve proper impedance matching. The optimum value of L_{bow} is 15.5 mm, which is approximately half of the free space wavelength at 10.2 GHz. As the width of bow W_{bow} or flaring angle of the bow varies, the impedance matching varies, and the optimum value of the width of the bow for a maximum impedance bandwidth is 7.52 mm with a flare angle of 26°. The position of the short rectangular slot plays a vital role in increasing the bandwidth. With increasing the rectangular slot length (L_{rs}) from 2.1 mm to 2.6 mm, the impedance matching at the upper resonant frequency increases. But if we increase the length (L_{rs}) to 3.1 mm, the bandwidth gets decreased and also poor impedance matching at upper resonant frequency. Hence, the length of the rectangular slot L_{rs} is chosen as 2.6 mm for the maximum bandwidth. If we increase the rectangular slot width (W_{rs}), impedance matching gets decreased, hence the slot width (W_{rs}) is chosen as 1.6 mm for better impedance matching.

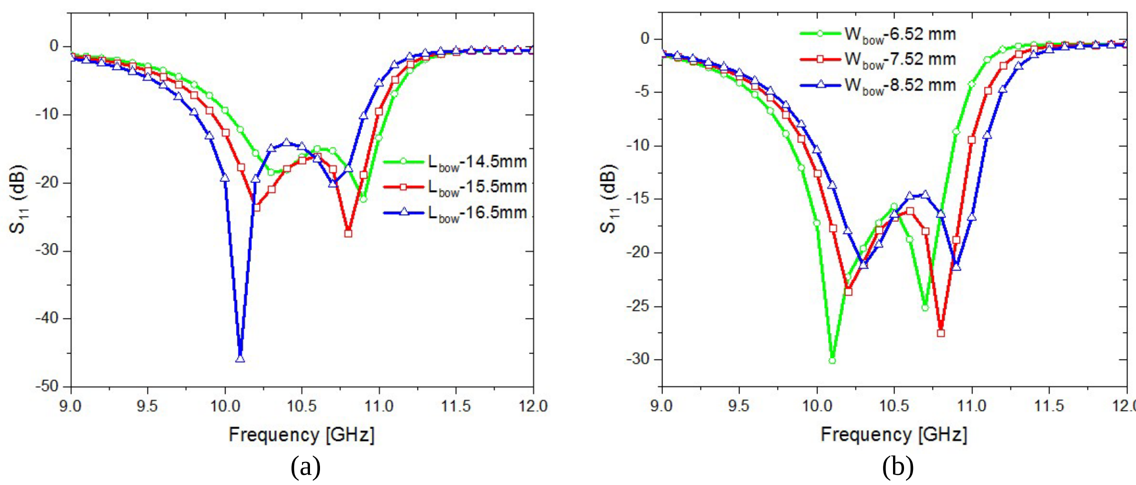

Figure 8. Effect on reflection coefficient (S_{11}) with the change in (a) L_{bow}, (b) W_{bow}.

