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Performance Evaluation of Rectangular Microstrip Patch Antenna Using Different Substrate Materials for 5G Applications

O. Olabisi[1], O.A Aremu[2], O.A Ajeigbe[3], O.S Ajao [4], S.O Areo [1] and S.S Adebisi[5].

[1]*Deparment of Science Laboratory Technology, Ladoke Akintola University of Technology, Ogbomoso, Oyo state, Nigeria.*
[2]*Department of Physics, The Polytechnic, Ibadan, Oyo state, Nigeria.*
[3]*Department of Electrical and Electronics, Ajayi Crowder University Oyo, Oyo state, Nigeria.*
[4]*Department of Science Laboratory Technology, Oke-Ogun Polytechnics, Saki, Oyo, Nigeria*
[5]*Deparment of Pure and Applied Physics, Ladoke Akintola University of Technology, Ogbomoso, Oyo state, Nigeria.*
Email: oolabisi@lautech.edu.ng, soareo60@lautech.edu.ng and adebisisegun1999@gmail.com.

ABSTRACT

This research investigates the intricate relationship between various substrate materials and the performance of rectangular microstrip patch antennas tailored for 5G applications at 3.5 GHz. The study focuses on three different substrate materials: FR-4 Epoxy, Rogers RO4350B, and Duroid 588. The HFSS software was utilized to design and simulate the antenna.FR-4 Epoxy, characterized by a 4.4 dielectric constant, exhibits a peak gain of 2.7254 with a wider bandwidth, catering to the demands of higher data rates in 5G communication. Rogers RO4350B, with a higher dielectric constant of 3.55 shows a peak gain of 5.1166. Duroid 5880 with 2.22 as dielectric constant produces a gain of 6.0338 and strikes a balance between these factors, offering competitive performance in terms of both bandwidth and size efficiency. This research provides valuable insights into optimizing rectangular microstrip patch antennas for 5G applications, contributing to the ongoing advancements in wireless communication technologies. The findings offer guidance for engineers and researchers working on the design and implementation of efficient antennas for the evolving landscape of 5G networks. The findings indicate that the highest gain is achieved by Duroid, which has the lowest dielectric constant, along with a broad beam radiation pattern. Rogers follows closely behind, while FR-4 has the lowest gain among them.

Keywords: *Duroid, FR-4, Rogers, Microstrip patch antenna, 5G, HFSS*

1.0 Introduction

Wireless technology has become an integral part of daily activities and transactions, playing an important role in people's lives. As a result, the demand for high data rate services with enhanced capabilities has increased. The volume of mobile data traffic has grown rapidly, and research predicts that this trend will continue due to high demand. Despite reducing latency and increasing data rates, the Fourth Generation (4G) technology cannot meet current needs [1],[2]. There is a need for faster data rates and reduced latency as more and more devices are interconnected for data transmission purposes. The evolution of Fifth Generation (5G) technology has the potential to address this demand by using millimeter wave (mmWave) frequencies to offer unprecedented high spectrum performance, bridging the limiting performance of 4G technology [3].

A microstrip patch antenna is a type of antenna that utilizes a dielectric substrate with a conducting medium on either side. The substrate is a crucial element in the design of the antenna, as it determines both the radiating range and the overall size of the structure [4]. The patch, located on the upper side of the substrate, is the radiating element of the antenna, while a lower conducting material serves as the ground plane [5]. The size of the patch is determined by the dielectric constant of the substrate, and there are several shapes available, including hexagonal, circular, square, and rectangular. In this instance, a rectangular patch was chosen for the antenna design due to its superior performance. The physical and electrical dimensions of the antenna are determined by the thickness of the substrate and its dielectric constant [6][7].

Different substrates like RT-Duroid, FR-4, and Rogers are used for the performance evaluation of microstrip patch antennas. The performance of the antenna is determined by the size of the substrate. To increase the antenna efficiency and bandwidth, thicker substrates containing low dielectric constant are used in an antenna design. However, this results in a larger antenna size, which limits its use in other smart applications. For this reason, thinner substrates with higher dielectric constants are used, which provide a smaller antenna size but a reduction in antenna efficiency and bandwidth. Therefore, it is important to design an optimized antenna based on the application in which it will be used.

2.0 DIELECTRIC SUBSTRATE

The descriptions of the three substrate materials used with their dielectric constants are explained

2.1 FLAME RETARDANT - 4 (FR-4)

FR-4 is a high-pressure thermoset plastic that is flame retardant and provides excellent mechanical strength and weight ratio. It is commonly used in transformers, switches, printed circuit boards, and relays as an electrical insulator with exceptional mechanical strength. FR4 is a useful material for electrical insulation with mechanical strength.

