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Design and Analysis of Dual Dumbbell and Rectangular Slots SIW Cavity-Backed Antenna at 2.45 GHz

Mekaladevi Velusamy[1], Nirmala Devi Manickam[1], Jayakumar Madasamy[1]

Abstract: The design and realization of a wideband substrate-integrated waveguide (SIW) cavity-backed slot antenna operating at 2.45 GHz for WLAN applications are presented. Dual dumbbell-shaped slots with rectangular slots are used to achieve increased bandwidth. The bandwidth observed is 160 MHz with the dumbbell-shaped slots. Further, it has been improved up to 9.2% by adding a rectangular slot. The wideband antenna is analyzed using ANSYS HFSS and fabricated on FR-4 substrate. The measured results of the proposed design are in good agreement with the simulation results and comparable with the reported results.

Keywords: Cavity-backed antenna, Dual dumbbell slot antenna, Substrate-integrated waveguide (SIW), Bandwidth enhancement.

1 Introduction

There has been a growing interest to improve the overall efficiency of antennas used in WLAN applications to optimize power consumption [1]. Moreover, the antenna design requires low profile, conformal, wideband, ease integration with mobile devices [2] is preferred. Conventionally, slot antenna had been the choice of designers, but in a lossy medium, this antenna exhibits low radiation efficiency on account of its bidirectional radiation. To overcome this problem, a cavity-backed slot antenna design was proposed by Vallecchi et al. in [3] that eliminated the backside radiation with the use of a quarter wavelength cavity behind the slot. But bandwidth limitation was observed because of the constraint on the height of the substrate. As a viable alternative, SIW has been proposed, which overcomes the backside radiation and also improves the bandwidth by suitable modification in the size and shape of the slots in the antenna [4]. There have been concerted efforts to improve the bandwidth of SIW based antennae by adopting different techniques.

[1]Department of Electronics and Communication Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, India;
E-mails: v_mekaladevi@cb.amrita.edu; m_nirmala@cb.amrita.edu; m_jayakumar@cb.amrita.edu

Yun et al., [5] had changed the effective permittivity by removing the substrate below the slot and obtained a bandwidth up to 2.16%. A shorted via inserted on top of the I-shaped slot was used in [6] to enhance the bandwidth to 3.7%. Luo et al., [7] used the conventional rectangular slot of length greater than half wavelength to excite hybrid modes to achieve high bandwidth up to 6.3%. A conventional cavity-backed slot antenna was implemented with a varactor diode to obtain frequencies tuned between 1 to 1.9 GHz [8]. A SIW-fed cylindrical dielectric resonator antenna with a plus-shaped slot was used in [9] to increase the bandwidth up to 8.8%. A bowtie-shaped slot with a grounded coplanar waveguide (GCPW) feeding technique had been tried to produce a bandwidth of 9.4% [10]. A modified dumbbell-shaped slot antenna is proposed for dual-frequency applications with fractional bandwidth up to 2.02% and 1.46% respectively [11]. The SIW cavity-backed slot antenna with a circular array achieved a high gain of 10.5dB [16]. A combined dumbbell slot was used in [17] to get a wideband response. A dual-band SIW cavity-backed antenna with bilateral slots achieved wideband as well as the high gain [18, 19].

It can be seen that the size and shape of the slot and the type of feed network influence the bandwidth to a great extent. In this paper, we explore the possibility of combining slots of varying sizes and shape on a lossy substrate to achieve bandwidth improvement. A SIW cavity-backed antenna with a dual dumbbell and small rectangular slots has been designed to achieve an impedance bandwidth of 9.2%.

This paper is organized as follows; Section 2 presents the design and analysis Section 3 presents the bandwidth enhancement, Section 4 shows the parametric analysis and Section 5 explains the results and discussion and the paper concludes in Section 6.

