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Optimizing Arbitrary Patch Antenna Design Using HFSS Simulation: A Comparative Analysis of FR4 and Rogers Materials

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***Abstract* - The study of arbitrary patch antenna design represents a critical endeavor in the advancement of wireless communications technologies. This study delves into the construction of a random patch antenna using 3D electromagnetic software, namely the HFSS simulation program. By altering the antenna's physical structure, particularly its ground plane and patch section, we hope to enhance the antenna's performance. Antenna efficiency as measured by gain, S11 parameter, and bandwidth is compared between two different materials, FR4 and Rogers, with varying relative permittivity. Advancements in communications systems and technologies have been made possible by optimizing efficiency, reducing antenna size, and improving performance through modifications to the patch antenna's material composition and design.**

Keywords: Arbitrary Patch Antenna, HFSS, FR4, Rogers, Directional Antennas.

I. INTRODUCTION

Antennas are essential elements of contemporary communication systems, facilitating the transfer and reception of electromagnetic waves across different applications and frequencies [1]. Antennas can be categorized into two primary groups: omni-directional antennas and directional antennas [2]. Omni-directional antennas offer extensive coverage and are well-suited for situations that necessitate connection with numerous devices or in circumstances where the orientation of the transmitter or receiver is uncertain or continually shifting. Due to their adaptability and omni-directional coverage capabilities, they are highly suitable for various applications like Wi-Fi routers, cellular base stations, and broadcast radio and television. Directional antennas concentrate their radiation in specific directions, resulting in enhanced signal strength and range in one direction while compromising coverage in other directions [3]. These antennas are well-suited for point-to-point communication, specifically in situations when the precise location of both the transmitter and receiver is known and a link needs to be established over a significant distance. Yagi-Uda antennas and patch antennas are both examples of directional antennas. Directional antennas are frequently employed in several applications, including long-range radio links, satellite communications, and radar systems. These antennas are crucial for optimizing signal strength and avoiding interference.

Patch antennas, which are directional antennas, have become widespread in many applications because they are small in size, easy to integrate with other devices and can be used in many different ways [4]. Patch antennas provide a viable alternative for space-constrained applications, such as mobile devices, IoT systems and satellite communications, where traditional antenna designs may not be practical. Traditional patch antenna systems have drawbacks [5].

- Due to their small bandwidth, they cannot operate over many frequencies.
- Their rectangular or round shapes may not fit into compact or irregular devices.
- Interference and cross-coupling from nearby antennas or structures may occur.

By incorporating arbitrary forms into the design of antennas, it is possible to bypass these limits and create opportunities for enhancing performance metrics and meeting unique application needs. Irregular shapes offer the potential for increased bandwidth and improved performance in difficult working conditions, such as urban or indoor situations. By modifying the geometry of the antenna, it is possible to enhance the gain characteristics and emission patterns, leading to enhanced signal strength and coverage. The objective of this study is to enhance the methods used in designing antennas by tackling the difficulties involved in optimizing patch antennas with irregular shapes. The goal is to obtain optimal performance in different wireless communication applications.

II. RELATED WORK

Multiple studies have examined different aspects of patch antenna design and optimization, including dual-band operation, circular polarization, ultra-wideband (UWB) characteristics, integration of meta materials, optimization algorithms, and applications in emerging communication technologies like 5G and satellite communications. A study presented a microstrip antenna array with dual-band, dual-polarization characteristics and the capacity to scan a wide range of frequencies for millimeter wave applications [6]. The achievement of wide bandwidth and high port isolation is made possible in a compact multi-layer design by the utilization of dual-layer mesh patches along with three sets of metal fences. A 2×2 array prototype was created, produced, and evaluated specifically for beam scanning. The empirical findings are in strong accordance with the computer-generated simulations. This combination offers the advantages of multi-band and broadband capabilities, with two orthogonal polarizations and a competitive range for beam steering. It also has compact dimensions, making it a potential solution for 5G millimeter-wave mobile communications.

A novel antenna design was introduced in [7] to address the issue of interference with narrowband communications in the IR/UWB spectrum (2-3 GHz). The antenna is capable of reconfiguring its bandwidth, making it suitable for IR/UWB applications. A cost-effective, small-sized pulse generator has been developed and manufactured. It utilizes a low-pass filter and a pulse shape filter to produce a narrow pulse with a width of 696 picoseconds and a sub-bandwidth of 133%. This pulse generator is specifically designed for use in an IR-UWB system. The antenna employs changeable diodes to achieve adaptable bandwidth, enabling it to mitigate interference from IR-UWB signals and enhance spectrum usage efficiency for narrowband communications.

