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International Journal of Electrical and Electronics Research (IJEER)
Research Article | Volume 12, Issue 4| Pages 1273-1280| e-ISSN: 2347-470X

Design and Optimization of a Half-Circular Ultra-Wideband Patch Antenna Using Genetic Algorithm

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ABSTRACT- This research introduces an optimization design of an ultra-wideband (UWB) half-circular planar antenna using genetic algorithm. The optimization process is conducted using an Application Programming Interface (API) links two softwares; MATLAB environment and ANSYS HFSS software. The UWB antenna design includes a semi-circular patch element, the UWB behavior is obtained using truncated ground plane incorporating a rectangular slot cut out of the ground. Genetic algorithm is exploited to optimize the length of partial ground plane and the size and position of the rectangular slot. The overall size of the antenna is 28×29×1.6 mm^3. Using the proposed fitness function, the ultra-wide band antenna configuration achieves an extensive impedance bandwidth spanning approximately 14.76 GHz (139.38%), covering frequencies from 3.21 GHz to 17.97 GHz for reflection loss S11 less than -10dB. The findings also indicate that the antenna exhibits a favorable peak gain of 3.7–6.24 dB in the desired band. Therefore, the proposed methodology proofs to be effective to acquire the best UWB behavior of the antenna.

Keywords: Genetic Algorithm optimization, ultra-wide band, patch antenna, objective function.

ARTICLE INFORMATION

Author(s): Malika Ouacifi, Karim Ferroudji, Fouad Chebbara, Mounir Amir, Mohamed Lashab, and Chan Hwang See;
Received: 02/07/2024; **Accepted**: 26/09/2024; **Published**: 30/11/2024;
e-ISSN: 2347-470X;
Paper Id: IJEER240411;
Citation: 10.37391/ijeer.120419
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-12/ijeer-120419.html

1. INTRODUCTION

UWB technology was initially of little importance for civil purposes due to a lack of frequency approvals. This changed in 2002, when the FCC (Federal Communication Commission) in USA granted general approval for UWB systems for the first time. The frequency interval from 3.1 GHz to 10.6 GHz has the largest available absolute bandwidth and promises the highest data rate for communication systems and the highest spatial resolution in sensor technology, which is later used in the majority of potential applications of UWB technology, including communications and medical technology [1]. UWB technology has grown to be widely implemented. The adoption of UWB technology has expanded significantly thanks to its potential features, including high data transfer rates (over 100 Mbps), a coverage area of about 10 meters, and impressive electromagnetic emission performance [2]. Several devices require an antenna with different operating frequencies. UWB antennas are good alternative of multiple narrow band antennas, reducing therefore costs and power consumption in one hand and the number of antennas in other hand. Furthermore, the impulse nature and bandwidth of UWB antenna make it resistant to interference and multipath, besides its low power spectral density allows it to coexist with little interference to surrounding systems [1, 2]. Consequently, in recent studies, researchers have focused extensively on designing and improving UWB antennas for various applications, including diagnostic imaging [3, 4], wearable devices [5-7], 4G/5G systems [8], multiple-input multiple-output configurations [9], and other wireless technologies [10].

Several antenna architectures and configurations have been suggested in published works for ultra-wideband systems. These include designs such as elliptical and circular planar antennas [11, 12], octagonal and pentagonal antennas with or without slot loading [13, 14], and various other geometric configurations [15, 16]. However, the primary difficulty lies in designing antennas capable of effectively covering the broad range of frequencies of 3.1 to 10.6 GHz, while ensuring compactness and reduced energy consumption, alongside with adequate electromagnetic emission characteristics. These radiation properties include achieving a return loss below -10dB over the entire frequency band, an optimal impedance alignment between the antenna's transmission line and the emitting patch, high gain throughout the UWB region, lower phase distortion of the pulse within the operational frequency range, and exhibiting an omnidirectional emission behavior. In order to enhance the performance and reduce the dimensions of UWB antennas, various approaches have been employed. These techniques involve the incorporation of parasitic elements whether in the ground or within the patch, augmenting the substrate thickness, and adjusting the geometry of patch and ground plane through the integration of slots [17]. By utilizing these methods, significant enhancements can be achieved in both the functionality and compactness of UWB antennas. The previously mentioned techniques often improve the antenna characteristics and may lead to a reduction of the entire antenna dimensions. However, implementing these techniques increases the number of parameters that need to be tuned, resulting in complex antenna geometries. This complexity, coupled with the difficulties raised earlier, makes the design process of UWB antennas quite challenging. Conventional heuristic approaches, such as parameter sweeps, are commonly employed in the design of UWB antennas. Nevertheless, these techniques are time consuming and may not lead to an optimum design. Consequently, significant attention has been devoted to evolutionary algorithms for the optimization of the UWB antenna behavior. These algorithms have garnered considerable interest because of their capability to address the challenges associated with antenna model complexity and to produce improved designs. Several algorithms, that are natural phenomena inspired, have been used to provide solutions to solve antenna's UWB optimization problems. These algorithms include Genetic algorithm [18] particle swarm optimization [19] which exploit a process of minimization of an objective function to acquire the antenna optimum design.

