International Science and Technology Journal
المجلة الدولية للعلوم والتقنية

Volume 37 العدد
Part 1 المجلد

http://www.doi.org/10.62341/mmes1069

Received	2025/08/20	تم استلام الورقة العلمية في
Accepted	2025/09/14	تم قبول الورقة العلمية في
Published	2025/09/16	تم نشر الورقة العلمية في

Study on the Effect of Dielectric Permittivity on the Performance of Microstrip Patch Antenna at 2.4 GHz

Moataz Moftah Hamad

Electrical Department, Higher Institute of Science and Technology, Almarj, Libya
fm1885.mm@gmail.com

Abstract:

This study aims to explore the effect of changing the substrate type on the performance of a microstrip patch antenna, in terms of gain, directivity, bandwidth, and bandwidth efficiency. Three different substrates were investigated: Rogers RT5880, FR-4, and Alumina. Each substrate has distinct physical and electrical properties, which influence the antenna's performance and overall dimensions. The design and simulation were carried out using CST Microwave Studio, where a simple microstrip patch antenna operating at 2.4 GHz was modelled. The performance for each substrate was analyzed, and the simulation results were discussed. The results highlighted clear differences in performance among the three substrates. Rogers RT5880 demonstrated the best performance in terms of gain and radiation efficiency, while FR-4 was the most cost-effective, albeit less efficient. On the other hand, Alumina exhibited a very compact size due to its high dielectric permittivity, but faced challenges related to material losses.

Keywords: Microstrip Patch Antenna, Rogers RT5880, FR-4, Alumina, CST Microwave Studio.

http://www.doi.org/10.62341/mmes1069

دراسة تأثير السماحية الكهربائي على أداء هوائي الرقعة عند التردد 2.4GHz

معـــتز مفتـــــــاح حمـــــد
قسم الهندسة الكهربائية، المعهد العالي للعلوم والتقنية، المرج، ليبيا
E-mail: fm1885.mm@gmail.com

الملخص:

تهدف هذه الدراسة إلى استكشاف تأثير تغيير نوع المادة الأساسية على أداء هوائي الرقعة من حيث الكسب، الاتجاهية، عرض النطاق الترددي، وكفاءة عرض النطاق الترددي. تم دراسة ثلاث مواد أساسية مختلفة Rogers RT5880 ، FR-4، Alumina. لكل مادة أساسية خصائصها الفيزيائية والكهربائية المميزة، والتي تؤثر على أداء الهوائي وأبعاده الكلية. تم تنفيذ التصميم والمحاكاة باستخدام برنامجCST Microwave Studio ، حيث تم تصميم نموذج لهوائي رقعة بسيط يعمل عند تردد 2.4 جيجاهرتز. تم تحليل الأداء لكل ركيزة، ومناقشة نتائج المحاكاة. أبرزت النتائج وجود فروقات واضحة في الأداء بين المواد الأساسية الثلاث. حيث أظهرت المادة Rogers RT5880 أفضل أداء من حيث الكسب والكفاءة الإشعاعية، في حين كانت FR-4 الأكثر اقتصادية لكنها أقل كفاءة. من ناحية أخرى، أظهرت المادة Alumina حجماً صغيراً جداً بفضل سماحيتها الكهربائية العالية، إلا أنها واجهت تحديات تتعلق بالخسائر المادية.

الكلمات المفتاحية: هوائي الرقعة، Rogers RT5880، FR-4, Alumina, , برنامج CSTلمحاكاة الموجات الدقيقة.

1.Introduction

Microstrip patch antennas are widely used in wireless communication applications due to their compact structure and ease of fabrication [1][2]. However, the performance of these antennas is significantly influenced by the type of substrate employed, which plays a critical role in the overall design process [3].

The dielectric permittivity (ε_r) of the substrate directly affects the antenna's characteristics; higher permittivity values result in smaller antenna dimensions, contributing to overall size reduction [4]. Nevertheless, this reduction often comes at the cost of increased material losses and decreased radiation efficiency [5][6]. Conversely, substrates with lower permittivity enhance efficiency

http://www.doi.org/10.62341/mmes1069

and increase bandwidth, though they may require a larger physical size to maintain the same operating frequency [7][8].

Therefore, substrate selection is not merely a design preference but a fundamental decision that must be carefully evaluated to achieve an optimal balance between performance, size, and cost. This consideration becomes even more crucial in the context of emerging technologies such as fifth-generation (5G) networks and compact integrated systems. In recent years, several studies have examined the impact of substrate on the performance of microstrip patch antennas [9][10].

