Design and Simulation of Compact UWB Bow-tie Antenna with Reduced End-fire Reflections for GPR Applications

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Abstract—**The efficiency of the ground penetrating radar (GPR) system significantly depends on the antenna performance as signal has to propagate through lossy and inhomogeneous media. In this research work a resistively loaded compact Bow-tie antenna which can operate through a wide bandwidth of 4.1 GHz is proposed. The sharp corners of the slot antenna are rounded so as to minimize the end-fire reflections. The proposed antenna employs a resistive loading technique through a thin sheet of graphite to attain the ultra-wide bandwidth. The simulated results obtained from CST Microwave Studio v14 and HFSS v14 show a good amount of agreement for the antenna performance parameters. The proposed antenna has potential to apply for the GPR applications as it provides improved radiation efficiency, enhanced bandwidth, gain, directivity and reduced end-fire reflections.**

***Index Terms*—Ground penetrating radar (GPR), end-fire reflections, UWB, resistive loading.**

I. Introduction

Ground penetrating radar (GPR) is the general term applied to EM techniques which employ radio waves to map structures and features buried in the shallow sub-surface [1]. An antenna can be used for the GPR system provided that it possess certain important characteristics [2-3] i.e. ultra-wide bandwidth (UWB) for high resolution, low frequency operation for more depth of penetration, high front-to-back ratio to minimize the clutter, good gain and radiation efficiency to increase the received power. Bow-tie antenna is one of the most popularly used antennas for the GPR applications due to light weight, ease of design and fabrication, better symmetry in radiation, planar structure, compact size, etc. Different variants of Bow-tie antenna with improved antenna performances i.e. gain, efficiency, bandwidth, etc. have been proposed for GPR applications in [2-8], [10], [11]. Special efforts are taken to reduce the lower cutoff frequency so that higher depth of penetration can be achieved [2], [6], [7]. A double sided bow-tie structure printed on dielectric substrate where truncation of the ground plane is used to achieve UWB from 3.1 GHz to 10.6 GHz [3]. The efficiency of the bow-tie antenna can be improved significantly by utilizing the energy in end-fire reflections if the antenna is excited by the bipolar pulse [5]. The bandwidth of the bow-tie antenna can be enhanced to achieve UWB performance by using different bandwidth enhancement techniques such as using tapered slot, multi-stage twin feed lines, round or stair case bow-tie antenna structures [3], Coplanar waveguide feed lines [4], using triangular monopoles with rounded corners [4], loading stubs and using annular ring load [5], etc. The resistively loaded bow-tie antenna is preferred for the GPR applications as it can radiate very short pulses & provides UWB [2], suppresses late-time ringing [5]. However, due to embedded loading and resistive loading, the lowest operating frequency and antenna impulse response can be slightly affected at different operative conditions [6]. The radiation of a bow-tie antenna is mainly due to the superposition of the direct radiations from the feed (or main pulse) and the strong diffractions from the two ends (or end reflections) [5]. Though number of research works have tried to improve the bowtie antenna performance to make it suitable for GPR applications, there are ample scopes to improve the bow-tie antenna with respect to compactness, high efficiency, reduced end-fire reflections etc.

In this paper, the basic bow-tie antenna is modified to obtain a compact UWB antenna with enhanced bandwidth of 167 % (0.4 GHz – 4.5 GHz) and reduced end-fire reflections. The proposed antenna is designed and simulated in CST Microwave studio v14 as well as in high frequency structure simulator (HFSS) v14. The similarity of the results obtained from CST and HFSS provides good confidence on the antenna performance parameters.

II. Antenna Design

A. Theory of Bow-tie Antenna

The characteristic impedance of a bow tie antenna is given by [8] as followings.

$$Z_c = 120 \ln\left(cot\left(\frac{\theta_0}{4}\right)\right) \quad (1)$$

where θ_0 is the opening angle of each side (also known as flare angle).The length of the bow-tie antenna is can be determined by using the following equation [6]

$$l = \lambda_0 \times \left(\frac{1}{\sqrt{\epsilon_{eff}}}\right) \quad (2)$$

where λ_0 is the wavelength corresponding to expected lowest operating frequency. The effective dielectric constant can be calculated by using the following expression [6].

