

## Research Article

# A Super Wideband Directional Compact Vivaldi Antenna for Lower 5G and Satellite Applications

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In this paper, a super wide band (SWB) Vivaldi antenna has been proposed for lower 5G bands in Sub-6 GHz and satellite applications (S, C, X, Ku, and K band) using various performance improvement techniques. In the presented Vivaldi antenna, different slots are applied not only to increase the gain and directivity but also to get operating frequency at the intended specific frequency range. All dimensions of those slots were chosen by using the sweep parameter method. Ten corrugated side slots, two circular slots, and one via have been used to enhance the performance especially bandwidth and gain of the antenna. At the edge of wireless communication, we want to enhance two key aspects within the communication systems: the quality of service and the cost. The proposed antenna incorporates a simple structure and small size with dimensions of  $45 \times 35 \times 0.79 \text{ mm}^3$ . Thus, after design, optimization, and simulation, the antenna produces a good reflection coefficient over the very large operating bandwidth of 23.19 GHz,  $1 < \text{VSWR} < 2$ , maximum gain of 10.2 dBi, and average radiation efficiency of above 90%, which can be recommended as a suitable antenna for lower 5G as well as satellite applications. The antenna is designed, simulated, and analyzed by using computer simulation technology microwave studio (CST-MWS). Finally, the performance of the Vivaldi antenna has been validated by FEKO and HFSS software, and we achieved a very good matching among the results.

## 1. Introduction

Since the first Vivaldi antenna was proposed in 1979 by Gibson [1], it is widely used in ultrawideband applications such as wireless communication, biomedical detection, Radar, Satellite communication system, and so on [2]. A Vivaldi antenna is a planar broadband antenna that is made of a dielectric substrate metalized on both sides. The feed-line encircles the microstrip line, terminated with a sector-shaped area that encircles the circular space. The radiating energy at the resonant points reaches over exponential patterns through the symmetrical slot lines [3]. The Vivaldi antennas are categorized into three types: tapered slot Vivaldi antenna (TSVA), antipodal Vivaldi antenna (AVA), and balanced antipodal Vivaldi antenna (BAVA). The authors in [4–6] discussed the different parameter variation of the Vivaldi antenna both analytically and

experimentally. In today's life, it is inevitable to have very high speed data exchanging channels for wideband applications. A Vivaldi antenna can produce ultrawideband frequencies with high directivity and stable radiation pattern. There are several advantages of using a Vivaldi antenna such as broadband characteristics, simple structure, small size, and easy manufacturing. In [7], an ultrawideband patch antenna with a U-shaped slot on the radiating patch is introduced for triband satellite applications. The operating frequency ranges of the proposed structure are 4.9 GHz–7 GHz, 7.92 GHz–11.08 GHz, and 11.85 GHz–15.94 GHz, and gain is varied from 2.3 to 4.5 dBi. In [8], a novel patch antenna is proposed consisting of parasitic elements and rectangular slots on the ground plane. The proposed structure has a dimension of  $16 \times 8 \text{ mm}^2$ . The antenna shows the bandwidth of 11.34–17.46 GHz and gain of 4.92–6.30 dBi. A pair of

square-shaped slotted Vivaldi antenna with dimension of  $110 \times 80 \text{ mm}^2$  has been proposed in [9]. Its operating frequency range is 2 GHz–11 GHz and has maximum gain of 10 dBi. To enhance the performance of the traditional Vivaldi antenna, the side-slotted Vivaldi antenna (SSVA) for imaging application is proposed in [10]. It has a size of  $45 \times 37 \text{ mm}^2$  and covers an ultrawideband frequency range. It possesses a maximum gain of 6.8 dBi and radiation efficiency is about 88%. To detect brain tumor within the human head, a coplanar feed ultrawide band Vivaldi antenna is proposed in [11, 12], which has a dimension of  $30 \times 30 \text{ mm}^2$  and operated at a bandwidth of 3.1 GHz–10.6 GHz. The gain and directivity are improved by applying corrugated slots in both sides and gratings in front of the proposed antenna. A monopole Vivaldi antenna for cellular communication including LTE, GSM, UMTS, WiMAX, and WiFi bands has been simulated and presented in [13]. The novel compact broadband monopole Vivaldi antenna has been fabricated in [14]. The size of the final prototype is  $73 \times 69 \text{ mm}^2$ . In [15], an ultrawideband novel Vivaldi antenna for mobile communication application with pattern diversity has been proposed and fabricated. It covers 0.7–2.7 GHz. The huge bandwidth and high gain have been achieved by the designed antenna [16]. The operating frequency is 2.5–57 GHz and gain is 16 dBi. To get a huge bandwidth, a comparatively larger size of antenna is opted. It results higher VSWR ( $<3$ ). A fern leaf inspired fractal structure has been introduced for UWB applications in [17]. In [18], the folding technique is applied on the tapered slot antenna, which shows the peak gain of 15 dBi with a balance radiation pattern to the whole operating range. In another technique, a number of metamaterial structures have been presented to improve the directional property of conventional antenna by reducing side lobe [19]. A miniaturized AVA with slits and dielectric lens has been fabricated in [20], which operated at a bandwidth of 1–30 GHz. In [21], a flexible UWB Vivaldi antenna with 3D-phase adjusting unit has been proposed which has better gain and pattern diversity. It has a dimension of  $68 \times 52 \text{ mm}^2$  and covers 6–18 GHz. Many other different techniques have been applied to increase antenna performance such as slotting technique, directors, patches, and lens loading technique. The antenna is fabricated by dielectric material of Rogers 5880 with a thickness of 20 mil. After analyzing the newly revealed Vivaldi antennas from [22–28], the basic motive is to decrease the size of the antenna as well as step up the higher operating bandwidth, gain, and efficiency.

During the design process of an ultra wideband Vivaldi antenna, one faces many challenges. One of them is the miniaturization of the antenna with wide impedance bandwidth and good radiation performance. In some cases, a low gain is exhibited through the entire ultrawide operating band. In the minimization process, reducing the size of the antenna also decreases the performance of the antenna. Therefore, developing a compact design of the directional Vivaldi antenna with good gain and directivity, better efficiency, and VSWR for satellite communication and other ultra wideband applications is a very challenging task. In this

paper, a super wideband Vivaldi antenna having a huge bandwidth of 23.19 GHz (3.06 GHz–26.25 GHz) and compact size of  $45 \times 35 \times 0.79 \text{ mm}^3$  has been presented and discussed briefly. The main achievement of this research work is to develop a compact and super wide band Vivaldi antenna without compromising stability of gain and high radiation efficiency.