2 Design and Analysis

The structure of the designed SIW cavity-backed antenna is shown in Fig. 1. The dumbbell-shaped slots and a rectangular slot are etched on the top layer of the cavity and at a distance of 5.5 mm from the back end of the cavity. The SIW cavity is built on a single substrate surrounded by three rows of metallic vias that form three sidewalls of the cavity. The orientation of the field is in a zigzag direction inside the SIW, and the surface waves contribute to radiations that travel in the vertical direction and not in the direction of propagation.

The diameter and pitch of the cylindrical via holes are chosen in such a way to ensure minimum radiation leakage losses [4]. Because of the discontinuity in via holes, the sidewall current cannot flow longitudinally across the regular interval that stops the TM mode of propagation. [12]. Fig. 2 shows the top view of the proposed antenna and the dimensions of the same are illustrated in **Table 1**.

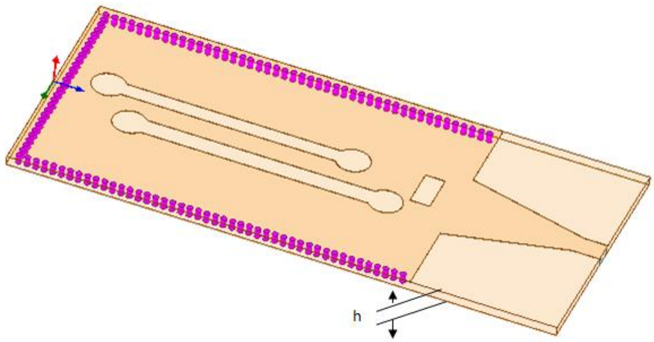

Fig. 1 – *Three-dimensional view of the proposed antenna.*

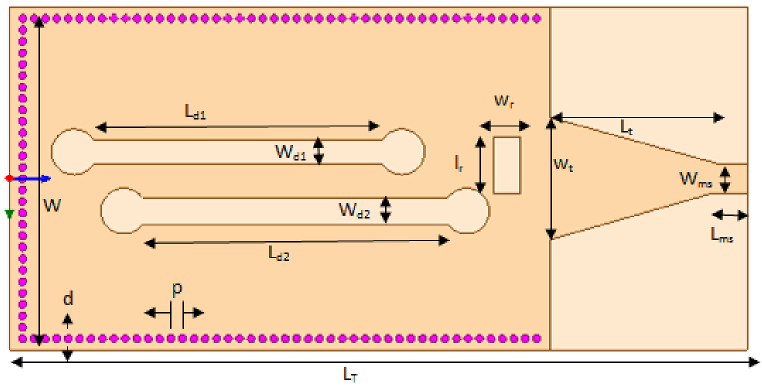

Fig. 2 – *Proposed antenna: Top view.*

Table 1
Dimensions of the proposed antenna.

Parameters	Values in mm	Parameters	Values in mm
W	45	p	1.5
h	1.6	L	71
d	1	L_T	96.87
W_{d1}	3	w_t	16
W_{d2}	3.5	L_t	21.8
L_{d1}	40	W_{ms}	4
L_{d2}	45	L_{mS}	4.07
wr	3.5	lr	7.5

The length (L_T) of the SIW cavity-backed antenna is kept as half of the free-space wavelength. The effective width (W) of the SIW, the via hole diameter (d), and the spacing between the vias (p) are calculated as in equations (1) – (3) where λ_g is the guided wavelength [13].

$$W_{eff} = W - \frac{0.95d^2}{p}, \tag{1}$$

$$d \leq \frac{\lambda_g}{5}\ d \leq \frac{\lambda_g}{5}, \tag{2}$$

$$p \leq 2d\ . \tag{3}$$

The antenna is fed with a tapered microstrip line to match the 50 Ω impedance of the load that keeps the electric field profiles of the SIW cavity-backed slot antenna the same as that of a microstrip line. The width and length of the tapered feed are chosen as per [14].

