Ultra-Wideband Antenna Design for GPR Applications: A Review

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***Abstract*—This paper presents a comparative review study on ultra-wideband (UWB) antenna technology for Ground Penetrating Radar (GPR) applications. The proposed antenna designs for UWB ground penetrating radar include a bow-tie antennas, Vivaldi antennas, horn antennas, planar antennas, tapered slot antennas, dipole antennas, and spiral antennas. Furthermore a comprehensive study in terms of operating frequency range, gain and impedance bandwidth on each antenna is performed in order to select a suitable antenna structure to analyze it for GPR systems. Based on the design comparison, the antenna with a significant gain and enhanced bandwidth has been selected for future perspective to examine the penetration depth and resolution imaging, simultaneously suitable for GPR detection applications. Three different types of antennas are chosen to be more suitable from the final comparison which includes Vivaldi, horn and tapered slot antennas. On further analysis a tapered slot antenna is a promising candidate as it has the ability to address the problems such as penetration depth and resolution imaging in GPR system due to its directional property, high gain and greater bandwidth operation, both in the lower and higher frequency range.**

Keywords*—Ultra-wideband antennas; ground penetrating radar; antennas; antenna review

I. Introduction

The research interest on ultra-wideband (UWB) systems has gained popularity mainly after the year 2002 when the US department of Federal Communications Commission (FCC) allocated a license-free spectrum for Industrial and Scientific purposes. This greater step of FCC has opened new doors of researches for UWB in the field of wireless communications and microwave imaging [1], [2]. The UWB covers a frequency band ranges from 3.1 to 10.6 GHz that has foreseen the applications in the field of Wireless Local Area Networks (WLAN), Wireless Body Area Networks (WBAN), Wireless Interoperability for Microwave Access (WiMAX), Wireless Personal Area Networks (WPAN) and Ground Penetrating Radar (GPR) technology where wide bandwidth is required [3], [4].

GPR is one of the major applications of UWB technology, which is widely used in military and civilian applications such as the detection of land-mines [5]. In addition, GPR is also used in remote sensing techniques such as nondestructive testing of concrete and detection of trapped people under-debris or in opaque environment [6]. For the implementation of UWB GPR systems, the performance of various antenna designs, such as bow-tie antenna [7], [8], spiral antenna [7], loaded dipole antenna [9], TEM horn antenna [10], [11], tapered slot antenna [12], [13] and Vivaldi antenna [14], [15] have been evaluated.

This paper examines the technical and methodological aspects involved during the design of ultra-wideband antennas for ground penetrating radar detection applications. The study has been performed based on antenna gain, directivity, complexity of the design as well as the frequency bandwidth. Later the comparison of results to address the fundamentals of GPR applications, such as penetration depth and resolution has been performed. Finally one of the best suitable antenna design is chosen for further research and future directions. The organization of this paper is as follows: Section II discusses the UWB antenna designs and methodologies suitable for GPR application. Section III presents the results and analysis of the antennas discussed in the previous section. Finally, the paper is concluded in Section IV.

II. Antenna Design for GPR

A number of ultra-wideband antennas have been designed for GPR applications. The study based on the lower frequency band is conducted mainly to improve the penetration depth while the designing in the higher frequency band is performed to achieve better resolution imaging for GPR systems. Some of the work focus on the entire UWB frequency range to further enhance the bandwidth while other focused on gain enhancement.

Based on these previously mentioned requirements, different types of antennas such as bow-tie antennas, Vivaldi antennas horn antennas and few more antenna designs have been studied and implemented for GPR applications.

A. Bow-tie Antenna

A bow-tie UWB antenna is widely used in the design for GPR applications, as it has the ability to reduce ground susceptibility during GPR operations [16]. Fig. 1 shows a simple bow-tie antenna design which consists of two flares connected to a common feed.

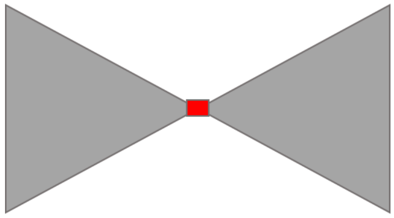

Fig. 1. Bow-tie antenna design [24].