## 2. Tapered Slot Vivaldi Antenna Geometry

The geometrical structure of a microstrip line fed tapered slot super wideband compact Vivaldi antenna is described in this section. It is an exponential double-sided corrugated tapered slot Vivaldi antenna. The total design processes have been presented in five steps. Figure 1(a) represents a simple tapered Vivaldi aerial which is the first step of our proposed antenna. Two exponential tapered slots are placed symmetrically on the top of the substrate. Rogers RT 5880 dielectric material has been used as substrate of the antenna, having a relative permittivity of 2.2, tangent loss of 0.0009, and thickness of 0.79 mm. The microstrip line feeding is used as a feeding technique, which connects the two exponential tapered slots. The overall dimension ( $L \times W$ ) of the Vivaldi antenna is  $45 \text{ mm} \times 35 \text{ mm}$ . The thickness of the copper plate which is used as a radiating patch is 0.035 mm. The exponential profile of the designed Vivaldi antenna can be described by the following equation [11]:

$$x = C_1 e^{Rz} + C_2, \quad (1)$$

where

$$C_1 = \frac{x_2 - x_1}{e^{Rz_2} - e^{Rz_1}}, \quad (2)$$

$$C_2 = \frac{x_2 e^{Rz_2} - x_1 e^{Rz_1}}{e^{Rz_2} - e^{Rz_1}}. \quad (3)$$

Here, the points  $(x_1, z_1)$  and  $(x_2, z_2)$  are the endpoints of the flare. In this case, the taper rate is 0.135 which results in a wide mouth opening of 25.34 mm at the upper edge between the flares. At the second step, four corrugated slots are created in the top two sides of the metallic plates, which are shown in Figure 1(b). Each flare has two corrugated slots. The width of the slots is 2 mm. The lengths of the slots are 4 mm and 4.5 mm. In the third step, similarly additional six corrugated slots are made with the previous four slots and optimized the dimensions of the corrugated slots to ensure better performance than previous steps. The dimensions of the slots are 5 mm and 5.5 mm. The described structure of the antenna is presented in Figure 1(c). Two identical circular slots having a radius of 5 mm are added at the fourth step. The tapered slot Vivaldi antenna with all corrugated and circular slots is shown in Figure 1(d).

All the slots including corrugated slots make the antenna ultrawideband and enhance gain as well as increase the efficiency than previous steps. And finally, a shorting pin named via has been used which makes direct connection between the feed line and metal flare. This via promotes the antennas bandwidth from ultrawideband to super wideband.

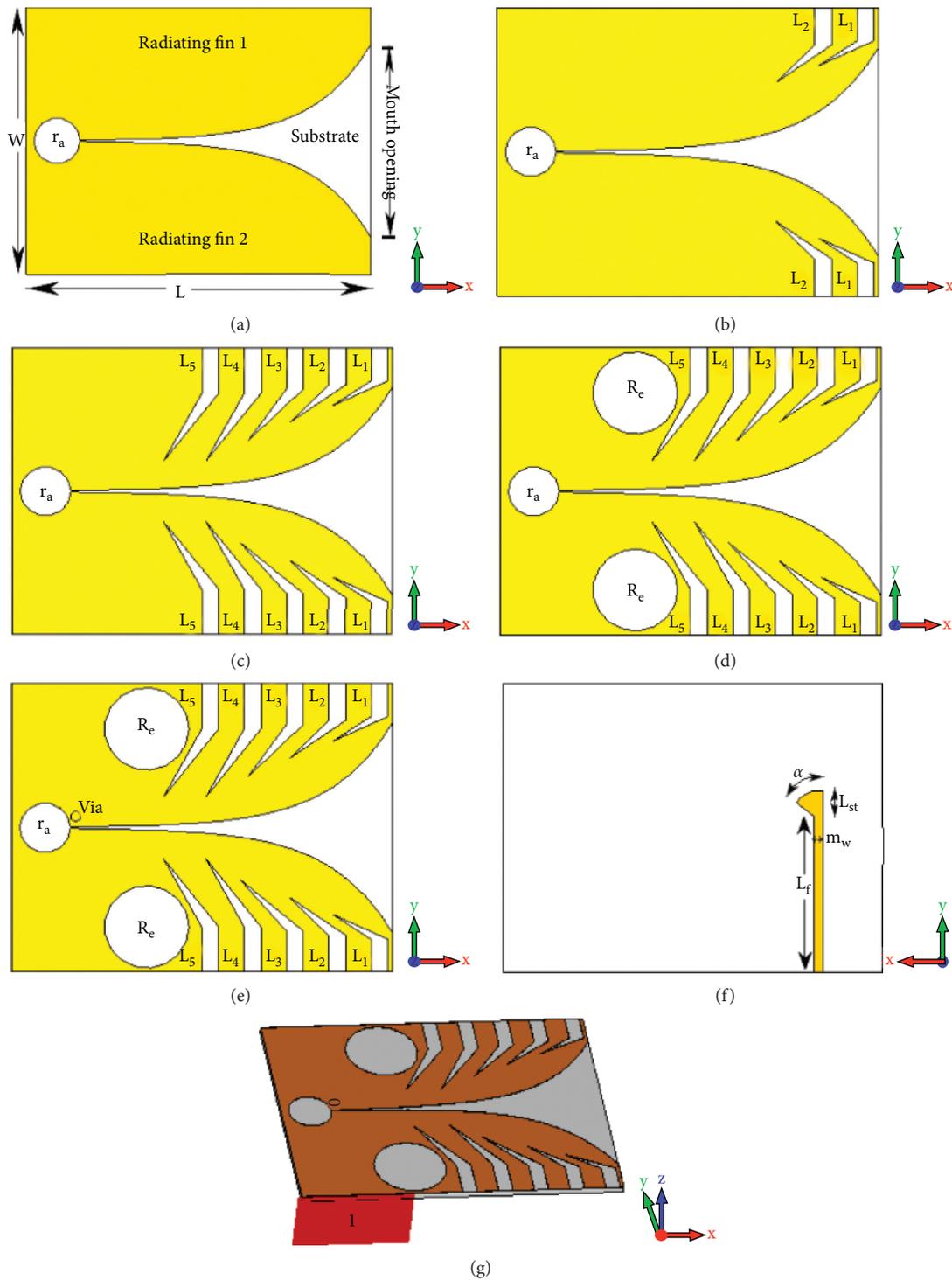


FIGURE 1: Evolution process of the proposed Vivaldi antenna: (a) Step 1 (front view); (b) Step 2 (front view); (c) Step 3 (front view); (d) Step 4 (front view); (e) Step 5 (front view) (proposed); (f) back view; (g) 3D view of the proposed antenna.

