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Research Article

Logarithmic Slots Antennas Using Substrate Integrated Waveguide

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This paper represents new generation of slotted antennas for satellite application where the loss can be compensated in terms of power or gain of antenna. First option is very crucial because it totally depends on size of satellite so we have proposed the high gain antenna creating number of rectangular, trapezoidal, and I shape slots in logarithm size in Substrate Integrated Waveguide (SIW) structure. The structure consists of an array of various shape slots antenna designed to operate in C and X band applications. The basic structures have been designed over a RT duroid substrate with dielectric constant of 2.2 and with a thickness of 0.508 mm. Multiple slots array and shape of slot effects have been studied and analyzed using HFSS (High Frequency Structure Simulator). The designs have been supported with its return loss, gain plot, VSWR, and radiation pattern characteristics to validate multiband operation. All the proposed antennas give gain more than 9 dB and return loss better than −10 dB. However, the proposed structures have been very sensitive to their physical dimensions.

1. Introduction

Rapid development in the field of wireless communication system that operates in the microwave range is payed more attention from industry and academia [1–3]. In the present, rectangular waveguides are widely used in microwave engineering for antenna [4], filters [5, 6], couplers [7], and so forth due to their advantages of low losses, high power handling, and high isolation [8]. In addition, slot array antennas based on waveguides that feature favorable antenna performance such as high directivity, low cross-polarization, and low cross-talk have been presented [9, 10, 15].

In 1943, the slot array was invented at McGill University in Montreal by Watson. One of the best features of this antenna is horizontal polarization and omnidirectional gain around the azimuth. A slot along the length is cut into the wall of a waveguide that disrupts the transverse current flowing in the wall, which enforces the current to travel at border of the slot and induces an electric field in the slot [11, 12]. The location of the slot in the rectangular waveguide decides the current flow. Thus, the pose determines the impedance introduced to the transmission line and the amount of energy coupled and radiated from the slot. Slotted waveguide arrays (SWA) have some advantages over microstrip antennas such as having low loss, high isolation, and high power handling [11]. Due to these advantages, SWA antennas are widely used in communication and radar systems particularly at microwave wave frequencies. Regarding conformal array applications, microstrip antennas are easier to implement compared to SWA antennas; however, excitation of antenna elements by a waveguide feed network is advantageous compared to microstrip feed network in terms of eliminating radiation losses and cross coupling problems. Moreover, complex feed network structure is not needed in SWA to excite the slots in the same waveguide. Furthermore, the array of waveguides can be formed without cross coupling problems.

However, the manufacturing of these waveguides needs to be accomplished with sufficient accuracy so as to allow for operation at millimeter wave frequencies. On the other hand, antennas and microwave components used at lower frequencies typically rely on planar designs which are mostly realized with the Printed Circuit Board (PCB) processing technique [13, 14]. Moreover, conformal arrays have a specific shape determined by the parameters other than radiation pattern and input match requirements and they can easily be implemented using microstrip technology using a flexible substrate or multifaceted surfaces [15].

This mature technology leads to, not only low-cost designs, but also the possibility to easily integrate them with common electronic components. However, these planar designs are by nature not fully shielded and thus subject to radiation, cross-talk, and packaging problems [16]. It has also complex feed networks such as probes feeding patch elements. Strip line can be used to eliminate the radiation losses; however, cross coupling problems are encountered in the feed network with strip line structure. These drawbacks added to the potentially high conductor losses make this technology not feasible to implement high frequency complex structures, such as large feeding networks [17]. It is then obvious that a large performance gap exists between components based on metallic waveguides and the ones based on PCBs.

A very promising candidate to fill this gap and to provide widespread commercial solutions is the SIW technology or, more in general, the Substrate Integrated Circuit (SIC) architecture [18]. This technology allows building high performance, low cost, and reliable waveguide-like components using planar processing techniques, such as the PCB or the Low-Temperature Cofired Ceramic (LTCC) [19]. It has also unique features such as compact size in comparison with waveguide antennas and also simpler structure in comparison with reflector antennas [1].

On the basis of the above two, SIW slot array antennas have been proposed with high gain and ultrawide bandwidth specifically for C band, X band, and Ku band applications. The proposed structures contain three different shapes of slots like rectangle, trapezoidal, and I shape and its size varies according to logarithm value. All the structures generate quite better results and respond to resonant frequencies according to their size. One of the unique features of them is that they generate sharp radiation pattern and isolation between bands is much more high. Due to these advantages, the slotted SIW antennas are good candidates for the conformal array applications especially when SIW is implemented using a flexible substrate. There is a limited study in the literature on the conformal array applications with slotted waveguide arrays.

With the aim of the above, the structure of paper is as follows: Section 2 describes the theory of basic SIW and based on it is the design of slotted linear arrays of antenna. Then, Section 3 shows the design and calculation of various proposed antennas and their simulation results are shown in Section 4. Section 5 contains comparison of all the proposed antennas and discussion of results. Finally paper is ended with conclusion.

2. SIW Antenna Design

SIW is described as two conducting layers are connected by cylindrical vias row at both sides which is shown in Figure 1 [20]. In Figure 1, d is the diameter of vias, w is the equivalent width of SIW, p is the spacing between two vias, and h is the thickness of substrate. Structure of SIW contains low cost, high Q-factor, low radiation, and high density integration which makes it preferable.

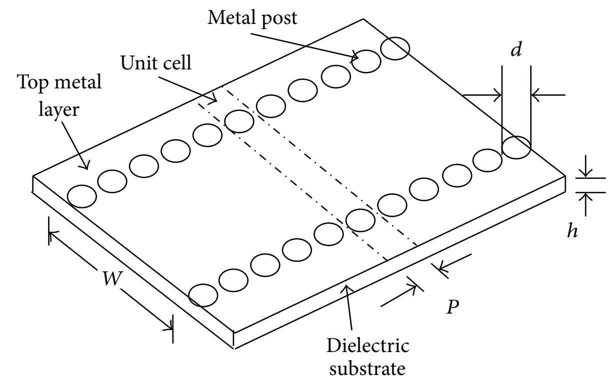


Figure 1: Basic structure of SIW.