The methodology of this study was organized into four consecutive phases to ensure a systematic investigation of the antenna design. First, the research problem was defined by focusing on the influence of substrate dielectric permittivity on the performance of a microstrip patch antenna operating at 2.4 GHz, with particular attention to return loss, gain, directivity, bandwidth, bandwidth efficiency, and the effect on physical size. Following this, three substrates with distinct dielectric properties—Rogers RT5880, FR-4, and Alumina—were carefully selected to provide a representative comparison between high-performance and compact design options. The next phase involved the design of a rectangular inset-fed microstrip patch antenna, where the patch width, patch length, and ground plane dimensions, were determined using well-established design equations. In this process, the operating frequency was maintained at 2.4 GHz with a constant substrate thickness of 1.7 mm to ensure uniformity across all models. Finally, the designed structures were simulated using CST Microwave Studio, and the results were analyzed to evaluate and compare the performance of the antennas on the basis of the selected substrates, thereby highlighting the practical implications of dielectric permittivity on antenna behavior.

2. Antennas Design

The design and simulation results for antennas with Rogers RT5880, FR-4 and Alumina substrates are designed at operation frequency of 2.4GHz. The designs were implemented using CST Microwave Studio, maintaining the same geometric structure for each model while only varying the substrate type. This approach aimed to analyze the direct impact of the substrate on the overall performance of the antenna.

http://www.doi.org/10.62341/mmes1069

Microstrip patch antennas consisting of three layers of patch made from copper, Rogers RT5880 substrate which has permittivity ε_r = 2.2, or FR-4 substrate which has permittivity ε_r = 4.3, or Alumina substrate which has permittivity ε_r = 9.4 and then the ground plane made from copper. Figure 1 shows the configuration of the designed microstrip patch antenna.

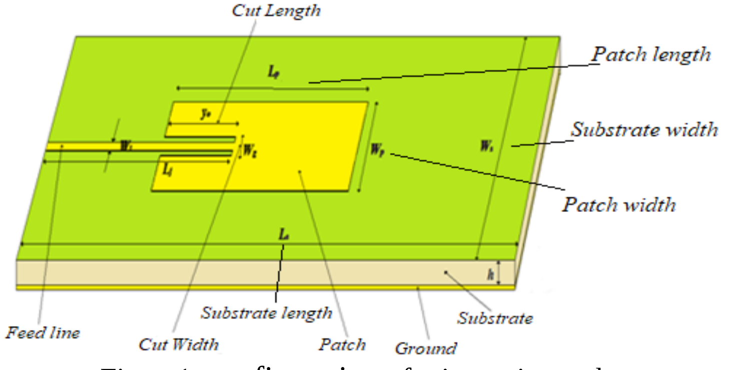


Figure1: configuration of microstrip patch
The figure was

"created by the author based on the design process carried out in this study."

The microstrip feed line, characterized by a width (W_f) and a length (L_f), is employed to excite the patch. The connection between the patch and the feed line is achieved through an inset cut, defined by the inset length (y_o) and inset width (w_g). The initial design step involves selecting the operating frequency f_o =2.4 GHz, the substrate relative permittivity, and the substrate thickness h=1.7 mm. Based on these parameters, the dimensions of the patch and substrate are determined by applying the standard microstrip patch antenna design equations [11].

$$w_p = \frac{c}{2f_o\sqrt{\frac{\varepsilon r+1}{2}}} \tag{1}$$

Due to move the electric field lines via the vacuum before passing throe the substrate. it is necessary to evaluate the effective

http://www.doi.org/10.62341/mmes1069

dielectric constant (ε_{eff}), which represents the combined influence of both the substrate material and the surrounding medium.