The via also enhances the surface current distribution throughout the antenna. The metal via has a height of 0.86 mm and radius of 0.6 mm as shown in Figure 1(e). Figure 1(f) shows the structure of the microstrip line feed of the proposed Vivaldi antenna. After applying all different techniques (like corrugated both sided slots, circular slots,

and via) to enhance the antenna performance and using sweep parameters process, finally a super wideband compact tapered slot Vivaldi antenna has been proposed whose 3D view with port is depicted in Figure 1(g). The geometrical parameters of the proposed SWB Vivaldi antenna are listed in Table 1.

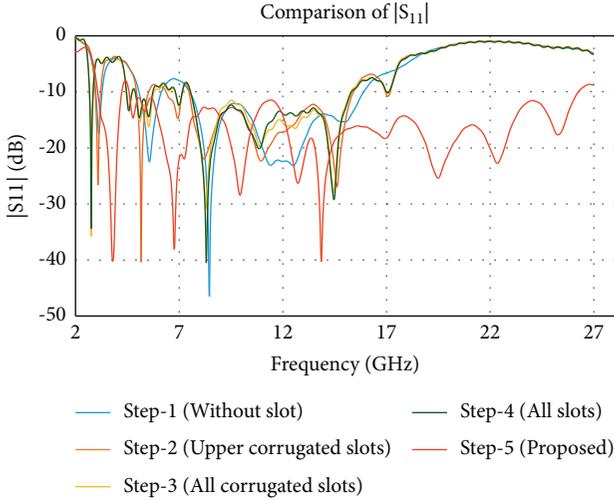


FIGURE 2: Return loss curve for different evolution stages.

TABLE 1: Geometrical parameters of the proposed tapered slot super wideband vivaldi antenna.

Parameter with symbol	Value (mm)
Length of antenna, $L$	45
Width of antenna, $W$	35
Height of substrate, $h$	0.79
Thickness of patch, $m_t$	0.035
Width of microstrip feed line, $m_w$	1.2
Tapper rate, $r$	0.135
Throat width, $s$	0.05
Back wall offset, $ext$	1
Radius of cavity, $r_a$	3
Port coefficient, $k$	9.53
Dielectric constant of substrate, $\epsilon_r$	2.2
Tangent loss of substrate, $\delta$	0.0009
Angle of radial stub, $a$	70 deg
Length of the radial stub, $L_{st}$	4.5
Outer mouth opening, $W_o$	25.34
Radius of circular slots, $R_c$	5
Distance of via from the slot, $te$	1.4

### 3. Results and Performance Estimation

This section describes all the results and analysis of the proposed Vivaldi antenna that is presented in previous sections. Initially, the proposed Vivaldi antenna is analyzed and optimized using 3D EM simulator software named CST microwave studio. At the end, the obtained results are also verified by other two professional softwares: FEKO and HFSS. A comparison of the  $S_{11}$  curves from Step 1 to Step 5 is depicted in Figure 2 to understand the successive bandwidth improvement after applying different aforementioned techniques on the designed SWB Vivaldi antenna. It can be easily noted that no other steps except Step 5 has operating bandwidth after 16 GHz, and only for Step 5, it holds up to 26.25 GHz. So, Step 5 has a larger bandwidth than the previous four steps. In this case, the metal via has a great influence on extending the UWB to SWB and also improves the current distribution of the antenna. The final Step 5 also provides much better return loss than any others. The antenna possesses the maximum return loss of  $-40.322$  dB at 13.86 GHz.

Figure 3 illustrates the gain of the five consecutive steps of this presented work. The average gain of the proposed antenna is above 8 dBi through the whole operating super wideband ranging from 3.06 GHz to 26.25 GHz. The comparison of radiation efficiency between Step 1 to Step 5 is shown in Figure 4. The maximum radiation efficiency of the proposed antenna is approximately 99%, and the average is above 95%. Therefore, the antenna reveals good efficacy to radiate energy. The voltage standing wave ratios of all the stages of the antenna at the frequency range of 3 GHz to 27 GHz are displayed in Figure 5. It is certified that the VSWR of a radiating antenna varies from 1 to 2. For the best performance, the value tends to unity at every resonant frequency of the finally proposed compact Vivaldi antenna. It can be seen that the VSWR of the proposed antenna is 1.01, 1.02, 1.08, 1.09, 1.07, 1.15, 1.18, and 1.25 at resonant frequencies of 3.81 GHz, 6.75 GHz, 10 GHz, 12.4 GHz, 13.86 GHz, 19.5 GHz, 22.5 GHz, and 25.5 GHz, respectively. Figure 6 depicts the 3D view of gain for the proposed antenna at major three resonant frequencies of 3.81 GHz, 6.75 GHz, and 13.86 GHz. The surface current distribution of the proposed antenna is 196.184 A/m, 186.8222 A/m, and 351.789 A/m at the frequencies of 3.81 GHz, 6.75 GHz, and 13.86 GHz, respectively, which are represented in Figure 7. It can also be seen that the current of the antenna is mostly spread on the radiating fins at both lower and higher frequencies, which favors to assemble the electromagnetic energy and expand the stability of radiation of the proposed SWB Vivaldi antenna. Figure 8 represents the  $S_{11}$ -parameter of the finally proposed SWB Vivaldi antenna from 2 to 27 GHz. It has been seen that there is a super wide operating band (SWB). The  $-10$  dB bandwidth of the antenna covers from 3.06 GHz to 26.25 GHz. There are multiple resonant frequencies that are 3.81 GHz, 6.75 GHz, 10 GHz, 12.4 GHz, 13.86 GHz, 19.5 GHz, 22.5 GHz, and 25.5 GHz. The operating band covers prescribed all the lower 5G bands in sub-6 GHz like in USA, 3100–3550 MHz and 3700–4200 MHz, in Europe, 3400–3800 MHz; in Spain, 3600–3800 MHz; in China, 3300–3600 MHz, 4400–4500 MHz, and 4800–4990 MHz; in Ireland, 3.4–3.8 GHz; in Japan, 3600–4200 MHz and 4400–4900 MHz; in Korea, 3400–3700 MHz; in India 3300–3400 MHz as well as the designed antenna also covers many satellite bands like S-band (2–4 GHz) (partial coverage), C-band (4–8 GHz), X-band (8–12 GHz), Ku-band (12–18 GHz), and Ka-band (26–40 GHz) (partial coverage). Some key performance indexes estimated by CST are listed in Table 2. The performances estimated by CST have also been buttressed and verified by redesigning with the help of other two renowned electromagnetic (EM) simulators: FEKO and HFSS. FEKO uses Method of Moments (MoM) integral formulation of Maxwell's equations where HFSS uses finite element method and CST has multiple EM simulation solvers which use methods such as finite element method (FEM), finite integration technique (FIT), and transmission line matrix method (TLM). In Figures 9–11, we have presented the estimated reflection coefficient, gain, and efficiency validation, respectively. There are very high similarity index among all the results obtained from CST, FEKO, and HFSS for the proposed antenna.