The length, l and width, w of the flares in bow-tie structure can be determined by (1) and (2) [16-19]:

$$l = \frac{1.6\lambda_o}{\sqrt{\varepsilon_r}} \quad (1)$$

$$w = \frac{0.5\lambda_o}{\sqrt{\varepsilon_r}} \quad (2)$$

Where λo is the wavelength of the low frequency range in free space. The flare angle is totally dependent on impedance [19].

In [17], a monolithic bow-tie UWB antenna for GPR applications is designed by using a total geometric morphing approach with small pads to form an array. The antenna has been fabricated on a glass epoxy FR-4 substrate with a dielectric constant value, Ɛr of 20 and it is fed by a coaxial cable for impedance matching to the balanced current balun.

A slot and reflector have been introduced into the antenna structure to achieve a wide beam width and unidirectional radiation pattern [18]. The antenna is fed by a coplanar waveguide (CPW).

Furthermore, a modified bow-tie antenna with a shielded back cavity for omnidirectional radiation pattern is also proposed for GPR application [19]. The antenna is fabricated on a FR-4 substrate with a dielectric constant, Ɛr of 4.6 and centered at 900 MHz. The edge of the antenna is cut to make the antenna to be more compact and study the effect of edges on reflection coefficient.

As the research progresses, new designs have been developed with modifications in the shapes and dimensions of the bow-tie antenna. In addition, one of the antennas has been designed by using the finite difference time domain approach [20]. CPW is used as the feeding method while metal stubs is introduced for impedance matching. The work in [7] introduces the structure of a bow-tie antenna into its dipole antenna to improve the gain for GPR. The ideal performance of a bow-tie dipole antenna can be achieved by feeding the antenna with 100-200 ohm impedance. In [8], a resistive-loaded UWB bow-tie antenna is proposed to improve the forward gain from the employment of metamaterial lens.

As the signal of the GPR system required propagating through inhomogeneous media, the efficiency of the antenna must also be taken into account. Thus, in order to enhance the efficiency, a compact shape slotted bow-tie antenna is designed [21]. The compactness in the shape of antenna is achieved by rounding the sharp corners of the bow-tie structure and triangular stubs with extended arms. The antenna is fed by a CPW and a thin graphite sheet is used to reduce the end-fire reflection of the UWB antenna for GPR application.

In [22], an elliptical shape of bow-tie antenna is proposed to broaden the bandwidth. A semicircular slotted-tuned half-ellipse antenna in a bow-tie formation is designed in [23]. The proposed antenna has four semicircular slots in the bow-tie ellipse to further improve its penetration properties for vital signs detection.

A low cost UWB bow-tie antenna for GPR is presented in [24]. A reflector cavity design technique is used where the model is initially tested with only a bottom reflector followed by a side reflector and both reflectors at the same time. There is also a gap between both flares of the bow-tie where a balun is deployed to match the impedance. Finally, the antenna is equipped with a four-sided reflector to study the gain parameters.

B. Vivaldi Antenna

Vivaldi antennas are commonly used for the applications such as GPR which require a greater bandwidth usually with a ratio 10:1 [16]. Therefore, various designs of Vivaldi antennas have been studied and discussed. Fig. 2 shows the design of a Vivaldi antenna.

A Vivaldi antenna consists of a radiating and ground planes of a similar shape placed in the opposite of each other separated by a substrate. The exponential curves in the Vivaldi antenna as shown in in the figure can be described by (3) and (4) [15]:

$$x = \pm 0.14e^{0.27y} \quad 0.1 \le y \le 11.4 \quad (3)$$

$$x = \pm 3.04e^{0.425y-4.845} \quad 11.5 \le y \le 14.2 \quad (4)$$

In [14], a Vivaldi antenna array is designed for GPR measurement application. An experiment is conducted to observe the penetration through a concrete structure. Five array elements are used in the receiving antenna to gather all the information.

