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New Compact CPW-UWB Antenna Based on Slotted Quasi-Fractal Patch Radiator

This paper presents the design, simulation, and fabrication of a new microstrip antenna of Ultra-Wide Band (UWB) technology operating within the frequency range of 3.4237 GHz to 10.824 GHz. The feeding technique used for the antenna is the Coplanar Waveguide (CPW) in conjunction with a slotted quasi-fractal patch on an FR4 substrate. The physical responses of this study show that the considered antenna covers the entire range of the UWB frequency spectrum providing the operational bandwidth of 7.4 GHz and obtaining input reflection of less than -10 dB. This type of design is different from planar antennas or microstrip patch antennas and has bidirectional radiation patterns. Its low mass, beneficial emission properties, and versatile frequency range make this small antenna suitable for many wireless communications uses, such as wireless body area networks (WBANs), microwave imaging and advanced radar systems.

Keywords: Bi-polar radiation patterns; Miniaturization; UWB; CPW; Physical parameters
Received: 30 July 2024; **Revised:** 9 October 2024; **Accepted:** 03 November 2024

1. Introduction

Prolific advancements in technology in the recent past have tended to reform the face of wireless communications. Of these, the incorporation of Ultra-Wideband (UWB) technology has proven to be a promising direction to improve wireless communications modalities, especially because of its capacity to transmit/receive data with an extensive frequency band [1,2]. The use of UWB technology in wireless imaging systems has a direct impact on increasing imaging resolution, minimizing signal attenuation, and improving the diagnostic performance of the imaging system. In the center of this technological convergence, the design of compact microstrip UWB antennas could be considered [3]. These kinds of antennas feature compactness, are cheaper to make, and are easy to integrate into products due to the use of microstrip technology which is beneficial when it comes to the development of small portable wireless communications devices without reaching for a more degraded performance. Microstrip UWB antennas have extraordinary flexibility of use, starting with precision imaging for initial disease identification and continuing with use during procedures where constant monitoring is necessary. That they can both send and receive signals across a wide band of frequencies holds a great potential for enhancing the performances of the wireless imaging instruments towards dramatic diagnosis enhancement [5,6]. Wireless communications applications determine how well definite parameters such as impedance matching, steady pattern of radiation, and generation of short duration pulse and their reception has been attained [8]. For instance, Islam M. et al. [8] have developed a miniaturized metamaterial UWB antenna suitable for use in microwave imaging systems as an imaging probe. Given these observations the high correlation factor and the ability to detect tumor simulants means that this antenna design could be considered as a candidate for an imaging sensor.

In the same manner, Othman A. et al [1] designed a planar UWB antenna with a small dimension of 36x26 mm^2 for imaging at the frequency of 6 GHz. This hexagonal shape microstrip patch antenna contains H-slot in the center top of the patch part and one slot in the ground part. The use of slots broadens the bandwidth of operation and also improves the impedance matching. Furthermore, in [9], the authors presented a microstrip antenna for microwave imaging system of breast cancer detection using GPR- UWB system. These return losses are important in ensuring that the antenna constructed reconstructs the image within the required bandwidth as was the case with the proposed antenna. For early detection of breast cancer, microstrip patch antenna was demonstrated by Çalğun R. et al. [10]. Done with a 3D breast structure incorporating distributive permittivity and conductivity to evaluate the image of the antenna. Also, compact UWB printed circular monopole antenna (PCMA) for microwave imaging especially was investigated in [11]. Hence, the proposed PCMA had a relatively high selectivity in terms of its impedance bandwidth while providing a satisfactory radiation pattern in the broadside direction for improving image reconstruction and clutter suppression in breast cancer detection systems.