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + (\epsilon_r - 1)(1 + \left(10\frac{d}{w}\right)^{-0.555} \quad (3)$$

where w = bowtie width, d = substrate thickness, ϵ_r = substrate dielectric constant. Resonant frequency corresponding to the various modes is given below [9].

$$f_r = c\frac{K_{mn}}{2\pi\sqrt{\epsilon_r}} \quad (4)$$

where f_r= resonant frequency, K_{mn}= resonating modes, m and n are number of modes, c = velocity of light in free space, a = side length of the bow-tie strip. The basic geometry of the bow-tie antenna is determined by three parameters [5] i.e. flare angle 'θ_0 'which mainly affects the bandwidth, gap distance 'g' which can slightly influence the antenna performance, arm length 'a' which is closely related to radiation efficiency.

B. Design of CPW Feed line

The coplanar waveguide (CPW) feed line is chosen to be used for feeding the antenna for various advantages [9] i.e. ease of fabrication, easy control over characteristics impedance of the line, easy connection facility to the small miniature version A (SMA) connector, comparatively more bandwidth of operation. The characteristic impedance, Z_0, of the ungrounded CPW line is calculated by using different design equations specified in [9] as follows.

$$Z_0 = \left(\frac{30\times\pi}{\sqrt{\epsilon_{eff}}}\right)\left(\frac{K(k')}{K(k)}\right) \quad (5)$$

where

$$\epsilon_{eff} = 1 + \{\, (\epsilon_r - 1)/2 \,\}\{\left(\frac{K(k')}{K(k)}\right)\left(\frac{K(k_1)}{K(k_1')}\right)\} \quad (6)$$

$$k = \frac{W}{W+2S} \quad (7)$$

$$k_1 = \frac{sinh\left(\frac{\pi W}{4H}\right)}{sinh\left(\frac{(W+2S)\pi}{4H}\right)} \quad (8)$$

Here, 'K' denotes complete elliptic integral of the first kind.

$$k' = \sqrt{(1-k^2)} \quad (9)$$

The ratio of complete elliptic functions in Eq. (5) can be approximated as follows.

$$\frac{K(k)}{K(k')} \approx \frac{1}{2\pi} ln[2\frac{\{\sqrt{1+k} + \sqrt[4]{4k}\}}{\{\sqrt{1+k} - \sqrt[4]{4k}\}}]\; for\; 1 \le K/K' \le \infty,\quad 1/\sqrt{2} \le k \le 1 \quad (10\text{-a})$$

Or,

$$\frac{K(k)}{K(k')} \approx \frac{2\pi}{\ln[2\frac{\{\sqrt{1+k}+\sqrt[4]{4k'}\}}{\{\sqrt{1+k}-\sqrt[4]{4k'}\}}]}\; for\; 0 \le \frac{K}{K'} \le 1,\quad 0 \le k \le 1/\sqrt{2} \quad (10\text{-b})$$

By using the design Eq. 5-10, values of the design parameters of the CPW line of characteristic impedance of 50Ω are calculated so that the proposed antenna can be fed through a 50Ω SMA connector. The CPW feed line has line width $a = 2.8\,mm$, slot width $b = 0.6\,mm$ and is connected to the triangular stubs with rounded corners which helps in attaining better impedance matching as in Fig. 1 (c).

C. Design of proposed Bow-tie Antenna

The design of the proposed antenna follows the design flow as in Fig. 1. The Bow-tie antenna with extended arms as proposed in [7] is taken as the basic antenna in our design. Further, in the second stage, the basic design with extended arm is modified to minimize the end-fire reflections by rounding of the sharp corners as this leads to provide flatter input impedance which can be easily matched in wide frequency band [4]. Lastly, in the third stage the antenna with extended arm and rounded corners is single-sided resistively loaded with the help of thin sheet of graphite to further enhance the bandwidth by lowering the lower cutoff frequency.

