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Miniaturization of Dipole Antenna for Low Frequency Ground Penetrating Radar

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Abstract—In this paper, a miniaturized dipole antenna operating at 100 MHz frequency for Ground Penetrating Radar (GPR) application is presented. A conventional dipole antenna length is half of its lowest operating frequency wavelength. As low frequency GPR system is vital for high depth penetration, the size of the antenna used reduces its easy handling and portability. Therefore, the technique of miniaturizing a dipole antenna by adding extra radiating arms is presented here. The antenna design and analysis is carried out using Advanced Design System (ADS) and FEKO simulation software, and a network analyser is used to validate the prototype antenna performance. The antenna of 66.5×22 cm dimension, fabricated on an FR4 substrate exhibits a frequency resonance at 104 MHz with 8 MHz of -10 dB bandwidth. The proposed antenna radiates in omnidirectional pattern and features 55% reduction in length compared to a conventional dipole antenna of same frequency operation.

1. INTRODUCTION

Ground Penetrating Radar (GPR) is a Non-Destructive Testing (NDT) equipment that find its application in archaeological and military fields that use electromagnetic waves to detect and identify buried objects and structures [1]. GPR is required to accurately resolve the depth, orientation, size and shape of buried objects and can be applied to find the positions of buried targets with an accuracy of about 3 cm at depths up to 50 m [2]. The operating frequency band of GPR ranges from 10 MHz to a few GHz, depending on the measurement and penetration depth requirements. A higher frequency GPR system emits narrower pulses in picosecond region, yielding a higher time and depth resolution. However, the depth penetration of high frequency signal is low as signal attenuation increases with frequency [3]. Whereas a low frequency system has a lower depth resolution but higher depth penetration as given in Table 1. Moreover, GPR can be best implemented in dry subsurface sand, gravel and pit, but the presence of moisture in the media can cause minor signal attenuation. As in [4] severe signal attenuation problems were found in slit, clay with moist saline conditions. Therefore, low frequency GPR systems are ideally suited for outdoor geotechnical, archaeological and environmental applications where moisture is a regular occurrence and high depth penetration is highly desired.

Antennas are essential components of GPR systems for transmission and reception of the electromagnetic waves. Efficient emitting and receiving of electromagnetic energy is ensured by high antenna gain as antennas with a high gain improve the signal-to-noise ratio [3]. As physical size and gain of antennas are determined by the operating frequency, small antennas offer compact system dimension. However, small antennas have a low gain at lower frequencies, and larger antennas are required to operate at lower frequencies.

Various types of antennas are used for GPR systems, but dipole and bow-tie antennas are most common as they are easy to fabricate on a variety of substrates because of planer surface structure [6]. Theoretically, the length of a dipole antenna is half of its lowest operating wavelength. Few samples of

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Table 1. Depth penetration and resolution for GPR systems with different frequencies [5].

	Antenna Frequency (MHz)			
	2000	**900**	**500**	**300**
Resolution, m	0.04–0.08	0.2	0.5	1.0
Depth, m	1.5–2	3–5	7–10	7–10
Blind Zone, m	0.06	0.1–0.2	0.25–0.5	0.5–1.0

Figure 1. Archaeological GPR scanning with 100 MHz unshielded and shielded dipole antenna [7].

dipole antennas for different frequencies given in Figure 1 show that, due to the low frequency operation, the antenna size is quite an issue since the antenna size determines the whole system size and portability.

The half-wavelength size of 1.5 m at 100 MHz is considerably large; therefore, it is very desirable to miniaturize the dipole antenna length in order to scale down the whole system size.

In this paper, a technique is applied to the conventional 100 MHz dipole antenna to minimize its length by approximately 55%. Reduction in length is achieved by introducing multiple sets of radiating arm at a certain distance from the primary dipole arms. Agilent Advance Design System (ADS) and FEKO software platform are used in order to examine the antenna resonance and radiation characteristics. The paper consists of the following sections: Section 2 gives an overview of the existing antenna miniaturization techniques. Section 3 describes the proposed miniaturized dipole antenna design and design parameters. The simulation results of those parameters on antenna bandwidth, resonance frequency and directivity gain are presented in Section 4. Section 5 presents the fabrication process of the antenna and experimental setup for antenna performance verification, and finally, the paper concludes with a brief summary and recommendation in Section 6.