Nonetheless, a few potential drawbacks are widely admitted in the field. However, there is one drawback: the frequency response in the given design spreads over a wide frequency range; the construction becomes intricate, which may lead to increased material costs and manufacturing complexity. Also, it was observed that most UWB antennas larger compared with the narrowband antennas, which makes it difficult to integrate them into today's miniature devices. Concerns have also arisen in the area of interference since UWB systems use a wide band of frequencies in a frequency environment shared with other wireless systems. Regulations governing the operation of UWB can be rigid which requires engineering precaution during its implementation to avoid playing its horns in other services. Additionally, although UWB can achieve high data rate solutions in the short range, the coverage area is typically smaller than those of the conventional NB systems. It is also found that on eradicating the microstrip patch antenna its performance may also depend on material present in the vicinity and thus may not perform effectively in real scenario. Last but not least, the wide bandwidths could result in signal processing problem, where more advanced methods have to be adopted in order to correctly determine data being transmitted. Although other considerations may tend to have an effect on the choice of an antenna technology based on the application and surroundings [12].

One of the areas that we may not commonly hear in the concerns of UWB technology is the issue of latency. Despite the high data rates and accurate location information that UWB provides for communication systems, the technology can also bring latency into applications. As seen before, the signal processing to decode wide bandwidth may be complicated making systems prone to delays especially when it comes to real-time data delivery. Furthermore, the ranging and positioning position apply functions such as calculating the time-of-flight of signal which adds to the total latency using UWB. Besides, in multiple device scenario they increase the network overhead and in turn add on the latency if many devices are communicating at a time. Environmental factors, for example interference with signals and barriers to the actual signal may slow down the transmission times and also the latency. Where low latency is a key issue, e.g., tracking or control, extra latency introduced by UWB technology must be controlled. Knowledge of these latency factors is therefore essential so that the overall hardware and software implementation of UWB systems can be fine-tuned to meet any desired timing specifications [13].

It has been found that for UWB systems it is critical to achieve high level of interference rejection at the front-end due to the wide bandwidth. On possible solution is bandpass filtering where only the specific UWB frequency is allowed by the filter while other frequencies are suppressed [14-17]. Different classification of filters can adaptively change its filter characteristics depending on the particular characteristics of the incoming signal to effectively reduce interference while passing on the desired signal. Besides, there are other procedures for getting diversity like spatial diversity with multiple inputs and multiple outputs and frequency diversity by transmitting through different frequency [18,19].

For these frequencies narrowband interference is a potential problem and so many UWB systems use time hopping spread spectrum which spreads the signal in time domain. These short duration pulses require pulse shaping so as to minimize on the interference they cause to other signals occupying the same bandwidth. In addition to that other applications of UWB involve the use of signal processing techniques such as matched filtering and interference cancellation algorithms which improves on the filter ability in rejecting noise from the transmitted UWB signals. Another aspect of management is dynamic power control where transmission power is changed depending on levels of interference; additionally, UWB systems have to operate within the allowed frequency bands meaning there are few conflicts with other technologies. The authors in [20-22] have shown that by using all of these strategies it is possible to remove interference and hence provide a reliable signal for these systems.

This research introduces a microstrip antenna design with operating frequency response between the lower end of 3.4237 GHz and the upper end of 10.824 GHz to support UWB. It allowed extending the value of the frequency limit beyond the upper frequency point of 10.6 GHz, thus exploring higher data rates, stronger signal stability, and improved interference handling. It might also help in the attainment of compliance with new norms or systems which necessitate higher frequency bandwidth so as to set versatile uses in the directions such as wireless personal area networks, microwave imaging, advanced radar systems and the rest. Moreover, it might be necessary to study this wider frequency range to obtain required information about propagation characteristics and channel behavior in order to further develop UWB technology in practical applications.

2. Design of CPW-UWB Antenna

The UWB antenna, in this study, has been designed using CPW feeder and microstrip patch, which provides great benefits for systems with high-frequency signal handling like wireless communication systems, radar, and satellite communications. Relatively few antenna designs have been proposed in the UWB range using coplanar waveguides which are particularly good for antennas due to their inherent characteristics of wide bandwidth, small size, and easy integration with other circuits [23-30].

