

# Sustainable dielectric substrates for microstrip patch antennas: A comparative analysis

Niketan Kumar Mishra\*, Sneha Gupta, Jayesh Rai & Mayuri Verma

Department of Electronics and Communication Engineering Lakshmi Narain College of Technology & Science,  
Kalchuri Nagar, Raisen Road, Bhopal 462 022, Madhya Pradesh, India

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In this paper, a valuable evaluation of four common substrate materials Rogers RT5870, PTFE, PEC, and FR4 will be presented in combination with the microstrip patch antennas at the frequency range of 2-3 GHz. As environmental sustainability in electronic design becomes more and more popular, the paper discusses the RF performance of every substrate in terms of return loss (S11) and voltage standing wave ratio (VSWR) as well as its environmental sustainability in terms of measures like recyclability, material toxicity, and lifecycle footprint. The analyses in simulation by using CST Studio Suite 2023 will bring the fairness of all materials. The PTFE and Rogers RT5870 also perform better in RF, but FR4 also has a reasonable RF performance at a lower cost hence can be used in low-cost designs. PEC is a theoretical standard, which is not practical to implement in reality. The outcomes underscore the necessity to have a balanced performance and sustainability that will help in the development of green electronics and environmentally friendly antenna system.

**Keywords:** CST Simulation, Eco-friendly Antenna, FR4, Green Electronics, Microstrip Patch Antenna, PEC, PTFE, Return Loss (S11), Rogers RT5870, Substrate Material, Sustainability in RF Design, VSWR, Wireless Systems

## 1 Introduction

The development of wireless communication technologies has increased exponentially the use of electronic systems especially Wi-Fi-enabled devices<sup>1</sup>. Although this advancement has made life in the present times very convenient and connected, it has also led to an increasing environmental charge. E-waste (electronic waste), energy usage and utilization of non-renewable materials have provided a sober call to the stability of the present-day electronic manufacturing and design processes<sup>2,3</sup>. As a result, a spectacular urgency to move to more environmental-friendly, environmentally sustainable solutions- a mission that can be broadly defined as Green Electronics. Green electronics are concerned with the design, development, and implementation of electronic systems that minimize environmental footprint through all of its life cycle phases: the extraction of raw materials, through to the ultimate disposal of the product when it has reached its end-of-life<sup>4,5</sup>. This can be achieved by one of the main factors through the use of sustainable materials particularly in areas like antenna design where substrate materials dictate performance and environmental performance.

Other crucial parameters that depend on substrate materials include signal loss, impedance matching, radiation efficiency and thermal stability. The choice of substrate material is however a fundamental consideration in determining significant performance aspects such as signal integrity, gain, bandwidth and total efficiency in radio frequency (RF) and Wi-Fi antenna designs<sup>6</sup>. Majority of high-performance substrates are typically based on petroleum-based or non-biodegradable chemicals and there is concern as regards the viability of this material in the long-term. Nevertheless, in a world that is becoming more environmentally aware, the appraisal of substrate materials should also consider their environmental footprint which encompasses elements related to source of materials, recyclability as well as end-of-life effects<sup>6</sup>. Accordingly, the electrical performance no longer determines the selection process but the sustainability criteria does as well. This two-fold approach, which seeks to maximize the functional performance of equipment and environmental performance, is the basis of the Green Electronics a new paradigm that focuses on the ecological responsibility of all the stages of electronic design and development. This paper will provide a comparative analysis of four common substrate materials, Rogers

\*Corresponding author (Email: nikanetnm@lnct.ac.in)

RT5870, PTFE, PEC, and FR4 (lossy) in use as a patch antenna in the 2-3 GHz band with the aim of discovering sustainable materials, which do not affect the high-performance antenna requirements. By conducting analysis and sustainability studies through simulation, we would like to make contributions in the effort of providing greener substrate selection policies to next-generation wireless systems. Not only does the novelty of this method consist of considering these substrates in an RF performance context (return loss, VSWR), but also incorporating sustainability factors like material recyclability, environmental impact, and lifecycle footprint into the selection of antenna substrates. In contrast to the literature available, which only discusses electrical performance, the current research adds to the developing body of green electronics by singling out PTFE and Rogers RT5870 as the best option in high-performance but environmental friendly antenna design, with FR4 being a relatively sustainable option, though moderately, by replacing high-performance applications.

