A Low Profile, Broadband Linearly and Circularly Polarized Cavity Backed Antenna Using Halved-Dual Mode SIW Cavity

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Abstract **─** In this paper, a low profile single fed cavity backed slot antenna producing both linear and circular polarizations at two different frequency is presented using a halved dual mode cavity. The proposed antenna has a planar structure using a single layer of printed circuit board (PCB) which allows for integrating the antenna to other planar circuits and provides straight forward connection to SMA connector. One prototype of the antenna is designed and fabricated and very good agreement between measurement and simulation results are obtained. Results show that the proposed antenna is able to present suitable radiation characteristics as both linearly polarized (LP) antenna and circularly polarized (CP) antenna.

Index Terms **─** Cavity backed antenna, half mode substrate integrated waveguide (HMSIW), linear and circular polarization.

I. INTRODUCTION

Nowadays, design of low profile planar antennas for use in compact wireless communications systems, is in large demand. Varieties of solutions have been presented for this purpose in literature. Microstrip patch antennas are a good candidate in these applications. They have usually simple structures which makes their fabrication process easy and low cost. However, they have some drawbacks including low impedance bandwidth and low radiation efficiency at high frequencies.

Cavity backed antennas provide high performance properties including high radiation efficiency and suppress surface waves effectively. The primary designs for this class of antennas using rectangular metallic waveguide are bulky, heavy and expensive [1-3]. Moreover, their integration with planar circuits is not easy.

Recently, substrate integrated waveguide (SIW) technology has been presented as a good and useful solution for planar implementation of different microwave components [4]. In [5-14], different SIW cavity backed antennas were presented. In [5], a linear polarized (LP) antenna is designed using a resonating slot on the broad wall of SIW cavity. In [6], by using a meandered slot, a LP cavity backed antenna with enhanced bandwidth is proposed. In [7], a circular polarized (CP) antenna is presented applying an annular slot and a shorting pin in a circular cavity. In [8], using a crossed slot, three antennas with different polarizations (LP, right handed CP and Left handed CP) are designed and investigated. The one with LP is designed and made in such a way that both vertical and horizontal polarizations depending on the frequency of operation are obtained. In [9], an inter-digital slot is used to develop a LP composite left/right handed (CRLH) SIW cavity backed antenna. In [10], a LP antenna with enhanced bandwidth (BW) up to 6.3% is presented by applying a long non-resonating slot on the surface of a rectangular cavity.

Despite all advantages of SIW technology, the size of these structures might be large in some applications, and therefore new methods for size reduction are needed. Half mode substrate integrated waveguide (HMSIW) is one effective solution for this purpose [11]. By this technique, size of the SIW structures is lowered up to 50% without affecting its performance. By using HMSIW technique to a non-radiating cavity in [12], a LP cavity backed antenna is designed and implemented. In [13], by applying HMSIW technique to a LP cavity backed slot antenna, a CP cavity backed antenna is developed; in which two orthogonal quarter-wavelength patch provide the circular polarization at far field of the structure. Also, in [14] perturbation technique in applied in a rectangular SIW cavity and its impedance bandwidth is improved in case of linear polarization. All the cavity backed antennas presented in [5-14] can radiate either LP wave or CP wave and none of them can generate both of LP and CP waves.

In this paper, HMSIW technique is used in conjunction with a dual mode cavity. A new cavity backed slot antenna with capability of producing both CP and LP wave is introduced. Based on the operating frequency of the structure, the proposed antenna radiates a LP or CP waves. The introduced structure is the modified version of the presented antenna in [13]. In [13], the slot length is chosen to be quarter of a

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wavelength of resonant frequency. But, in this paper, the slot length is extended much more than a quarter of wavelength lead to exciting two resonating hybrid modes of the cavity. One of these hybrid modes generates LP wave, while the other one generates CP wave. LP wave is caused by the dominant radiation of the long slot, whereas the CP wave is radiated by two quarter wavelength patches. A prototype of the proposed antenna is designed, implemented, numerically studied and experimentally investigated. Results including reflection coefficient, radiation patterns and gain are reported.