Here we will be concentrating on a quasi-fractal patch radiator in this particular antenna design (as shown in Fig. 1). The use of quasi-fractal geometry offers improved performance that capitalizes on the multiple resonant frequencies generated within a very small area by designing antennas with this technique. The substrate size (25x27x1.6mm) is an important parameter to be included in the layout as it indeed affects seriously with performance and operating frequency of the antenna. The dielectric constant is 4.4, dielectric thickness is 1.6 mm, and loss tangent is 0.02.

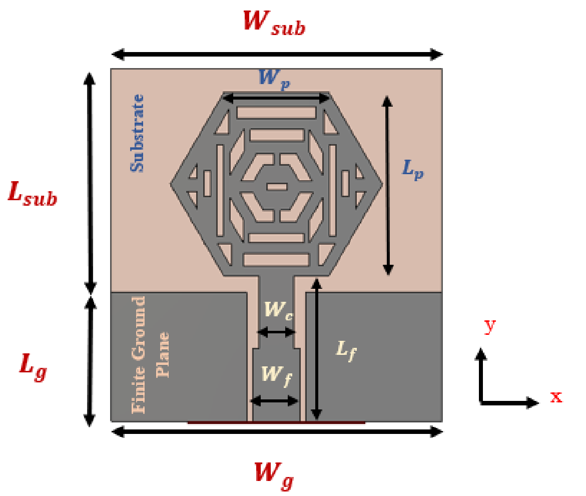

Fig. (1) The structure along with the dimensions of the antenna. W_{sub}=25, $Lsub$=17.1, L_g=9.9, Wg=25, W_p=8, L_p=13.96, W_c=3, W_f=4, L_f=9.9 (all in mm unit)

To improve the UWB features more and more, it is also intended that many design choices as well as size parameters were carefully examined. Finally, these dimensions were optimized using the CST simulator to ensure that both signal transmission and reception across the ultra-wideband frequency range (3.4237-10.824 GHz) are optimally achieved through them. The quasi-fractal design helps in the compactness of the antenna and allows the ability to wider bandwidth by introducing other resonances which can be utilizable for better performance.

An impedance match for signal transmission is realized through the integration of a 50-ohm microstrip line coupled with a coaxial feed line to energize the radiator. This combination is a standard practice in antenna designs, as it effectively minimizes reflection losses and maximizes power transfer. Furthermore, the configuration allows for a more compact design since the dielectric substrate, ground plane, and CPW feeder are all situated on the same plane. This coplanar arrangement not only reduces the overall size of the antenna, but also contributes to lower manufacturing costs.

The RLC equivalent circuit based on the microwave office simulator's projected UWB antenna is presented in Fig. (2). In a parallel configuration, resistors and capacitors are linked. Assigning different values to the capacitors and resistors in an antenna circuit allows one to alter the input reflection. A wider variety of impedance bandwidths can be achieved by switching out the first and last inductors. To achieve multi-resonance features and super wide bands, CPW-UWB antenna designs that use RLC tank circuits are the way to go. This is why the RLC tank circuit—consisting of an inductor (L), a resistor (R), and a capacitor (C)—can be adjusted to different frequencies, as it may be linked in series or parallel. So, it can handle a broader frequency accordingly the antenna works better. Designers should take these into account when selecting an RLC tank circuit architecture for CPW-UWB antennas, such as the realized bandwidth or Q factor, radiation efficiency. The impedance matching to be required. Decisive value selection for parts in the RLC tank circuit to control antenna resonances at different areas of the UWB spectra, allows data transmission and reception to be optimized. However, when we employ RLC tank circuits to improve the tuning and optimization of CPW-UWB antennas for wider band operation it is not easy.