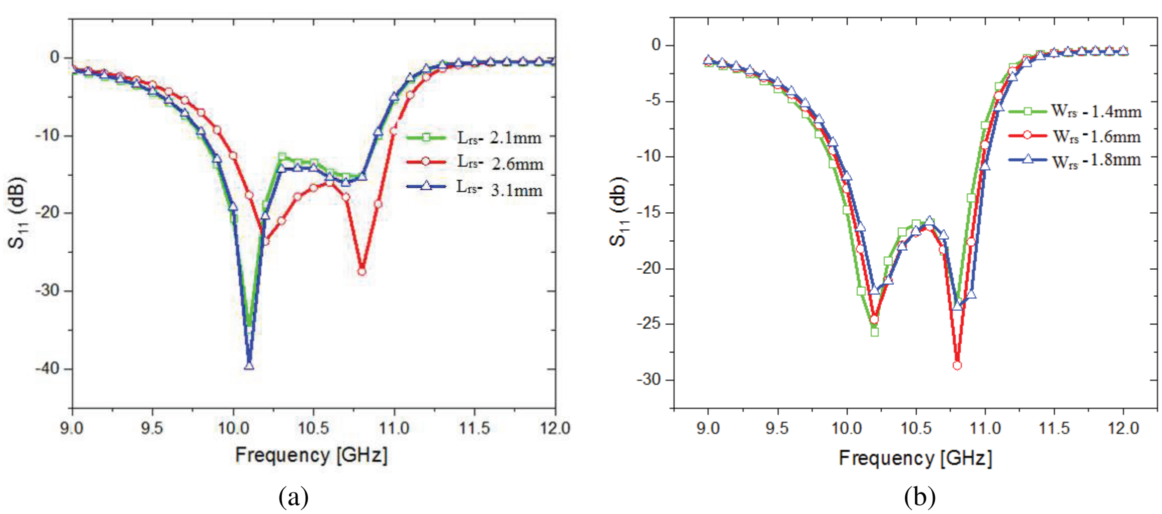

Figure 9. Effect on reflection coefficient (S_{11}) with the change in (a) L_{rs}, (b) W_{rs}.

5. EXPERIMENTAL RESULTS

A model of the proposed antenna is fabricated to validate the simulation results. It is fabricated on a 1.57 mm Rogers RT/Duroid 5880 substrate. The antenna's reflection coefficient characteristics (S_{11}) are measured using an Agilent N5247A network analyzer. Fig. 10 shows the proposed antenna's upper and lower faces of the fabricated prototype. Fig. 11 shows the simulated versus experimental values of the reflection coefficient (S_{11}) and gain of the suggested antenna. The measured value of bandwidth is 1.1 GHz ranging from 10.1 GHz to 11.2 GHz (10.3%), and the gain is 6.25 dBi. The antenna provides a stable gain that varies from 5.5 dBi to 6.25 dBi in the desired band, as depicted in Fig. 11.

(a) (b)

Figure 10. (a) Upper face of the suggested antenna. (b) Lower face of the suggested antenna.

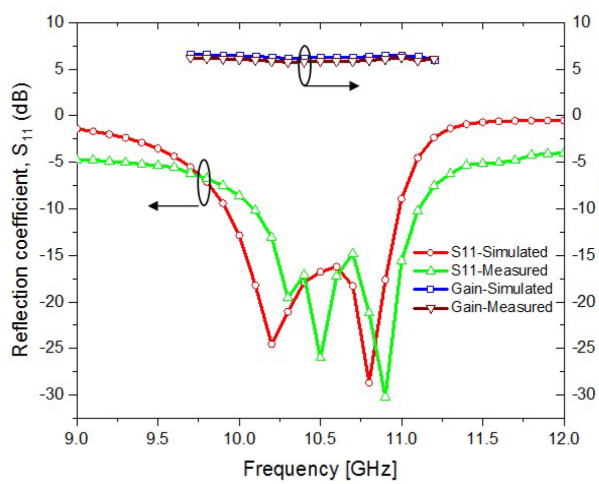

Figure 11. Simulated versus measured values of reflection coefficient S_{11} and gain.

Figures 12 and 13 depict the simulated and measured normalized radiation patterns (co-pol and cross-pol) in H plane (X-Z plane or azimuthal angle $\Phi = 0°$ plane) and normalized E plane (Y-Z plane or azimuthal angle $\Phi = 90°$ plane) radiation patterns for the resonant frequencies 10.2 GHz and 10.8 GHz. The radiation pattern is unidirectional as shown in Figures 12 and 13, which is because of the cavity backing of the antenna. The measured values of cross-polarization values at resonant frequencies 10.2 GHz and 10.8 GHz are −23.05 dB and −30.42 dB in the H plane and −24.82 dB and −31.09 dB, respectively in the E plane in the directions of maximum gain in the respective planes. The experimental results comply with the simulated ones.