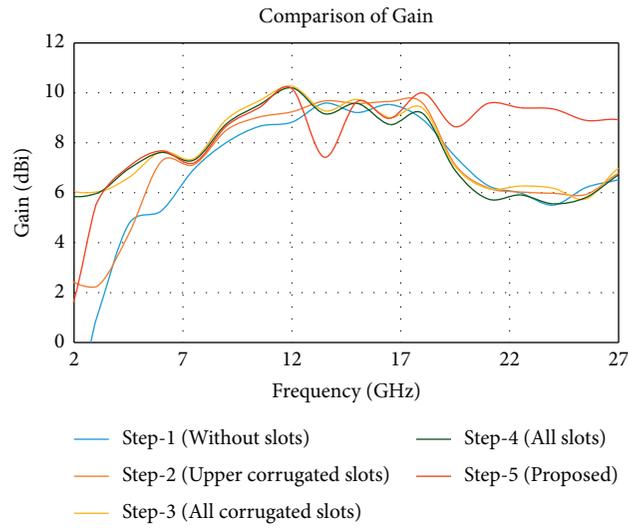


FIGURE 3: Gain curve for different evolution stages.

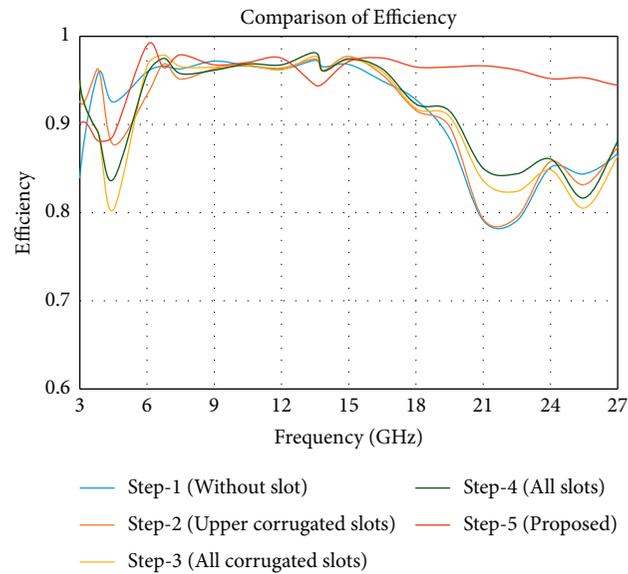


FIGURE 4: Efficiency curve for different evolution stages.

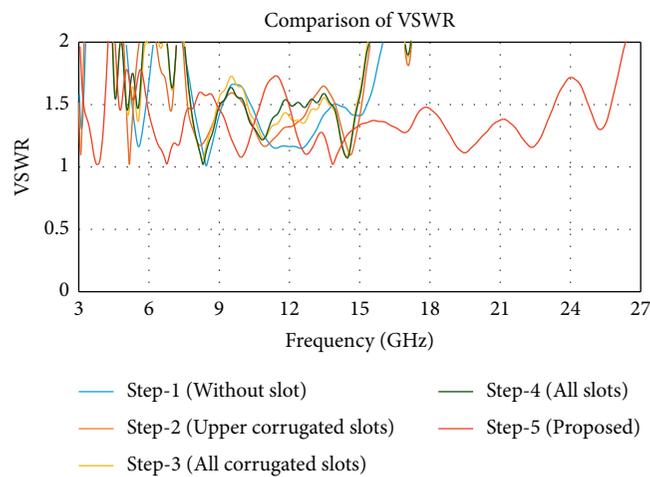


FIGURE 5: VSWR curve for different evolution stages.