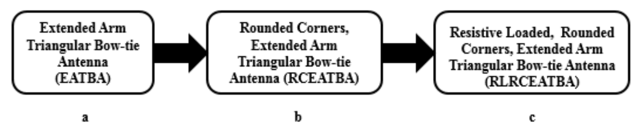

Fig. 1 Design Flow of Proposed Antenna

a. Basic Design with Extended Arms
b. Improved Design with Rounded Corners
c. Improved Design with Resistive Loading

The geometry of the proposed antenna is as shown in the Fig. 2. The slot type structure is chosen as it provides an easy and better control over the radiation pattern of the antenna. The basic triangular Bow-tie antenna is modified with extended arms to achieve a wider bandwidth of operation and also incorporates triangular stubs with rounded corners so as to attain a better impedance matching with minimal end-fire reflections.

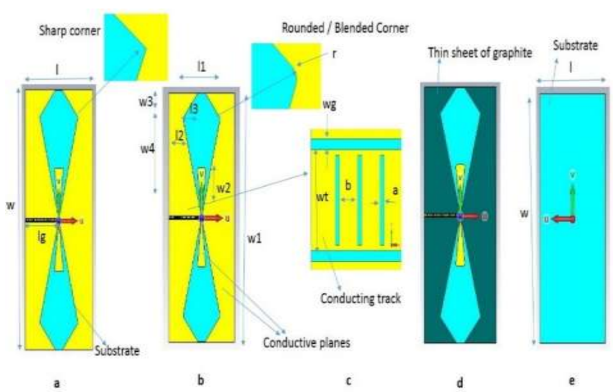

Fig. 2 Geometries of purposed antennas

a. Top view of the Basic Bow-tie antenna with Extended Arms
b. Top view of the Improved Bow-tie antenna with Rounded Corners
c. Top view of the CPW feedline
d. Top view of the Improved Bow-tie antenna with Resistive Loading
e. Bottom view of the all antennas

The antenna is designed on a single-sided copper clad FR4 substrate due to its easy availability & less cost. The thickness of substrate is t_s =1.6 mm and its relative dielectric permittivity $\epsilon_r = 4.4$ which are chosen so as to reduce the antenna size and wider bandwidth. The thickness of copper clad is $t_c = 0.035mm$. The sharp corners of the arms are rounded or blended at an angle $r = 5^0$ so as to minimize the end fire reflections. The dimensions of the antenna are as follows. The width of the antenna is $l = 225mm$, length of the antenna is $w = 505mm$. Other important parameters are $l_1 = 127.4mm, l_2 = 30mm, l3 = 63.7mm, w_1 = 503mm,$ $w2 = 100mm, w3 = 51.5\ mm,\ w_4 = 200\ m.$ The basic dimensions of the antenna are initially calculated for a resonant frequency of 1.5 GHz by using the design equations as given in Eq. 1-4. Then these parameters are further fine-tuned using parametric analysis and inbuilt optimizer present in CST Microwave studio v14.

Late-time ringing phenomena which are potentially responsible for the masking of the buried targets in a GPR survey can be prevented by making the antenna resistively loaded [6]. In this paper, a resistive loading technique for enhancing the bandwidth of the proposed antenna by lowering the lower cutoff frequency is proposed as in Fig.1 (d). It is achieved by covering the whole conducting portion of the copper clad by a thin sheet of graphite having conductivity very less as compared to that of copper. In this process the overall surface resistance of the antenna reduces significantly. The thickness of the graphite layer is chosen as 1mm which is obtained by the parametric analysis by the CST software. The antenna is resistively loaded only on printed side so that the radiation from the other side i.e. substrate side will be less affected. The radiation efficiency is slightly degraded due to resistive loading. The proposed antenna is placed in such a way that its conducting patch portion faces upward while the substrate side faces towards the ground so as to transmit more radiation to the ground. The compactness of the antenna is achieved with the help of single thin sheet of graphite instead of using more than one layer of volumetric absorbing materials.

III. Simulation Results & Discussion

Firstly, the proposed antenna is designed and simulated in CST Microwave studio v14 with the help of a PC having octa core i5 processor with 8 Gb RAM. Then, it is designed and simulated in HFSS v14 using High Performance Computing (HPC) cluster with 32 computing nodes (Intel Xeon 2.0 GHz, two CPU 16 cores, 64GB) facility available in the institute. A comprehensive analysis of simulation results is presented in this section.