The FR-4 glass epoxy is a common substrate material that has a high-pressure thermoset plastic laminate grade with excellent strength-to-weight ratios. The FR-4 has a dielectric constant of 4.3 and a loss tangent (tanδ) of 0.025 as loaded from the HFSS software [8].

2.2 RT-DUROID 5880

RT-Duroid composites are specifically designed for precise strip line and microstrip circuit applications. This material has a low density, low electrical loss, and is highly reliable with low moisture absorption. It is also lightweight and has a dielectric constant 2.2, which provides a wide frequency range. RT-Duroid is commonly used in military radar systems, space satellite transceivers, and ground and airborne-based radar systems. The RT-Duroid is one of the most widely used substrate materials among the five substrate materials due to it is excellent chemical resistance, ease of fabrication, and environment friendly. It has a dielectric constant of 2.2 and a loss tangent of 0.0004 as loaded from the HFSS software [9].

2.3 ROGERS RO4003C

The RO4003 is a type of High-Frequency Circuit Material that is specifically designed for commercial applications, with glass-reinforced hydrocarbon or ceramic laminates that provide high sensitivity and volume. According to the HFSS software [10], this material has a dielectric constant of 3.38 and a loss tangent of 0.0027. Each of the five antenna models created utilizes a different dielectric constant, resulting in varying antenna model parameters. Another variation of the RO4003 material is the RO4003 Series, which is also designed with high sensitivity and volume for commercial use. This material has a dielectric constant of 3.38 and a loss tangent of 0.0027 as loaded from the HFSS software [11]. The antenna model parameters for each of the five antennas are modified based on different dielectric constants. Table 1 below [12] presents a summary of the various properties of the dielectric substrates used.

Table 1: Properties of Different Substrate Materials

Parameters	**FR4 (Glass Epoxy)**	**ROGERS RO4003C**	**RT DUROID 5880**
Dielectric Constant	4.3	3.38	2.2
Loss Tangent	0.025	0.0027	0.0004
Water Absorption	< 0.25%	0.06%	0.002%
Tensile Strength (MPa)	310	1.41	450
Breakdown Voltage (kV)	55	< 50	> 60
Peel Strength (N/mm)	9	1.05	3.5
Density(kg/m3)	1850	1.790	220
Thermal Conductivity(w/m-k)	0.29	0.95	1

3.0 Antenna design

The design of the antenna was created using the HFSS software platform. A microstrip is used to feed the patch of the antenna. This is because the microstrip feed provides good impedance matching between the patch and transmission line. The length and width of the patch vary depending on the substrate, and the length and width of the ground plane will be equal to that of the substrate. To create the proposed antenna design, a rectangular patch that is 0.04mm thicker with a microstrip feed is attached to a substrate layer with a thickness of 1.6mm and a dielectric constant that varies based on the substrate used. On the other side of the substrate, a ground plane of 0.04mm is attached [13].

ANTENNA DESIGN

The antenna has been specifically designed to operate at a frequency (fr) of 3.5 GHz, which is the frequency commonly used for 5G applications. The length and width of the MPA have been calculated based on the height and dielectric constant of the substrate. As a result, the patch height is 0.04mm and the dielectric substrate (h) height is 1.6mm [15,16].

Patch Width (W): $$W = \frac{c}{2fr}\sqrt{\frac{2}{\varepsilon r+1}} \quad (1)$$

Where *c* is the velocity of light, *W* is the width of the patch for the operating frequency *fr*, and dielectric constant εr.

Effective Dielectric Constant ($\varepsilon reff$): It is possible to use the effective dielectric constant to determine the length of the patch. However, in reality, due to the fringing effect, the antenna's field will extend beyond the length and width of the antenna dimension. As a result of the fringing field along the edges of the antenna patch, the effective dielectric constant reff is modified.

$$\varepsilon_{reff} = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}\left[1 + \frac{12h}{W}\right]^{-1/2} \quad (2)$$

Patch Length Extension (ΔL): Due to the fringing effect on the other side or at the end of the patch, an additional line length is needed. Thus, patch length extension is evolved.

$$\Delta L = 0.412h\,\frac{[\varepsilon reff+0.3]}{[\varepsilon reff-0.258]}\,\frac{\left[\frac{W}{h}+0.264\right]}{\left[\frac{W}{h}+0.8\right]} \quad (3)$$

Effective Patch Length (Leff): Effective Patch Length is the actual length of the antenna design which includes the length of the antenna and twice the length extension.