II. ANTENNA STRUCTURE

The top view of the proposed antenna and its geometrical parameters are shown in Fig. 1. Its backside is totally metallic and acts as the ground of the microstrip structure. The introduced antenna consists of a halved rectangular cavity with length and width of a and b respectively. It is realized by two arrays of metallic vias and a magnetic wall of length b. A radiating slot of length l_s is also etched at the center of the upper side of the structure. An inset microstrip feed line is used to excite the cavity. This also simplifies planar integration and in turn SMA connector can be easily applied to the structure.

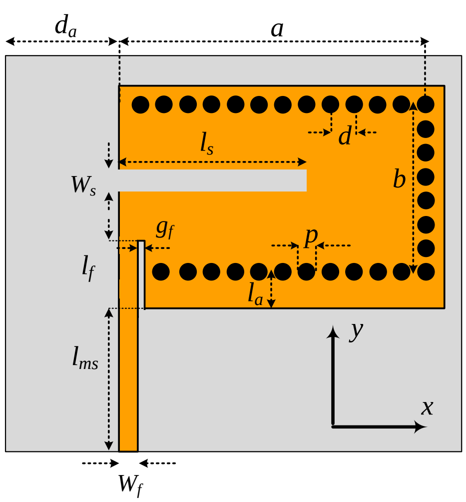


Fig. 1. Top view of the proposed antenna and its geometrical parameters.

III. THEORY OF OPERATION

The proposed structure is similar to that presented in [13], except the shape of the cavity and the slot length. These differences give to the antenna the capability of generating both LP and CP waves. In [13], the resonating slot with the length of quarter wavelengths is used on the broadside of the cavity, while in this paper a non-resonating slot with a length much more than a quarter wavelengths is used. So, the proposed antenna can only be implemented by rectangular cavity.

In the proposed structure, as discussed in [10], a dual mode cavity is used in which two hybrid modes including two different combinations of half TE_{110} and half TE_{120} modes, are excited. Choosing a non-resonant length for the slot, a dual mode cavity is obtained. In this antenna both magnetic wall and rectangular slot are radiating, while the rectangular slot produces co-polarized wave, whereas the magnetic wall produces cross-polarized one. Due to the large size of the slot, it radiates a LP wave by the lowest frequency hybrid mode, which is the 1st hybrid mode.

At the other resonant frequency of the cavity, both magnetic wall and a part of slot, which is equivalent to a quarter resonant wavelengths efficiently radiate. As a result, two quarter-wavelength patches, as shown in Fig. 2, are obtained. Two orthogonal E-fields with equal magnitudes are generated by these two quarter wavelength patches [13] and also 90° phase difference between orthogonal fields can be provided by tuning the slot length l_s. Therefore, a CP wave can be radiated.

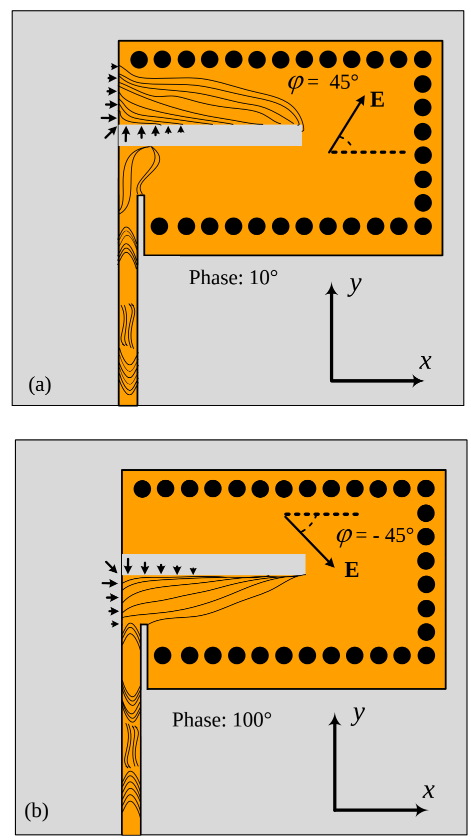


Fig. 2. E-field isolines of the proposed antenna at 10.53 GHz corresponding to the two orthogonal quarter-wavelength patch modes: (a) direction of radiated E-field at φ = +45°, and (b) direction of radiated E-field at φ = -45°.