The anticipated data rates for low-mobility users in 5G networks are projected to reach 50.0 Gbps, whereas for high-mobility users, the predicted data rates are 5.0 Gbps. Conversely, the objective of the ITU for 5G is to achieve a spectral efficiency that is three times greater than that of Long-Term Evolution (LTE). A comprehensive study was carried out in [8] to assess the influence of 5G antennas on many factors such as antenna size, substrate size/type, gain, efficiency, isolation, and so on. Patch and magnetic antennas have also been utilized in conjunction with various input multi-output arrays (MIMOs). The following concepts have been examined: electric dipole, microstrip grid antenna array, folded dipole, serial feed array, linked antenna array, and MIMO. A printed antenna is introduced in [9] for 28 GHz 5G communication systems. This antenna offers the benefits of compact size and a straightforward geometric design. Both the ground plane and the patch antenna cooler have a rectangular aperture in order to enhance performance and reduce size. The antenna provides a broad operating frequency range and excellent radiation efficiency, while also maintaining a satisfactory level of gain. The impact of parasitic elements on the performance of a MIMO patch antenna was investigated in [10]. Several square parasitic elements have been placed near a rectangular patch element. These parasitic elements have an impact on the distribution of the electromagnetic field, resulting in a decrease in mutual coupling. Furthermore, a broader range of frequencies has been successfully attained. Bigger.

A microstrip patch antenna was developed for high-quality online education and other 5G applications, utilizing 5G millimeter wave bands at a resonance frequency of 26 GHz [11]. A rectangular patch was utilized, which has a dielectric constant of 2.2 and a dielectric loss tangent of 0.0010. The design was simulated and examined utilizing the FEKO software. A Microstrip Patch Antenna was constructed and analyzed at a frequency of 2.4 GHz for potential use in future Wireless communication technologies in [12]. The substrate utilized is Rogers RT/Duroid5880, which has a dielectric loss of 2.2 and a thickness of 0.3451 mm. The antenna design is simulated using the CST studio suite. The objective was to attain a reduced Return Loss, increased gain, and decreased VSWR. The simulation results revealed that the Return Loss, Gain, and VSWR values were -13.89 dB, 6.66 dBi, and 1.50, respectively. Studies highlight the importance of antennas in modern communications systems and the progress made in their design and improvement of their performance standards through improved antenna designs. The focus of this study will be on patch antennas of arbitrary shape.

III. DESIGN PROPOSED PATCH ANTENNA USING HFSS PLATFORM

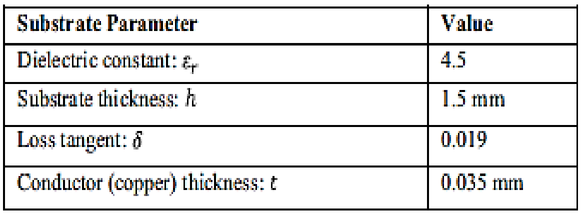
As modern technology is moving day by day at a very fast rate, many platforms and software have been modified and developed in antenna design. High frequency structure simulator (HFSS) will be used as a simulation tool due to its flexibility in formulation and implementation in various fields of electromagnetic simulation, especially antenna modeling and design [13]. HFSS expands the boundaries of antenna design and tends to handle a wide range of numerous EM applications and other peripheral devices.

In this section, we will utilize the HFSS program to design a random patch antenna with an ideal structure. Our main objectives are to achieve maximum gain, minimize the S11 parameter, and maximize the bandwidth of the directional patch antenna. Examine the benefits of focusing radiation in a certain direction and the impact of the material used on the performance of an antenna. At hand key design parameters are specified, including substrate material, patch geometry, ground plane dimensions, feeder structure, and operating frequency (2.4 GHz). To achieve optimal efficiency and desired outcomes, it is necessary to utilize specific materials (substrates) that can enhance the performance of the patch antenna. The modeling process included two materials: FR4 and Rogers.

3.1 FR4

Its low cost and convenient availability are the mainstay of its choice. Table 1 shows the different static parameters related to FR4 [14].

