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Bow-tie-shaped wideband conformal antenna with wide-slot for GPS application

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Abstract: In this article, a novel wideband cylindrical conformal antenna using a wide slot in the ground plane is proposed. A bow-tie-shaped patch antenna is designed for Global Positioning System applications. The bandwidth of the antenna is improved by using a similar bow-tie-shaped slot in the ground plane with a larger dimension. The bandwidth is further enhanced by introducing a dumbbell-shaped slit in the patch. The antenna is fed by a 50-Ω microstrip line. The proposed planar antenna is printed on a ground plane of size 0.5λ mm $\times$ 0.5λ mm, where λ is the operating wavelength, and then it is transformed into a cylindrical conformal antenna with the desired radius of curvature. The proposed planar antenna is simulated, fabricated, and measured for conformal geometry with good agreement between measurements and simulation results. It is observed that the conformal antenna exhibits a fractional bandwidth of 81.4% operating from 0.75 to 1.78 GHz, which is useful for all GPS and Galileo frequencies. The radiation pattern exhibits an omnidirectional pattern and gain of the proposed antenna is 3.5 to 4.78 dBi within the operating frequency range.

Key words: Conformal antenna, bow-tie antenna, GPS application

1. Introduction

Microstrip antennas are broadly utilized as a part of wireless communication systems since they have numerous points of interest such as easy fabrication, low profile, easy integration with devices, light weight, stable radiation patterns, and low cost [1–7]. However, narrow bandwidth is one of the drawbacks of patch antennas.

With the improvement of communication technologies, bandwidth improvement is becoming vital for practical utilization of microstrip antennas. For instance, wideband antennas are required for GPS receivers installed on hand-held devices, moving vehicles, and missiles. These antennas are pivotal parts of the GPS receiver as they need to work in remote zones and also receive weak signals from satellites.

For bandwidth improvement of patch antennas, a few methodologies have been proposed [8–17]. A three-dimensional microstrip feed line was reported in [8], in which an additional plastic supporting post is required in between the ground plane and radiating patch to obtain a bandwidth of 31%. Combined utilization of both L-probe feeding and a patch loaded with a U-slot was used in [9], where an extra foam substrate is required between the ground and patch for the bandwidth of 42.7%. A similar foam layer was used in the L-probe feed antenna designed by Guo et al. in [10]. A capacitively probe-fed structure was implemented in the microstrip antenna design to enhance bandwidth up to 35% by using hard foam material, which can be considered as a shortcoming [11].

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A microstrip antenna loaded with a chip-resistor was proposed in [12]. These antennas are designed using lossy material, which is a drawback, and bandwidth obtained is 9.8%. A patch antenna was designed with a U-shaped slot for reactive loading in [13]. The difficulty is the presence of air or foam medium in between the ground plane and radiating patch. The bandwidth obtained in this design is 12.4%. An antenna with two gap-coupled parasitic patches and a directly coupled patch was proposed to obtain broadband characteristics with 12.7% bandwidth in [14], but in the design, the stacking of four patches was used. Various resonators and thick substrates with low dielectric constant have been utilized to design patch antennas on a planar surface for obtaining bandwidth up to 20% to 32.3% [15, 16]. Pues et al. designed an impedance matching system to enhance bandwidth up to 12% [17].

Ke described a ground plane loaded with an H-shaped slot in which bandwidth achieved is 21% [18]. Antennas with a wide slot and different shapes of the feed line have been described on a planar surface for large impedance bandwidths [19–21].

Applications are developed for the Global Positioning System in L_1 (1.57 GHz), L_2 (1.22 GHz), L_3 (1.38 GHz), L_4 (1.7 GHz), and L_5 (1.17 GHz) bands. The L_1 band is required for C/A procurement, and the L_2 band is necessary for military and P(Y) codes. The L_5 band is used for safety of life of civilians, and the L_3 band is used for atomic explosion identification. The L_4 band is under development for climatic analysis. Along these lines, it can be viewed that use of GPS bands reaches from L_5 to L_1 bands.

In some applications, GPS antennas are to be placed where the omnidirectional scope is guaranteed with no signal distortion. Sometimes the antenna mounting platform is not planar. In those cases, there is a requirement for conformal antennas to make it less noticeable to the enemy eye, reduce aerodynamic drag, and ensure omnidirectional coverage like on aircrafts and missiles. Hence, development of omnidirectional coverage conformal antennas is required for GPS receivers.

A few circularly polarized antenna designs have been reported [22–26] for GPS applications on planar surfaces, but according to [27], in the multipath environment, the linear polarized signal is less vulnerable to distortions compared to the circularly polarized signal. Thus, omnidirectional linearly polarized antennas can also be used for receiving purposes. A few studies were published on GPS antennas on planar surfaces and working at the single band with narrow operating bandwidth. A cylindrical conformal antenna array for GPS in an L_1 band with 20 MHz bandwidth and a gain of 1.65 dBi was proposed in[28].