In Fig. 2, the orthogonal quarter-wavelength patch modes and the radiated E-field caused by each one are illustrated at 10.53 GHz. As shown, the radiated fields are orthogonal, one is directed at φ = +45° and the other one at φ = -45°. At following, it is shown that this two quarter-wavelength patches are excited by higher hybrid mode (2[st] hybrid mode) of the cavity. In the proposed structure, in order to excite the two patches symmetrically and consequently provide circular polarization, the slot should be placed at the center of cavity.

The presented half mode cavity has the same frequency characteristics as that of the full cavity. However, it cannot support some resonating modes of the full one due to its half mode configuration. So, for the resonating modes that can be supported, the well-known formulation used for full mode cavity [15-16] can also be used here for calculation of the resonance frequencies. In SIW cavity, the conditions $d<2p$ and $p/\lambda_0<0.1$, where λ_0 is the free space wavelength, should be satisfied in order to effectively prevent power leakage through the side walls of the cavity [15-17].

IV. RESULTS AND DISCUSSION

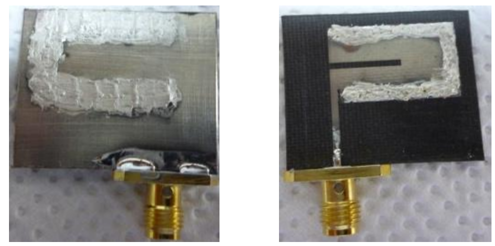
To verify the operating conditions of the proposed antenna, a prototype of the cavity backed slot antenna is designed and implemented. The antenna structure is studied numerically using High Frequency Structure Simulator (HFSS) software based on Finite Element Method (FEM) and investigated experimentally. The geometrical parameters of the antenna are summarized in Table 1. It is made using Rogers Duroid 5880 substrate with electrical characteristics of ε_r = 2.2, thickness of 0.787 mm and tangent loss of 0.001. Photo of the fabricated antenna is illustrated in Fig. 3.

Simulated and measured results for reflection coefficient and axial ratio (*AR*) are illustrated in Fig. 4. Apart from a shift in frequency response, there is a good agreement between measured and simulated results. The difference between results is due to fabrication imperfection. It can be seen that reflection coefficient is less than -10 dB for frequency range from 9.43 GHz to 10.54 GHz, providing fractional bandwidth of 11.75%. Moreover, two distinct resonance frequencies are obtained at 9.65 GHz and 10.3 GHz, corresponding to the two different modes of the cavity. It can be seen that near the second one, proposed antenna radiates a CP wave at 10.3 GHz with minimum *AR* and 3 dB *AR* bandwidth of -0.35 dB and 180 MHz respectively.

From *AR* plot versus frequency, Fig. 4, it also can be observed that the proposed antenna radiates a LP wave at frequencies near to the frequency of its 1[st] hybrid mode. Also, near the frequency of its 2[st] hybrid mode, it radiates CP wave. Measured results indicate that the designed antenna provides LP wave from 9.43 GHz to 9.75 GHz. In case of CP, its *AR* bandwidth is from 10.11 GHz to 10.35 GHz.

Table 1: Geometrical parameters of the proposed antenna (units in mm)

Parameter	Value	Parameter	Value
d_a	7	l_{ms}	10
d	1.5	h	0.78
p	1	W_f	1.137
g_f	0.4	W_s	1
l_s	11.5	a	39
l_f	1	b	10.5
l_f	2.3		



(a) (b)

Fig. 3: Photo of the fabricated antenna: (a) front view and (b) rear view.