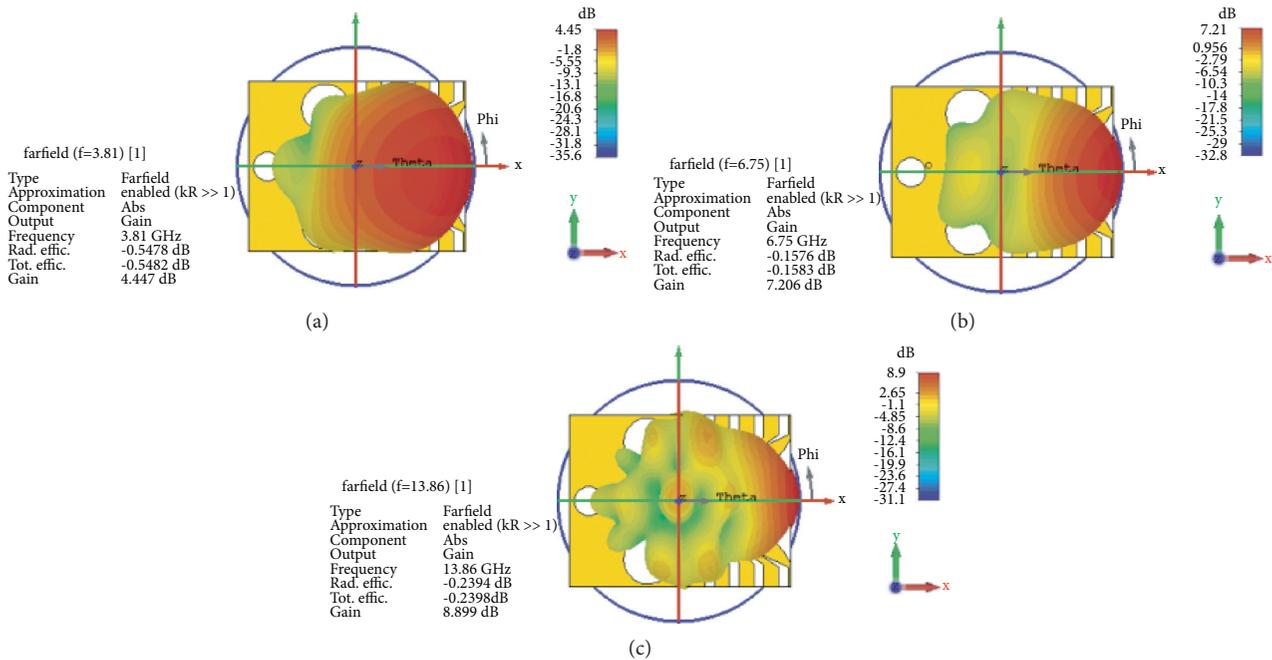


FIGURE 6: 3D radiation pattern at (a) 3.81 GHz, (b) 6.75 GHz, and (c) 13.86 GHz.

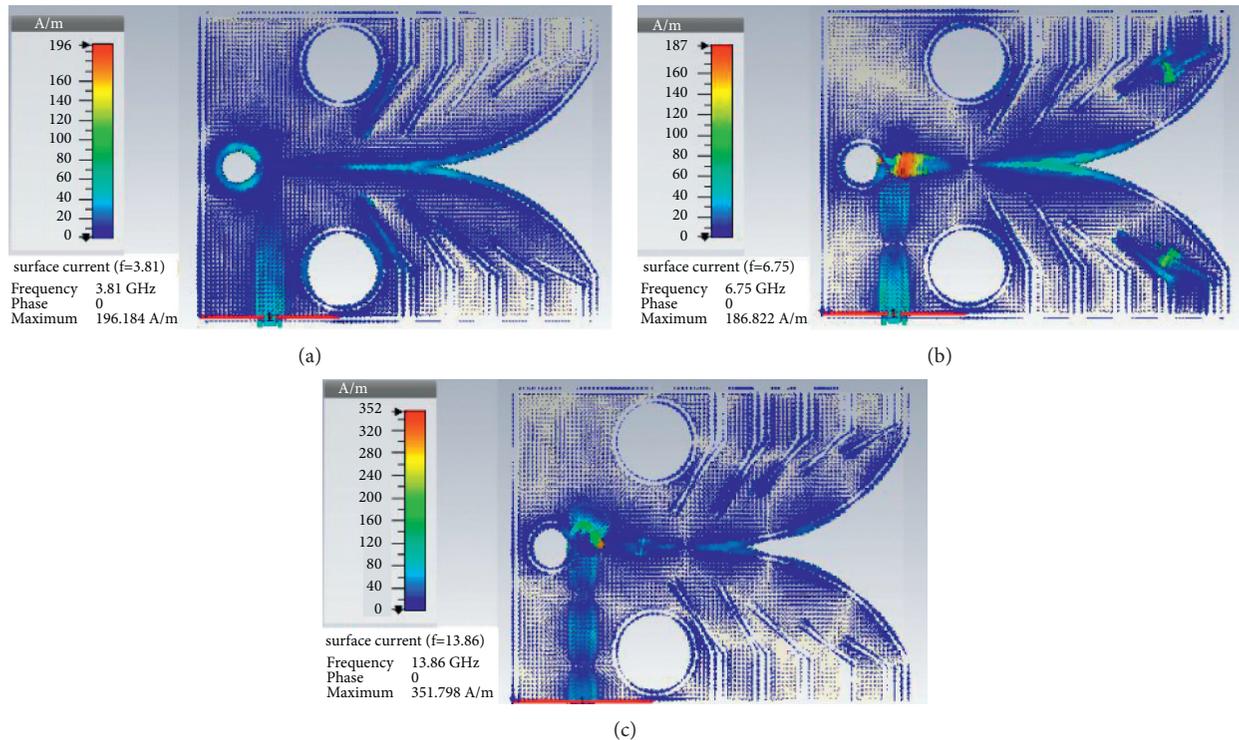


FIGURE 7: Surface current distribution at (a) 3.81 GHz, (b) 6.75 GHz, and (c) 13.86 GHz.

The electric fields (E-fields) for all the steps for  $\phi = 0^\circ$  and  $90^\circ$  are depicted in Figure 12 at 3.81 GHz, 6.75 GHz, and 13.86 GHz, respectively. For  $\phi = 0^\circ$  and 3.81 GHz as presented in Figure 12(a), Step 5, i.e., the proposed antenna possesses the main lobe of 20.6 dBV/m with the angular

width of  $163.5^\circ$  where as Step 1 has the main lobe of 19.1 dBV/m with the angular width of  $24.1^\circ$  only. Though directions of the main lobe for the proposed antenna and Step 1 antenna are same ( $72^\circ$ ), the proposed antenna shows better main lobe magnitude (23.6 dBV/m) and wider angular width

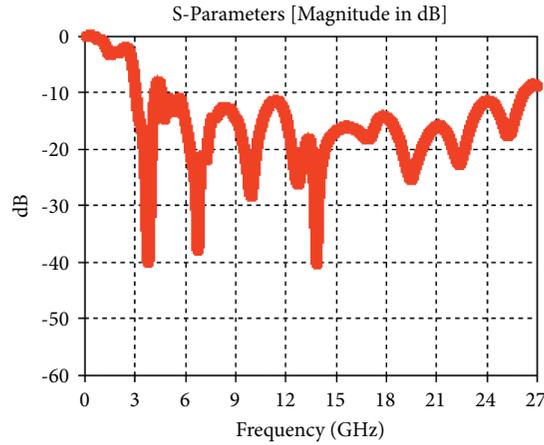


FIGURE 8: Return loss curve of Step 5 (proposed Vivaldi antenna).

TABLE 2: Performance metrics of the proposed super wideband Vivaldi antenna.

