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Design monopole antenna of ultra-wideband high bandwidth and high efficiency for ground penetrating radar application

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ABSTRACT

Over the past years, remote sensing, radar, and imaging applications have all made use of ultra-wideband (UWB) technology. This study undertakes an extensive analysis of tree-shaped monopole antennas tailored for UWB systems. The intended antenna has an incomplete ground plane and a circular radiating patch. To increase bandwidth, two ears have been added to the circular structure. Possessing a dielectric constant of 4.3. The antenna substrate consists of FR-4 material with a dielectric constant of 4.3. To achieve optimal impedance matching for UWB systems, the antenna is fed via a coplanar waveguide (CPW). Design antenna is a simple structure, small size, easy design, and simple integration with the substrate with dimensions of 54 mm ×36 mm ×1.6 mm. All simulation results presented in this article were generated using computer simulation technology (CST) software. He monopole antenna exhibits an impressive impedance bandwidth of 9.6 GHz (146.68%), spanning from 1.99 GHz to 11.56 GHz. Furthermore, the simulated UWB circular monopole antenna exhibits omnidirectional radiation characteristics, boasting a peak gain of 8 dB, and a directivity of 8.2 dBi at the frequency of 5 GHz, and a remarkable radiation efficiency of 97%. With these attributes, the suggested monopole UWB antenna shows significant potential for ground penetrating radar (GPR) applications.

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1. INTRODUCTION

Ground penetrating radar (GPR) is a significant technological advancement in recent years, utilizing electromagnetic waves (EM) to detect buried objects, including both metal and non-metallic materials, such as cables, pipelines, and concealed pathways beneath the earth's surface [1]. The key component of a ground-penetrating radar system is its antennas, which play a crucial role in the overall performance of GPR devices [2]. Modern high-resolution radar systems, including remote sensing and advanced radar frameworks like GPR, heavily rely on ultra-wideband (UWB) technology to achieve superior capabilities. Its primary recommendation is to create a short-term beat, conveying a large data transfer capacity in frequency space that involves both transmitting electromagnetic waves and receiving EM waves that are reflected back from the item being detected [3]. Additionally, we require an antenna that has a broad frequency bandwidth and emits very narrow pulses.

The introduction of wireless technology has facilitated the simultaneous operation of UWB signals alongside nearby communication systems in the radio environment. UWB systems heavily rely on UWB antennas, which have been the topic of intensive study in the last years [4]. The key characteristics of a UWB antenna include omnidirectional radiation pattern and a wide impedance bandwidth, UWB signals are known for their extensive absolute or relative bandwidth [5], [6].

The utilization of wide transmission bandwidths offers several advantages, including improved barrier penetration, covert operation, enhanced interference rejection, and compatibility with narrow bandwidth (NB) systems [7]. Additionally, UWB technology facilitates low-rate communications with precise geolocation capabilities and supports radar systems such as GPR, which provide exceptional spatial resolution and the ability to overcome barriers [8]. UWB technology has emerged as a promising choice for both military and commercial wireless communication applications. Its versatility is evident in its various uses, ranging from multimedia applications for home entertainment to sensor networks and the personal computer industry. The assigned spectrum for UWB communication systems is characterized by an exceptionally wide bandwidth. The spectrum allocated for UWB communication systems is distinguished by an exceptionally broad bandwidth. The initial publication of UWB by the Federal Communication Commission [9] the event occurred in 2002, with the designated frequency range extending from 3.1 to 10.6 GHz [10]-[12]. In neat for a system to be categorized as UWB, the main requirement that must be met is a bandwidth width of more than 500 MHz, and the fractional bandwidth requirement is 20% of the center frequency. The advantage of UWB technology, especially in radar applications, is wider bandwidth so some of the advantages that can be obtained are accuracy of distance detection, resistance to fading, resistance to jamming, and several other benefits [13]. The impressive radiation properties of UWB antennas, including their substantial bandwidth [14], high data rate capabilities, and low power requirements, have made them extensively utilized in a range of applications [15]. These applications encompass precision locating, tracking systems, radar imaging, and numerous commercial uses, thanks to the promising attributes exhibited by UWB antennas [16], [17].