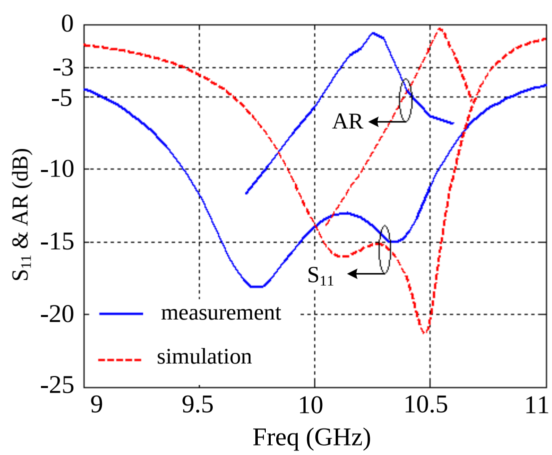


Fig. 4. Measured and simulated reflection coefficient and axial ratio of the proposed antenna.

The corresponding simulated field distribution inside the cavity for the two operating modes including TE_{120} and TE_{110} are shown in Fig. 5 (a) and 5 (b), in which vertical scale of 0-250 A/m is used for illustrating H-field vectors and red arrows represent the direction of H-vectors. Figure 5(a) shows H-vectors of the hybrid mods at 10.06 GHz is divided into an upper half part and a lower half cavity by the radiating slot. Also, field distribution at both sides of the slot is out of phase. Figure 5 (b) shows H-vectors of the hybrid mode at 10.47 GHz. It can be observed that field distribution at both sides of the slot is in phase and field distribution at the upper side of the slot is dominant.

The schematic combination of TE_{110} and TE_{120} modes and generating 1st hybrid mode at 10.06 GHz is shown in Fig. 6 (a). Dominant E-filed isolines are shown by red and blue lines. The signs + and – represent the phase of the field distribution. It reveals that the hybrid mode at this frequency is the combination of strong TE_{120} mode and weak TE_{110} mode which makes field distributions at both sides of slot, out of phase and greatly different in magnitude. As a result the slot is able to radiate effectively. Figure 6 (b) shows that the generated 2nd hybrid mode at 10.47 GHz is the combination of strong TE_{110} and weak TE_{120} modes, and in turn field distributions at two sides of slot are in phase and greatly different in magnitude which also results in efficient radiation by the rectangular slot.

A parametric study is carried out and the effect of slot length, l_s, and dielectric aperture width on the radiation performance of the proposed antenna is investigated. The effect of slot length l_s on antenna parameters including co-polarized gain, the difference between co- and cross-polarized gain G_d, axial ratio and reflection coefficient is shown in Fig. 7 (a) and Fig. 7 (b) versus frequency. It can be seen that when the structure operates as a LP antenna, higher gain and lower cross polarized level (CPL) is achieved by extending the slot length. In fact, in this case its co-polarized gain is due to the efficient exciting of the applied slot and the cross-polarized gain is due to the magnetic wall of the cavity. As a result, by extending the slot length higher gain and lower CPL can be obtained. *AR* plot in Fig. 7 (c) shows by adjusting the slot length, 90° phase difference between orthogonal patch modes and consequently circular polarization at far field can be provided.

S_{11} plot in Fig. 7 (d) reveals that the slot length has also some effect on the location of the two resonate frequencies corresponding to the two hybrid modes. By extending the slot length, these two frequencies are departed from each other and broadband operating condition is obtained.

