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Improved Bandwidth and Gain in Ultra-wideband Staircase Antipodal Bowtie Antenna with Rounded Edge for Microwave Imaging Applications

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Abstract: We propose the ultra-wideband antipodal bowtie antenna with staircase steps at the corners of the antipodal bowtie patch with a rounded edge and a reflector is placed at the bottom part of the antenna. The modified design of the bowtie antenna of a step cut is made to improve the bandwidth. Furthermore, in the bottom side of an antenna, the reflector is united with the feed to improve the gain. This antenna operates over for the frequency between 3.1 to 10.6 GHz, with a directive radiation pattern of peak gain 4.29 dB with the bandwidth of 3.17 GHz. This improvement in the bandwidth, gain and directional type of radiation pattern results the proposed antenna is suitable for microwave imaging applications on the early detection of breast cancer and brain tumor.

Keywords: Ultra-wideband, Antipodal bowtie antenna, Reflector, Microwave Imaging.

1 Introduction

In 2002, the Federal Communication Commission [FCC] had decided to allow spectrum range for UWB transmission [1], in the band range between 3.1 to 10.6 GHz. The FCC sorts the frequency range of UWB applications were suitable for radar, imaging and communications devices. The most useful application of the UWB technology is radar. The critical aspect in the radar is the transmission of narrowband UWB pulses for high-resolution radar which is within a few centimeters in the military and civilian applications. UWB signals can easily penetrate into various obstacles, the human body for many analysis. Recently, the microwave imaging method used in the early detection of many cancerous issues like breast cancer, brain tumor, lung cancer. The malignant and benign tumor can be detected using microwave imaging measuring the water content of both the malignant and benign tissue of a healthy human body. Various types of antennas designed in this medical imaging applications.

In UWB imaging systems, the antennas are designed to achieve UWB impedance bandwidth, improved gain, low cross polarization and compact-size. To transmit and receive pulse signals into the human body for analyzing the scattering of the signals from the tumor in the breast, brain or from any parts of the human body [2–4]. These scatterings are received even from the small changes in the tissues in the human body.

Various types of antenna like planar, dipole antenna, Vivaldi antenna, bowtie antennas are designed for wireless applications, microwave imaging like a brain tumor, breast cancer and phased array applications. These type of microstrip antennas has a low profile, compact-size, less weight and easy fabrication [5–8]. Array configurations are presented for improving the radiation pattern in the bowtie antenna [9]. Moreover, double-sided printed bowtie can be used for UWB applications [10]. For investigating the small tumor, compact-size antennas are designed [11].

In radar applications such as the directional finding of objects in military and detection of tumor position in human body most suitable characteristics of an antenna should be unidirectional. In improving the gain, directivity and front to back ratio, the resonance based reflectors are preferred [13–16].

In this proposed design, an antipodal bowtie antenna with step cuts is incorporated in both sides of the bowtie antenna, which is designed using HFSS software. A stepped cut 50 Ω microstrip feed is intended to achieve

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the impedance matching characteristics in this UWB frequency band. To enhance the bandwidth of an antenna periodic step cuts are introduced in the corners of the bowtie antenna. The increase in the iteration of the periodic step cut results in an effective impedance matching over the UWB frequency range. Moreover, the gain of the antenna is improved by introducing a reflector in the bottom part of the antenna results in unidirectional radiation of the proposed antenna for medical imaging applications.

2 Antenna Design Configuration

The proposed antenna is designed using an FR4 substrate of dielectric constant 4.4, loss tangent 0.025 and a thickness of 1.6 mm respectively. The design steps of the proposed antenna begin with the radiating antipodal bowtie patch with the substrate, reflector, and a feed line. The sides of the antipodal are cut like a staircase to improve the bandwidth of the proposed antenna which is best applicable to microwave imaging applications.

