Development of a Broadband Substrate Integrated Waveguide Cavity Backed Slot Antenna Using Perturbation Technique

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Abstract ─ A novel method for bandwidth enhancement of Substrate Integrated Waveguide (SIW) cavity-backed slot antenna is introduced for a single element and an array configuration. Using a corner cut in the SIW square cavity, resonant frequency of two degenerate TE_{210} and TE_{120} modes of a square cavity are separated and impedance bandwidth is improved. The simulated and measured results of the antennas show at least 140% and 220% wider bandwidth compared to the bandwidth of a conventional single cavity antenna for single and two element array antennas, respectively. The presented antennas provide a few advantages including low profile, light weight, easy fabrication with low cost and convenient integration with planar circuits.

Index Terms ─ Antenna array, cavity-backed antenna, slot antenna, Substrate Integrated Waveguide (SIW).

I. INTRODUCTION

Wireless communication systems have been rapidly growning up in recent years and low profile, low cost antenna with high performance radiation characteristics are in a great demand, especially in some applications such as satellite, aircraft and radar systems.

Slot antennas exhibits favorable characteristics including compact size, low cost, conformability and easy integration with planar circuits, so they are highly suitable for wireless communication applications. However, one evident drawback of the slot antenna is its bidirectional radiations [1], which limit its performance in some applications. Cavity backed slot antennas eliminate backward radiation and provide high performance radiation characteristics. The conventional metallic cavity backed antennas are bulky and it is not easy to integrate them with planar circuits. So they are not suitable for many applications.

Recently Substrate Integrated Waveguide (SIW) technology has been greatly suggested due to its useful substitute to the conventional bulky metallic waveguide, and therefore, implementation of microwave circuits and antennas by SIW technique is easy using low cost Printed Circuit Board (PCB) process. SIW technology firstly proposed by Wu [2], is an integrated waveguide structure fabricated using two rows of vias, metallic cylinders, embedded in dielectric substrate. These vias connect two parallel metal plates of PCB. SIW waveguides provide same propagation characteristic as the propagation properties of the metallic waveguides [3]. They also allow the integration of planar and non-planar structures on a same substrate.

Low profile cavity backed slot antennas based on Substrate Integrated Waveguide (SIW) technology have been proposed in [4] and [5]. These antennas have good radiation performance and provide the advantages of low cost fabrication, low profile and easy integration with planar circuit. There are some inherent drawbacks in using a thin substrate in a cavity backed slot antenna. The height of the substrate affects Q, quality factor, of the slot and cavity. A low height substrate increases Q of the antenna, which causes to obtain narrow bandwidth [4]. Overcoming these problems is an important issue in designing a low profile cavity backed slot antenna. Various methods have been proposed to enhance bandwidth of the cavity backed slot antennas.

A dual mode cavity backed slot antenna has

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been investigated in [5], in which two hybrid modes are simultaneously excited. By merging the two hybrid modes, cavity bandwidth could be enhanced. In [6], by removing the substrate under the slot and in turn, by decreasing Q of the slot, 24% wider bandwidth compared to those of the conventional cavity backed slot antenna has been achieved. The proposed technique is more useful for substrate, which have high relative permittivity or high loss tangent. Bandwidth enhancement of SIW cavity backed slot antenna using a via hole above the slot has been demonstrated in [7], in which the via hole is used to create the second resonate frequency. By adjusting the location of the via hole, the second resonate can be moved to improve bandwidth of the antenna.

Despite the fact that this antenna provides high radiation performance, obtaining higher gain is realized by array structure. A 2×2 SIW cavity backed slot array antenna has been proposed in [8]. The presented antenna provides high gain and radiation efficiency of 12.1 dBi and 87% respectively. However, its impedance bandwidth is about 1%.

In this paper, a perturbation technique using a corner cut in the SIW square cavity is used to enhance impedance bandwidth of the cavity backed slot antennas. Furthermore, in order to increase gain of the proposed antenna, a two element antenna array is introduced. The presented antennas show dual resonance due to splitting of resonant frequency of the two degenerate modes. The proposed antenna structures are fabricated on single layer substrate using ordinary low cost Printed Circuit Board (PCB) process. The design and simulation of the proposed antenna is performed using full wave software High Frequency Simulator Structures (HFSS) based on Finite Element Method (FEM). The simulated and measured results show the impedance bandwidth of the both antennas is greatly enhanced.