3 Bandwidth Enhancement

To improve the bandwidth of operation, the designed antenna is augmented with three differently shaped slots. Two dumbbell-shaped slots of unequal length (40 mm and 45 mm) and one rectangular slot (length 7.5 mm *and* width 3.5 mm) are etched on top of the metallic layer. The dumbbell slots are at a distance of 2 mm and 2.5 mm from the center of the cavity, respectively. The lengths of these are maximized under the constraint that they fit within the antenna length. The position of the rectangular slot is determined by analyzing the mode of the cavity resonator. The radius of dumbbell slots is kept as λg/20 to maintain the resonance frequency.

Fig. 3 shows the different configurations of the antenna design and the corresponding performance analysis, respectively. The position and size of the slots decide the amount of current flow and the frequency at which it resonates. The current distribution is greatly affected by the shape of the slots. The SIW cavity-backed antenna without slots is excited with a single mode over the frequency band, and it has peak input impedance (z_{11}) at 2.5 GHz. Then, by introducing a single dumbbell-shaped slot below the center axis of the antenna, it brings down the input impedance and generates a next higher mode near the dominant mode. But there is little increase in bandwidth because of a mismatch in the input impedance that prevents maximum radiation of the energy. A dumbbell-shaped slot is positioned above the center axis of the antenna leads to high input impedance same as that of the impedance obtained without slots hence there is no change in bandwidth. The placement of dumbbell-shaped slots on both sides of the center axis of the antenna reduces the input impedance and merging the dominant mode and the next higher mode to get a wideband response. These slots radiate the energy by keeping the high and low magnitude of electric field intensity on either side of the slots. Further, the improvement of bandwidth is obtained by keeping a rectangular slot near the tapered feed by forcing the current additionally to flow on the sidewalls of the slot.

