

Design of Substrate Integrated Folded Waveguide H -Plane Horn Antenna Array with Simultaneous Omnidirectional and Directional Radiation Characteristics

Wriddhi Bhowmik^{1, *} and Shweta Srivastava²

Abstract—A compact substrate integrated folded waveguide (SIFW) H -plane horn antenna array with simultaneous omnidirectional and directional radiation characteristics for potential utilization to high-speed wireless communication is presented in this article. The realization of the proposed design has been accomplished by placing the apertures of nine exponentially tapered SIFW H -plane horns towards the circumference of a cylindrical substrate with an angular separation of 40° between the horns. Every horn flaring includes a column of three slots. Centre probe feed technique has been used to excite the antenna. The radiation of the field by the horn apertures and through the slots of the horns flaring, respectively, results in an omnidirectional and a directional radiation pattern at 13.8 GHz and 18.42 GHz, with the gain of 7 dBi and 10.92 dBi. The proposed antenna has performed well and is in good agreement between simulation and measurement. The dimension of the antenna is 37.3 mm (diameter) \times 1 mm (height) ($1.71\lambda_0 \times 0.046\lambda_0$ at 13.8 GHz and $2.29\lambda_0 \times 0.061\lambda_0$ at 18.42 GHz). SIFW technology makes low profile antenna. The proposed design can be a promising option to be used as a low-profile antenna for high-speed wireless communication.

1. INTRODUCTION

In the present times, wireless technology's evolution has entered the era of high-speed voice and data communication. In this context, the ISM bands of 900 MHz and 1800 MHz for voice communication and 2.4 GHz and 5 GHz for WLAN applications have been extensively utilized. However, recently the low power high speed voice and data communication in the frequency range of tens of GHz have drawn special attention due to the additional bandwidth's availability at these higher frequencies [1]. The frequency reuse results in capacity boosting of the wireless system. In the cellular system, the frequency reuse can be obtained by restricting the transmitted power of an antenna within a cell's boundary. Typically, an omnidirectional antenna can be used to cover a cell structure. The cell coverage can also be obtained by replacing a single omnidirectional antenna with several directional antennas [2].

Earlier several kinds of research have been undertaken to achieve omnidirectional and directional radiation patterns by using microstrip antenna. The designs of the microstrip omnidirectional antenna have been presented in [3–8]. Similarly, extensive researches have also been carried out on microstrip directional antennas [9–12]. The microstrip patch antenna has various benefits such as compact structure, easy realization, and simple integration to the other planar devices. However, it exhibits some disadvantages, namely: surface wave excitation along with high conductor and dielectric losses at very high frequencies. These losses are a major concern for degrading the radiation performances of microstrip patch antenna at high frequencies. In this context, the waveguide horn antenna is

Received 13 December 2021, Accepted 12 January 2022, Scheduled 16 January 2022

* Corresponding author: Wriddhi Bhowmik (wriddhi.bhowmikfet@kiit.ac.in).

¹ School of Electronics Engineering, Kalinga Institute of Industrial Technology, Bhubaneswar, Odisha 751024, India. ² Department of Electronics & Communication Engineering, Jaypee Institute of Information Technology, Noida, Uttar Pradesh 201309, India.

considered as a suitable replacement of the microstrip patch antenna at high frequencies to overcome these obstacles. The waveguide horn antenna exhibits higher bandwidth and gain and smaller half power beam width (HPBW) [13] than microstrip patch antennas. Its non-planar structure makes the system profile cumbersome, the process of realization costly, and its incorporation to the numerous planar microwave devices very complex. The complications caused by the waveguide technology can be resolved by a promising alternative named SIW. The SIW technology results in the realization of classical rectangular waveguide (RW) in planar form while at the same time upholding the merits of RW such as high Q factor [14].

Several research works have been undertaken on the design of SIW directional and omnidirectional horn antennas. In [15–22], the detailed descriptions of the designs of directional SIW horn antennas have been presented. The inclusion of a thin substrate in the designs presented in [15–20] results in higher side lobe level (SLL), lower gain, and lower front to back ratio (FBR). The upgradation in the directional radiation characteristic has been obtained by integrating rectangular and elliptical dielectric loading, rectangular metallic patch, printed transition to the horn's aperture as well as etching of slots in the horn's flaring. In [21], a more complex structure of wideband horn antenna has been described. A crossed horn structure with dual feeds has been reported in [22], to obtain directional radiation characteristics. The realization process of the crossed horn structure is quite complex. In the above literature [15–22], the centre of attention has been set to improve the directional SIW H -plane horn's radiation performance. Further, some investigations have been done on the omnidirectional SIW H -plane horn antenna [23–26]. Omnidirectional SIW H -plane horn antennas described in [23–24, 26] have exhibited low gain. Furthermore, in [24], quite low gain and bandwidth have been obtained despite the complex design.

Typically, in wireless communication, an omnidirectional antenna is used to provide complete coverage to a cell. However, directional antennas are also used as they significantly reduce the interference level [2]. In literature, it has been observed that the researchers have always been interested in obtaining optimal design of omnidirectional and directional SIW H -plane horn antennas individually. No design has been reported yet to obtain both the radiation patterns (omnidirectional and directional) simultaneously. The authors of this communication have suggested an idea to obtain omnidirectional and directional radiation patterns concurrently by one antenna structure as both types of radiation patterns play an important role in wireless communication. With these observations, the present research proposes a miniaturized structure of H -plane horn antenna array [27] for high-speed wireless communication. This miniaturization has been obtained by SIFW technology. The pivotal aim of the research is to miniaturize and simplify the proposed antenna design, and the attainment of simultaneous high gain omnidirectional and directional radiation patterns.

In this communication, nine compact exponentially tapered SIFW H -plane horns are placed on the top of a two-layered cylindrical thin substrate ($h = 0.046\lambda_0$ at 13.8 GHz and $h = 0.061\lambda_0$ at 18.42 GHz) to achieve omnidirectional pattern at 13.8 GHz and directional pattern at 18.42 GHz, respectively. The formation of the array has been accomplished by placing horn apertures towards the cylinder's circumference while the waveguide sections are towards the centre of the cylinder. The excitation to the antenna has been achieved by using centre probe feed. Typically, it can be observed that a design using a thin substrate shows poor radiation performance. In such designs using a thin substrate, the inclusion of dielectric loading and printed transition to the horn's aperture may cause radiation performance to improve [15–20]. However, the proposed structure, despite using a thin substrate, eliminates the application of the above techniques (presented in [15–20]) to obtain satisfactory radiation characteristics. The non-inclusion of dielectric loading and printed transition in achieving good radiation performances make the trade-off independent of several design parameters, and the realization process is quite simple. The design includes three radiating slots in the flaring of each horn. The radiation of the field by horns' aperture results in omnidirectional pattern, and the radiation through the slots results in directional pattern. Thus, the proposed design generates the two patterns simultaneously. The inclusion of nine SIFW H -plane horns results in the high gain omnidirectional and directional radiation patterns. Hence, the proposal to obtain simultaneous high gain omnidirectional and directional radiation characteristics using a compact antenna structure without the inclusion of any design complexity makes the design unique.

2. DESIGN OF SIFW *H*-PLANE HORN ANTENNA

The layout of the antenna is presented in Figure 1. The SIFW [27–31] reduces the width of SIW (the width can be calculated using the formulae reported in [14]) by a factor of half, which can be obtained by folding the SIW structure along the horizontal centre line. The width of the SIFW transmission line of 4.65 mm has been maintained in the proposed horn antenna. The computation of other design parameters such as diameter (d) of metallic posts and centre to centre spacing between the metallic posts (S) for the formation of the side wall of the SIFW horn has been accomplished by following certain conditions outlined in [14]. These design conditions help to minimize the leakage loss of EM wave. Unlike SIW [14, 32], the SIFW technology [27–31] is a double layer model, including a strip line in the middle layer. This strip line has been connected to the bottom layer by metallic vias. Thus, the bottom layer acts as a ground plane to the strip line. The height of metallic vias, which connects the strip line to the bottom layer is 0.5 mm as observed in Figure 1(c). Also, from Figure 1(c) it has been observed that the height of metallic vias of the horn’s sidewall is 1 mm.