The UWB antenna proposed for GPR use must incorporate essential components, including ultrawide data transmission capabilities, high impedance coordination, and features specific to GPR antennas. These components, developed over an extensive period, are crucial for achieving the desired high-quality performance and significant penetration depth required for a portable GPR system [18], [19]. Vivaldi antennas, TEM horns, and bow-tie receiving antennas are generally utilized in business GPR systems. Super wideband (SWB) antennas have recently been designed for use in GPR. The planar monopole receiving antenna has received the most emphasis among the several UWB antenna developed since it is usually lightweight and inexpensive to construct. The test for antenna design for a GPR framework is to improve the data transfer capacity while preserving radiation capacity with a smaller antenna [20].

This paper introduces an antenna design appropriate to GPR applications. The UWB properties are achieved by incorporating a tree circular patch on the substrate with a partial ground plane and a semicircular slot on the ground plane. This configuration ensures a good impedance match in the UWB range circular patches offer design flexibility, provide the highest bandwidth in GHz, and exhibit desirable characteristics such as acceptable losses, enhanced gain, and favorable electric and magnetic field strength patterns for GPR applications [21]. The proposed design features a small and relatively compact geometry (54 mm × 36 mm) compared to other antennas operating within the same frequency range. The assessment of antenna performance progressed through successive stages, taking into account parameters such as s-parameters (S11), efficiency, gain, and directivity. These assessments were carried out utilizing computer simulation technology (CST) Microwave Studio 2018 for all simulations.

2. ANTENNA DESIGN

In this part, we introduce a monopole circular patch antenna featuring a defective ground plane. The antenna design is executed using CST. The geometry of the monopole antenna is illustrated in Figure 1. The comprehensive depiction of the suggested design is presented in Figure 1(a) showcases the front view, in Figure 1(b) is shown the back view for monopole antenna and Figure 1(c) displays the side view of the proposed design for this design, we utilize an FR-4 substrate with a dielectric constant of 4.3 and a thickness of 1.6 mm. The suggested feeding technique for the antenna is the coplanar waveguide (CPW) method [22]. One of the main reasons the CPW feeding process is widely preferred in designing planar antennas with a characteristic impedance of 50-ohm [23], is due to its simplicity in fabrication and impedance matching. The volume of this substrate is made to be 36 cm × 54 cm × 1.6 mm. In this Figure 1 [24].

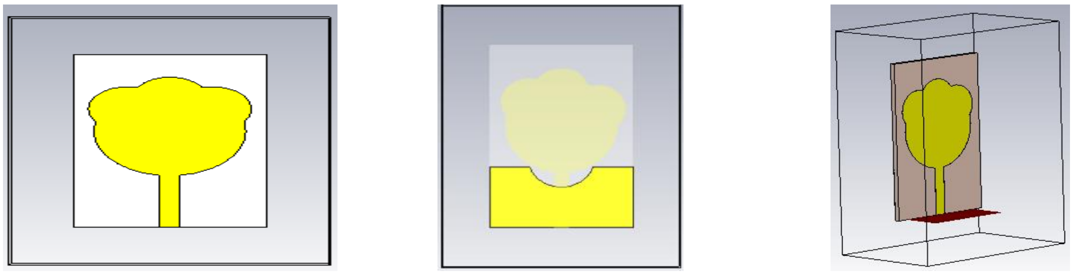
The other dimensions of antennas are provided in Tables 1 and 2. The size of the circular radius, R, is 14 mm. Using the circular correction equation, it can be calculated [25]. The addition of two ears in the circular increases bandwidth, particularly at lower frequencies [26].

$$r = \frac{F}{\left[1+\frac{2h}{\pi F \varepsilon_r}\left(\ln\left\{\frac{\pi F}{2h}\right\}+1.7726\right)\right]^{0.5}} \quad (1)$$

Where,

$$F = \frac{8.791 \times 10^9}{f_r \sqrt{\varepsilon_r}} \quad (2)$$

The overall improved dimensions of the suggested antenna are presented in Table 2 The other dimensions of antennas are given in Table 1.