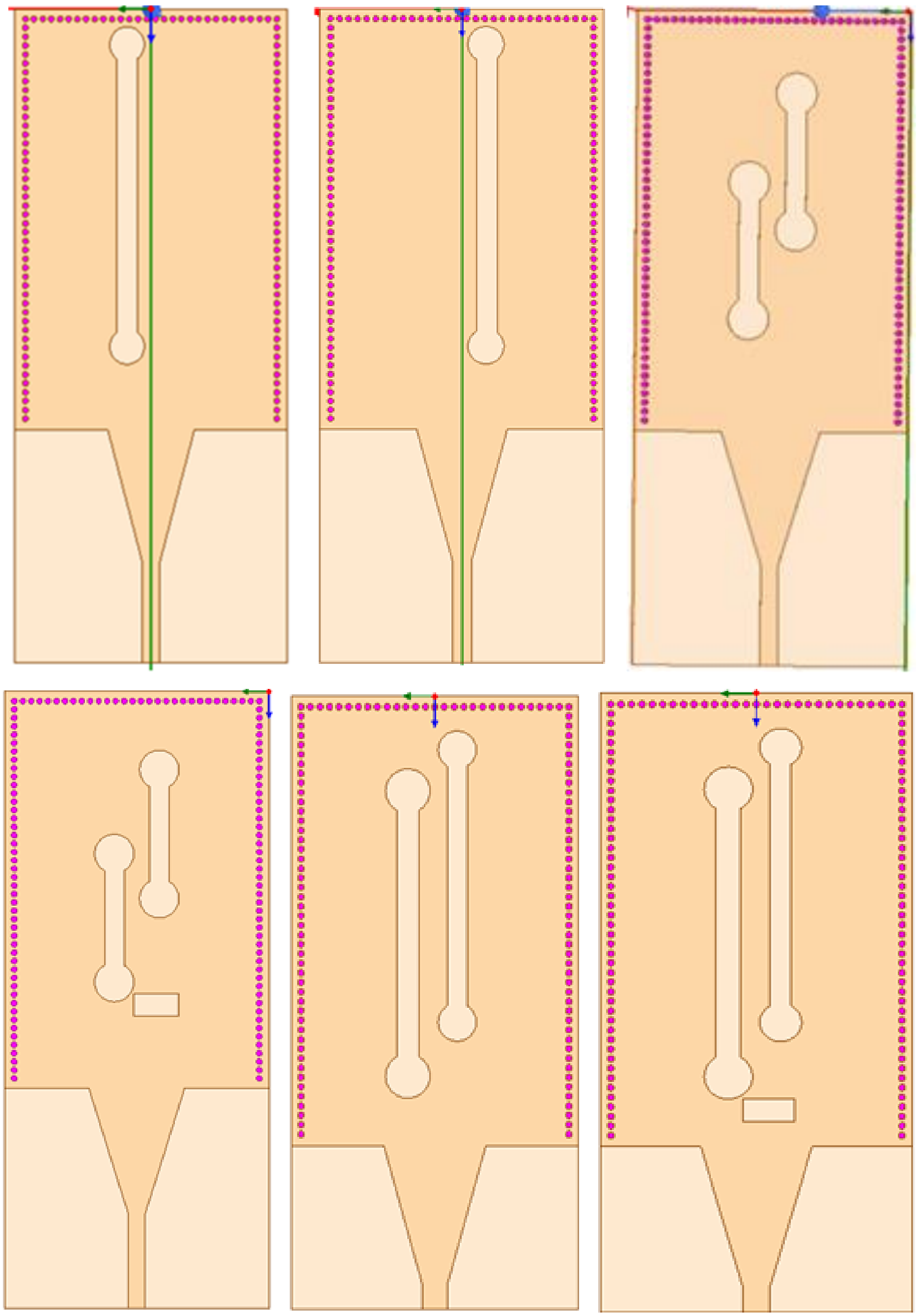

Fig. 3 – *Configurations (C1~C6) of the SIW antenna.*

Table 2 shows the performance analysis of various configurations of the antenna. Thus, the broadband response is achieved by merging two modes in a closely spaced region without affecting the dominant mode frequency. Hybrid modes are a combination of two or more modes in which one mode is stronger and the other mode is weaker. There is a shift in dominant mode frequency and the generation of the next higher-order mode in the proximity region because of placing slots. Hence the dominant mode and higher-order mode are merged which leads to the generation of hybrid modes and bandwidth enhancement. Fig. 4 shows the electric field distribution plot to explain how the dumbbell slots are radiating energy.

Table 2
Performance analysis of various configurations of the antenna.

Configurations	Return loss [dB]	Bandwidth		Gain [dB]
		(%)	MHz	
C1	–30.02	3.26(2.49-2.41/2.4511)	80	1.3544
C2	–24.7390	2.85(2.48-2.41/2.4489)	70	1.3860
C3	–20.9753	2.858(2.49-2.42/2.4489)	70	2.1957
C4	–17.96	2.77(2.56-2.49/2.52)	70	–1.30
C5	–19.29	6.37(2.59-2.43/2.51)	160	2.28
C6	–17.38	9.09(2.62-2.39/2.53)	230	2.61