A. Simulation Results

The initial design parameters of the proposed antenna are fine-tuned with the help of parametric analysis by CST Microwave studio v14 and are also optimized by the inbuilt time domain optimizer of CST Microwave studio v14 which uses a trust region framework algorithm. A similar approach is followed for the design and simulation of the proposed antenna in HFSS v14. Design and simulation of the proposed antenna are carried out rigorously so that the fabricated antenna will provide antenna performance close to the simulated results. The proposed antenna provides an impedance bandwidth of 169% (0.4 GHz - 4.8 GHz) measured with respect to S_{11} = -8 dB level and impedance bandwidth of 118% (1.2 GHz - 4.7 GHz) measured with respect to S_{11} = -10 dB level with the help of resistive loading and rounded corners with a best case gain of 7 dB and worst case gain of 4 dB. The results obtained for various antenna performance parameters from CST Microwave studio v14 and HFSS v14 are presented as follows.

1) *S11 Performance:* The S11 performance obtained from CST and HFSS shows a high degree of similarity throughout the said band, however HFSS gives provides 8 % more frequency band of operation with respect to S11 = -10 dB level and 38 % more frequency band of operation with respect to S11 = -8 dB level due to resistive loading and rounded corners. Specifically, due to resistive loading the lower cutoff frequency is shifted from 1.3 GHz to 0.4 GHz.

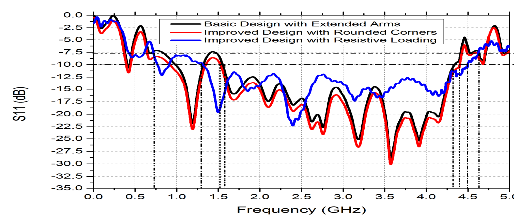

Fig. 3 Reflection coefficients Vs frequency plots obtained from CST.

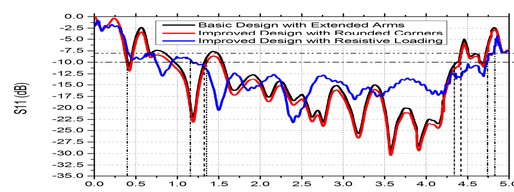

Fig. 4 Reflection coefficients Vs frequency plots obtained from HFSS.

2) *Gain:* Result obtained from CST and HFSS shows that the maximum of 7 dB at the frequency of 2.5 GHz while the minimum gain of the antenna throughout the said band is more than 2.8 dB as in Fig. 5-6. However, the gain of the improved design with resistive loading is slightly degraded as compared to that of improved design with rounded corners due to resistive loading effect while it provides an extension of bandwidth in the low frequency range.

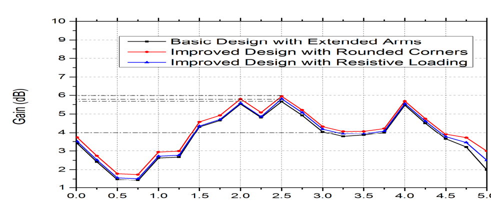

Fig. 5 Gain Vs frequency plots obtained from CST.

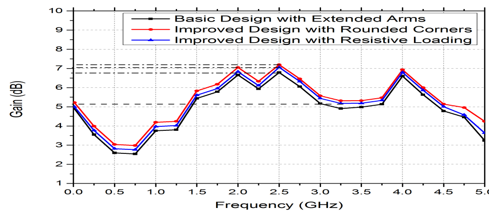

Fig. 6 Gain Vs frequency plots obtained from HFSS.

3) *Directivity:* The directivity throughout the said band is more than 4.2 dBi obtained as shown in Fig. 7-8. Directivity of the improved design with resistive loading is slightly less than that of the improved design with the rounded corners due to loss in resistive loading.