The cutoff frequency of SIW is defined as $f_c = c/2a$, where a is width of waveguide; it can change by varying the width in conciliation of degrading the overall characteristics of its components.

As we know that, the current in the walls of the waveguide must be comparative to the difference in the electric field between two points (so the selection of slot in SIW is very important) [21]. Therefore, to make a slot in the correct center of the broad wall of the waveguide will not radiate at all, since the electric field is not asymmetrical around the center of the guide and thus is indistinguishable at both edges of the slot. If the position of slot is moved from the centerline, the difference in field concentration between the rims of the slot is larger, so that more current is interrupted and more energy is coupled to the slot that ultimately increases radiated power. In other sides of the waveguide, the field strength is very weak, since the sidewalls are short circuited for the electric field. The produced current must also be small; longitudinal slots which are far from the center or created in the sidewall will not radiate significantly.

In this paper, we keep the distance between slots as $\lambda_g/2$ such that the slots will be fed in the same phase (spacing between the slots at $\lambda_g/2$ intervals in the waveguide is an equivalent electrical spacing of 180°. Therefore, each slot is exactly out of phase with its neighbors, so their radiation cancelled each other. On the other side, slots on opposite sides of the center axis of the guide are out of phase (180°), so we can swap the slot displacement around the center axis and have a total phase difference of 360° between slots, putting them back in phase) and the beam will not be inclined [22]. For the position of the last slot, the center of slot is kept at guided quarter wavelength away from the closed end of the waveguide. As we know that a short circuited quarter wavelength stub of transmission line works as an open-circuit, the closed end does not impact on the impedance. Another reason to keep the closed end is space $3\lambda_g/4$ for mechanical fabrication; the extra half-wavelength is crystal clear.

3. SIW Slots Array Antenna Parameters

The SIW slots array antenna is shown in Figure 2. Here, prime important parameters in the design are distance and diameter of posts which controlled the flow of electric field. Slots are

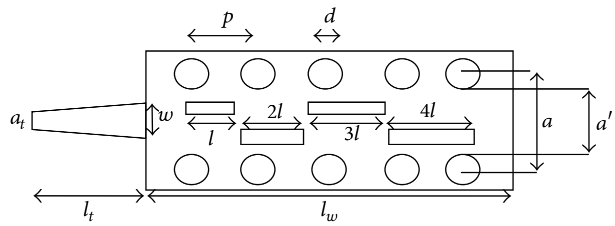


FIGURE 2: Schematic of proposed antenna.

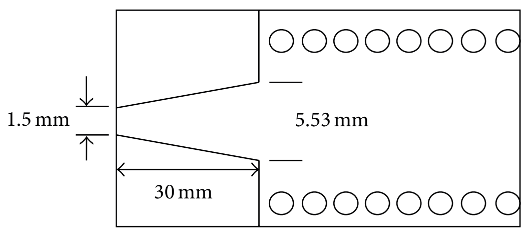


FIGURE 3: Microstrip to SIW transition.

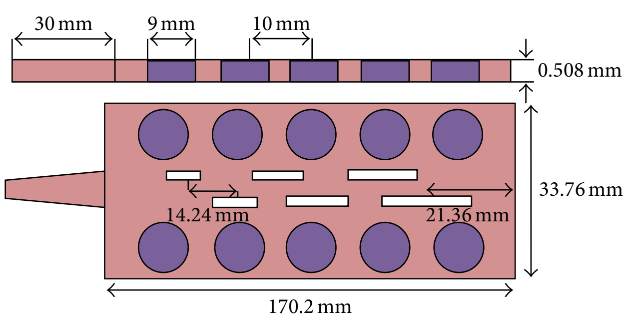


FIGURE 4: Side and top view of 1st proposed logarithmic rectangular slots array antenna.

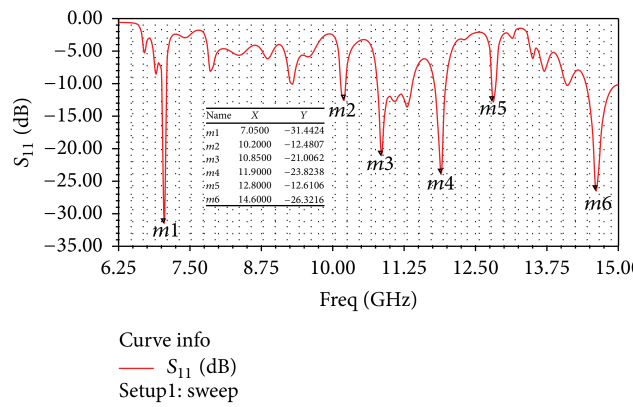


FIGURE 5: S_{11} of 1st proposed logarithmic rectangular slots array antenna.

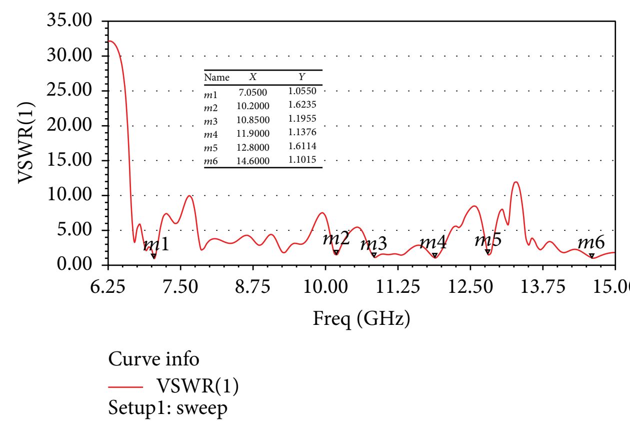


FIGURE 6: VSWR of 1st proposed logarithmic rectangular slots array antenna.

printed on a 0.508 mm thick Roger RT duroid 5880 substrate (the relative dielectric constant is 2.2) with the size of $W \times L = (33.76 \times 170.2)$ mm. The selection of feed is also very important and here we have selected feeding using tapered slot which is shown in Figure 3 that provide transition from microstrip to SIW [23]. A tapered microstrip line has the following parameters: the width of the feed line $a_t = 1.5$ mm, $w = 5.53$ mm and the length of feed line $l_t = 30$ mm (calculation of all the parameters are shown below). The finite ground plane has an area of $W \times H = (33.76 \times 170.2)$ mm.