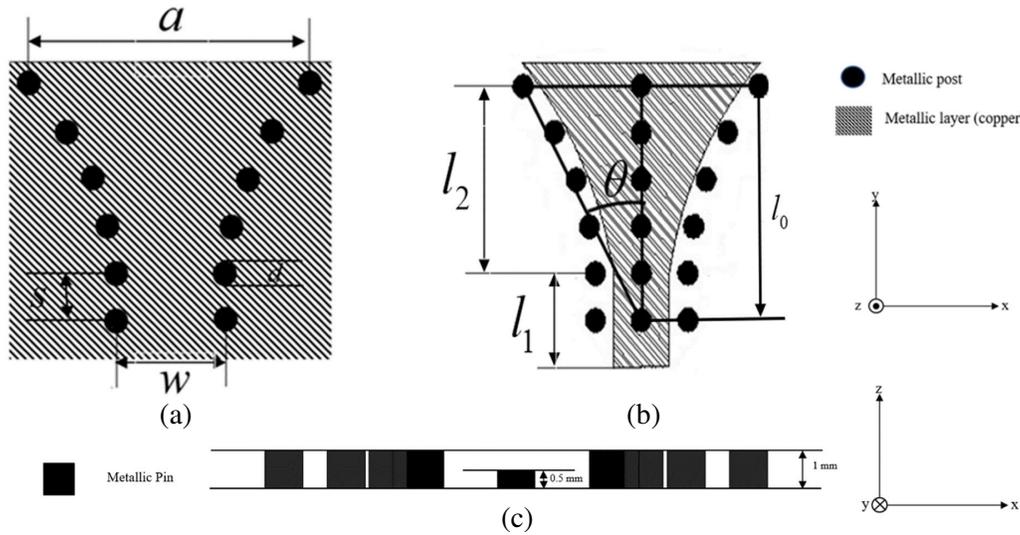


Figure 1. Layout of SIFW exponentially tapered *H*-plane horn: (a) top layer: width of waveguide (w) = 4.65 mm; metallic post diameter (d) = 1 mm; centre to centre distance (S) = 2 mm; and aperture size (a) = 11.9 mm, (b) middle layer: flaring length (l_2) = 8 mm; waveguide section length (l_1) = 4 mm; horn length (l_0) = 10 mm; and flaring angle (θ) = 30.73° , and (c) cross-sectional view.

Figure 1 presents the layout of the SIFW horn antenna for a given aperture (a). l_0 is the length of the line from the apex point to the horn aperture. It equally divides the aperture at right angle (90°). For each length (l_0), the horn aperture should be optimized to attain maximal gain [33]. The flaring angle (θ) is responsible for the impedance matching between the SIFW transmission line and free space [20]. The proper selection of the flaring angle provides satisfactory impedance matching as well as maximum gain. The flaring angle (θ), aperture size (a), and the length of horn (l_0) are related with each other by the following relation [33].

$$\theta = \tan^{-1} \left(\frac{a}{2l_0} \right) \quad (1)$$

It has been observed that for a larger aperture and lower horn length, the gain can be reduced [33]. Hence, one needs to do rigorous parametric analysis on the length of horn (l_0), flaring angle (θ), and aperture size (a), to obtain satisfactory impedance matching as well as good gain. The aperture size (a), length of horn (l_0), length of flaring (l_2), length (l_1) and width (w) of waveguide section of the proposed horn are 11.9 mm ($0.66\lambda_0$), 10 mm ($0.55\lambda_0$), 8 mm ($0.44\lambda_0$), 4 mm, and 4.65 mm, respectively as observed in Figures 1(a) and (b). For a given aperture, unlike linear tapering, the exponential tapering reduces

the discontinuity between the waveguide section and flaring of horn that results in an improvement in the radiation characteristics. The horn ($0.66\lambda_0 \times 0.65\lambda_0 \times 0.055\lambda_0$) has a flaring angle (θ) close to 30.73° as reported in Figure 1(b).

Satisfactory impedance matching ($S_{11} = -14.35$ dB) has been obtained at 16.63 GHz as reported in Figure 2. Figures 3(a) and (b) present the simulated normalized radiation performances of the antenna on X - Z and X - Y planes at 16.63 GHz, respectively. It is observed from Figure 3 that high back radiation is present in both the planes. The gain of 3.2 dB as well as half power beam width (HPBW) of 64° are achieved. The cross-polarization level is below -20 dB and -15 dB respectively in X - Z and X - Y planes.

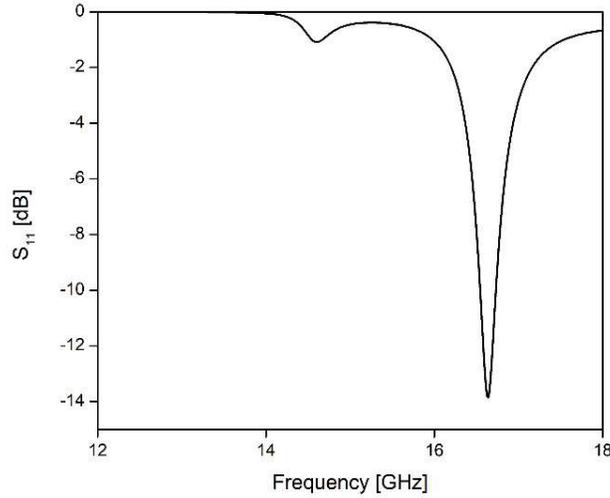


Figure 2. Reflection coefficient of the horn.

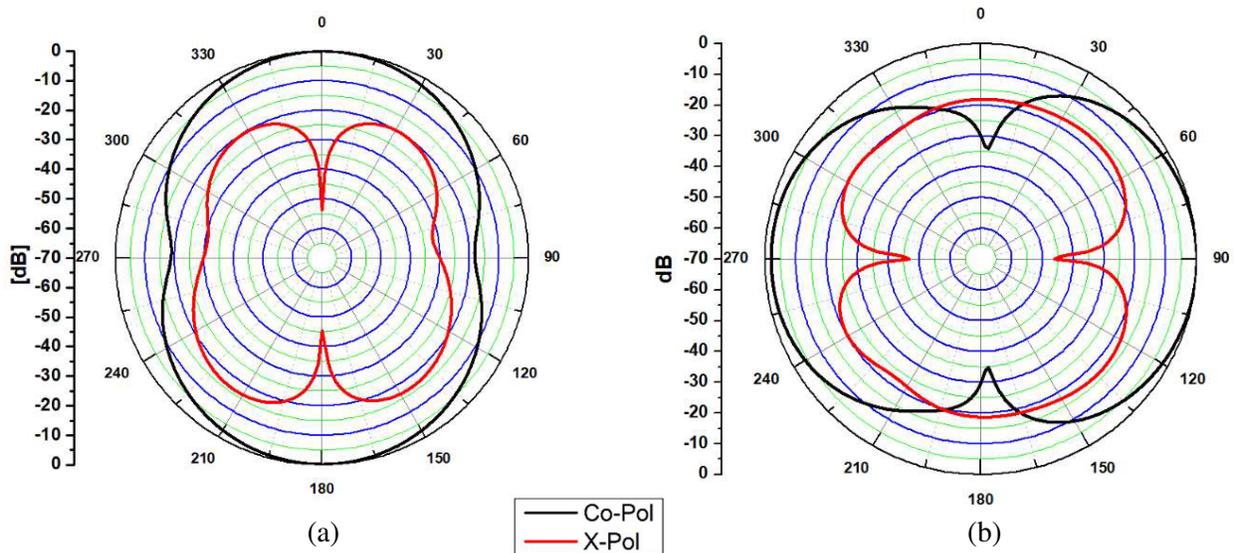


Figure 3. Normalized radiation pattern at 16.63 GHz: (a) on X - Z plane, and (b) on X - Y plane.