In order to achieve the compactness, small size, balanced bandwidth and a reasonable gain for GPR applications, an antipodal structure semi-empirical Vivaldi antenna is proposed [25]. The antenna is fed by a microstrip line with PTFE board as the substrate. The antenna is designed based on two aspects: the transition aspect and radiation aspect, to meet the UWB system requirements.

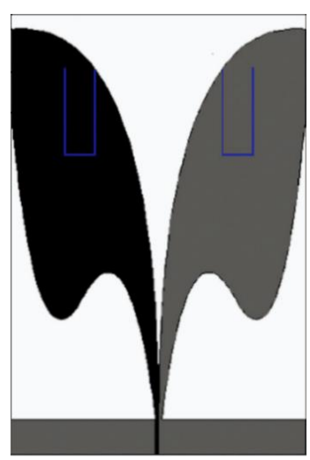

Fig. 2. A Vivaldi antenna [27].

Another balanced antipodal Vivaldi antenna structure has been proposed in which an L-shaped slot has been introduced at the edge of a radiating patch [26]. In the design, a structural increase in the radiating patch has increased the electrical length of the antenna while the L-shaped slot has enabled a radiation from the outer edge of the antenna. A comparison is then made with a conventional Vivaldi antenna with various substrates such as a FR-4, Rogers, PTFE and TP-2. In [27], two antipodal-shaped Vivaldi antennas are proposed. The first antenna consists of a simple antipodal shape to achieve compactness and comparatively small in size with a wider bandwidth and good gain. U shaped slots have been introduced into the structure to enhance the gain.

A novel Vivaldi antenna with an exponentially tapered slot edge (TSE) is designed in [15]. Seven pairs of electromagnetic band gaps in either a loop or square shapes have been introduced in the ground plane. The purpose of these band gaps is to extend the lower end bandwidth of the UWB antenna and improve the impedance matching over the same band. The proposed antenna also helps in the electrical length reduction in comparison with the original antenna without tapered slots.

A double-slot antenna structure is proposed in [28] to further improve the gain and directivity of the Vivaldi antenna. The antenna is also suitable for UWB GPR applications. The slots are excited by using a T-junction power divider to generate plane waves in the E-plane at the aperture of the antenna and it is compared with a conventional Vivaldi antenna that uses an exponentially tapered method. Another directional Vivaldi antenna with eye-shaped slots is proposed in [29] to reduce the side lobes and increase the efficiency to approximately 80%. The proposed antenna also has a greater gain which makes it suitable for GPR systems.

C. Horn Antenna

In a GPR system, better depth penetration and ease of scanning the shallow targets often require elevated antennas because the energy must radiates into the ground for detection. Thus, it makes a horn antenna as one of the best candidates as it is less susceptible to the effects of ground [16]. A typical horn antenna can be seen in Fig. 3.

The construction of a horn antenna mainly consists of two parts: An aperture and waveguide transition. The dimensions of an aperture can be approximated by (5) and (6) [11]:

$$\Delta = \frac{w^2}{8R} \tag{5}$$

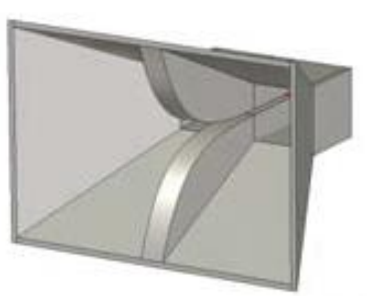

Fig. 3. A horn antenna [30].

$$S = \frac{\Delta}{\lambda} = \frac{w^2}{8\lambda R} \tag{6}$$

Where S is a dimensionless quantity, w is the distance between the horn apertures, R is the length of aperture and λ is the wavelength.

A double ridged horn (DRH) antenna is presented in [30]. The antenna has a wider bandwidth and is proposed for GPR applications. The reduction in operating frequency will compromise the size of the antenna. Thus, in order to achieve a small size but with lower operating frequency, the ridges have been extended from the aperture plane and the gap is filled with dielectric material. In [7], another DRH antenna is also designed to increase the bandwidth.

