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Ultra-Wideband Bow-tie Antenna for Ground Penetrating Radar Applications

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Abstract: The Ground-penetrating radar (GPR) system is used for the detection of buried objects inside the earth and the classification of the subsurface structures. Ultra-wide band antenna is one of the major component of the GPR system; which is used to transmit and receive short pulse of electromagnetic nature. The performance of the GPR system in detecting buried object is mainly affected by the reflections of the GPR antenna. The reflections from the antennas itself is a basis of late-time ringing and distortion of antenna. These factors create problem in the identification of the objects. Several UWB antennas are used in the GPR system. This paper presents theoretical study for the design of ultra-wideband Bow-tie antenna as a GPR antenna. Bow-tie antenna is designed for a frequency range of 4-18 GHz. Transient and spectral behavior of the antenna is simulated. The time behavior of the antenna shows a reflected signal from the bow-tie antenna of the duration of 2.0 ns. The antenna provides a VSWR less than 2.0 and a return loss of less than -15 dB in the operating frequency range. Bow-tie antenna is then modeled and simulated in the GPR environments which includes the buried object (i.e. scatterer) and beam floor. The design, modeling and simulations are performed by using CST Microwave Studio.

Keywords: Ground penetrating radar (GPR), Ultra-wide band (UWB), Bow-tie antenna, Reflection coefficient, Voltage standing wave ratio(VSWR) .

1. INTRODUCTION

Ground-penetrating radar (GPR) is a noninvasive technique, which utilizes short electromagnetic (EM) pulse to detect objects beneath the earth and the electrical discontinuities in the subsurface layers (Neal,2004). The object can be of a nature of a metallic, a dielectric or the combination of both structures (Daniels,2004). GPR is widely used to locate buried mines, to detect utility pipelines, and in the application of forensics and archaeology (Daniels,2004). GPR system consists of three main components which include power supply, antenna and control unit.Power supply unit provides electrical power to the device for operation. GPR system sends an EM wave through a GPR antenna into the subsurface for the detection of buried object. Some part of thepulseis reflected from the earth's boundary and other part ofpulse is transmitted inside the ground and reflected from the buried object (or the electrical discontinuity) after striking it. Then, the reflected wave of weak in nature from the buried object is received by the GPR antenna. The weak reflected signal is recorded, processed and displayed in real-time by the control unit as a pattern on the display. The displayed signal is interpreted by the GPR operator.

Antenna is a major component of the GPR system as it transmits and receives EM waves for interpretation purpose. GPR antenna sends short pulse of EM wave for the detection of buried objects. This pulse of short duration is sent by using ultra-wide band (UWB) antenna. There are two types of GPR system in terms of antenna unit, that is monostatic type and bistatic type(Neal,2004). In bistatic, there are two antennas in the GPR system, one is used to transmit the signal and the other is used to receive the reflected signal. In monostatic type GPR system, only one antenna is usedfor transmission of incident signal and reception of reflected signal.The designing and suitability of the antenna plays a crucial role in the performance characterstic of the GPR system; as the quality of the transmitted and received signal is highly influenced by the antenna. The main problem in identifying the hidden object is the reflection from the GPR antenna itself. If the antenna has higher reflections of its own then it would produce in the resonances and late-time ringings in the transmitted signal. This results in giving incorrect information about the hidden object. Therefore, it is important to design an antenna in such a way that it has less reflections. Here, we focus on the design and theoretical analysis of the UWB bow-tie antenna for GPR applications. The transient and spectral analysis of the designed antenna is performed by utilizing CST MWS simulation software.

This paper is divided in to six sections. Section1, describes the introduction of the GPR system and the

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problem statement. Section 2 briefly reviewsthe available literature on UWB antennas. Section 3 emphasizes on the design formula and design parameters of UWB bow-tie antenna. The modeling of the antenna and GPR environment is illustrated in Section 4. Simulation results are discussed in Section 5 and the conclusion remarks are given in Section 6.

2. LITERATURE REVIEW

Several UWB antennas are used for GPR applications which include, bow-tie antenna, dipole antenna, vivaldi antenna, spiral antenna, TEM horn antenna and cone antenna (Ali,*et al.,* 2017) (Hertl, andStrycek, 2007) Wiesbeck, *et al.,* 2009).

An adaptive bow-tie antenna concept for different ground types was introduced by (Lestari, *et al.*,(2002). It was demonstrated that the wire bow-tie antenna can be made adaptive for different types of floor by varying the angle of flare. Furthermore, it was also shown that the combination of both the capacitive and inductive loads can enhance the bandwidth performance of the solid bow-tie antenna.