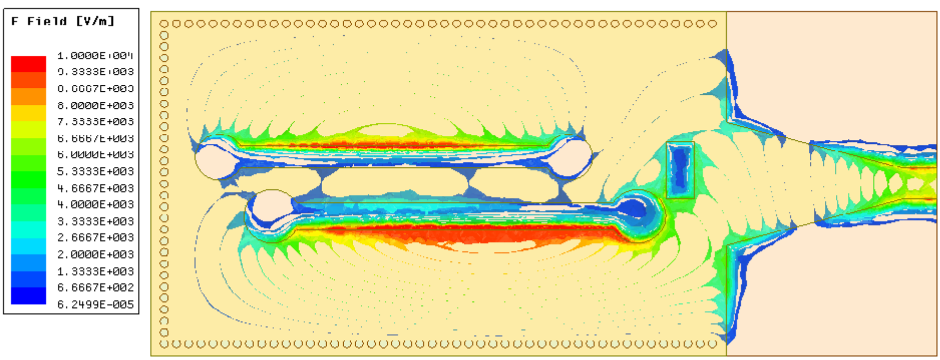

Fig. 4 – *Electric field distribution.*

4 Parametric Analysis

The effect of the antenna parameters on bandwidth is analyzed using an optimization tool in Ansys HFSS. It is necessary to analyze because the slot position and dimension determine the lower and upper resonance frequency boundary. The key parameters that affect the input impedance and bandwidth of the dual dumbbell slot and a rectangular slot antenna are widths (W_{d1} and W_{d2}) and the lengths of the dumbbell slots (L_{d1} and L_{d2}). The variation in input impedance and the bandwidth is due to the effect of W_{d1} and W_{d2} are shown in Figs. 5 and 6. The width of the slots is kept very much less than the wavelength of the resonating antenna. The position and width of the slots decide only the impedance matching conditions of the antenna. As the width of slots increases, the input impedance is greatly affected. The proper impedance matching is obtained at the optimum values of the widths of the slots.

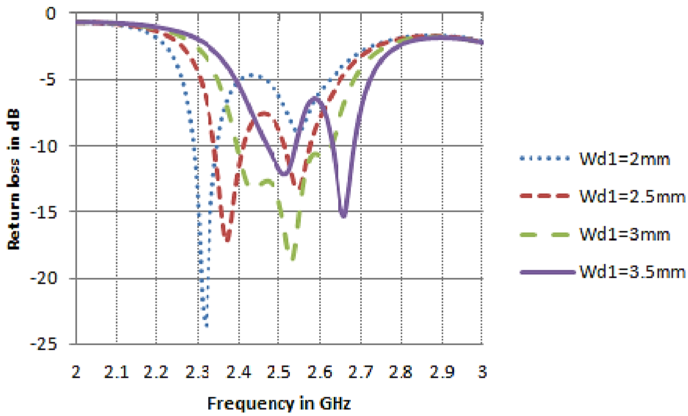

Fig. 5 – *Return loss variation when width W_{d1} is changed.*

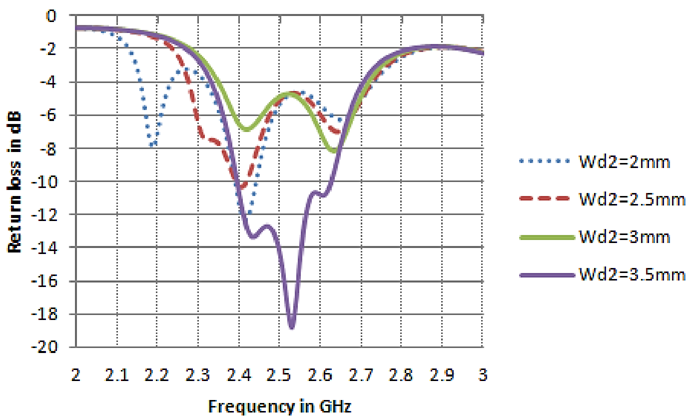

Fig. 6 – *Return loss variation when width W_{d2} is changed.*

The lengths of the slots are kept higher than a half wavelength of the resonance frequency to radiate the maximum energy. The major shift in resonance frequency and improvement in bandwidth is due to the variation in lengths of the dumbbell-shaped slots. The broadband responses for varying lengths of the dumbbell slots (L_{d1} and L_{d2}) are shown in Figs. 7 and 8, respectively.