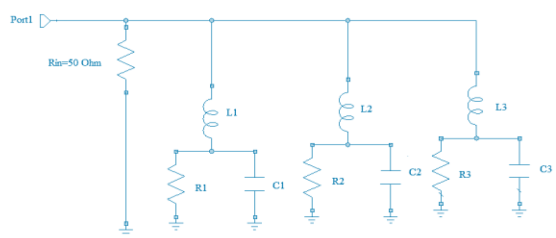

Fig. (2) The equivalent RLC circuit for the projected CPW-UWB antenna. L1=5 nH, L2=40 nH, L3=1.3 nH, R1=1000 Ω, R2=4000 Ω, R3=3000 Ω, C1=1.1 pF, C2=0.01 pF, C3=0.1 pF

3. Simulation Results

The microstrip CPW- UWB antenna with an extensive operation bandwidth is simulated using CST Microwave Studio software on a high-powered electromagnetic simulation tool, which can provide better interpretations of intricate structures related to proposed antennas. Simulation results show that UWB frequency response from 3.4237 GHz (lower frequency band) to 10.824 GHz (upper frequency band) with a bandwidth of around 7.4 GHz as illustrated in Fig. (3). This wide frequency band is of utmost importance in UWB applications to allow the antenna to communicate very well on different frequencies.

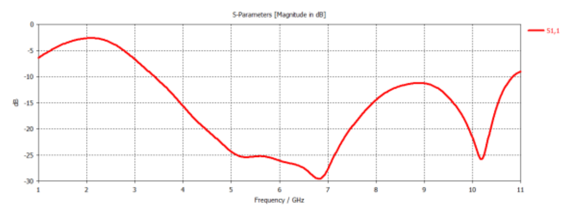

Fig. (3) Input reflection (S11) response for proposed UWB antenna

The modeling of 3D and multilayered structures is a specialty for CST Microwave Studio, which makes it a preferred choice in antenna design. In general, the software can solve for and visualize many characteristics of circuit performance (e.g., return loss, SWR from a Smith chart; real power vs frequency, etc.), as well as EM field distributions at desired frequencies (E-field or H-field). In addition, it permits gains and radiation patterns to be checked which are essential so that we recognize how the antenna is going to function after being applied.

A 7.4 GHz of impressive Impedance bandwidth with a central frequency equal to 7.12 GHz is achieved from the simulation results as well. Return loss (S11 parameter): This is one of the most important measurements that we can perform to evaluate how well an antenna works because it shows us what power levels are reflected into our radio system due to any mismatch between impedance at the feed line and the antenna. Return loss of lower value will be better matched and it have higher power transfer efficiencies. This established a low return loss value of -29 dB which implies that the UWB antenna reflects only an insignificant part of the incoming power and appears to be permissible in theory for efficient design.

Figure (3) shows the S11 response of the projected antenna to give an overview of how return loss is at a higher operational frequency. This confirms that the antenna can retain suitable characteristics over its design band and shows it is feasible for UWB systems. Consequently, the simulation results corroborate engineering decisions that were followed in designing of CPW- UWB antenna and prove its feasibility to become an integral part of future wireless as well as communication systems.

Figure (4) depicts the surface current distribution of the CPW- UWB antenna designed at 5.2 GHz. It demonstrates where currents flow across the structure of the antenna and are informative as to how well this frequency operates both in efficiency and for a given matched or mismatched impedance. For surface current distribution in feeding lines and the right side of the patch radiator, the currents are highest in these areas that will absorb more energy. This concentration means that the feed line successfully couples to patch and manifesto efficient transmission of the signal. The apparent patterns seen in the current distribution suggest that energy is being efficiently radiated from the antenna and there are little losses due to improper loading of currents. The maximum magnetic field strength was 100.1 A/m, indicating a high level of power transmission within the antenna structure. We mostly found those areas of the high-strength magnetic field surrounding the feeder region and at the patch radiator base. These areas play an important role in the performance of the antenna due to their contribution towards the improvement of radiation efficiency and directivity. The strong magnetic fields in these regions imply that the design is indeed benefiting from electromagnetic principles to modify radiation characteristics. The Feeder Feeding RF energy into the patch, which is a direct feed type element i.e. only radiates and receives from where there is thus no need for additional reflectors or directors. As simple as it might sound but indeed a very crucial part of the antenna that greatly affects both impedances matching and the overall efficiency of an Antenna's performance. The patch has in style being considered with just two terminals. A connector can be connected directly to each end (transmit or receive end) to supply all necessary transmit power (or for received power if it is required). The performance of the UWB-CPW antenna for different frequencies is discussed by measuring both surface current distribution and magnetic field strength. These analyses are essential for antenna designs to be tailored in a way that will meet the demanding requirements of UWB applications, where ultra-broad bandwidth and high efficiency are needed.

