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REGULAR ARTICLE

Design of a High Efficiency Monopole Antenna Array for GPR Application

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Over the past few years, remote sensing, radar, and imaging applications have all utilized Ultra-Wideband (UWB) technology. This work provides a parametric study on monopole antennas for Ground Penetrating Radar (GPR) systems. The intended antenna has an incomplete ground plane and two circular radiating patches, known for their compact design, notable high gain, and high efficiency. Furthermore, it provides an advantageous bandwidth. The suggested antenna design show-cases its appropriateness for lower frequencies, attributed to its compact dimensions. The proposed design for antenna characteristics in ground-penetrating radar systems emphasizes a requirement for large bandwidth and high gain to achieve optimal image resolution. This article delineates the design methodology and simulation of a monopole antenna developed specifically for applications in Ground Penetrating Radar (GPR). In this design, we utilize the Roger RT Duroid 5880 substrate, characterized by a relative permittivity of 2.2, a height (h) of 1.575 mm, and a loss tangent of 0.0009. The dimensions of the substrate are miniaturized to 42 mm × 40 mm × 1.575 mm. The antenna results are obtained using CST computer simulation technology software to derive the results for this antenna, and the simulations yielded favorable outcomes. The proposed array antenna demonstrates commendable characteristics at an operating frequency of 5.6 GHz, with a reflection coefficient (S11) of – 46 dB, a bandwidth of 1.6 GHz, a gain of 8.302 dB, VSWR of 1.009, and an efficiency of 99.9 %. The obtained results are highly competitive, suggesting that the proposed antenna is well-positioned to fulfill the requirements associated with Ground Penetrating Radar (GPR) applications.

Keywords: Antenna, Gain, Directivity, Efficiency, CST, GPR.

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1. INTRODUCTION

Ground Penetrating Radar (GPR) systems showcase their efficiency as non-destructive tools by utilizing the transmission and reception of electromagnetic waves. They are capable of detecting targets beneath a variety of surfaces, such as ground, water, ice, cement, and other propagation mediums with different permittivites. The Ground Penetrating Radar (GPR) system consists of two antennas, with one functioning as the transmitting antenna responsible for emitting electromagnetic waves. Meanwhile, the other antenna serves as the receiving component, capable of operating independently or concurrently with the transmitting antenna [2] Transmitting antennas generate electromagnetic waves, directing them towards objects concealed in the ground or behind walls [3]. The speed of the wave is linked to the dielectric constant of the medium. Upon encountering an object, a portion of the wave gets reflected by the object, and the receiving antenna captures this reflected segment. Antenna are crucial component in GPR systems, demanding designs that fulfill specific system criteria. These capabilities include the need to operate at low frequencies for enhanced penetration depth and the capability to function at high frequencies to achieve superior resolution in detecting small targets. The imaging quality of the GPR system is directly influenced by the performance of the antenna. Therefore, the design and advancement of UWB antennas are crucial for enhancing the overall performance of GPR systems. [4-6].

Achieving high-resolution imaging is feasible with Ultra-wideband (UWB) technology, and its implementation for antennas operating above 1 GHz frequencies is relatively uncomplicated [7]. Recognizing that lossy subsurface mediums contribute to the rapid attenuation of electromagnetic waves; antenna design needs to prioritize a low operating frequency for sufficient penetration depth. Nevertheless, achieving a balance between low operating frequency, high gain, and wide bandwidth has proven to be a substantial challenge in the design of GPR antennas [8]. TEM horn antennas, Vivaldi antennas, bow-tie antennas, and monopole antennas are commonly regarded as appropriate for GPR systems [9]. Among these choices, monopole antennas are especially favored for their simple structure, low profile, and linear phase characteristics within the operating frequency range [10]. Nevertheless, substantial research efforts have been devoted to improving the broadband characteristics and optimizing the gain of printed monopole antennas [11]. The significance of the GPR antenna's gain underscores the focus of our work on improving the characteristics of the monopole antenna [12]. Monopole antennas

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are the preferred option for GPR applications. This preference can be ascribed to their advantageous features, such as high gain, relatively broad bandwidth, and a straightforward manufacturing process [13-14]. Hence, we have chosen to concentrate on enhancing the characteristics of the monopole antenna in our work. Our research endeavors to progress a monopole antenna specifically designed for GPR applications. The antenna consists of three elements: the truncated ground, the substrate, and two circular patches. It is fed through a coplanar waveguide (CPW) connected to it. This antenna is extensively used, particularly in Ground Penetrating Radar, and finds widespread applications across various fields.