$$L_{eff} = \frac{c}{2fo\sqrt{\varepsilon reff}} \quad (4)$$

Patch Length (L):

$$L = L_{eff} - 2\Delta L \quad (5)$$

Substrate Width (*Ws*) and Ground plane Width (*Wg*):

$$Wg = Ws = 6h + W \quad (6)$$

Substrate Length (*Ls*) and Ground Plane Length (*Lg*):

$$Lg = Ls = 6h + L \quad (7)$$

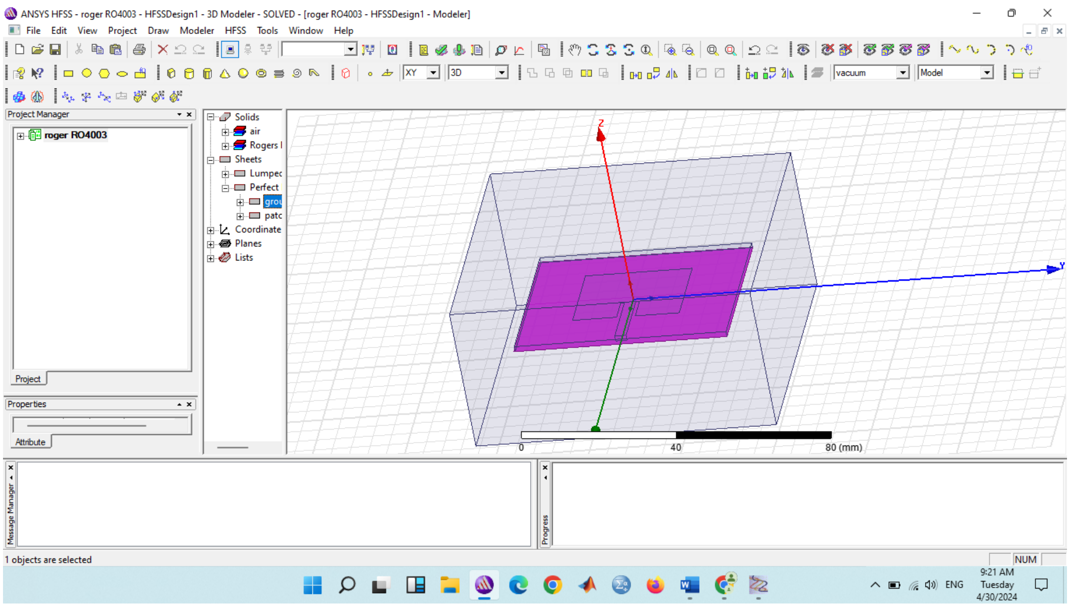

Figure 1: Design of rectangular patch antenna

Equations (1) to (7) describe how to calculate the width and length of a rectangular patch antenna for various substrates. Table 2 displays the dimensions of the rectangular MPA for different substrates. The equations reveal that the antenna's size is influenced by the dielectric constant and substrate height used in the antenna design. The assessment involves six different substrates, each with varying dielectric constants but the same substrate height. Tangential losses are present in the surroundings of each substrate. The patch and ground plane have a thickness of 0.04 mm, while the substrate has a thickness of 1.6 mm [15, 16]. The proposed antenna designs are based on the patch antenna dimensions presented in Table 2, with the dimensions of the rectangular MPA varying according to the substrate materials employed.

Table 2: Dimension of the Rectangular MPA

Substrate	Dielectric Constant	Length (mm)	Width(mm)
FR-4	4.4	19.99	26.08
Duroid	2.2	28.04	33.88
Rogers	3.55	22.22	28.41

4.0. SIMULATION RESULTS

The antenna design parameters were obtained using the HFSS software, operating at a frequency of 3.5 GHz. The simulated parameters for the antenna are described below. The antenna's performance was evaluated based on several indicators, including return loss, radiation efficiency, VSWR, gain, and bandwidth. The figures below display graphs depicting the designs for all three antennas at 3.5 GHz.

FLAME RETARDANT – 4

FR-4 substrate provides a peak gain of 4.3834dB with a return loss value of -34.5868 dB and bandwidth of 0. 2575 GHz at 3.5 GHz as shown in Figures 2 and 3. Figure 4 represents the VSWR value of 0.3240.