(a) (b) (c)

Figure 1. The geometry of monopole antenna; (a) front part, (b) back part, and (c) side part

Table 1. Design specifications for monopole antenna

Parameters	Specifications
Frequency operating	(1-12 GHz)
Resonant frequency	5 GHz
Substrate material	(FR-4)
Material of patch and ground	Copper
Thickness of the patch and ground	0.035 mm
Permittivity relative	4.3

Table 2. The proposed antenna's dimensions

Antenna parameters	Symbol	Values
The radius of circular radiator	R	14 mm
Substrate width	Ws	36 mm
Substrate length	Ls	54 mm
Ground width	Wg	36 mm
Ground length	Lg	15 mm
Feed linewidth	G	3.5 mm
Substrate thickness	Hs	1.6 mm
Conductor height	Tc	0.035 mm

3. RESULTS AND DISCUSSION

Simulations were conducted utilizing the CST microwave studio package, which applies the finite integration technique for EM calculation, to assess the performance of the planned antenna. The parameters of the proposed microstrip antenna are discussed in this chapter, including the reflection coefficient S11, voltage standing wave ratio (VSWR), bandwidth, gain, and directivity, Time domain analysis and group delay.

3.1. Radiation efficiency

Figure 2 the remarkable efficiency of the sugessted design within its designated frequency bands. In the first band, the calculated efficiency reaches an impressive 95.4%, determined by evaluating the interplay between gain and directivity. Moving to the second band, the efficiency rises even further, achieving an impressive 97%. Similarly, the third band attains a commendable efficiency of 95.8%. Notably, these outcomes underscore the superiority of the second band, indicating an outstanding match of the antenna design at its center frequency when compared to the first and third bands.

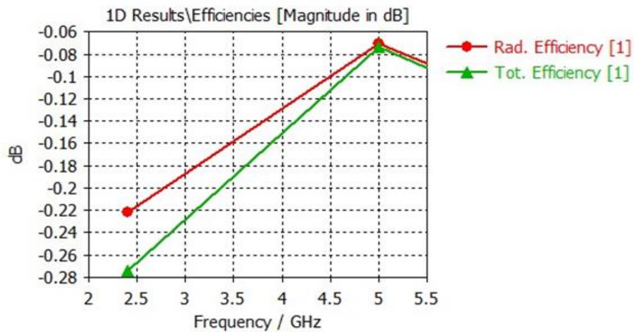


Figure 2. The radiation efficiency of the suggested antenna at 5 GHz

3.2. Return loss s-parameters of antenna monopole

During this phase, the simulated results of the UWB antenna were thoroughly examined to determine the optimal design characteristics for the monopole antenna under simulation Figure 3. The results displayed satisfactory resonances within the frequency range of 1 to 12 GHz, revealing distinct resonances occurring at 2.4 GHz, 5 GHz, and 9.3 GHz, each with corresponding reflection coefficient values of -19.4 dB, -33.03 dB, and -23.7 dB, respectively. Moreover, it was observed that the antenna exhibits operation over a vast bandwidth, spanning from 1.9 to 11.5 GHz. This notable attribute significantly enhances the antenna' suitability for deployment in diverse advanced communication systems that rely on broadband capabilities.