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}[1+12\frac{w_p}{h}]^{\frac{1}{2}} \tag{2}$$

The length of the patch antenna (L_p) as given in formula.

$$L_p = L_{eff} - 2\Delta L \tag{3}$$

The effective length (L_{eff}) and (ΔL) can be calculated from equations.

$$L_{eff} = \frac{c}{2 f_o\sqrt{\varepsilon_{eff}}} \tag{4}$$

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)\ (\frac{w_p}{h}+0.264)}{(\varepsilon_{eff}-0.264)\ (\frac{w_p}{h}+0.8)} \tag{5}$$

The width and the length of the substrate can be calculated by using equations.

$$w_s = w_p + 6 * \mathrm{h} \tag{6}$$

$$L_s = L_p + 6 * \mathrm{h} \tag{7}$$

Table 1: Parameters of antennas

Parameters of the antenna	**Definition of the parameter**	**Value of parameter mm of different substrates**		
		Rogers RT5880	FR-4	Alumina
Ws	Substrate width	65	49	38
Ls	Substrate length	54	40	31
h	Substrate Thickness	1.7	1.7	1.7
Wp	Patch width	60	44	28
Lp	Patch length	40.82	29.28	19.8
Wf	Feed line width	3	3	3
Lf	Feed line length	12	10	10
Wg	Inset cut width	4	4.5	3.5
y_o	Inset cut length	5	10	7
t	Patch thickness	0.035	0.035	0.035
ε_r	permittivity	2.2	4.3	9.4

http://www.doi.org/10.62341/mmes1069

3. Antennas Simulation

After calculating the parameters of Antennas, the design is simulated by using the microwave simulation software CST. Figure 2 below shows the 3D design structure of microstrip patch antennas in CST.

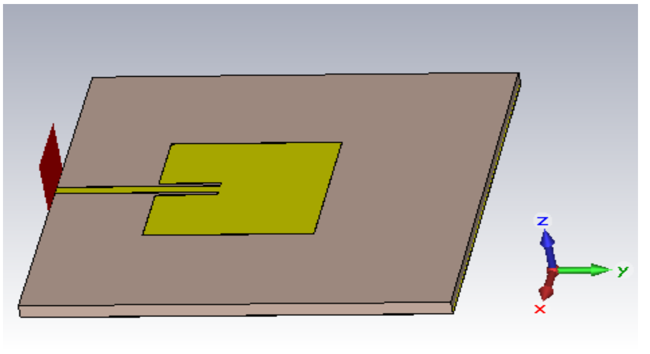


Figure 2: 3D Structure of microstrip patch in CST

3.1 Antennas with Rogers RT5880

The simulation process demonstrates that return loss was -27.19 dB at resonant frequency 2.4 GHz. The bandwidth is 55.4 MHz and bandwidth efficiency at -10dB is 2.3%. Figure 3 illustrates return loss of Rogers RT5880.

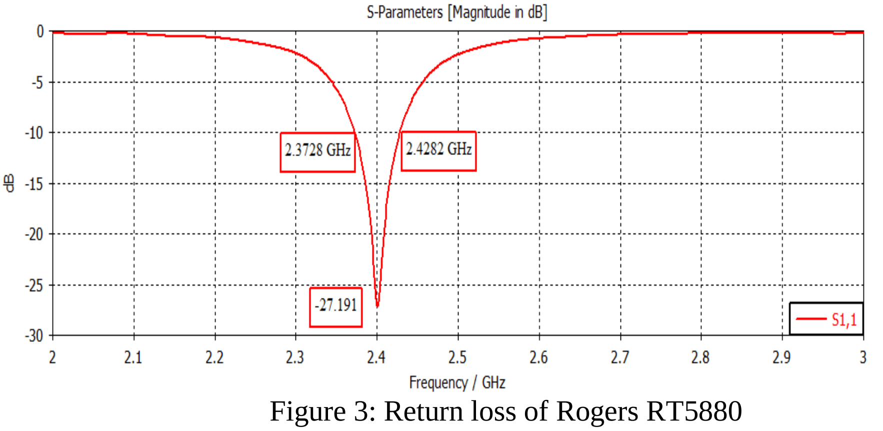
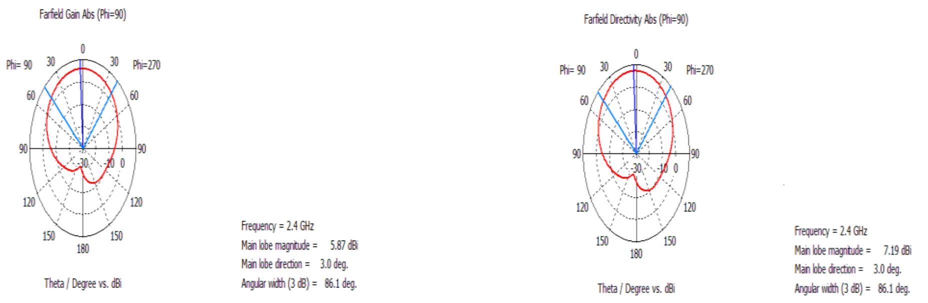


Figure 3: Return loss of Rogers RT5880

The antenna gain of Rogers RT5880 is 5.87 dBi as illustrated in figure 4(a) and the antenna directivity of the Rogers RT5880 is 7.19 dBi as shown in figure 4(b).