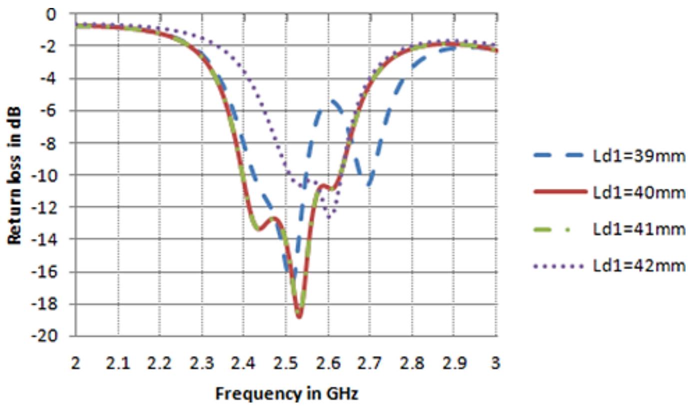

Fig. 7 – *Return loss variation when width L_{d1} is changed.*

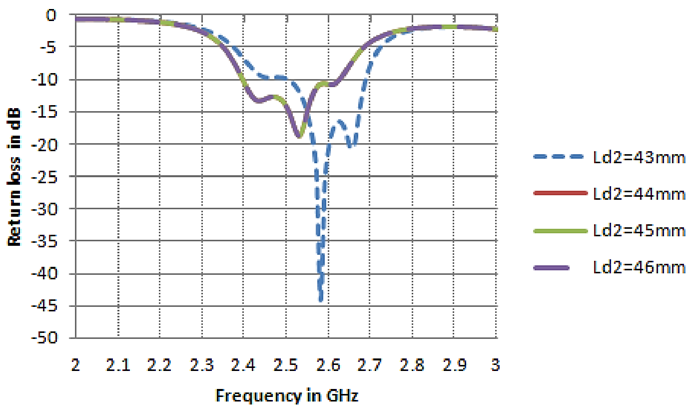

Fig. 8 – *Return loss variation when width L_{d2} is changed.*

The antenna designed with a single dumbbell slot produced a bandwidth of 80 MHz. With the addition of a second slot, producing a bandwidth of 160 MHz ranging from 2.43 GHz and 2.59 GHz was observed. Further, the bandwidth is enhanced up to 230 MHz ranging from 2.39 GHz and 2.62 GHz is shown in Fig. 9. This was achieved with the following dimensions of the slot W_{d1} = 3 mm, W_{d2} = 3.5mm, L_{d1} = 40mm and L_{d2} = 45mm.

As the width of the rectangular slot decreases from its optimum value, it is observed that only the bandwidth changes and the input impedance remain constant. The change in bandwidth is only 10 MHz as the width changes with the step size of 0.5 mm. The width and length of the rectangular slot decide the shift in lower and higher resonance frequencies and not affecting the impedance shown in Figs. 10 and 11.

