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SIW cavity-backed dual inverted L slot antenna array for Ku band applications

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Abstract

A novel concept of SIW cavity-backed dual inverted edge curved *L* slots antenna array with the defective ground plane is proposed in this paper. A linearly placed six-element inverted dual *L* slots array antenna is designed separated by a distance of $0.55\lambda_g$ to achieve high gain. Each pair of slots is separated by a column of the vias to form sub-cavities and those are fed individually. Defective ground structure (DGS) is introduced at the ground plane to manage the propagation of wave to the last slots in the array. The slots are enclosed by a SIW cavity of height $0.24\lambda_g$ in a single substrate. A measured peak gain of 8 dBi is achieved at 14.29 GHz. The antenna shows a front-to-back ratio of 24.9 dB. The design is also compared with various aspects to show the advantages of each element introduced in the design. The validity of the design is proved by the good agreement between the simulated and measured results. This novel design can be used to achieve the performance requirement of a satellite antenna working in Ku band.

Introduction

In the contemporary world, a requirement of low profile and radiation efficient antennas are in demand for high-speed wireless, satellite, radar and aircraft applications. Microstrip slot antenna finds its numerous applications due to its low-cost design, small size, low weight, and suitable isolation from feeding network and easy integration with planar circuits [1]. Few researchers have proposed slot antennas using microstrip technology. In [2] the author has developed the thirteen element linear slot antenna array for the X band and forms the relation to compute the mutual coupling between the slots and *E*/*H* plane field. The major drawback of the slot antenna is a bidirectional radiation pattern. To reduce the back radiation, a metal reflector or a shallow cavity can be introduced [3,4]. The use of a non-planar cavity at the back of the slot is bulky and consumes a large area [5].

Substrate integrated waveguide (SIW) is a promising technology to transform the non-planar conventional waveguide structure into a planar form [6]. The foundation of SIW was previously laid by D. Deslandes; K. Wu in [7]. SIW is made up of metallic via side walls separated by a distance "*p*" and sandwiched between the two metallic plates on each side of the substrate. The SIW technology can be used to form the cavity [8], which can be formed by enclosing all sides by the four rows of metallic vias. The application of the SIW cavity was further extended to form an antenna in [3]. This technology replaces the non-planar form of the metallic cavity to reduce the back side lobe and provide a directional radiation pattern [5].

In the present endeavor, a 1×6 slot antenna array is proposed which is enclosed inside a SIW cavity. As the SIW cavity gives advantages over conventional methods of making a non-planar cavity, the proposed antenna has the advantage of reduced back lobe radiation. Due to the reduction in the back lobe, the proposed design gives high gain, improved radiation efficiency by giving an advantage of low cost and compact size. The two *L*-slots presents inside the sub cavity, try to minimize the electrical length in comparison to straight rectangular slots, hence reduces the size of an antenna. The slots are created by putting two *L* slots inducted one above the other. The edges of the *L* slots are curved to improve the gain. Due to the curve structure at the edges, the losses occurred due to corners reduced considerably to achieve significant gain improvement. On a ground surface, two defective ground structure (DGS) are introduced to improve the flow of current to the terminal slots. The DGS was created by two split rings slots at both ends. The antenna is fed by a through-hole SSMA connector.

When compared to the available literature, the proposed design has high gain and small size with respect to the number of slots and the frequency of operation. The available literature either cited high gain due to higher frequency of operation or due to the introduction of a number of elements.