2. ANTENNA MINIATURIZATION TECHNIQUES

Several compact design antennas have been proposed in the literature for Ultra Wide-Band (UWB), telemetry, biomedical applications. Reference [8] proposes a miniaturized bow tie antenna for wideband applications. The length of a bow-tie antenna is generally $\lambda/2$ of the lowest operating frequency. The length of the bow-tie could be shortened by connecting the right and left arms of the bow-tie with thin conductor called folded elements as in Figure 2. Folded elements bring the lowest frequency for VSWR ≤ 2 from 540 MHz to 300 MHz and a reduction of 31% in size. However, the folded bow-tie antenna (FBTA) suffers from degradation of VSWR characteristics at 920 MHz 1860 MHz. The authors suggest adding additional elements (AE) between the folded element and the bow-tie element to improve the VSWR characteristics. However, final results show improvements in VSWR values at 920 MHz and 1860 MHz, but the lowest operating frequency still stays at 300 MHz and no further reduction in size compared to original folded bow-tie antenna without additional elements. The results can be found in Figure 2 below.

In [9], a high frequency bandwidth antenna for low frequency operation is proposed (Figure 3). The antenna dimension is 10 cm $\times$ 10 cm $\times$ 15 cm, and the resonant frequency is 40 MHz. Even though the

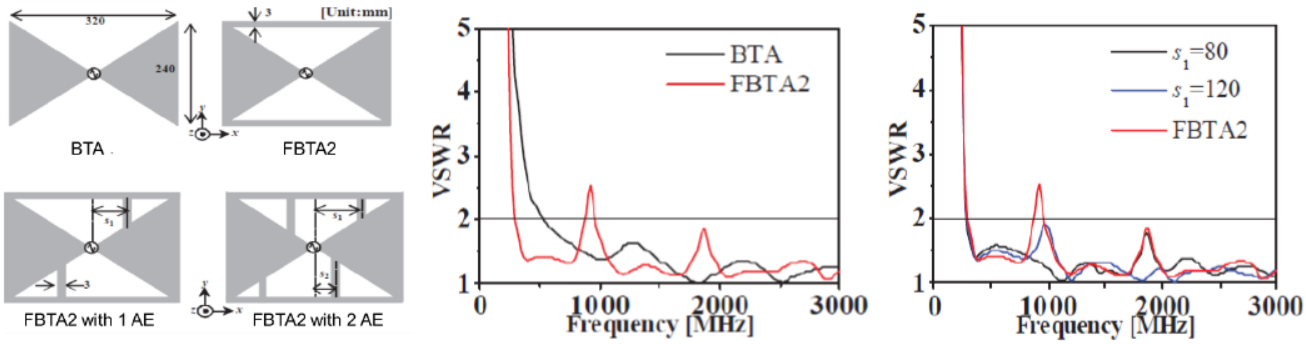

Figure 2. Bow-tie antenna with additional elements and their corresponding VSWR as proposed in [6].

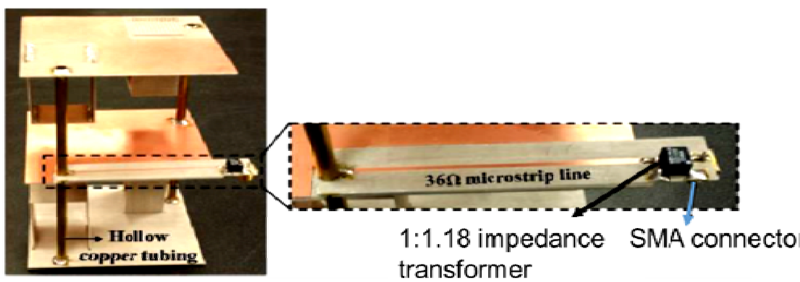

Figure 3. The fabricated antenna in [7].

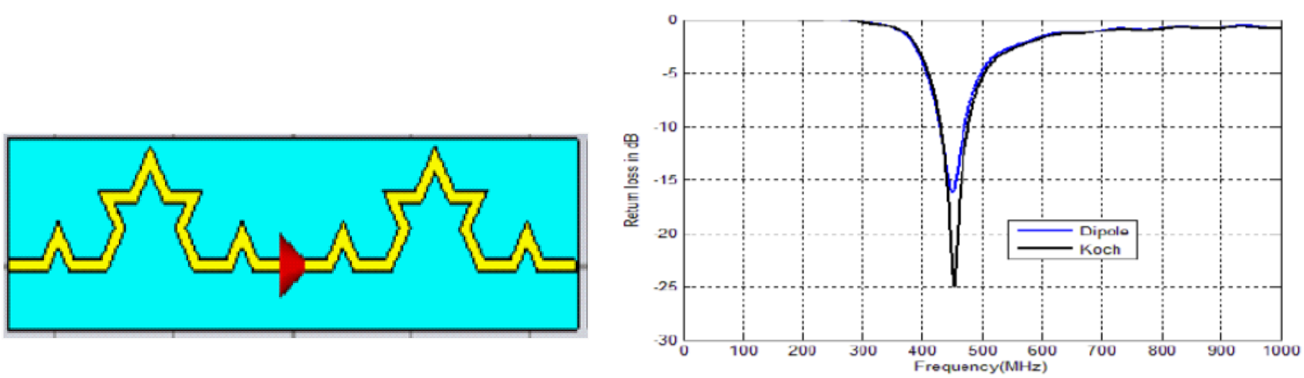

Figure 4. Layout of a fractal dipole antenna with its reflection coefficient values compared to a conventional dipole antenna [10].

resonant frequency of the antenna is considerably low, the shape of the antenna makes it impractical to implement in GPR applications.