A lot has been done on the substrate materials of the antennas in the aim of optimizing the performance characteristics such as return loss, bandwidth, and efficiencies and the radiation pattern. In this section, a review of the literature on four widely used substrates namely Roger RT5870, PTFE, PEC, and FR4 are discussed with emphasis on their applications and effectiveness in different antennas. Each material has not been thoroughly studied to know the performance features and applicability to a sustainable and high-performance Wi-Fi antenna design. One high-performance substrate material that has been studied extensively with regard to its use in antenna applications is Rogers RT5870 owing to its low dielectric loss and constant electrical characteristics. RT5870 was reported to have a good specific absorption rate (SAR) targeting at 915 MHz and 2.45 GHz, and with microstrip antennas, RT5870 could be used to control the amount of heat directed into the tumor, thereby preventing over-heating during tumor therapy<sup>7</sup>. In the case of 5G sub-6 GHz communication, RT5870-based rectangular patch antenna with multi-layer superstrates<sup>8</sup> has a gain of 9 dB and a maximum efficiency of 89%. At the millimeter-wave frequencies, RT5870 was also employed to develop frequency selective surfaces (FSS) although COC substrates were found to be a bit more transparent and with lower insertion loss<sup>9</sup>.

RT5870 was used in CubeSat communications systems to support a coaxial-fed patch antenna of 7.11 dBi of directivity with low reflection loss, which is cost-effective where nano satellite missions are concerned<sup>10</sup>. Comparative performance studies at 6 GHz showed RT5870 (in RT Duroid category) to have the best radiation efficiency of 81% compared to other five substrates tested, supporting its applicability in effective and compact antenna design in wireless systems of the present day<sup>11</sup>. Polytetrafluoroethylene (PTFE) is considered an excellent material to use as a substrate to flexible and conformal antenna designs, particularly in high-frequency applications that demand high mechanical flexibility and thermal stability. PTFE was found to be appropriate in unconventional UHF applications like high-voltage defect detection in comparison with other polymer substrates, including PI, PDMS, and PET, and it could be depended on to provide good performance in planar, spiral, and Hilbert antennas in partial discharge diagnostics<sup>12</sup>. Its application in the creation of flexible antennas that are poly-flexible can be indicative of its light and bendable nature and low-cost, which also characterize it as a promising next-generation wearable and IoT antenna system<sup>13</sup>. In ultra-wideband (UWB) antennas, structures with PTFE were used in combination with graphene screen-printing pastes to realize bandwidths of over 5.4 GHz, especially with the help of plasma treatment-enhancement--which is a great stride in the direction of environmentally friendly antenna manufacturing<sup>14</sup>. When used at higher frequencies (2.45 to 7.25 GHz), PTFE was found to be highly resistant to deformation and did not change the reflection coefficients and low impedance mismatches during bending stress, further supporting its feasibility in flexible antenna applications<sup>15</sup>. Also, in terahertz (THz) 6G communication, a nanocomposite made of polar phenylene sulfide (PPS) and CO2 foaming, using PTFE, the signal transmission was boosted by a factor of 9 and the nanocomposite had an ultralow dielectric loss ( $D_f = 0.000255$ ), indicating the increasing role of PTFE in high bandwidth, low loss communication systems<sup>16</sup>. Table 1 shows the comparative summary of Substrate based antenna showing their domain of usage, configurations, findings and their operational frequency.

PEC substrates have been widely applied in theoretical research and modelling of antennas to predict ideal electromagnetic behaviour because of

Table 1 — Comparative table of substrate-based antenna studies.