This paper presents a methodology for optimizing the geometry of ultra-wideband antennas in order to achieve the best ultra-wide behavior by maximizing the bandwidth and minimizing return loss values in the operating frequency band. To demonstrate the effectiveness of this approach, we introduce an UWB patch antenna characterized by a semi-circular shape and reduced ground surface which incorporates a rectangular aperture. The optimized antenna achieves a frequency range from 3.21 GHz to 17.97 GHz, all while maintaining a compact size of 28×29×1.6 mm^3. The optimization process for constructing UWB antenna is carried out using an Application Programming Interface (API) that connects two software platforms, namely MATLAB and ANSYS HFSS. Utilizing a Genetic Algorithm approach and minimizing the proposed fitness function, the antenna structure is optimized to achieve the optimal UWB behavior. This approach has demonstrated its effectiveness in the design and construction of UWB antennas. The antenna geometries developed in this research are created utilizing an Application Programming Interface (API) that integrates two software environments: MATLAB and ANSYS HFSS.

This paper is organized as follows. *Section 2* illustrates the methodology exploited in this study where the antenna geometry and the GA optimization process are presented. *Section 3* shows the implementation and measurement of the fabricated antenna. The findings and discussion are presented in *section 4*. *Section 5* shows a comparative analysis between the suggested antenna and newly designed UWB antennas. *Section 6* concludes the paper.

2. METHODOLOGY

Figure 1 depicts the flowchart illustrating the sequential steps involved to obtain the desired UWB antenna. Using the HFSS software, we initially design the proposed antenna. Subsequently, a MATLAB code is developed to replicate the HFSS script instructions, following the same methodology and chronological order as the graphical interface of HFSS. The MATLAB code interacts with the HFSS software to achieve the desired results. By executing the script MATLAB, the code exports the results from HFSS, which are then imported back into MATLAB for further processing. A Genetic Algorithm (GA) approach, implemented in MATLAB, is employed to optimize the length of the partial ground plane and the position and dimension of the rectangular slot, aiming to achieve the desired UWB antenna characteristics. This seamless interaction between MATLAB and HFSS has proven to be effective in various studies within the literature, particularly in the realization of microwave structures [20, 21].

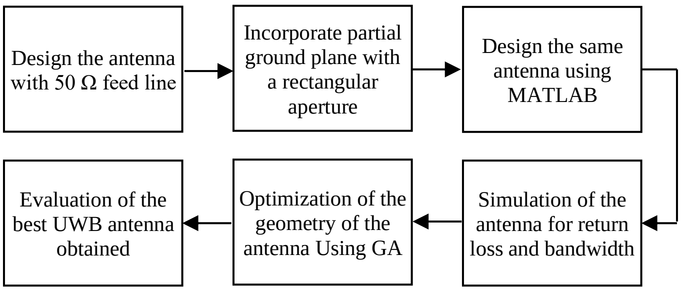
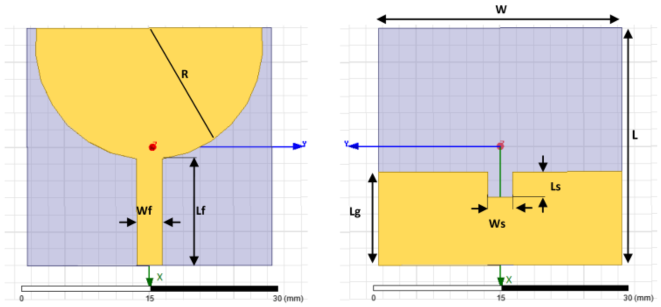


Figure 1. Antenna design methodology flowchart

2.1 Antenna Design

Figure 2 illustrates the geometry of the UWB patch antenna. The antenna takes the form of a semi-circular shape with a radius of 13.5mm. A FR4 epoxy substrate is exploited, having a dielectric constant of 4.4 and a loss tangent of 0.02. The antenna measures 28×29mm² in area and has a thickness of 1.6mm.



(a) (b)

Figure 2. Initial configuration of the UWB antenna: (a) top view, (b) bottom view (Before optimization)

The proposed antenna employs a standard microstrip transmission line coupled with the radiating element. The copper cladding is 0.035 mm of thickness. To attain the targeted ultra-wide bandwidth characteristic, a modification is made to the ground plane structure. This later is partially truncated and it incorporates a rectangular aperture as depicted in *figure 2(b)*. The top surface of the antenna is configured as illustrated in *figure 2(a)*. The design of the antenna is carried out using HFSS software. The initial specifications of the suggested UWB antenna are detailed in *table 1*.