The slot separated by one-half the guide wavelength to form an array achieves a high gain and directive pattern [9]. The study of *L*-slot antenna is done by the authors in [10], where an

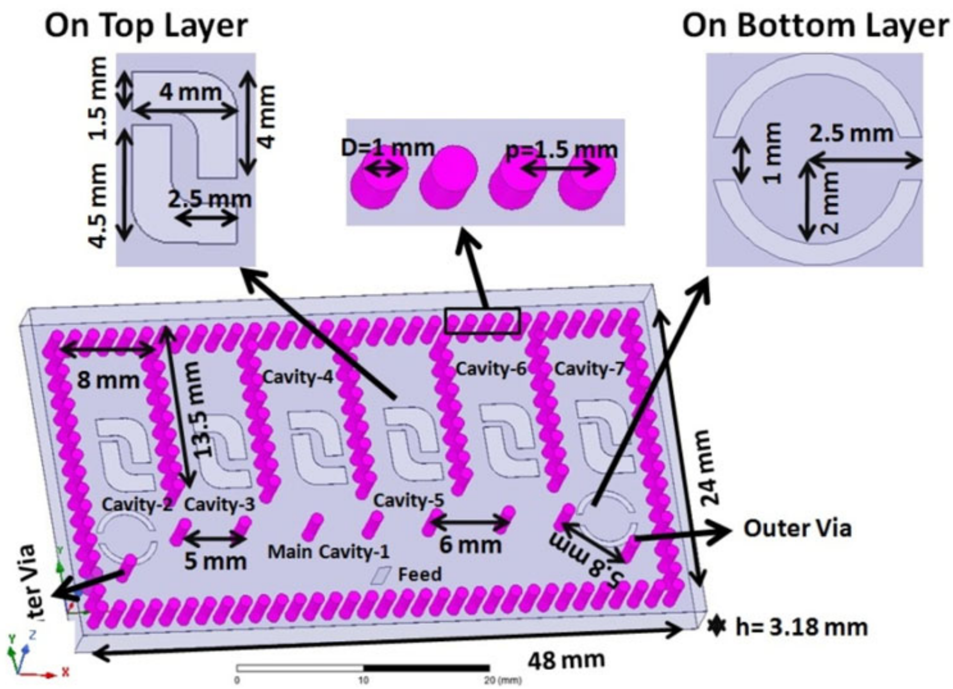

Fig. 1. The proposed antenna design.

L-slot is made by combining longitudinal and transversal slot antenna. Several literature studies are available which prove that the array formation of slot antenna can provide high gain. In [11] four inclined slots are created in a SIW cavity and further multiplied to form 1×8 a phased array antenna. The 45° inclined slots are created in a series and enclosed in a SIW cavity was done by the authors in [12]; where the antenna works for Ka-band frequency. In [13] single layer monopulse antenna was proposed which was fed from two different ports. The antenna was formed by two subarray of slots placed in cavity-2 and cavity-3. A single layer, dual-frequency slot antenna was proposed by the authors in [14]. The antenna has two ports; each of it is used to resonate the antenna at different frequencies. The prototype has 24 elements to achieve high gain. A wideband slot antenna array was proposed by [15], where the reflection-slope method was introduced to optimize the position of the slot. The working of the antenna was optimized to sub-6 GHz band for 5 G applications. A 4×4 planar slot antenna was proposed by the authors in [16], where the antenna is fed by a feeding network from the bottom of the SIW cavity. But all of the designs either are working at a higher frequency band or has a larger number of slots enclosed in a SIW to achieve high gain.

The proposed antenna is fabricated on 3.18 mm RT/Duroid 5870 substrate with $\varepsilon_r = 2.33$. The design was simulated and verified using the High-Frequency Simulation Software. The antenna was optimized on various parameters to achieve a high gain at 14.29 GHz.

Antenna geometry

The SIW cavity of size $3.6\lambda_g \times 1.8\lambda_g$ is used to enclose six L-slot antenna pairs. The antenna elements were further separated from each other by the via boundary to form sub-cavities of size $1.0\lambda_g \times 0.6\lambda_g$ as shown in Fig. 1.