The parameters of the suggested antenna are compared with earlier designs and are tabulated in Table 1, which illustrates the importance of the suggested design. From Table 1, it is evident that the suggested design has a larger impedance bandwidth than the antennas mentioned in [9–16]. The

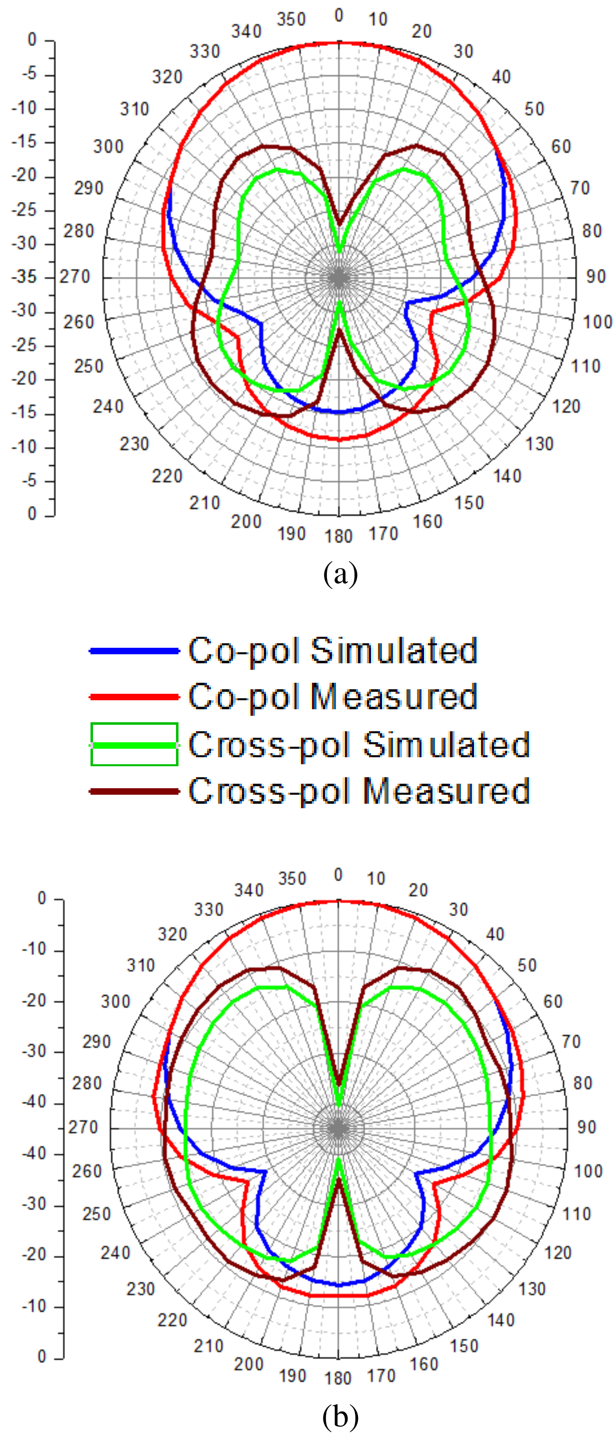

Figure 12. Simulated and measured normalized H plane (X-Z plane) ($\Phi = 0°$) radiation patterns at (a) 10.2 GHz, (b) 10.8 GHz.