II. TEORY OF OPERATION

A. Square SIW cavity

Figure 1 (a) shows a square SIW cavity. It is made by four rows metalized via arrays made on a single layer board. Length of the cavity is designated by a and diameter of the metallic vias and distance between the centre of two adjacent vias is nominated by d and p, respectively. In order to make the SIW cavity to be equivalent to a conventional metallic cavity, two conditions $d/p \geq 0.5$ and $d/\lambda_o \leq 0.1$ must be satisfied and λ_o represent free space wavelength [9].

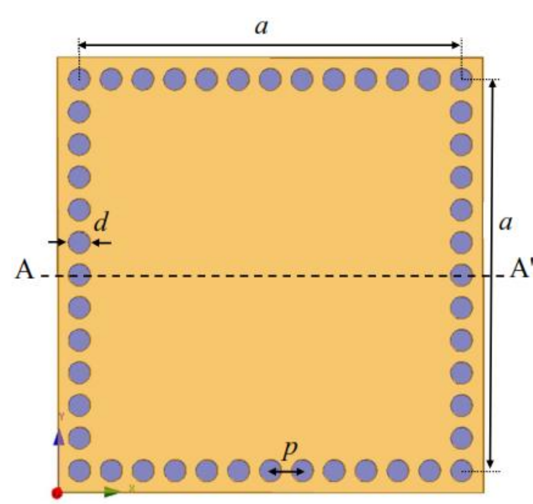
The equivalent width of the SIW cavity is approximately expressed by equation 1 [10]:

$$a_e \approx a - \frac{d^2}{0.95p}, \tag{1}$$

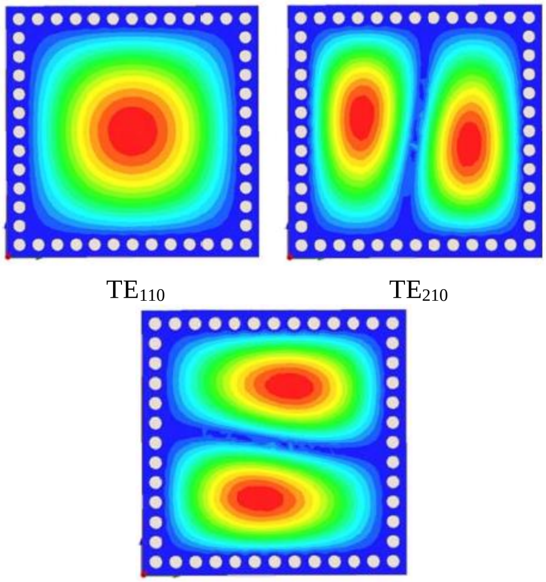
where a_e is the effective width of the equivalent conventional metallic cavity. In a square SIW cavity only TE_{mn0} modes can be excited and their resonant frequency is determined by equation (2) [11]:

$$f_{mn0} = \frac{c}{2a_e\sqrt{\varepsilon_{rs}}}\sqrt{m^2+n^2}, \tag{2}$$

where c is light velocity in free space and ε_{rs} is permittivity of the filled material inside the cavity. The simulated electric field distribution for the first three modes in the square SIW cavity with a length of a=17.8 mm using full wave electromagnetic Eigen mode of HFSS is shown in Fig. 1 (b). It can be seen that TE_{120} and TE_{210} modes provide odd and even symmetric field distribution with respect to AA' plane. Moreover, using equation (2), it can be calculated that these modes resonate at 13.2 GHz, and so they are decoupled degenerate modes with the same resonate frequency [12].



(a)



TE_{110} TE_{210}

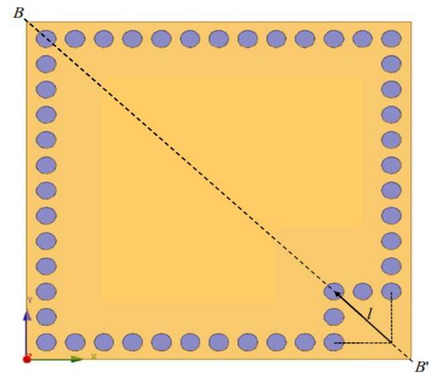
TE_{120}

(b)