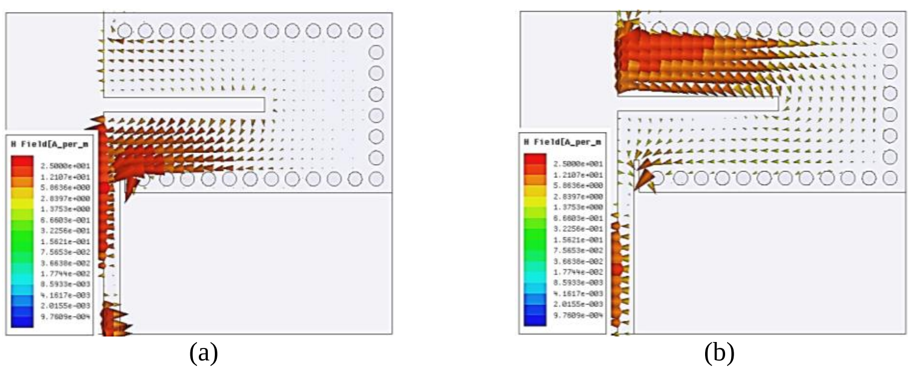


Fig. 5. Simulated magnetic field distributions of the hybrid modes in half mode cavity: (a) H-vectors at 10.06 GHz, and (b) H-vectors at 10.47 GHz. Red arrows represent direction of H-vector.

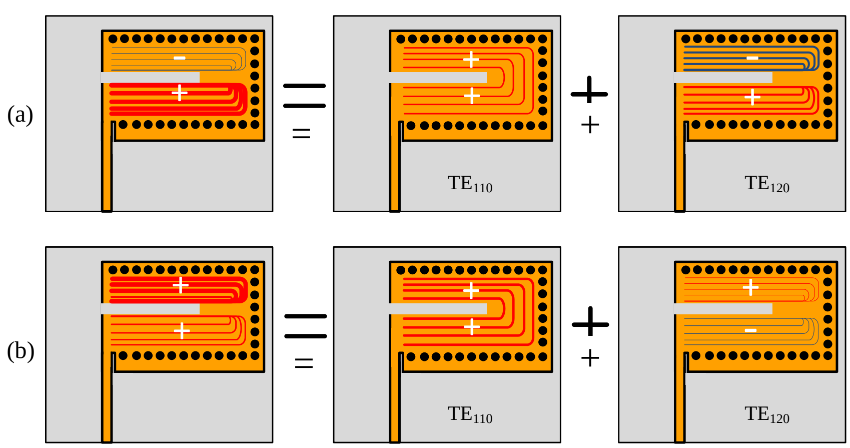


Fig. 6. Schematic combination of TE_{110} and TE_{120} modes and generating: (a) dominant E-filed isoline at 1st hybrid mode at 10.06 GHz, and (b) dominant E-filed isolines at 2nd hybrid at 10.47 GHz. Signs + and – represent phase of field distribution.

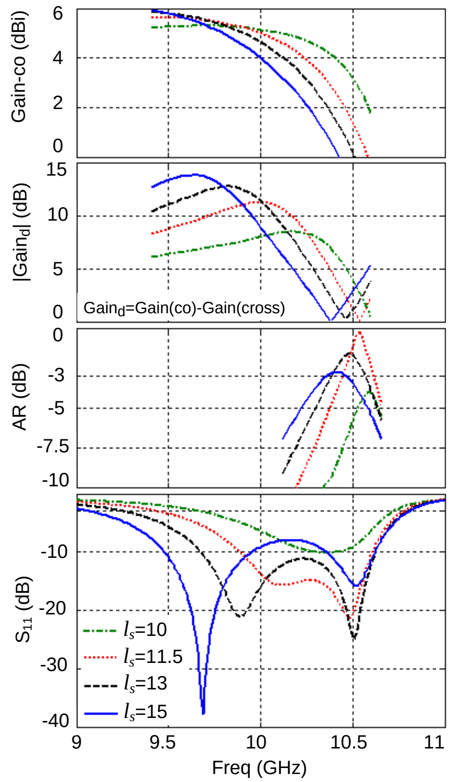
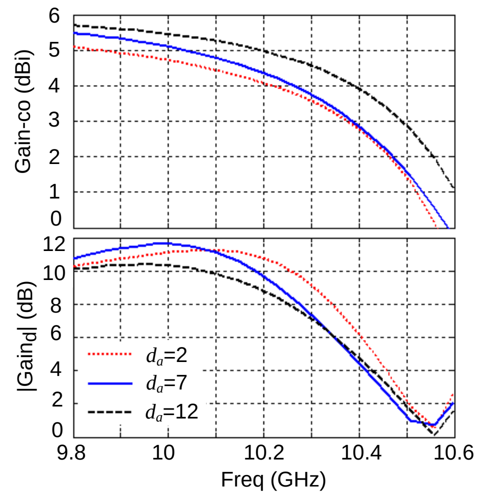