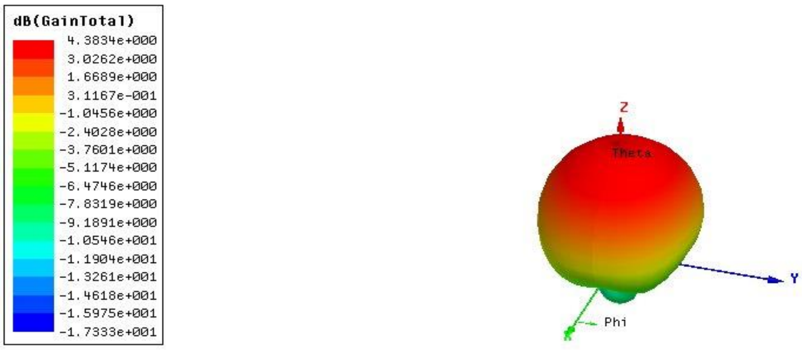

Figure 2: FR-4 gain in 3D

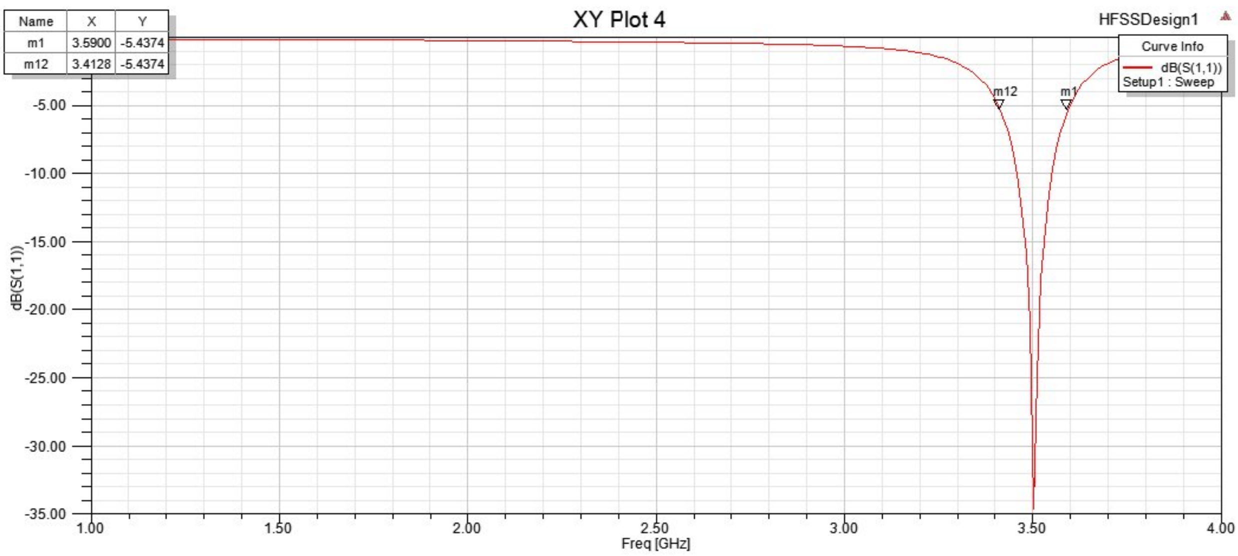

Figure 3: FR-4 Bandwidth

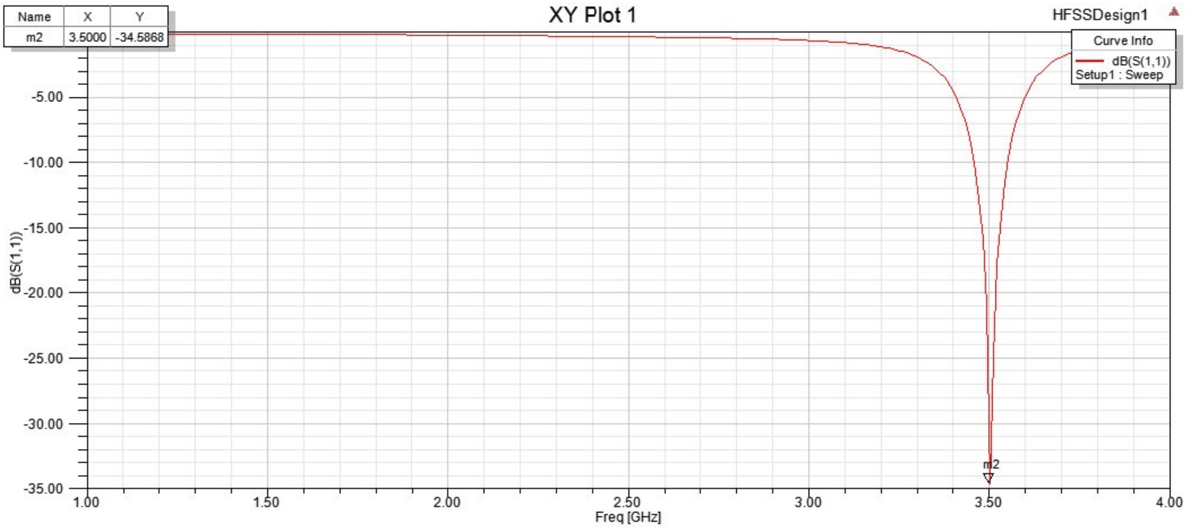

Figure 4: FR-4 Return loss

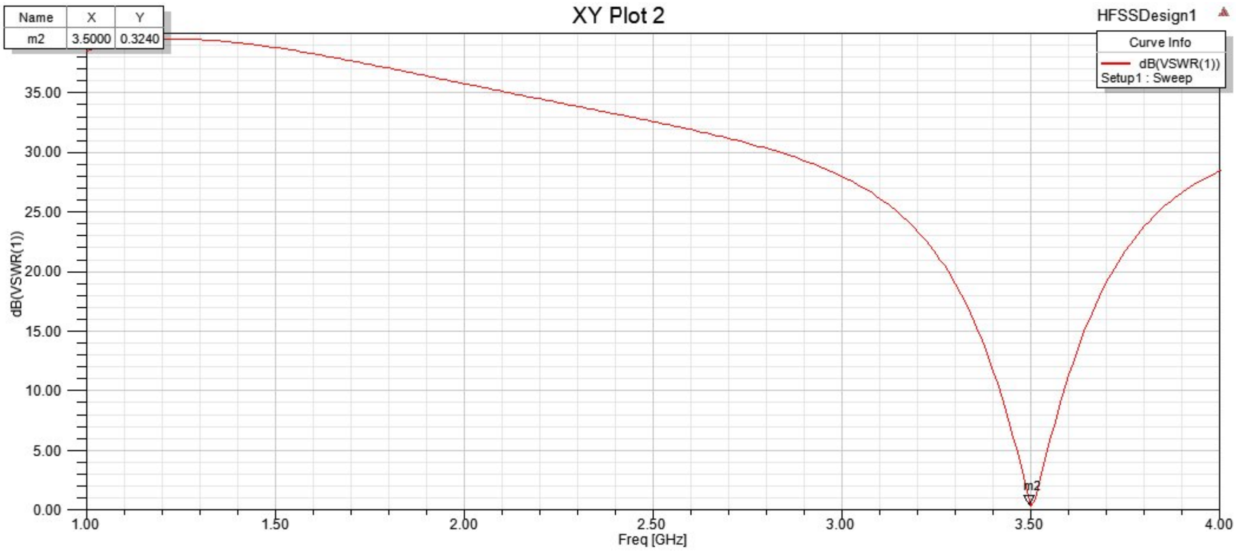

Figure 5: FR-4 VSWR

RT-DUROID

Figure 5 shows that the RT-Duroid substrate provides a gain value of 8.1182 dB and a bandwidth of -2.1887 GHz. Figure 6 represents the VSWR value of 0.6297, while Figure 7 represents the return loss value of -28.818 dB.