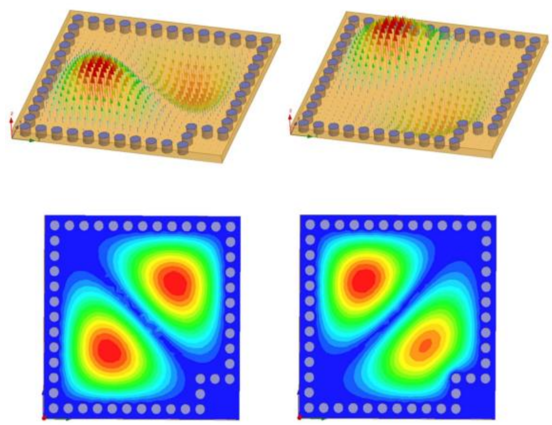
Fig. 1. (a) Geometry of a square cavity, and (b) electric field distribution at three first modes.

B. Perturbed square SIW cavity

Figure 2 (a) shows a perturbed square SIW cavity. In fact, this cavity is same as the square cavity which is perturbed by a corner cut. By perturbing the square cavity using the corner cut, two degenerate modes will be coupled to each other, and their resonate frequencies will split [13]. Based on the symmetry of the structure with respect to diagonal *BB*' plane, field distributions of degenerate modes is symmetric. This is verified by simulated E-field distribution of TE_{210} and TE_{120} modes, using Eigen mode analysis, as is shown in Fig. 2 (b). It can be seen that electric field distribution is symmetric for odd and even modes with respect to *BB*' plane. To study the splitting of resonate frequency of degenerate modes due to the corner cut, a parametric study was carried out for the perturbed SIW cavity using HFSS software. The variation of resonate frequency of the degenerate modes, TE_{210} and TE_{120}, versus cut size *l*, is shown in Fig. 3. It can be concluded that resonant frequency of odd mode remains almost fixed, but for even modes resonant frequency is increased by increasing *l*. This is due to the location of perturbation, which is at null position of electric field, whereas for even mode, the corner cut is located at maximum of magnetic field. Furthermore, the effective volume of the cavity is decreased by increasing the cut size.



(a)



(b)

Fig. 2. (a) Geometry of the perturbed square cavity, and (b) simulated electric field distribution at TE_{210} and TE_{120}.

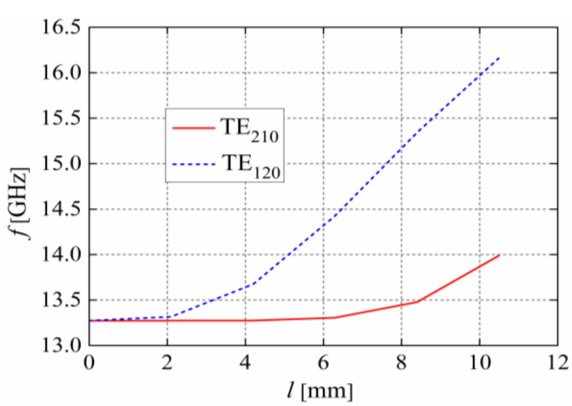


Fig. 3. Variation of the simulated resonate frequency of the degenerate modes versus perturbation size *l*.

III. ANTENNA STRUCTURE

A. Single element antenna

Figure 4 shows a perturbed square SIW cavity as a single element antenna. A non-resonate slot with a length L_s, far more than a half resonant wavelength, and width of W_s is placed at the distance y_s from the centre of the cavity as the radiating element. In order to isolate the spurious radiation from the feed line, radiating slot is etched at the ground plane of the structure. Moreover, a 50 Ω microstrip inset feed line is adopted as the feeding network to excite the cavity. For measurement convenience, a section of 50 Ω microstrip line is added at the end of inner conductor of the feed line with the same width. All the presented antennas are designed and made on a single TLY031 substrate with permittivity of 2.2, thickness of h=0.787 mm and loss tangent of 0.001. The detailed geometrical parameters of the single element antenna are summarized in Table 1.

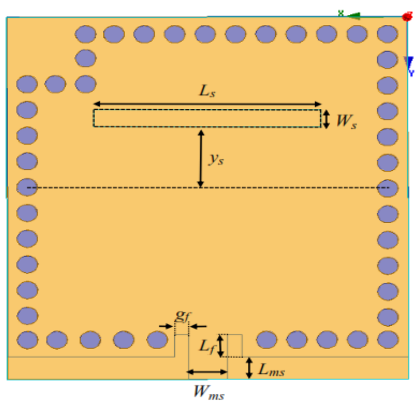


Fig. 4. Single element antenna structure.