The dual L-slots are clubbed together in inverted form to produce inductive and capacitive loading. The direction of the wave along the y-axis is affected by the parallel combination of an inductor (due to slot) and capacitor (due to the gap between two slots). The corners of the L-slots are curved to improve the gain by almost 0.3 dB. The overall structure is divided into seven different cavities. Cavity-1 is used to feed the L-slots available in the remaining six sub cavities. The main Cavity-1 is having a metallic vias in-front of the sub-cavities, which was introduced to help individually feed the slots in cavities. The positions of these vias are optimized to improve the front to back and side lobe radiation ratio and hence achieve the desired gain. The design is fed by a lumped port, the position of which is adjusted after a detailed parametric study. The L-slots are created on the top copper layer of the substrate, while DGS is created at the bottom surface. The position and the inner /outer radius of the DGS are also optimized to achieve a low side lobe level. The design also integrates two metallic vias just below the DGS structure. These vias help to modulate the current till the last L-shaped slots. Various parameters of the design are given in Table 1.

Working principle

The resonant frequency of the sub-cavity containing the L-slots can be calculated by using equation-1[8].

$$F_{R(TEm0q)} = \frac{c_o}{2.\sqrt{\varepsilon_r}} \sqrt{\left(\frac{m}{W_{eff}}\right)^2 + \left(\frac{q}{L_{eff}}\right)^2} \tag{1}$$

where,

$$L_{eff} = L - \frac{D^2}{0.95 \cdot p} \tag{2}$$

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Table 1. Design parameters

Parameter name	Dimension	Parameter name	Dimension
Via radius	0.5 mm ($0.04\lambda_g$)	Distance b/w two vias	1.5 mm ($0.1\lambda_g$)
Height of substrate	3.18 mm ($0.2\lambda_g$)	Outer cavity dimension	48 mm × 24 mm ($3.6\lambda_g \times 1.8\lambda_g$)
Sub cavity dimension	13.5 m× 8 mm ($1.0\lambda_g \times 0.6\lambda_g$)	DGS Inner/outer radius	2.5 mm / 2 mm ($0.19\lambda_g/0.15\lambda_g$)