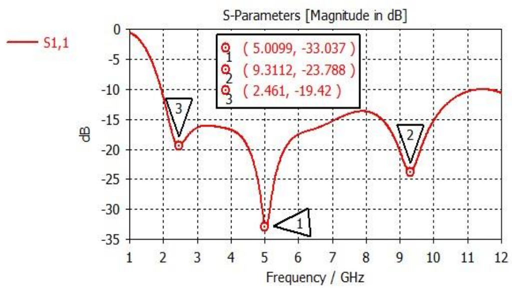


Figure 3. Return loss s-parameters of antenna monopole

3.3. Voltage standing wave ratio

In Figure 4, the VSWR curve of the proposed antenna is presented, showing acceptable values across the frequency range. Specifically, VSWR1 measures 1.23 at 2.4 GHz, VSWR2 records 1.047 at 5 GHz, and VSWR3 registers 1.138 at 9.3 GHz. These values signify a favorable match between the antenna and transmission line, as lower VSWR values indicate better matching. An optimal VSWR for an antenna would ideally be one, indicating an excellent matching condition. The antenna demonstrates exceptional performance since its VSWR values are significantly lower than the standard threshold of 2, signifying an outstanding matching capability.

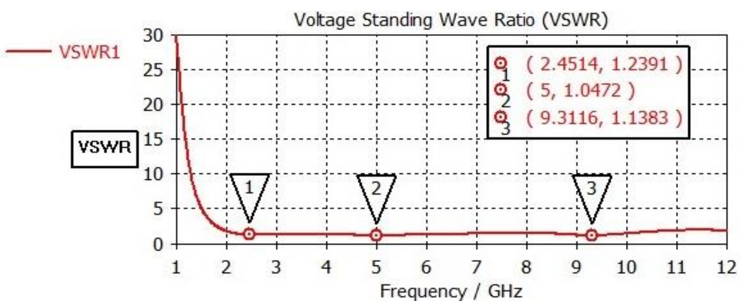


Figure 4. VSWR

3.4. Bandwidth

The radiation bandwidth is merely the bandwidth that is calculated from the S11 value, which is below -10 dB, from the space between the two spots, as illustrated in Figure 5 from, the antenna bandwidth was calculated by employing this [27].

$$Bandwidth = 2 \times \frac{f_2 - f_1}{f_1 + f_2} \times 100\% \tag{3}$$

The values of f1 and f2 are taken at-10 dB, and the bandwidth of the design is obtained at 146.687%**.** Simply said, our design antenna's bandwidth is between 1.9167 GHz and 11.568 GHz, equal to 9.6513 GHz.

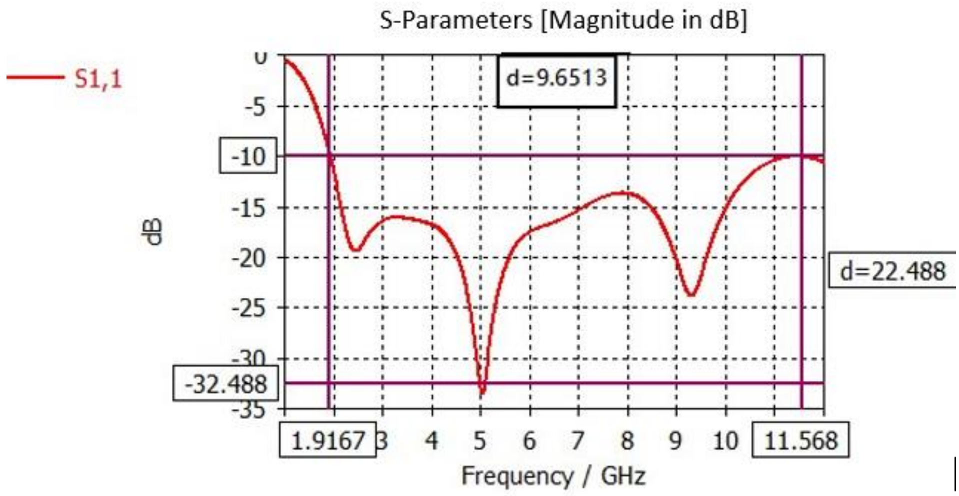
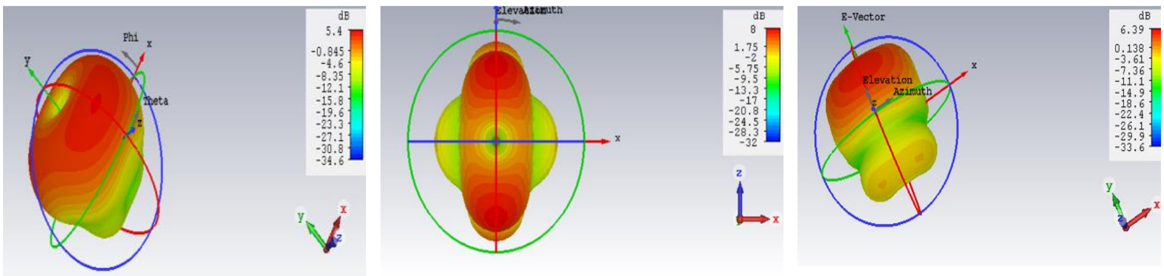