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

Parameter	Single Antenna	Antenna Array	Power Divider	
L_t	17.8	17.8	L_1	9.6
L_{ms}	1.3	1.3	L_2	4.15
W_{ms}	1.9	1.9	L_3	7.96
L_f	1.3	1.3	L_4	7.9
l	4.1	4.1	L_c	0.9
L_s	11	11.2	W_1	3
W_s	1	1	W_2	1.13
y_s	3.6	3.6	-	-
g_f	0.7	0.7	-	-
d	1	1	-	-

A full wave simulation of the proposed antenna has been investigated using HFSS. To study the effect of size perturbation l, a parametric study was carried out and S_{11} of the proposed antenna was considered for different values of l. The simulated result of reflection coefficient versus frequency for different values of l is shown in Fig. 5. It can be seen that by increasing l, two separate resonate frequencies are obtained, while only the second resonate frequency is increased by l. Therefore, dual mode operation is achieved and by merging these two, wideband operation can be obtained. Furthermore, for a square cavity without corner cut, l=0 mm, simulated bandwidth, for return loss of +10 dB, is nearly 100 MHz, which shows fractional bandwidth of 0.76%. In case of perturbed cavity with l=4.1 mm, simulated impedance bandwidth is 240 MHz, from 13.13 GHz to 13.37 GHz, provides fractional bandwidth of 1.8%.

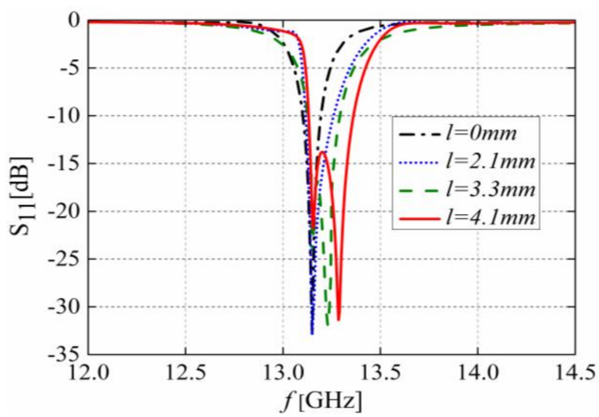


Fig. 5. Simulation results of S_{11} versus frequency for a perturbed cavity and different values of l.

B. Two elements array

In order to increase gain and to obtain narrower beamwidth, a two element antenna array is formed by placing two perturbed cavity side by side as shown in Fig. 6. The array elements are similar to that of the designed single perturbed cavity, whereas, the distance between the elements is nearly $d_x \approx 0.7\lambda_o$ and λ_o is free space wavelength at the centre frequency.

To excite the cavities, a microstrip T junction in phase power divider is adopted as the feed network, which is symmetric to its horizontal axis, so input power is divided equally between its two arms. The 50 Ω microstrip line split into two quarter wave transformers lines using T junction. In fact, there are 100 Ω lines before these 70.7 Ω lines, but their length is considered to be zero. The feed network with the removed 100 Ω lines works exactly same as the feed network with non-zero length of 100 Ω lines [14]. The geometrical parameters of the array are listed in Table1.

For antenna array, a parametric study was investigated and its reflection coefficient is studied for different values of the beveled line size L_c. Simulated results are shown in Fig. 7, which can be seen that L_c has an important effect on S_{11} and impedance bandwidth. From this figure, it can be found that when L_c increases, the impedance matching improves because the effective width around the corners becomes smaller. However if L_c becomes greater than a special value, the effective width around the corners will be too small, so impedance matching gets worse.

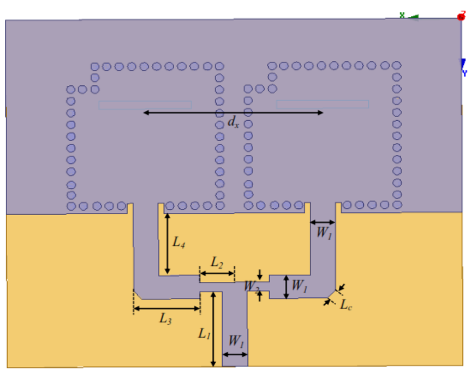


Fig. 6. Two elements antenna array.