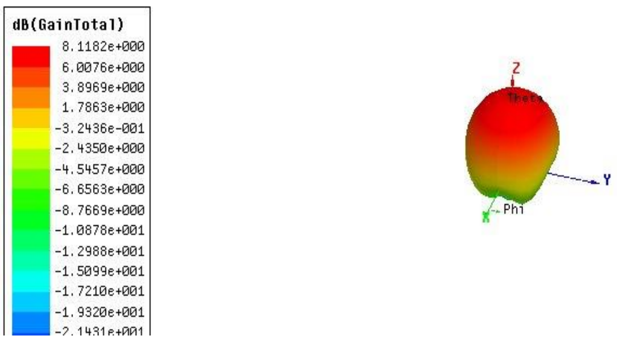

Figure 6: Duroid Gain

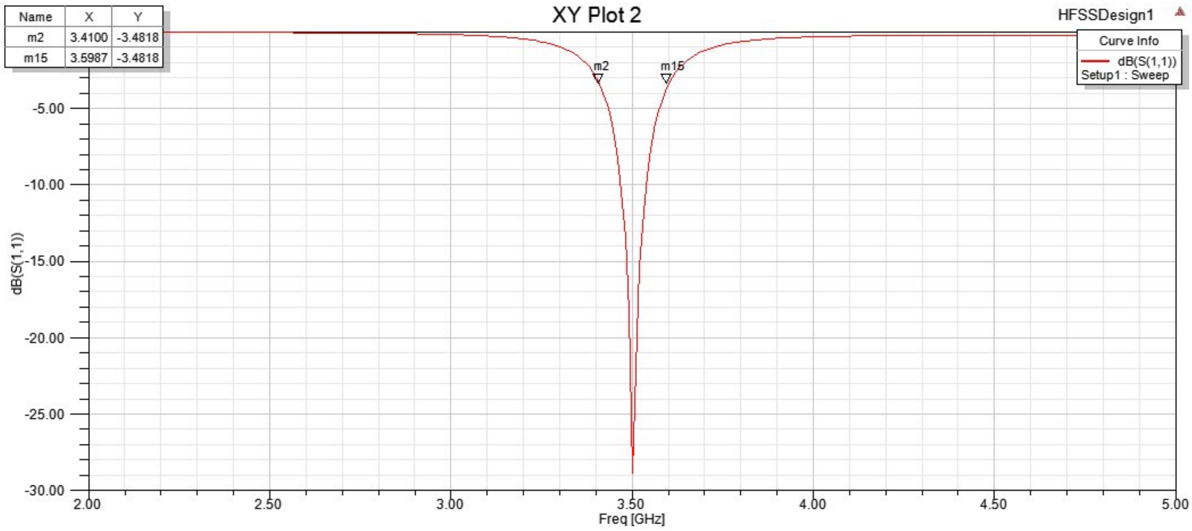

Figure 7: Duroid Bandwidth

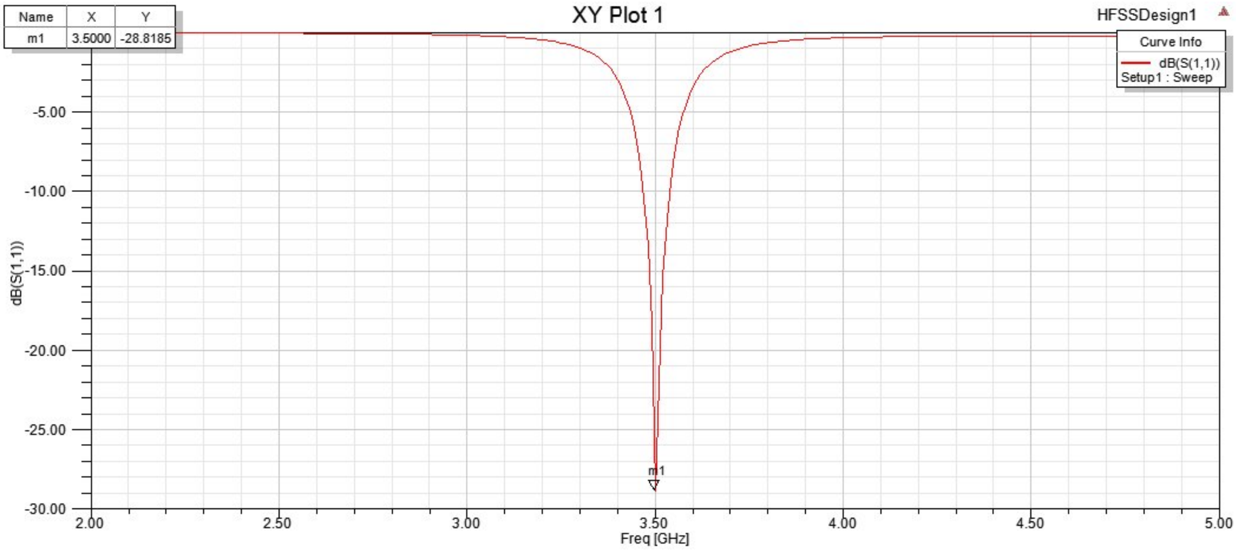

Figure 8: Duroid Return loss

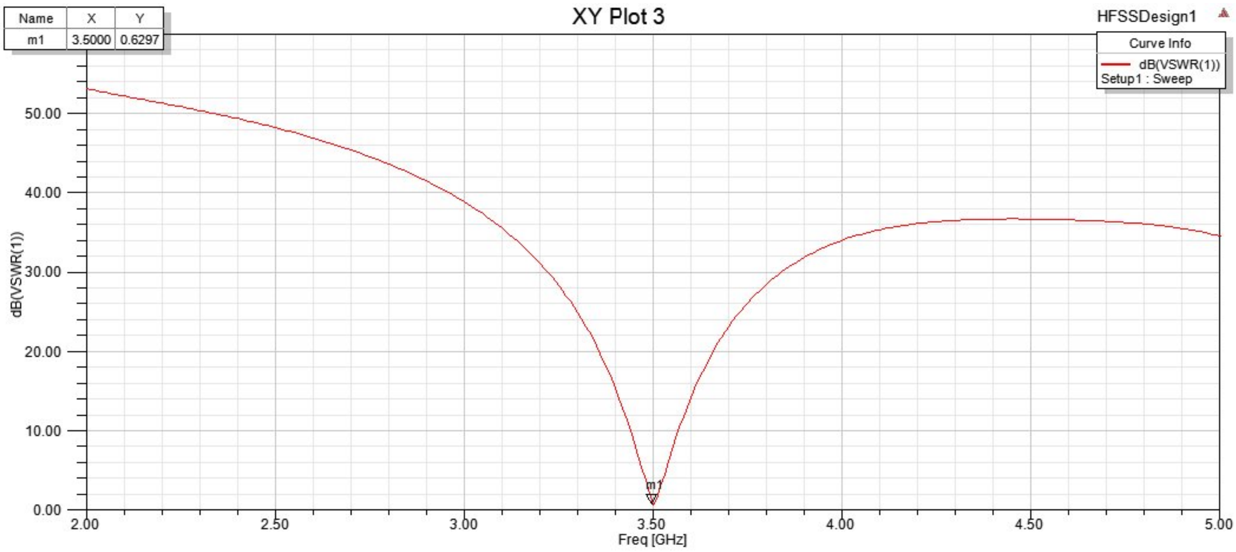

Figure 9: Duroid VSWR

ROGERS

The substrate design of Roger's antenna provides a gain value of 7.1234 dB and a bandwidth value of 0.2575 GHz for an operating frequency of 3.5 GHz. As shown in Figures 8, 9, and 10, the antenna also provides a VSWR value of 1.7690. Additionally, Rogers substrate is resistant to chemical attacks and has more strength.