The SIFW technology has significantly reduced the aperture size of the horn. The antenna's height is 1 mm ($h = 0.055\lambda_0$). Hence, the inclusion of thin substrate, significant reduction in aperture's size (a) as well as in horn's length (l_0) has resulted in high back lobe radiation, poor FBR (FBR = 0.2 dB), and lower gain. The present research aims to convert these drawbacks of the single antenna element into

advantages in designing the proposed antenna structure. However, to achieve the desired performance without inclusion of design complexity is very challenging.

3. AIMS OF THE PROPOSED RESEARCH

Typically, an omnidirectional antenna radiates equal power in the azimuthal direction. In contrast, the power varies in accordance with the elevation angle and drops to the null at the minimum (0°) and maximum (180°) elevation angles. Hence, the lower FBR and higher HPBW for the omnidirectional pattern in both the planes are not matters of concern. Unlike the omnidirectional antenna, a directional antenna radiates or receives electromagnetic (EM) waves more efficiently in certain directions than in the others. Hence, the FBR and HPBW are very crucial parameters to characterize the directional pattern. It is desirable to have higher FBR, lower HPBW, and lower side lobe level (SLL) for an adequate directional radiation pattern. With these observations, the primary targets of the proposed research have been set to obtain good omnidirectional and directional radiation patterns simultaneously. To achieve an adequate directional pattern, the following specifications such as HPBW of less than 30° , SLL of below -20 dB, and FBR of above 15 dB have been incorporated. To obtain compactness in the structure as well as design targets as mentioned above, several investigations have been carried out with different numbers of SIFW H -plane horn antennas as well as slots in the horn's flaring. Finally, the best performances have been obtained while nine horn antennas along with the three radiating slots at each horn's flaring in a cylindrical substrate are included. Tuning the slots' length and width has been done to acquire the optimum design. The configuration of the suggested structure, the mechanism of obtaining omnidirectional and directional radiation patterns, and the benefits of the proposed design compared to the designs presented in the literature will be discussed in the next sections.

4. PROPOSED ANTENNA STRUCTURE

Figure 4 presents the antenna's optimum configuration. It is perceived from Figure 4 that nine SIFW H -plane horns with exponential tapering are placed on the top of the two layered cylindrical shape polytetrafluoroethylene (PTFE) substrate with the radius (r) of 18.65 mm, dielectric constant (ϵ_r) of 2.5, loss tangent ($\tan \delta$) of 0.00015, and height (each layer) of 0.5 mm. The diameter of the proposed antenna is 37.3 mm ($D = 1.71\lambda_0$ at 13.8 GHz and $D = 2.29\lambda_0$ at 18.42 GHz), and height is 1 mm ($h = 0.046\lambda_0$ at 13.8 GHz and $h = 0.061\lambda_0$ at 18.42 GHz). To obtain a high gain, the necessity of including a large number of horns in a compact manner has been made possible by utilizing the cylindrical substrate. On the cylindrical substrate, the horns have been accommodated at 40° angle with each other as observed in Figures 4(a) and (b). The placing of horn apertures towards the cylindrical substrate's circumference has resulted in the omnidirectional pattern, whereas etching slots in the horns' flaring has produced a directional radiation pattern. The length (S_l) and width (S_w) of the slots etched in the flaring of horns are 4.5 mm and 0.5 mm, respectively, as perceived in Figure 4(a).

It can be inferred from Figure 1 and Figure 4 that the SIFW technology has significantly reduced the overall size of the single antenna element as well as the proposed antenna structure. The SIFW technology has reduced the aperture size of the horn antenna (Figure 1) by 15% as compared to the SIW horn aperture presented in [15], and also the overall length of the antenna has been reduced by 29.4%. Similarly, 15% and 36.02% size reduction has been achieved in horn aperture as compared to the designs reported in [16] and [17], respectively. The length of horn antenna (Figure 1) has also been reduced by 43.33% and 54.19% respectively as compared to the overall antenna length presented in [16] and [17]. A reduction of 70.25% has been obtained in the aperture size of the proposed horn as compared to the single SIW horn presented in [20]. Also, the length of the horn antenna (Figure 1) has been minimized by 70.73% as compared to the length of the SIW horn in [20]. In comparison to the design of a single SIW horn presented in [22], the proposed structure of horn (Figure 1) in this communication has attained 68.68% and 56.68% reduction in aperture size and in length, respectively. The SIFW technology has reduced the width of SIW by 50% and the size of the horn aperture by 55.09%, compared to the SIWhorn presented in [25]. The length of the proposed horn antenna (Figure 1) has also been reduced by 53.85% as compared to the horn antenna's length in [25]. The overall size, especially the radius and circumference of the proposed antenna (Figure 4), has also been reduced by 53.37% as compared to

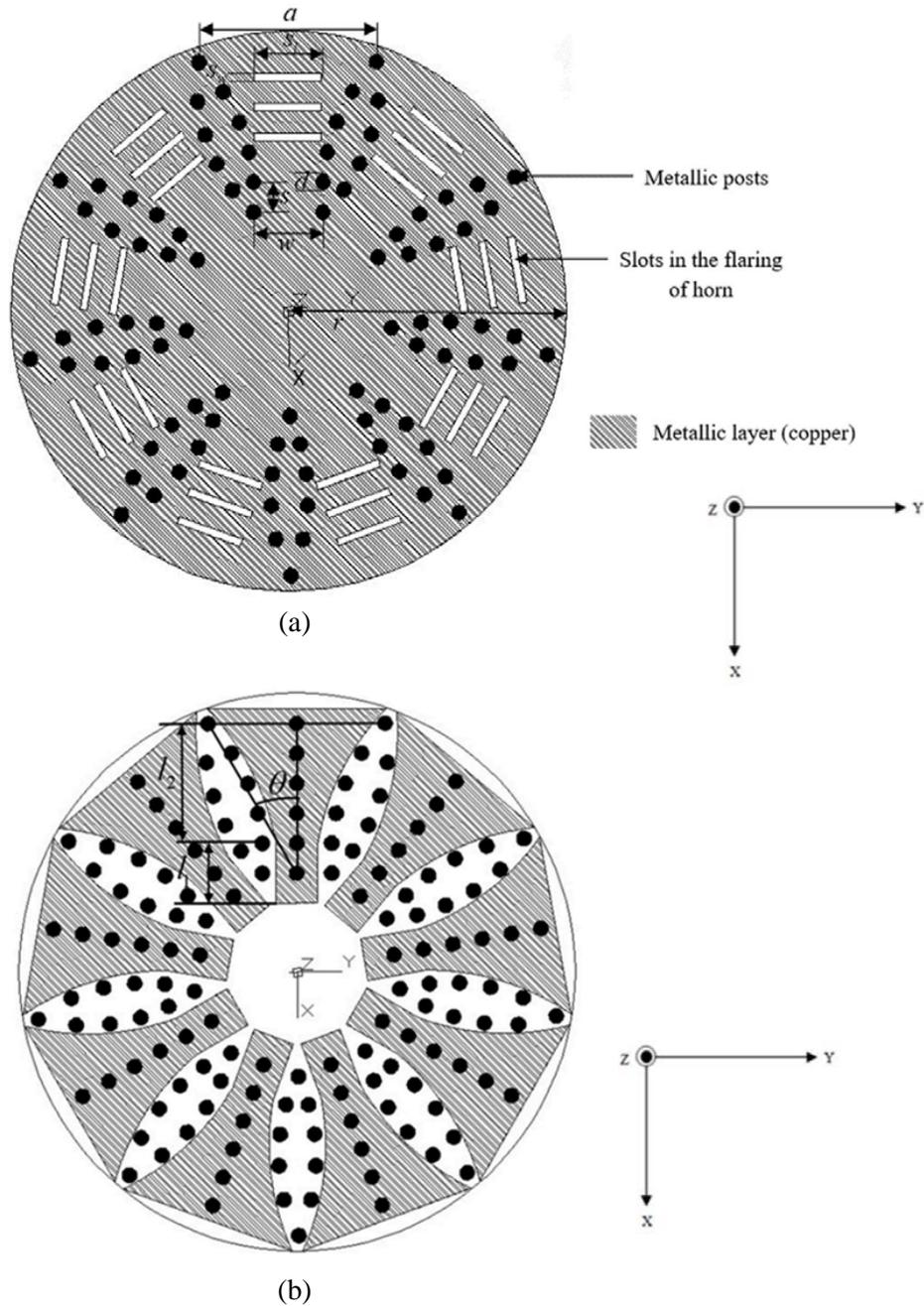


Figure 4. Antenna's optimum configuration: (a) top layer: radius (r) = 18.65 mm; (w , d , and S are same as Figure 1); slot length (S_l) = 4.5 mm; slot width (S_w) = 0.5 mm and aperture size (a) = 11.9 mm; (b) middle layer: flaring length (l_2) = 8 mm; waveguide section length (l_1) = 4 mm and flaring angle (θ) = 30.73°.