Table 1: Static parameters related to FR4



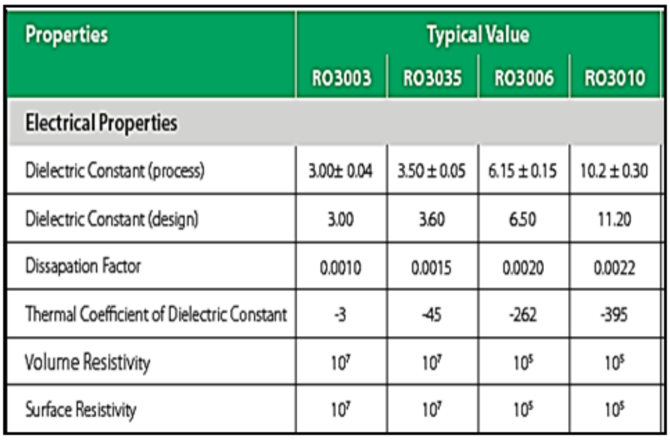
Substrate Parameter	Value
Dielectric constant: ε_r	4.5
Substrate thickness: h	1.5 mm
Loss tangent: δ	0.019
Conductor (copper) thickness: t	0.035 mm

FR4 is commonly employed as an electrical insulator (dielectric) due to its favorable mechanical characteristics and specifications, which include solvent resistance and water absorption properties. These properties are significant in relation to various applications involving dielectric semi conductivity [15].

3.2 Rogers

It has many features that are very convenient for stochastic antenna design simulation tools. There are a large number of classes of materials mentioned by Rogers with slight differences in properties among them. Table 2 shows the characteristics of some of the categories.

Table 2: Static parameters related to FR4



Properties	Typical Value			
	RO3003	RO3035	RO3006	RO3010
Electrical Properties				
Dielectric Constant (process)	3.00± 0.04	3.50 ± 0.05	6.15 ± 0.15	10.2 ± 0.30
Dielectric Constant (design)	3.00	3.60	6.50	11.20
Dissapation Factor	0.0010	0.0015	0.0020	0.0022
Thermal Coefficient of Dielectric Constant	-3	-45	-262	-395
Volume Resistivity	10^7	10^7	10^5	10^5
Surface Resistivity	10^7	10^7	10^5	10^5

The material chosen for the study is Rogers_RO3006. It possesses highly compatible properties that allow for accurate modeling in the controlled construction of the proposed random patch. Figure 1 illustrates the different structures of FR4 and Rogers. Both have a lot of similarities regarding the mechanical properties, same platform (concerning printing on PCBs), etc.

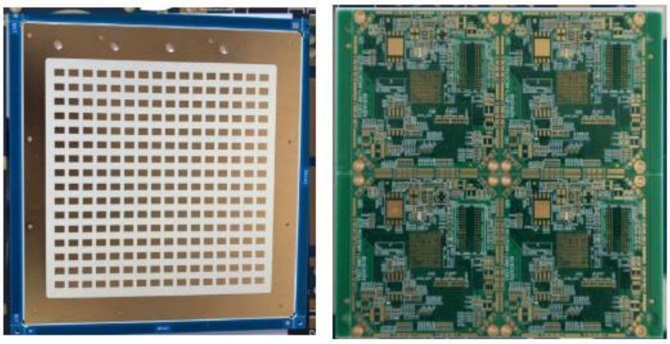


Figure 1: Rogers (left) vs. FR4 (right)

On the other hand; there are still some basic differences between them as shown Table 3.

Table 3: Main differences between FR4 and Rogers RO3006

Rogers RO3006	FR4
Tightly controlled electrical features with a stability across a broad BW	Less regular electrical features
Precisely and accurate controlled relative permittivity (insulator constants)	Dielectric constant or relative permittivity $\varepsilon_r = 4.2 - 4.6$ at $1 MHz$, and above 5 at higher frequencies depending on the resonance of the material
Very low loss tangents	Loss tangent approximately 0.02 at 1 MHz and increases obviously when frequency increases
Very suitable thermal conductivity in order to control the dissipation of heat	Thermal conductivity is low (0.25 W/mK)
Expensive	Low cost
Very harmonized and tight material property consistency from batch to batch	Moisture absorption is moderate towards high (maximum 0.2%)

3.3 Arbitrary Patch Antenna Design

This section shows the main outline of the prototyping, taking into account that the work consists of two categories during orientation, one of which is responsible for the FR4 material and the other is responsible for the Rogers material, mainly RO 3006 type. Then the basics and backbone of the design are installed and implemented starting from the ground level up to the line. Nutrition that passes through all intermediate mechanisms from multiple lines of ingredients, substrates, excitation feeders, zones, etc. The proposed methodology includes the following steps:

- Starting by preparing the ground plane either made up of FR4 substrate or Rogers, related to the patch antenna for the modeling.
- Draw a path using a polyline. To make measurements and calculations simpler, the length of a single edge or edge is assumed to be “a” in “mm”.
- The substrate design consists of two basic parts for the proposed arbitrary patch antenna: the ground plane and the patch. Figure 2 shows the case of the FR4 substrate on the other hand the content in Figure 3 shows the case of the Rogers material such that it is the same layout with a different distinct substrate.