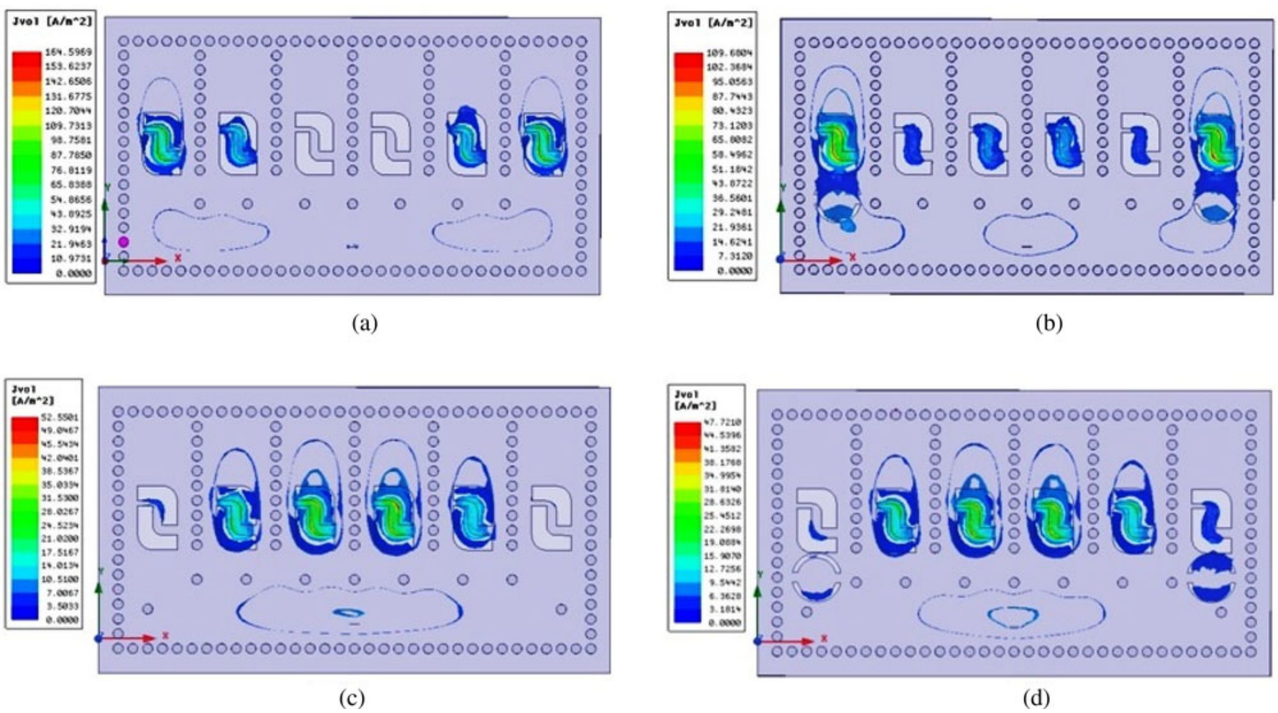

Fig. 2. The current distribution in structure at 14.59 GHz (a) without DGS and outer slots vias (b) without outer vias (d) without DGS (c) proposed design.

and

$$W_{eff} = W - \frac{D^2}{0.95 \cdot p} \qquad (3)$$

'D" is the diameter of the via, whereas "p" is the pitch of the via. The above equations are only valid for $b < \lambda_o.\sqrt{\varepsilon_r}/2$ and $b < 4D$. The above formula got verified for sub-cavity, by putting the value of "D" = 1 mm, "p" = 1.5 mm, "L" = 13.5 mm, "W" = 8 mm, "ε_r" = 2.33 and the height of the substrate "h" = 3.18 mm. The cavity resonates at 15.5 GHz in its fundamental TE_{101} mode. The resonant frequency in the measured result is 14.29 GHz whereas in the simulation it is 14.59 GHz. This proves the closest approximation of the resonant frequency in theoretical, simulated and measured results. The resonant frequency shifted to the left due to the inductive loading of the slots created inside the cavity. This also helps to miniaturize the antenna for the given frequency of operation.

The array factor of the proposed 1 × 6 antenna array can be evaluated by using equation (4) and (5) [17].

$$(AF)_N = \frac{1}{N}\left[\frac{\sin\left(\frac{N}{2}\psi\right)}{\sin\left(\frac{1}{2}\psi\right)}\right] \qquad (4)$$

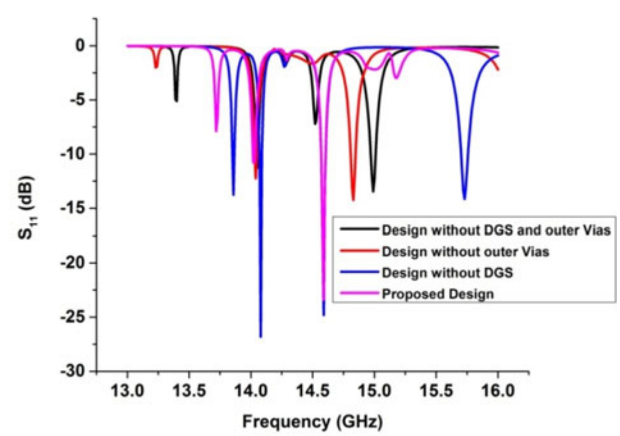

Fig. 3. Comparison S_{11} (dB) graph for various designs.

where,

$$\psi = k.d.cos\theta + \beta \qquad (5)$$

Here, β is the successive phase difference between the antenna elements, "d" = 8 mm/$0.55\lambda_o$ is the distance between the two antenna elements and "N = 6", k is the free space wave number.