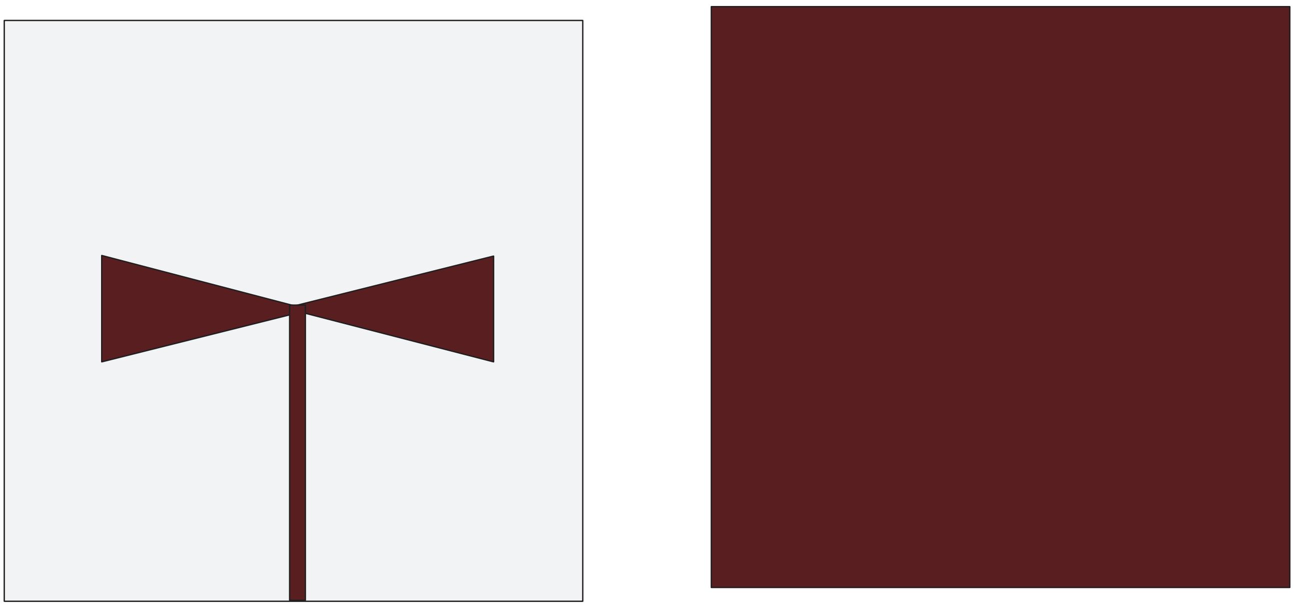
The design of a bow-tie microstrip antenna, which has more extensive bandwidth than dipoles, was reported [29–31]. The radiation attributes of the bow-tie microstrip printed antenna were also reported in [32]. The bandwidth of this antenna relies on the flare angle, and this is utilized in wideband applications.

In this article, a new printed bow-tie patch cylindrical conformal antenna excited by a microstrip line for wideband GPS is introduced. The novelty of the work is the design of a GPS conformal antenna, which is devised with 60-mm radius of the cylinder, and this type of design is not reported in the earlier published literature. Although a bow-tie patch antenna was used for broadband characteristics in previous works, the use of a bow-tie-shaped slot in the ground plane and dumbbell-shaped slit in each corner of the bow-tie patch for bandwidth enhancement was not reported in the previous literature. Generally the fabrication of a conformal antenna is a challenging task, but a conformal antenna is fabricated here and there is good agreement between experimental and simulation results. The proposed cylindrical conformal antenna not only radiates in an omnidirectional pattern with high gain but also operates in the whole frequency band of 0.75 to 1.78 GHz, which can be considered as a wideband antenna.

2. Antenna design and parametric study

2.1. Design of conventional cylindrical conformal bow-tie antenna

As compared to a printed dipole and linear wire antenna, bow-tie antennas have broadband characteristics and simple geometry. They are additionally utilized for compact patch size without expanding the overall patch area to obtain lower operating frequencies [33]. Figure 1a provides the front view and Figure 1. the back view of the conventional bow-tie printed antenna.



(a) (b)

Figure 1. Structure of conventional bow-tie antenna without ground slot: (a) front view, (b) back view.

The bow-tie antenna design step is like that for rectangular patches. The resonant frequency in the dominant mode TM_{10} can be calculated using the following equations [33, 34]:

$$f_r = \frac{c}{2\sqrt{\varepsilon_r L}}(\frac{1.152}{R_t}), \tag{1}$$

$$R_t = \frac{L}{2}\frac{(W+2\Delta)+(W_c+2\Delta)}{(W+2\Delta)+(S+2\Delta)}, \tag{2}$$

$$\Delta = h\frac{0.412(\varepsilon_e+0.3)+(\frac{W}{h}+0.262)}{(\varepsilon_e-0.258)+(\frac{W}{h}+0.813)}, \tag{3}$$

$$\varepsilon_e = (\frac{\varepsilon_r+1}{2})+(\frac{\varepsilon_r-1}{2})(1+\frac{12h}{W_i})^{-1/2}, \tag{4}$$

$$\varepsilon_e = (\frac{W+W_c}{2}), \tag{5}$$

where:

L/2 is the side length of the bow-tie patch
W is the height of the bow-tie patch,
c is the velocity of light,
ε_r is the relative permittivity,
ε_e is the effective permittivity,
S is the length of the bow-tie patch,
f_r is the resonant frequency of the bow-tie antenna,
h is the thickness of the substrate,
W_i is the height at the center of the bow-tie patch.