Fig. 7. The effect of slot length l_s on: (a) co-polarized gain, (b) difference between co- and cross-polarized gains, and (c) *AR*, d) S_{11}.

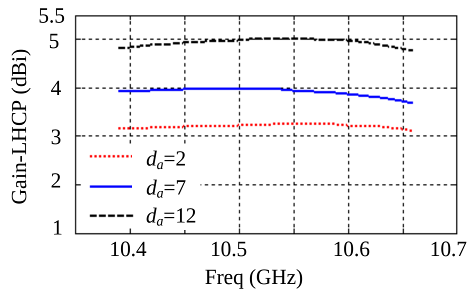
The effect of the dielectric aperture d_a on co-polarized gain (LP gain), gain difference G_d and gain in case of CP operation is depicted in Fig. 8. The co-polarized gain plot illustrates in case of LP operation, its gain is slightly enhanced by increasing d_a which also increases the antenna size. However, the gain difference G_d plot reveals that by increasing d_a, the frequency range in which the CPL is less than -10 dB (G_d>10 dB), is decreased. Figure 8 (b) reveals that in case of CP operation, higher gain can be achieved by increasing the dielectric aperture d_a.

Variations of co- and cross-polarization gains versus frequency at boresight direction are plotted in Fig. 9. Simulated result shows CPL is -11.2 dB at 10.06 GHz, which confirms that the structure is LP antenna at its lower resonate frequency. Also, measured result indicates that at the frequency range from 9.43 GHz to 9.75 GHz, CPL is less that -10 dB. Moreover, in case of LP antenna, measured gain is from 3.7 dBi to 5 dBi, which agree well with that obtained by simulation which is 4.5 dBi to 5.5 dBi in operating bandwidth.

Figure 9 also shows that at the vicinity of 10.25 GHz measured co- and cross-polarized gains are almost equal and CP wave is generated. Measured *AR* in Fig. 4 reveals that at the frequency range from 10.11 GHz to 10.35 GHz, the proposed antenna radiates CP wave. In this case, measured gain is 3.4 dBi, however simulated result shows gain is nearly 4 dBi. Table 2 summarizes simulated and measured radiation performance of the proposed antenna.



(a)



(b)

Fig. 8. The effect of d_a on antenna performance: (a) co-polarized, (b) difference G_d, and (c) gain for CP operating antenna.

