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Performance Analysis of Dielectric Resonator Antenna on Substrate Integrated Waveguide Cavity with Dumbbell Slot for Wideband Applications

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ABSTRACT

The Dielectric Resonator Antenna (DRA) is one of the efficient radiator which is used to achieve broadband and cost effective communication in wireless technology. The Substrate Integrated Waveguide (SIW) technology is the most assuring structure for implementation of circuits and components for millimeter wave and microwave applications. A design approach to improve the impedance bandwidth of cavity backed dumbbell slot antenna using Substrate Integrated Waveguide for X band (8-12 GHz) application is presented in this paper. The proposed design improves impedance bandwidth by the use of Cylindrical Dielectric Resonator Antenna and metal strip along with offset feeding technique. The performance characteristics of the proposed antenna design is evaluated and studied.

Index Terms: Substrate Integrated Waveguide(SIW), Dumbbell Slot , Dielectric Resonator Antenna(DRA)

1. INTRODUCTION

In recent times, the Dielectric Resonator Antenna have got great attention in microwave and millimeter wave communication systems due to their exciting characteristics which includes low profile, light weight, low loss, wide bandwidth etc. The DRA can be fed with several feeding methods such as aperture coupling, microstrip lines probes, coplanar lines, slots and dielectric image waveguide feeding. They are available in few geometries which includes rectangular, cylindrical, spherical, half split cylindrical disk, hemispherical shaped etc.[1]. It provide omnidirectional and broadside radiation pattern regardless of its shape [2]-[3]. The DRA become widespread in core sectors such as military, radar, satellite and millimeter wave applications.

An immense amount of investigation has been done in the past in order to develop high performance millimeter and microwave systems that can be fabricated using low cost technologies. The transmission lines, microstrip, coplanar strips, coplanar waveguides etc. were used earlier for the design purpose of these systems but they have certain limitations such as high losses and low power handling capacity etc. The integration of conventional waveguide with the planar circuits was difficult because of their non planar nature. The metallic waveguides, which have better waveguiding options, but are non-planar and bulky in nature. The concept of SIW arises from the above stated limitations. The planar slot antennas suffer from bidirectional radiation characteristics and narrow bandwidth. It can be eliminated by the usage of metallic void which enhances the gain but with increased weight because of its non planar characteristics. The SIW is included under Substrate Integrated Circuits (SICs), which appeared as an attractive substitute that integrates planar and non planar waveguide structures using rows of metallic vias which is employed in the sidewall of the waveguide The advantages of SIW include easy integration, with planar circuits, easy

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fabrication and less cost [4]. The SIW fed Dielectric Resonator Antenna is an attractive candidate for low loss millimeter wave systems due to high quality factor of SIW and low loss of DRA in millimeter wave frequency[5]. The SIW based Cavity backed slot antenna was studied in literatures [6]-[7].

The cavity backed slot antenna using Substrate Integrated Waveguide with dielectric resonator loading for X band application was proposed [8] and an impedance bandwidth of about 11.74% was achieved. The antenna with dielectric resonator loading has demonstrated as a convinient approach to enhance the bandwidth[9]-[10]. In [11], a dual frequency SIW cavity backed slot antenna was proposed. The rectangular slot was substituted by dumbbell slot which builds extra hybrid current circulation in the cavity.

In this paper, Cylindrical Dielectric Resonator fed cavity backed dumbbell slot antenna using SIW for bandwidth improvement is presented. The bandwidth of the dumbbell shaped slot antenna is again improved by keeping a metal strip above cylindrical DRA. The proposed structure improves the impedance bandwidth when compared to [8]. The paper is organized as follows. The proposed antenna design is discussed in Section 2. Section 3 discusses about the Substrate Integrated Waveguide. Section 4 discusses Dielectric Resonator Antenna. The Simulation results and discussion are presented in Section 5. Section 6 concludes the paper.