(Nayak*et al.,* 2016) have proposed compact bow-tie with resistive loading for a bandwidth of 4.1 GHz (Nayak, *et al.,* 2016). The resistive loading is used to get wide bandwidth. The sharp corners of the antenna are circled to obtain less end-fire reflections. It was demonstrated that the antenna provides high gain, enhanced bandwidth and less reflections.

(Joula, *et al.,* 2018) have presented an UWB bow-tie for GPR in 2018. It is demonstrated in (Joula, *et al.*,2018) that the antenna provides high gain of 10.3dBi for a bandwidth from 0.98 GHz to 4.5 GHz.

Hendevari proposed a monopole antenna of wideband from 3.9 GHz to 18 GHz with a defected ground plane for GPR applications (Hendevari,*et al.,* 2018). It is shown that the simulation results matches with the experimental results.

UWB vivladi antennas with different modifications have been proposed for GPR applications to provide high gain and good impedance matching (Chakrabarti, *et al.,* 2016).(Hood,*et al.,* 2008) (Moosazadeh, and Kharkovsky, 2015)

(Skiljo, *et al.*,2015).have proposed UWB parabolic bi-cone antenna for the GPR application at the range of 0.67- 4.3 GHz showing a negligible distortion of the excitation signal in the direction of maximum radiation (Skiljo, *et al.*,2015).

A TEM horn and quad-ridged horn antennas have been demonstrated to provide low late-time ringing for GPR application (Jamali, andMarklein, 2011). (Mohamed, *et al.,* 2014)

(Caratelli*et al.* 2010)have developed printed dipole having resistive loading for utilizing it in the GPR system (Caratelli,*et al.*,2010). It efficiently operate over a bandwidth of 275-475 MHz.

3. BOW-TIE ANTENNA DESIGN

Bow-tie antennas are types of patch antennas used in different application areas of communication; as it provides light-weight and cost effective way of designing a braod band antenna. The performance of the bow-tie antenna can be enhanced by adding capacitive as well as resistive loading and the optimization of the flare angle.

Here, the antenna is designed by using transmission line model. The bow-tie antenna is placed on the dielectric substrate. The width (W), the dielectric constant (ε_{eff}), and length (L) of the patch (bow-tie) can be calculated by using equation 1, equation 2, and equation 3, respectively(Shuaib,2017).

$$W = \frac{c}{2f_0\sqrt{\frac{(\varepsilon_r+1)}{2}}}, \quad \text{(equation 1)}$$

$$\varepsilon_{eff} = \frac{(\varepsilon_r+1)}{2} + \frac{(\varepsilon_r-1)}{2}\left[1+12\left(\frac{h}{W}\right)\right]^{-\frac{1}{2}}, \text{(equation 2)}$$

$$L = L_{eff} - 2\Delta L, \quad \text{(equation 3)}$$

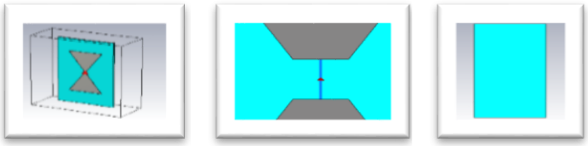
since,

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} \text{and } \Delta L = 0.412h\left[\frac{(\varepsilon_{eff}+0.3)\left[\frac{W}{h}+0.264\right]}{(\varepsilon_{eff}+0.258)\left[\frac{W}{h}+0.8\right]}\right].$$

Where, W is the width of the patch, c ($3x10^8$m/s) is the speed of incident wave in free space, ε_r is the relative permittivity of substrate, f_0(10.5 GHz) is the cutoff frequency in GHz, and h is the thickness of the patch. The dimentional parameter of the bow-tie antenna is given in **(Table 1)**. The designed antenna is shown in **(Fig. 1)**.The 3D view of is shown in **(Fig. 1(a))**; which illustrates the Bow-tie on a substrate. Feed section of antenna is depicted in**(Fig. 1(b))**. Grey plates are the patches of the antenna and blue line with red arrow in between is the discrete port for exciting the antenna. Feed gap is the distance between the plates and feed width is the width of patch at the feeding section. **(Fig. 1(c))** illustrates the substrate section of the Bow-tie antenna. Vertical side shows the length whereas horizontal side shows width of the substrate.