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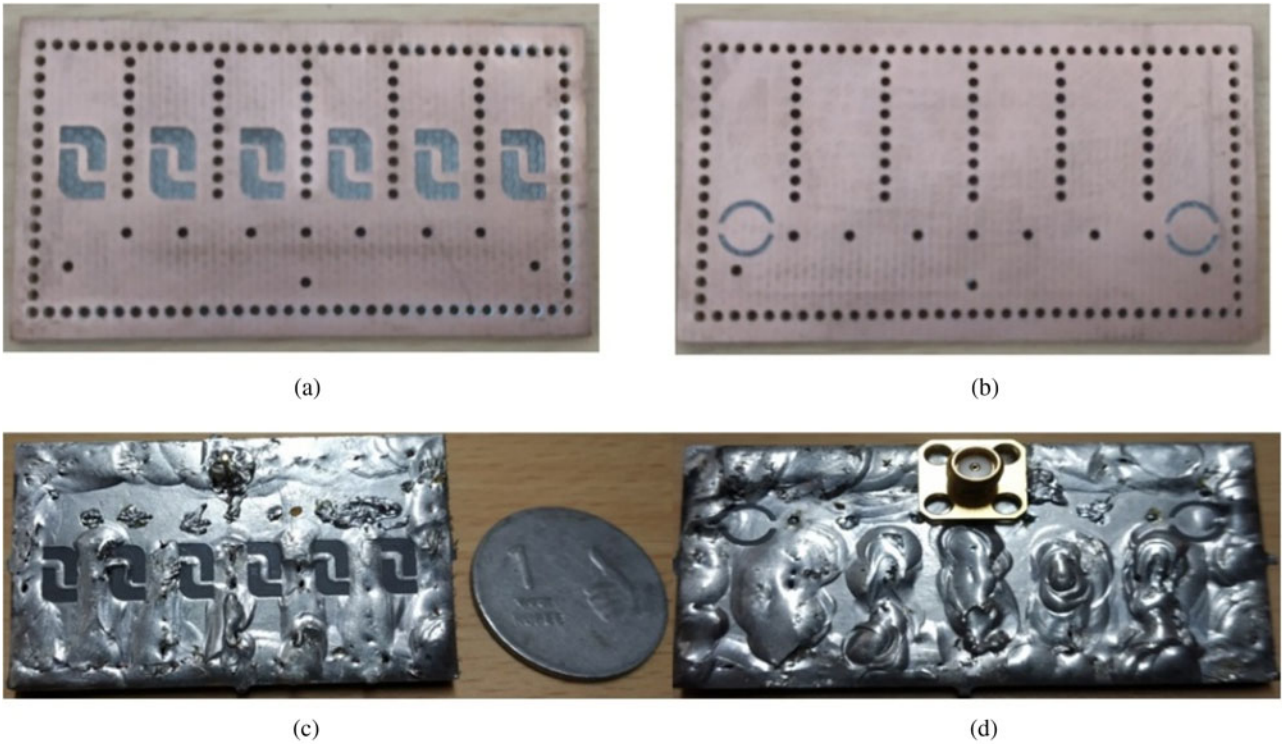

Fig. 4. The fabricated antenna prototype (a) Top layer (b) Bottom Layer (c) Top layer after tinning process (d) Bottom Layer after tinning.