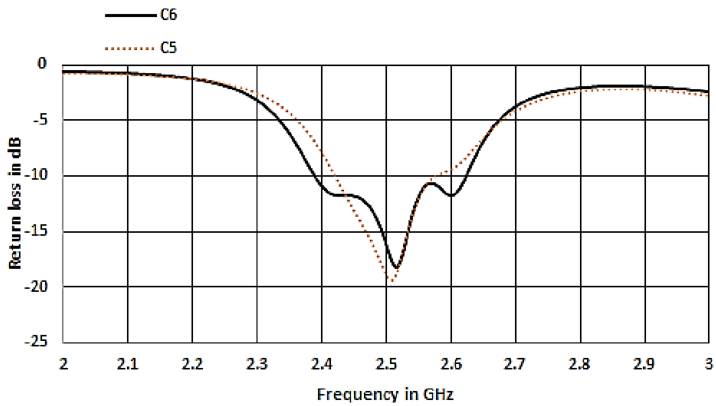

Fig. 9 – *Return loss variation for configurations C5 and C6.*

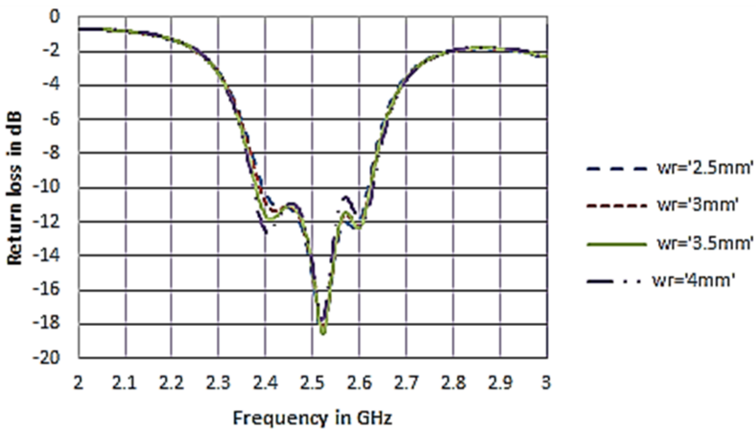

Fig. 10 – *Return loss variation when width w_r is changed.*

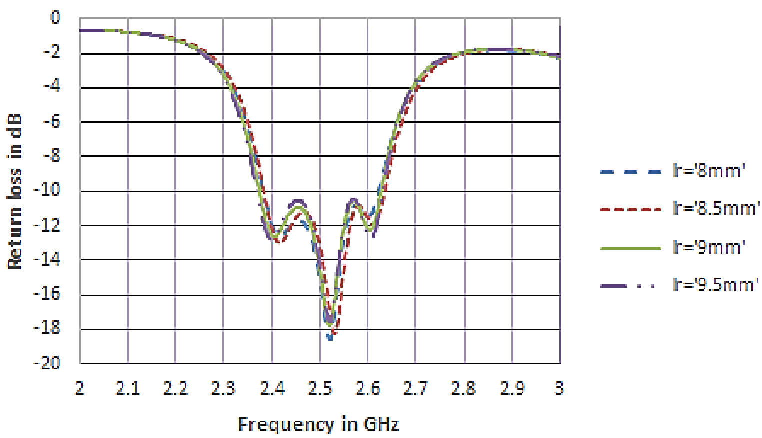

Fig. 11 – *Return loss variation when width l_r is changed.*

5 Results and Discussion

The designed antenna is fabricated on a single layer FR-4 substrate with a loss tangent of 0.02 and thickness of 1.6 mm using standard PCB fabrication technology. This antenna is fed with an SMA connector and its performance is measured using Agilent Vector Network Analyzer 9923A. The top view of the fabricated antenna and the comparative analysis between the return loss of the simulated and measured values are shown in Figs. 12 and 13.

Fig. 12 – *Photograph of the fabricated antenna.*

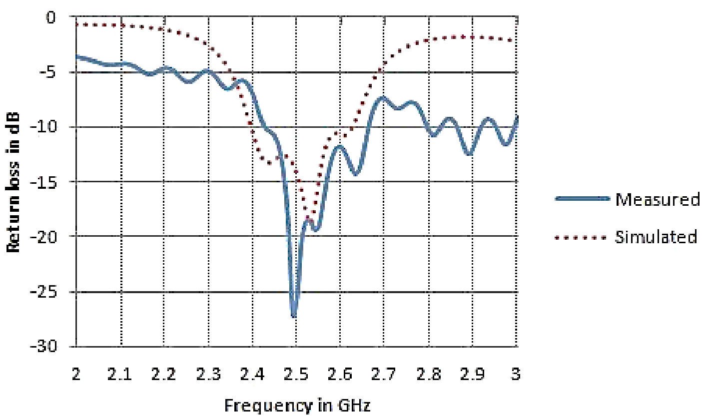

Fig. 13 – *Comparison between the simulated and measured return loss of the proposed antenna.*

The lower resonance frequencies are observed at 2.42 GHz and 2.39 GHz, while the higher resonance frequencies occur at 2.65 GHz and 2.62 GHz for the fabricated and the simulated antenna, respectively. Even though there is a slight shift in the location of the resonance frequencies, the bandwidth of the fabricated antenna matches exactly with the simulated design. The gain and cross-polarization analysis is also performed on the simulated antenna and the results are shown in Figs. 14 and 15 respectively. The simulated antenna gain is resulted as high at the resonance frequency, and it is a little lower for other frequencies over the band. The cross-polarization in E-plane is higher due to the dumbbell-shaped slots and rectangular slot as it disturbs the current distribution.