An UWB quad ridged horn (QRH) antenna is proposed in GPR application for deep penetration by modifying a conventional triangular transverse electromagnetic (TEM) horn [11]. First modification is performed by tapering the horn plates with a curvature and the second modification is the addition of double ridges in between the horn aperture [30]. A substrate with a high dielectric constant is used to fill the gap. The substrate used is the Rogers RT-3010 with εr of 10.2. The fabricated antenna is then compared with the SH-68 Satimo horn antenna that is commercially available.

There are some reflections and ringing effects in the conventional TEM horn antenna that are not suitable in GPR application. Therefore, an optimized design of TEM horn antenna for UWB is proposed [10]. The antenna is designed by carving an arc in the two exponentially tapered plates of horn and perpendicular plates are connected at the lower end.

In [31], another TEM horn with a flare shape is designed with a balun for proper current balancing. The design consists of two flaring conductors constructed by cutting a brass sheet for the top and bottom flare and combined together with a triangular slab from Styrofoam to secure the conductor in a flare. The antenna is experimentally tested with a concrete to observe the gain when in contact with other materials.

In [9], an UWB horn antenna consists of a coaxial feed line and a proper waveguide with a round and tapered-shaped aperture. The antenna is designed by using the D-angle and W-angle methods for the waveguide. The aperture has rounded corners to improve the performance.

Various feeding techniques are also discussed in [6] other than proposing a new feeding technique. In order to realize the new technique, the waveguide of the antenna is fixed and a screw is added on the opposite side of the feeder to increase the gain.

D. Planar Antenna

A planar antenna, as shown in Fig. 4, is a popular candidate for UWB due to its simplicity, conformity in design, cost effectiveness and light weight properties [32], [33].

A planar antenna mainly consists of a radiating patch and either a full or partial ground plane with a defected ground structure (DGS) [15] which can be varied according to the design requirement. The length, L and width, W of the patch can be determined from (7) and (8) [32], [37]:

$$W = \frac{c}{2f}\left[\sqrt{\frac{c}{(\varepsilon_r + 1)}}\right] \quad (7)$$

$$L = \frac{c}{2f} - \Delta L \quad (8)$$

Where:

$$\frac{\Delta L}{h} = \frac{0.412\left[\left(\varepsilon_{reff} + 0.3\right)\left(\frac{w}{h} + 0.264\right)\right]}{\left[\left(\varepsilon_{reff} - 0.258\right)\left(\frac{w}{h} + 0.8\right)\right]} \quad (9)$$

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left\{\left[1 + 12\frac{h}{w}\right]^{-\frac{1}{2}}\right\} \quad (10)$$

In [34], a hexagonal fractal patch antenna is proposed to achieve a wideband characteristic. The design is modified by iteration of hexagonal fractals with slits in the ground plane to create a notch that affects the impedance bandwidth. Hexagonal slots are also introduced in the patch and slots in the ground plane alongside the slits.

A modified circular patch antenna for UWB GPR applications is proposed in [35]. The conventional circular disc is modified to produce a mickey-shaped patch radiator with a CPW feed. The substrate used is FR-4 with Ɛr of 4.3. A rectangular copper reflector is inserted below the antenna to make it directional.

Another circular disc antenna is designed in [36] to improve the impedance bandwidth and efficiency of the planar antenna. A rectangular slot is introduced at the edge of the ground.

A stepped feeding and two level notched stairs in the patch with a partial ground plane over Rogers Duroid RT-5880 with a dielectric constant, Ɛr of 2.2 are included in the design of an UWB planar antenna in [37]. The antenna is tested in step-by-step basis. Firstly, the antenna is simulated and tested only with a simple rectangular patch and a partial ground followed by a stair patch and a partial ground. Finally, the stubs are introduced in the stairs feed patch for band notch. A multioctave frequency selective antenna with a reflector is proposed in [38] to study the gain performance.

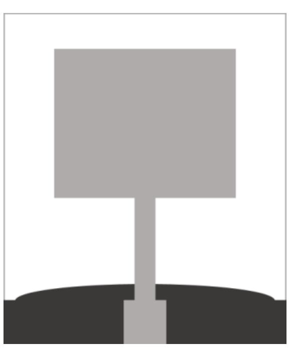

Fig. 4. A planar antenna [37].