International Science and Technology Journal
المجلة الدولية للعلوم والتقنية
Volume 37 العدد
Part 1 المجلد
http://www.doi.org/10.62341/mmes1069



(a) (b)

Figure 4: (a) Polar plot of antenna gain (b) Polar plot of antenna directivity

3.2 Antennas with FR-4

The simulation process demonstrates that return loss was -20.321 dB at resonant frequency 2.4 GHz. The bandwidth is 51.5 MHz and bandwidth efficiency at -10 dB is 2.14 Figure 5 illustrates the return loss of FR-4.

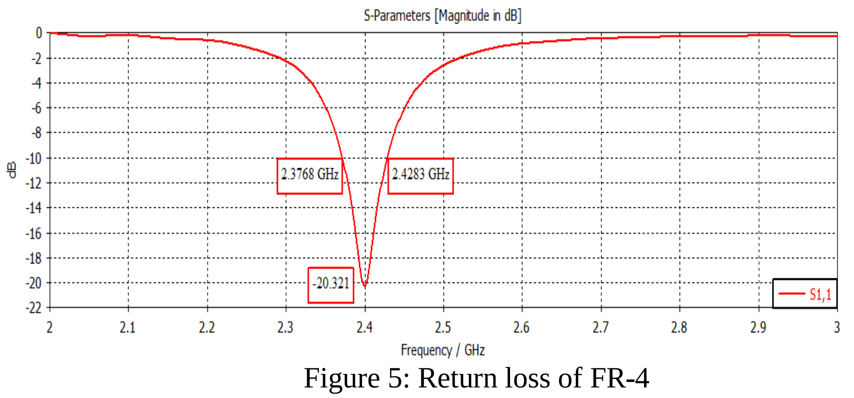
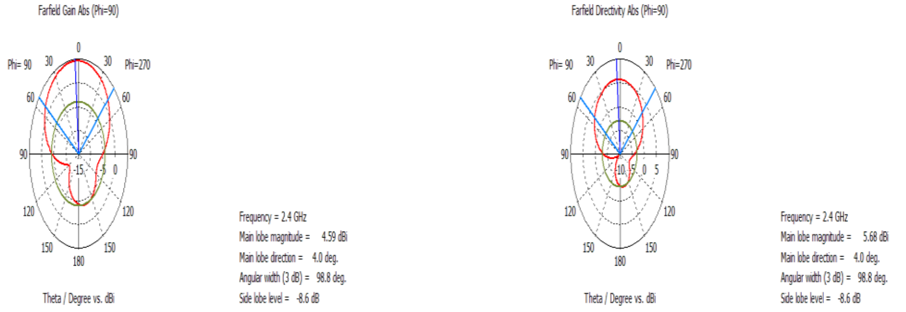


Figure 5: Return loss of FR-4

The antenna gain of FR-4 is 4.59 dBi as illustrated in figure 6 (a) and the antenna directivity of FR-4 is 5.68 dBi as shown in figure 6(b).



(a) (b)

Figure 6: (a) Polar plot of antenna gain (b) Polar plot of antenna directivity

International Science and Technology Journal
المجلة الدولية للعلوم والتقنية
Volume 37 العدد
Part 1 المجلد
المجلة الدولية للعلوم والتقنية
International Science and Technology Journal
ISTJ
http://www.doi.org/10.62341/mmes1069

3.3 Antennas With Alumina

The simulation process demonstrates that return loss was -27.78 dB at resonant frequency 2.4 GHz. The bandwidth is 32.7 MHz and bandwidth efficiency at -10 dB is 1.36%. Figure 7 illustrates return loss of Alumina.