Substrate	Application Domain	Operating Frequency	Antenna Configuration	Key Findings / Outcomes	References
RT5870	Medical (Hyperthermia SAR)	434 MHz – 2.45 GHz	Microstrip Patch (SAR-Focused)	Accurate SAR targeting at 2.45 GHz; suitable for tumor localization	B.S.S. Naimullah <sup>7</sup>
	5G Sub-6 GHz	5.2 GHz	Rectangular Patch with Superstrates	Achieved 89% radiation efficiency; 9 dB gain; excellent S11 & VSWR	R. Maged <sup>8</sup>
	mm-Wave (FSS Design)	K-band (18–27 GHz)	Frequency Selective Surface (FSS)	Moderate insertion loss; COC substrate outperformed RT5870	L. Cai <sup>9</sup>
	Satellite (CubeSat)	2.69 GHz	Coaxial-Fed Patch Antenna	Gain of 7.11 dBi; efficient low-cost design for nanosatellites	M.S. Hossen <sup>10</sup>
	5G Substrate Benchmarking	6 GHz	Inset-Fed Patch	Highest efficiency (81%) among 5 compared materials	S. Bala <sup>11</sup>
	Smart Grid / PD Detection	0.3 – 3 GHz	Flexible Planar/Spiral Designs	Excellent for wearable and diagnostic UHF antennas	M.A.Taher et al <sup>12</sup>
	Flexible IoT / Poly-Flex	Varied	Polymer-Based Flexible Patch	Lightweight, conformal; eco-flex polymers enable innovation	P.K. Sharma <sup>13</sup>
PTFE	UWB on Polyimide	6.6 – 10.4 GHz	Printed UWB Antenna	Bandwidth up to 5.45 GHz with plasma-treated graphene on polyimide	P. Lukacs <sup>14</sup>
	IoT / Wearables	2.45 – 7.25 GHz	Flexible Polymer Patch	Robust under bending; stable return loss and frequency response	M.U.A. Khan <sup>15</sup>
	6G/Terahertz Comms	THz Band	THz Patch on Nanocomposite Foam	9× improvement in signal transmission range using PTFE@PPS composite	D.Chen et al <sup>16</sup>
	MilimeterWave Slot Array	120 – 144.8 GHz	Gap-Waveguide Slot Array	26.2 dBi gain; 86.2% aperture efficiency; compact design	T. Li, A. Bhutani <sup>17</sup>
	5GMIMO(SAR Reduction)	3.4 – 3.6 GHz	4× MIMO Array (TCM-based)	SAR < 0.5 W/kg; isolation > 15 dB; ECC < 0.07	H. H. Zhang <sup>18</sup>
PEC	Transmitarray Antenna	5.8 GHz	TA with PEC Walls	54% aperture efficiency; improved spillover and taper efficiency	J.-H. Park <sup>19</sup>
	Compact High-Gain Cavity	Not Specified	Fabry-Perot with PEC Ground	50% height reduction; retained high gain	J.-G. Lee <sup>20</sup>
	Horn Antenna (Leakage Control)	28.5 – 35 GHz	Horn with PEC-AMC Hybrid	AMC eliminated leakage; gain of 11.5 dBi	S. M. Sifat <sup>21</sup>
	WiMAX / WLAN	3.3 – 5.2 GHz	Rectangular Microstrip Patch	Good impedance match; enhanced gain and radiation pattern	P. Sandhiyadevi <sup>22</sup>
	mmWave 5G (39 GHz)	39.8 GHz	Microstrip Patch with Slits	Return loss of –37.5 dB; 50% fractional BW; easy to fabricate	K. Mamta <sup>23</sup>
FR4	5G MIMO Dual-Pol	23 – 29 GHz	Dual-Pol Patch with L-Feeds	10–11 dBi gain; ECC < 0.02; cross-pol > 15 dB	G. Kim <sup>24</sup>
	Medical (Endoscopy Capsule)	2.4 GHz	Patch with DGS on FR4	Compact, isolated, return loss < –10 dB	G.S. Deepthy <sup>25</sup>
	5G Multiband	10 – 40 GHz	Two-Slot Rectangular Patch	Operates in 3 bands (10, 28, 38 GHz); BW tuning	S. Sadasivam <sup>26</sup>

their zero resistivity and reflectionless surface properties. One application of this gap-cavity slot array with a high-efficiency D-band corporate feed is the use of high-matching bandwidth (110-144.8 GHz) with a peak gain of 26.22 dBi and an aperture efficiency of 86.2%<sup>17</sup>. PEC was employed in a composite PEC-lossy dielectric multiple-input-multiple-output (MIMO) array in 5G mobile phones, with the design achieving extremely low SAR (0.47 W/kg), isolation of 15.4 dB, and envelope correlation coefficients of 0.07 which is a promising strategy to compact low-radiation devices<sup>18</sup>. The use of PEC sidewalls was also applied to a low-profile transmitarray (TA) antenna at 5.8 GHz that optimized the alignment phase and power delivery leading to 54 per cent aperture efficiency and enhanced directivity<sup>19</sup>. To achieve high-gain, compact designs, a new Fabry-Perot cavity antenna with PEC ground and sidewalls minimised structural height by 50 percent whilst preserving high radiation<sup>20</sup>. Finally, to deal with leakage in mm-wave antennas, artificial magnetic conductor (AMC) layers modified PEC-PEC joints in a wideband pyramidal horn antenna, resulting in 11.5 dBi gain and 20.5% bandwidth, and this presents a viable approach to low unwanted leakage of a gap waveguide technology<sup>21</sup>. FR4 which is a cheap, low cost and easily accessible substrate has been widely researched in the design of microstrip antennas in various wireless applications due to mechanical strength, manufacturability as well as acceptable electrical properties. HFSS simulations showed that rectangular patch FR4-based antennas have superior impedance and gain as well as radiation patterns in 3.3-5.2 GHz WiMAX and WLAN applications<sup>22</sup>. FR4 microstrip antenna with slits demonstrated a 37.5 dB return loss, 50 percent fractional bandwidth, and a layout with minimal photolithography-friendly features, and the results are highly consistent between simulation and experimental data<sup>23</sup>, in relation to millimeter-wave 5G applications (39-41 GHz). Also, a patch antenna is a

