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High gain UWB bow-tie antenna design for ground penetrating radar application

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Abstract

This article presents an elliptical shaped slot ultra-wideband antenna with high gain (10.3 dBi) and compact size (107.7 × 68 mm^2) that designed and improved by four steps. Also, it can perform in an impedance bandwidth (IBW) from 0.98 GHz to 4.5 GHz that is satisfactory IBW for ground penetrating radar (GPR) application. The proposed antenna is fabricated for experimental testing and getting GPR images in a sandbox. Simulation and measured results ensure a desirable GPR antenna.

KEYWORDS

bow-tie antenna, ground penetrating radar, ultra-wideband

1 | INTRODUCTION

Ground penetrating radar (GPR) is the general term applied to electromagnetic (EM) techniques which employ radio waves and detect the reflected signal to show structures and features buried in the subsurface.[1] Transmitting and the receiving units with antennas, control unit and monitoring are main components of a GPR system.[2] The antenna plays an important role in GPR systems. Antenna could be placing in three states of the monostatic, bistatic, and multistatic. In the monostatic state, transceivers of signals are implemented on one antenna. But in bistatic state, minimum two or more antennas for transmission and reception can be utilized. In multistatic state, the system uses more than one antenna for transmitting and receiving.[3]

Moreover, GPR systems are classified as air-coupled and ground-coupled systems which depend on work methods. In air-coupled systems, the antennas are normally 40-50 cm above the ground surface, however, a ground-coupled system's antenna is almost above 5-10 cm. Another difference is scanning speed in highway surveys. While air-coupled systems are allowed to operate at speeds of up to 120 km/h, the ground-coupled systems are limited to the speed of 80-100 km/h.[4]

UWB is a system with relative bandwidth BW/fc (fc is the carrier frequency and BW is bandwidth) larger than 20% or BW larger than 0.5 GHz.[5] Low-frequency operation for more penetration depth and, besides good gain to increase

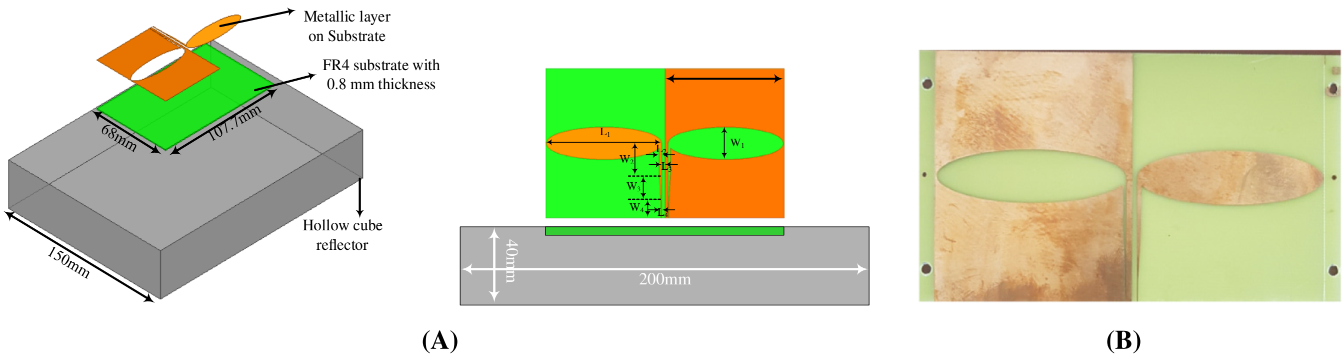


FIGURE 1 Configuration of (A) proposed antenna structure and (B) fabricated antenna [Color figure can be viewed at wileyonlinelibrary.com]

range resolution, and also stable radiation pattern is the common requirements for a UWB GPR antenna.[6] UWB GPR is used in both military and civilian applications, due to high resolution and appropriate penetrating factors. UWB radars have used in the detection of land-mines and hidden human.[5,7] UWB GPR uses a frequency range above 100 MHz with a 100% rate of bandwidth. A higher frequency range gives a higher resolution, whereas cannot propagate far and the depth of detection becomes shallower. Therefore, a lower frequency results in a lower resolution but higher penetration depth.[2,8]