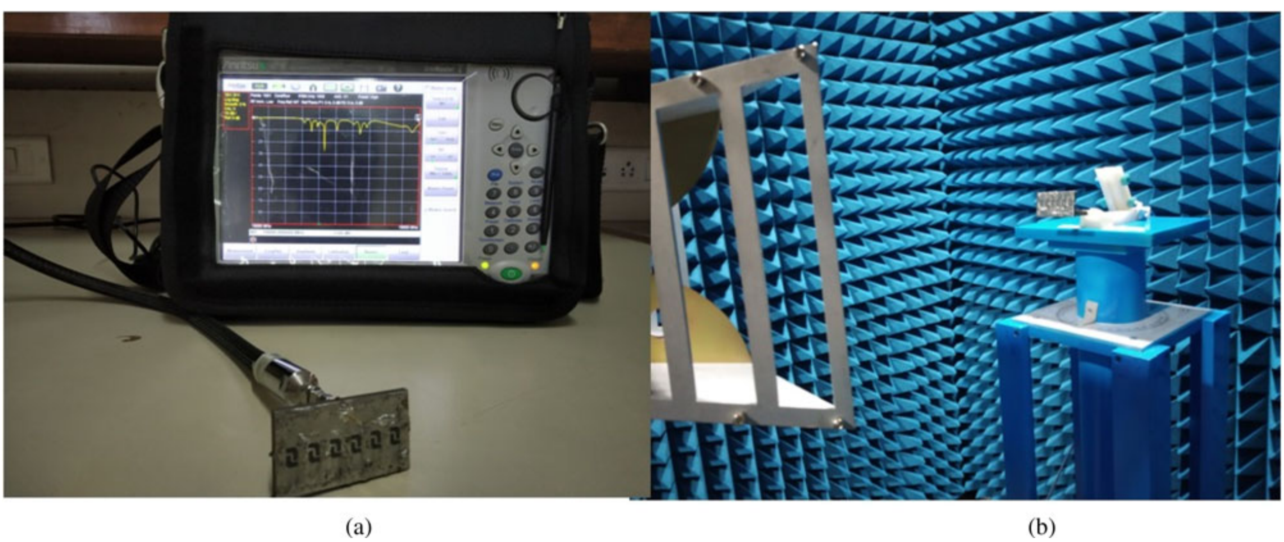

Fig. 5. Antenna under test at (a) Antrisu Site Master, S820E VNA (b) Anechoic Chamber for testing antenna radiation pattern and gain.

The advantage of using end metallic vias and DGS structure can be seen in Fig. 2. It is clear from Fig. 2(b) that the outer metallic vias helps to restrict the maximum current to flow on the outer *L*-slots. Figure 2(c) shows that the DGS structure allows some amount of power to flow to the outer L-slot, which in turn improve the overall gain of the antenna. The comparison of the designs shown in Fig. 2 is explained on the basis of S_{11} (dB) parameter through Fig. 3.

The S_{11} (dB) comparison graph shows one important aspect of the design. The design without DGS shows one more prominent frequency of operation at 14.08 GHz, which was quite suppressed in the proposed antenna design with the introduction of DGS. The reason not to include the lower frequency is that the radiation pattern at 14.08 GHz for the design without DGS shows a dip in the center.

Simulated and measured results

The device is fabricated through a PCB prototyping machine on an RT/Duroid Roggers substrate of thickness 3.18 mm.

Due to the use of the thicker substrate, the process of creating the printed though hole across it was typical, hence the vias are filled with copper wire and soldered at both ends as shown in Fig. 4. During this process the copper layer on the top and bottom layers were tined. Tinning is a common phenomenon in PCB design

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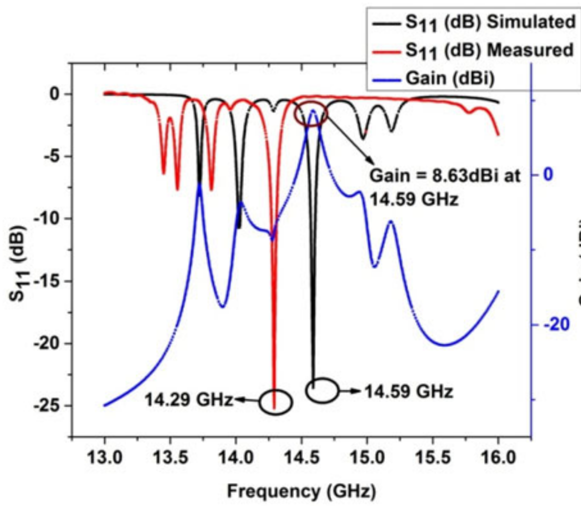

Fig. 6. Tested and Measured S_{11} (dB) parameter with Gain (dBi).