Parameters Calculation [21]

(1) For designing SIW based antenna define first substrate dimensions which are given by $a \times b$ for that a' and a must be known as shown below (a' inversely propositional to cutoff frequency):

$$a' = \frac{c}{2 f_c \sqrt{\varepsilon_r}}. \tag{1}$$

(2) Now obtain center-to-center distance with the help of a' as

$$a = a' + \frac{d^2}{0.95 p}. \tag{2}$$

(3) To select the diameter of post and also distance between two posts, we have to consider the following condition which minimizes the losses [1]:

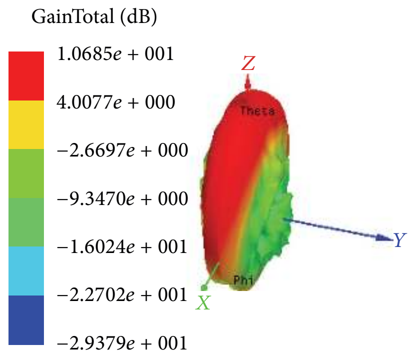
$$p \le 2d$$
$$0.05 < \left(\frac{p}{\lambda_c}\right) < 0.25 \tag{3}$$
$$\frac{\lambda_g}{5} < d,$$

where λ_g is given by

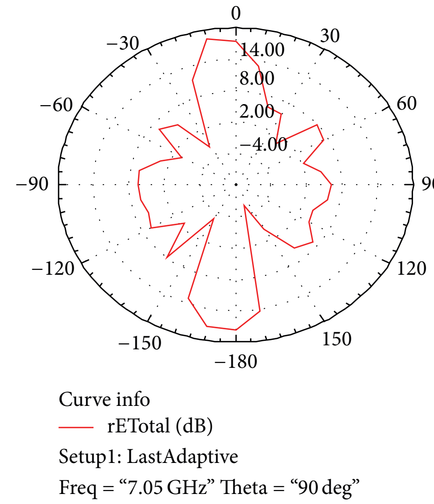
$$\lambda_g = \frac{\lambda_c}{\sqrt{\varepsilon_r}}. \tag{4}$$

Here, p is the center-to-center distance between two posts; d is the diameter of the post; λ_g is guided wavelength; λ_c is cutoff wavelength; ε_r is relative permittivity of dielectric medium.

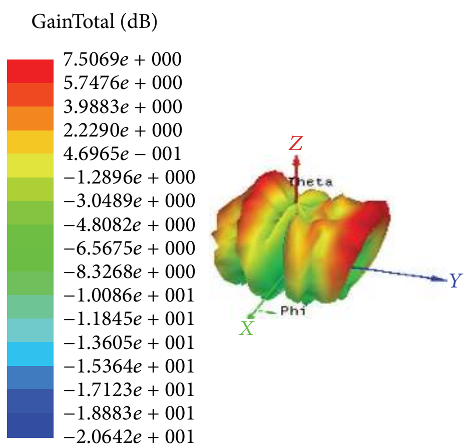
(4) To apply tapper feed at antenna, first find the tapper width by using traditional microstrip calculation which is denoted by (w_1) and after that feeding width at dielectric side.



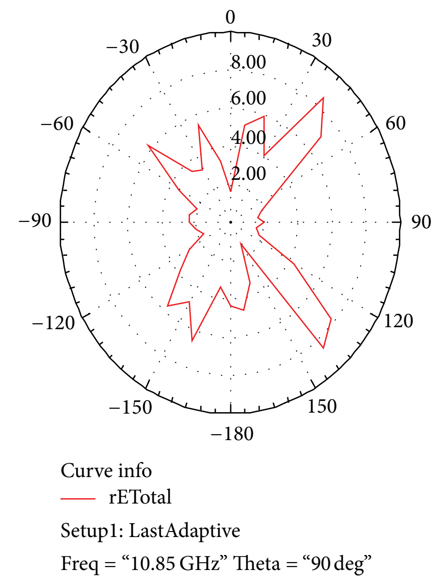
Antenna gain plot for 7.05 GHz



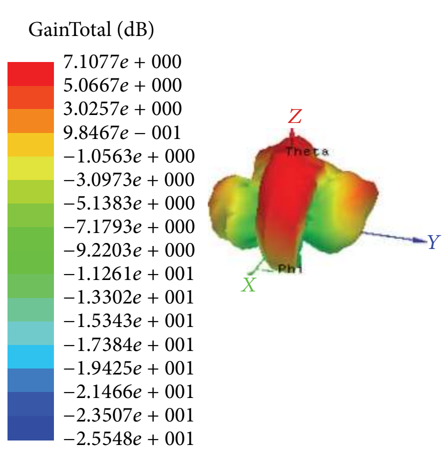
Radiation pattern for solution frequency 7.05 GHz