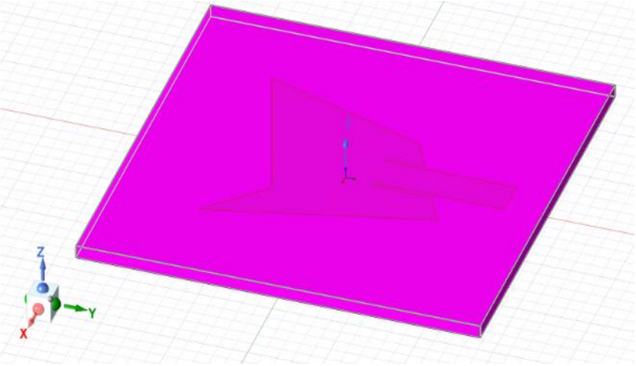


Figure 2: FR4 substrate (patch + ground plane)

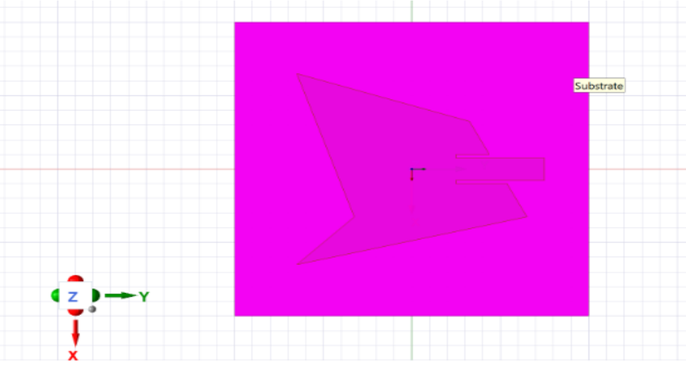


Figure 3: Rogers_RO3006 substrate (patch + ground plane)

- Achieving the approach concerned with the excitation point and the lumped port which are two concepts in one context with a direction and proportional relationship to the edge extended from the ground plane to the initial feed line path; it’s responsible also to attain the targeted operating frequency and plays an essential role in detecting and recognizing the main point of the antenna’s radiation.
- A radiation surface or zone for an integrated hybrid mass antenna system (patch + ground) must be implemented as a means of avoiding unlimited or infinite radiation. For this reason, certain box or fence-like boundaries were included, to reach a certain radiation limit and increase the speed of the simulation process.
- Fulfilling the whole region as a next stage dealing with the radiation issue.
- A margin should be made for the emitter feed line, which completes the antenna input impedance matching control, the latter also related to the antenna geometry, shape, characteristics and properties. In Figure 4, an illustration of the feed line is given. The length of this line usually also affects the phase of the signal wave in question.

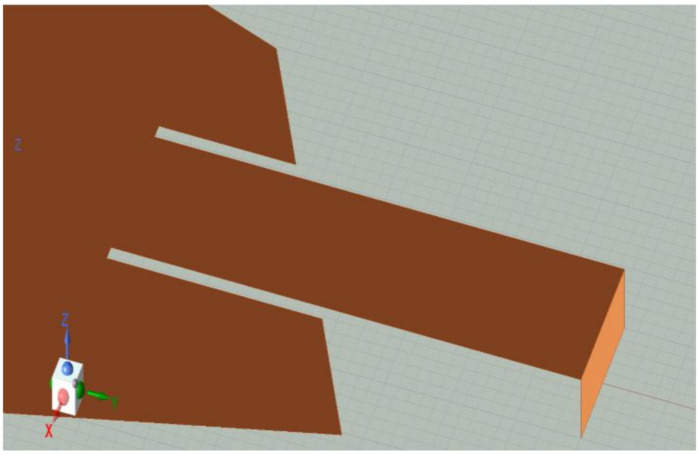


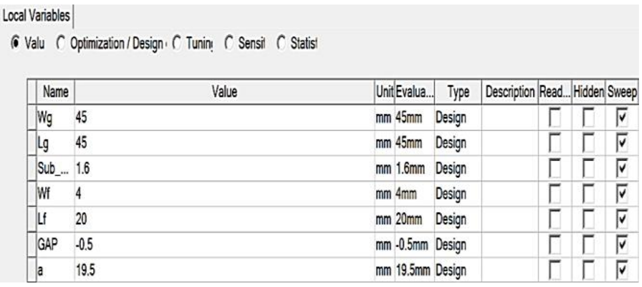
Figure 4: Length of the feed line

IV. SIMULATION AND RESULTS

In order to optimize the performance of the antenna in terms of three main requirements (gain, S11 parameter and the pattern of the radiation), the material used in the antenna will be modified. Initially, the antenna will be modeled using FR4 material, and once the desired results are obtained, it will be replaced with Rogers RO3006 material. Discounts in both categories will be acknowledged and analyzed, taking into consideration the operating frequency of 2.4 GHz.