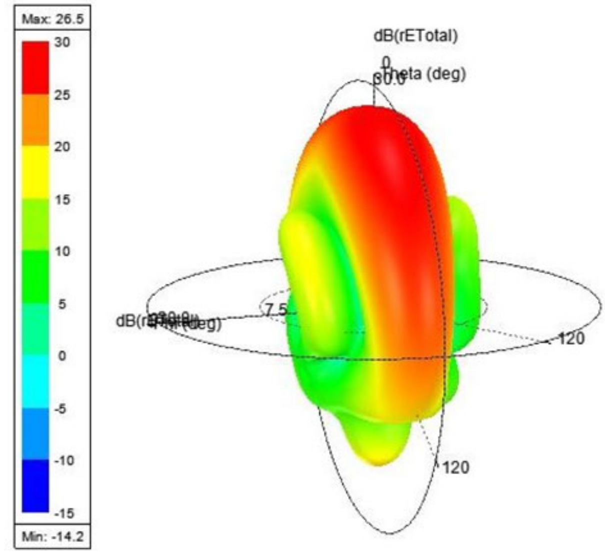

Fig. 8. Three-dimensional electric field.

and does not affect antenna parameters to a larger extent. The proposed design was tested for S_{11} (dB) parameter on the Antrisu Site Master, S820E VNA for 30 GHz. The test bench of the antenna under test can be seen in Fig. 5(a). Figure 5(b) shows the Anechoic Chamber setup for testing antenna radiation pattern and gain.

The S_{11} (dB) of the proposed antenna is shown at Fig. 6. The measured results shifted left by 0.3 GHz. The shift can be explained by the loading done by tin material at the top and bottom layer of the antenna. The lower frequency band in the measured S_{11} (dB) is suppressed by a considerable amount, so the band can be neglected. The measured result shows that the antenna achieves a 10 db bandwidth of 44 MHz.

Figure 6 also shows that at the operating frequency of 14.59 GHz the antenna shows a gain of 8.63 dBi. The measured gain at 14.29 GHz is calculated as 8 dBi when the distance between the test antenna and referenced antenna is kept 1 m and the gain of the referenced double ridge horn antenna at 14.29 GHz is 14.35 dBi. Figures 7(a) and 7(b) shows the measured and simulated normalized electric field for two planes (a)angle phi = 0° (xz plane) and (b)angle phi = 90° (yz plane) for the proposed antenna.

The two dimensional and three-dimensional electric field in Figs 7 and 8 respectively, shows that the radiation pattern is projected only in a single direction. A high directive beam with low side and back lobe radiation leads to achieving a high gain. The FBR of the proposed antenna structure is 24.9 dB.

The comparison of the proposed design is done in Table 2, with seven different references cited in this communication. From Table 2 it is clear that the proposed antenna design is smaller in size and achieves good gain.

Since, there are limited numbers of designs of the *L*-slot antenna, hence the major comparison was done with other types of the slot antenna enclosed in a SIW cavity and further divided into sub cavity. In [11], the author further replicated his design to form a phased array antenna, hence the comparison was done only with a single element slot antenna.