Various types of antennas are used for UWB GPR systems in the literature. These researches have been investigated on some types of antenna such as planar antenna,[7] Horn,[9], Bow-tie,[10] and Vivaldi.[11] These antenna types maintain satisfactory GPR performances but large size and complexity limited their uses in GPR. In ref., 12 a bowtie slot antenna by (0.4 GHz-1.5 GHz) frequency band and with the large size of 50 cm × 22 cm for GPR that usually used in UWB applications is presented. Hertl and Strýček offered Vivaldi because of lower manufacturing complexity in ref., 13 based on some different antennas by fabricating and analyzing, in which the Vivaldi antenna was presented as 5.8 dB on 1 GHz with 405 × 12 × 318 mm^3 dimension and bowtie as 3.3 dB with 12 × 532 × 600 mm^3 dimension.

Ground structures that are close to each other require a broadband signal with good resolving power. Thus, ultra-wideband antennas, with high gain, are highly desired in GPR systems. However, many ultra-wideband GPR antennas have disadvantages such as low gain or large volume which restrict them for certain GPR applications.[14]

Therefore, in this article, a bowtie slot antenna has been developed with a self-complementary method and a reflector for UWB GPR applications which has a small-size, low-cost, and also high gain. In Section 2, antenna configuration and the simulation results are presented. All simulations are done by CST studio suite 2017 and ANSYS (HFSS) version 17. The experimental results are introduced in Section 3 too.

TABLE 1 Values of proposed antenna parameters

Parameters	Values (mm)	Parameters	Values (mm)
L_1	53	W_1	15
L_2	1	W_2	14
L_3	0.25	W_3	13.3
L_3	1	W_4	6.7

2 | METHODOLOGY OF ANTENNA DESIGN AND RESULTS DISCUSSION

In this paper to attain improved characteristics of antenna to have better results of GPR systems, some techniques such as use of complementary and cavity backed methods have been considered.[15,16] Figure 1 shows proposed antenna configuration.

The antenna consists of two sections as (i) a hollow cube reflector section and (ii) a planar antenna. The hollow cube reflector section with a size of 150 × 200 × 40 mm^3 plays a role as an antenna gain enhancer. The planar section printed on a commercial inexpensive FR4 substrate thickness of 0.8 mm with the relative permittivity of $\varepsilon_r = 4.4$ and $\tan\delta = 0.02$ which it performs as radiation antenna. The offered

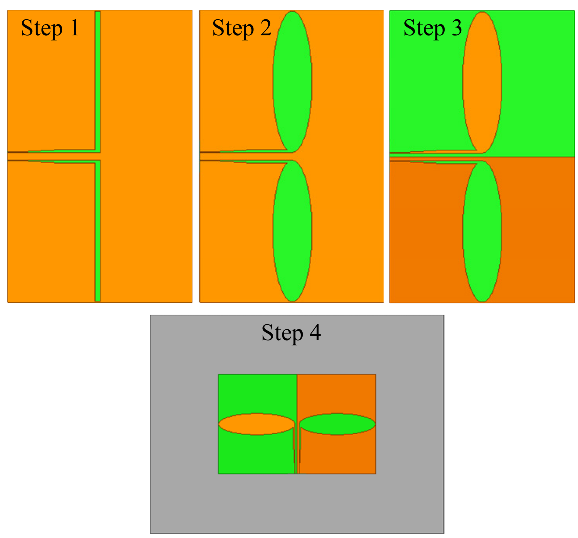


FIGURE 2 Steps of proposed antenna designing [Color figure can be viewed at wileyonlinelibrary.com]