4.1 Simulation with FR4

In this simulation, the dielectric constant of FR4 is set as 4.4, such that $\varepsilon\_r=4.4$. We started by calculating and measuring the area of the ground level, and the square shape was chosen for the latter to make the work simpler, clearer, and more executable. After that, start changing the relevant parameters. Figure 5 represents the initial values of parameters during the design of the proposed ground plane antenna in the case of FR4 material.



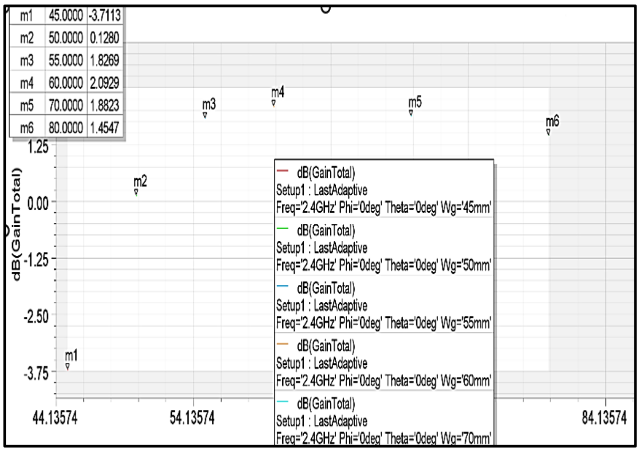
Local Variables

● Valu ○ Optimization / Design ○ Tunin ○ Sensit ○ Statist

Name	Value	Unit	Evalua...	Type	Description	Read...	Hidden	Sweep
Wg	45	mm	45mm	Design		☐	☐	☑
Lg	45	mm	45mm	Design		☐	☐	☑
Sub_...	1.6	mm	1.6mm	Design		☐	☐	☑
Wf	4	mm	4mm	Design		☐	☐	☑
Lf	20	mm	20mm	Design		☐	☐	☑
GAP	-0.5	mm	-0.5mm	Design		☐	☐	☑
a	19.5	mm	19.5mm	Design		☐	☐	☑

Figure 5: Primitive values of the parameters during the design of the proposed ground plane antenna in the case of FR4 material

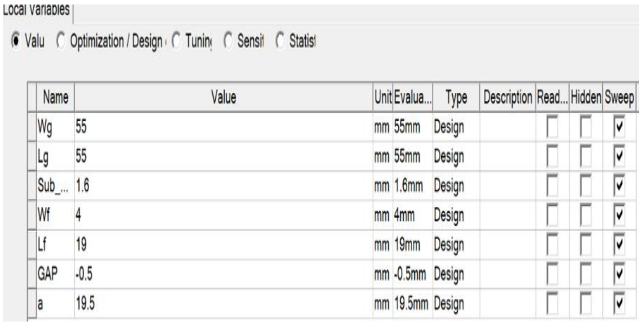
W_(g) and L_g represents the width and length of the ground plane, respectively, knowing that they are equal (in the case of a square shape). The results in Figure 6 show that at W_g=L_g=45 mm, a gain equal to -3.7113 dB is achieved, which changes as you continue to change the measurements in the design and increase the floor length or width until it reaches 80 mm.



m1	45.0000	-3.7113
m2	50.0000	0.1280
m3	55.0000	1.8269
m4	60.0000	2.0929
m5	70.0000	1.8823
m6	80.0000	1.4547

Figure 6: Different gain values with respect to disparity in ground plane lengths

After completing the simulation of the ground plane with all calculations related to its area, the second part (patch) of the hybrid antenna system was achieved. Different variants of the correction-related parameters are shown in Figure 7.



Local Variables

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Name	Value	Unit	Evalua...	Type	Description	Read...	Hidden	Sweep
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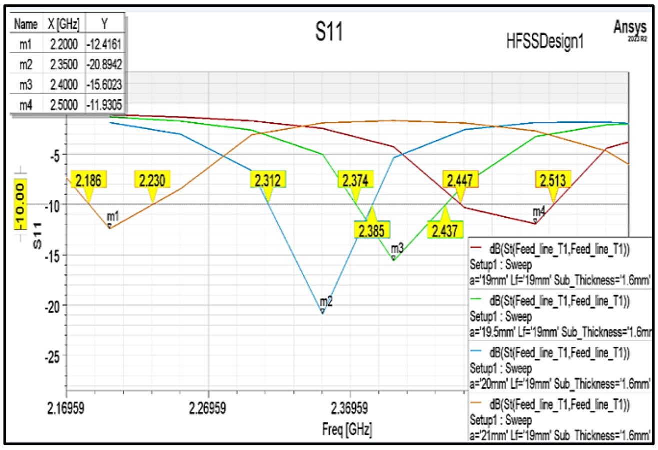
Lg	55	mm	55mm	Design		☐	☐	☑
Sub_...	1.6	mm	1.6mm	Design		☐	☐	☑
Wf	4	mm	4mm	Design		☐	☐	☑
Lf	19	mm	19mm	Design		☐	☐	☑
GAP	-0.5	mm	-0.5mm	Design		☐	☐	☑
a	19.5	mm	19.5mm	Design		☐	☐	☑