2. METHODOLOGY

The first step in the antenna design process involves using the provided formula to calculate the dimensions of the antenna. These computations establish both the length and width of the antenna. The design and simulation of microstrip patch antennas are conducted with a specific emphasis on meeting a frequency requirement of 5.6 GHz. The circular monopole patch antennas are designed using the CST software program [15]. the antennas are designed using ROGERS RT5880 substrate, characterized by a thickness of 0.035 mm the development process involves employing a substrate with a relative permittivity (ε_r) of 2.2, a loss tangent (tanδ) of 0.0009, and a substrate height (h) of 1.575 mm Fig. 1, [16] illustrate the design, showcasing the use of an internal microstrip line to feed both patches [17]. The two patches are organized in a linear array configuration with an inter-element spacing of 0.5λ. The 1×2-array circular monopole antenna is fed by a 50 Ω line using the corporate feeding technique, following the Wilkinson dividing rule for optimizing high gain [18]. This configuration utilizes copper annular in the ground plane along with circular patches. When designing a circular microstrip antenna, several parameters need consideration, including the radius of the circular patch, the thickness of both the patch and ground, and the dimensions of the substrate in terms of width, length of ground, substrate, and the radius of the circular patch. These values can be calculated using the provided equations. [19, 20].

$$W = \frac{c}{2f_r\sqrt{\frac{(\varepsilon_r+1)}{2}}} \tag{1}$$

$$L = \frac{c}{2f\sqrt{\varepsilon_{reff}}} - 2\Delta l \tag{2}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{w}\right]^{-\frac{1}{2}} \tag{3}$$

$$\frac{\Delta l}{h} = 0.412 \times \frac{(\varepsilon_{reff+0.3})(\frac{W}{h}+0.264)}{(\varepsilon_{reff}+0.258)(\frac{W}{h}+0.8)} \tag{4}$$

The W represents the width, L is the actual length, L_{eff} is the effective length, ε_{reff} is the effective dielectric constant and ΔL is the Fringe length where the radius of a circular patch is calculated using the following equation [20].

$$r = \frac{F}{\left[1+\frac{2h}{\pi F\varepsilon_r}\left(\ln\left\{\frac{\pi F}{2h}\right\}+1.7726\right)\right]^{0.5}} \tag{5}$$

Where

$$F = \frac{8.791\times10^9}{f_r\sqrt{\varepsilon_r}} \tag{6}$$

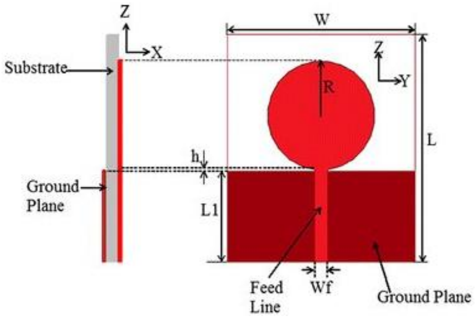


Fig. 1 – Geometry of microstrip p monopole antenna

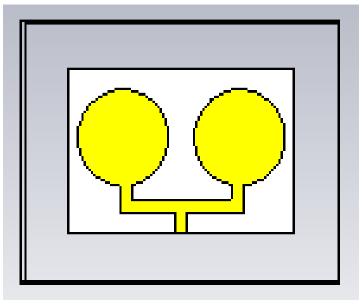


Fig. 2 – Design of a monopole antenna array in CST

Table 1 – Dimensions of the antenna design

Parameters	Values (mm)
W	42
L	40
W_F	2.7
L_f	12
R	8
W_G	42
L_G	12
t	0.035
h	1.575

3. RESULTS AND DISCUSSION

The circular microstrip patch antenna presented here has been meticulously crafted and simulated using CST simulation software the approach in this study has focused on striking a balance between reducing the antenna's size while enhancing its performance. we diligently pursued this iterative procedure until attaining outcomes that met our satisfaction. assessment of the antenna's effectiveness involves a comprehensive evaluation of pivotal measures, encompassing return loss, bandwidth, (VSWR), impedance, gain, directivity, and efficiency.