2. ANTENNA DESIGN

The Substrate Integrated Waveguide based cavity backed dumbbell slot antenna with and without Cylindrical DRA is shown in Figure 1(a) and 1(b). A metal strip is fixed on the top of Cylindrical DRA for bandwidth improvement and it is depicted in Figure 1(b). The metal strip is used in literature for size reduction [12]. The proposed dumbbell slot antenna is designed using Roger’s RT/Duroid 5880 substrate with height 0.7874mm using ANSYS HFSS electromagnetic simulation software. The Cylindrical Dielectric Resonator has permittivity of 2.2. The radius and height of Cylindrical Dielectric Resonator is calculated from Eq.6.

The inset feed technique is used in the bottom metal of Substrate Integrated Waveguide cavity inorder to fed antenna. The dimension of the vias, slot, cavity and length of the feed are the fundamental elements to find the resonant frequency of the antenna[13].

An offset feeding technique which was proposed in [6] is used to improve the impedance bandwidth. The dumbbell slot is engraved on the top metal layer of SIW cavity. The dumbbell shaped slot consists of two circle apertures of diameter d connected by short gaps of length L_{slot} and width W_{slot}. It builds an extra hybrid current circulation inside the cavity along with normal mode[11]. This is another way to enhance the slotted waveguide antenna bandwidth, but these slots have limitation such that it is hard to manufacture.

3. SUBSTRATE INTEGRATED WAVEGUIDE

The Substrate Integrated Waveguide concept was first introduced in [14] and has important feature to incorporate all components on same substrate such as active (oscillators, amplifiers etc.) and passive components (filters, couplers etc.) SIWs are dielectric filled rectangular waveguide structure constructed by two rows of metallic slots embedded in dielectric substrate. The SIW does not support the Transverse Magnetic (TM) modes due to the gaps between slots [15]. The key parameters in SIW design are diameter of vias D, pitch P, integrated waveguide width A_r and equivalent SIW width A_e. The design rules related to diameter of vias and pitch in [16]-[17] are given in Eq.1 and Eq.2. These two parameters controls the radiation loss and return loss.

$$D < \lambda_g / 5 \tag{1}$$

$$P \le 2D \tag{2}$$

Where λ_g denotes the guided wavelength. The equivalent SIW width is given in Eq. 3 where ε_r denotes permittivity of substrate and a denotes the broadside dimension of SIW.