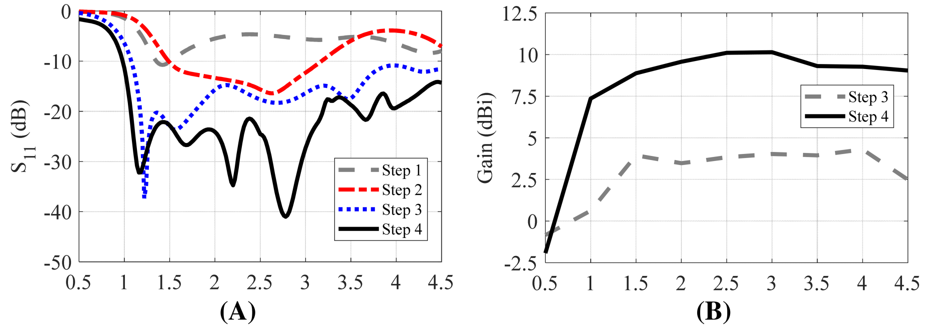


FIGURE 3 S_{11} and gain of designing steps at Figure 2: (A) S_{11} and (B) gain [Color figure can be viewed at wileyonlinelibrary.com]

antenna is fed by a 50 Ω coplanar waveguide (CPW). To provide self-complementary antenna conditions, CPW feed is ended to a 180 Ω impedance line. An elliptical shape is used as radiation patch while in another side an elliptical slot plays a role as complement structure. Table 1 displays the size of proposed antenna.

To attain an ultra-wideband antenna with high gain, the proposed antenna has been progressed using the following mentioned procedure. According to Figure 2, step 1 of the proposed antenna is based on slot dipole design. To conquer low impedance bandwidth (IBW) of basic structure, instead of using rectangular slot two elliptical slots are utilized. Elliptical slot can turn surface current at all structures and prevents its accumulation. Despite step 2 can provide a broadband bandwidth from 1.5 to 3.2 GHz (Figure 3A), needing an ultra-wideband antenna for GPR application is an essential aim.

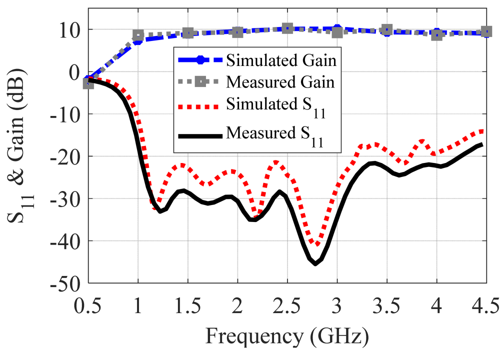


FIGURE 4 The comparison between simulated and measured gain and S_{11} [Color figure can be viewed at wileyonlinelibrary.com]

To attain mentioned object, the self-complementary technique is used. This technique by increasing impedance of antenna helps to increase impedance matching of antenna in a wider bandwidth. Finally, by resorting on a hollow cube, as seen in Figure 3B, gain of antenna is increased about 5.5 dBi. The proposed antenna with hollow reflector has been fabricated and measured. The photograph of fabricated antenna is displayed in Figure 4.

The scattering parameter of proposed antenna was measured by Agilent 8722ES vector network analyzer (VNA). As seen in Figure 5, a good agreement between simulated and measured S_{11} result is achieved. The measured result of antenna exhibits the proposed antenna can perform in an IBW from 0.98 GHz to 4.5 GHz. The peak gain of antenna