3.1 S1.1 Parameter and Bandwidth

The return loss, or S-parameter, assesses the extent of electromagnetic power reflection from a circular microstrip patch antenna. Functioning as a reflection coeffi-cient, it signifies the effectiveness of impedance matching between the source (transmitting end) and the measured load (receiving end). Attaining a return loss sur-passing – 10 dB is essential for establishing an effective radiation mode. The accom-panying graph provides a visual representation of the return loss in relation to the operating frequency of the antenna.in this visual representation, the X-axis denotes different frequency values under investigation, while the Y-axis indicates the corresponding return loss rates. The illustration emphasizes three main focal points, each represented by triangles. The initial and second triangles on the chart delineate the boundaries of the antenna's operational frequency. These triangles elucidate the examined frequency range based on specified opera-tional criteria. This triangular representation offers a distinct visual insight into the operational frequency range suitable for the antenna, ensuring optimal performanc. The third triangle delineates the frequencies encompassed within the antenna's band-width. Within this triangular region, a frequency range exists where the antenna demonstrates commendable performance, efficiently transmitting or receiving signals. Thus, this graph provides a comprehensive perspective on the operational frequency char-acteristics of the antenna, facilitating informed selection and under-standing of antenna performance across diverse frequency scenarios. In Figure 3, depicting the $S1.1$ parameter, the antenna functions with a return loss of – 46.48 dB at 5.68 GHz. In this chart, the antenna's bandwidth is computed as 1.6 GHz at – 10 dB, maing it well-suited for applications in GPR.

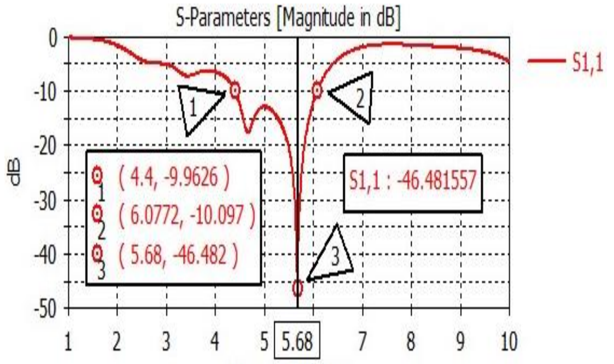


Fig. 3 – Return loss vs frequency of the antenna

3.2 VSWR

The VSWR serves as a metric for assessing the level of mismatch between an antenna and its connecting feed line. A VSWR value within the range of 1 to 2 is considered satisfactory, but the optimal condition is achieved when the VSWR value is precisely 1. Most antenna applications are considered feasible when VSWR values remain below 2. The antenna exhibits a condition referred to as a "good match". Conversely, when an antenna is characterized as "poorly matched", it generally implies that the VSWR value surpasses 2 at the intended frequency. in Figure 4, the graph provides an overview of the standing wave ratio (VSWR) values. The x-axis spans a frequency range from 1 GHz to 10 GHz, while the y-axis denotes the associated VSWR values Significantly, at a frequency at 5.6 GHz, the VSWR registers of 1.009, signifying a highly favorable impedance matching rate, particularly conducive to the requirements of wireless technology

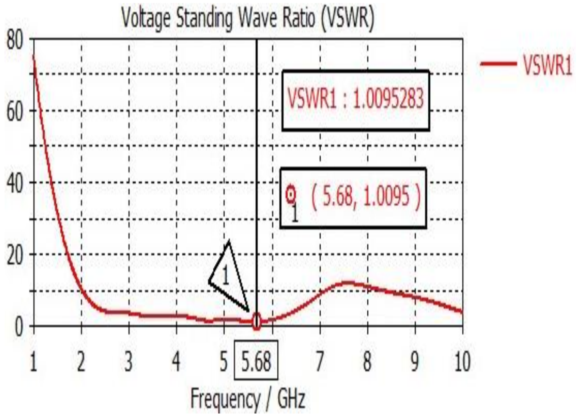


Fig. 4 – VSWR

3.3 Impedance

In Figure 5 the showcased reference value for antenna impedance exhibits a peak of 46.5 ohms at a frequency of 5.6 GHz. This parameter plays a pivotal role in both the design and assessment of performance in wireless communication systems. In this context, impedance refers to the resistance that the signal encounters while traversing through the antenna system. This factor holds significant importance as it influences the overall performance of an antenna, impacting its capacity to effectively transmit and receive signals within a specified frequency range. Comprehending and fine-tuning impedance is crucial for establishing seamless communication and guaranteeing that antennas align with the specified operational criteria of wireless systems.