In [10], the authors described a miniaturized dipole antenna for wearable devices. They used Koch fractal technique to reduce the antenna size and recorded a reduction of 108 mm in length for a 450 MHz fractal dipole compared to a conventional dipole. Jeans fabric was used as the material with permittivity of 1.6 to make it applicable to wearable applications. Moreover, the Koch antenna provided better reflection coefficient value of −26 dB compared to −16 dB for a dipole of the same frequency range as given in Figure 4.

Miniaturization technique for a strip folded dipole antenna (SFDA) by using two vertical linear conductors as shown in Figure 5 is described in [11]. A reduction of 26% is claimed for the SFDA antenna compared to a conventional folded dipole of 700 MHz resonant frequency. The antenna was built on material with permittivity of 1. However, VSWR characteristics graph shows that for antennas

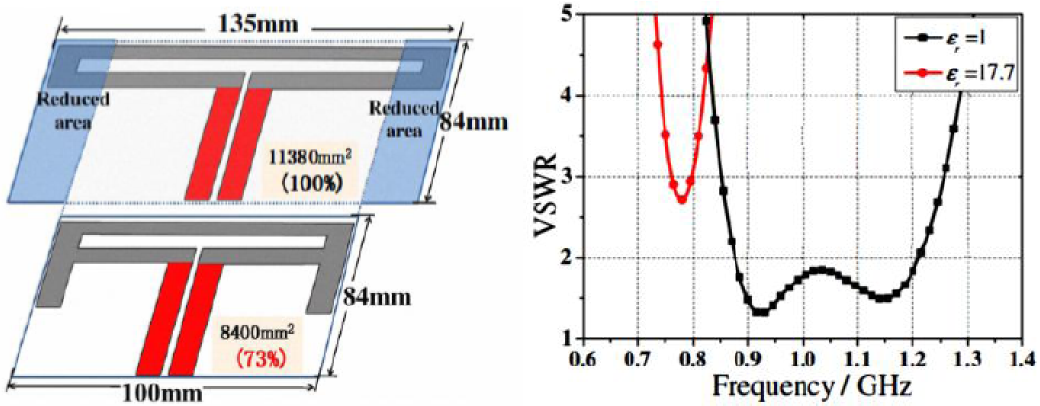

Figure 5. Proposed SFDA antenna and its VSWR behaviour [11].

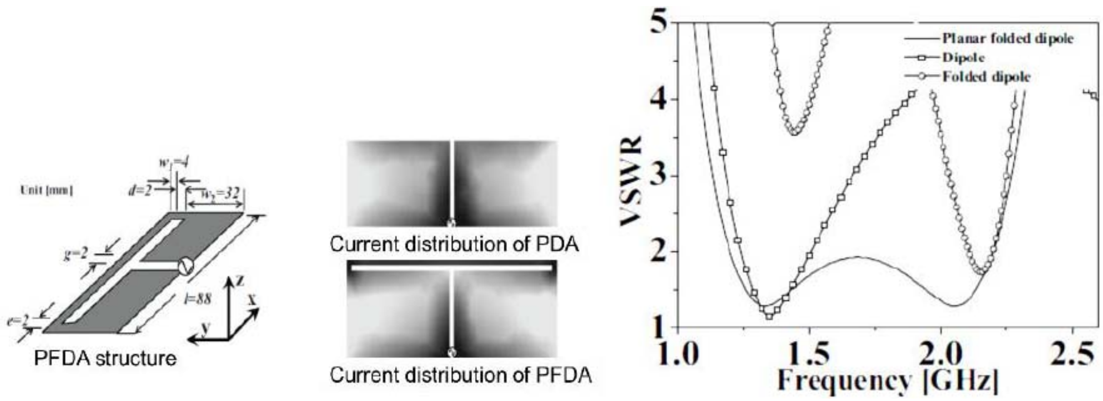

Figure 6. PFDA antenna and VSWR characteristics [13].

built on materials with higher permittivity such as 17.1, the resonant frequency can be lowered, but VSWR values worsen as a result.

Likewise, in [12] bow-tie antenna with folded elements of various inclinations have been studied. However, they offer no considerable improvements compared to conventional folder bow-tie antenna of the same resonant frequency. A planer folded dipole antenna with wide ground plane has been proposed in [13]. The current distribution of the folded elements in Figure 6 shows that by loading the folded element of the antenna, the current at the upper edges increases strongly. It means that impedance characteristics of the antenna could be controlled by the current pathway at the edges of folded structure. However, VSWR results show that widening ground plane and folded arms do increase the overall bandwidth of the antenna, but the resonant frequency stays at 1.35 GHz which is equal to a conventional dipole.