Table 1. Initial configuration for the UWB planar antenna

Parameter	Value (mm)
Radius of patch (R)	13.5
X coordinate (Xp), Y coordinate (Yp) of patch	-12, 0
Substrate length (L)	29
Substrate Width (W)	28
Ground plane length (Lg)	12
Feed line Width (Wf)	3
Feed line Length (Lf)	13.5
Slot Length (Ls)	3
Slot Width (Ws)	3
X coordinate (Xs), Y coordinate (Ys) of slot	3, -1.5

The dimensions (Ls, Ws) and position (Xs, Ys) of the aperture, along with the length of the modified ground plane (Lg), are systematically adjusted and optimized using a Genetic Algorithm approach to attain the desired ultra-wideband behavior of the antenna. *Table 2* illustrates the lower and upper limits of the optimized parameters.

Table 2. Range setup of optimized parameters

Parameter	Optimization range (mm)
Lg	8—16
Ls	2—8
Ws	2—8
Ys	-2—8
Xs	-2.5—5.5

2.2 Genetic Algorithm-Based Optimization of the Proposed Antenna

Genetic algorithm (GA) is a stochastic search method that draws inspiration from Darwin's theory of evolution [22]. It is highly effective in addressing problems characterized by a wide search space. GA finds applications in various scenarios, including the optimization of many variables, both continuous and discrete. Additionally, GA is well-suited for parallel computing and can handle different data types, including numerically and empirical data, or mathematical functions [23]. An iterative procedure is applied to solve the problem by means of genetic algorithms, where potential solutions, referred to as chromosomes, are used to generate new solutions. This collection of potential solutions is called a population. To generate the next generation, only the fittest population will prevail and be used. Solutions for creating new offspring are chosen depending on their objective function, with the most suitable chromosome having the strongest probability of replication.

In the process of employing GA for antenna optimization to achieve predefined performance objectives, it's imperative to accurately program and interface both the optimizer and antenna structure code. Upon execution of the structure code, a new antenna model is generated in each iteration with updated performance characteristics using Visual Basic script (VBS) MATLAB code. Then HFSS calls the VBS file and simulate the antenna model. The results are exported back to MATLAB to GA which assesses the fitness function for every newly generated antenna structure, culminating in the identification of the model that best fits along with its associated parameters. *Figure 3* illustrates the incorporation of the Genetic Algorithm for antenna optimization, implemented through MATLAB and interfaced with HFSS.

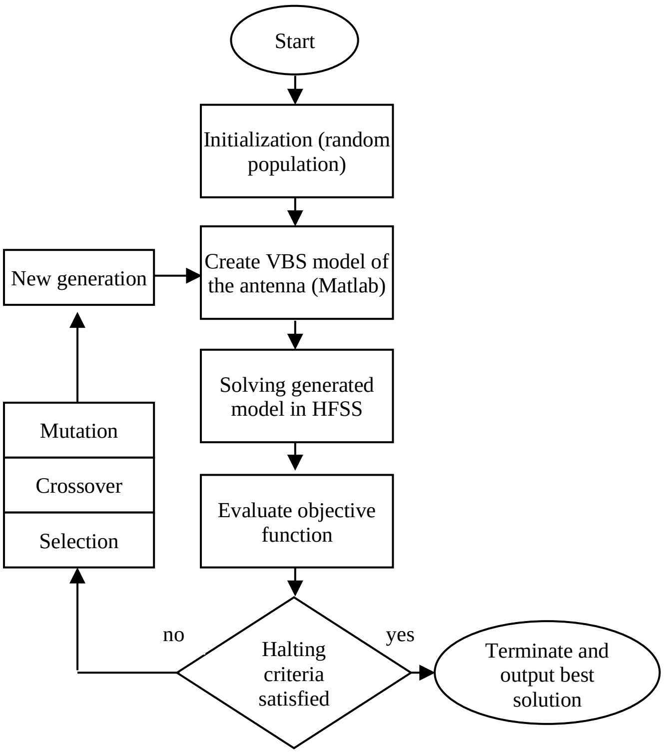


Figure 3. Antenna optimization based on API using GA

The optimization approach using GA comprises the outlined sequence.