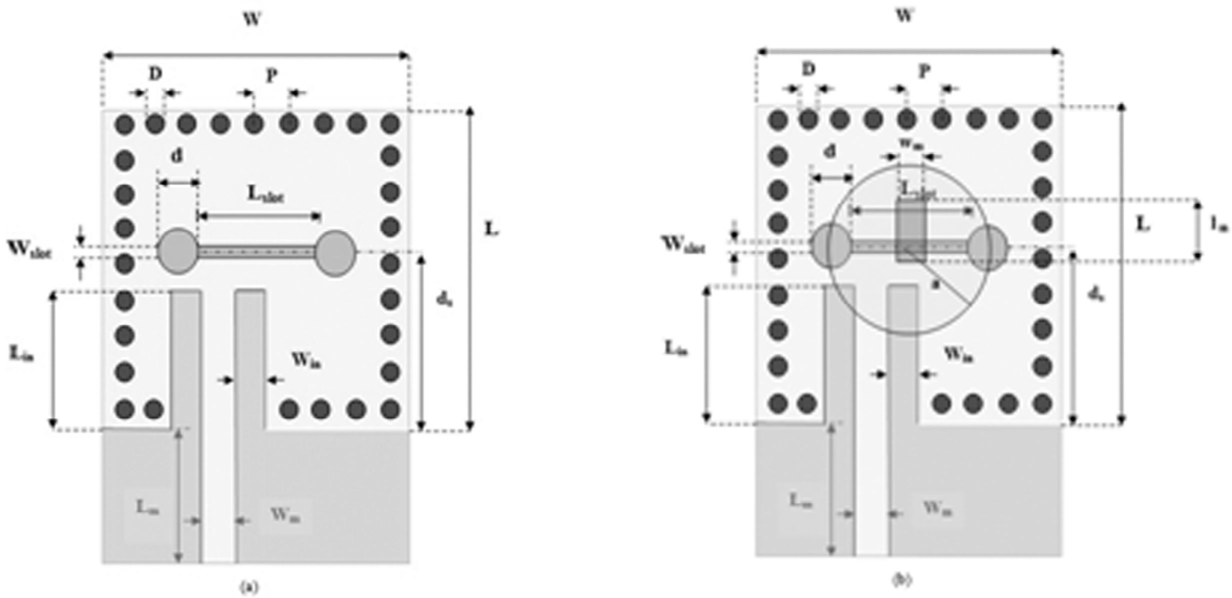


Figure 1: (a)Dumbbell slot antenna without cylindrical DRA (b) Proposed antenna design

$$A_e = \frac{a}{\sqrt{\varepsilon_r}} \tag{3}$$

The integrated waveguide width is given in Eq. 4

$$A_r = A_e + \frac{D^2}{0.95P} \tag{4}$$

The cut off frequency of Substrate Integrated Waveguide is given in Eq. 5.

$$f_c = \frac{c}{2\sqrt{\varepsilon_r}}\left(A_r - \frac{D^2}{0.95P}\right)^{-1} \tag{5}$$

4. DIELECTRIC RESONATOR ANTENNA

Dielectric resonator antenna consist of a metal on the one side and dielectric resonators on other side of the substrate [1],[5]. The DRAs are very flexible in offering different geometries such as rectangular, cylindrical, hemispherical, spherical, disc etc. The DRA is an excellent radiator with low loss, small size, low cost and wide bandwidth and can be used in many applications such as military, satellite communication, direct digital broadcast etc.

4.1. Cylindrical Dielectric Resonator Antenna

The Dielectric Resonator Antenna is analyzed in terms of its resonant modes, far-field radiation into the space, near-field distribution inside the resonator, impedance bandwidth and resonant frequency. The Cylindrical Dielectric Resonator offers mainly three fundamental modes such as HEM11δ, TM01δ and TE01δ. A cylindrically shaped resonator, operating in hybrid electromagnetic mode HEM11δ placed above a ground plane, is likely the most commonly used DRA configuration. There are different formulas in literature which calculates resonant frequency and quality factor [1], [18], [19]. In the proposed design, the Cylindrical DRA with HEM11δ mode is used. The resonant frequency with HEM11δ mode can be calculated from Eq. 6. where k_0 represents free space wave number, c denotes velocity of light in free space and $x=a/h_{dra}$.

$$k_0 a = \frac{6.324}{\sqrt{\varepsilon_r + 2}} \left\{ 0.27 + 0.36\frac{x}{2} - 0.02\left(\frac{x}{2}\right)^2 \right\} \quad (6)$$

where $k_0 = {2\pi f_0}/{c}$

5. RESULTS AND DISCUSSION

The simulation of the proposed design is performed using electromagnetic simulation software ANSYS HFSS. The proposed antenna structure is designed for X band applications and the design parameters are shown in Table 1. The performance of the antenna depends up on different parameters and these should be optimized to get good results. The length L_{slot} and width of the slot W_{slot} is changed slightly and the variations of the slot resonance with respect to dimension of slot is shown in Figure 2 and Figure 3.

In the proposed design, an offset feeding method is used to improve bandwidth which is better compared to center feed, is shown in Figure 4. The dumbbell slot which builds extra hybrid current circulation in the cavity is used in the proposed antenna design. A cylindrical DRA is placed above dumbbell slot for improving impedance bandwidth. The inset feed position and the length of the slot are optimized after loading of Dielectric Resonator inorder to get wide band performance. Figure 5 depicts the reflection coefficient variations with change in height of cylindrical DRA h_{dra}. The impedance bandwidth of the proposed dumbbell slot antenna is again improved by keeping a metal strip above cylindrical DRA. The length of metal strip l_m is varied and the results are shown in Figure 6. In Table 2, comparison of the proposed antenna design with some other designs in literature are provided. The simulated result demonstrated that the proposed antenna design enhances the impedance bandwidth to 15.05%.