More examples of miniaturizing dipole and bow-tie antennas can be found in [14–17], etc. But most of the designs discuss antenna miniaturization techniques for high frequency UWB and RFID applications, hence, it is ideal to focus on miniaturization techniques of low frequency antennas.

3. MINIATURIZED DIPOLE ANTENNA DESIGN

In impulse GPR applications, short pulses, corresponding to wide bandwidth are used. An accurate time-of-flight measurement is available at the receiving side because of the pulse's high time resolution. In this paper, pulses with 10 ns duration are used as transmitting signals, corresponding to a 100 MHz centre frequency operation. Figure 7 shows conventional dipole antenna characteristics for the 100 MHz resonance frequency. The material is FR4 with a dielectric constant of 4.4. Total length of the dipole is

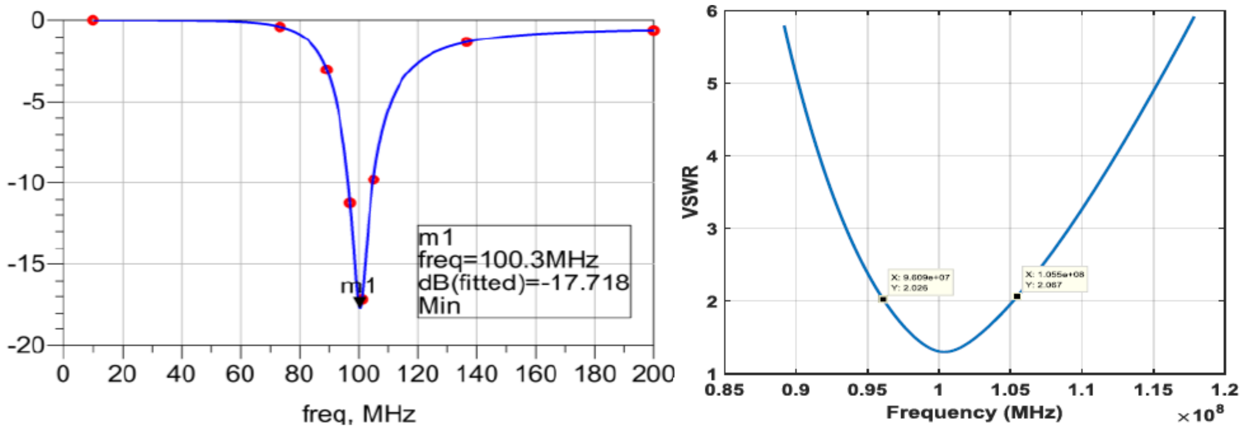

Figure 7. Reflection coefficient and VSWR characteristics of dipole antenna.

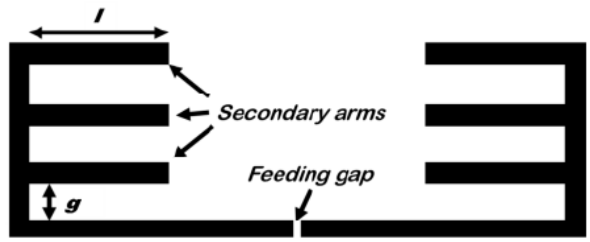

Figure 8. Configuration of the proposed miniaturised dipole antenna for 100 MHz centre frequency.

1.5 m, and width is 15 mm. The reflection coefficient (S_{11}) and VSWR graphs show that the bandwidth of the antenna is 8 MHz for VSWR ≤ 2 values.

The configuration of the proposed symmetric dipole antenna with multiple radiating arms operating at 100 MHz is shown in Figure 8. The antenna is fed in the centre of its structure by 50 Ω coaxial cable. The radiating arms consist of 17 μm thick and 15 mm width copper layer. The whole radiating structure is set on an FR4 dielectric substrate of 1.6 mm thick.

The distance between the primary dipole arm and extra radiating arm is G, and length of the secondary arms is L. In this paper, the antenna characteristics are investigated as the parameters are changed to establish an optimum value for the dipole length reduction.

4. SIMULATION RESULTS

Every aspect of antenna dimension has an effect on the operating bandwidth and centre frequency. To understand the design criteria and their effect on overall antenna performance, antenna design optimization was carried out by Moment of Method (MoM) based ADS and Finite Different Time Domain (FDTD) based FEKO electromagnetic simulator to better comparison study. To establish the optimum antenna design parameters, parametric studies of the distance between the primary dipole arm and extra radiating arms, g, and length of extra arms, l, were carried out.