2.2.1 Initial population Generation

The initial set of individuals is created using a random process that generates a diverse set of individuals, forming the foundation for subsequent generations. For this research, we have opted for a total of 600 generations. The appropriate range for a population size in Genetic Algorithms (GA) can vary depending on the specific problem and computational resources available. Smaller populations may converge faster but risk getting stuck in local optima, while larger populations may explore the search space more thoroughly but require more computation time. This work employs a population size of 16 individuals, where each individual's chromosome consists of five genes which represent the number of parameters to optimize (Ls, Ws, Xs, Ys, and Lg). Each possible solution (chromosome) is encoded using a binary string of five bits.

2.2.2 Selection

The populations are assessed and ranked using the fitness function. The individuals with the lowest fitness scores are designated for the following generation.

2.2.3 Crossover

New chromosome is created by combining genes from parents, with a constant probability applied to the population.

Typically, this probability is context-dependent and often set at a high value [24, 25]. For this study, a fixed probability of 0.5 is employed.

2.2.4 Mutation

To generate new offspring, a small number of bits within the chromosome are altered. Binary encoding allows for the random alteration of selected bits between 1 and 0. Generally, a low mutation rate is chosen for this operation. This rate typically falls within the range of 0.01 to 0.3 [24, 25]. In this study, it is set to 0.1.

2.2.5 Fitness Evaluation

The step of fitness assessment holds paramount importance in every optimization algorithm as its purpose is to assess the adequacy of a solution (individual). The preferred solution is the one that reduces the fitness function. In the context of optimizing the ultra-wideband antenna geometry, a fitness function objective is proposed. This function is designed to refine the antenna's characteristics in terms of bandwidth and return loss.

2.2.6 Stopping criteria

Evolutionary algorithms, such as GA, commonly employ two types of stopping criteria. Firstly, a fixed maximum generation limit (iterations) is defined, and the algorithm yields the optimal solution found in the final generation. Secondly, the algorithm continues to run until the disparity between the optimal solution achieved throughout the evolutionary method and the target solution is reduced. This difference-based halting criterion ensures that the algorithm converges toward an optimal solution [26]. In the proposed scenario, the optimization procedure is iterated as far as the halting criterion, set at 10^{-6}, is not satisfied or the overall number of generations, set at 600, is not attained. Given that the optimized parameters fall within the range of -2 to 16 mm, an error of 10^{-6} is considered acceptable in this context. *Table 3* summarizes the parameters setting for the GA optimization approach.

Table 3. Parameters setting for the GA optimization approach

Parameter	Value
Number of populations	16
Dimension	5
Maximum Iteration	600
Stopping criteria	Reaching 600 Generation, or an error of 10^{-6}

2.3 Objective function

A fundamental aspect of an evolutionary algorithm optimization involves the development of a robust evaluation criterion that aligns with the target performance parameters. The aim is to design a microstrip antenna capable of operating within an ultra-wide bandwidth. To attain the best UWB behavior, a novel fitness function is proposed (OF). This objective function is designed to adjust the ultra-wideband antenna geometry, to minimize signal reflection and enhance the antenna's operational frequency range. Besides, a penalty factor P is used to avoid the occurrence of return loss peaks $peak\_S_{11}(f_i)$ above -12dB in the operating bandwidth as show in *figure 5*. The proposed objective fitness function is determined as the sum of S11 coefficient samples under -12 db and it is calculated as follows:

$$\mathrm{OF} = \min\left(\mathrm{P} \times \sum_{i=1}^{N} \mathrm{S}_{11}(\mathrm{f_i})\right) \tag{1}$$

Where, *P* is the penalty factor and it is formulated by:

$$\mathrm{P} = \begin{cases} 1 & \text{if } \ \mathrm{peak\_S_{11}(f_i)} < -12\mathrm{dB} \\ 1000 & \text{otherwise} \end{cases} \tag{2}$$

where
N is the total number of samples (*N* = 161).
f_i : the operating frequencies, set from 2 GHz to 18 GHz, with a frequency step of 0.01 GHz.

The choice of a -12dB threshold, provides an acceptable balance between achieving sufficient impedance matching and minimizing signal reflection within the operating frequencies of the antenna. Therefore, it contributes in the enhancement of the antenna efficiency and overall performance.

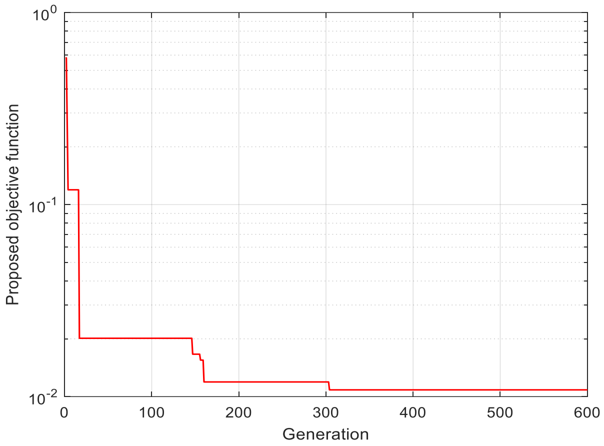


Figure 4. Convergence pattern of the proposed objective function across generations

Figure 4 demonstrates the convergence pattern of GA using the proposed objective function versus the number of generations. It can be seen that GA starts to converge after 300 generations. Therefore, the final design (optimum solution) that minimizes the fitness function is achieved after 300 generations. The entire optimization process requires approximately 65.67 hours executed on a personal computer sporting a 2.6 GHz Core i7 processor and 64 GB RAM.