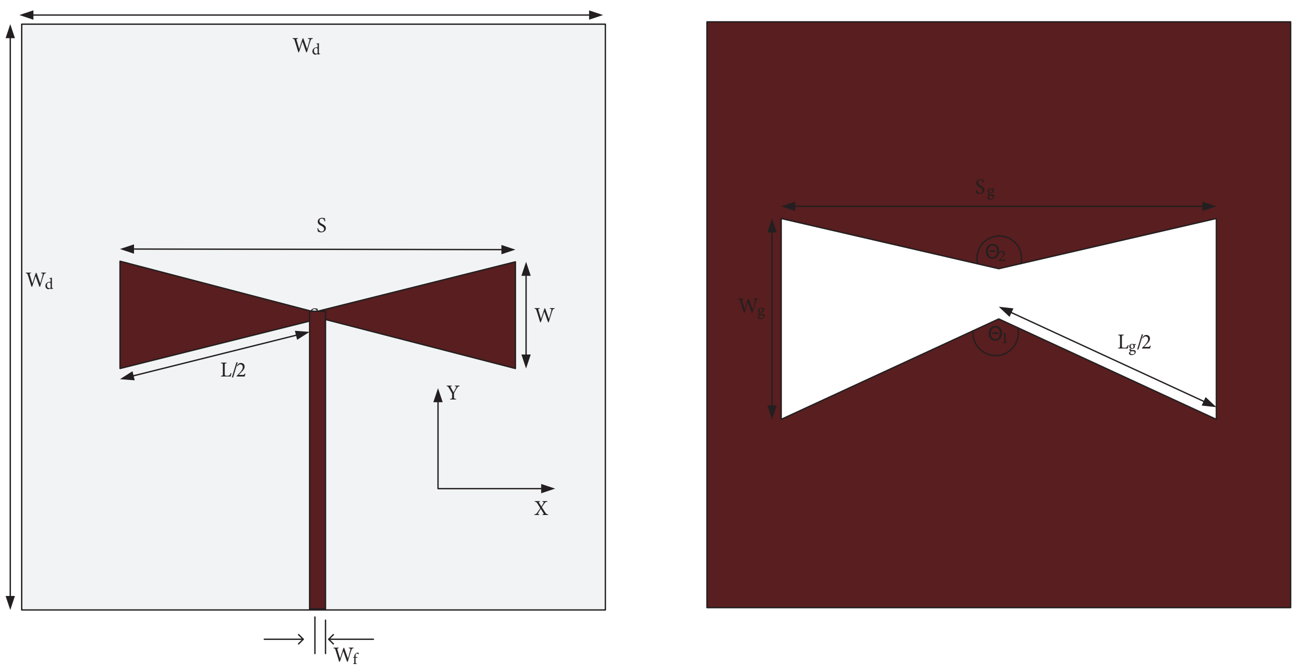


Figure 2. Geometry of conventional bow-tie antenna with wide-slot on ground: (a) front view, (b) back view.

The substrate RT/duroid 5880 is chosen for flexibility and heat stabilization. The low dielectric constant of 2.2 of the substrate is considered to meet the wide bandwidth specification. The simulation of the antenna is done using the commercially available Computer Simulation Technology (CST) Microwave Studio.

The antenna used in the proposed work utilizes a microstrip line feed with characteristic impedance of 50 Ω to excite the bow-tie patch. The 10-dB impedance bandwidth of the bow-tie antenna can be enhanced by applying a slot in the ground.

2.2. Design of cylindrical conformal bow-tie antenna with wide slot in ground

A similar bow-tie shaped slot is also placed on the ground. The combination of the bow-tie slot on the ground and bow-tie radiating patch is selected on account of its good radiation characteristics and wide impedance bandwidth. As a wide slot is utilized in the design, large coupling results in the feed line. The coupling property can be changed by varying the slot shape or feed shape, and therefore control of impedance matching is possible.

The geometry of the front view and back view of the proposed wide-slot planar antenna is demonstrated in Figure 2a and 2b, respectively. The dimensions of the proposed bow-tie antenna are illustrated in Table 1. The planar bow-tie antenna is transformed to the conformal one on a cylinder of radius 60 mm, which is shown in Figure 3.

The effect of length of the feed line on the impedance matching is observed. It can be noted that better impedance matching is achieved by increasing the length of the feed line. The optimized value for L_f in the proposed conformal antenna is 60 mm. However, if the length is further increased beyond this value, the size of the antenna will be more. Figure 4a shows the simulated reflection coefficient (dB) of the proposed conformal antenna with feed-line lengths of 30, 40, 50, and 60 mm.

The effect of the dimension of the patch on the impedance matching is also investigated. The impedance matching can be obtained by increasing the length of bow-tie dimension 'S' from 70 to 85 mm. The optimized

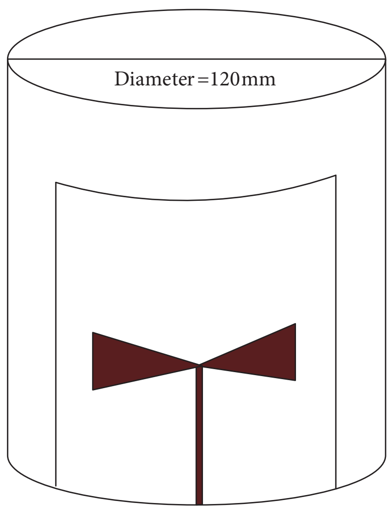


Figure 3. Configuration of conventional conformal bow-tie antenna.

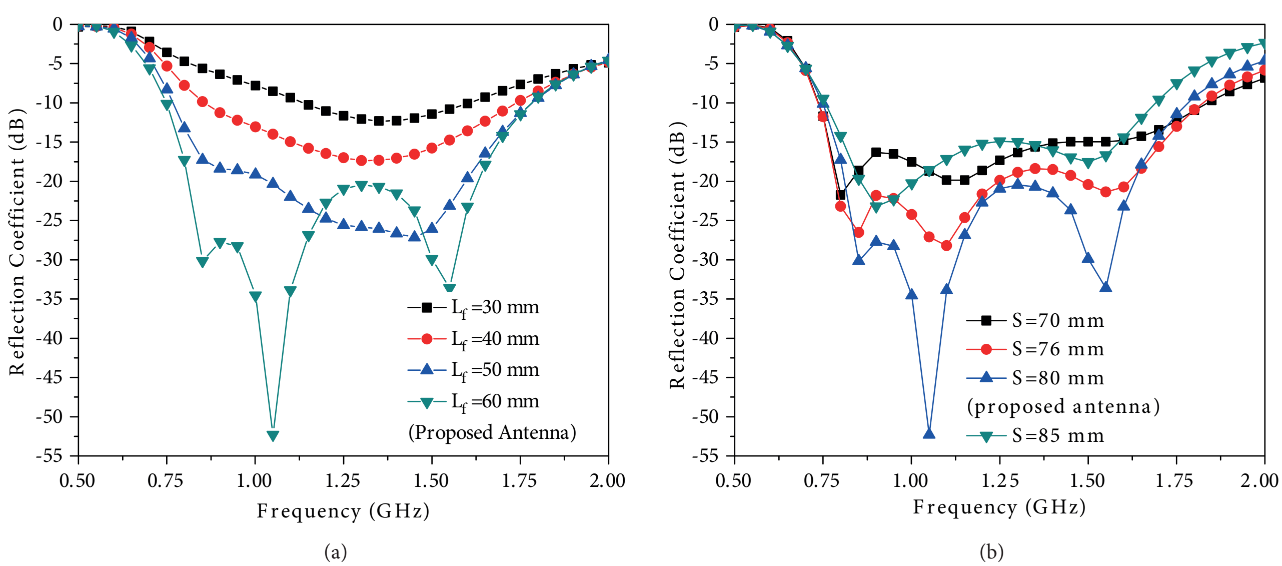


Figure 4. Reflection coefficient of the proposed conformal antenna: (a) for different L_f, (b) for different S.