4.1. Parametric Studies

Firstly, the effects of change in antenna arm's length, l, from 300 mm to 15 mm are investigated. The antenna feed gap is kept to 2 mm for FR4 dielectric material. Figure 9 shows the reflection characteristics of the antenna for various lengths. It is seen that long extra radiating arm length of 300 mm provides the lowest resonance frequency operation of 137 MHz, but reflection coefficient, S_{11} value, is below -10 dB and is not acceptable for good performance. As the extra arm length is reduced to 250 mm, the

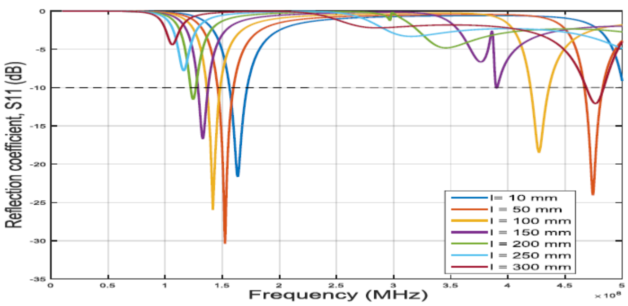

Figure 9. Reflection coefficient values for different radiating arm lengths, l.

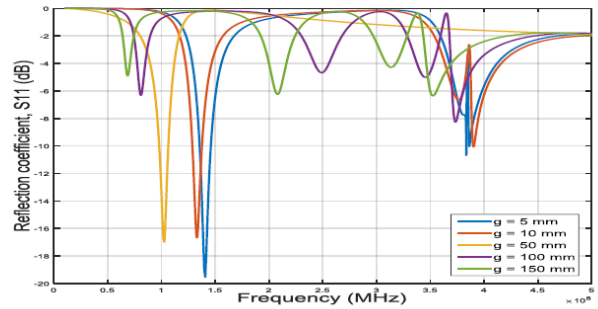

Figure 10. Reflection coefficient values for different gaps between the dipole arm and extra radiating arms.

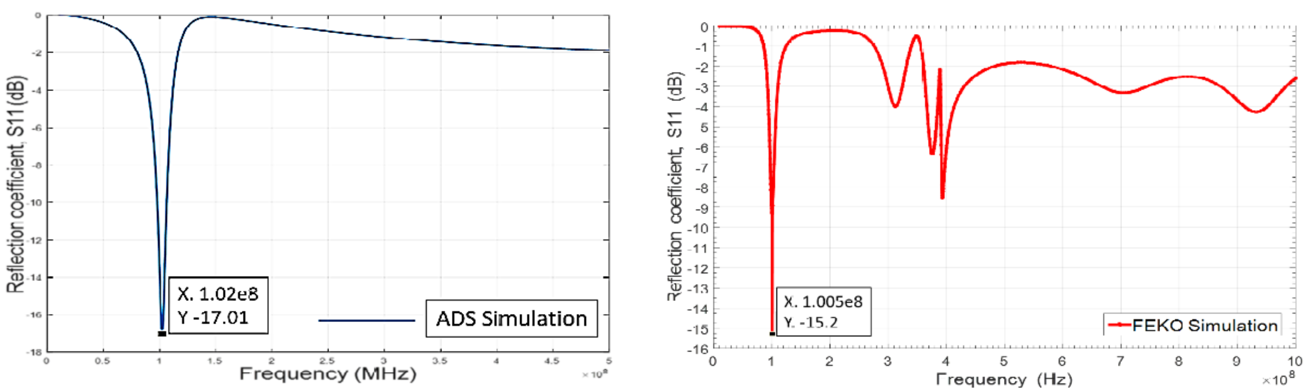

Figure 11. Result comparison of two simulation methods.

centre frequency increases to 147 MHz, but it shows better S_{11} value of -15 dB. Further reduction of l to 15 mm results in antenna operating at 183.5 MHz centre frequency with -18.6 dB of the reflection coefficient. Therefore, reduction in extra arm's length causes the resonance frequency to go higher and reflection coefficient value to go down. For an acceptable performance of the antenna, length of extra radiating arms is set to the optimum level of 150 mm which represents 156.7 MHz of centre frequency with -24 dB of reflection coefficient value.

Next, the effect of the gap between the dipole arm and the extra radiating arms, g, is examined. The additional arm's length is set to 150 mm, and g values are varied from 10 mm to 300 mm. According to reflection coefficient graph given in Figure 10, at g value of 10 mm, centre frequency of 164 MHz and S_{11} value of -35 dB can be achieved. However, there is a presence of another resonance at 385 MHz region. As the gap is increased to 50, 100 and 150 mm, centre frequency shifts to lower frequency region of 141, 126 and 115 MHz, respectively. The same pattern is observed at higher gap. However, to keep the total area of the antenna to an acceptable minimum level, a value of 50 mm is chosen optimum where a good S_{11} value of -17 dB is observed at 102 MHz centre frequency.