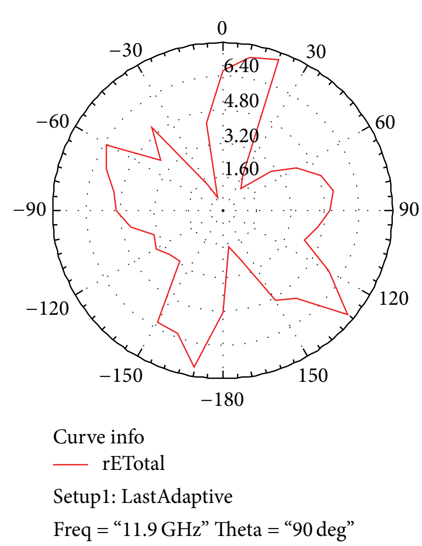
Antenna gain plot for 11.9 GHz



Radiation pattern for solution frequency 10.8 GHz

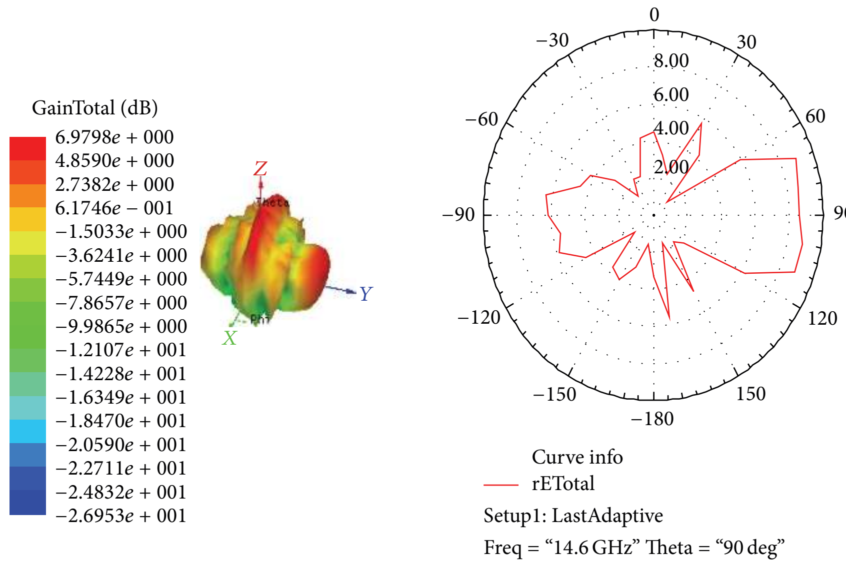


Antenna gain plot for 10.8 GHz



Radiation pattern for solution frequency 11.9 GHz

Figure 7: Continued.



Antenna gain plot for 14.6 GHz   Radiation pattern for solution frequency 14.6 GHz

Figure 7: Gain plots and radiation patterns at different resonant frequencies.

The width of tapper at feed side is 0.4 times the opening of patch antenna:

$$a_t = 0.4\,(a - d)\,. \tag{5}$$

The width of tapper at antenna side is

$$w = \frac{c}{2f\sqrt{(\varepsilon_r + 1)/2}}. \tag{6}$$

Finally, length of tapper for impedance match is given by

$$l_t = \frac{n * \lambda_g}{4} \quad \text{where } n = 1, 2, 3, \ldots. \tag{7}$$

It is already derived that the gain and beamwidth formula for the slots have equal distance end to end and spacing along the waveguide. A simple procedure to calculate the gain of a slot antenna is on array of dipoles. As we double the dipole slots they increase the double gain. So for 16 slots it is possible to get gain of 12 dB. Each time we double the number of dipoles, we double the gain, or add 3 dB. Thus, a 16-slot array would have a gain of about 12 dB. Gain can be calculated from the equation $G = 10\log(N)$ dB, for N total slots.

Now, include the effect of gain with spacing of slot better to be described as

$$\text{Gain} = 10\log\frac{N * \text{slotspacing}}{\lambda_0}\ \text{dB}. \tag{8}$$

Calculated gain is always equal to average gain; now beamwidth is given by

$$\text{Beamwidth} = 50.7\frac{\lambda_0}{(N/2) * \text{slotspacing}}\ \text{Degree}. \tag{9}$$

Table 1: Specification of the proposed structure.

Parameters	Value
Center frequency	7 GHz
Return loss	>−10 dB
VSWR	1
Gain	>5 dB
Dielectric constant (RT duroid)	2.2

4. Design of Proposed Structures

Here, we have considered the design of proposed structure based on the specification given in Table 1. These specifications are considered based on the satellite and RADAR applications in which we are targeting C, X, and Ku band frequencies. The C band, X band, and Ku Band defined by an IEEE standard for radio waves and radar engineering with frequencies that range from 4.0 to 8.0 GHz, 8.0 to 12.0 GHz, and 12.0 to 18.0 GHz, respectively. Frequency range of 3.7 to 4.2 GHz is used for the satellite downlink communication in C band and the band of frequencies from 5.925 GHz to 6.425 GHz for their uplinks. The X band is used for short range tracking, missile guidance, marine, radar, and airborne intercept. It is used, especially, for radar communication ranges roughly from 8.29 GHz to 11.4 GHz. The Ku band is used for high resolution mapping and satellite altimetry. Ku band, especially, is used for tracking the satellite within the ranges roughly from 12.87 GHz to 14.43 GHz.

From the above applications, the proposed structure design is targeted at center frequency of 7 GHz. Physical dimensions of the first proposed structure are calculated by the above formula and summarized in Table 2. The wire line structure of proposed antenna is shown in Figure 3.