Table 1. Optimized dimensions of the proposed antenna.

Parameters	Value	Paramaters	Value
W_d	120 mm	W_s	1.1 mm
S	80 mm	S_g	93 mm
W	22 mm	W_g	40 mm
L/2	41 mm	$L_g/2$	47.5 mm
L_f	60 mm	θ_1	135.56 drgree
W_f	1.5 mm	θ_2	156.46 degree
L_s	12.7 mm	Radius of circle in dumbbell shape slit	1 mm

value for S in the proposed antenna is 80 mm. With further increase the value of S, the return loss is increased. The reflection coefficient (dB) of the designed antenna with a dimension of a patch of S of 70, 76, 80, and 85 mm is shown in Figure 4b.

So as to obtain a large coupling, a wide slot is introduced in the ground. To observe the effect of the angle of the slot θ_1, θ_2, and length of slot S_g, the reflection coefficients of the antenna are shown in Figures 5a, 5b, and 5c. As shown in these figures, there is good impedance matching for $\theta 1 = 135.56$ degrees, $\theta_2 =$ 156.46 degrees, and $S_g = 93$ mm.

2.3. Design of proposed cylindrical conformal bow-tie antenna with dumbbell-shaped slit loading in patch

According to [1-3], the feed inductance counters capacitance introduced by slits and slots in the patch. In addition, additional resonances caused by the slot combine with the patch resonance, which makes an antenna have a wideband response. Patch antennas with slits have different shapes like circular, square, and rectangular. In Figure 6a, a dumbbell-shaped slit is introduced on the four corners of the patch without modifying the ground plane like in Figure 6b. The use of the circle on one end of the slit is the best case among the other geometries. It is because the circle makes the fields on the slits more uniform than in the other cases. The proposed planar antenna in Figure 6 is transformed to the conformal antenna of 60 mm in cylinder radius, which is shown in Figure 7.

The effect of slits on the patch is explored in Figure 8. The impedance matching is improved by introducing different slits like rectangular or dumbbell on the patch. In the case of the dumbbell-shaped slit, the impedance matching is better than a rectangular antenna with the effect of slits on patch.

3. Results and discussion

A prototype planar antenna is fabricated on RT/duroid 5880 substrate with thickness of 0.787 mm. By using an LPKF S100 milling machine, the antenna is fabricated on a planar surface as shown in Figures 9a and 9b, and it is rolled up to form a cylindrical shape on foam of radius of 60 mm as shown in Figure 9c. The foam material is used as mechanical support for making the 60-mm radius of the cylinder, which has negligible radiation effect on the antenna.

Both the simulated and experimental reflection coefficients (S_{11}) in dB of the proposed conformal antenna with 60-mm radius of cylinder are demonstrated in Figure 10. Generally a 10-dB reflection coefficient is considered to obtain the impedance bandwidth, but it can be seen that the peak of the reflection coefficient for both simulation and experimental results is below 40 dB, which signifies that the return loss is much less.