An UWB quasi-planar antenna in [39] is designed for gain enhancement. The antenna consists of a CPW-fed semicircular disc monopole antenna with a short horn. The shape of this quasi antenna makes it a potential candidate for GPR technology.

A quadruple-band planar antenna is developed in [40]. This is a simple microstrip patch antenna with four slots of different geometries namely, square, rectangle, circle and ellipse. Similarly, another slotted monopole planar antenna with a key shape is designed in [41] where the shape is achieved by etching two symmetrical curved slots in the circular patch which in return, increases the efficiency of the antenna. A spanner-shaped antenna is proposed in [42] which is achieved by cutting a rectangular slot on the upper side of minor axis in an elliptical-shaped antenna to improve the gain and bandwidth for GPR applications.

E. Tapered Slot Antenna

Gain is one important parameter that is required in a GPR system as it can enhance the signal appearance which can be affected by signal attenuation and other losses as well [43]. In order to improve the gain factor in an antenna design, different methods are used. One of them is the tapered slot method. Fig. 5 shows the UWB tapered slot antenna which consists of a coplanar patch and ground that is suitable for GPR applications.

In [12], one of the tapered slot compact antennas with a high gain for GPR applications is proposed. This compact planar antenna is fed by a CPW with one slot line to supplement the taper slot. A resistive loading is introduced with some discontinuities in the design to avoid any strong reflections. The antenna is designed by introducing two main slots: one slot is represented by a Vivaldi shape and another slot is a triangular slot.

A double exponentially tapered slot antenna (DETSA) is designed in [13] in which the exponential arms of the antenna are rolled back to improve the bandwidth. Another modification in the design is the introduction of a coupled-strip line (CPS) instead of a CPW for feeding purpose. The measured losses of a CPS are less than that of a CPW. The antenna is designed on a FR-4 dielectric material with Ɛr of 4.4.

In [44], another modified slotted antenna with a backed absorber is investigated for broadband antennas. The proposed design is modified by cutting a slot in the patch and then tapering the slot edges so that the antenna can perform better in GPR applications. This model is designed on a lossy TMM-10 substrate with Ɛr of 9.2.

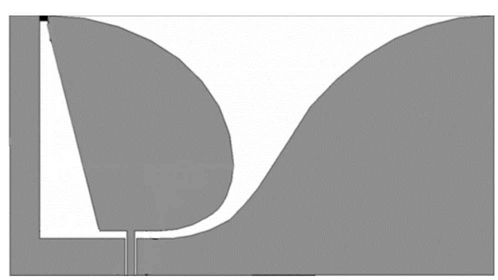

Fig. 5. Tapered slot antenna [12].

A semicircular slotted antenna is introduced in [5] to enhance the gain factor. In the design, semicircular slots are introduced with tapered transitions for a CPW feed. A frequency selective surface (FSS) method with a dual-layer reflector is used which helps in the gain enhancement and impedance matching. The distance between the antenna and reflector can be approximated by (11) [45]:

$$\phi_{FSS} - 2\beta h_{FSS} = 2n\Pi; \qquad n = ...,-2,-1,0,1,2,..... \quad (11)$$

Where:

ϕ_{FSS} = Reflection phase

h_{FSS} = Distance between reflector and antenna

β = Propagation constant of free space

Another high gain antenna with FSS has been designed by etching two elliptical structures for the slot [45]. The gain of the antenna without the FSS is very low and has been further enhanced with the presence of FSS. A star-shaped antenna is designed with an asymmetric slot in the ground plane with an open ended CPW feed [46] for gain enhancement from the employment of FSS which makes it suitable for GPR applications.