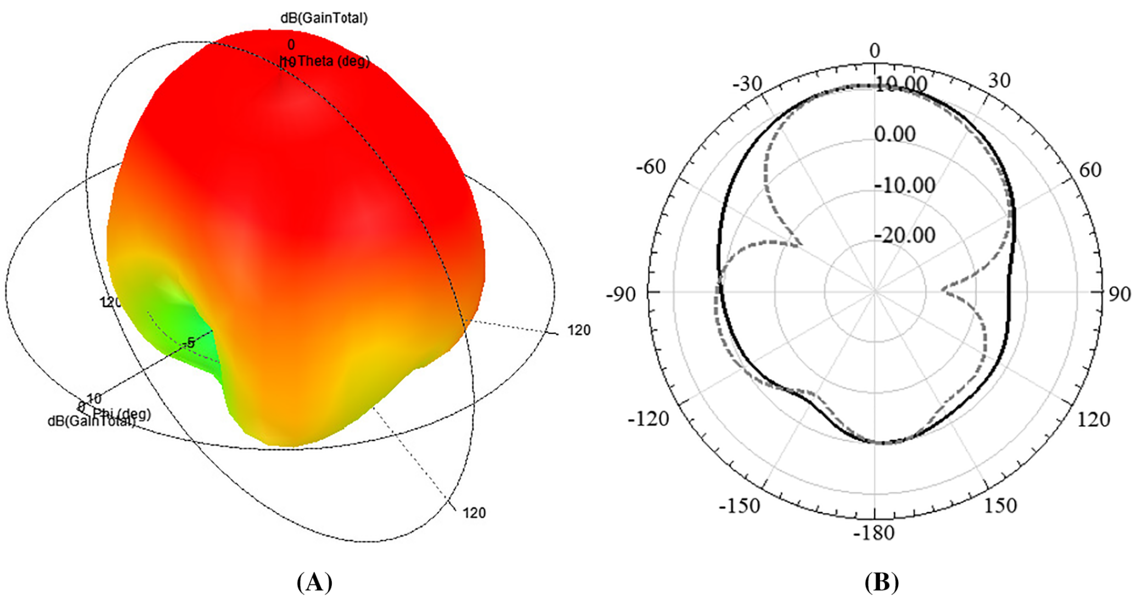
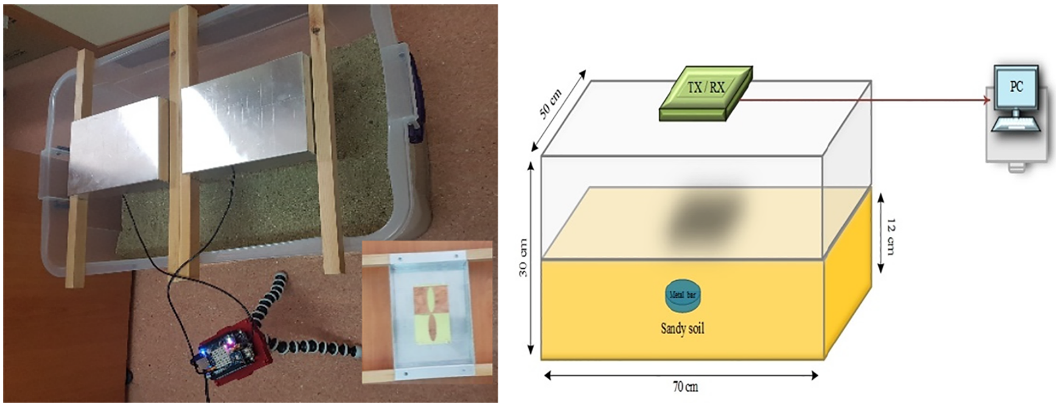


FIGURE 5 The comparison between simulated and measured pattern at 2.5 GHz: (A) the simulated 3D pattern and (B) the measured pattern (black solid line is $\phi = 0°$ and gray dash line is $\phi = 90°$) [Color figure can be viewed at wileyonlinelibrary.com]



(A) (B)

FIGURE 6 The photograph of experimental setup [Color figure can be viewed at wileyonlinelibrary.com]

is 10.3 dBi and measured gain of antenna is almost constant in over bandwidth with a variation less than 2.7 dBi and average gain of 9.1 dBi (Figure 5).

The comparison between simulated 3D pattern and measure pattern at 2.5 GHz is depicted in Figure 6. Measured pattern illustrates a wide E-plane and H-plane pattern with HPBW almost 51 and 58°, respectively.