3. RESULTS AND DISCUSSION

The antenna is printed on double sided FR4_epoxy substrate of εr=4.4 and loss tang δ=0.002. The conductors are modeled as copper with 0.035mm thickness to provide a more realistic representation of the physical antenna structure and its electromagnetic characteristics. The frequency is set from 2 GHz to 18 GHz, with a frequency step between samples set to 0.01 GHz. The antenna geometry is designed to rely only on a small set of parameters, providing flexibility in achieving different shapes by controlling these parameters.

The geometry is effectively manipulated by adjusting five key parameters as illustrated in *table 2*. Theses parameters are the length of the partial ground plane (Xground :Lg), the length of the slot (Ls: Lslot), the width of the slot (Ws), and the X, Y coordinates of the slot (Xs, Yst).

The limitation of the number of parameters to five not only enhances the performance of the optimization algorithm but also significantly reduces processing time. The GA algorithm configuration applied utilizes a population size of 16 individuals across 600 generations, requiring a total of 9600 function evaluations.

Through HFSS software, the performance metrics of the optimized UWB antenna, including reflection coefficient, voltage standing wave ratio (VSWR), gain, radiated field characteristics, group delay, and angular stability are estimated.

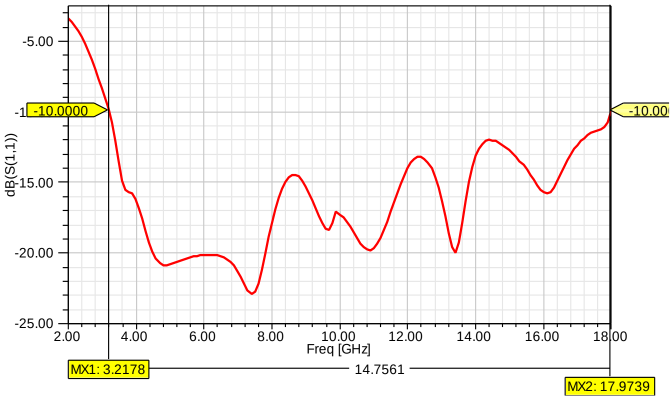


Figure 5. Return loss of the proposed UWB antenna using HFSS

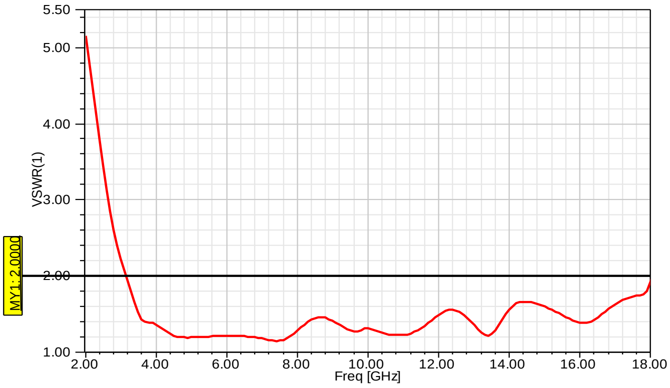


Figure 6. Voltage standing wave ratio (VSWR) of the optimized UWB antenna

Figures 5 and *figure 6* illustrate the modeled reflection coefficient |S11| and the VSWR of the optimized UWB antenna configuration. As expected, the design presents a reflection level maximum under -12dB throughout the UWB frequency spectrum. The UWB antenna presents a minimum VSWR value of 1.1551 and it remains less than 2 over the operating frequencies, which demonstrates an excellent impedance matching between the radiating element and the transmission line. Moreover, the measured bandwidth for |S11|≤-10 dB is 14.7561 GHz from 3.2178 GHz to 17.9739 GHz, which presents a fractional bandwidth (BW_f) of 139.38% calculated by:

$$BW_f = \frac{(f_H - f_L)}{f_c} \times 100 \qquad (3)$$

where, f_H and f_L are the higher and lower cut off frequencies respectively, and f_c is the center frequency and it is calculated by:

$$f_c = \frac{(f_H + f_L)}{2} \qquad (4)$$

The simulated gain of the optimized UWB antenna is portrayed in *figure 7*. The proposed antenna presents a good proper gain, ranges from 3.7 to 6.24 dB, across all frequency bands from 3.2178 GHz to 17.9739 GHz. Therefore, the designed UWB antenna is well-suited for diverse wireless communication applications, including WLAN, WIMAX, and beyond.