the antenna structure reported in [25], due to the significant size reduction of a single antenna element. Hence, from the above discussions, it can be stated that the proposed design has been miniaturized by the utilization of SIFW technology. Unlike the designs presented in [23] and [25], the proposed antenna does not include any additional metallic vias for the improvement of the impedance matching and the well-round nature of radiation pattern in azimuthal plane. The non-inclusion of additional metallic vias has minimized the design complexity. The proposed design is symmetric around the $X-Z$ plane.

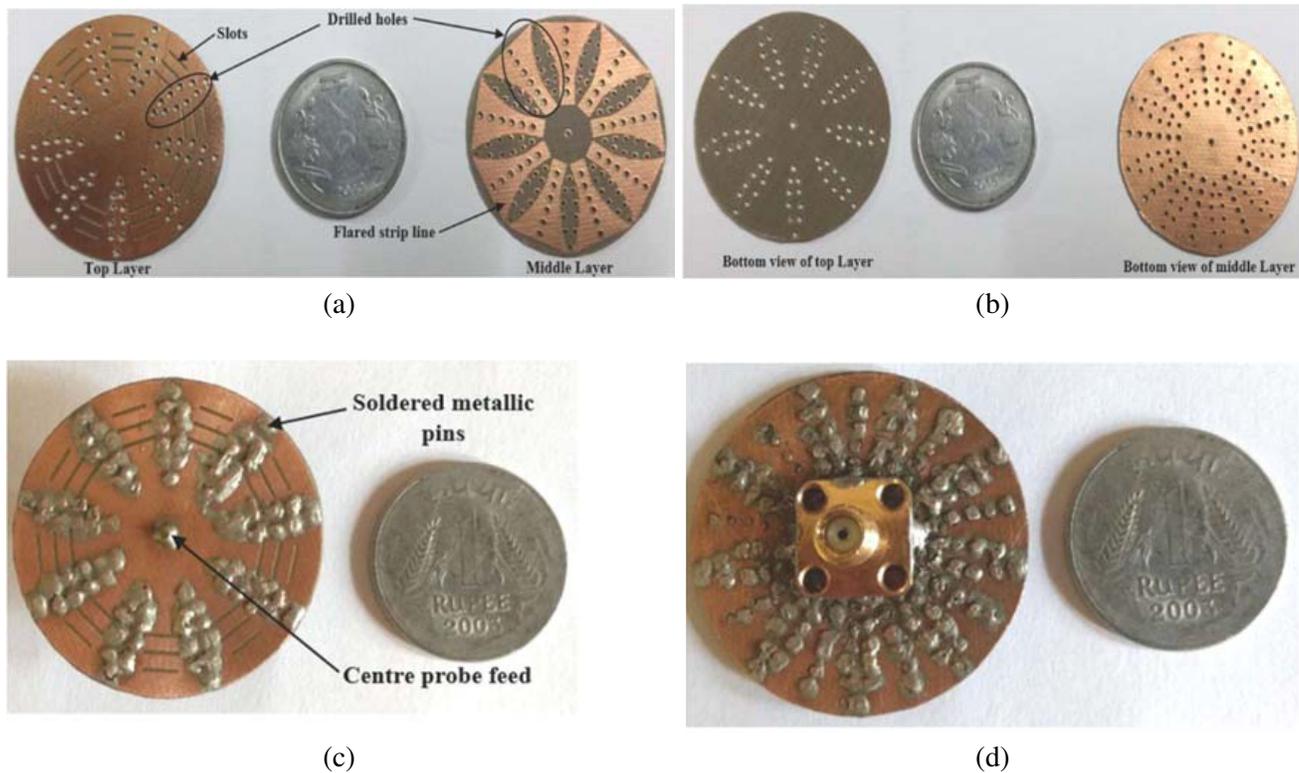


Figure 5. Fabricated structure: (a) top and middle layer, (b) bottom view of top and middle layer, (c) top view and (d) bottom view.

The fabricated structure is reported in Figure 5. The two layers of the proposed antenna have been realized separately, followed by the drilling of holes, as observed in Figures 5(a) and (b). At first, the strip line in the middle layer has been connected to the bottom of the substrate by inserting metallic pins with the diameter and height of 1 mm and 0.5 mm, respectively. The placement of the two layers, one on the top of the other, has been done very cautiously so that the drilled holes for the formation of the sidewall of SIFW horn could be properly aligned. The filling of the holes by inserting metallic pins (diameter and height = 1 mm) from the top conducting surface through the middle dielectric layer to the ground plane has accomplished the formation of electrical walls (Figures 5(c) and (d)). This wall provides a guiding path to the EM waves as well as arrests the outflow of the same.

5. RESULTS AND DISCUSSIONS

The simulation of the proposed antenna has been accomplished by utilizing the Ansys HFSS v 13.0 (high-frequency structure simulator) and the measurement by using the Agilent E5071C network analyzer.

It can be seen from Figure 6 that adequate impedance matching has been obtained without the inclusion of additional metallic vias. Fabrication limitations have been attributed to the small discrepancies in the simulated and measured reflection coefficient (S_{11}). The reflection coefficients (S_{11}) of -15.93 dB and -19.62 dB have been achieved in simulation at 13.8 GHz and 18.42 GHz, respectively. In measurement, S_{11} of -14.37 dB and -23.32 dB have been obtained at 14 GHz and 18.4 GHz, respectively. The formation of array and etching of slots in the flaring of horn antennas may be responsible for frequency shifting in the lower range (13.8 GHz) as well as in the higher range (18.42 GHz), respectively, as compared to the single antenna element. The design has exhibited a 10 dB fractional bandwidth (FBW) of 1.6% at 13.8 GHz and 0.27% at 18.42 GHz in simulation. In measurement, the 10 dB FBWs of 0.71% and 4.89% have been obtained at 14 GHz and 18.4 GHz, respectively. The utilization of the thin substrate is responsible for the confinement of electromagnetic

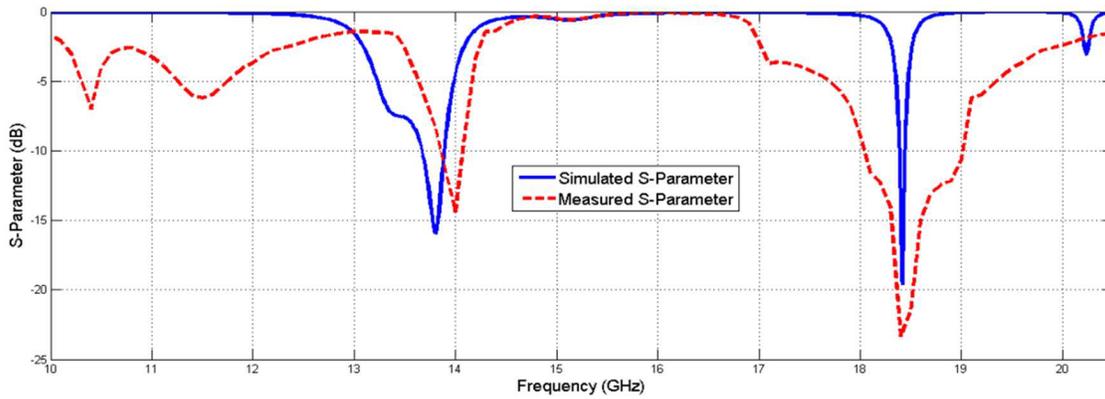


Figure 6. Reflection coefficient of the antenna.