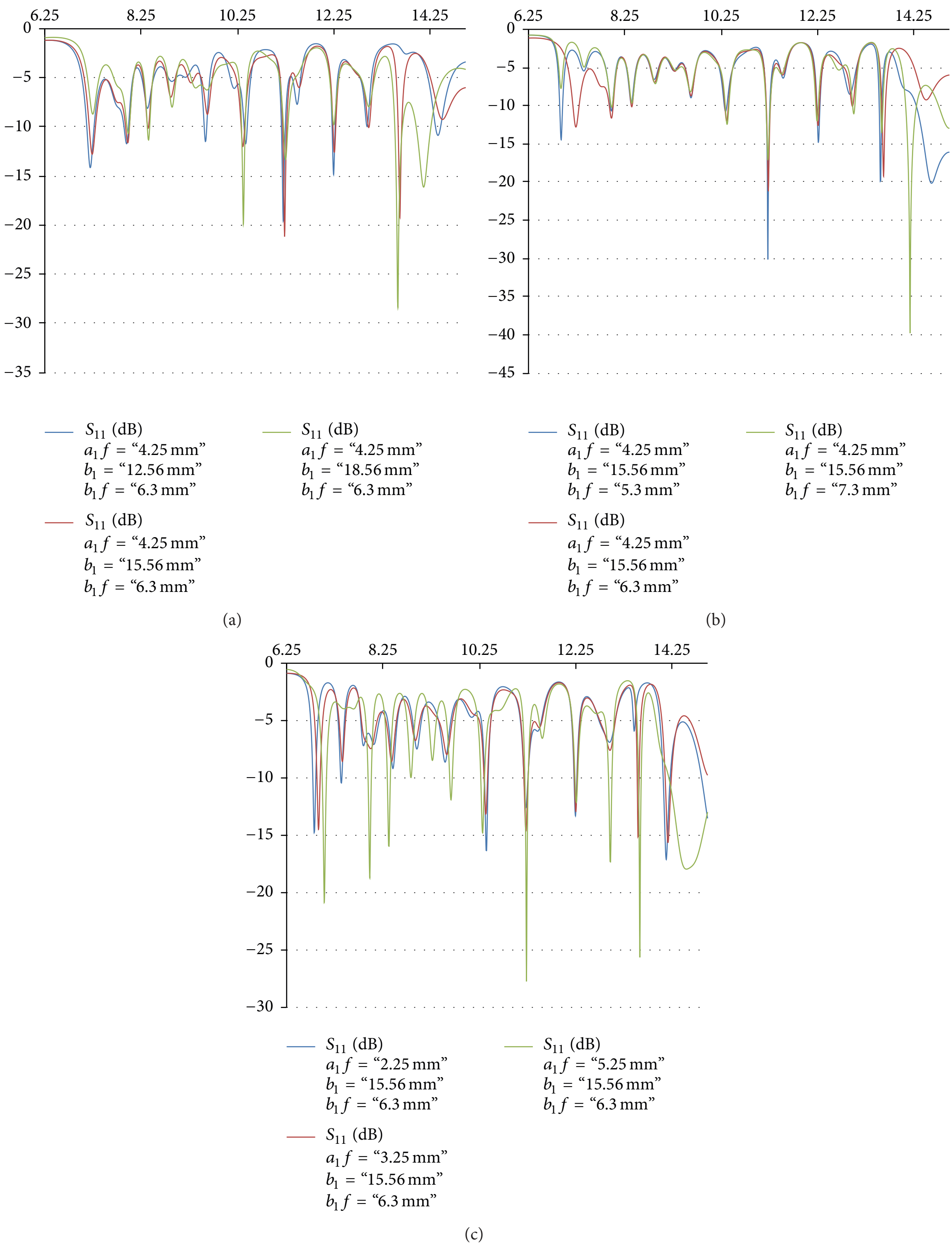


FIGURE 8: (a) S_{11} of logarithmic rectangular slots array antenna with respect to variations in 1st slot position. (b) S_{11} of logarithmic rectangular slots array antenna with respect to variations in 1st slot position. (c) S_{11} of logarithmic rectangular slots array antenna with respect to variations in width of 1st slot.

TABLE 2: Calculated parameters.

Parameter	f_c	a'	D	P	a_s	ε_r	λ_c	λ_g	w	a_t	l_w	l_t
Value	7.1 GHz	14.2 mm	9 mm	10 mm	22.76 mm	2.2	42.25 mm	28.48 mm	5.504 mm	1.5 mm	170 mm	30 mm

TABLE 3: Summaries of simulated parameters.

Resonant frequency	Gain in dB	Bandwidth in MHz	VSWR	Peak return loss in dB
7.05 GHz	10.85	100	1.05	−31.43
10.85 GHz	7.5	200	1.19	−21.00
11.9 GHz	7.1	250	1.13	−23.71
14.6 GHz	6.9	400	1.097	−26.64

As shown in Figure 4, it contains six rectangular slots array whose longitudinal length is varied according to logarithmic manner. We are keeping center-to-center distance between two slots as 14.24 mm ($\lambda_g/2$) and center of last slot to broadside wall as 21.36 mm.

The structure has been simulated using HFSS (High Frequency Structure Simulator) and it generates return loss shown in Figure 5. As shown in Figure 5, the structure generates six resonant frequencies one in C band (7.05 GHz), three in X band (10.2, 10.55, and 11.5 GHz), and two in Ku band (12.8 and 14.6 GHz), respectively. These results are totally expected since the proposed antenna is composed of different resonant slot lengths providing the multiband performance. At all the resonant frequencies VSWR is also good which is shown in Figure 6. One of the extraordinary performances generated by this structure is shown in Figure 7 which represents the gain value that is more than 10 dB in single layer and single array combination compared to other traditional antennas having multilayer and 2 to 3 arrays for achieving higher gain. Various gain and radiation patterns of the proposed logarithmic slots array of antenna for different resonant frequencies are shown in Figure 6. All the simulation results are summarized in Table 3.

It is possible to tune the frequency by changing the geometrical position with respect to wave propagation direction and physical dimensions of the slots. All these methods ultimately changed the value of reactance of resonators and coupling of the EM field. Here we have demonstrated three possible methods to tune the response: (i) pose of slot; (ii) length of slot; (iii) width of slot. For demonstration and analysis purpose only we applied the above tuning methods to the first slot. These methods can also be applicable for other remaining slots. Figure 8(a) demonstrates simulation result of reflection coefficient obtained by changing the position of first slot which was kept at $\lambda_g/2$ distance with respect to second slot in longitude direction. It shows that when we move the slot position in positive longitude direction, it improves the value of return loss and increment in opposite direction, it reduces the value of return loss. Figure 8(b) shows the simulation result with increasing the length of the first slot. It decreases the values of inductance and increases the capacitance value. Variation in length gave minor effect on a reflection coefficient value. Similarly Figure 8(c) is the result of reflection coefficient with the change in width of

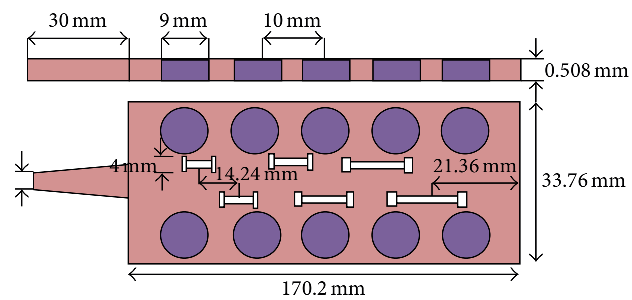


FIGURE 9: 2nd proposed structure contains I shape logarithmic slots array antenna.