Table 2 displays a comparison between proposed antenna and recent reported works. On perusal of Table 2, the peak gain and the fractional bandwidth percentage observed for the proposed antenna is highest among the reported papers[13,14,16–18] which has also smaller size. Also, according to ref., 16 the proposed antenna is fabricated to be more reachable and with cheap substrate.

3 | EXPERIMENT SETUP

The time domain measurements have been obtained using a coaxial cable (50 Ω) with a SALSA CAYENNE X1 up to 100 MHz Pulse Repetition Frequency on a Sandbox of dimension 70 × 50 × 30 cm^3 as shown in Figure 6. A moist sandy soil layer with a thickness close to 12 cm is considered in the sandbox. The transmitter and receiver antennas that backed by proper aluminum boxes for reflect back side radiation are kept in 40 cm, to the surface of the soil, with the wooden sticks (air-coupled). Also, a metal bar with diameter of ratios: 5 cm and height: 4 cm is placed 8 cm under the layer of sandy soil.

A sample GPR image that is got by designed antenna is shown in Figure 7. This image is a result of B-scan (antenna location was fixed and scanning time was 60 s). The reflection of object is clear in the 48 cm of range. Actually, it is just a row data and object detection could be improved by signal and image processing methods.

TABLE 2 Comparison between proposed antenna and recent reported works

References	Dimension (mm^2)	Substrate	S11 < -10 dB (GHz)	Peak gain (dBi)
13	500 × 220	FR4	(0.4-1.5) 116%	6
16	210 × 100	ARLAN	0.8-2.3 97%	4
14	700 × 600	FR4	0.05-0.5 164%	5
17	106 × 136	FR4	0.5-1.6 105%	2.5
18	720 × 700	FR4	0.047-0.15 105%	6.5
Proposed antenna	107.7 × 68	FR4	0.98-4.5 128%	10.3

4 | CONCLUSION

In this work, a compact size UWB slot antenna with a CPW fed is proposed. The proposed antenna gives bandwidth of

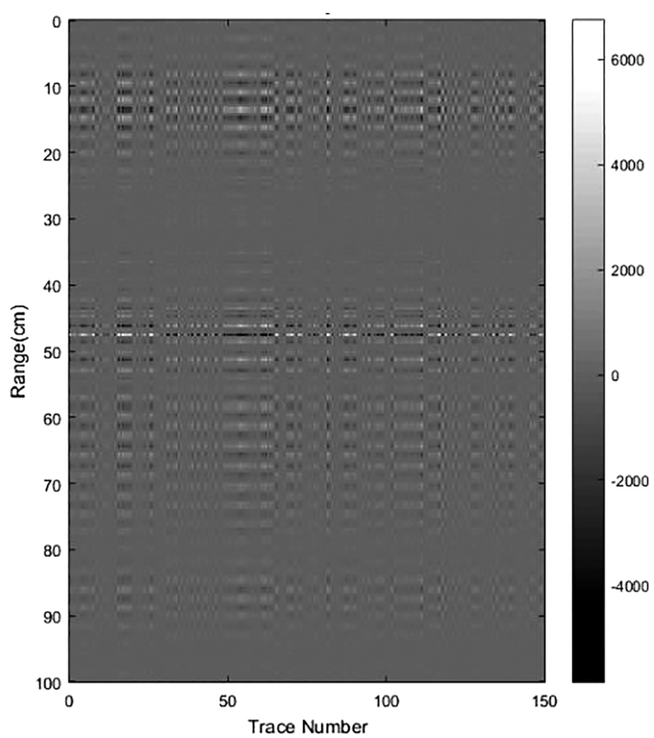


FIGURE 7 A sample GPR image getting by designed antenna

more than 128% (0.98-4.5 GHz) and peak gain of 10.3 dBi. GPR image that collected with proposed antenna from the experimental setup with a sandbox, metal bar and the moist sandy soil layer, shows that it is good candidate for GPR applications.

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Non-contact thickness measurement with multilayer radiation structure

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