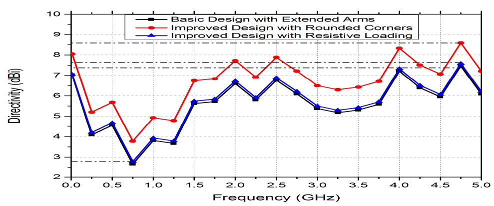

Fig. 7 Directivity Vs frequency plots obtained from CST

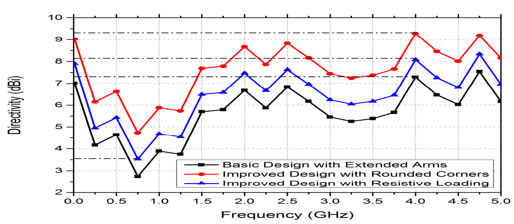

Fig. 8 Directivity Vs frequency plots obtained from HFSS

4) *Efficiency:* Radiation efficiency is more than 71 % with respect to S_{11} = -10 dB level and more than 60 % with respect to S_{11} = -8 dB level as shown in Fig. 9-10. Total efficiency is more than 60 % with respect to S_{11} = -10 dB level and more than 55 % with respect to S_{11} = -8 dB level as shown in Fig. 9-10. The total efficiency is slightly less than the radiation efficiency as total efficiency calculation includes different losses such as parasitic emission, thermal losses, etc. Due to the introduction of rounded corners, the minimum radiation efficiency of the improved design with rounded corner is 90% which denotes the reduced end-fire reflections.

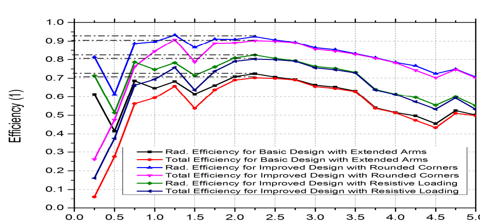

Fig. 9 Efficiency Vs frequency plots obtained from CST

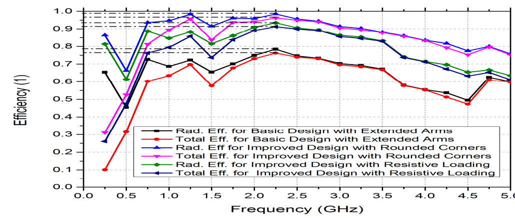

Fig. 10 Efficiency Vs frequency plots obtained from HFSS

5) *Farfield radiation Patterns:* The polar plots of farfiled radiation patterns as in Fig. 11-12 show that the E-Plane has maximum gain of 6.08 dB for ϕ = 275 deg. and H-Plane has maximum gain of 2.46 dB for θ =85 deg. This shows that proposed antenna has narrow beam width compared to [6] which is also a required characteristic of the UWB antenna. The farfield radiation patterns for E-plane and H-plane are summarized in the TABLE I. The polar plots of farfield radiation patterns for the worst case at frequency of 0.5 GHz is as shown in Fig. 11-12 shows that the proposed antenna has E-plane pattern which is bidirectional and H-plane pattern which is omnidirectional which are similar to the dipole with improved gain, efficiency and directivity.

TABLE I. FARFIELD RESULTS OF THE PROPOSED ANTENNA

Freq. (GHz)	E-plane			H-plane		
	Main lobe Magnitude (dB)	***Main lobe Direction (deg.)***	***Angular (3 dB) Beam Width (deg.)***	***Main lobe Magnitude (dB)***	***Main lobe Direction (deg.)***	***Angular (3 dB) Width (deg.)***
0.5	1.82	180	68.9	-1.87	144	40.5
1	2.99	-38	39.9	1.39	-57	30.8
1.5	4.57	-37	29.6	-0.735	-35	18.5
2	5.72	-50	29.8	0.838	-85	45.4
2.5	6.04	-57	23.8	2.35	80	30.8
3	3.6	-87	97.1	3.64	-94	23.2
3.5	3.9	-70	87.3	4.02	91	20.6
4	5.68	109	22.4	3.93	-91	21.2
4.5	3.22	-88	38.6	3.21	-95	29.6