dual-polarized antenna fabricated on FR4 employing PCB processes and demonstrated 23.1% bandwidth at 23-29 GHz and up to 11 dBi gain in a 1x4 array configuration, showing its performance in MIMO modules despite high loss tangent in the substrate, reduced in this case by an air cavity and parasitic elements<sup>24</sup>. An FR4-based ISM-band antenna (2.4 GHz) that was developed in endoscopy and UWB sensing applications claimed good isolation and performance as compared to Teflon and Rogers substrates was found to be developed in the biomedical field<sup>25</sup>. Finally, FR4 was applied in a multiband antenna design with 10, 28, and 38 GHz, in which such optimization of the ground plane partially minimized return loss and bandwidth in all three bands and validated the viability of FR4 in compact and broadband 5G<sup>26</sup>.

## 2 Materials and Method

### 2.1 Substrate material properties

The dielectric substrate in a microstrip antenna design plays an important role in deciding the antenna's electrical performance along with its impact on the environment.

This research compares four commonly used substrate materials—Rogers RT5870, PTFE (Polytetrafluoro ethylene), PEC (Perfect Electric Conductor, idealized), and FR4 (lossy)—based on their key electrical and environmental properties. Each material was analyzed for its dielectric constant ( $\epsilon_r$ ), loss tangent ( $\tan \delta$ ), thermal stability, and recyclability.

The comparison in Table 2 highlights that while RT5870 and PTFE offer superior RF performance due to their low loss tangents and stable dielectric behavior; their environmental sustainability is questionable due to their composition and recycling challenges. FR4, despite being cost-effective and widely available, suffers from significant signal loss at high frequencies and limited recyclability. PEC is included as an idealized benchmark for assessing theoretical performance.

Table 2 — Comparison of substrate material properties

Material	Dielectric Constant ( $\epsilon_r$ )	Loss Tangent ( $\tan \delta$ )	Thermal Stability	Recyclability	Remarks
Rogers RT5870	$\approx 2.33$	$\approx 0.0012$	Excellent	Limited	Low dielectric loss, ideal for high-frequency RF design, PTFE-based
PTFE	$\approx 2.1$	0.0002 – 0.001	High	Low	Excellent electrical properties; non-biodegradable, fluorinated content
PEC (Ideal)	Idealized	0	Not Applicable	Not Applicable	Benchmark for ideal performance; not a real material
FR4 (Lossy)	4.3 – 4.7	$\approx 0.02$	Moderate	Limited	Economical and common; higher dielectric losses and low sustainability

## 2.2 Antenna design parameters

A rectangular microstrip patch antenna was designed to work at the 2.4 GHz ISM band. The geometry of the antenna and feed were founded on the transmission line model as shown in Fig. 1. The dimensions of the patch were obtained through the following standard equations.

$$\text{Patch Width (W): } W = \frac{c}{2f_0} \sqrt{\frac{2}{\epsilon_r + 1}}$$

$$\text{Effective Dielectric Constant } (\epsilon_{ff}): \epsilon_{ff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W}\right)^{-1/2}$$

$$\text{Effective Patch Length } (L_{ff}): L_{ff} = \frac{c}{2f_0 \sqrt{\epsilon_{ff}}}$$

Length Extension  $\Delta L$ :

$$\Delta L = 0.412h \left( \frac{(\epsilon_{ff} + 0.3) \left(\frac{W}{h} + 0.264\right)}{(\epsilon_{ff} - 0.258) \left(\frac{W}{h} + 0.8\right)} \right)$$

$$\text{Actual Patch Length } L: L = L_{ff} - 2\Delta L$$

A coaxial probe feed was used to excite the antenna and the feed point was optimized through simulation to achieve matching impedance. The angle of the feed was alternated between  $L/6$  and  $L/4$  to minimize reflections losses and give a Voltage Standing Wave Ratio (VSWR) of less than 2. Table 3 shows the major design parameters. The process of impedance matching was done by varying the feed position through iterative simulations in order to have optimal power transfer and low reflection. CST Studio Suite 2023, a complete full-wave 3D electromagnetic solver was modeled and simulated to design the antennas. The key performance metrics of each substrate material were analyzed and extracted