A comparison study of two simulation suites — ADS and FEKO simulation software is carried out by using selected optimized value of $g = 50$ mm and $l = 150$ mm. This can help to identify any discrepancies in results between two numerical methods. According to the results in Figure 11, ADS simulations fail to identify small but significant resonance between 305.6 MHz and 400.2 MHz which is clearly seen in FEKO simulation result. However, resonance at the lower frequency band is in good match between the two methods which is of most interest for this paper. FEKO shows -15.2 dB of reflection coefficient at 100.5 MHz centre frequency compared to -17.01 dB at 102.8 MHz obtained from ADS.

Moreover, the effect of multiple sets of arm on antenna performance is carried out for $g = 50$ mm and $l = 150$ mm using FEKO. Only one set of arm delivers -22.38 dB of reflection coefficient at 141.8 MHz,

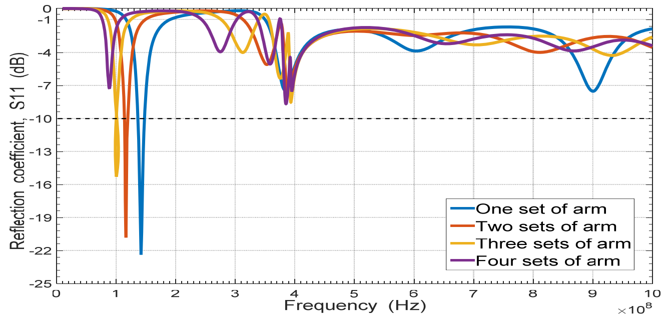

Figure 12. Reflection coefficient values for antennas with multiple sets of radiating arm.

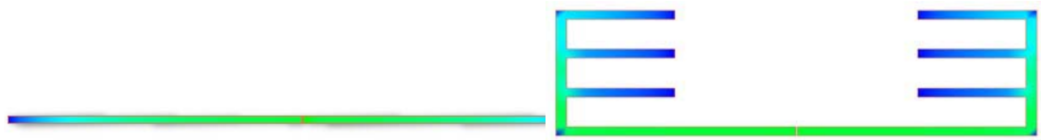

Figure 13. Distributed surface current along the proposed antenna structure compared to a conventional dipole antenna at 100 MHz centre frequency.

and increasing the number of sets reduces the resonant frequency to lower band as shown in Figure 12. While three sets of arms are implemented, −15.3 dB of reflection coefficient can be achieved at 100.5 MHz centre frequency. However, four and more sets of arms cannot deliver satisfying S_{11} value, and a result antenna with three sets of extra radiating arms has been selected as optimized design and prototyping.

Figure 13 shows the simulated surface current of the proposed antenna with $l = 150$ mm and $g = 50$ mm at 100 MHz centre frequency. It is observed that the extra arms offer significant current distribution along the side bars and extra radiating arms compared to a conventional dipole antenna.

4.2. Radiation Performance

The radiation pattern in the E-plane and H-plane of the antenna in Figure 14 demonstrates that the proposed antenna has a typical dipole-like characteristics at the resonant frequency band. The patterns are nearly omnidirectional with an efficiency value of 71%. In this condition, the directivity gain is 2.06 dBi compared to 2.15 dBi for more conventional dipoles. These values are considered as good in the literature.

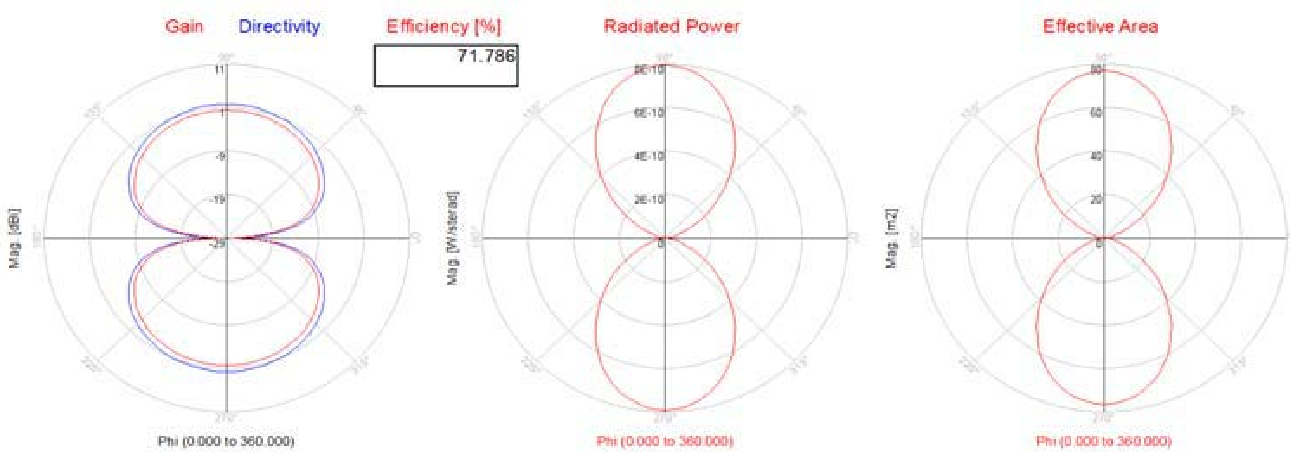

Figure 14. Radiation pattern of the proposed antenna at 102 MHz centre frequency.