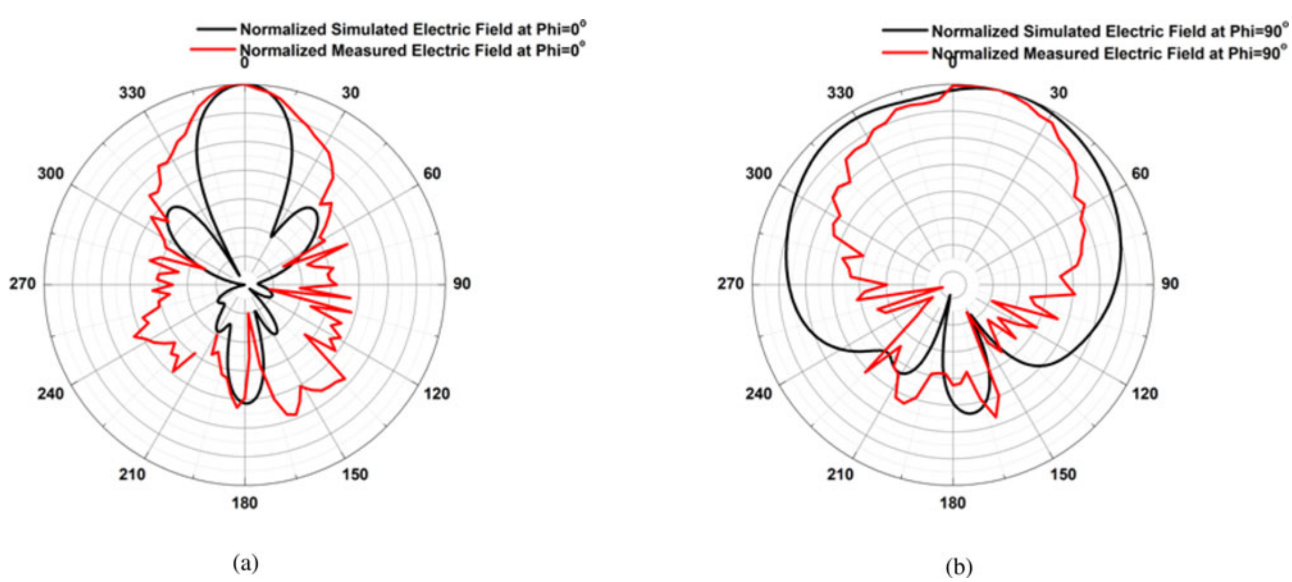

Fig. 7. Electric Field (a) measured and simulated for angle phi = 0° (b) measured and simulated for angle phi = 90°.

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Table 2. Comparison Table

Reference	Number of Slots (elements) / cavity	Operating Frequency (GHz)	Cavity Size (wavelength$^{2)}$	Gain (dBi)
[10]	1/(single cavity)	10.93 /12.69	>11.25 mm and 9.25 mm	6.58 / 6.82
[11]	4/ (single cavity)	5.4 to 6.45	300 mm × 200 mm($9.7\lambda_g \times 6.4\lambda_g$)	6–8
[12]	16/ (single cavity)	34.07~ 35.1	60.6 mm × 17 mm($13\lambda_g \times 3.7\lambda_g$)	15.64
[13]	16 /(two cavity)	10	36.5 mm × 42.5 mm + 21 mm × 25 mm ($2.3\lambda_g \times 2.7\lambda_g$ + $1.3\lambda_g \times 1.6\lambda_g$)	11.9
[14]	24/ (four cavity)	5.772 -port1 / 5.964 -port-2	153.4 mm × 148.3 mm ($4.4\lambda_g \times 4.3\lambda_g$)	15.3–16.01
[15]	4 /(single cavity)	27	……..	7–9.8
[16]	16 /(four cavity)	9.9–10.34	59 mm × 48 mm ($3.7\lambda_g \times 3.0\lambda_g$)	12.5–14.9
This Work	6 /(seven cavity)	14.59	48 mm × 24 mm($3.6\lambda_g \times 1.8\lambda_g$)	8.63

Conclusion

This article proposed a novel dual *L*-slot array antenna structure with DGS on the ground plane, which achieves high gain and low front-to-back lobe ratio. The design of the antenna is simple which makes it easier to fabricate at a low cost. The antenna is compared with other designs based upon its operating frequency and gain (dBi). The simulated results show a narrow half-power beamwidth of 25 degrees, which can be used for various high-frequency applications working in the Ku band. The design can be replicated to form a bigger array, which can be used for the front end antenna in the satellite communication.

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