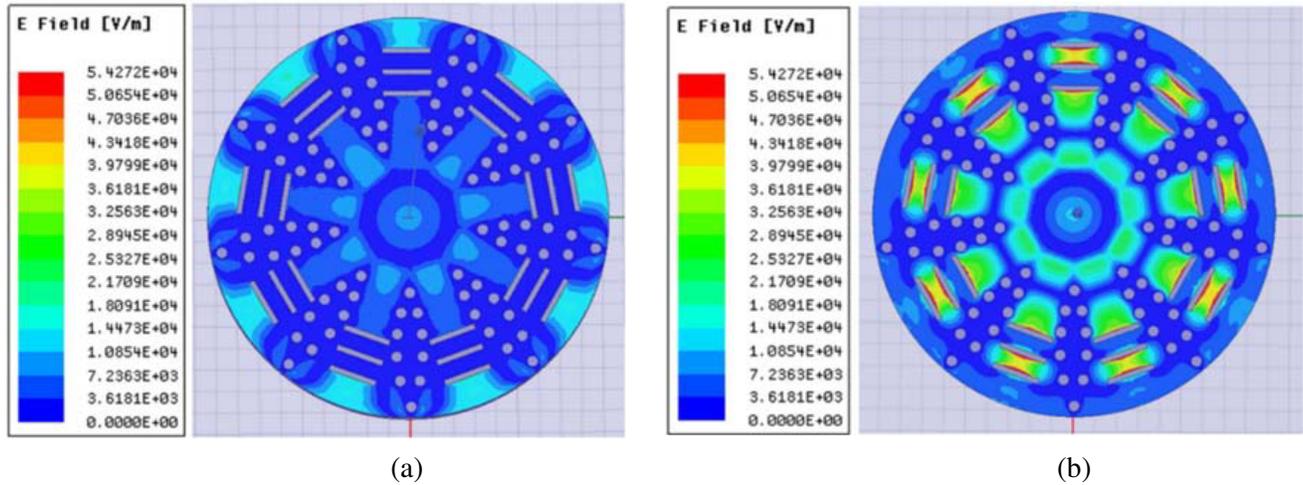


Figure 7. Field distribution: (a) at 13.8 GHz (only horn apertures are radiating), and (b) at 18.42 GHz (only slots are radiating).

waves inside the substrate instead of flowing out as radiation [33]. The increased incompatibility between the SIFW horn and the air has resulted in a narrow BW.

The uniformity in field distribution in the horns has been approximately obtained by the proposed design as observed in the Figure 7. It is obvious from Figure 7(a) that all the horns radiate in the horizontal direction as most of the field is concentrated around the horn aperture making the radiation pattern omnidirectional at 13.8 GHz. The slots in the horns' flaring have been excited at 18.42 GHz as observed in the Figure 7(b). The field has been radiated through the slots resulting in the directional pattern.

The normalized radiation pattern of the antenna is reported in Figure 8 and Figure 9. To measure the radiation pattern, this cylindrical shaped multi-horn antenna and a ridge pyramidal horn antenna have been kept inside an anechoic chamber as an antenna under test (AUT) and as a transmitting antenna, respectively. The amount of power received by the AUT has been measured by using the E5071C network analyzer.

Figures 8(a) and (b) present the simulated normalized radiation performances of the horn in X - Z and X - Y planes at 13.8 GHz, respectively. In measurement, the impedance matching has been obtained at 14 GHz. Hence, the radiation pattern has been measured at the same frequency and reported in Figures 8(c) (X - Z plane) and (d) (X - Y plane).

The patterns reported in Figures 8(b) (simulation) and (d) (measurement) respectively have

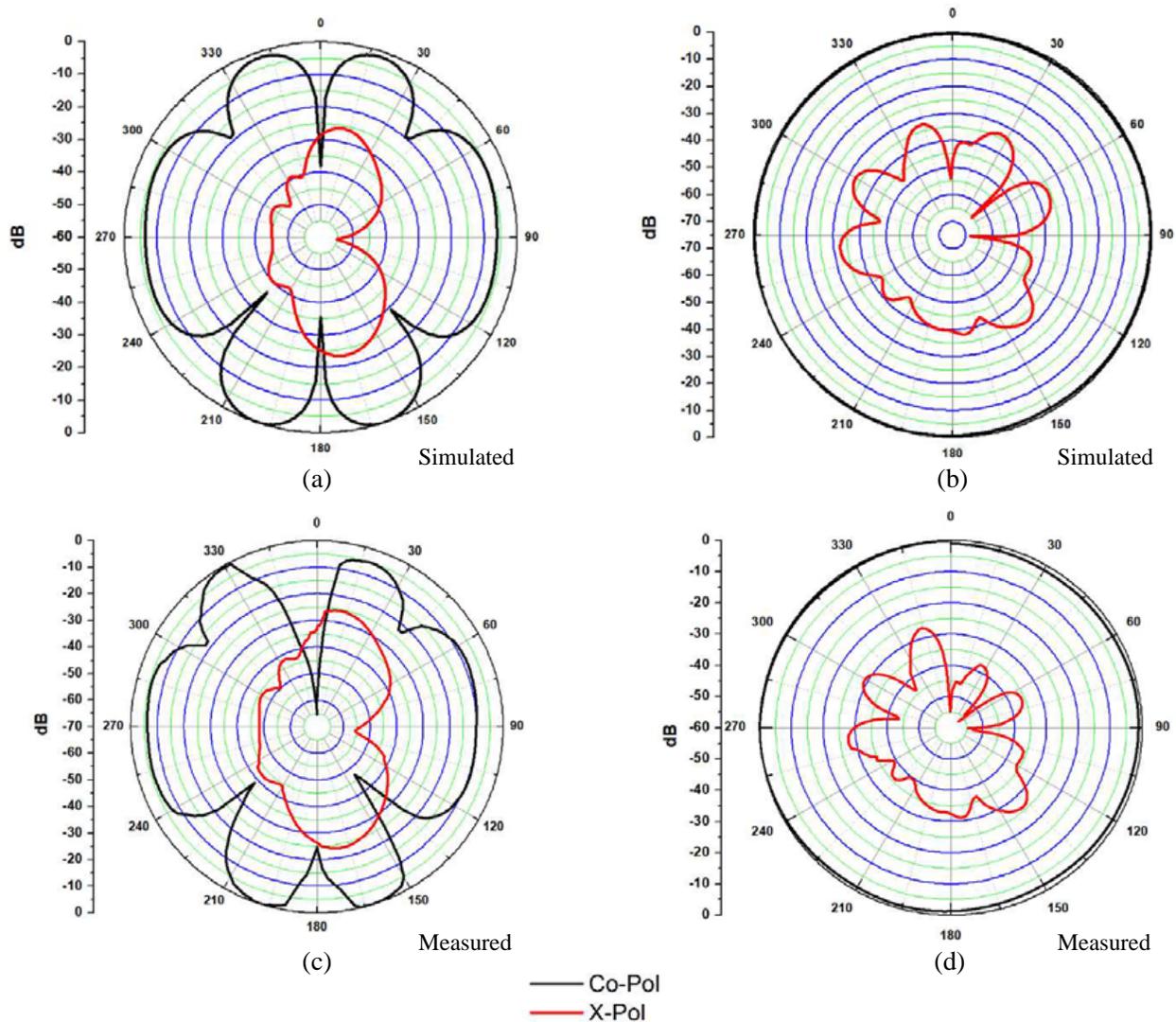


Figure 8. Normalized radiation pattern: (a) at 13.8 GHz on $X-Z$ plane, (b) at 13.8 GHz on $X-Y$ plane, (c) at 14 GHz on $X-Z$ plane and (d) at 14 GHz on $X-Y$ plane.