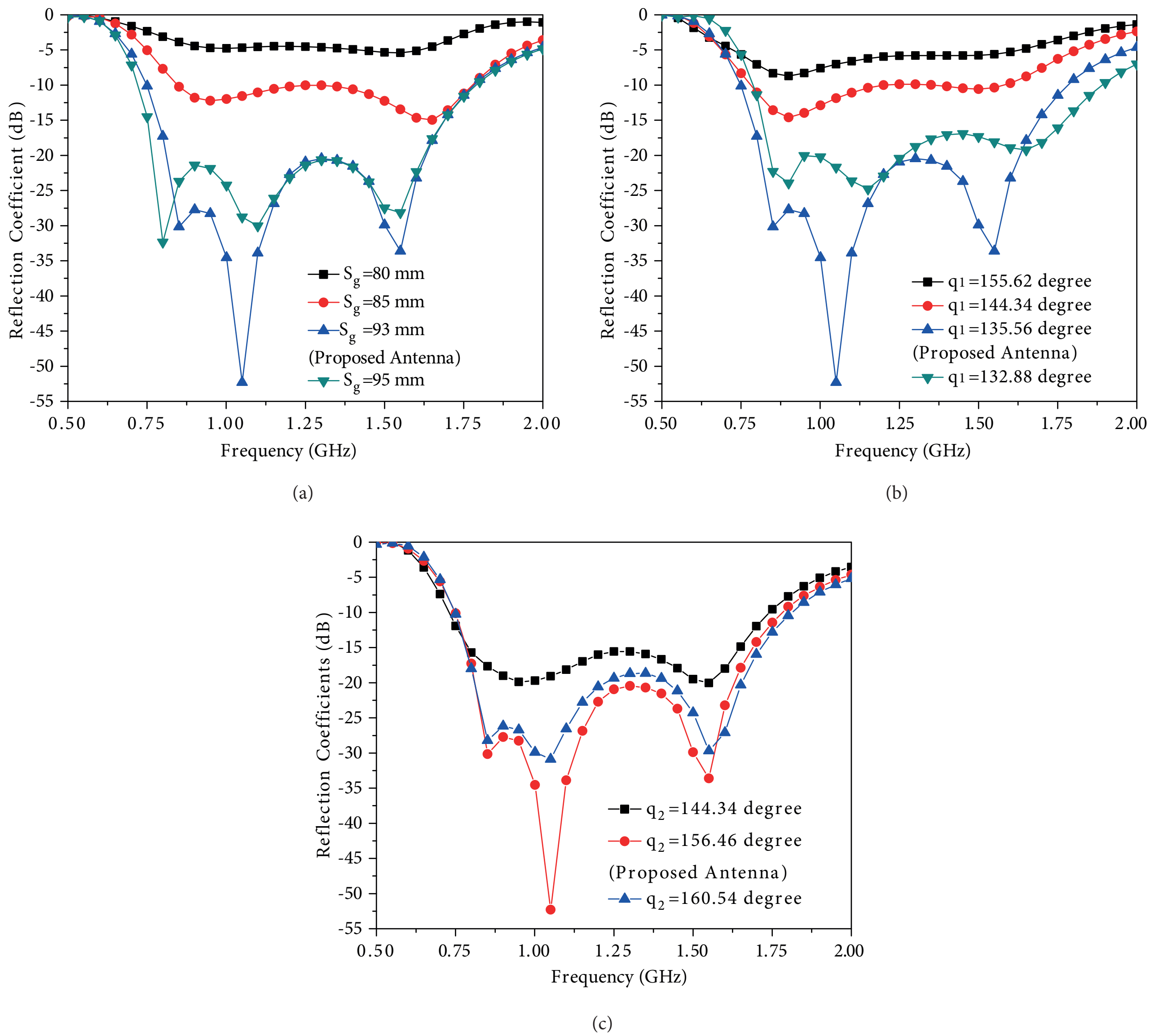


Figure 5. Simulated reflection coefficient of the proposed conformal antenna: (a) for different S_g, (b) for different θ_1, and (c) for different θ_2.

The simulated reflection coefficient is obtained using CST STUDIO SUITE 2016 by considering discrete port type with 50-Ω impedance. A four-hole round pin with female type SMA connector working in the range DC to 18 GHz is connected to the fabricated antenna. The antenna is measured utilizing an HP vector network analyzer within the frequency range of 130 MHz to 13 GHz. It is seen that the proposed designed cylindrical conformal patch antenna has a wide 10-dB reflection coefficient fractional bandwidth of 81.4%, operating from 0.75 to 1.78 GHz. It can also be investigated that the experimental reflection coefficient (dB) agrees with the impedance bandwidth achieved by using the commercially available CST software.

The radiation patterns at 1.17645, 1.2276, and 1.5754 GHz in both the E and H planes are shown in Figures 11a, 11b, 11c, 11d, 11e, and 11f, respectively. The two-dimensional patterns of the antenna are obtained in an anechoic chamber. To measure the radiation pattern, a standard horn antenna is used at the transmitter

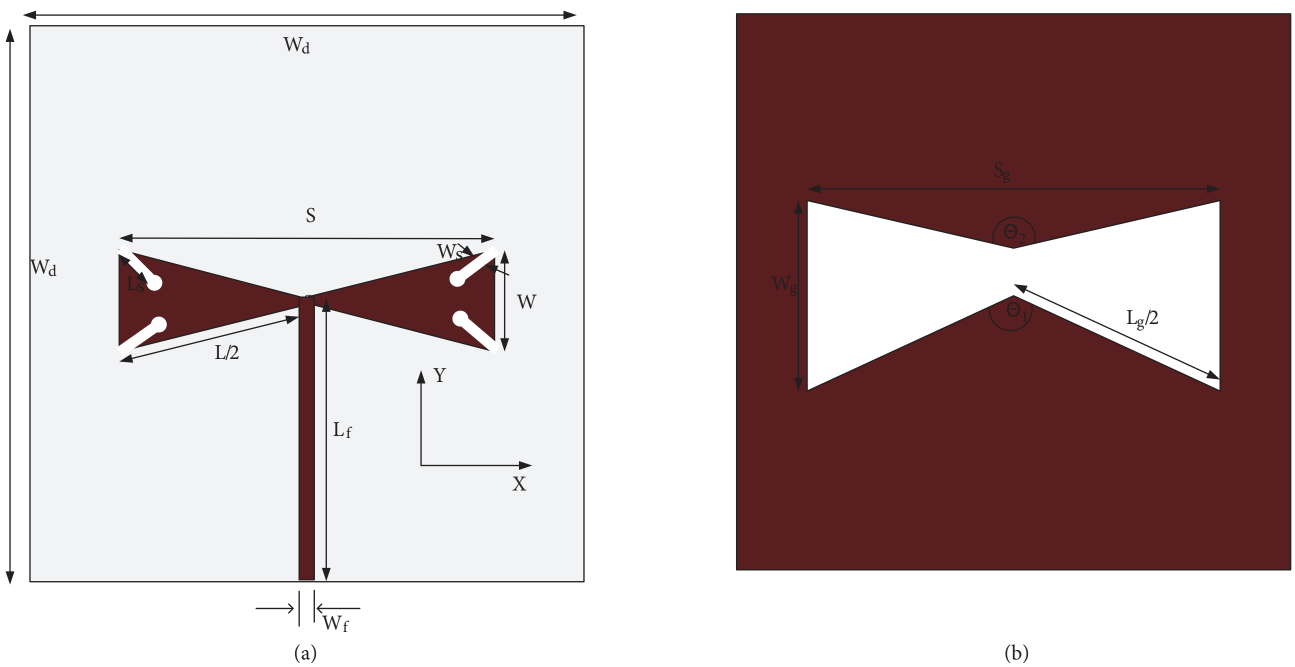


Figure 6. Geometry of the proposed bow-tie antenna: (a) front view and (b) back view.

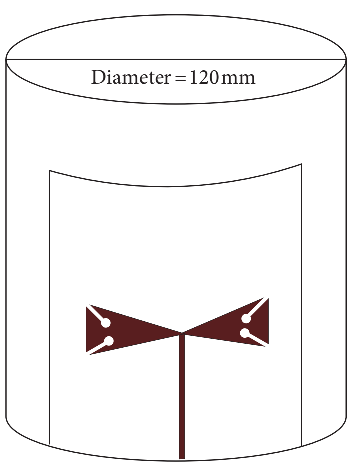


Figure 7. Configuration of proposed cylindrical conformal antenna with 60-mm radius of curvature.