The simulated results of dumbbell slot antenna with and without Cylindrical DRA are compared with proposed design and are shown in Figure 7. The simulation result shows that the dumbbell slot antenna resonates at 10.16 GHz and 10.8 GHz frequencies. The simulated return loss is less than -25dB over wide

Table 1
Design Parameters

Parameters	Dimension
Length of waveguide (L)	16 mm
Width of waveguide (W)	17.72 mm
Length of Slot (L_{slot})	4 mm
Width of Slot (W_{slot})	1 mm
Diameter of Dumbbell (d)	4 mm
Height of DRA (h_{dra})	6.7 mm
Radius of DRA (a)	6.7 mm
Diameter of Via (D)	1 mm
Pitch of Via (P)	1.6 mm
Length of metal strip (l_m)	6 mm
Width of metal strip (w_m)	2 mm
Distance from slot to cavity (d_s)	8.6 mm
Width of microstrip line (W_m)	2.42 mm
Notch width (W_{in})	1.22 mm
Inset feed length (L_{in})	7 mm

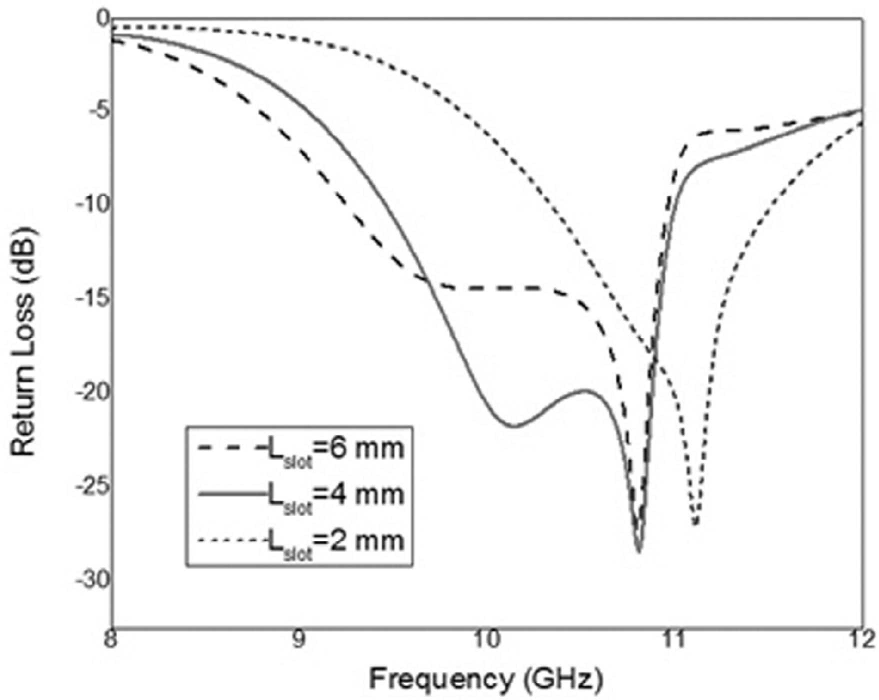


Figure 2: Reflection Coefficient variation with different slot length

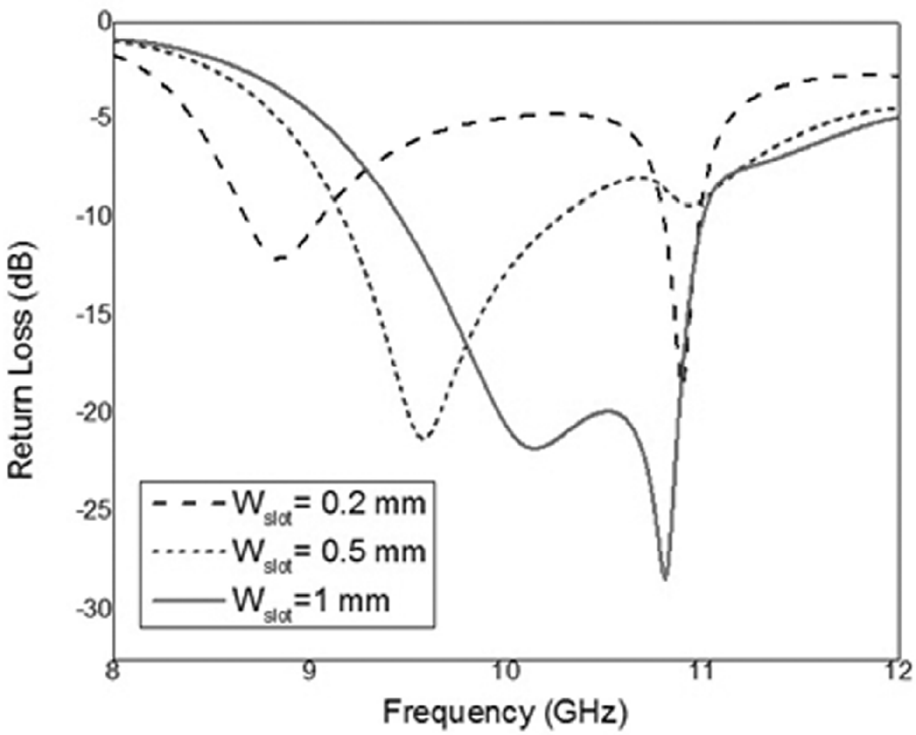


Figure 3: Reflection Coefficient variation with different slot width

bandwidth. The width W and length L of the cavity should be properly chosen inorder to maintain the resonant frequency in the design band. The dimension of the dumbbell slot should also properly designed because it interrupts the current flow and correspondingly frequency shift occurs.

The simulated gain of the proposed antenna at 10.16GHz and 10.8GHz are 6.72 dB and 5.6dB respectively and is shown in Figure 8. The radiation characteristics are taken for cross polarized and copolarized response in case of linearly polarized antenna and are shown in Figure 9. The plot depicts that radiation pattern is

Table 2
Comparative Study

Properties	Proposed Antenna	[8]	[7]	[6]
Thickness	0.7874 mm	0.787 mm	0.787mm	0.5 mm
Permittivity	2.2	2.2	2.2	2.2
Gain	5.6 dB	5.6 dB	5.3 dB	5.4 dB
Bandwidth(%)	15.05 %	11.74 %	4.2 %	1.7 %
Feeding Technique	Offset feeding	Offset feeding	Offset feeding	Grounded Coplanar Waveguide