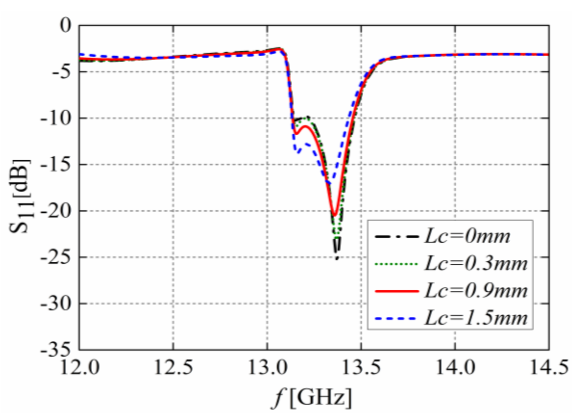


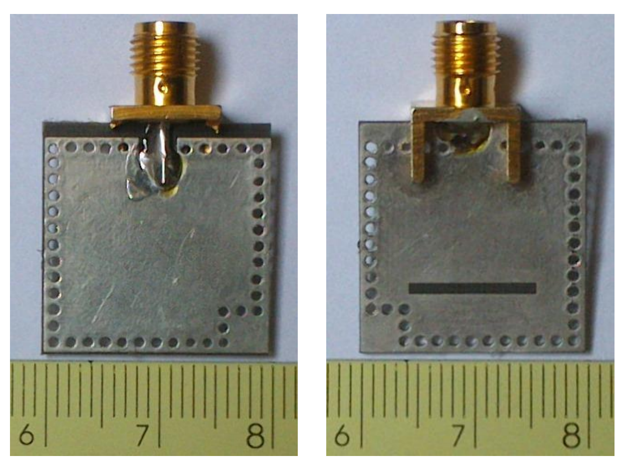
Fig. 7. Simulation results of S_{11} for the proposed array versus frequency and different values of L_c.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Single element antenna

In order to validate the design method, a sample of the proposed single element antenna has been made on a single layer of TLY031 substrate by the low cost PCB process. To improve ground connection, the connector legs are soldered to the substrate ground. The photo of the fabricated antenna is shown in Fig. 8, in which the detailed geometrical parameters in Table 1 are used.

Measured S_{11} of the proposed antenna is shown in Fig. 9 (a), compared with full wave simulated results. It can be seen that measured results are in a good agreement with those obtained by simulation. Measured impedance bandwidth is 220 MHz, with a fractional bandwidth of 1.65%, which is slightly less than the predicted value of 1.8%. Measured and simulated gain of the antenna at boresight direction, θ=180°, versus frequency is also plotted in Fig. 9 (b). It can be seen that the proposed antenna provides almost uniform gain throughout the operating bandwidth within the range of 3.25 dBi to 5.2 dBi. The simulated maximum gain is of 6.1 dBi, which is slightly more than the measured maximum gain. The slight discrepancy between measured and simulated results is due to imperfection in fabrication process and transmission loss in measurement.



Top view Rear view

Fig. 8. Photo of the fabricated proposed single element antenna.

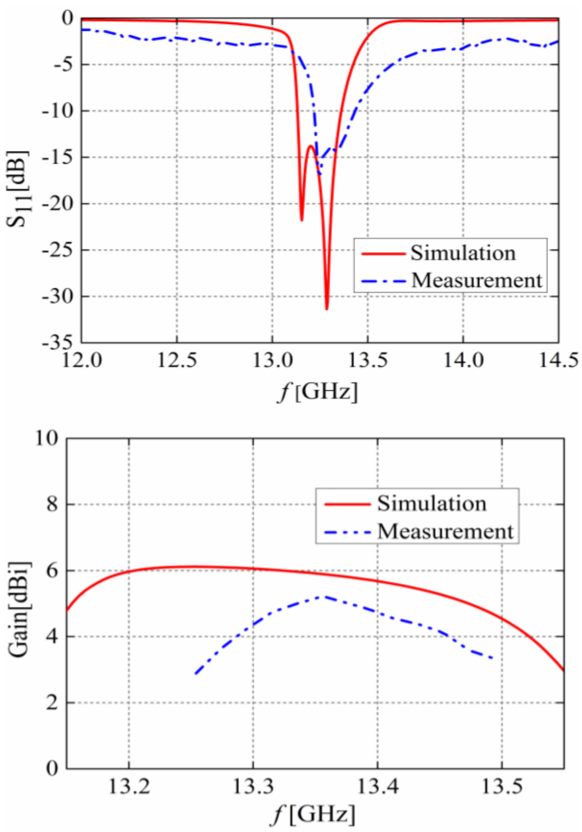


Fig. 9. Measured and simulated results of the single element antenna at boresight direction of: (a) S_{11}, and (b) gain.