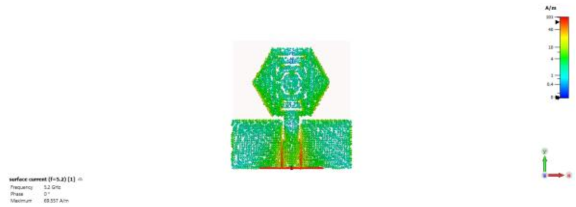

Fig. (4) Surface current intensity distribution for the CPW-UWB antenna

The expected 3D radiation patterns at a frequency of 5.2 GHz for the proposed ultra-wideband (UWB) antenna have been shown in Fig. (5). These patterns show how the antenna radiates power to space, and this gives important information about its directivity, and global performance. It shows the maximum gain of the projected antenna at this working frequency naturally with a value of 2.16 dBi which is in part due to moderate power radiated from it.

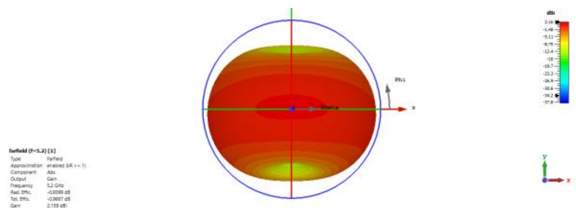

Fig. (5) 3D radiation patterns of the anticipated CPW-UWB antenna

The 3D radiation patterns are demonstrated to illustrate the performance stability of our antenna in different directions, which is significant for deployment that needs flawless communication over multiple orientations. The 2.16 dBi gain indicates that the antenna does increase its directionality in certain parts of space while ensuring enough coverage is maintained everywhere else. This is useful for ultra-wideband applications especially when it comes to both signal integrity and coverage. In addition, the radiation patterns' shape and spatial distribution offer extremely valuable references for us to infer about its polarization properties as well as potential interferences on other nearby devices. Understanding these bounds will enable the integration of this UWB antenna in complex communication systems while providing efficient performance and interference freedom.

Figure (6) illustrates the UWB gain values within the UWB frequency range of the proposed UWB antenna with a peak gain of 13.618 dBi. It is important to note that there is a direct proportionality between the antenna gain and the square of the operating frequency. This relationship is depicted in Fig. (6), while efficiency remains unaffected by this correlation.

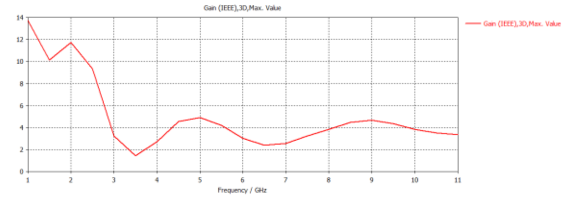

Fig. (6) Gain for designed UWB-CPW antenna

The primary factors leading to a decrease in efficiency include conduction loss, dielectric loss, and slightly restricted feedline-antenna impedance matching. An important aspect of antenna design is the consideration of losses, which can impact various factors. When the size of the antenna is comparable to or larger than the wavelength, a reduction in directivity occurs, resulting in the appearance of side lobes. The antenna exhibits a bi-polar radiation pattern, as shown in Fig. (7).

This pattern indicates that the antenna emits or collects electromagnetic energy in two opposite directions, resulting in two significant lobes of radiation strength on either side of the antenna structure. The bi-polar radiation pattern allows for symmetrical radiation around the antenna axis, with energy broadcasted in two opposing angles with uniform strength. This pattern is commonly observed in antennas designed for symmetrical radiation in two directions, featuring two main peaks in the radiation pattern oriented differently based on the antenna design. The offset beam pattern generated by the bi-polar radiation pattern enables signal coverage in multiple directions, akin to transpiration systems. The radiation pattern at different frequencies demonstrates symmetrical behaviors, ensuring consistent performance. Assessing antenna performance involves comparing the total power received from the generator to the total radiated power by the antenna. Optimal radiation extends into the surrounding space, while inefficient radiation results in energy losses due to factors like magnetic, dielectric, and metal conduction losses.