F. Dipole, Cone, and Spiral Antenna

Dipole, canonical and spiral antennas are also the potential candidates for GPR applications and are discussed in this section. A dipole antenna can be constructed on either a planar structure or from a wire [7]. Various dipole antennas have been designed such as wired dipole, elliptical dipole and short dipole [47] for UWB applications. The length, L of a dipole from a simple wire can be calculated as follows [52]:

$$L = \frac{1}{4\lambda} \quad (12)$$

Where:

$$\lambda = \frac{c}{f} \quad (13)$$

The advantage of using a wired dipole is that it ensures high microwave power which is preferable in GPR technology [7]. Similarly, cone and spiral antennas are also proposed for UWB applications. To increase directivity, a radiation stub cone or disk cone [48] has been introduced into the antenna with a fractional bandwidth of 70-80% [7]. Spiral antennas are also favorable as the antennas have a balanced feed over the entire frequency band [49]. The arms of spiral antenna can be defined by using a polar function which is given by (14) [16]:

$$r = R_o e^{a\phi} \quad (14)$$

Where Ro controls the radius of the spiral as it grows exponentially, while a controls the flare rate.

In [50], an elliptical-shaped structure is introduced into each of the dipole's arm as shown in Fig. 6. The proposed design is capable to improve the gain and reflection coefficient for UWB applications. The elliptical slots are used for time domain analysis. Another antenna consists of a 16-port shared-arm dipole array is proposed for radar imaging [51].

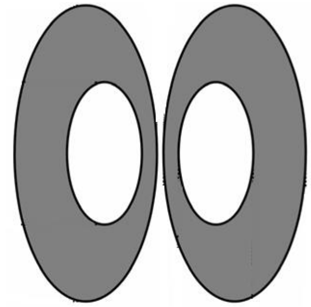

Fig. 6. A dipole antenna [50].

A magneto-electric dipole is investigated in [52]. In the design, a greater bandwidth is achieved by introducing two slots in the magneto-electric dipole by using a rectangular box reflector to fix the broadside direction of main beam.

Other antenna designs for UWB GPR applications are constructed from the cone and spiral shapes [7]. A cone antenna, as shown in Fig. 7, is an elementary antenna in 3-D structure to improve the impedance bandwidth for GPR systems. The angle of the cone is always related to the impedance, which can be calculated from (15) [49]:

$$Z = 120 \ln\left(\cot\left(\frac{\phi_k}{2}\right)\right) \quad (15)$$

On the other hand, spiral antennas with two uniform width arms with gain are also suitable for GPR applications. Fig. 8 shows the spiral antenna.

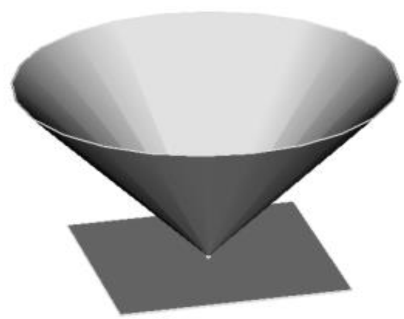

Fig. 7. Cone antenna design [7].

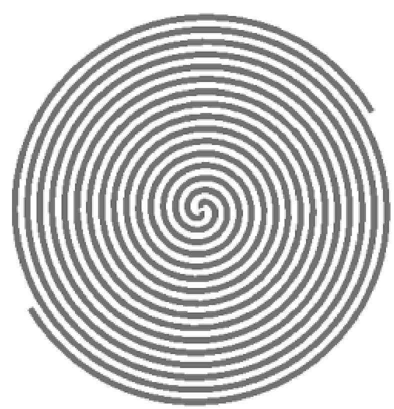

Fig. 8. A spiral antenna [7].

III. Results and Discussions

Ultra-wideband antenna designs that are suitable for ground penetrating radar applications mainly require greater frequency bandwidth along with the parameter of high gain. Based on the above mentioned parameters, results of antenna designs discussed in Section 2 are presented for the analysis during this section.

The operating frequency of the designed antenna, its percentage bandwidth and the maximum value of obtained gain over the entire UWB band are summarized in tabular form. This summarization helps us to develop a better understanding regarding antenna performance for GPR applications. The measured results for bow-tie antennas are shown in Table 1. From these results, it can be observed that the bow-tie antenna designed by cutting edges has sufficient percentage bandwidth, which is suitable for an UWB GPR system. But there are some significant differences shown in the gain obtained for these antennas. The results of a backed cavity bow-tie antenna designed in [24] and bow-tie slotted antenna in [21] have a comparatively better gain with the value around 7 dB. But the bow-tie antenna designed using metamaterial lens has the highest gain with the value of 11.52 dB. In addition to this, these designed bow-tie antennas also have a sufficient flares length which is preferable to match the lower frequency band. Because of this reason these antennas are mainly capable of targeting the penetration depth properties for the GPR detection applications. However, the discussion about the ability of these antennas to distinguish among different detectable objects through imaging is difficult because of low resolution properties, as lower frequencies are not suitable for imaging characteristics.