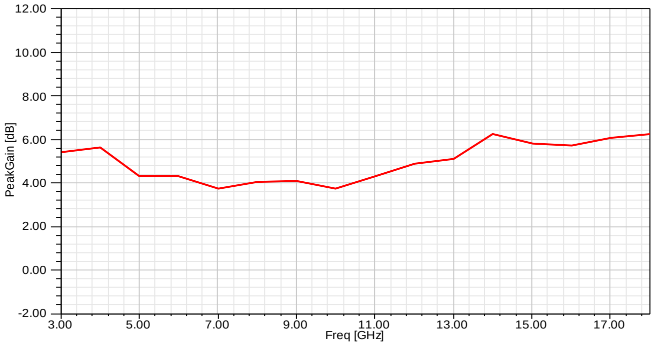
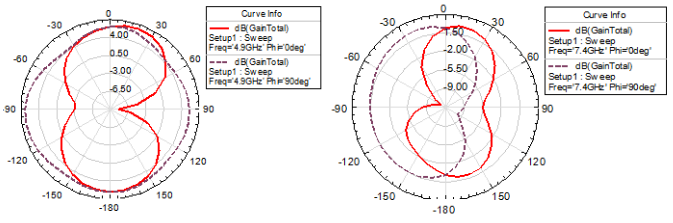
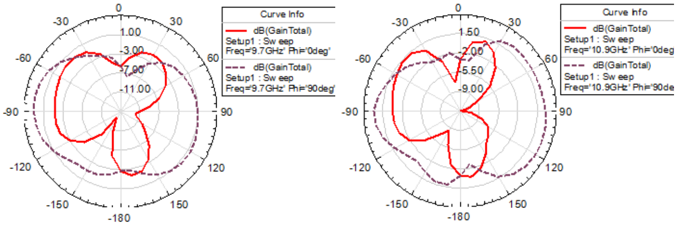


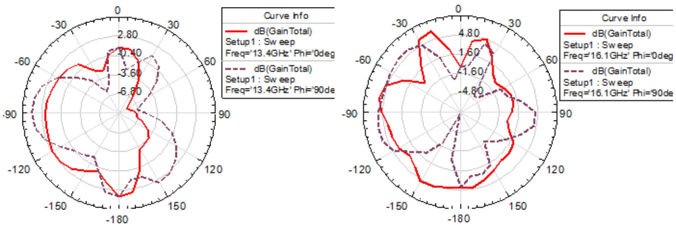
Figure 7. Gain vs. frequency of the optimized antenna



(a) 4.9GHz (b) 7.4GHz



(c) 9.7GHz (d) 10.9GHz



(e) 13.4GHz (f) 16.1GHz

Figure 8. 2-D radiation characteristics of the optimized UWB antenna

In *figure 8*, the radiation patterns simulation in 2-D of the optimized patch antenna in E-Plane (Φ=0°) and H-Plane (Φ=90°) are shown at different resonant frequencies. At the operating frequencies of 4.9 GHz, 7.4 GHz, 9.7 GHz, and 10.9 GHz the optimized UWB antenna presents a nearly omni-directional characteristic in H-Plane. At 4.9 GHz and 7.4GHz, the radiation pattern in E-Plane is like eight shape the maximum radiation directions are 20°and 160° and 10°and 180°, respectively. At 9.7GHz and 10.9 GHz the radiation behavior in E-Plane doesn't change a lot and has three side lobes with maximum radiation directions of 20°, -40°, and 170° and 30°, -40°, and 170°, respectively. At frequencies 13.4GHz and 16.1GHz the antenna's radiation pattern starts to present multiple side lobes, due to higher dielectric loss with higher frequencies.

Additionally, the time-domain performance of the optimized UWB antenna is assessed in terms of group delay. This later is an important criterion in ultra-wide band communication systems, it evaluates the time distortion of the transmitted wave. To prevent the pulse distortion, the antenna should be able to present a group delay variation under 1 ns second across the full range of operating frequencies.

Figure 9 depicts the results of group delay. The variation between the lowest and highest group delay values is below 1 ns across the frequency spectrum from 3.2178 GHz to 17.9739 which is in acceptable limits. This demonstrates the antenna's low impulse response distortion which is well-suited for applications requiring ultra-wideband capabilities. According to the group delay measurements, the optimized antenna exhibits a time-domain response with minimal distortion.