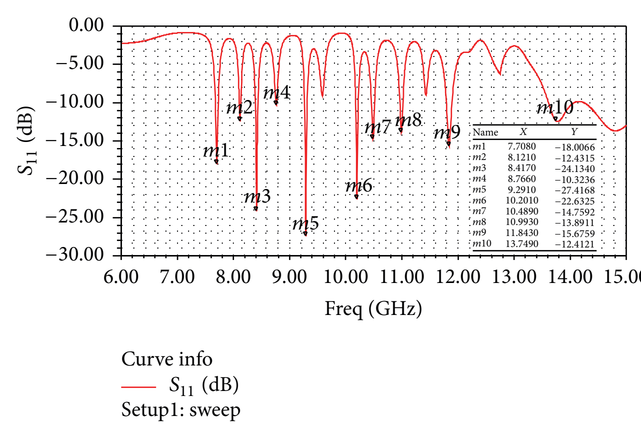
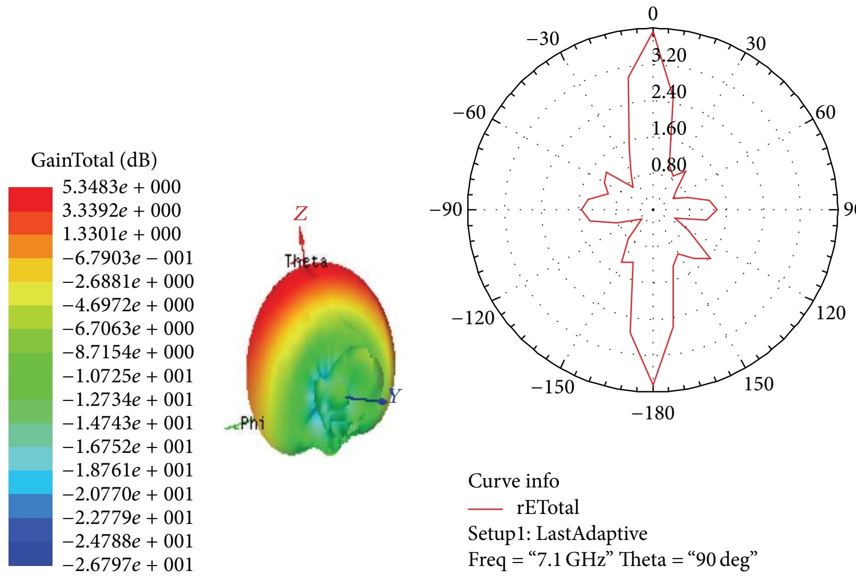


FIGURE 10: S_{11} plot for I shaped logarithmic slots array antenna.

the first slot that tunes resonant frequency effectively and also produces very sharp bandwidth.

In the second proposed structure, instead of taking rectangular shape slots, longitudinal I shape is selected which is shown in Figure 9. Spacing between two slots and center distance of last slots from the end boadsie wall are the same as 1st proposed design. In first I shape slot, vertical height of the slot is 4 mm and length of slot is 10 mm which progressively increases for other slots according to logarthmic nature.

This structure is also simulated by using HFSS and its return loss is shwon in Figure 10. This structure radiates at six resonant frequencies: one in C band (7.7 GHz), three in X band (8.12, 8.41, 8.76, 9.29, 10.2, 10.48, 10.99, 11.45, and



(a) (b)

FIGURE 11: (a) Gain plot and (b) radiation pattern for I shape logarithmic slots array antenna.

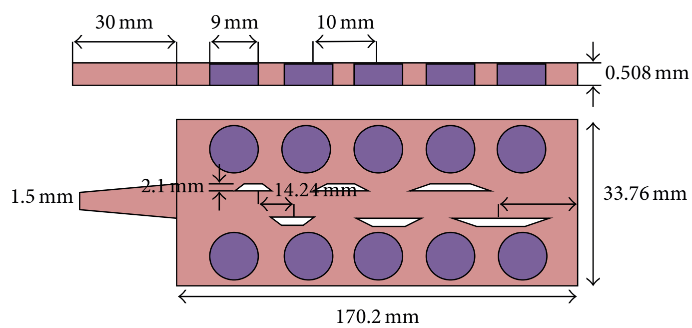


FIGURE 12: 3rd proposed structure contains trapezoidal logarithmic slots array antenna.

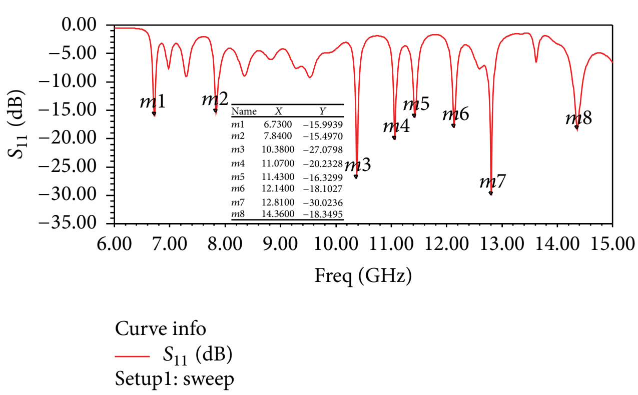


FIGURE 13: S_{11} plot for trapezoidal logarithmic slots array antenna.

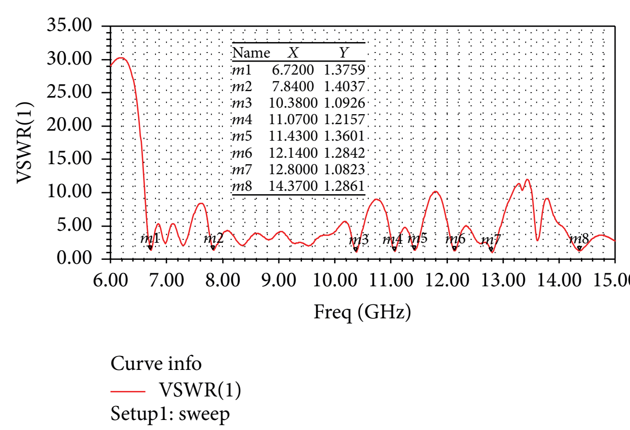


FIGURE 14: VSWR of 3rd proposed trapezoidal logarithmic slots array antenna.