Name of the parameter	Value
-10 dB bandwidth (GHz)	23.19
Lower cut off frequency (GHz)	3.06
Higher cut off frequency (GHz)	26.25
Return loss (dB) at 13.86 GHz	-40.19
Max. gain (dBi)	10.2
VSWR	$1 < \text{VSWR} < 2$
Efficiency (%)	Above 90

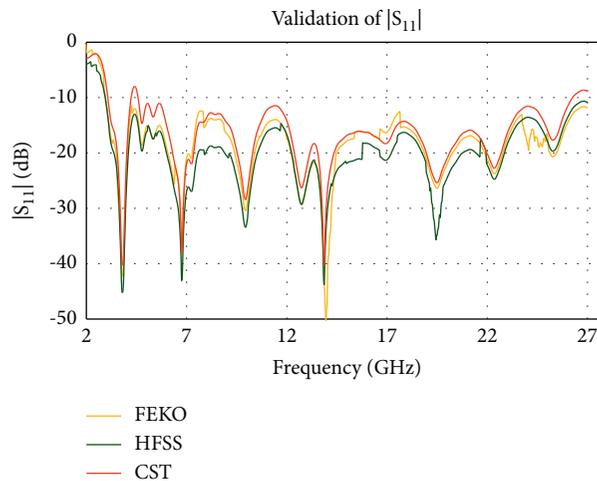


FIGURE 9: Validation of return loss curve of the proposed Vivaldi antenna.

(110.7°) as in Figure 12(b). For the proposed antenna at  $\phi = 0^\circ$  as shown in Figure 12(c), the main lobe direction slightly shifted from  $89^\circ$  (Step 1) to  $91^\circ$  at 13.86 GHz, and in this case, the side lobe label is  $-7.6$  dB. In Figure 12(d), the designed antenna has a main lobe direction of  $2^\circ$ , magnitude of main lobe of  $17.1$  dBV/m, and  $3$  dB angular width of  $35.3^\circ$ . On the other hand, as presented in Figures 12(e) and 12(f), the proposed antenna holds the magnitude of main lobe of  $9.78$  dBV/m and  $16.3$  dBV/m and  $3$  dB angular width of  $28.1^\circ$  and  $31.9^\circ$ ; directions of main lobes are  $2^\circ$  and  $4^\circ$  at 6.75 GHz and 13.86 GHz, respectively.

The magnetic fields (H-fields) for all the steps of the proposed antenna are presented in Figure 13 considering different conditions. Figures 13(a)–13(c) present the H-fields for  $\phi = 0^\circ$  at 3.81 GHz, 6.75 GHz, and 13.86 GHz, respectively. And Figures 13(d)–13(f) show the H-fields for  $\phi = 90^\circ$ . At  $\phi = 0^\circ$  and 3.81 GHz resonant frequency, the finally designed antenna shows the main lobe magnitude of  $-30.9$  dBA/m and main lobe direction of  $136^\circ$ . The antenna (Step 5) presents the side lobe label of  $-9.4$  dB and  $-4.6$  dB for  $\phi = 0^\circ$ ; 6.75 GHz and  $\phi = 0^\circ$ ; 13.86 GHz. At  $\phi = 90^\circ$ , the proposed antenna has the main lobe

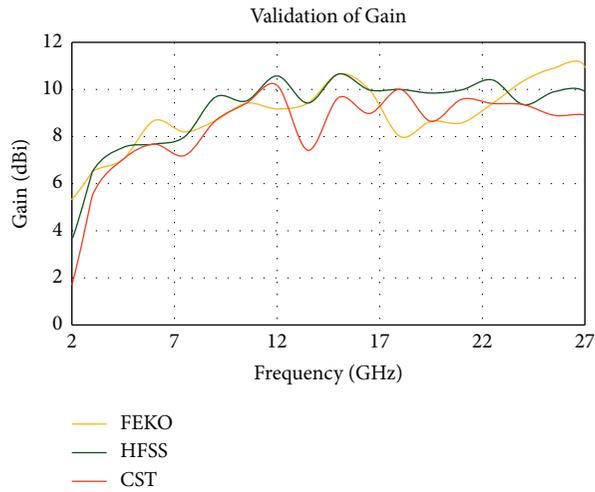


FIGURE 10: Validation of gain curve of the proposed Vivaldi antenna.

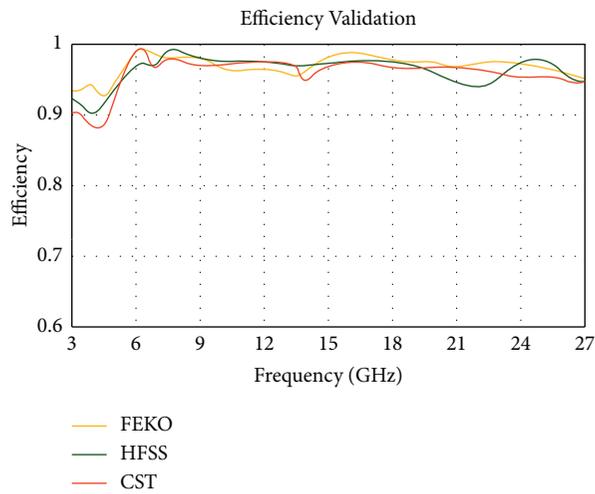


FIGURE 11: Validation of efficiency curve of the proposed Vivaldi antenna.

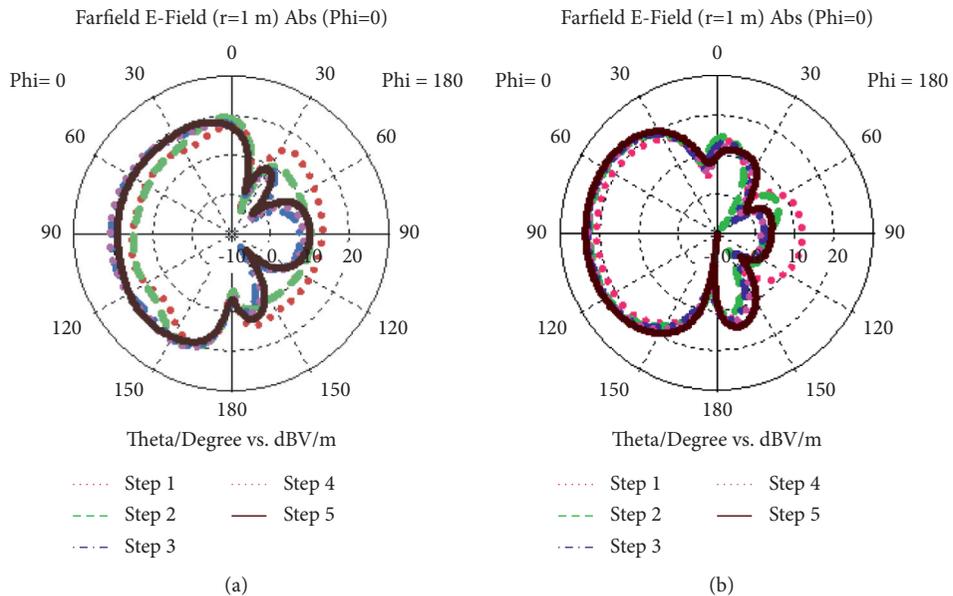


FIGURE 12: Continued.