Figure 7: Primitive values of the parameters during the design of the proposed patch antenna in the case of FR4 material

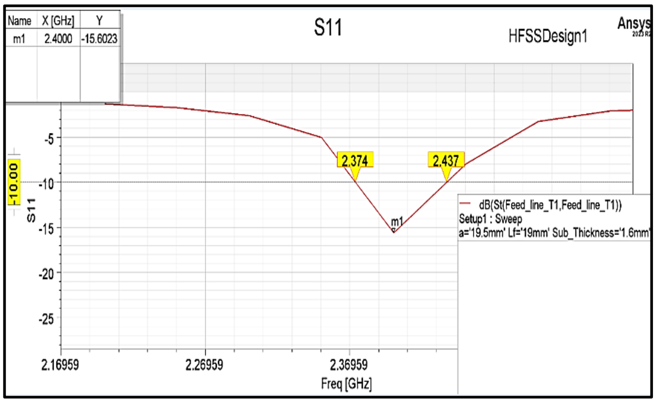
In Figure 8 and according to the table of variables, for different values of “a”, the parameters of S11 are plotted given that L_f is the length of the feed line set to 19 mm.



Name	X [GHz]	Y
m1	2.2000	-12.4161
m2	2.3500	-20.8942
m3	2.4000	-15.6023
m4	2.5000	-11.9305

Figure 8: S11 parameter plot with respect to frequency with variations in “a” parameter

Some adjustments were made to try to reach the desired operating frequency. The "a" was changed to 19.5mm, and the frequency was 2.4GHz. In Figure 9, a clear representation of parameter S11 with the desired frequency (2.4 GHz) is shown.



Name	X [GHz]	Y
m1	2.4000	-15.6023

Figure 9: S11 parameter at the desired resonance frequency (2.4 GHz) using FR4

Another aspect that is highly related to the proposed antenna design is the effect of substrate thickness. On the FR4 substrate the thickness of the PCB it is dealing with is set to 1.6mm initially so that the gain is only about 1dB. The substrate thickness is adjusted and it is observed that the increase in substrate thickness not only increases the gain, but also causes the frequency to shift from 2.35 GHz to 2.3 GHz. The maximum gain reached is 5.98 dB with respect to the substrate thickness step. The beam-width plot in Figure 10 shows that the maximum gain achieved is 6.1 dB at 0°, subtracting it from 3 dB with the BW rule, we get a result of 3.09 dB (about 3.1 dB). By using the marker where the magnitude (gain) is 3.1 dB, we can see the angle obtained is 44 degrees.

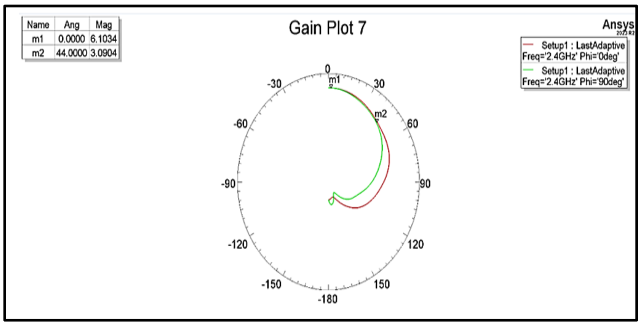


Figure 10: Beam-width with an angle44 at magnitude 3.1 dB using FR4

In the final steps adjustments were made to various parameters as a way to reach the optimum for the proposed arbitrary patch antenna design. Figure 11 is the expanded representation of the final design with respect to the FR4 substrate, where the final values were obtained with the maximum gain attained.