5. EXPERIMENTAL VALIDATION

To validate the simulation results and antenna performance, a prototype antenna with extra radiating arms was fabricated using a 1.6 mm thick FR4 dielectric substrate ($\varepsilon_r = 4.4$, $\tan d = 0.02$). The antenna arms were printed on the substrate using 17 µm thick copper strips. The whole length of the antenna was 665 mm, and width was 220 mm. Figure 15 shows the fabricated prototype antenna with all the dimensions and fed by a 50 Ω BNC connector.

To measure the antenna performance, an Agilent 4395A network analyser was used. This particular analyser can provide 10 Hz–500 MHz sweep frequency capability. Figure 15 shows the reflection coefficient graph of the antenna under test at 75–125 MHz frequency sweep with centre frequency at 104 MHz. However, the used network analyser does not support digital screen capture facility. Therefore, the test was carried out for the full 500 MHz frequency sweep, and the raw data were saved as comma-separated values (csv) format and regenerated using Matlab which is shown in Figure 16 along with the radiation pattern graph.

Experiments show that the proposed antenna resonates at centre frequency of 104 MHz compared to 100.5 MHz obtained by FEKO simulation. The measured reflection coefficient value is −15.88 dB, which is fairly in line with the value of −15.2 dB obtained during simulation. Measured radiation pattern graph shows an expected omnidirectional radiation at 1.52 dBi of directional gain with 68% efficiency compared to 2.01 dBi resulted in simulation. Also, judging from the Figure 17, the fabricated antenna delivers a bandwidth of 8 MHz where VSWR ≤ 2 compared to 9.5 MHz bandwidth obtained from simulation. This is a reduction of only 2 MHz compared to a conventional dipole antenna. A comparison of the proposed antenna with a conventional dipole and other miniaturization techniques found in the literature is presented in Table 2.

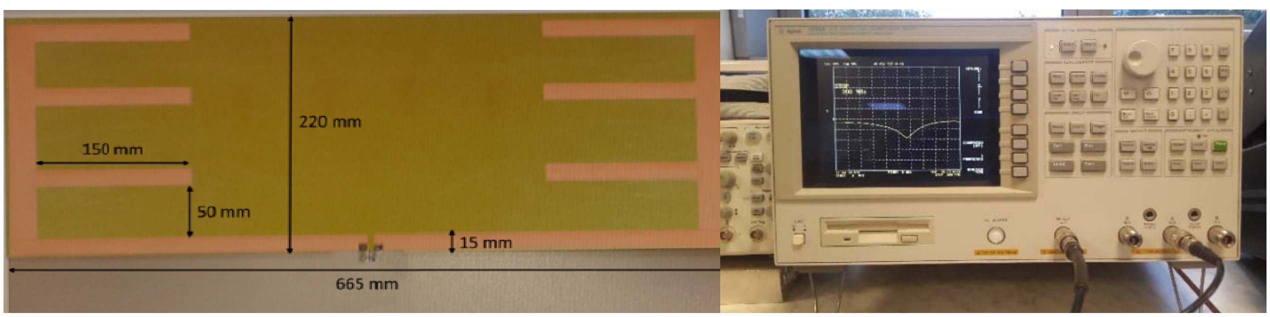

Figure 15. Prototype antenna and antenna testing using Agilent 4395A network analyser.