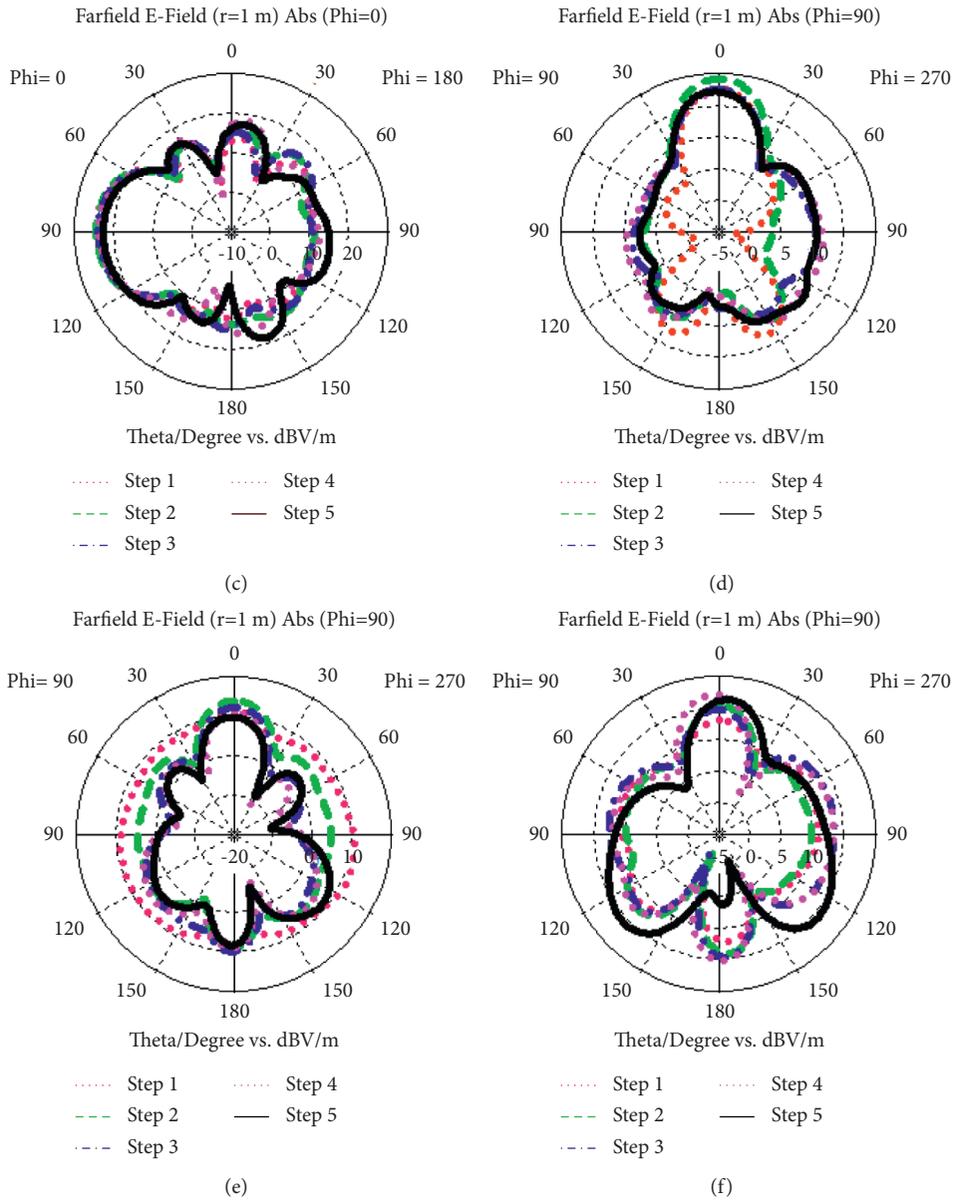


FIGURE 12: Electric field (E-field) for all the steps at  $\Phi = 0^\circ$  and  $90^\circ$ : (a) E-field ( $\Phi = 0^\circ$ ; 3.81 GHz); (b) E-field ( $\Phi = 0^\circ$ ; 6.75 GHz); (c) E-field ( $\Phi = 0^\circ$ ; 13.86 GHz); (d) E-field ( $\Phi = 90^\circ$ ; 3.81 GHz); (e) E-field ( $\Phi = 90^\circ$ ; 6.75 GHz); (f) E-field ( $\Phi = 90^\circ$ ; 13.86 GHz).

magnitude of  $-34.4$  dBA/m,  $-41.7$  dBA/m, and  $-35.2$  dBA/m, and main lobe directions are  $2^\circ$ ,  $2^\circ$ , and  $4^\circ$  for 3.81 GHz, 6.75 GHz, and 13.86 GHz, respectively. Table 3 shows a comparison scenario with some recently published relevant works. From the table, our proposed Vivaldi antenna has compact size compared with many

other antennas and also possesses a super wide operating band covering sub-6 GHz band, S-, C-, X-, Ku-, and K-bands of satellite applications. It also shows excellent return loss profile and maximum gain of 10.2 dBi holding good average gain over the entire operating super wideband.