The antipodal bowtie antenna is designed to look like a two-triangle mirror image one on the top of the substrate and other at the bottom of the substrate. Numerical calculation of width, diameter and the height of the bowtie arm s are calculated using (1)–(3). In addition to the bandwidth enhancement of the UWB antenna, multiple resonances are obtained over the operating frequency range. For better return loss over the broad bandwidth, four-step cut at the corners of the bowtie antenna is designed [9], using (4) and (5). The metal reflector placed in the bottom of the plane which acts as the ground to reduce the backward radiation. The transmission line equation gives the mathematical solution for the dimensions of the staircase steps at the edges of the bowtie antenna is shown in Fig. 1. The step cut microstrip feed line is designed for 50 Ω impedance matching for delivering maximum current to the antenna. Various length and width of the microstrip feed line is calculated using (6)–(8) for $w_1 = 1$ mm, $L_1 = 6$ mm, $w_2 = 3$ mm, $L_2 = 18.75$ mm.

Since the directional antenna is the major requirement in the medical imaging and radar applications, the directivity of the proposed antenna is improved by adding a reflector at the bottom of the substrate. A better Perfect Electric Conductor (PEC) reflector or Artificial Magnetic Conductor(AMC) reflector can be used in a bidirectional or omnidirectional type of antenna to improve its directivity [13, 14]. Therefore, in the proposed design, the simple reflector is placed at the bottom in along with an antipodal bowtie antenna, the output gain has increased of about 4.29 dBi.

The mathematical approach for the design of an antenna staircase parameter dimensions such as height and width engraved at the edges of the patch antenna is expressed in (4) and (5), for multiple resonances frequencies like 4 GHz, 5 GHz, 6 GHz, and 7 GHz. The four cut at the corners of the bowtie antenna is calculated and their dimensions are shown in Table 1.

3 Mathematical Calculation of Proposed Antenna

Step 1: Bowtie arm dimensions

$$\text{Width of the arm: } w = 0.375 \times \lambda = 28.125 \text{ mm} \quad (1)$$

$$\text{Diameter of the arm: } D = 0.02066 \times \lambda = 1.55 \text{ mm} \quad (2)$$

$$\text{Height of the arm: } H = 0.25 \times \lambda \quad (3)$$

Step 2: Length and width of the staircase arm
The width and length of the staircase in bowtie antenna for various iteration is given as

$$W = \frac{0.375 \times c \times 1000}{f} \quad (4)$$

$$l = \frac{0.25 \times C}{f} \quad (5)$$

where c is the speed of light, f is the resonant frequency.

Let the resonant frequencies and width of the triangles be $f = 4, 5, 6$ and 7 GHz and w_4, w_5, w_6 and w_7 respectively.

The antipodal bowtie antenna patch covers the middle portion of the substrate and the patch is fed by a microstrip line method with 50 Ω input impedance respectively.

Step 3: The effective dielectric constant:
ε_{reff} is given as

$$\varepsilon_{reff} = \left(\varepsilon_r + \frac{1}{2}\right) + \left(\varepsilon_r - \frac{1}{2}\right)\left(1 + 12\left(\frac{h}{w}\right)\right)^{-1/2} = 7.9 \text{ mm} \quad (6)$$

Step 4: Calculate length and width of microstrip line

$$\text{Length of stripline: } L = d\lambda_g \quad (7)$$

$$\text{Width of stripline: } \frac{w}{d} = \frac{8e^A}{e^{2A} - 2} \quad (8)$$

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \quad (9)$$

Table 2 shows the design parameters of the proposed antenna along with the reflector, and the design layout of the proposed antenna is shown in Fig. 1.

The dimensional parameters of the bottom patch and the fabricated bowtie antenna is shown in Fig. 2(a) and Fig. 2(b). The top portion of the simulated and fabricated bowtie antenna is shown in Fig. 3(a) and Fig. 3(b). In these figures, the top portion is provided with the step cuts in the corners and the bottom portion provided with reflection is mentioned.