11.9 GHz), and two in Ku band (13.95 and 14.5 GHz). The gain plot and radiation pattern for 6.7 GHz frequency are shown in Figures 11(a) and 11(b), which shows that it generates gain of 5 dB which is half compared to first proposed structure.

Third proposed structure contains trapezoidal logarithmic slots array as shown in Figure 12. Distances of all the slots are the same as 1st proposed design. Simulated result of the proposed structure is shown in Figure 13, which shows higher return loss occurring at eight different frequencies: two in C band (6.7 and 7.54 GHz), four in X band (10.25, 11, 11.43, and

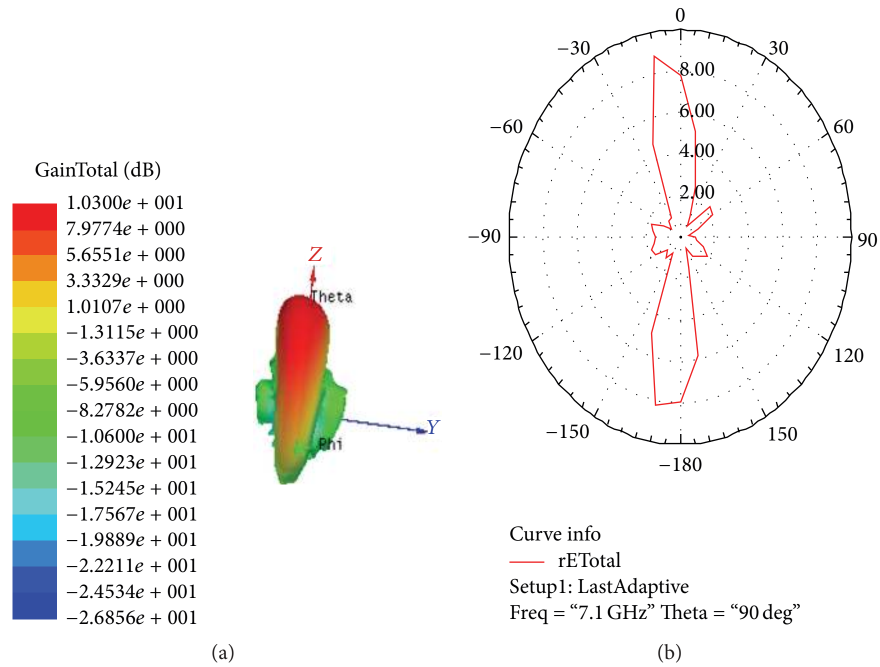


Figure 15: (a) Gain plot and (b) radiation pattern for trapezoidal logarithmic slots array antenna.

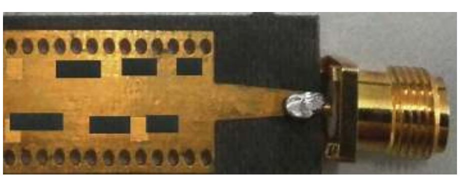


Figure 16: Fabricated model of logarithmic rectangular slots array antenna.

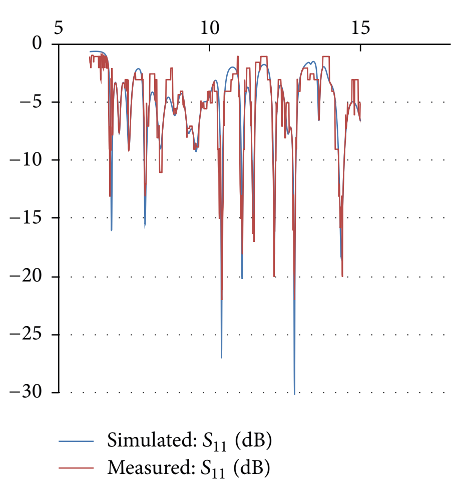


Figure 17: S_{11} of logarithmic rectangular slots array antenna.