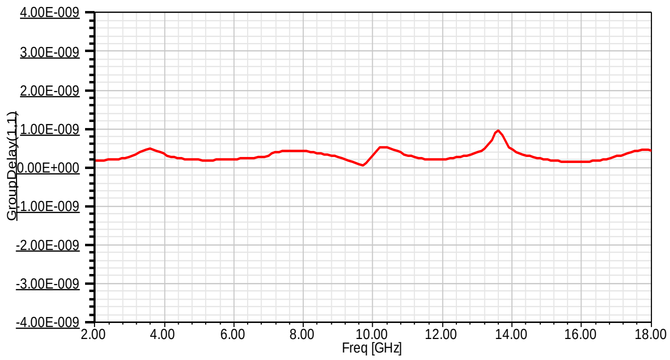
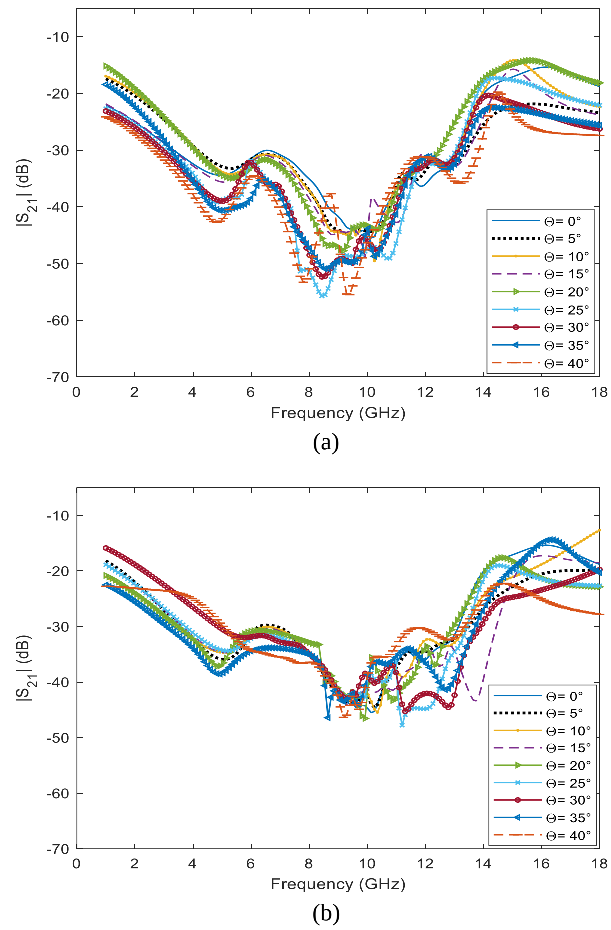


Figure 9. Group Delay vs. frequency of the optimized UWB antenna



(a)

(b)

Figure 10. Angular stability of the UWB antenna at different incident angles a) TE-polarization, b) TM-polarization.

Figure 10 illustrates the angular stability of the transmission coefficient ($|S_{21}|$) of the proposed UWB antenna for different incident angles (θ) in TM and TE polarization. The antenna demonstrates angular stability across edges up to 35° for TE and TM polarization.

4. IMPLEMENTATION AND MEASUREMENT

In order to validate the effectiveness of proposed objective function, the prototype of the optimized antenna is fabricated on a FR-4 substrate material and then experimental tests are carried out using RS-ZVA40 vector network analyzer under the guidance of Pr. Chan Hwang See at Edinburgh Napier University, Bradford, UK. *Table 4* presents the antenna's optimized structural dimensions.

Table 4. Parameters setting for the GA optimization approach

Parameter	Value (mm)
Partial ground plane (Lg)	13
Slot Length (Ls)	7.25
Slot Width of (Ws)	2.75
X position (Xs), of slot	1
Y position (Ys) of slot	-0.5

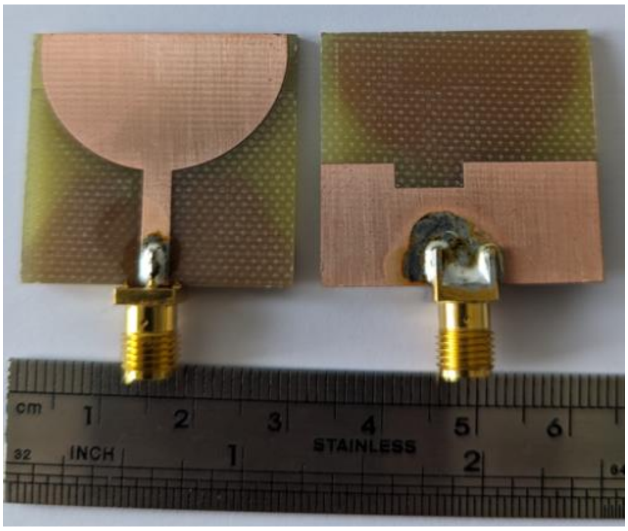


Figure 11. Top and bottom view of the fabricated antenna (After optimization)