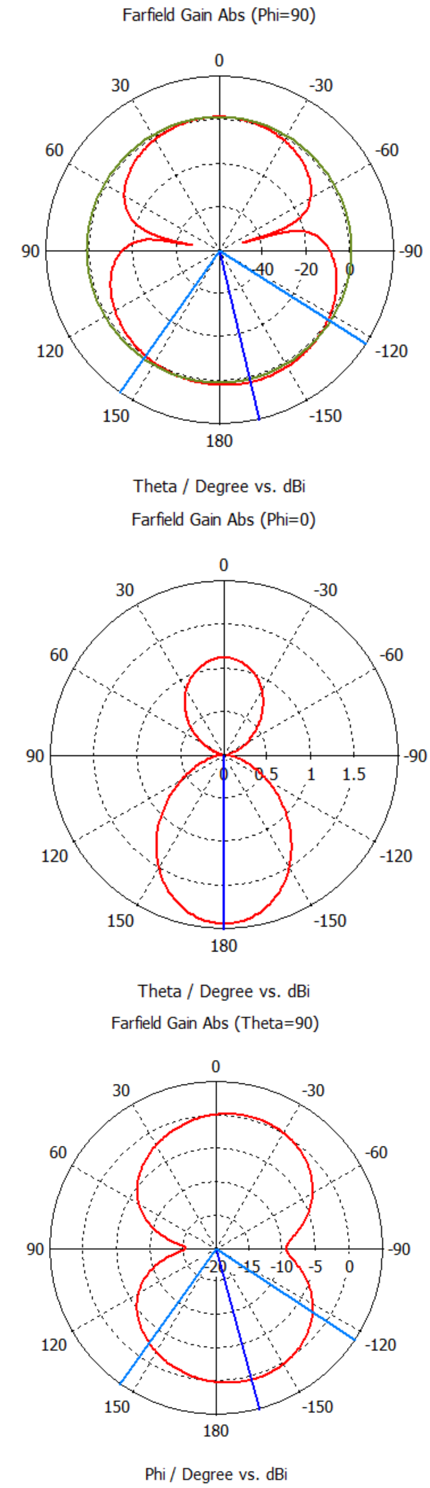

Fig. (7) Radiation patterns for projected UWB-CPW antenna at 5.2 GHz

Figure (8) displays the total efficiency of the designed antenna, with minimum efficiency at 1.5 GHz (-14.95) increasing significantly as frequency rises, reaching -0.55 at 6.407 GHz.

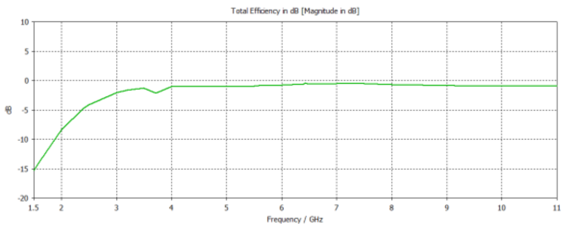

Fig. (8) Total radiation efficiency for the UWB-CPW antenna

4. Fabrication and Measurement

Figure (9) shows a prototype of the microstrip CPW-UWB antenna that is built on a 1.6 mm thick FR4 substrate. The simulation results are used to optimize the patch and ground plane dimensions. A vector network analyzer (VNA) takes S11 readings from an antenna that is linked to it via a coaxial wire.