Table 1: Structural dimensions of bow-tie antenna(Shuaib,2017)

Parameter	Value
Width of dielectric substrate	63.53mm
Permittivity of dielectric substrate	1.5
Length of dielectric substrate	103.6mm
Thickness of dielectric substrate	2.34mm
Feed width	0.991mm
Feed gap	0.991mm
Patch arm width	36.79mm
Patch arm length	31mm
Patch thickness	0.14mm
Flare angle	60°



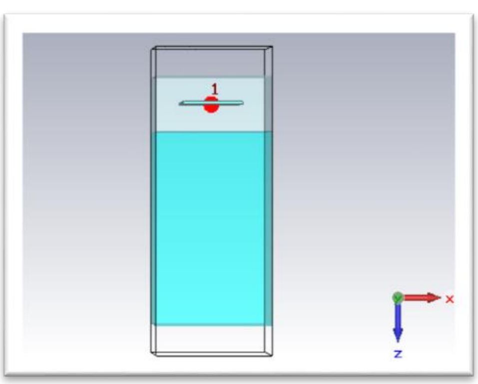
(a) (b) (c)

(Fig. 1) Bow-tie antenna: (a) 3D view; (b) Feed section(feed gap is the distance between the plates and feed width is the width of patch at the feeding section); (c) substrate section(length along the vertical direction and width along the horizontal direction).

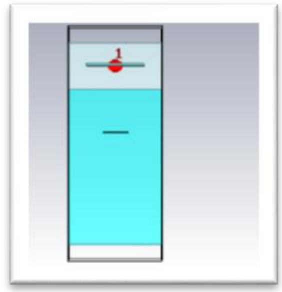
4. MODELING OF BOW-TIE ANTENNA

The bow-tie antenna is designed and modeled by using CST MWS.Computational domain is filled with free space. The boundary conditions are set as open boundary conditions (i.e. perfectly matched layer) in all directions of the computational domain. The frequency range is set to 4 GHz (as minimum frequency) to 18GHz (as maximum frequency). Coarse meshing are taken near the structure and the loose meshing is taken far from the structure. Electric and magnetic field monitors are chosen to analyze the field behavior of the antenna. In order to analyze the transient behavior of the antenna, time domain solver is selected for simulations. The antenna is excited by using the discrete port at feeding section. The modeled antenna with a feeding section is shown in **(Fig. 1)**.

After studying and optimizing the transient and spectral behavior of the antenna, antenna is modeled in the scenario of GPR. The GPR environment includes the modeling of antenna above the earth and the scatterer inside earth. The antenna is placed one wavelength (i.e. λc = 28.57 mm) and scatterer is twowavelengths ($2\lambda c$) above the earth and inside the earth, respectively. The dielectric constant (relative permittivity) of the earth and size of the scatterer is chosen to be 5 and $\lambda c x \lambda c$, respectively. The modeling scenario of antenna earth and scattereis shown in **(Fig. 2)**.



(a)



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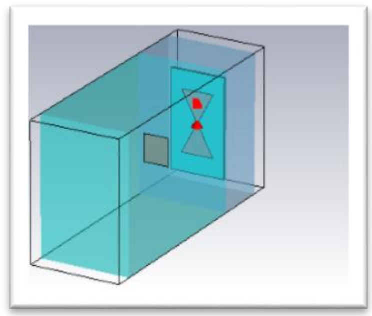


(c)

Fig. 2 Modeling: (a) antenna one wavelength above the earth; (b) antenna with scatterer buried inside the earth; (c) perspective view of antenna, earth and scatterer.

5. RESULTS AND DISCUSSION

An UWB bow-tie antenna is designed and modeled for a frequency range of 4-18 GHz. Simulations are performed by using finite integration technique (FIT). It is a numerical method which solves integral form of Maxwell's equations around the discretized computational domain. In FIT simulations, the frequency dependent and time dependent problems can be analyzed. Here, the frequency domain and time domain analysis is performed. The simulation results are depicted and discussed in this section.

The antenna is excited with an input signal i.e. raised cosine of order 2 (RC2) pulse. The RC2 pulse is excited at the discrete port of the antenna due to its narrow width of 0.19 ns in time domain, as shown in **(Fig. 3)**.