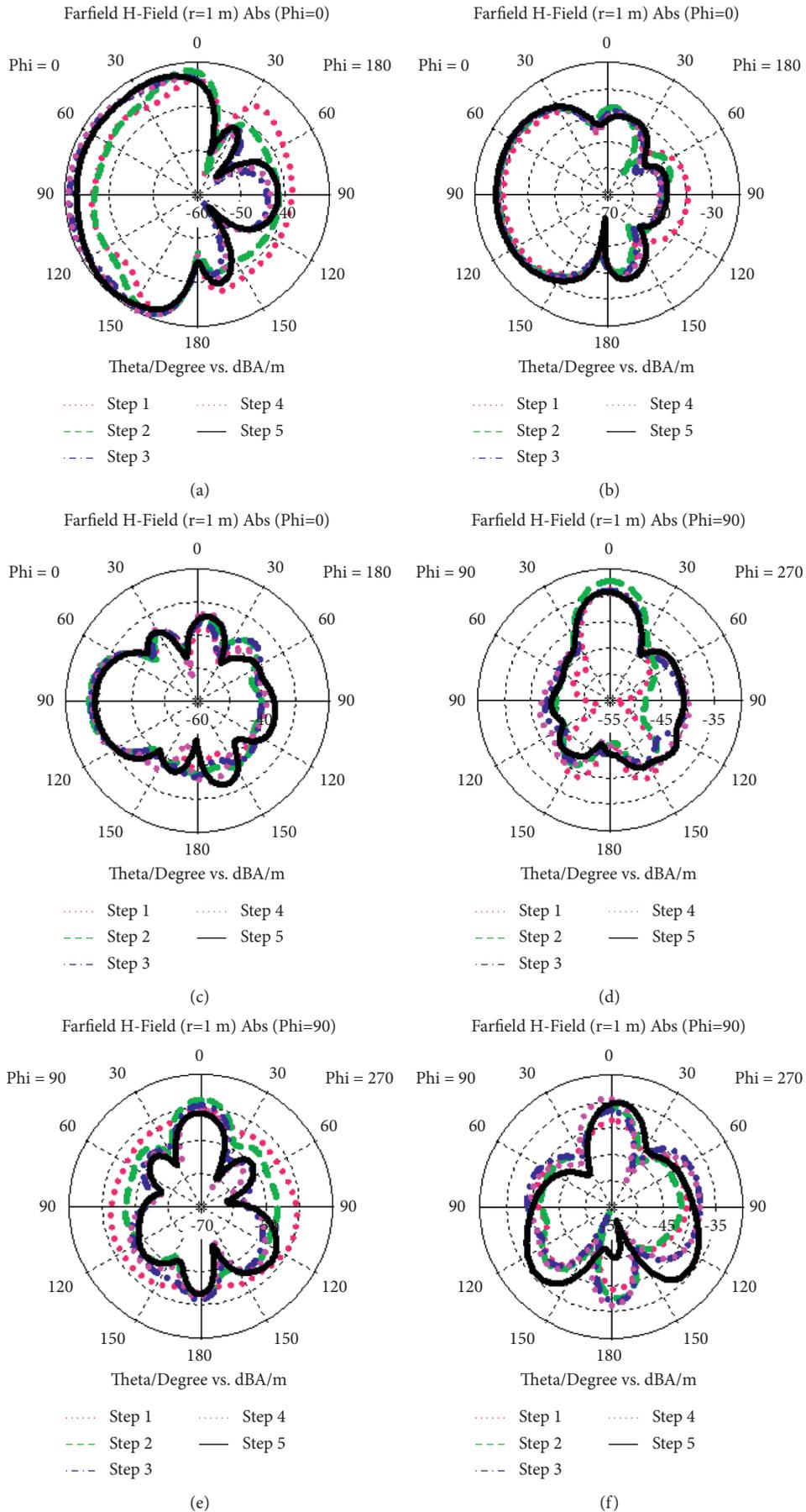


FIGURE 13: Magnetic field (H-field) for all the steps at Phi = 0° and 90°: (a) H-field (Phi = 0°; 3.81 GHz); (b) H-field (Phi = 0°; 6.75 GHz); (c) H-field (Phi = 0°; 13.86 GHz); (d) H-field (Phi = 90°; 3.81 GHz); (e) H-field (Phi = 90°; 6.75 GHz); (f) H-field (Phi = 90°; 13.86 GHz).

TABLE 3: Comparison with some recently published works.

Ref. no.	Size ( $L \times W \times h$ ) mm <sup>3</sup>	Max. gain (dBi)	BW (GHz)	Return loss (dB)
[16]	186 × 77 × 0.55	16	2.5–57	—
[17]	62 × 50.8 × 0.8	10	1.3–20	≈−33
[18]	100 × 60 × 0.008	15	3–22	≈−45
[19]	60 × 40 × 0.508	17.7	3.68–43.5	≈−43
[20]	100 × 96 × 0.508	2.2–11	1–30	≈−35
[21]	68 × 52 × 0.25	14	6–18	≈−43
[22]	80 × 44 × 9.2	-	2.4–18	≈−40
[23]	140 × 66 × 1.5	≈10	5–27	≈−25
[24]	70 × 50 × 1	15	2.8–15	≈−31
[25]	66.5 × 50 × 1	8.5	10–30	≈−50
[26]	36 × 32 × 2	8	2.5–11	≈−40
[27]	31 × 20 × 0.51	11	5.3–40	≈−25
[28]	200 × 125 × 1.2	10.5	0.95–15.5	—
Our designed	45 × 35 × 0.79	10.2	3.06–26.25	−40.32

#### 4. Conclusion

A super wideband Vivaldi antenna for lower 5G and satellite applications at C-, X-, Ku-, and K-bands has been presented. Different strategies are applied to enhance the performance as well as to make it compact. It is achieved by etching ten opposite corrugated slots and two circular slots in the metallic flares. The material of substrate, radiating fins, cavity diameter, stub radius, stub angle etc. parameters are optimized to reduce the size of the antenna and to get better performance especially to get super wideband. Results show that the modified flares change electrical length and enhance the gain greater than 8 dBi, by adjusting the radius and angle of stub. There is an important effect of substrate material over the performance parameters, especially bandwidth and efficiency. The proposed Vivaldi antenna covers super wideband (3.06 GHz to 26.25 GHz), showing a returning loss of −40.322 dB, maximum gain of 10.2 dBi, VSWR of 1.07, and average radiation efficiency of above 95%. Given that, there are very good matching index during performance validation by the CST, FEKO, and HFSS. Therefore, the proposed design can be considered as an excellent model for the lower 5G and satellite applications.

#### Data Availability

The data used to support the findings of this study are included within the article.

#### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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