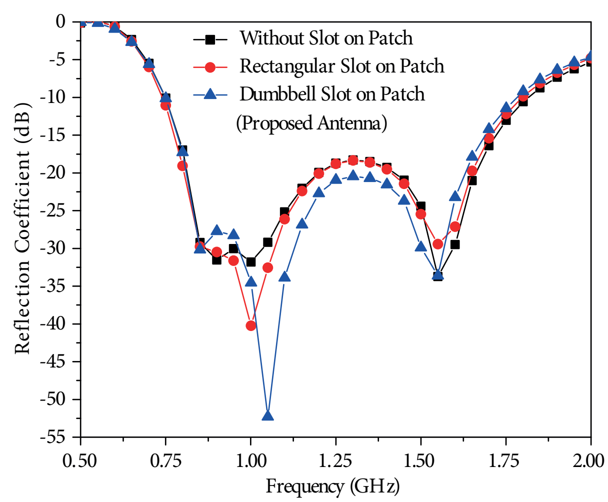


Figure 8. Reflection coefficient of the proposed conformal antenna with the effect of slits on the patch.

and a conformal antenna is connected to the receiver. The conformal antenna radiation pattern is measured in receiving mode. It is seen that the two-dimensional patterns at various frequencies are comparative, which is expected from a wideband antenna. From Figure 11, it can be seen that the proposed designed cylindrical conformal patch antenna has symmetrical radiation patterns. In the E plane, a figure eight-like pattern is obtained, and a roughly omnidirectional pattern in the H plane is obtained.

Figures 12a and 12b show the surface current distribution at 1.17 GHz and 1.575 GHz, respectively. The strongest current distribution is around the end of the dumbbell-shaped slits. The slits on the radiating patch can cause meandering of the excited surface current paths. Similarly, the field distributions of the proposed

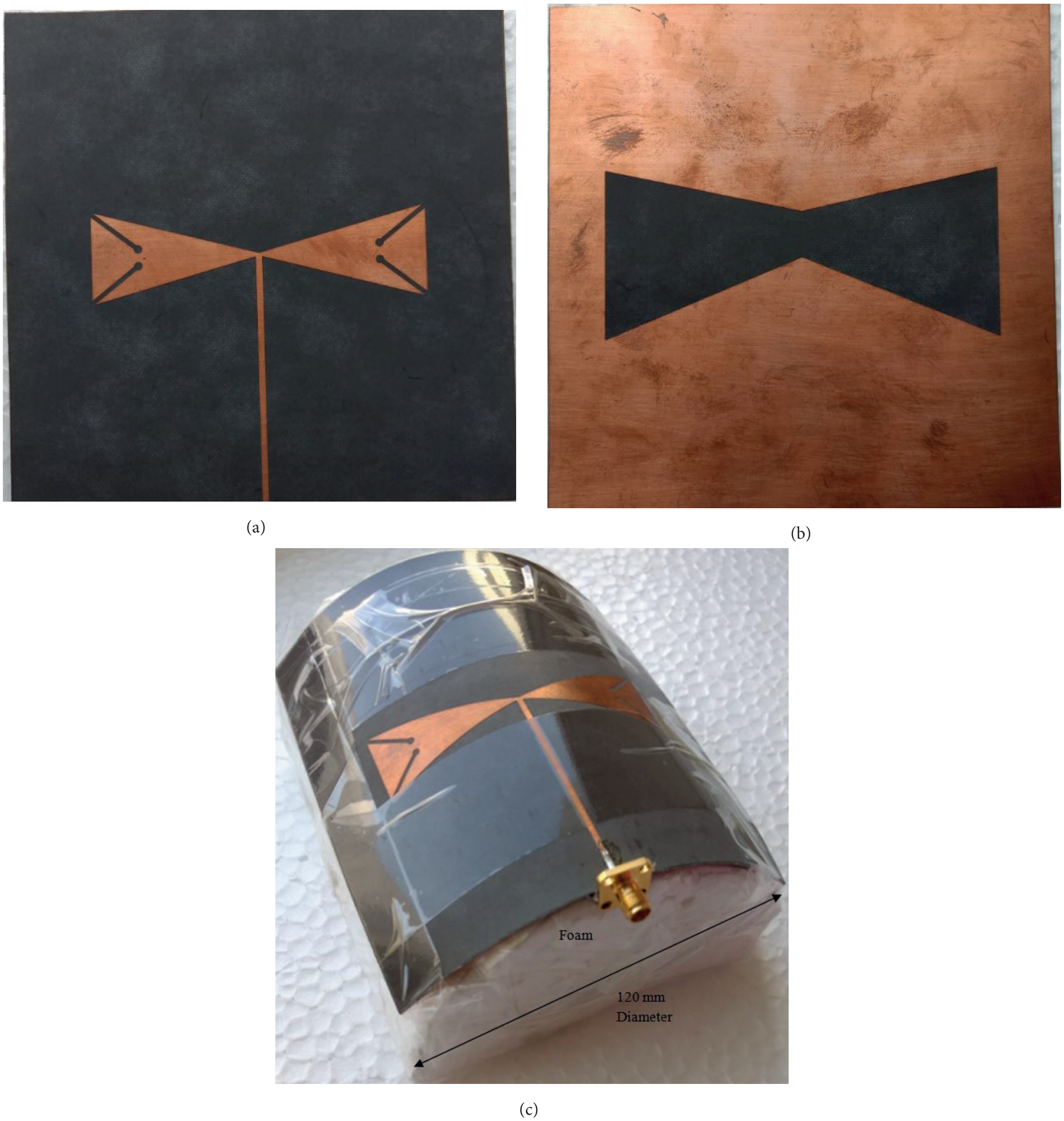


Figure 9. Photograph of prototype fabricated antennas: (a) front view of the proposed planar antenna, (b) back view of the proposed planar antenna, and (c) top view of a proposed cylindrical conformal antenna with 60-mm radius of curvature.

conformal antenna at 1.17 and 1.575 GHz are given in Figures 13a and 13b, respectively. The simulated and measured gain with respect to frequency is presented in Figure 14. By the gain transfer method, the gain of the proposed antenna is measured. The gain transfer method requires an antenna with known gain standard. In the experiment, the standard horn antenna is used, whose gain is known. Compared to the low frequency