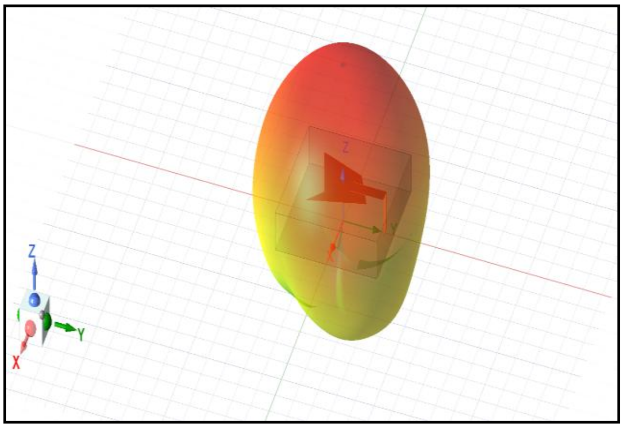
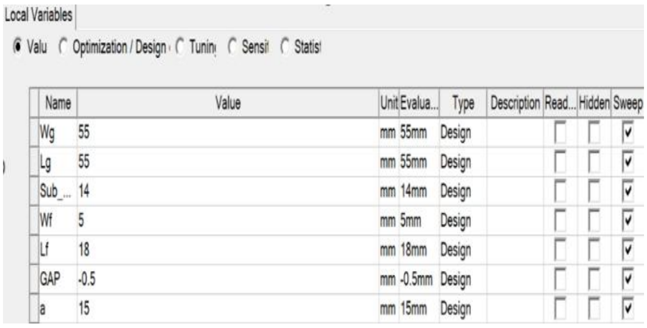


Figure 11: Whole design of the antenna with the maximum gain attained using FR4

The table in Figure 12 shows the final setting of the parameter values as a means of obtaining the manufactured antenna based on these values.



Name	Value	Unit	Evalua...	Type	Description	Read...	Hidden	Sweep
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Lg	55	mm	55mm	Design		☐	☐	☑
Sub_...	14	mm	14mm	Design		☐	☐	☑
Wf	5	mm	5mm	Design		☐	☐	☑
Lf	18	mm	18mm	Design		☐	☐	☑
GAP	-0.5	mm	-0.5mm	Design		☐	☐	☑
a	15	mm	15mm	Design		☐	☐	☑

Figure 12: Final values of the parameters that may be used for the antenna's fabrication in the case of FR4 material

4.2 Simulation with Rogers

In order to obtain the desired results from dealing with Rogers; The same steps as were performed with FR4 material were repeated in chronological order for the entire modeling (ground plane area, patch area, feed line length, substrate thickness, etc.). Some adjustments have been made to try to reach the desired operating frequency. In Figure 13, a clear representation of parameter S11 at the desired frequency (2.4 GHz) is shown.

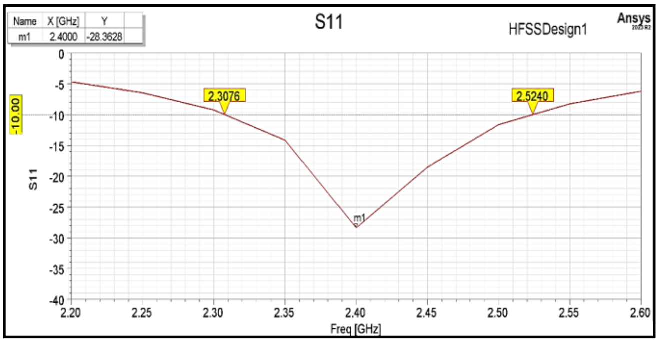


Figure 13: S11 parameter at the desired resonance frequency (2.4 GHz) using Rogers

Figure 14 shows that the optimal beam-width was obtained with an angle of 56 degrees at magnitude of 3 dB.

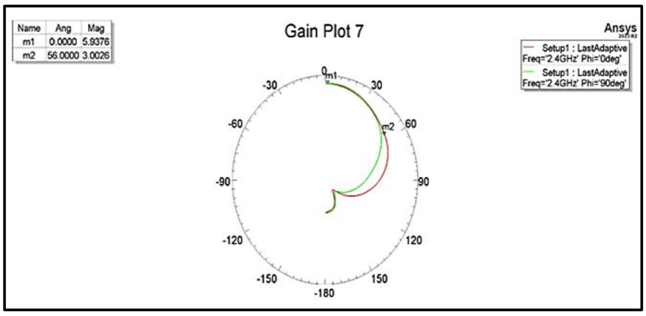


Figure 14: Beam-width with an angle 56at magnitude 3 dB using Rogers

Figure 15 is the expanded representation of the final design with respect to the Rogers substrate, where the final values were obtained with the maximum gain attained.