In a similar manner, the measured gain and bandwidth obtained for Vivaldi antenna designs are shown in Table 2. The percentage bandwidth of all the proposed UWB antennas is sufficient to consider Vivaldi shape design for GPR applications. This is due to the fact that Vivaldi antennas offer dimensionality as well as ground optimization to achieve the desired bandwidth. The exponentially tapered slotted edge antenna designed in [15] has the least percentage bandwidth and the value of gain for this antenna is 8 dB, due to which this design is also considerable for GPR systems. From the table, it can be deduced that the gain of Vivaldi antennas have considerable values and also they covered the complete UWB frequency band defined from 3.1 to 10.6 GHz. The antipodal Vivaldi antenna designed in [27] performs better with greater bandwidth of approximately 15.9 GHz and the gain of 9.6 dB.

TABLE. I. Performance of Bow-Tie Antennas

Ref. #	Frequency (GHz)	Percentage Bandwidth (%)	Maximum Gain (dB)
7	0.5 to 3	142	5.8
8	0.3 to 3	163	11.52
17	0.3 to 1	107	-
18	0.8 to 2.3	96	4
19	0.4 to 1.2	100	-
20	0.4 to 1.5	115	6
21	0.4 to 4.8	169	7
22	0.012 to 0.143	169	2.5
23	0.01 to 0.9	195	-
24	0.2 to 0.7	111	7.4154

TABLE. II. Performance of Vivaldi Antennas

Ref. #	Frequency (GHz)	Percentage Bandwidth (%)	Maximum Gain (dB)
7	0.5 to 3	142	7.7
14	0.5 to 6	169	-
15	0.05 to 0.12	82	8
25	3.1 to 10.6	109	5.03
26	3.7 to 18	131	6.9
27	4.1 to 20	132	9.6
27	1.3 to 12	161	15.2
28	2.5 to 15	142	10.8
29	3 to 12.8	124	8.3

Another antipodal antenna is also proposed in [27] with U-shaped slots and a mouth opening at the order of $\lambda/4$ also gives significant results with a gain of 15.2 dB and a greater bandwidth that covers UWB band. These results shown in Table 2 provides a wider opportunity for the Vivaldi shape antenna designs that makes it one of the suitable candidate for GPR applications with deep penetration and better resolution imaging.

Horn antenna designs, discussed in the earlier section possess high gain value mainly because of its directional properties. Measured results of horn antennas in the form of gain and percentage bandwidth are shown in Table 3. From the table, the performance of the antennas in terms of gain and bandwidth is analyzed and the results showed a significant increase in gain. As such, a TEM flare horn antenna designed in [31] can be used in a GPR system for detection as it addresses the requirements of deep wave penetration and better resolution imaging to distinguish among the detected objects due to its high gain as well as greater bandwidth compared to remaining horn designs. While other designed antennas seemed to target penetration depth as their operating bandwidth lies within the lower frequency band. The horn antenna designed in [6] has the least percentage of bandwidth even though its gain value is significantly higher due to which it can penetrates up to few feet under the ground. Nevertheless, a horn antenna design is still one of the best suitable candidates for GPR applications because of its highly directional properties, suitable gain, proper impedance bandwidth and less susceptibility to ground effect the performance of antenna.