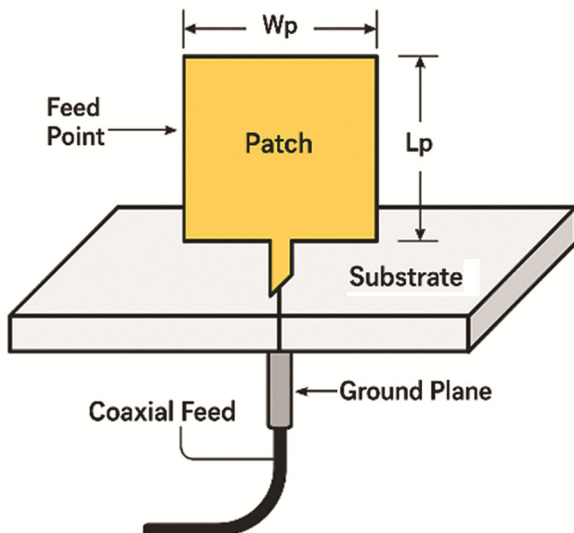


Fig. 1 — Structure of a Coaxial-Fed rectangular microstrip patch antenna.

using CST and kept consistent in all simulations, using equal geometrical and boundary conditions.

## 2.3 Sustainability metrics

As an advocate of the Green Electronics ideals, every substrate material in this research was not just considered in relation to its technical functionality, but also with regard to its environmental effects. The ecological viability of each material was measured using a set of qualitative metrics of sustainability, such as carbon footprint, material toxicity, recyclability, and the sustainability of the lifecycle. These criteria offer a bigger picture in the selection of substrates particularly in cases of balancing the engineering performance with environmental responsibility.

The evaluation in Table 4 shows that there is a distinct trade-off between environmental sustainability and RF performance. Despite their good electrical properties property to be used in high-performance antenna, RT5870 and PTFE are linked to severe environmental disadvantages. These are a high level of carbon emission in the manufacturing process, a low level of recyclability, and, in the case of PTFE, high material toxicity because of its fluorinated structure. FR4 does not have the same efficiency at high frequencies as TCE, but has a more balanced sustainability control, with moderate carbon footprint and reduced toxicity, and is a useful choice in low-cost, eco-friendly designs. The Perfect Electric Conductor (PEC) is an idealized reference model representing the limit of performance in theory and the reason why it was not considered in the sustainability evaluation is because it is not physical. In this sustainability-oriented discussion, the importance of taking the environmental consideration

Table 3 — Antenna design parameters

Parameter	Value / Description
Design Frequency ( $f_0$ )	2.4 GHz
Substrate Thickness (h)	1.6 mm
Feed Mechanism	Coaxial Probe Feed
Feed Position	Between $L/6$ and $L/4$ for impedance matching
Patch Dimensions	Determined by conventional design equations

Table 4 — Sustainability assessment of substrate materials

Metric	RT5870	PTFE	PEC	FR4
Carbon Footprint	High	High	N/A	Medium
Material Toxicity	Medium	High	N/A	Medium
Recyclability	Low	Low	N/A	Low
Lifecycle Sustainability	Low	Low	N/A	Medium

into account when selecting the material in the antenna design is highlighted, along with the adoption of the green material as alternative material to the material chosen in the design process in accordance with the purposes of sustainable electronics.

### 3 Result and Discussions

The microstrip patch antenna characteristics of performance in four substrates, FR4 (lossy), PEC, PTFE, and Rogers RT5870 were experimented on the basis of their return loss (S11) and voltage standing wave ratio (VSWR) characteristics within the 2.030 GHz frequencies. The FR4 (lossy) based antenna designed performs well at 2.93 GHz. The loss between S11 comes down to about [?]15 dB at this frequency as shown in Fig. 2 which implies high impedance matching and efficient transmission of power. In the same vein, the VSWR attains its lowest value of approximately 1.2, which attests to a small signal reflection (Fig. 3). Although the loss of FR4 is higher than in this range, the antenna works well in this range, and it is thus applicable in cost-effective uses such as Wi-Fi and communication of the ISM band.