revealed that the proposed antenna radiates equal power in the azimuthal plane ($X-Y$ plane). The variation in the radiated power with respect to the angular direction both in simulation (Figure 8(a)) and measurement (Figure 8(c)) has been noticed in the elevation plane ($X-Z$ plane). The placement of the horn apertures towards the cylindrical substrate’s circumference leads to the constructive interference between the emitted fields of the horns in most of the angular directions in the elevation plane. This phenomenon results in variation of radiated power with respect to the elevation angle (Figures 8(a) and (c)). This design topology also helps to obtain complete roundness in the azimuthal plane (Figures 8(b) and (d)). Apart from the broadside null, a few nulls have also been noticed at multiple angular directions (Figures 8(a) and (c)) as a result of the destructive interference of the emitted power of SIFW horns. Most of these nulls are well below 25 dB from the maxima (0 dB), and some are well below 15 dB from the maxima (0 dB), as observed in the Figures 8(a) and (c). These nulls provide a better capability to suppress interference from undesired users. Hence, from the above discussions, it may be stated that the presented antenna has exhibited omnidirectional pattern at 13.8 GHz. Significantly less cross polarization level has been obtained both in simulation and measurement (well below -25 dB) in $X-Z$ and $X-Y$ planes, as observed in the Figure 8.

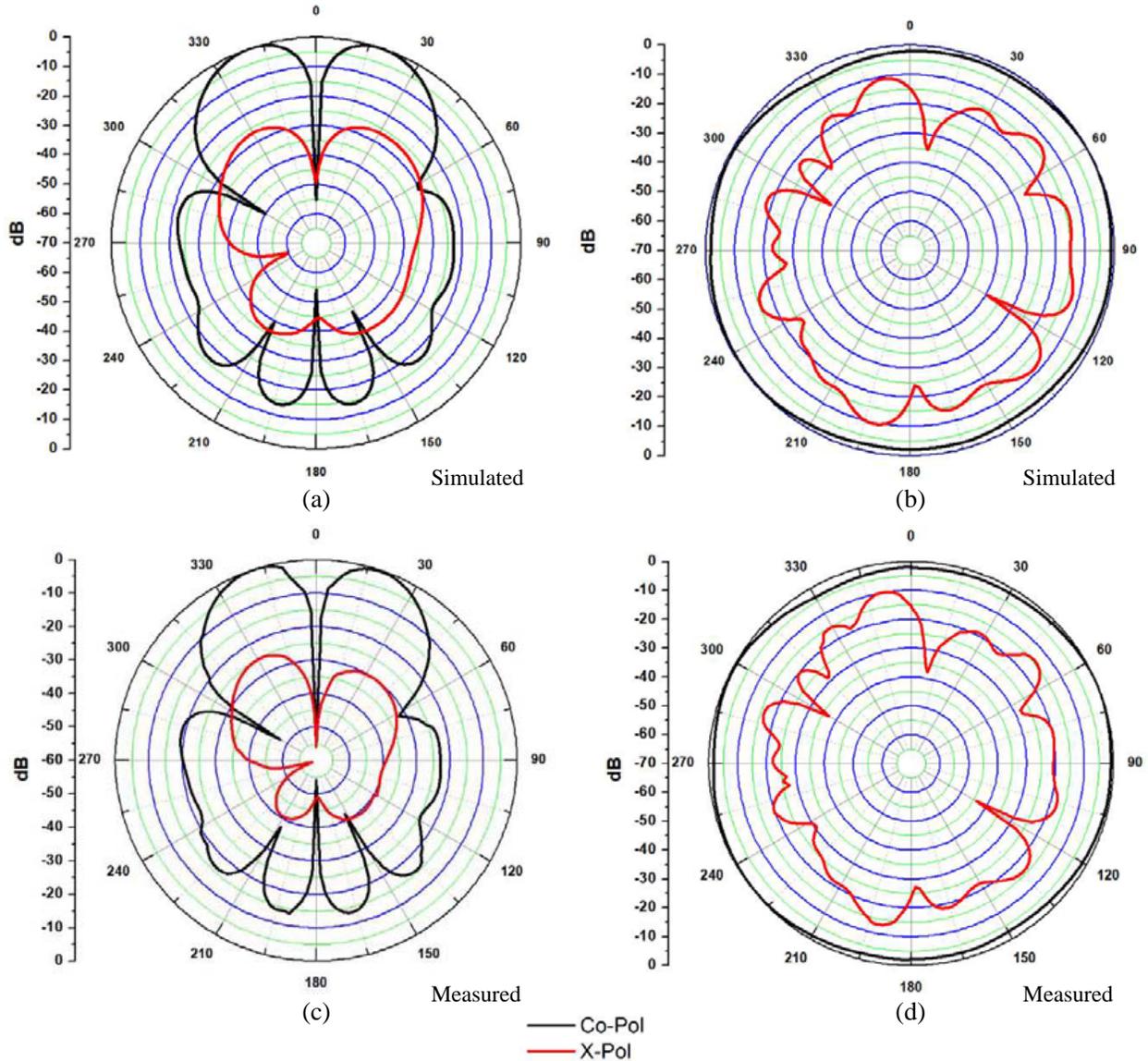


Figure 9. Normalized radiation pattern: (a) at 18.42 GHz on X-Z plane (b) at 18.42 GHz on X-Y plane, (c) at 18.4 GHz on X-Z plane, and (d) at 18.4 GHz on X-Y plane.

The simulated normalized radiation pattern at 18.42 GHz is reported in Figures 9(a) and (b). In measurement, the impedance matching has been obtained at 18.4 GHz. Therefore, the radiation pattern has been measured at the same frequency and presented in Figures 9(c) and (d). The proposed antenna radiates significantly more power in the specific angular direction ($\pm 18^\circ$) in the X-Z plane, as observed in the Figure 9(a). The measured result (Figure 9(c)) has adequately matched the simulation. The radiation of field through slots and the constructive interference of the radiated fields in specific angular directions make the radiation pattern directional in nature (Figures 9(a) and (c)). The antenna exhibits a completely round radiation pattern in the azimuthal plane as observed in Figures 9(b) and (d). The side lobe levels (SLLs) both in simulation and measurement are below -20 dB, and the back lobes are below -13 dB in the X-Z plane as observed in the Figures 9(a) and (c), respectively. The destructive interference between the slots' radiated power might have resulted in the broadside null in the X-Z plane, as observed in Figures 9(a) and (c). Thus, the radiation patterns reported in Figure 9 have established that the proposed design exhibits directional pattern at 18.42 GHz. The broadside null provides better

isolation between the two directive beams that have pointed towards the angular direction of $\pm 18^\circ$, as observed in Figures 9(a) and (c). The directive beams with reduced SLL and back lobes possess the potential to minimize interference from the undesired users. It is evident from Figures 9(a) and (c) that the cross-polarization level is well below -25 dB. That in the azimuthal plane (Figures 9(b) and (d)) is well below -10 dB.

The three-dimensional patterns have been presented in Figure 10. Figures 10(a) and (b) show that the presented antenna has exhibited omnidirectional pattern at 13.8 GHz and directional pattern at 18.42 GHz, respectively, as discussed earlier. The directional pattern of the antenna has the FBR of 15.2 dB.