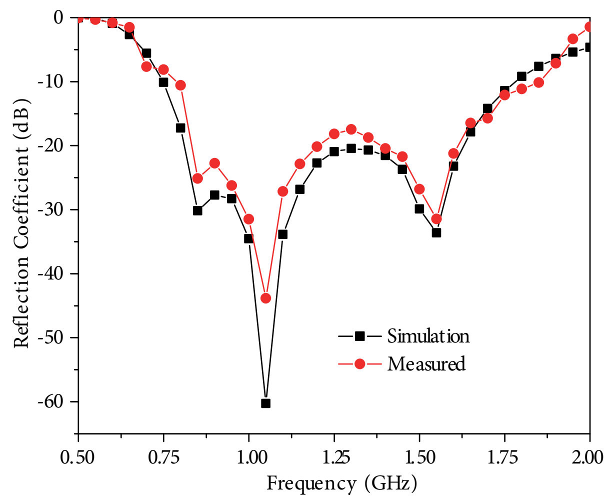


Figure 10. Reflection coefficient of the proposed conformal antenna.

region, the gain is effectively increased at high frequency. Hence, the antenna gain is varying from 3.5 to 4.78 dBi over the operating frequency band.

The overall performance of the proposed cylindrical conformal antenna was compared with those of previously reported planar antennas at GPS frequency in [22–25] and other frequencies in [33, 34] and is given in Table 2. In spite of the fact that the proposed cylindrical conformal antenna is larger in size, it gives competitively wide bandwidths. Moreover, the peak gain is also more than that of the antennas existing in the literature [22, 24].

Table 2. Performance of the proposed conformal antenna and planar ones existing in the literature.

Antenna	Perimeter (mm)	Frequency (GHz)	10 dB bandwidth	Gain (dBi)
Proposed work	480	L_1,L_2, L_3,L_4,L_5 band	81.4%	4.78
[22]	314.15	L_1	2.1%	-11
[23]	395.84	L_1	20 MHz	6.5
[24]	240	L_1	20 MHz	4
[25]	360	L_1	27 MHz	5.4
[33]	264	0.737	15 MHz	-
[34]	120.86	2.66	168 MHz	7.83

4. Conclusion

A bow-tie-shaped wideband conformal antenna with a wide slot is fabricated on a cylinder of 60-mm radius of curvature, which can be used for GPS and Galileo frequency applications. The performance of the antenna is validated through simulation and measurement results. The operating bandwidth of the proposed conformal antenna is obtained as 81.4%, which includes the bandwidth necessary for GPS applications. Good agreement is seen between the measurement and simulation results. Furthermore, the proposed antenna demonstrates stable radiation attributes with a gain of about 3.5 to 4.78 dBi in the whole operating frequency range of 0.75 to 1.78 GHz. In view of the attributes, the proposed bow-tie patch with wide slot loaded on the ground cylindrical conformal antenna can be considered as a suitable candidate for nonplanar surfaces like missile applications to

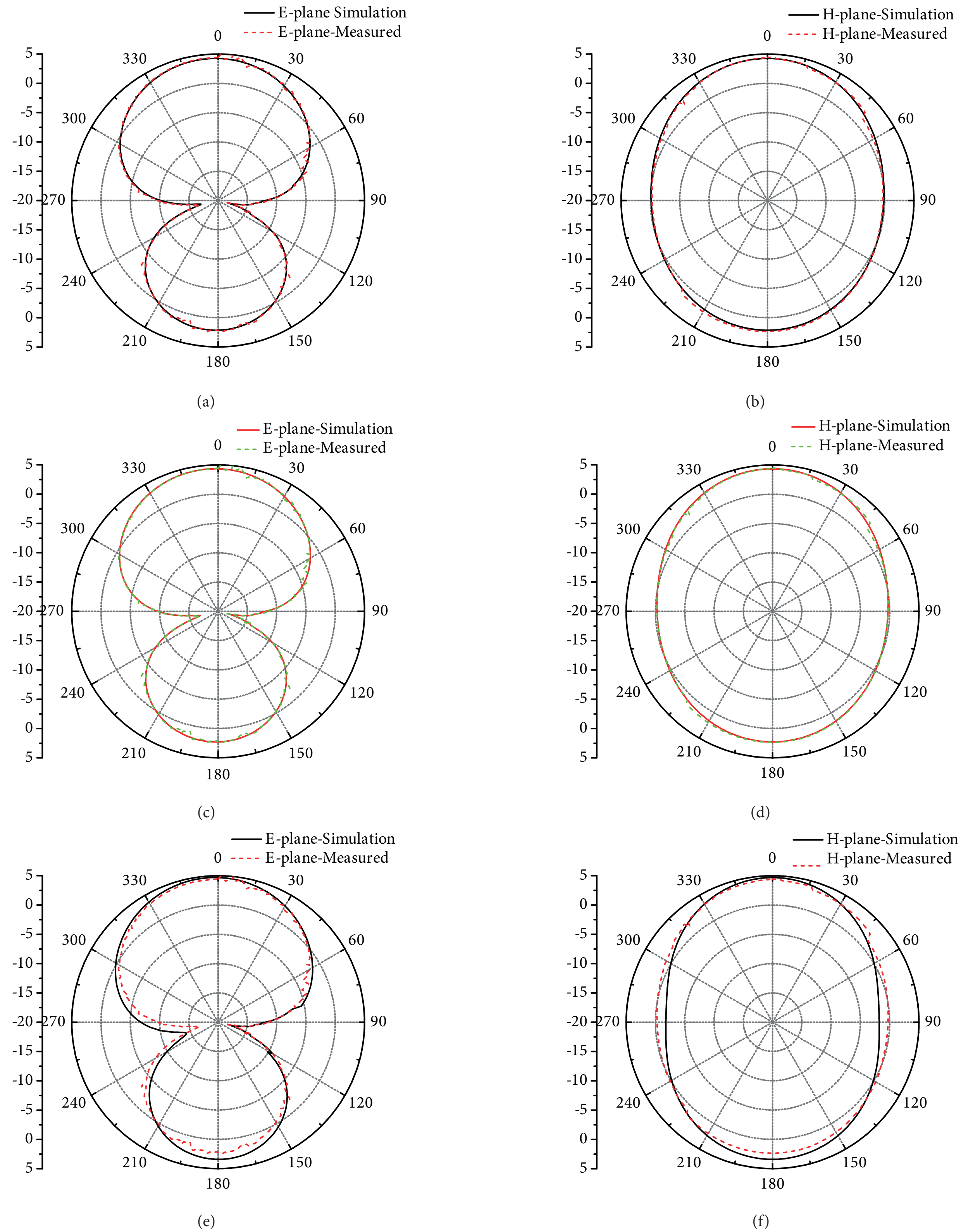


Figure 11. Radiation pattern: (a) E plane at 1.17645 GHz, (b) H plane at 1.17645 GHz, (c) E plane at 1.2276 GHz, (d) H plane at 1.2276 GHz, (e) E plane at 1.57542 GHz, and (f) H plane at 1.57542 GHz.