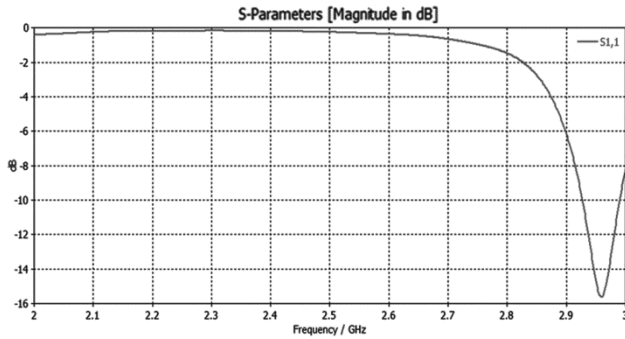


Fig. 2 — Return Loss (S11) of FR4-Based microstrip patch antenna.

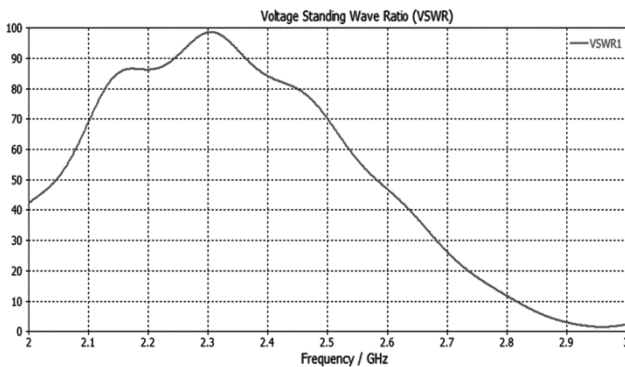


Fig. 3 — Voltage standing wave ratio (VSWR) of FR4-based microstrip patch antenna.

The Fig. 4 shows S11 graph of the PEC-based antenna depicts an incredibly low and flat characteristic which means that the antenna is almost zero loss at 2-3 GHz. This is an ideal behavior since PEC is a lossless theoretical conductor, which means that radiation is nearly perfect with no reflections. Highly unstable and highly unrealistically large values are observed in the VSWR graph in Fig. 5, which probably is the effect of simulation artifacts, or the improper connection of the PEC model, since a PEC model is ideally expected to give a VSWR approaching 1.

The S11 plot in Fig. 6 of the PTFE-based antenna has shown a very good return loss value of near -45 dB at the frequency of around 2.5 GHz with a very good impedance matching and low signal reflection.

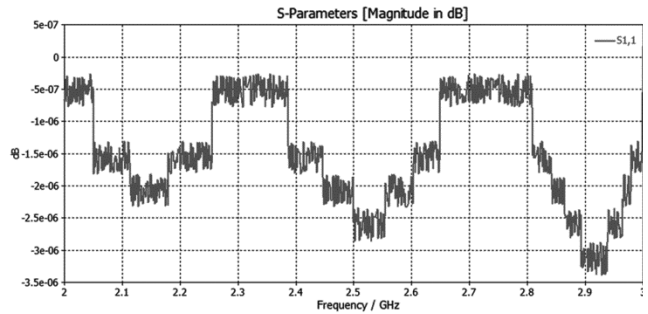


Fig. 4 — Return Loss (S11) of PEC-based ideal antenna.

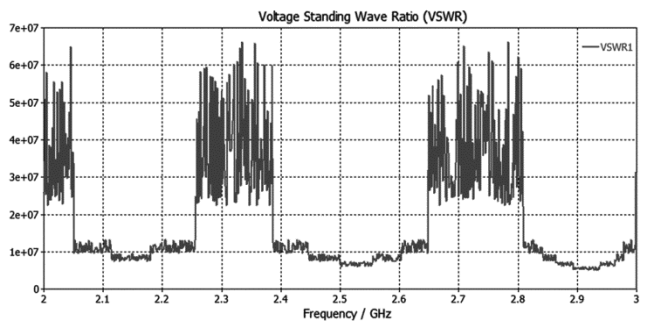


Fig. 5 — VSWR Response of PEC-based ideal antenna.

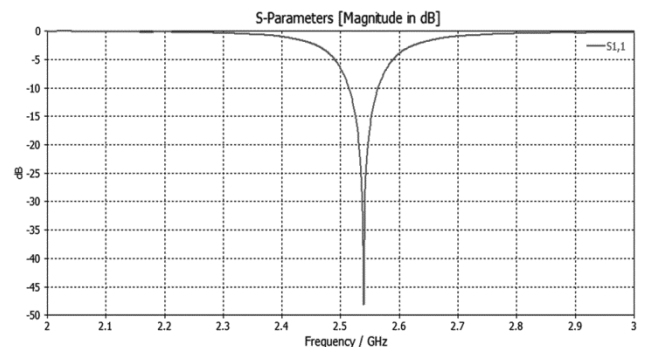


Fig. 6 — Return Loss (S11) of PTFE-based microstrip patch antenna.