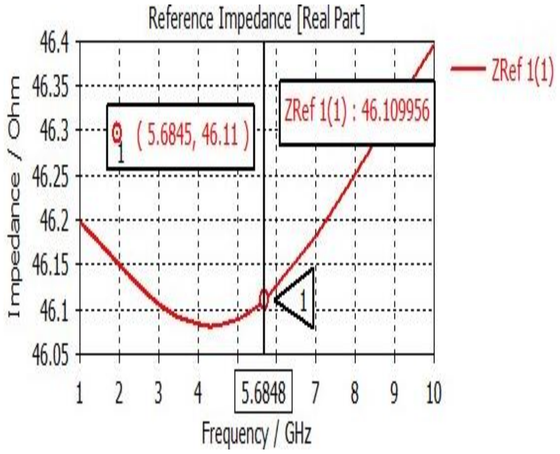
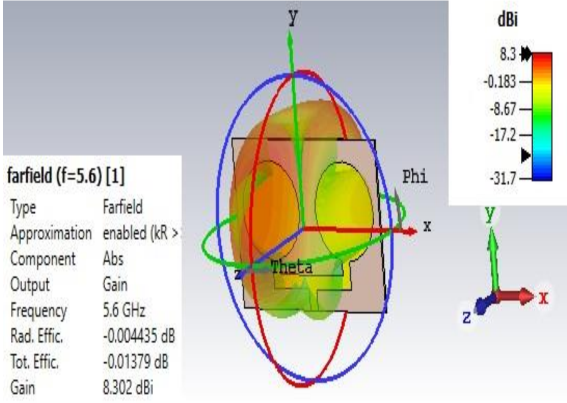


Figure. 5 – Impedance

3.4 Gain

Gain is associated with an antenna's capability to focus its signal radiation and receive signals from a specific direction. The gain of an antenna is defined as the ratio of its maximum radiation intensity to the radiation intensity of a reference antenna with identical input power. The antenna gain is quantified in decibels (dB) relative to the reference antenna. Figure 6 illustrates the frequency graph juxtaposed with gain values simulation in decibels (dB), where specific frequency and gain values are discernible. the gain is 8.302 dB at a frequency of 5.6 GHz.



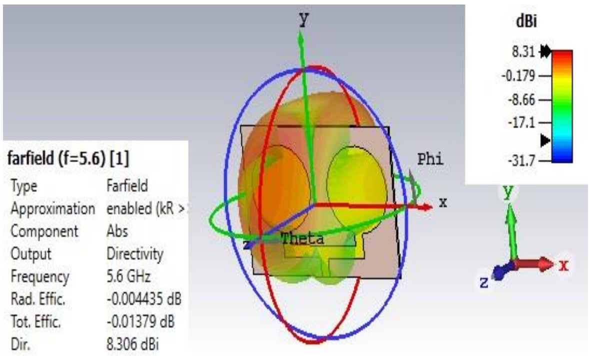
farfield (f=5.6) [1]

Type	Farfield
Approximation	enabled (kR >
Component	Abs
Output	Gain
Frequency	5.6 GHz
Rad. Effic.	-0.004435 dB
Tot. Effic.	-0.01379 dB
Gain	8.302 dBi

Fig. 6 – 3D Fairfield gain of the microstrip patch antenna

3.5 Directivity

The antenna design showcases notable directivity, registering of 8.306 dBi at a frequency of 5.6 GHz, as clearly illustrated in Figure 7. The principal objective is to enhance the antenna's radiation pattern, channeling its response toward a specific direction to improve power transmission or reception. Given that numerous antennas and optical systems are designed to emit electromagnetic waves within a limited angle or a singular direction, directivity stands as a crucial metric in tecommunication.