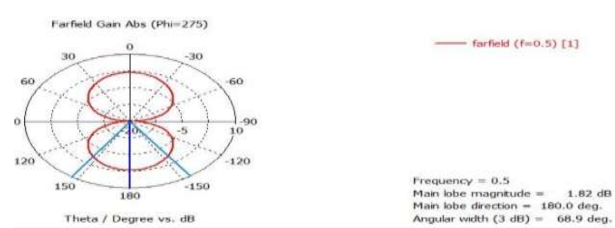

Fig. 11 E-Plane far field radiation pattern at f = 0.5 GHz

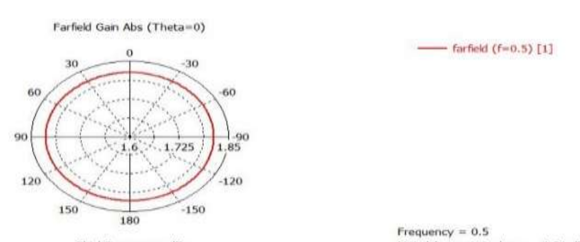

Fig. 12 H-Plane far field radiation pattern at f = 0.5 GHz

B. Discussion

The results obtained from CST (Computer Simulation Tool) Microwave studio v14 and HFSS (High Frequency Structure Simulator) v14 exhibit a high degree of similarity as shown in TABLE II. This provides us a good amount of confidence that the fabricated antenna will provide antenna performance close to the simulated results.

TABLE II. COMPARATIVE ANALYSIS OF THE OBTAINED RESULTS FROM CST AND HFSS

Antenna Parameters			Resulted from CST	Resulted from HFSS
Results with respect to S11= -10dB level	Cutoff frequencies (GHz)	F_L	1.3	1.2
		F_H	4.5	4.75
	BW %		110.34	119.32
	Gain (dB)	Max.	5.8	7
		Min.	4	5.2
	Directivity (dBi)	Max.	7.8	8.2
		Min.	4.2	3.8
	Radiation Efficiency (%)	Max.	81.5	94
		Min.	71	74
	Total Efficiency (%)	Max.	80.5	92
		Min.	64	74
Results with respect to S11= -8dB level	Cutoff frequencies (GHz)	F_L	0.75	0.4
		F_H	4.65	4.8
	BW %		121.87	169.23
	Gain (dB)	Max.	5.8	7
		Min.	1.6	2.8
	Directivity (dBi)	Max.	7.8	8.2
		Min.	2.8	2.75
	Radiation Efficiency (%)	Max.	81.5	94
		Min.	60	60
	Total Efficiency (%)	Max.	80.5	92
		Min.	60	55

Since the designed antenna couldn't be fabricated and tested, the simulated results are compared with the simulation results of existing antennas in literature as presented in TABLE III. The antenna performance of the proposed design is found to be promising compared to the antenna performances reported in the various literatures.

TABLE III. COMPARATIVE ANALYSIS OF PERFORMANCE OF PROPOSED ANTENNA WITH PRE-EXISTED ANTENNAS

Design Proposed by	F_L (GHz)	F_H (GHz)	BW (%)	Max Gain (dB)	Min Gain (dB)	Overall Size (cm^3)
[2]	0.3	3	163.63	6, 12 (with lens)	-10	50×20×4
[6]	0.055	1.5	185.8	…	…	40×40×10
[7]	0.4	1.5	115.8	6	2.5	50×22×15
[10]	0.46	4	158.7	4.2	2	36×23×7
[11]	0.25	0.75	100	8	2.6	18×30×8
Proposed Design	0.4	4.5	167.34	7	2.8	51×22×0.5

IV. CONCLUSIONS

In this paper, we have proposed an improved design of Bow-tie antenna i.e. resistive loaded compact CPW-fed slot bow-tie antenna with rounded corners which can provide better resolution due to its UWB nature and lager depth of penetration due to its low value of lower cutoff frequency. The overall efficiency of the GPR system may be enhanced significantly by using the proposed antenna as its worst case radiation efficiency is 71%. The proposed antenna with enhanced bandwidth, reduced end-fire reflections and compactness has advantageous for GPR application requirements. The future work should focus on the fabrication and testing of proposed antenna to verify the antenna performance parameters and improve the antenna based on test results feedback.

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