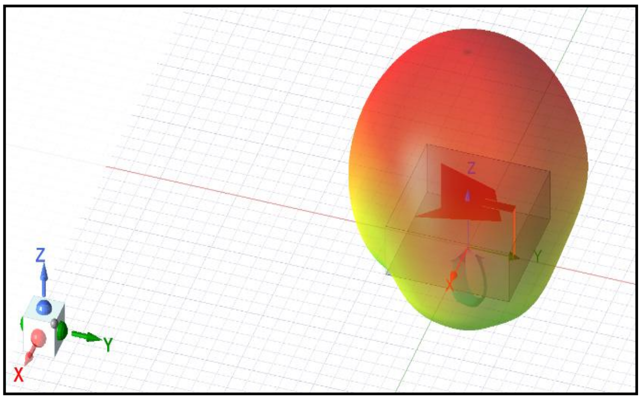
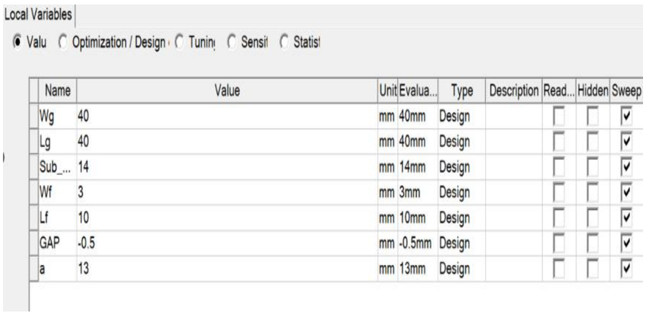


Figure 15: Whole design of the antenna with the maximum gain attained using Rogers

Figure 16 displays the important variables of the various parameters that can be used as references for the targeted modeling of the antenna. This is necessary in order to obtain the fabricated structure of the proposed arbitrary antenna using the Rogers substrate following the implemented approach.



Local Variables

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Name	Value	Unit	Evalua...	Type	Description	Read...	Hidden	Sweep
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Lg	40	mm	40mm	Design		☐	☐	☑
Sub_...	14	mm	14mm	Design		☐	☐	☑
Wf	3	mm	3mm	Design		☐	☐	☑
Lf	10	mm	10mm	Design		☐	☐	☑
GAP	-0.5	mm	-0.5mm	Design		☐	☐	☑
a	13	mm	13mm	Design		☐	☐	☑

Figure 16: Final values of the parameters that may be used for the antenna's fabrication in the case of Rogers material

4.3 Results

Upon designing a patch antenna using both FR4 material and Rogers RO3006 material, it was determined that the key characteristics of the antenna remain consistent. This is due to the fact that the relative permittivity of FR4 is lower than that of Rogers RO3006. The results suggest that the patch area related to Rogers is less compared to the FR instance. Thus, the obtained values for both the maximum gain and parameter S11 in both simulated situations are identical (or nearly identical with a negligible difference). It is worth noting that the achieved gain is 6 dB and the S11 parameter is -29 dB with an increase in the beam-width in Rogers' case (56 degrees) after it was 44 degrees in FR 4 case. Upon examining the ground plane and patch areas for each scenario, it is evident that the overall completed area of the completely hybrid integrated random patch antenna is less when using the Rogers substrate compared to the FR4 substrate.

V. CONCLUSION

The importance and spread of directional patch antennas in various communications applications is due to their small size, ease of integration, and directional radiation patterns. Specific application requirements can be met by designing patch antennas with arbitrary shapes and optimizing antenna performance parameters to better suit the requirements of modern communications scenarios. This study examines the design and analysis of patch antennas with various shapes using 3D electromagnetic software. It specifically compares the use of FR4 material and Rogers RO3006 material, and evaluates how differences in substrate material impact important antenna properties, such as gain and the S11 parameter. The performance of patch antennas is significantly influenced by the relative permittivity of the substrate materials used in their design. Nevertheless, despite variations in the patch area, the fundamental attributes of the antennas remained consistent. Both simulations generated the same maximum gain of 6 dB and S11 parameter of -29 dB, with beam-width increasing from 44 degrees (FR4) to 56 degrees (Rogers). Moreover, examination of the ground plane and patch regions indicated that the overall plenum area of the hybrid integrated patch antenna was less when employing Rogers RO3006 material in contrast to FR4. This implies that Rogers' material might have benefits in decreasing the size of the antenna while still achieving the acceptable performance standards. This study emphasizes the significance of fundamental material selection in the design of patch antennas and showcases the capacity of patch antennas with arbitrary shapes to attain maximum performance in wireless communication systems. The findings enhance comprehension of antenna design factors and offer valuable perspectives on enhancing antenna efficiency by selecting appropriate materials and manipulating geometric properties. It is feasible to develop an anti-jamming technology in the future by implementing diversity and beam forming methods. This involves using hybrid polarized antennas on both the transmitter and receiver for diversity, and employing adaptive filtering with a patch antenna array system either during transmission or reception. In order to mitigate the effects of conflicting signals and minimize noise disruptions.

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