Table 1: Calculated values of four cut at corners of staircase bowtie antenna

Resonating Frequency	Width (mm)	Length (mm)
4 GHz	$W_4 = 28.125$	$L_4 = 18.75$
5 GHz	$W_5 = 22.5$	$L_5 = 15$
6 GHz	$W_6 = 18.75$	$L_6 = 12.5$
7 GHz	$W_7 = 16.07$	$L_7 = 10.74$

Table 2: Design parameters of proposed bowtie antenna with reflector

Label	W	L	w_1	L_1	w_2	L_2
Value(mm)	30.4	57	1	6	3	18.75
Label	h_4	h_5	h_6	h_7	t	L_3
Value(mm)	18.75	15	12.5	10.74	1.6	13.1
Label	w_4	w_5	w_6	w_7		
Value(mm)	28.13	22.5	18.17	16.07		

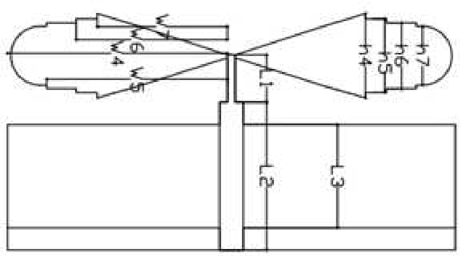
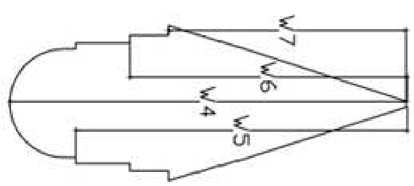
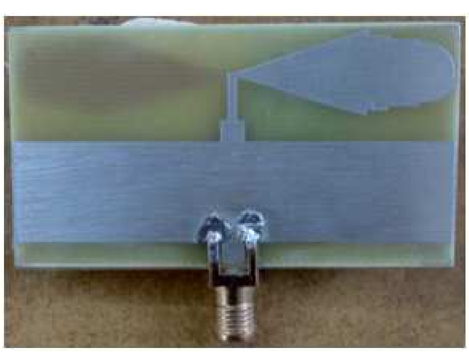


Fig. 1: Design layout of Staircase antipodal bowtie antenna

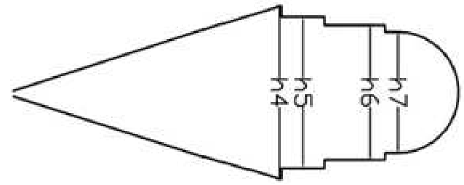


(a) Bottom side of antipodal bowtie antenna



(b) Bottom side of the fabricated antenna

Fig. 2



(a) Top side of antipodal bowtie antenna

(b) Top side of the fabricated antenna

Fig. 3

4 Experimental Results and Discussion

4.1 Variation of iteration in the staircase bowtie antenna

The simulated results of the proposed antenna for various iterations of the staircase steps at the corners of the antipodal bowtie are shown in the Fig. 4. Here the bandwidth of the antenna for different iteration levels as I_1, I_2, I_3, and I_4 are estimated in the simulation. The fourth iteration results in a better return loss and proper impedance matching over the UWB range. Fig. 4, shows improvements in the return loss and antenna bandwidth for various iteration levels. The first iteration I_1 shows the simulated results in the return loss for the solution frequency of 4 GHz with an achieved bandwidth of 2.7 GHz. The second iteration I_2 shows the designed simulation for adding of staircase steps for 4 GHz and 5 GHz with an achieved bandwidth of 2.9 GHz. The third iteration I_3 shows the design for adding of staircase steps for 4 GHz, 5 GHz, 6 GHz with an obtained bandwidth of 3 GHz. The fourth iteration I_4 shows the configuration of summing up of the staircase steps for 4 GHz, 5 GHz, 6 GHz, 7 GHz with an achieved bandwidth of 3.4 GHz. The above iterations are taken without a reflector at the bottom of the antipodal antenna. Moreover, the bandwidth level is performed in the iteration 4 with reflector is of about 3.17 GHz. The improvement in the bandwidth for different iterations for both with and without reflector is shown in the comparison Table 3.