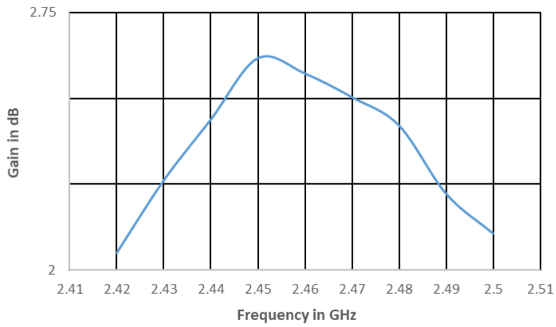

Fig. 14 – *Gain Plot.*

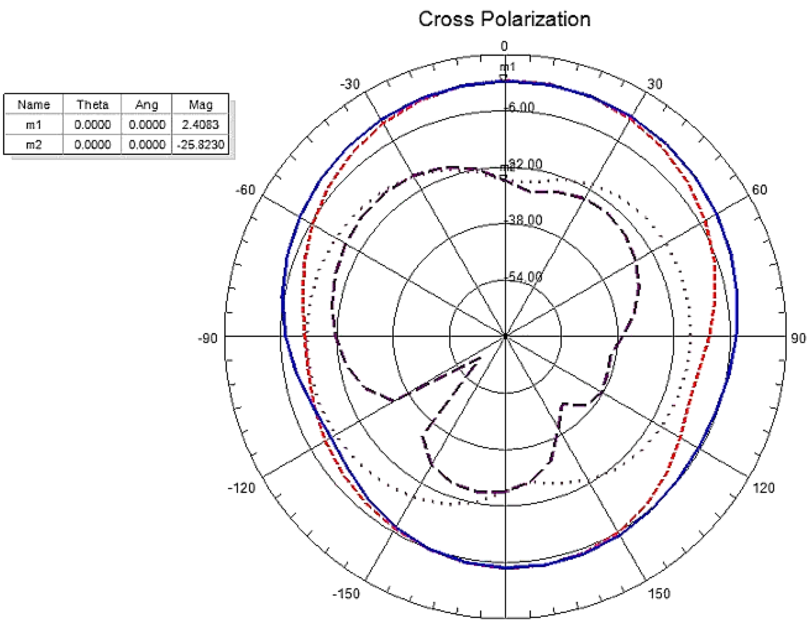

Fig. 15 – *Radiation pattern with cross-polarization.*

Even though a lossy dielectric is used, a moderate and unidirectional gain of 2.61 dB and a cross-polarization level of –25.8 dB at 2.45 GHz is observed. The maximum gain of the antenna is found at the resonance frequency. A comparative analysis of the designed antenna is done with the existing ones provided in the literature and **Table 3** shows the same. It can be seen that even with the use of the lossy substrate, a wide bandwidth antenna is realized.

Table 3
Comparison among the already existing antenna design and the proposed antenna design.

Ref	Frequency [GHz]	Substrate height [mm]	Bandwidth [%]	Permittivity [ε_r]	Feed type
[10]	8-12	0.787	9.43	2.2	GCPW
[6]	2.45	1.57	3.71	2.2	Co-axial feed
[15]	12-18	1.57	13.53	2.2	Tapered MSL
[Proposed]	2.45	1.6	9.2	4.4	Tapered MSL

6 Conclusion

A bandwidth enhanced substrate integrated waveguide cavity-backed antenna with triple slots is realized on a lossy substrate for wideband application. The proposed antenna is replaced with longitudinal slots of dual dumb-bell and a rectangular shape and fed by a tapered micro strip line. The resonances created by the radiated slots lead to a broadband response of 9.2%. The conventional method of placing the transverse slot is changed to longitudinal slots. The proposed antenna is maintained to have the advantage of a planar antenna. The simulated and fabricated antenna shows a similar bandwidth of 230 MHz, with only a slight deviation in the lower and higher resonance frequencies. This work can be further extended to high-frequency applications by tuning the key parameters to get desired bandwidth.

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