Figure 5. Bandwidth

3.5. Gain

Within the critical parameters, the radiation pattern bears significant importance as it dictates the precision of data transmission by the antenna. Furthermore, it validates the transmission power in the waveguide. While maintaining data integrity. The significance of gain increases with the ratio of the radiated field intensity of the antenna. Antenna gain also conveys information about the direction of peak radiation. In Figures 6(a) to (c), the 3D polar plots depict the gain of the microstrip antenna design at its triple resonant frequencies. At the UWB frequencies of 2.4 GHz, 5 GHz, and 9.3 GHz, the gains quantify 5.4 dB, 8 dB, and 6.39 dB, respectively. Remarkably, the antenna exhibits its maximum gain at 5 GHz, making it particularly advantageous for GPR applications. The higher gain at 5 GHz facilitates deeper signal penetration below the earth's surface, enhancing the antenna's capabilities for such applications. Figure 7 illustratesa gain vs frequency plot across various frequency bands, with the gain peaking of 8 dB during the resonant frequency at 5 GHz.



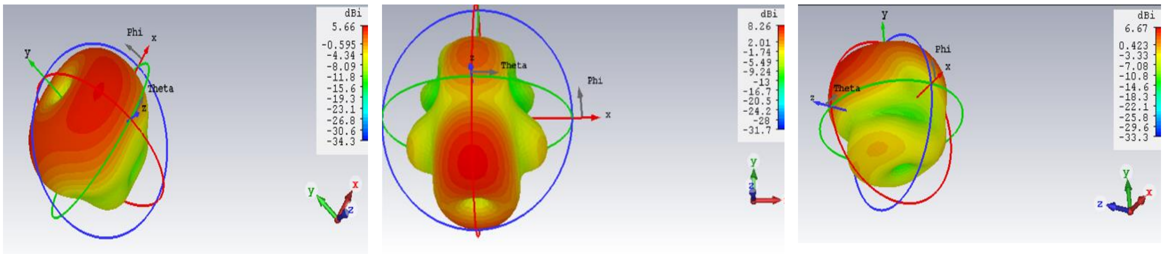
(a) (b) (c)

Figure 6. 3D radiation pattern gains of monopole antenna; (a) at 2.4GHz, (b) at 5GHz, and (c) at 9.3GHz

Figure 7. The curve of antenna gain

3.6. Directivity

In Figures 8(a) to (c) the simulation showcases the 3D far-field radiation pattern directivity of the proposed antenna design at three resonant frequencies. The directivity values at 2.4 GHz, 5 GHz, and 9.3 GHz are measured as 5.66 dBi, 8.2 dBi, and 6.67 dBi, respectively. Interestingly, the highest directivity is observed at 5 GHz, signifying a prominent directional focus at this operating frequency.