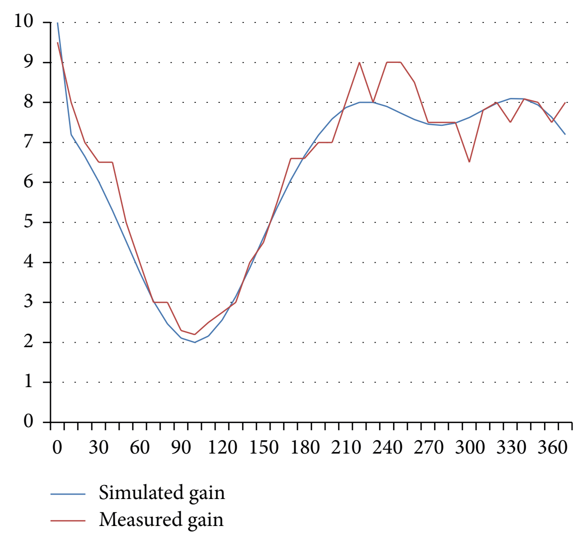


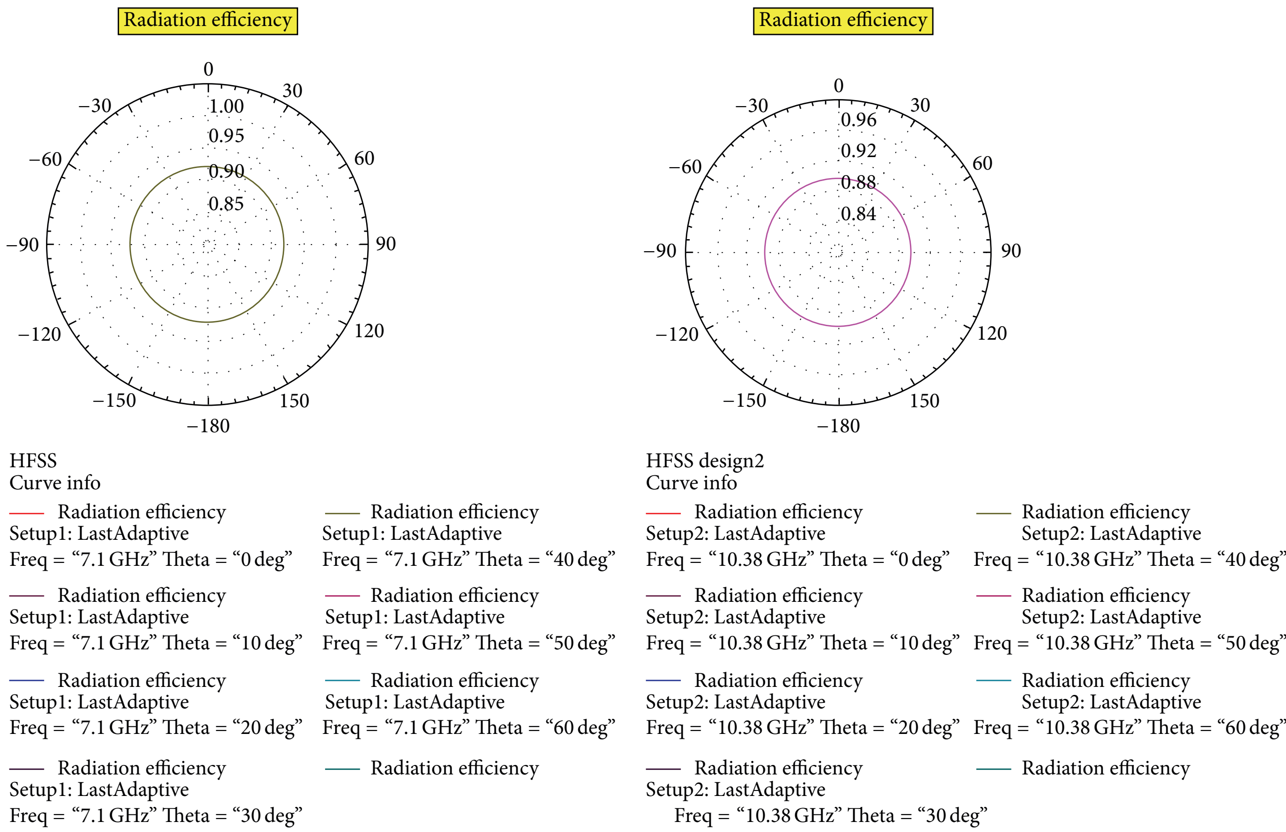
Figure 18: Gain of logarithmic rectangular slots array antenna.

12.14 GHz), and Ku band (12.81 and 14.36 GHz). Its VSWR is shown in Figure 14. Gain plot and radiation pattern are shown in Figures 15(a) and 15(b), respectively. It gives more than 10 dB gain at 6.7 GHz frequency.

5. Measured Results

Logarithmic rectangular slots array antenna has been fabricated on Rogers RT Duroid 5880 high frequency substrate with a thickness of 0.787 mm, relative permittivity of 2.2, and relative permeability of 1 and loss tangent of 0.0009. The top side of the antenna has logarithmic slots and the other side is ground plane. The photograph of fabricated antenna is shown in Figure 16.

The antenna S_{11} parameter and gain are measured using the Vector Network Analyzer MVNA-8-350 with probe station. The simulated and measured S_{11} parameter for antenna is shown in Figure 17. A slight difference is observed between



(a) (b)

Figure 19: Radiation efficiency of logarithmic rectangular slots array antenna in (a) C band and (b) X band.

the measured value and simulated value. The difference between the measured and simulated S_{11} of the antenna is caused by the microstrip to SIW transition.

The simulated and measured gain of the antenna are shown in Figure 18. The maximum measured gain is also very close to 10 dB at 7 GHz for the antenna which is max. The measured result shows that the bandwidth of the antenna covers over 300 MHz while the gain of the antenna is kept almost constant within such a wide bandwidth of the antenna. Simulation results specify that metallic and dielectric losses do not have a substantial effect on the bandwidth and matching condition of the antenna, while they decrease the measured gain of antenna by 0.5 dB. The apparent difference between the simulation and measured gains might be due to the calibration linked tolerance range of the antenna reference in anechoic chamber.

The radiation pattern of the antenna at resonant frequency is shown in Figure 18. The radiation pattern measurement is carried out in a conventional far field anechoic chamber which uses a V connector to connect the antenna. Due to the size of the connector compared to the antenna, the rear radiation patterns were not incorporated in the results. However, the similar effects were observed in the simulation results and most significantly, the radiating behavior of the antenna is very similar to simulation results. As shown in Figures 19(a) and 19(b), they represent the radiation efficiency in C band and X band, respectively, which is 92% and 88%.

6. Observation and Discussion

From the simulation results we have observed the following things:

(i) All the structure gives six or more than six resonant frequencies in C band, X band, and Ku band.

(ii) Gain generated by rectangular and trapezoidal logarithmic slots array antenna is more than 10 dB compared to I shape logarithmic slots array antenna.

(iii) Isolation between two radiation bands is much higher in trapezoidal logarithmic slots array antenna and also generates low leakage loss in stop band.

(iv) Size of entire proposed antennas is compact compared to traditional antennas which are proposed for high gain applications.

(v) Bandwidth produced by all the antennas at resonant frequencies is more than 100 MHz.

7. Conclusion

From the design and simulation results, it is clear that all the antennas are compact in size and they are capable to generate multiband frequencies which are very important factors for the proposed design process of antennas. Antennas based on SIW technology have been proposed in this paper.

These structures can find many applications in C band and X band for radar and remote sensing mechanism and are one of the major areas in docking satellite where communication is done in C band while ranging is carried out in X band. So this antenna fulfilled both requirements instead of using two different antennas. Significant increment of gain parameter has been obtained for introduction of more number and variety of shapes of slots. Compared to identical slots, logarithmic slots give higher gain. The effect has been extensively studied unlike any other recent publication in this field. The structure is very simple and development of the prototype is easy in presence of advanced PCB fabrication technology.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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