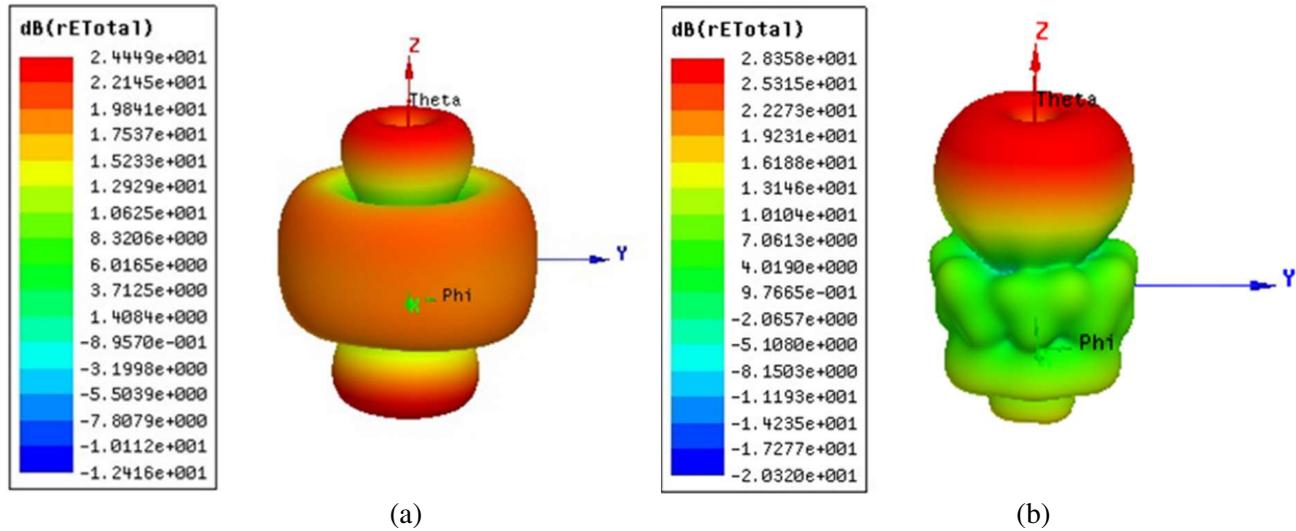


Figure 10. 3D pattern: (a) at 13.8 GHz and (b) at 18.42 GHz.

Figure 11 presents gain as a function of frequency in the X-Z plane. In the simulation, the gains of 7 dBi and 10.92 dBi have been acquired at 13.8 GHz and 18.42 GHz, respectively, as observed in Figure 11. In measurement, the gains of 6.02 dBi and 9.71 dBi have been obtained at 14 GHz and 18.4 GHz, respectively. The gain has been measured at every 1 GHz interval in the range of 13 GHz to 19 GHz as well as additionally at 18.4 GHz, and reported in Figure 11. This might be the reason for having sharpness in the measured gain curve and little discrepancies with the simulated result. As

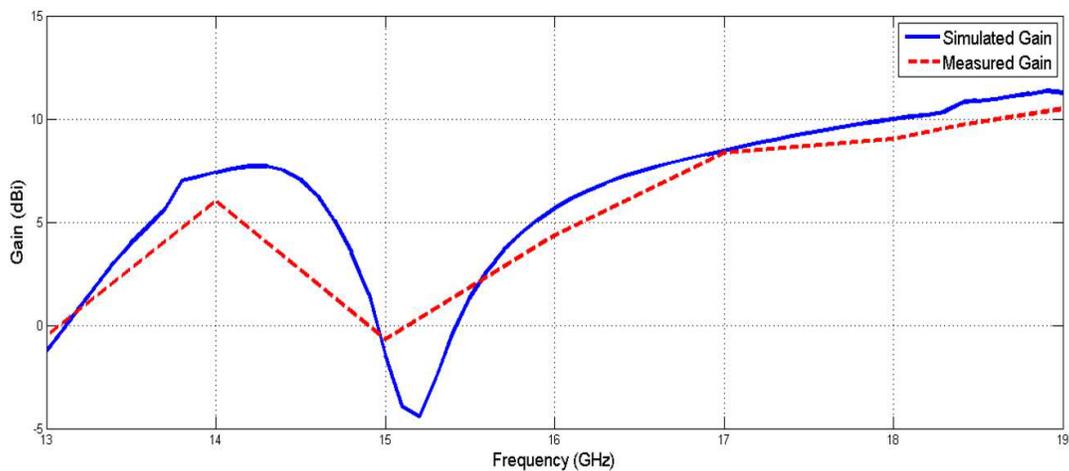


Figure 11. Gain on the X-Z plane.

Table 1. Juxtaposition of radiation characteristics of the presented antenna with the previously reported SIW horns.

Reference	Type	Operating Frequency (GHz)	Dielectric loading	Dimensions of antenna (length \times width \times height) / (diameter \times height)	Radiation Pattern		Omnidirectional Gain (dBi)	Directional Gain (dBi)
					Omni-directional	Directional		
[17]	SIW horn	22.7	Yes	$2.96\lambda_0 \times 1.4\lambda_0 \times 0.24\lambda_0$	NA	Yes	NA	10.1
[19]	SIW horn	12.4	No	$1.4\lambda_0 \times 0.95\lambda_0 \times 0.1\lambda_0$	NA	Yes	NA	10.4
[22]	SIW horn	18.5	Yes	$2.6\lambda_0 \times 2.34\lambda_0 \times 0.2\lambda_0$	NA	Yes	NA	10.9
[23]	SIW horn	2.41	No	$0.76\lambda_0 \times 0.76\lambda_0 \times 0.03\lambda_0$	Yes	NA	2.6	NA
[24]	SIW horn	2.45	No	$1.15\lambda_0 \times 0.024\lambda_0$	Yes	NA	-2.13	NA
This Work	SIFW horn	13.8 & 18.42	No	$1.71\lambda_0 \times 0.046\lambda_0$ & $2.29\lambda_0 \times 0.061\lambda_0$	Yes	Yes	7	10.92

discussed earlier, the field has been radiated by the horns' aperture (Figure 7(a)) at 13.8 GHz resulting in the omnidirectional pattern. The H -plane sectoral horn's gain is proportional to the size of the horn's aperture [13]. The placement of the nine SIFW horn apertures along the cylindrical substrate's circumference has enlarged the overall aperture size of the proposed antenna. Hence, the expectation to obtain higher gain at 13.8 GHz is quite inevitable. However, it can be observed from the simulation (7 dBi) and measurement (6.02 dBi) that the gain has marked an increase but not as per the expectation because the conductor loss is higher due to the inclusion of metallic pins in the middle layer of the design. The directional radiation pattern has been obtained at 18.42 GHz as the field has been radiated through the slots (Figure 7(b)). Hence, it can be stated that the proposed design has acted as a leaky wave antenna at 18.42 GHz, and quite high gain has been obtained both in simulation (10.92 dBi) and measurement (9.71 dBi).

The SIW horns (previously reported in the literature) have typically shown single band performance with either omnidirectional or directional pattern. It has been observed from Table 1 that the proposed design has exhibited dual-band behavior with omnidirectional and directional patterns. The smart arrangement of the horns in the presented design, despite being of compact structure, makes the omnidirectional gain higher than the gain of the SIW horn antennas reported in [23, 24]. The directional gain is also higher than that of the gain of SIW horn antennas presented in [17, 19, 22]. The attractive attribute of the design is the functioning of the structure as a leaky-wave antenna at a higher frequency, which makes the directional gain quite satisfactory without using dielectric loading. It can also be observed from Table 1 that the proposed design exhibits both the radiation characteristics simultaneously. It is a unique feature of the proposed research as this type of work has not been reported previously. It is quite evident from the presented antenna structure and its outcome that the authors have achieved all the design targets such as miniaturized and simplified design along with the satisfactory omnidirectional and directional radiation performances.

Typically, the capacity of the wireless system may be boosted by installing microcells between the existing cells. The radio coverage of the microcells can be obtained by reducing the omnidirectional antennas' transmitted power compared to the required radiated power for an existing cell. Another way of achieving capacity enhancement with a promising signal to co-channel interference ratio is by using directional antennas [2]. Following these observations, the simultaneous attainment of omnidirectional and directional radiation patterns by the proposed design without introducing any design complexity has made the antenna design distinctive and unique.