Figure (10) shows the deviations between the simulated, RLC equivalent circuit input reflection response and observed S11 responses for a manufactured CPW-UWB antenna. These tolerable variances could be due to several factors. Aiming for great precision during antenna construction doesn't guarantee that the manufacturing dimensions of the antenna elements won't lead to minuscule tolerances. The performance of an antenna can be impacted by such minute errors, causing a discrepancy between the simulated and measured S11 responses. In addition, these antennas' performance could be affected by differences in dielectric characteristics on FR-4 substrates caused by manufacturing techniques that differ from the calculated material values. Differences between measured and simulated S11 responses could be caused by changes in the dielectric constant or loss tangent. S11 readings can be affected by unaccounted reflections caused by convection effects during measurement, which are not considered in the simulation. Because of this, the findings of the simulations do not always match up with the actual measurements. Errors in the readings can be introduced by environmental factors like electromagnetic interference or surrounding objects, which might distort the S11 response.

The disparity between the two sets of data can be explained by the exclusion of these external influences from simulations. The measured S11 response may be inaccurate due to uncertainties introduced by calibration errors in the vector network analyzer. Nonetheless, differences in the simulated reactions will result from even small deviations from calibration. Commercial microwave antenna design models' simulated assumptions may include idealizations or oversimplifications that do not accurately reflect reality. These assumptions will lead to discrepancies between the results of simulations and those of measurements in cases where the behavior is complex or less than optimal.

At any rate, the impedance bandwidth at -10 dB for all responses are hugely similar with deviation error less than 15 %.

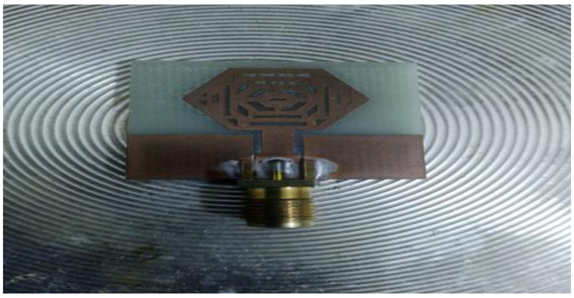

Fig. (9) A prototype of the projected antenna

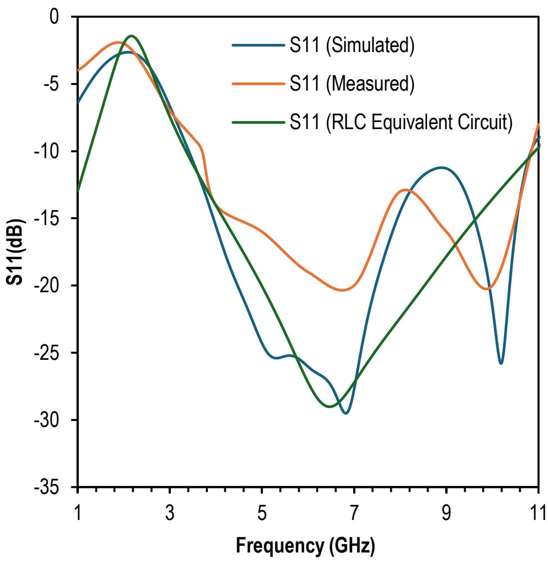

Fig. (10) Measured, RLC equivalent circuit and simulated input reflection responses for the projected antenna

5. Conclusion

The UWB microstrip antenna, designed with a coplanar waveguide (CPW) feed line and a quasi-fractal patch on an FR-4 substrate, operates effectively across a frequency range of 3.4237 GHz to 10.824 GHz, achieving a peak gain of 13.618 dBi. Its bipolar radiation patterns enhance versatility in multi-path environments, making it suitable for Wireless Body Area Networks (WBANs) and applications requiring high-resolution data transmission.

The antenna's compact and lightweight design is ideal for portable and wearable devices, particularly in microwave imaging settings where mobility is crucial. Its broad frequency responsiveness ensures reliable communication even in high electromagnetic interference environments, supporting remote patient monitoring and telemedicine.

Additionally, integrating established communication standards could improve connectivity for assistive technologies, such as hearing aids. In nutshell, this UWB microstrip antenna represents a significant advancement in wireless communication technology, with promising applications in healthcare and beyond, potentially enhancing quality of life across various sectors.

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