Measured and simulated far-field E- and H-plane co-polarized radiation patterns of the proposed antenna at 13.15 GHz and 13.29 GHz are shown in Fig. 10. The largest radiation direction of the perturbed square cavity is offset from boresight direction by nearly 15° for its structure asymmetry along y-direction. Measured results also show that the proposed antenna has very low level cross-polarized radiation at θ=180°. This is due to structure symmetry in x-direction. Measured Front to Back Ratio (FTBR) of the antenna is nearly 18 dB. Apart from deviation of measured and simulated radiation patterns, it can be found that the proposed perturbed SIW cavity antenna provides high radiation performance of the conventional cavity backed antenna with a significantly reduction in profile.

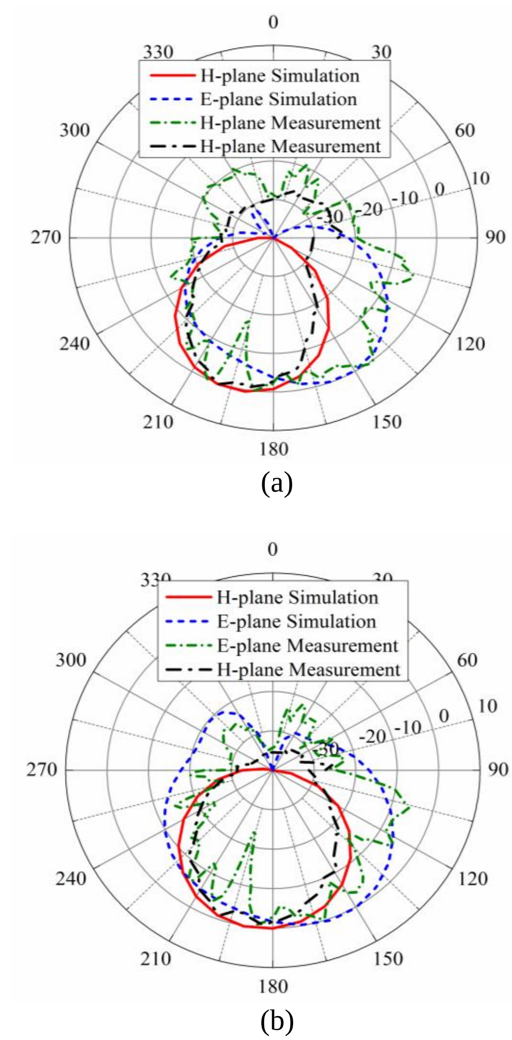


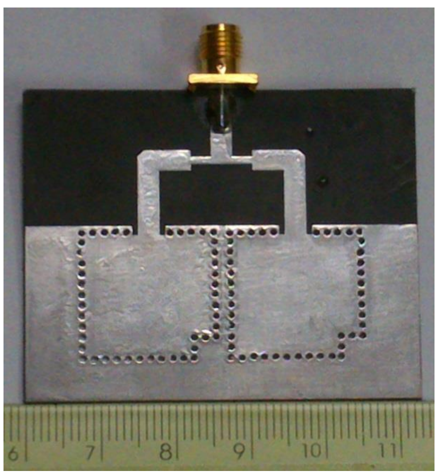
Fig. 10. Measured and simulated radiation patterns of the single antenna at: (a) 13.15 GHz, and (b) 13.29 GHz.