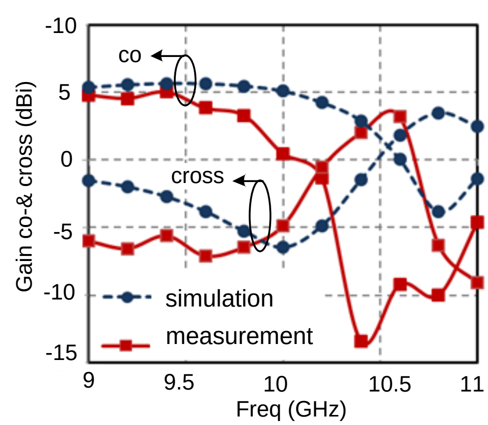
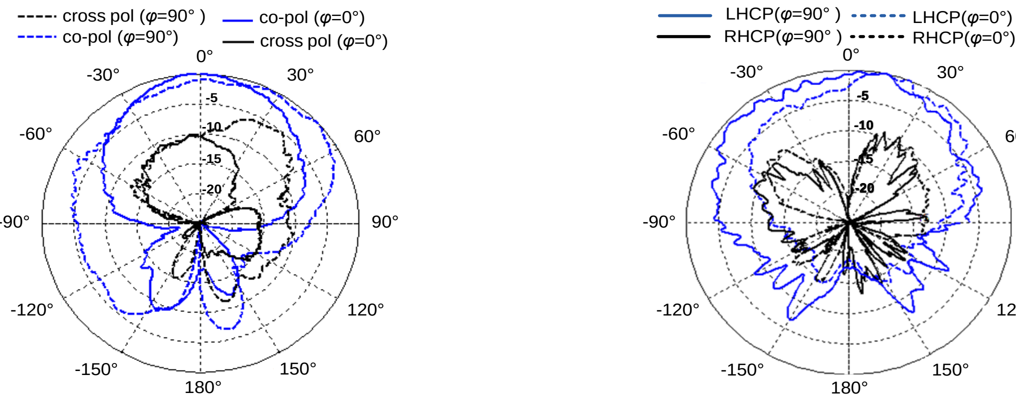


Fig. 9. Simulated and measured variation of co- and cross-polarization gains versus frequency.

In Fig. 10, measured radiation patterns of the proposed antenna are shown at two standard radiation planes. Figure 10 (a) shows radiation patterns at 9.5 GHz, in case of LP antenna. For CP operating condition of the antenna, radiation patterns at 10.25 GHz are shown in Fig. 10 (b). The measured cross polar level (CPL) at boresight direction is about -10 dB when antenna is LP and about -20 dB when it acts as a CP antenna.



(a) (b)

Fig. 10. Radiation patterns of designed sample at φ=0˚ and φ=90˚ cut planes: (a) at 9.5 GHz and (b) at 10.25 GHz.

Table 2: Summary of the simulated and measured results of the proposed antenna

Parameter	Simulated	Measured
Impedance BW (GHz)	9.88 - 10.59 (6.9%)	9.43 - 10.54 (11.1%)
AR BW (GHz)	10.44 - 10.62 (1.7%)	10.11 - 10.35 (2.34%)
LP BW	9.7 - 10.17 (4.7%)	9.43 - 9.75 (3.3%)
CP BW	10.44 - 10.62 (1.7%)	10.11 - 10.35 (2.34%)
Maximum *AR (dB)*	-0.24	-0.59
Maximum *AR* freq (GHz)	10.54	10.25
LP Gain (dBi)	4.5~5.5	3.7~5
CP Gain (dBi)	≈ 4	≈ 3.4

The measured front to back ratio (FTBR) is almost about 15 dB for LP case, while it is nearly 17 dB in case of CP operation. Detailed radiation performance of the proposed antenna is summarized in Table 2.

V. CONCLUSION

A low profile planar cavity backed slot antenna which is able to produce both linear and circular polarizations depending on the frequency of operation is developed. This feature is not observed in the previous designs [1-13, 18] for planar cavity backed antennas. HMSIW technique is used in antenna topology which makes the antenna compact and also light weight. Moreover, the antenna has a single layer structure using a low cost PCB which makes it easy to integrate to other planar circuits. The proposed antenna has two resonating frequencies corresponding to the two hybrid modes of the halved rectangular cavity. In this antenna a long slot generates LP wave at the frequencies near to the lower resonate frequency. However, two quarter-wavelength patches produce CP wave at the frequencies near to the higher resonate frequency. A prototype of the proposed antenna is designed and fabricated. The radiation performance including radiation patterns and antenna gain were measured. Results show that the proposed antenna provides good radiation characteristics such as high gain, wide bandwidth comparable to the traditional antennas presented in literature [1-13, 18], but presenting the discussed advantages including double polarization tunability in addition to low cost single layer implementation.

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