Figure 11 photographs the top and bottom view of the fabricated antenna after optimization, whereas *figure 12* shows the comparison between the measured and simulated input reflection coefficients. It can be noticed that both the results are showing are showing reasonably good agreement. This indicates that the optimization approach based on GA and HFSS software is effective for the design of UWB antennas. Nevertheless, small discrepancies were noted in the measured and simulated S11. These inconsistencies are due mainly to the substrate properties (thickness variation of substrate), manufacturing imperfections such as improper soldering, microstrip feed line mismatching, the effect of the SMA connector which may introduce other losses and environmental effect. Such minor deviations are commonly observed in practical antenna development and do not significantly impact the overall assessment of the antenna's performance. Fabricating the prototype at a commercial level of expertise would notably decrease these errors. Overall, in both simulations and measurements, the antenna effectively achieves the desired bandwidth.

5. COMPARATIVE ANALYSIS

Table 5 illustrates a comparison study between newly introduced UWB antennas and the proposed one. This comparison is conducted using key metrics such as antenna size, operating bandwidth, impedance bandwidth, and gain. It is noteworthy that all the antennas in this comparative study were fabricated on FR4 epoxy, since the substrate's characteristics influence significantly the antenna's behavior. This allows to maintain a more accurate assessment and reliability in the comparative analysis.

The proposed UWB antenna, with a size of 28×29 mm², occupies minimum area compared to most of the antennas listed, excepting Ref [27] (20×18 mm²) and Ref [28] (25×25 mm²). Nevertheless, it exhibits better performance such as its very wide frequency band from 3.21 GHz to 17.97 GHz and bandwidth of 14.76 GHz, which is notably broader than all other listed works. as well as an ultra-wide impedance bandwidth of 139.38%. Although few antennas report better maximum gain, the presented antenna ensures a proper range of gain (3.7–6.24 dB), exhibiting the proposed structure as an ideal and efficient option for different UWB applications.

Table 5. Evaluating the proposed UWB antenna in relation to recent research findings

Referred Antenna	Antenna size (mm^2)	Substrate	Operating band (GHz)	Bandwidth (GHz)	Impedance bandwidth (%)	Gain (dB)
[27]	20×18	FR4	3.09 –11.02	7.93	112.40	1.2–5.68
[28]	25×25	FR4	2.29–11.01	8.72	131.13	1.25–2.5
[29]	38.42×38.12	FR4	2.85–11.32	8.47	119.55	4.72– 8.26
[30]	40×40	FR4	2.76 –11.15	8.39	120.63	2–5.3
[31]	27×25	FR4	3.58–13.93	10.35	118.22	2.7–4.7
[32]	24×25	FR4	3.02–9.13	6.11	100.58	2– 3
Proposed	28×29	FR4	3.21–17.97	14.76	139.38	3.7–6.24

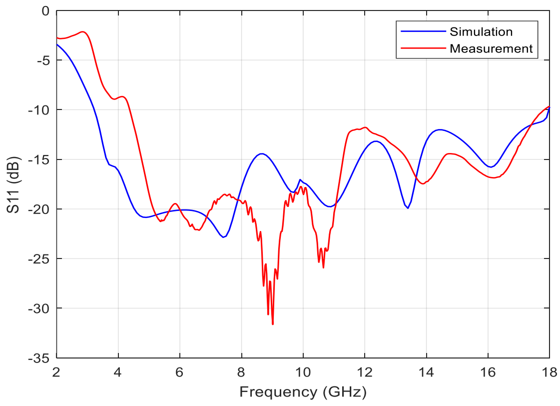


Figure 12. Simulated and measured reflection coefficient of the proposed UWB antenna

5. CONCLUSION

This paper presents an optimization methodology for an ultra-wideband semi-circular antenna using Genetic Algorithms integrated with HFSS. A novel fitness function is introduced, maximizing bandwidth and preventing the occurrence of return loss peaks exceeding a threshold of -12dB in the operating bandwidth. The optimized antenna achieves an ultra-wide bandwidth of 14.70 GHz, with an impedance bandwidth of 139.38% and gain ranging from 3.7 to 6.24 dB.

The comparative analysis indicates that the proposed antenna significantly outperforms other UWB designs in terms of bandwidth and overall performance. Given the increasing demand for high-performance antennas in communication systems, this methodology will enable the design of antennas that perform well across a relatively wide frequency range to support suitably robust and flexible wireless communication networks.

Future work could explore advanced materials, complex geometries, and faster optimization techniques to further enhance performance.

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