B. Aantenna array

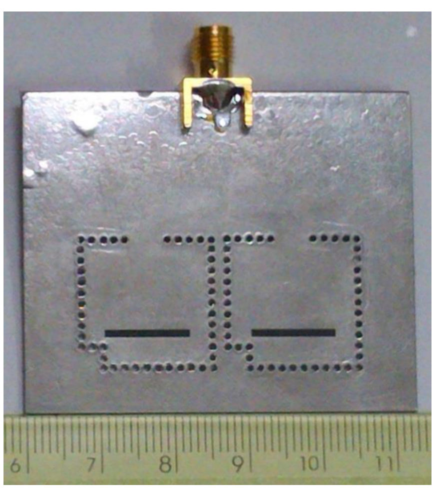
The photo of the fabricated antenna array is shown in Fig. 11. Figure 12 (a) and 12 (b) show measured S_{11} and gain of the proposed array compared with the simulation results. Apart from a shift in frequency response of S_{11}, a good agreement between measured and simulated results is obtained. The small shift at high frequencies of the provided S_{11} parameter may be attributed to the considered permittivity value of the substrate. Measured impedance bandwidth is

410 MHz, provides fractional bandwidth of 3%, which is more than the predicted value of 2.4%. The increasing bandwidth is due to coupling between the two elements and array configuration of the structure. Moreover, it can be seen that for the antenna array, the simulated and measured peak gain of 8.8 dBi and 8.4 dBi are obtained respectively at boresight direction θ=180°. Both of the results show that the antenna array provides 2.7 dBi more gain compared to the gain of the single antenna.

The simulated radiation efficiency of the presented antennas is also shown in Fig. 13. From this figure, it can be found that the simulated peak efficiency of 84% and 91% are achieved for proposed single and antenna array, respectively.

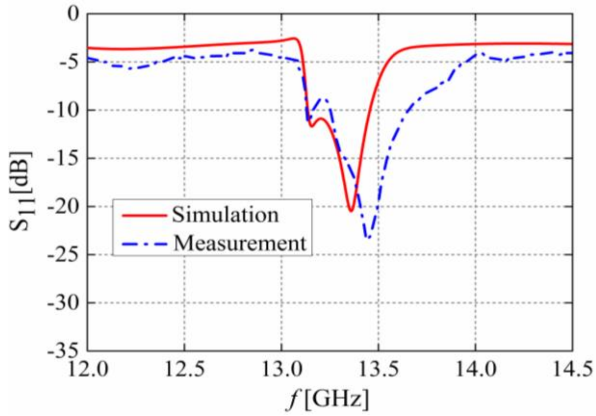


Top view

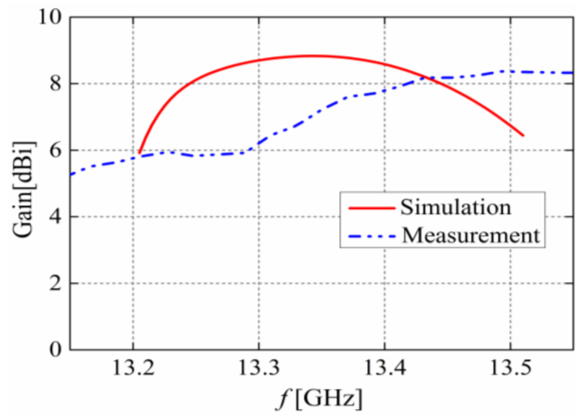


Rear view

Fig. 11. Photo of the fabricated proposed two elements antenna array.



(a)



(b)

Fig. 12. Simulated and measured results of the proposed antenna array versus frequency: (a) reflection coefficient, and (b) gain.