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Type	Farfield
Approximation	enabled (kR >
Component	Abs
Output	Directivity
Frequency	5.6 GHz
Rad. Effic.	-0.004435 dB
Tot. Effic.	-0.01379 dB
Dir.	8.306 dBi

Fig. 7 – 3D Fairfield directivity of the microstrip patch antenna

3.6 Efficiency

In Figure 8 the antenna demonstrates high efficiency at the frequency of 5.6 GHz, underscoring its crucial role as a pivotal parameter in the design and performance analysis of systems for wireless communication. Antenna efficiency, a fundamental parameter in antenna theory, assesses how effectively an antenna converts received frequency power at its terminals into radiated power. This efficiency is expressed as the ratio of the antenna's gain to its directivity. According to the aforementioned findings, the antenna exhibits an exceptionally high efficiency of 99.9 %, along with a gain of 8.303 dB and a directivity of 8.306 dBi. Consequently, the designed antenna proves to be a proficient choice for GPR applications.

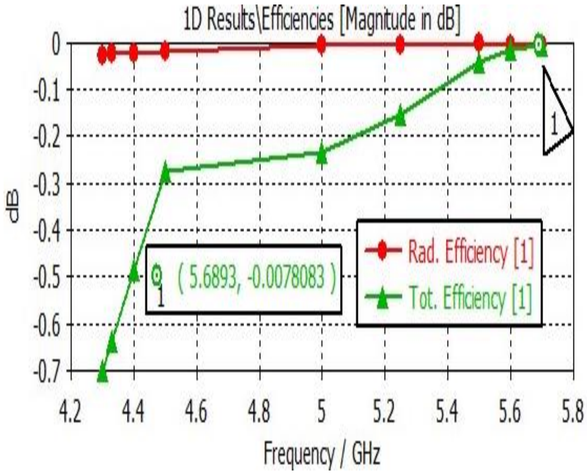

Fig. 8 – Radiation efficiency

4. CONCLUSION

This paper outlines the design of a monopole antenna array operating at 5.6 GHz. the proposed antennas were designed using a monopole patch and defected ground structure, incorporating a corporate feed network to uniformly distribute power to each element, thereby achieving a broad bandwidth and high gain. The impedance, radiation pattern, gain, VSWR, and efficiency characteristics of the proposed antenna array exhibited favorable results. The simulations were conducted using CST (Computer Simulation Technology) Microsoft Studio Simulation Software. The antenna simulation results revealed a substantial bandwidth of 1.6 GHz, spanning from 4.4 GHz to 6.07 GHz. The antenna exhibits a return loss of – 46 dB, a notable gain of 8.302 dB, a directivity of 8.306 dBi, and an impressive total efficiency of approximately 99.9 %, precisely at 5.6 GHz. The design bandwidth and radiation gain of the proposed antennas render them highly suitable for applications in Ground Penetrating Radar (GPR)

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Розробка високоефективної монопольної антенної решітки для георадара

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Протягом останніх кількох років програми дистанційного зондування, радари та зображення використовували технологію ультраширокого діапазону (UWB). У роботі представлено параметричне дослідження монопольних антен для систем георадара (GPR). Запланована антена має неповну площину заземлення та дві круглі випромінювальні зони, відомі своїм компактним дизайном, помітним високим коефіцієнтом підсилення та високою ефективністю. Крім того, він забезпечує вигідну пропускну здатність. Запропонована конструкція антени демонструє її придатність для низьких частот, пояснюючи її компактними розмірами та підкреслює вимогу до великої смуги пропускання і високого підсилення для досягнення оптимальної роздільної здатності зображення. У статті описано методологію проектування та моделювання монопольної антени, розробленої спеціально для застосування в георадарах (GPR). У цьому дизайні була використана підкладка Roger RT Duroid 5880, яка характеризується відносною діелектричною проникністю 2,2; висотою h = 1,575 мм і тангенсом втрат 0,0009. Розміри підкладки мініатюрні до 42 мм × 40 мм × 1,575 мм. Результати для антени отримані за допомогою програмного забезпечення технології комп'ютерного моделювання CST. Запропонована антенна решітка демонструє добрі характеристики на робочій частоті 5,6 ГГц, з коефіцієнтом відбиття – 46 дБ, смугою пропускання 1,6 ГГц, коефіцієнтом посилення 8,302 дБ, VSWR = 1.009 і ККД 99,9 %. Отримані результати є висококонкурентоспроможними, що свідчить про те, що запропонована антена має хороші можливості для виконання вимог, пов'язаних із застосуванням георадара (GPR).

Ключові слова: Антена, Посилення, Спрямованість, CST, GPR.