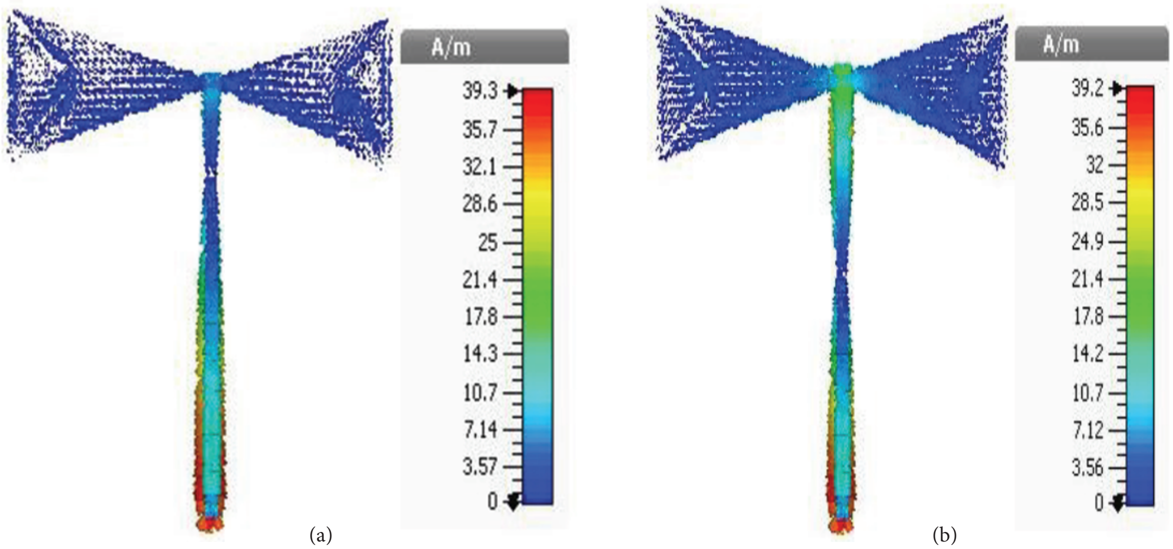


Figure 12. Current distribution of proposed conformal antenna at: (a) 1.17 GHz, (b) 1.575 GHz.

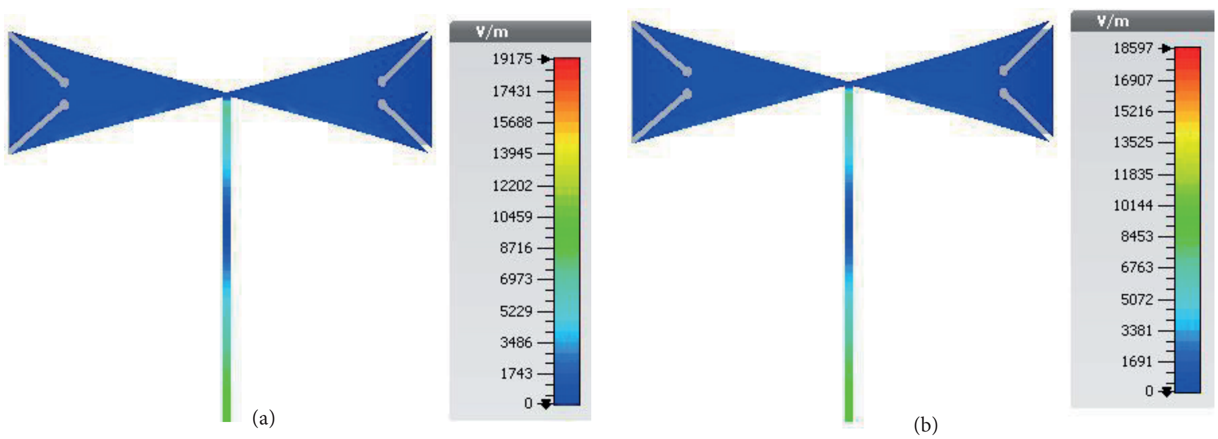


Figure 13. Field distribution of proposed conformal antenna at: (a) 1.17 GHz, (b) 1.575 GHz.

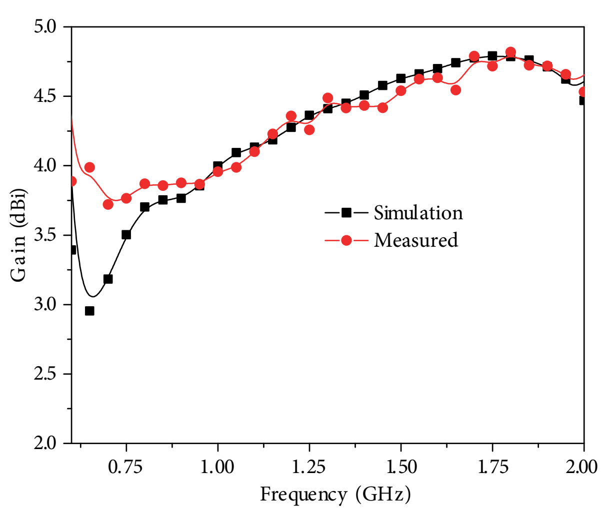


Figure 14. Simulated and measured proposed conformal antenna gain.

guide the antitank guided missiles. Similarly, the designed antenna can be used as a conformal array for gain enhancement, which can be used for many commercial purposes.

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