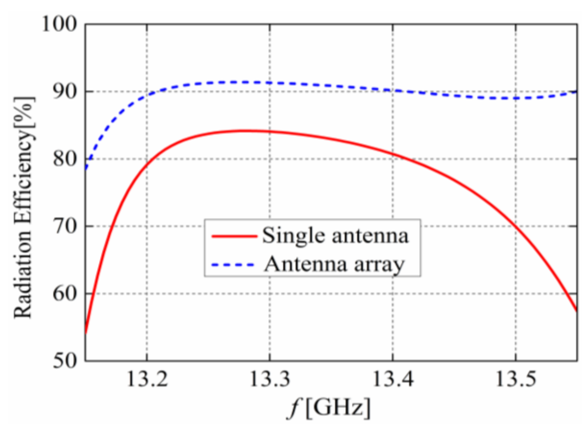
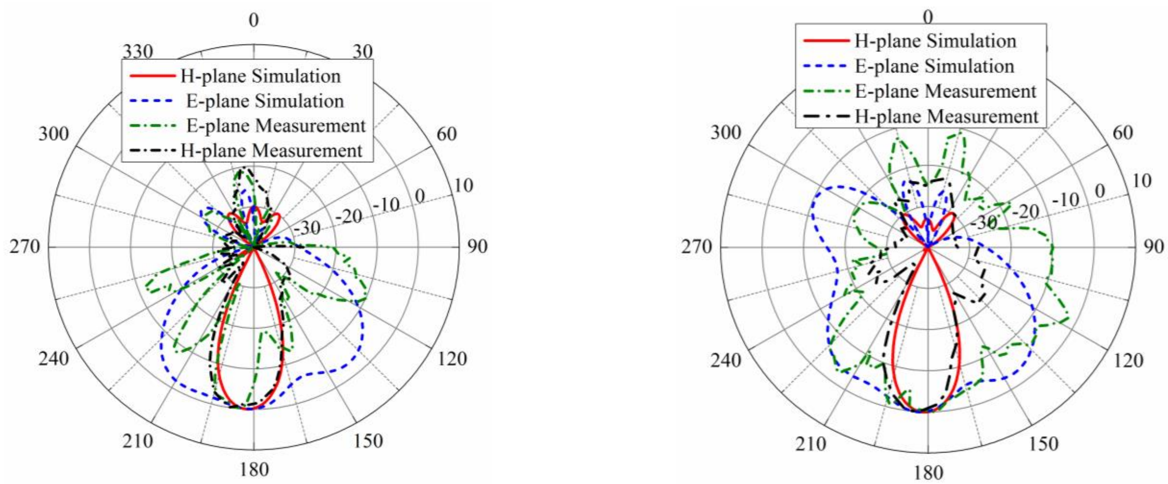


Fig. 13. Simulated radiation efficiency of the proposed single and antenna array.

Radiation patterns of the array are illustrated in Fig. 14 in two principal E- and H-planes at two resonate frequencies. It can be observed that radiation patterns are in boresight direction (θ=180º), perpendicular to the ground plane of the structures. As it expected, the H-plane radiation pattern of the array antenna is narrower than the H-plane beamwidth of the single antenna. Some of the specifications of designed antenna structures such as resonate frequencies, reflection coefficient and impedance bandwidth are summarized in Table 2. The presented antennas maintain good radiation performance of the SIW cavity backed slot antenna, although their bandwidth are greatly enhanced. Table 3 compares the detailed characteristics of the proposed single antenna with the antenna specifications of recently published research in literature.



13.15 GHz 13.36 GHz

Fig. 14. Measured and simulated radiation patterns of the antenna array at two frequencies.

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

	Single Antenna		Antenna Array	
Parameter	Simulation	Measurement	Simulation	Measurement
f_1 (first resonate frequency, GHz)	13.16	13.24	13.15	13.14
f_2 (first resonate frequency, GHz)	13.26	13.34	13.36	13.44
S_{11} at f_1 (dB)	-22	-17	-12	-12
S_{11} at f_2 (dB)	-31	-14	-20	-24
Gain (dBi)	6.1	5.2	8.8	8.4
Bandwidth (%)	1.8%	1.65%	2.4%	3%
Antenna size (mm^2)	20×21		44.5×54.5	

Table 3: Comparison between the presented single antenna and recently published antennas

Antenna	Operating Frequency (GHz)	Bandwidth (MHz)	Gain (dBi)	Radiation Efficiency (%)
Single proposed	13.2	220	6.1	84
Antenna in Ref. [4]	10	140	5.5	86
Antenna in Ref. [5]	10	630	6	92
Antenna in Ref. [6]	2.45	53	-	50.6
Antenna in Ref. [7]	2.45	91	5.9	89

V. CONCLUSION

A new technique to improve bandwidth of a SIW cavity backed slot antenna is presented in this paper. With the perturbation method, employing a corner cut in the square SIW cavity, resonant frequency of the two degenerated modes are separated, and in turn, impedance bandwidth of the antenna is enhanced. The proposed method has been experimentally and numerically investigated. Compared with SIW cavity backed slot antenna with no corner cut, impedance bandwidth of the proposed antenna is greatly improved. By employing proposed antenna in array configuration, at least 33% wider bandwidth and 44% higher gain compared to that of a single cavity backed slot antenna is achieved. The presented structures show favorable radiation performance and provide other advantages such as low cost, light weight and easy integration with planar circuits.

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