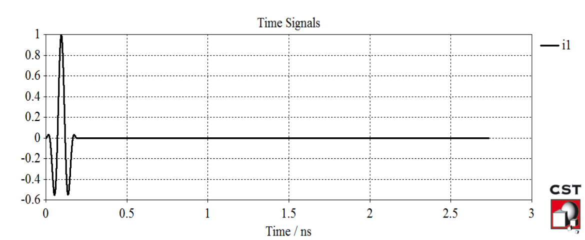
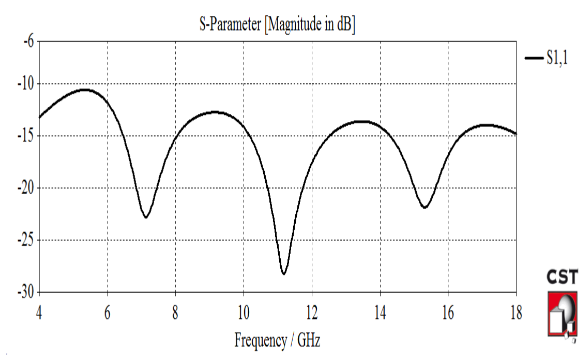


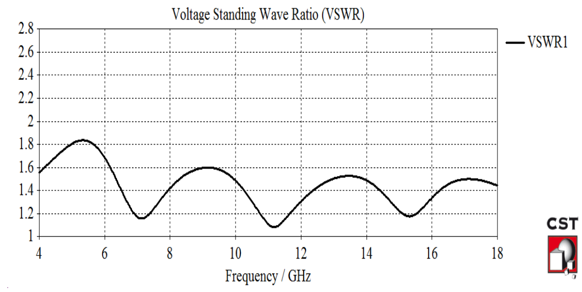
Fig. 3 Input signal of RC2 pulse at the feeding portas a function of time in ns.Vertical plot shows amplitude of the signal. Horizontal plot shows time in ns.

The reflection coefficient and voltage standing wave ratio (VSWR) of the antenna is computed for frequency domain analysis, as shown in **(Fig. 4)**. For antenna, Reflection coefficient (also called S-parameter) and VSWR measure how much of an electromagnetic (EM) wave incident from the feeding port reflected from the structure of the antenna. Ideally, all the EM wave excited at the feeding port of antenna should be radiated from the antenna without any reflection.But practically due to the impedance mismatching in the antenna structure there are always reflections in the antenna. These reflections could be minimized by efficient design of antenna. The optimized design could be where the S-parameter is below the value of -10 dB and VSWR be below the value of 2. These parameters are measuredover a bandwidth or over anspectral range of frequencies of an antenna.

Fig. 4(a) shows the S-parameters of the designed bow-tie antenna for a frequency range of 4-18 GHz. The S-parameter is below -10 dB from 2.4 GHz to 19 GHz. It has three resonant dips below -10 dB, first dip (-22.78 dB) is at 7.134 GHz, second dip (-28.23 dB) is at 11.18 GHz, and third dip (-21.87 dB) is at 15.31 GHz. The more the dip is at lower values, the more efficiently the antenna could radiate and it has less reflections. The dips at that specific frequency provides the information that the how much less reflection is for that specific frequency. **Fig. 4(b)** illustrates the VSWR of the designed antenna for the above mentioned frequency range.The VSWR is below the value of 2 from 4 GHz to 18 GHz. It has also four resonant dips at the same spectral positions as S-parameter have. The first dip (1.16) is at 7.134 GHz, second dip (1.08) is at 11.18 GHz, and third dip (1.18) is at 15.31 GHz. Similar to the S-parameter, lesser theVSWR for the specific frequency, it means the better the antenna would radiate in that particular frequency. Ideal value of VSWR is one, which represent all the power radiates from antenna and there is no reflection in antenna for that specific frequency. Results of the S-parameter and VSWR show that the designed antenna could be able radiate efficiently over the bandwidth of 4-18 GHz.



(a)



(b)

Fig. 4 Frequency domainanalysis: (a) Reflection coefficienti.e. S-parameter in dB (along vertical direction of plot) as afunction of frequency (along horizontal direction of plot); (b) Voltage standing wave ratio, VSWR (indicated on vertical direction of plot) as a function of frequency (illustrated along horizontal direction of plot).

For GPR applications, analysis of transient behavior of the antenna is important together with frequency domain analysis. For transient behavior, the time domain signal of the bow-tie antenna is studied, as shown in **(Fig. 5)**. As mentioned the discrete is used for the excitation of input RC2 pulse **(Fig. 2**), this port is also utilizedas an absorbing port for the absorption and saving of reflected signals. The information of the reflected signals are savedat the port in the time domain. These signals are reflected from the different location of the designed antenna. For an ideal antenna, where all the power is radiated from the antenna, this signal would be zero. For practical cases, there is always reflections coming from the antenna due to the mismatching of impedance. It is because the EM wave excited at the port observes different boundary due to difference in the impedance in the antenna structure. **(Fig. 5)** shows the amplitude of the reflected signal is less than 12%. The time width of the reflected signal is around 0.7 ns. The time domain results show reasonable good results.