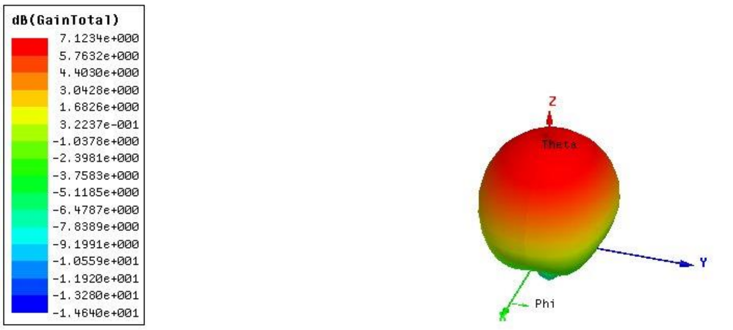

Figure 10: Rogers gain

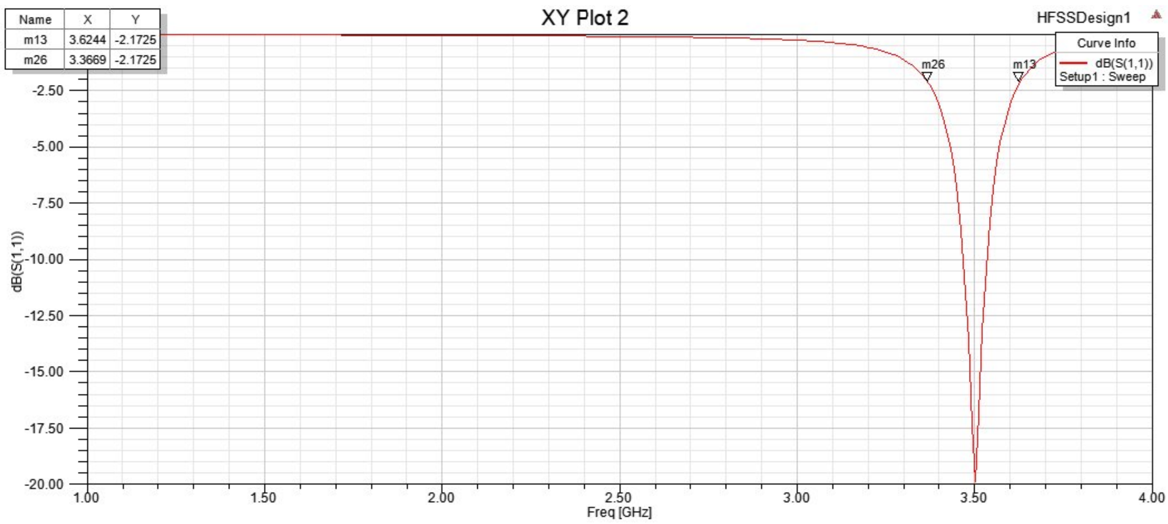

Figure 11: Rogers Bandwidth

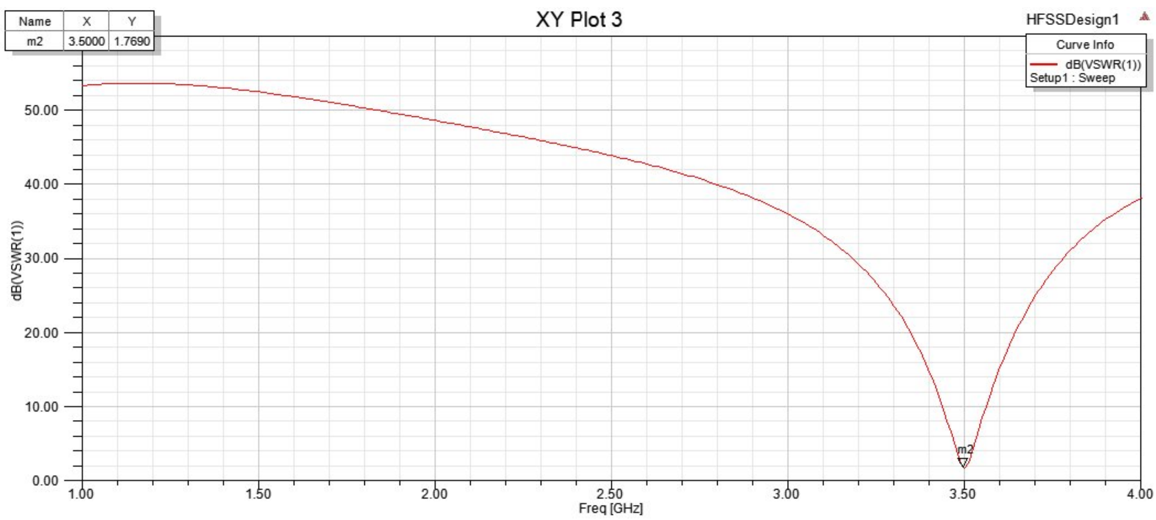

Figure 12: Rogers VSWR

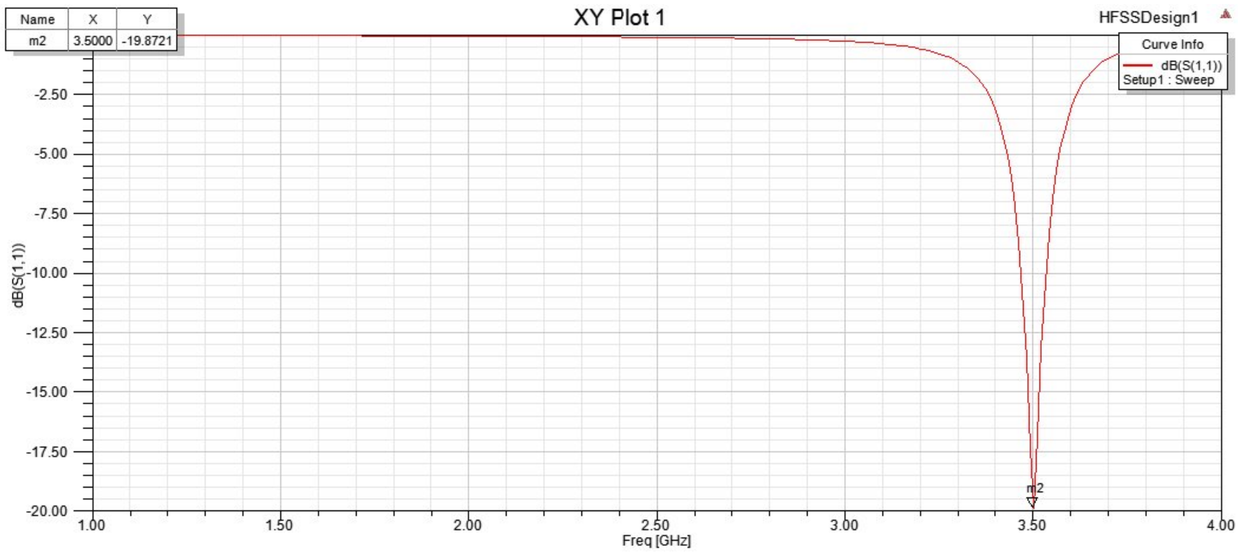

Figure 13: Rogers Return loss

Table 3: Simulation Output for different substrates

Substrate	Peak Gain(dB)	Return loss(dB)	VSWR(dB)	Bandwidth (MHz)
FR-4	4.3834	-34.5868	0.3240	260
Duroid	8.1182	- 28.818	0.6297	270
Rogers	7.1234	-19.8721	1.7690	210

CONCLUSION

A rectangular MPA has been designed in this paper, using different substrates such as FR-4, RT-Duroid, and Rogers, all for the same frequency of 3.5 GHz. The simulation results show that the proposed antenna design provides the best return loss and bandwidth for the substrate with a reduced dielectric constant. As a result, it can be concluded that the rectangular MPA design made of RT-Duroid substrate yields 23% improved results compared to other substrates. Moreover, after RT-Duroid, the FR-4 substrate provides a 19% increment in the simulation parameters. Therefore, it is suggested that a good MPA design that is made of substrates with lower dielectric constant can bring potential benefits in 5G applications, in terms of less reflection co-efficient, wider bandwidth, and good impedance matching.

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