(a) (b) (c)

Figure 8. 3D radiation pattern directivity of monopole antenna; (a) at 2.4GHz, (b) at 5GHz, and (c) at 9.3GHz

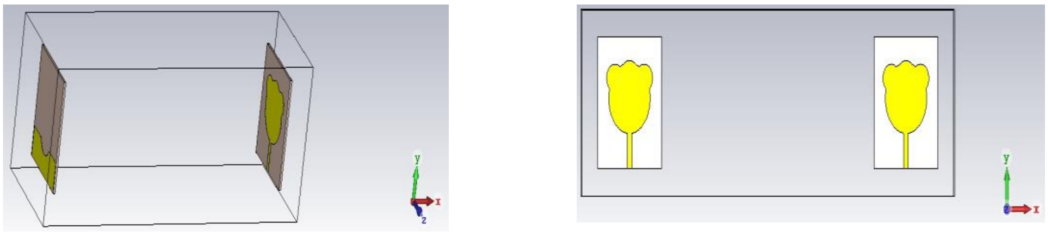
3.7. Time domain analysis and group delay

In order to fully understand antenna behavior during signal transmission and reception as it changes over time, it is crucial. Engineers can adapt the antenna's customizing design to fulfill specific needs in radar and wireless communication applications by analyzing the time domain of furthermore, potential challenges related to the antenna's performance, such as impedance mismatches, noise, or interference, can also be considered, can be found through time-domain analysis. This important information helps to improve the performance of the antenna, which enhances signal quality, boosts efficiency, and reduces interference investigating.

The antenna's time domain is a critical component of antenna engineering, providing insightful information about its behavior and enabling optimum design and performance for particular applications. In applications utilizing UWB antenna systems, time-domain analysis is essential. Two similar antennas are positioned at a distance sufficient to ensure the far-field scenario (20 cm in this case) during the analysis. One antenna function as the transmitter, while the other acts as the receiver. Using a short Gaussian pulse, the transmitter antenna is excited, and the received signals at the other end are carefully analyzed and evaluated. In the time domain analysis, to conduct this analysis, Figure 9. Two antenna configurations are employed Figure 9(a) face-to-face (F to F) and Figure 9(b) side-by-side (S to S) [28].

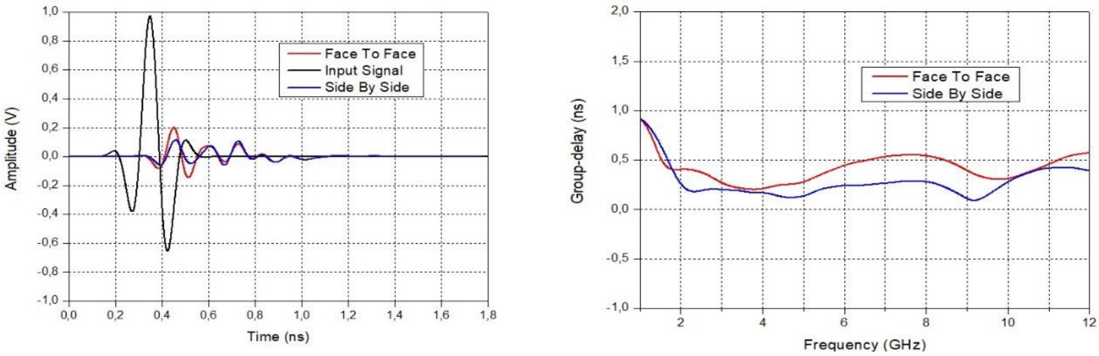
It is evident from Figure 10(a) Simulated is time domain analysis input signal and output, side by side and face to face. These findings show that the planned structure is capable of transmitting and receiving the UWB pulse signal without adding the dispersion effect. The present monopole antenna has very characteristic time-domain response parameters, indicating a favorable impulse response performance.