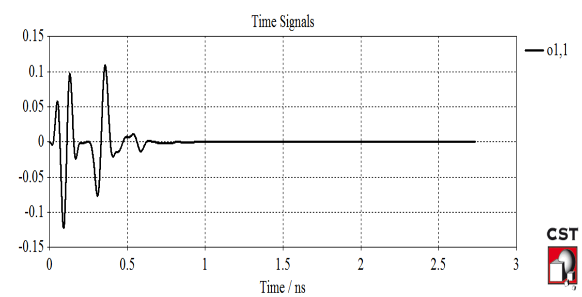
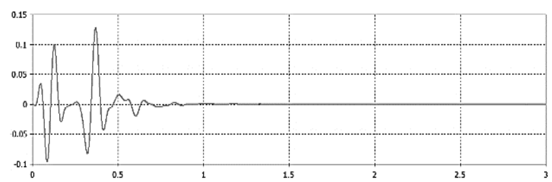
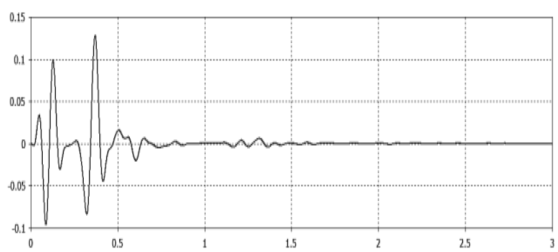


Fig. 5Transient behavior of the bow-tie antenna: reflected signal at the discrete port.Vertical bar of the plot indicates reflected signal and horizontal bar of the plot indicates time in ns from 0 to 3 ns.

The time and frequency domain results demonstrated that the designed bow-tie antenna can work efficiently as an UWB antenna. It is then tested in the GPR environment, where the antenna is placed above the earth where the PEC scatterer is buried **(Fig. 2).(Fig. 6)** shows the results of the designed UWB bow-tie antenna in the GPR environment. When the EM pulse is excited at the port, some part of the waves are reflected from the antenna itself and the part of the pulse is radiated from the antenna. Some of the radiated waves are then reflected from the boundary of the earth and other are transmitted into the earth. After thatsome of the radiated waves which are transmitted into the earth are reflected back from thescatterer and the remaining portion of the waves are propagated in to the earth. All the reflected waves such as from the internal antenna, boundary of earth, and from scattererare noted in the discrete port, as shown in **(Fig. 6)**. Reflected signal from antenna and earth are illustrated in **(Fig. 6 (a))**. Reflected signal from antenna, earth and scattereris shown in **(Fig. 6(b))**. In order to get the reflected signal only from the scatterer**(Fig. 6(c))**, the reflected signals of antenna and earth (see **Fig. 6(a)**) are subtracted from the reflected signals antenna, earth and scatterer**(Fig. 6(b)).**



(a)



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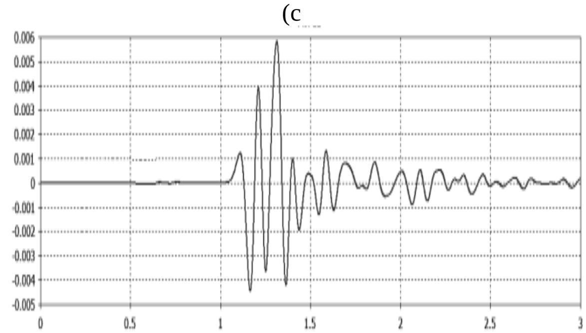

Fig. 6 GPR Reflected signals. Amplitude of Reflected signal is indicated in vertical direction of the plot and time function is indicated in the horizontal direction of the plot.: (a) from bow-tie antenna and earth interface; (b) from bow-tie antenna, earth and scatterer; (c) from scatterer only.

6. CONCLUSIONS

The UWB bow-tie antenna is modeled and simulated over a frequency range of 4-18 GHz for GPR applications. Frequency domain analysis of the designed bow-tie antenna is performed. Reflection coefficient (i.e. S-parameter) and VSWR of the antenna is computed. Results have shown that the bow-tie is an UWB antenna and can efficiently radiate in the frequency range from 4 GHz to 18 GHz. The transient behavior of the antenna is also computed. It is demonstrated from the results of the time domain that the UWB bow-tie antenna has less late-time ringing and hence could be utilized in the GPR applications. After that the bow-tie antenna is modeled in the GPR scenario. The GPR scenario consists of the bow-tie antenna placed in air above the earth where the scattereris buried. From the simulation results of the GPR scenario, it has depicted that the designed bow-tie antenna is suitable candidate for GPR applications.

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