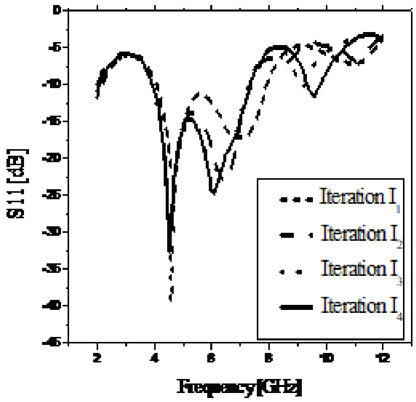


Fig. 4: Return loss of staircase bowtie with different iteration

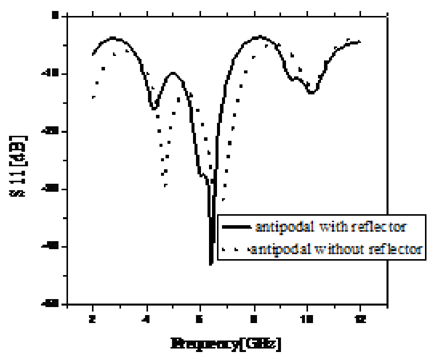


Fig. 5: Return loss antipodal bowtie antenna with and without reflector

4.2 Effects of insertion of reflector at the bottom of the antenna in return loss

Fig. 5 represents the simulated results of the improved return loss by adding of the reflector at the bottom of an antenna. Since this shape of the reflector is provided as a rectangular structure which is connected along with the feed point at the bottom of an antenna. This increases the return loss in the fourth iteration design of the step cut antipodal bowtie antenna. Return loss is improved from the antipodal bowtie antenna with a reflector as 36.8 dB to 42.8 dB in the inclusion of reflector in the bottom of the antenna. The microwave energy penetrates from the antenna towards the body when it has to have better return loss; therefore the improved results help in detecting the small size brain tumor properly.

The return loss of antipodal bowtie antenna of the simulated and fabricated antenna is shown in Fig. 6. The fabricated antenna is measured using Agilent Vector Network Analyzer(VNA). This result shows the better bandwidth with good return loss which is suitable for microwave imaging applications.

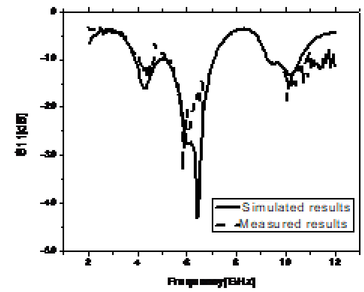
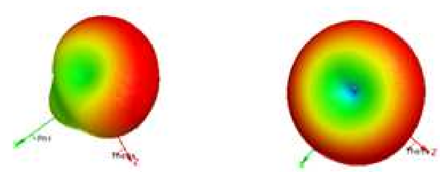


Fig. 6: Return loss antipodal bowtie antenna with reflector for simulated and measured results



(a) with reflector **(b)** without reflector

Fig. 7: 3D gain plot for antipodal bowtie antenna

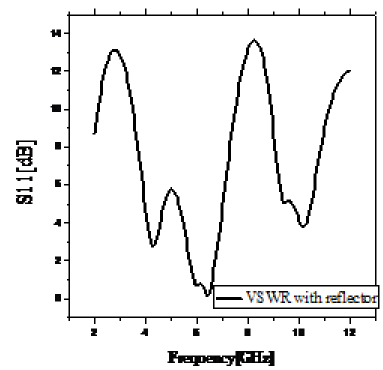


Fig. 8: VSWR of antipodal bowtie antenna with reflector

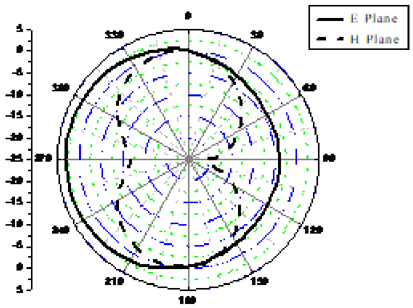
4.3 Effects of insertion of reflector at the bottom of the antenna in gain

Fig. 7(a) and Fig. 7(b) show 3D gain plot of the staircase antipodal bowtie antenna. The improved gain of an antenna for with and without reflector is of about 1.94 dB to 4.29 dB. The reflector at the bottom of an antenna along with feed improves the gain in a unidirectional manner results in a better directivity. In medical imaging systems, when the narrow pulses are transmitted into the body, the signals penetrate into the different layers of the human body. To find the location of the tumor at different depths as well as in the smaller size of cancer, the directivity of the transmitter should get improved. The step cut of the microstrip feed gives better impedance matching, and the adjusted bandwidth is shown in Table 3.