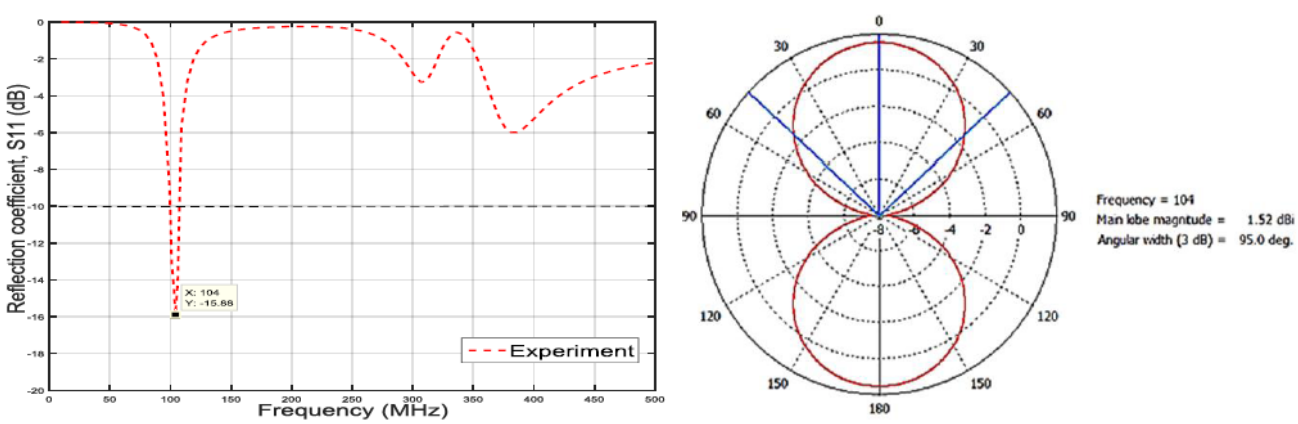

Figure 16. Measured S_{11} of the proposed antenna along with the radiation pattern.

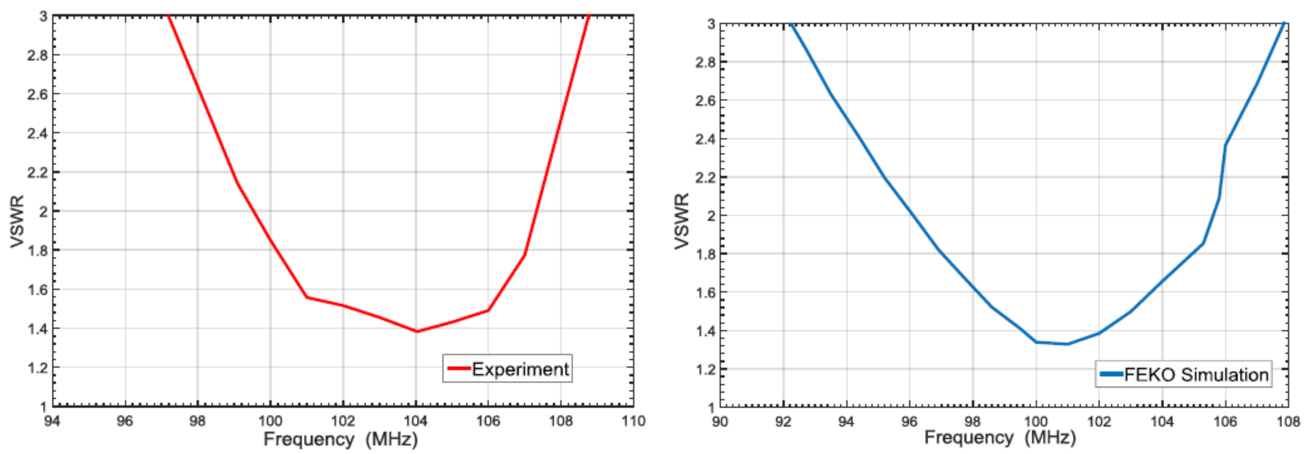

Figure 17. VSWR characteristic comparison of measured and simulated values.

Table 2. Comparison summary.

Antenna type	Centre frequency (MHz)	Bandwidth (MHz)	Antenna size (cm)	Efficiency	Remark
Dipole	100	10	150 × 1	-	-
This work	100	8	66.5 × 22	68%	55% reduction in length
[6]	1500	2700	32 × 240	68%	31% reduction in length
[18]	500	600	23 × 10	75%	46% reduction in length

6. CONCLUSION

In this paper, techniques of adding extra radiating arms to the conventional dipole antenna in order to miniaturize its length have been presented. Parametric studies of the design parameters show that adding three extra radiating arms to each primary dipole arm can help the antenna to resonate at a lower frequency. Experiments show that antenna with 150 mm long extra arms, placed at 50 mm gap between themselves can operate at 104 MHz frequency. Simulated and experimental results are in good agreement. There were some contrast in simulation results at frequency region over 300 MHz between ADS and FEKO simulation suite. However, experimental results confirm the validity of results from FEKO with close match. Nonetheless, a conventional dipole antenna operating at the same frequency level requires a dipole length of 150 cm, whereas, antenna proposed in this paper can achieve the same resonance level at 66.5 cm length. Therefore, a reduction of 55% can be achieved by the techniques presented in this paper. Moreover, the operating bandwidth of the antenna is 99–107 MHz which is in line with a dipole antenna. Although there is an increase of 20 cm in terms of width, however, by implementing this technique the length of a dipole could be halved. This feature will especially appeal to low frequency GPR applications where used antennas are relatively long in dimension. The proposed antenna can be printed on an FR4 substrate which offers quick and inexpensive fabrication process. All in all, the proposed miniaturized dipole antenna can offer lightweight, simple and great portability for low frequency GPR systems. Future works of this research involve incorporating GPR pulse generator with the fabricated antenna for the detection of buried objects in various media.

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