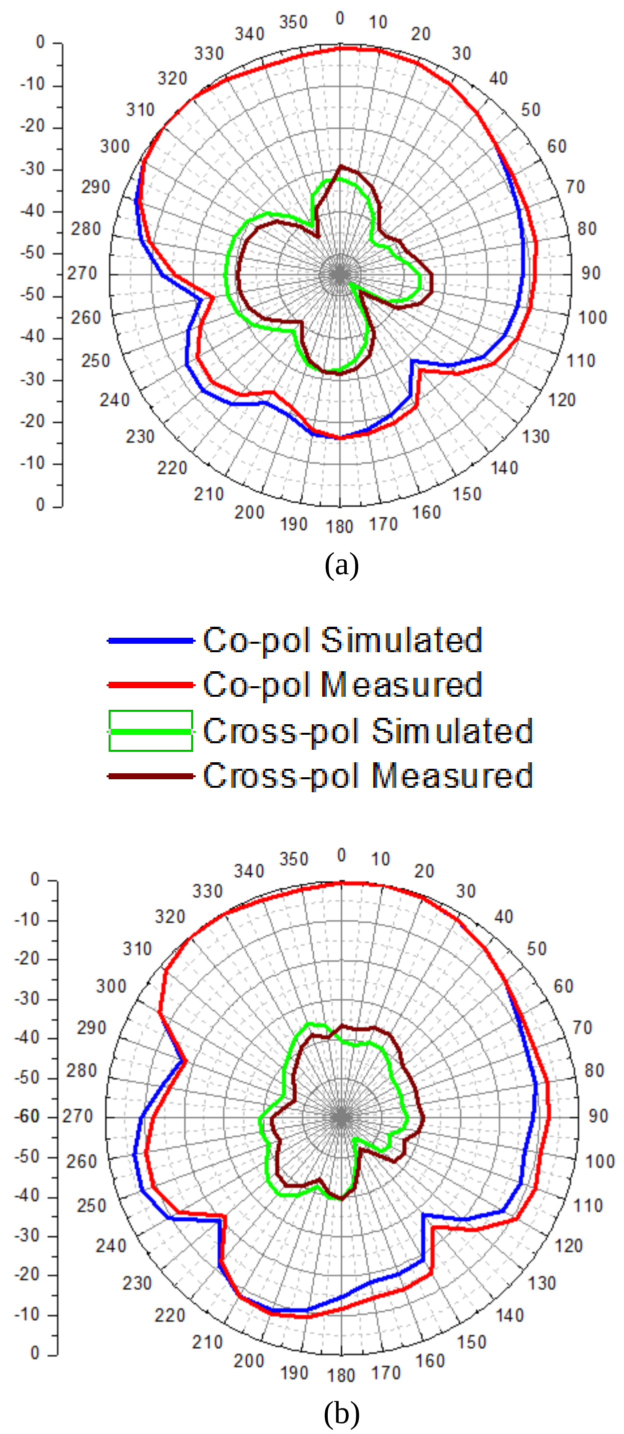

Figure 13. Simulated and measured normalized E plane (Y-Z plane) ($\Phi = 90°$) radiation patterns at (a) 10.2 GHz, (b) 10.8 GHz.

Table 1. Comparison of parameters of the suggested antenna with earlier designs.

Reference	**Frequency Band**	**Bandwidth (MHZ)**	**% of Bandwidth**	**Peak Gain (dBi)**	**Relative Permittivity (ε_r)**	**Feeding Mechanism**
Proposed work	X	1100	10.3	6.25	2.2	Microstrip line
[9]	S	53	2.16	Not Mentioned	4.4	Coaxial cable
[10]	S	82	3.34	5.8	2.2	Coaxial cable
[11]	X	630	6.3	6	2.2	Microstrip line
[12]	Ku	220	1.65	5.2	2.2	Microstrip line
[13]	Ku	800	5.7	6.4	2.2	Microstrip line
[14]	X	430	4.2	5.6	2.2	Microstrip line
[15]	S	150	3.75	4.42	2.5	Microstrip line
[16]	C	310	6	6.97	2.2	Microstrip line

suggested antenna achieves wide bandwidth, high gain, and a unidirectional radiation pattern over the operating bandwidth.

6. CONCLUSION

A detailed analysis on modified bow-tie slot loaded wideband, low profile cavity backed antenna based on SIW is proposed in this paper. A bow-tie slot and a short rectangular slot engraved on the ground plane generate two closely spaced hybrid modes, namely odd TE_{120} and even TE_{120}. As a result, a bandwidth of 1.1 GHz is achieved from 9.9 GHz to 11 GHz (10.5%) with a peak gain of 6.45 dBi. Measured values of bandwidth and gain are 1.1 GHz (from 10.1 GHz to 11.2 GHz) and 6.25 dBi, respectively. Experimental results of the antenna confirm the wideband operation, and a slight shift in resonant frequencies can be attributed to fabrication tolerances. Good impedance matching and low cross polarization levels make the suggested antenna a good candidate for all practical wideband applications. The suggested design also retains the benefits of conventional planar antennas, namely light weight, low profile, cost effective, and flexible planar circuit integration.

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