The simulation time domain was done in CST. It has been demonstrated that the suggested antenna has a good capability of successfully transmitting and receiving UWB signals with little distortion. Moreover, the time-domain UWB pulse signal from the electric probe demonstrates consistent performance, showing nearly identical received and transmitted pulse signals. Figure 10(b) show the group delay of the proposed antenna. Group delay plays a crucial role in UWB and other communication systems as it evaluates the distortion of transmitted pulses. Maintaining a consistent group delay across the entire frequency band is vital for achieving seamless pulse transmission. Remarkably, the proposed antenna demonstrates exceptional performance in this aspect, making it highly suitable for UWB and other high-bandwidth wireless communication applications.



(a) (b)

Figure 9. Design antenna structure; (a) face to face and (b) side by side



(a) (b)

Figure 10. Simulated; (a) simulated time domain analysis (input and output signal) and (b) the simulated group delay of the proposed antenna

The design proposed in this study was evaluated in relation to other UWB antennas discussed in the latest literature (listed in Table 3). The focus of this comparison was on key parameters crucial for determining the performance of the antenna under consideration, namely: antenna size, radiation efficiency, diversity gain. Values, radiation pattern directivity, bandwidth, date publication, and antenna application. Examining Table 3 It can be deduced that the proposed antenna has a efficiency and gain high compared to other designed antennas designed, making it suitable for GPR application. A summary of simulation results for the suggested antenna at resonant frequency 5 GHz, encompassing gain, directivity, bandwidth, S11, and VSWR, is presented in Table 4.

Table 3. The designed antenna comparative analysis with other UWB antennas

References	Date	Sizes (mm^3)	BW (GHz)	Gain (dB)	Eff (%)	Application
[29]	2017	17×19.5	4.87 (GHz) – 6.08 (GHz)	5.8	-	WLAN
[30]	2022	30×34×1.5	3.47 GHz – 12.11 GHz (110.91%)	6	90 %	GPR
[31]	2022	20×19×1.54	2.12 GHz to 9.8 GH	5.3	-	UWB
[32]	2022	62.5×63×1.6	3–12	8	87%	GPR
[33]	2022	245 mm×295×1.57	0.45–1.25	7.4	-	GPR
[34]	2022	36.23×41×1.524	3.05–10.96 GHz (113%)	5.6	90%	UWB
[35]	2022	0.7λ0×0.793λ0×0.035λ0	3.09–11.07	7.04	80%	GPR
[36]	2023	(0.36 λ × 0.26 λ)	2.70~11.06	3.88	88%	WIMAX
This work	2023	54×36×1.6	1.9167 GHz 11.568 GHz (146%)	8	97%	GPR

Table 4. Summary of monopole antenna performance

Parameter	Value
Fr (GHz)	5
Gain (dB)	8
Directivity (dBi)	8.26
Efficiency (%)	97
Bandwidth (GHz)	9.6
Return loss s-parameters	-33
VSWR	1.04
Bw (%)	146.687%.

4. CONCLUSION

The wideband antenna has been meticulously designed and simulated to cater to numerous ultra-wideband applications. The antenna takes on a circular shape resembling a tree and is fed by the CPW. CST microwave studio software is utilized for the simulation. The antenna is created on an (FR-4) substrate, the simulation results are highly promising, revealing the proposed antenna's outstanding performance, attributed to its miniature size and favorable characteristics. The suggested UWB antenna operates effectively across a wide frequency range, spanning from 1.9 to 11.5 GHz, allowing for an impressive bandwidth of 9.6 GHz and a frationary bandwidth of 146.68%. It delivers admirable performance, boasting a gain of 8 dB at the resonant frequency of 5 GHz, with a directivity of 8.2 dBi, the accompanying simulated UWB antenna demonstrates exceptional efficiency, reaching 97%. The design encompasses time-domain analysis and group delay exploration, further enhancing its performance. It also the suggested UWB antenna offers the advantage of a compact and straightforward design while achieving a high gain. The study's Simulation results for the antenna demonstrate its suitability for GPR applications.

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