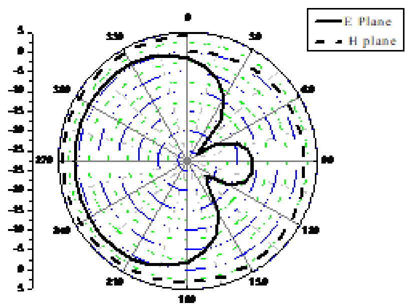
Fig. 8 represents the VSWR of the proposed antenna in which the VSWR < 2 in the resonating frequency of

Table 3: Comparison of results in various antenna parameters

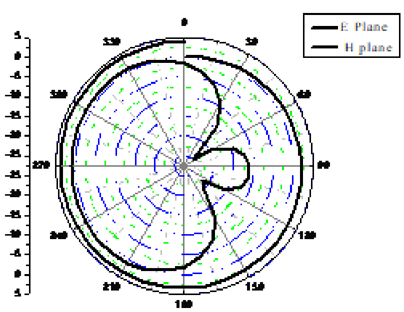
Parameters	Wide band antenna	Ultra-wideband antenna				
	Basic Bowtie with coplanar fed, Ref [4]	Antipodal Bowtie Without reflector I_1	Antipodal Bowtie Without reflector I_2	Antipodal Bowtie Without reflector I_3	Antipodal Bowtie Without reflector I_4	Antipodal Bowtie With Reflector
Return Loss	15.4dB	22.3dB	29.8dB	34dB	36.8dB	42.8dB
Bandwidth	900MHz	2.7 GHz	2.9 GHz	3 GHz	3.4 GHz	3.17 GHz
Gain	3.62dB	2.dB	2.2dB	2dB	2.4dB	4.29dB
Radiation Pattern	bidirectional	bidirectional	bidirectional	bidirectional	bidirectional	More directional



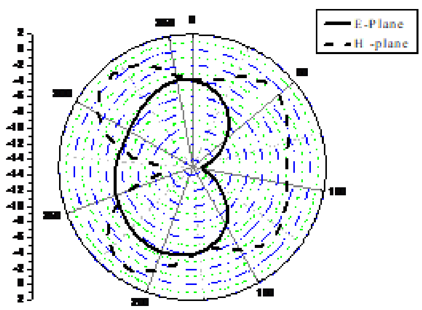
(a) 4 GHz



(b) 5 GHz



(c) 6 GHz



(d) 7 GHz

Fig. 9: Radiation pattern of E-plane and H-plane for different frequencies

the bandwidth between 5 to 7 GHz. The better impedance matching is achieved by the design of step cut microstrip feed line in the staircase antipodal bowtie antenna. Coplanar fed waveguide antenna gives broad bandwidth with good impedance matching [2], this step cut microstrip feed line gives still more improvement than that coplanar fed antenna.

4.4 Radiation pattern

The radiation pattern is shown in Fig. 9. It has E-Plane and H-plane pattern for a various resonating frequency of 4 GHz, 5 GHz, 6 GHz, 7 GHz. It shows that bidirectional and directional type of radiation pattern in the E-plane and H-plane region. Hence, in the solution frequency of 5 GHz, the E plane shows a unidirectional radiation pattern which is a more suitable pattern for microwave imaging applications.

Table 3 shows the comparison of antenna parameters results in the various levels of wideband and ultra-wideband range. The primary bowtie antenna using coplanar fed is compared with the proposed design of ultra-wideband staircase antipodal antenna with its different iteration levels in their step cut for the proposed medical imaging applications. In this comparison, the wideband antenna covers only 900 MHz bandwidth with a minimum return loss of about 15.4 dB and bidirectional type of radiation pattern. The antipodal staircase bowtie antenna with reflector shows a directional type radiation pattern which is suitable for medical applications. The ultra-wideband range antenna shows improvement in all the parameters like return loss, bandwidth, gain in the different ranges of iteration.

5 Conclusion

The proposed approach represents a staircase step cut in the corners of the antipodal bowtie antenna design for improving the bandwidth of about 3.17 GHz, in the results when compared to the other conventional bowtie antenna design. And reflector is placed in the bottom side of the antipodal bowtie antenna to improve the gain of 4.29 dB. This improvement in the results of the proposed design is suitable for medical imaging applications.

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