6. CONCLUSION

A compact SIFW H -plane multi-horn antenna is reported in this paper. Nine exponentially tapered horns have been incorporated into a two layered cylindrical substrate, and the slots have been etched in the flaring of each horn. The design is symmetrical in the X - Z plane. The omnidirectional pattern has been obtained at 13.8 GHz as the horns have radiated in the horizontal direction. The slots in the horns' flaring have radiated at 18.42 GHz resulting in the directional pattern. Satisfactory gain has been obtained for both the omnidirectional and directional radiation patterns. The proposed design has exhibited adequate performances both in simulation and measurement. Thus, the reported antenna is a prospective aspirant to be satisfactorily used in the base station requiring a compact radiating system with high gain omnidirectional and directional radiation patterns. The antenna, proposed in this paper, is highly conducive for high-speed wireless communication.

ACKNOWLEDGMENT

The authors appreciate AD ELECTRONICS, Kolkata, and RCCIIT, Kolkata for providing assistance in Antenna fabrication and measurement.

REFERENCES

1. Vannucci, G. and R. S. Roman, "Measurement results on indoor radio frequency re-use at 900 MHz and 18-GHz," *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, 308–314, Boston, MA, 1992.
2. Rappaport, T. S., *Wireless Communications: Principles and Practice*, Prentice-Hall, New Jersey, NJ, 2007.
3. Jung, J., W. Choi, and J. Choi, "A small wideband microstrip-fed monopole antenna," *IEEE Microwave and Wireless Component Letters*, Vol. 15, 703–705, 2005.
4. Tseng, C.-F., C.-L. Huang, and C.-H. Hsu, "Microstrip fed monopole antenna with a shorted parasitic element for wideband application," *Progress In Electromagnetics Research Letters*, Vol. 7, 115–125, 2009.
5. Luk, K. M. and S. H. Wong, "A printed high-gain monopole antenna for indoor wireless LANs," *Microwave and Optical Technology Letters*, Vol. 41, 177–180, 2004.
6. Xu, H. X., G. M. Wang, M. Q. Qi, and Z. M. Xu, "A metamaterial antenna with frequency-scanning omnidirectional radiation patterns," *Applied Physics Letters*, Vol. 101, 173501-1–5, 2012.
7. Xu, H.-X., G.-M. Wang, Y.-Y. Lv, M.-Q. Qi, X. Gao, and S. Ge, "Multifrequency monopole antennas by loading metamaterial transmission lines with dual-shunt branch circuit," *Progress In Electromagnetics Research*, Vol. 137, 703–725, 2013.
8. Xu, H.-X., G.-M. Wang, and M.-Q. Qi, "A miniaturized triple-band metamaterial antenna with radiation pattern selectivity and polarization diversity," *Progress In Electromagnetics Research*, Vol. 137, 275–292, 2013.
9. Quan, X. L., R. L. Li, Y. H. Cui, and M. M. Tentzeris, "Analysis and design of a compact dual band directional antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 11, 547–550, 2012.
10. Nasimuddin, and Z. N. Chen, "Wideband directional microstrip antennas fed by CPW loop combination," *IEEE International Conference on Ultra-Wideband*, 700–702, Singapore, 2007.
11. Majid, H. A., M. K. A. Rahim, M. R. Hamid, and M. F. Ismail, "Frequency reconfigurable microstrip patch-slot antenna with directional radiation pattern," *Progress In Electromagnetics Research*, Vol. 144, 319–328, 2014.
12. Xiong, H. and J. S. Hong, "A Wideband endfire directional microstrip antenna with metamaterials," *IETE Journal of Research*, Vol. 59, 150–155, 2014.
13. Balani, C. A., *Antenna Theory: Analysis & Design*, Wiley, New York, NY, 2005.

14. Xu, F. and K. Wu, "Guided-wave and leakage characteristics of substrate integrated waveguide," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 53, 66–73, 2005.
15. Wang, H., D. G. Fang, B. Zhang, and W. Q. Che, "Dielectric loaded substrate integrated waveguide (SIW) H -plane horn antennas," *IEEE Transactions on Antennas and Propagation*, Vol. 58, 640–647, 2010.
16. Che, W., B. Fu, P. Yao, and Y. L. Chao, "Substrate integrated waveguide horn antenna with dielectric lens," *Microwave and Optical Technology Letters*, Vol. 49, 168–170, 2007.
17. Gong, L., K. Y. Chan, and R. Ramer, "Substrate integrated waveguide H -plane horn antenna with improved front-to-back ratio and reduced side lobe level," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, 1835–1838, 2016.
18. Tang, Y., Z. Wang, L. Xia, and P. Chen, "A novel high gain K-band H -plane SIW horn antenna using dielectric loading," *Asia-Pacific Microwave Conference*, 372–374, Sendai, Japan, 2014.
19. Luo, Y. and J. Bornemann, "Substrate integrated waveguide horn antenna on thin substrate with back-lobe suppression and its application to arrays," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 2622–2625, 2017.
20. Agrawal, T. and S. Srivastava, "Ku band pattern reconfigurable substrate integrated waveguide leaky wave horn antenna," *Int. J. of Electron. and Commun. (AEÜ)*, Vol. 87, 70–75, 2018.
21. Park, W. B., J. M. Lee, Y. M. Park, and K. C. Hwang, "A 18–40 GHz substrate integrated waveguide (SIW) H -plane horn antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 66, 6322–6327, 2018.
22. Choudhury, S., A. Mohan, P. K. Mishra, and D. Guha, "Reconfigurable dual-fed horn with pattern switchability realized by SIW technology," *IEEE Transactions on Antennas and Propagation*, Vol. 68, 4072–4076, 2020.
23. Sun, L., B. Sun, J. Yuan, W. Tang, and H. Wu, "Low profile, quasi omnidirectional, substrate integrated waveguide (SIW) multi-horn antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, 818–821, 2015.
24. Guo, J. L., C. Li, Y. H. Yang, and B. H. Sun, "Low-profile omnidirectional circularly polarized antenna based on substrate integrated waveguide technology," *International Journal of RF and Microwave Computer-Aided Engineering*, Vol. 28, 1–8, 2018.
25. Bhowmik, W. and S. Srivastava, "Design of compact omnidirectional substrate integrated waveguide exponentially tapered multiple H -plane horn antenna," *Int. J. of Electron. and Commun. (AEÜ)*, Vol. 108, 29–35, 2019.
26. Khalichi, B., S. Nikmehr, and A. Pourziad, "Development of novel wideband H -plane horn antennas by employing asymmetrical slots based on SIW technology," *Int. J. of Electron. and Commun. (AEÜ)*, Vol. 69, 1374–1380, 2015.
27. Bhowmik, W., S. Srivastava, and L. Prasad, "Design of multiple beam forming antenna system using substrate integrated folded waveguide (SIFW) technology," *Progress In Electromagnetics Research B*, Vol. 60, 15–34, 2014.
28. Grigoropoulos, N., B. S. Izquierdo, and P. R. Young, "Substrate integrated folded waveguides (SIFW) and filters," *IEEE Microwave and Wireless Component Letters*, Vol. 15, 829–831, 2005.
29. Zhai, G. H., W. Hong, K. Wu, J. X. Chen, P. Chen, J. Wei, and H. J. Tang, "Folded half mode substrate integrated waveguide 3 dB coupler," *IEEE Microwave and Wireless Component Letters*, Vol. 18, 512–514, 2008.
30. Grigoropoulos, N. and P. R. Young, "Compact folded waveguides," *34th European Microwave Conference*, 973–9176, Amsterdam, Netherlands, 2004.
31. Kumari, S., V. R. Gupta, and S. Srivastava, "A novel feeding technique for folded substrate integrated waveguide," *Int. J. of Electron. and Commun. (AEÜ)*, Vol. 138, 1–6, 2021.
32. Bhowmik, W., S. Srivastava, and L. Prasad, "Design of a low cost 4×4 butler matrix fed antenna array partially loaded with substrate integrated waveguide (SIW)," *International Journal of Microwave and Optical Technology*, Vol. 9, 227–236, 2014.
33. Djerafi, T., A. Doghri, and K. Wu, *Handbook of Antenna Technologies*, Springer, Singapore, 2015.