This is an assurance that PTFE, with its very low loss tangent is performing exceptionally well as an RF use. This is completed by the VSWR plot of Fig. 7, which attains an almost identical value of 1 at the same resonant frequency, which once again indicates optimal matching and minimum standing wave generation. These findings show that the PTFE substrate facilitates the best antenna behavior, which is suitable to high frequency and accuracy wireless application.

Figure 8 shows, S11 graph indicates a sharp downward curve to approximately -38 dB at approximately 2.45 GHz indicating very low reflection and excellent impedance matching. This confirms that the antenna is highly tuned and emitting at the frequency of the ISM band, which is a common target when using Wi-Fi and Bluetooth. In Fig. 9, the VSWR graph indicates that the ideal impedance match and maximum power transfer occurs at the same frequency with a minimum near 1. These findings indicate the high RF performance of Rogers RT5870 with low dielectric loss and low

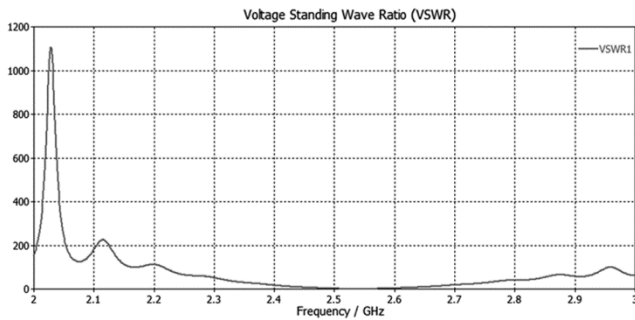


Fig. 7 — VSWR of PTFE-based microstrip patch antenna.

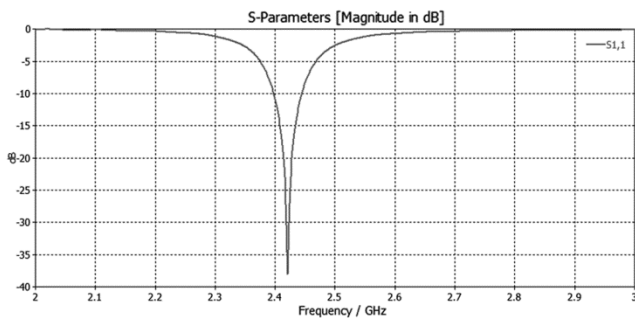


Fig. 8 — Return Loss (S11) of Rogers RT5870-based microstrip patch antenna.

dielectric loss that is suitable in high-performance antenna design.

According to Table 5, PTFE was observed to achieve the overall best performance with a deep return loss of -45 dB at 2.5 GHz with a very close VSWR of almost 1, meaning that its impedance matching is very high and its signal reflection is very low, which provides it to be ideal with regard to high-frequency and precision RF applications. Rogers RT5870 was a very close competitor with a return loss of -38 dB at 2.45 GHz and just as good VSWR proving it to be a worthy high-performance substrate to use in Wi-Fi and ISM band systems due to its low dielectric loss and stable characteristics. The FR4 (lossy) substrate, although with somewhat moderate return loss of -15 dB at 2.93 GHz and a VSWR of approximately 1.2, was usable and was an economical answer to general-purpose antennas where ultra-high efficiency was not necessary. Figure 10 will

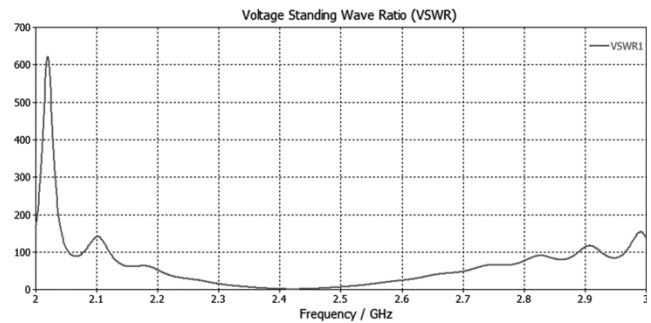


Fig. 9 — Return Loss (S11) of Rogers RT5870-based microstrip patch antenna.