TABLE. III. Performance of Horn Antennas

Ref. #	Frequency (GHz)	Percentage Bandwidth (%)	Maximum Gain (dB)
6	2.9 to 3.21	10	15
7	0.5 to 3	142	11.9
9	0.6 to 6	163	9.9
10	2 to 19	161	-
11	0.05 to 0.5	163	13
30	1 to 7	150	10
31	0.75 to 12	176	13

The results obtained from planar antenna designs are shown in Table 4. From the given table, printed circular patch antennas with the slotted ground are designed in [36], [38]. These antenna have sufficient gain value which is approximately 7.5 dB and also have greater bandwidth. This significant increase in the bandwidth of planar antennas can be attributed to the extra electromagnetic coupling between the ground and the radiating patch [36]. The performance of a circular patch antenna designed in [36], makes planar antenna a suitable candidate for GPR applications. The performance of the other designed planar antennas is also considerable only for deep penetration as the bandwidth operates in lower frequencies.

Tables 5 and 6 shows the results obtained from a tapered slotted antennas, dipole, spiral and cone antennas. From the results shown in Table 5, it can be observed that the tapered slot antenna (TSA) designed in [12], double exponentially tapered slot antenna (DETSA) designed in [13] and eye-shaped slotted antenna designed in [45] have comparatively high gain with greater percentage of bandwidth. The good performance of tapered slot antennas is mainly due to the coplanar properties of radiator and ground, and tapering characteristics, which is helpful in order to improve the performance of the antennas. Therefore, these tapered slot antennas have the ability to address the problem of deep penetration properties and high resolution imaging in GPR applications. From the results obtained in Table 6, it can be observed that the magneto-electric dipole antenna designed in [52] has significantly high gain value over the entire operating bandwidth. This magneto-electric antenna also cover the complete UWB band which makes this antenna design as one of the suitable antenna that can be designed for GPR detection applications.

TABLE. IV. PERFORMANCE OF PLANAR ANTENNAS

Ref. #	Frequency (GHz)	Percentage Bandwidth (%)	Maximum Gain (dB)
7	0.5 to 3	142	6.6
27	2.64 to 6.96	90	5.2
35	0.4 to 3	152	-
36	3.06 to 19.41	145	7.51
37	3.2 to 14	125	3.328
38	3 to 12	120	7.5
39	2.5 to 15	143	6.2
40	9.045 to 9.695	7	7.307
41	2.72 to 12.68	129	5.24
42	2.23 to 11.4	135	3.54

TABLE. V. PERFORMANCE OF TAPERED SLOT ANTENNAS

Ref. #	Frequency (GHz)	Percentage Bandwidth (%)	Maximum Gain (dB)
5	3 to 11.6	117	9.5
12	0.64 to 6	161	14
13	0.2 to 6	187	12
44	0.3 to 3	163	5
45	3.6 to 12.6	111	12.5
46	2.5 to 14	139	8

TABLE. VI. PERFORMANCE OF DIPOLE, CONE AND SPIRAL ANTENNAS

Ref. #	Frequency (GHz)	Percentage Bandwidth (%)	Maximum Gain (dB)
7	0.5 to 3	142	5.5
7	0.5 to 3	142	4
50	1.1 to 11	163	5
51	1 to 3	100	-
52	2.95 to 10.73	113	9.3

From the results obtained for different types of antennas, designed specifically for GPR applications for detection purpose, it can be observed that the Vivaldi, horn and tapered slot antenna designs have significantly better performance. However, based on further comparison between these designed antennas, a tapered slot antenna is the best suitable candidate for UWB ground penetrating radar system and it has the potential to be further developed due to significant gain and greater bandwidth.

IV. CONCLUSION

A comparative review based study into a potential ultra-wideband antenna for GPR applications has been performed in this paper. The detailed summary of a bow-tie antenna, Vivaldi antenna, horn antenna, planar antenna and tapered slot antenna along with different design methodologies have been presented. The demonstration of results and the discussion about it, mainly focused on the gain as well as the bandwidth because these two parameters shows a greatest interest to design UWB antennas for GPR systems. Based on the measured results, three different types of antennas have been selected which includes Vivaldi, horn and tapered slot antennas. But on further comparison it is concluded from the study that a tapered slot antenna can be considered for future research. These antennas have the potential to address the issues of deep penetration under the surface of ground and better resolution imaging for GPR systems mainly because of its directional properties, high gain and greater operational bandwidth, both in the lower as well as higher frequency range.

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