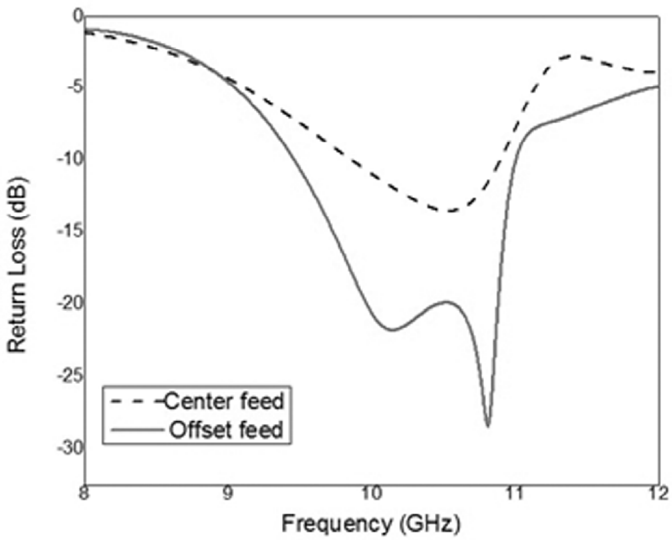


Figure 4: Reflection Coefficient variation with different feed positions

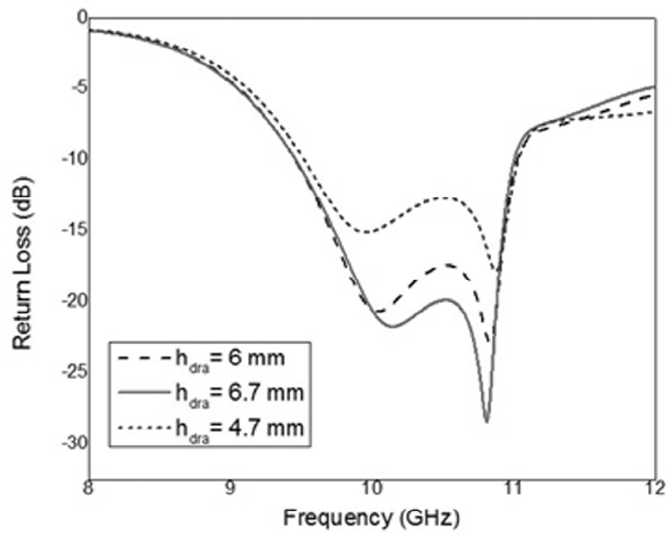


Figure 5: Reflection Coefficient variation with change in DRA height

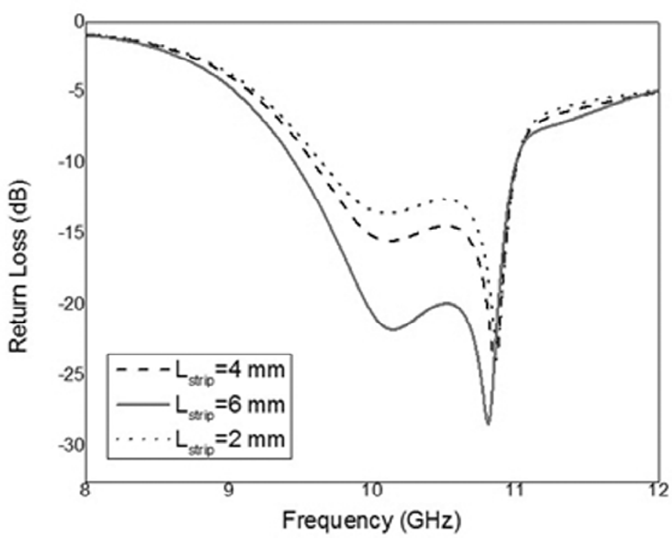


Figure 6: Reflection Coefficient variation with change in metal strip length

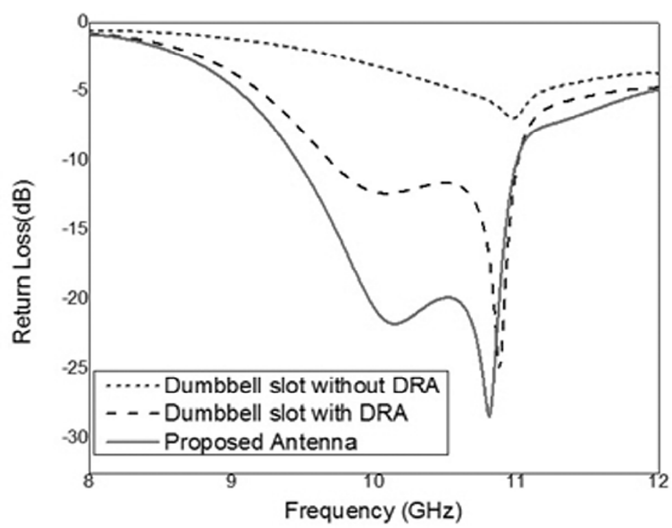
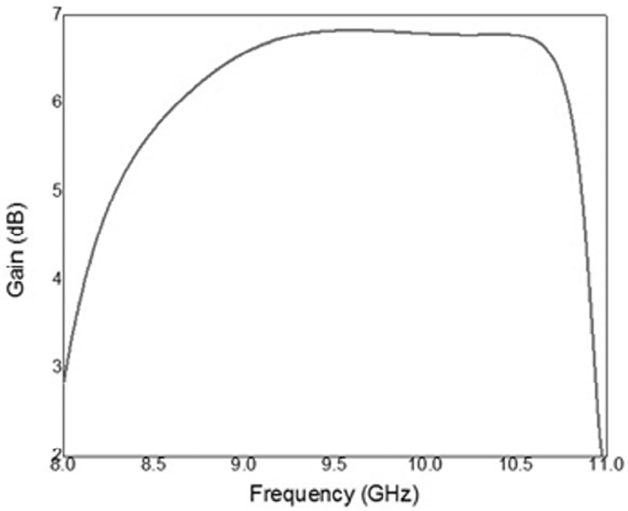
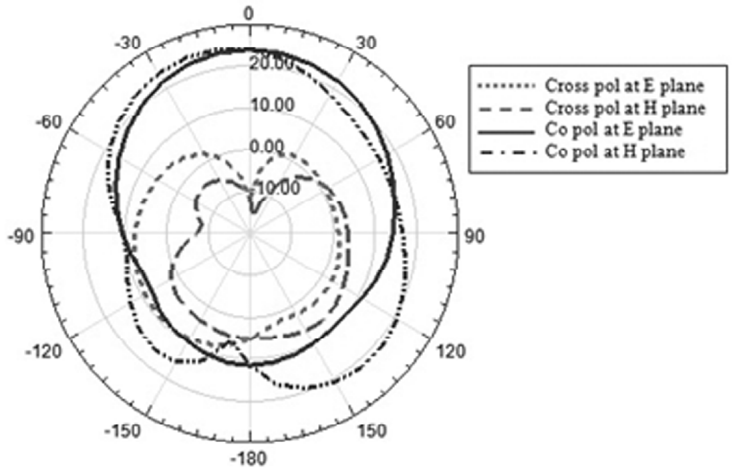


Figure 7: Reflection Coefficient variation with different structures

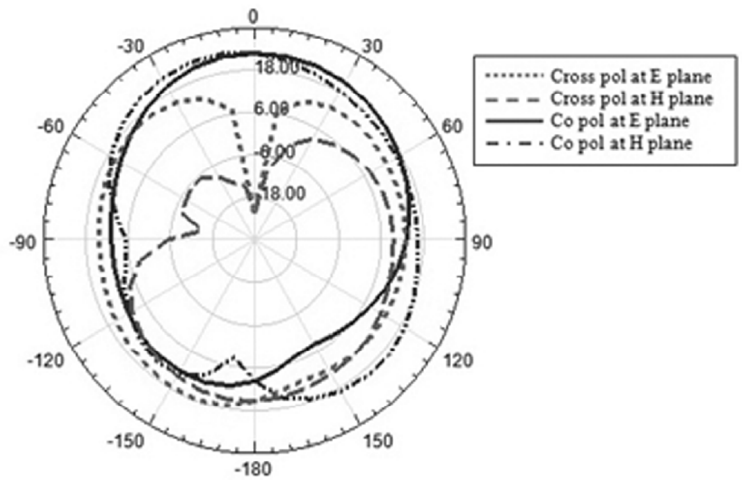
constant over the entire impedance bandwidth. The impedance matching is also properly achieved for the proposed antenna design.





(a)

Figure 8: Simulated gain of proposed antenna



(b)

Figure 9: Simulated radiation pattern of antenna at (a)10.16 GHz; (b) 10.8 GHz

6. CONCLUSION

A design approach to enhance the impedance bandwidth of cavity backed dumbbell slot antenna for X band application have been discussed in the paper. The proposed design improves impedance bandwidth to 15.05% by the use of Cylindrical DRA and metal strip along with offset feeding technique. The return loss below -25 dB and gain of 6.72 dB and 5.6 dB at 10.16GHz, 10.8GHz was obtained with good radiation characteristics over entire impedance bandwidth.

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