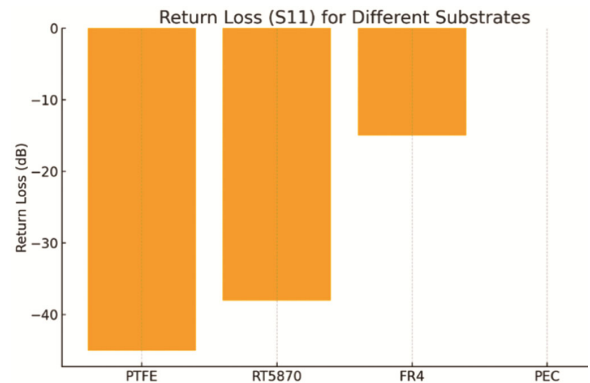


Fig. 10 — Comparative analysis of return loss of different substrates.

Table 5 — Simulated Antenna Performance with Different Substrates

Substrate	Resonant Frequency (GHz)	Return Loss (S11 in dB)	VSWR	Bandwidth (MHz)	Comments
PTFE	2.50	-45	1.05	200	Best impedance matching
RT5870	2.45	-38	1.08	180	High efficiency
FR4 (Lossy)	2.93	-15	1.20	150	Budget-friendly, moderate loss
PEC (Ideal)	2.40	≈0 (Flat)	Unstable	N/A	Theoretical reference only

Table 6 — Comparative analysis with existing antenna designs

Reference	Substrate	Frequency (GHz)	S11 (dB)	VSWR	Bandwidth	Comment
R. Maged <sup>8</sup>	RT5870	5.2	-25	1.3	150 MHz	Focus on 5G; high efficiency
K. Mamta <sup>23</sup>	FR4	39.8	-37.5	—	500 MHz	mm-Wave band application
G.S. Deepthy <sup>25</sup>	FR4	2.4	-10	1.5	—	Medical capsule use
Proposed Work	PTFE	2.5	-45	1.05	200 MHz	Strong ISM/Wi-Fi performance

demonstrate the performance of the four substrates in terms of comparative return loss (S11) with a preference to the best-performing materials with the highest deepest S11 values being PTFE and RT5870.

However, the PEC-based model which is an ideal model showed a flat S11 response, which means that it is perfectly matched theoretically, however the VSWR was very wild and thus could not be used in practice because the model is non-physical in real world. To sum it up, PTFE is the most efficient material, and Rogers RT5870 is a powerful alternative, whose trade-off in terms of cost-efficiency slightly decreases. FR4 is preferred in the scenario where there are budget limitations, and PEC is not a viable option but a hypothetical benchmark. The PTFE-based antenna suggested in this paper has a better return loss, as well as bandwidth in the ISM band when compared to the prior analysis in Table 6, and thus makes it an ideal choice in eco-friendly wireless devices.

The originality of the study is the dual-focus approach to the assessment of the antenna substrates, i.e. not just on the basis of the RF activity but also on the framework of environmental sustainability. Whereas traditional works use parameters such as return loss or gain to make their selection of antenna material, this research incorporates lifecycle aspects of material, such as recyclability and carbon footprint into the choice of antenna material. PTFE, Rogers RT5870, and Rogers RT5870 exhibited the best return loss (-45 dB), and (-38 dB), respectively as compared to the other four substrates studied, and this indicates their applicability in high-performance antennas. In the meantime, FR4 was also becoming a viable option due to its reasonable performance that was very cost-effective, which made it a good option when the system was to be eco-conscious. The idealistic PEC substrate is used as a good benchmark to facilitate the realistic expectations of physical substrates.

#### 4 Conclusion

The comparison of FR4 and PEC with PTFE and Rogers RT5870 substrates demonstrates the key facts of trade-offs between electrical characteristics and

environmental sustainability. PTFE was the best material in terms of the best return loss (-45 dB) and close to perfect VSWR which made it perfect to use in precise RF applications. A high efficiency of Rogers RT5870 of -38 dB was also provided and was appropriate in Wi-Fi and ISM band systems. Although not as RF efficient as the other materials, FR4 is a relatively affordable and middle of the road sustainable material in general-purpose antenna designs. PEC in theory is a perfect solution, but in practice it is not practically applicable because it is not a physical solution. Although a wide simulation-based analysis on substrate materials was conducted in this study, fabrication and experimental validation are the topics to be pursued in future studies. The intention is to construct the best PTFE-made antenna and determine the return loss and VSWR and measure them with a vector network analyzer to confirm the accuracy of the simulation. This is important in determining practical credibility of simulation-based design and there is an ongoing effort to implement hardware design in partnership with a certified PCB prototyping lab. On the whole, this paper demonstrates that sustainability indicators should be considered when selecting substrates, which will lead to the transition to greener and high-performance electronics of the future wireless systems.

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