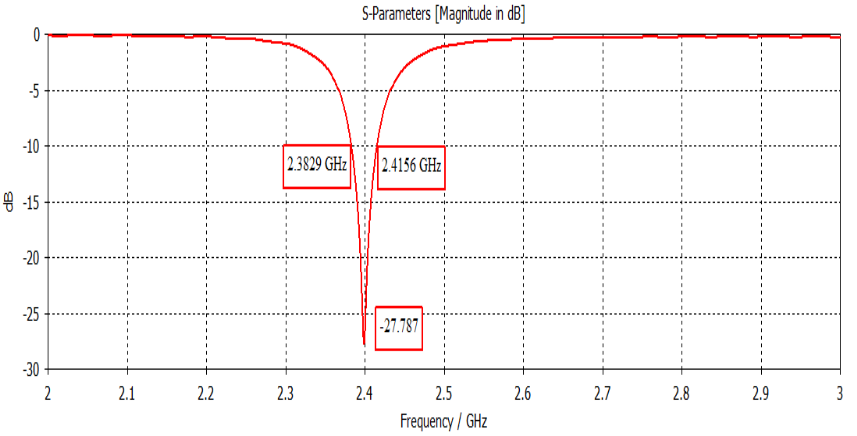
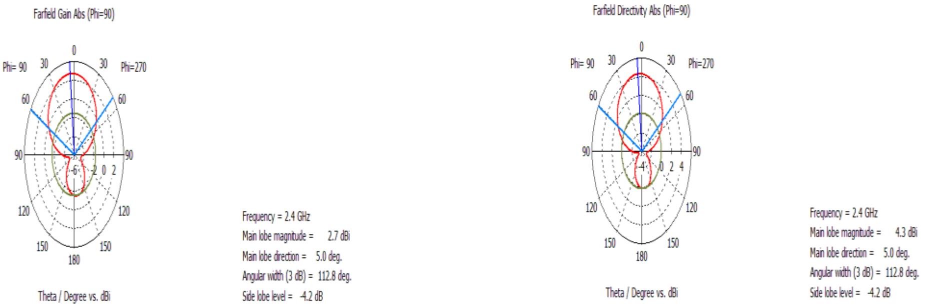


Figure7: Return loss of Alumina

The antenna gain of Alumina is 2.7 dBi as illustrated in figure 8 (a) and the antenna directivity of Alumina is 4.3 dBi as shown in figure 8(b).



(a) (b)

Figure8: (a) Polar Plot of Antenna Gain (b) Polar Plot of Antenna Directivity

3. Discussion and Comparison of Results

In this section, the simulation results obtained for the three substrates Rogers RT5880, FR-4, and Alumina will be compared in terms of gain, directivity, bandwidth, bandwidth efficiency, and antenna size. Table 2 presents a comparison of the results for the three substrates.

http://www.doi.org/10.62341/mmes1069

Table2: presents a comparison of the simulation results

parameters	Alumina	FR-4	Rogers RT5880
gain	2.7 dBi	4.59 dBi	5.87 dBi
directivity	4.3 dBi	5.68 dBi	7.19 dBi
bandwidth	32.7 MHz	51.5 MHz	55.4 MHz
bandwidth efficiency	% 1.36	% 2.14	% 2.3
Antenna's size	554.4 mm^2	1288.32 mm^2	2449.2 mm^2

From Table 2, it is observed that the Rogers RT5880 substrate outperforms the other two in all parameters gain, directivity, bandwidth, bandwidth efficiency and antenna size. This superior performance is attributed to its ideal properties, such as low permittivity and minimal losses, which result in excellent simulation outcomes, making it the most suitable choice for high-performance and precision-demanding applications. On the other hand, the FR-4 substrate demonstrated moderate performance, with acceptable gain and good impedance matching. The Alumina substrate showed the lowest performance in terms of gain and efficiency, mainly due to its high dielectric constant, which negatively affects radiation. However, this substrate achieved the smallest patch size compared to the other two, making it a viable option for applications where compact size is prioritized over antenna performance.

5. Conclusion

The primary objective of this study was to investigate the impact of substrate type on the performance of a microstrip patch antenna, based on simulations using three different substrates: Rogers RT5880, FR-4, and Alumina. All antennas were designed to operate at a frequency of 2.4 GHz. Among the three, the Rogers RT5880 substrate demonstrated superior performance across all key parameters, including gain, directivity, bandwidth, and radiation efficiency. The FR-4 substrate delivered moderate and acceptable performance, making it a suitable option for low-cost applications; however, it suffered from higher radiation losses compared to RT5880. On the other hand, the Alumina substrate showed the lowest performance, mainly due to its high dielectric constant, which negatively affected the antenna characteristics.

http://www.doi.org/10.62341/mmes1069

Overall, the simulations confirmed that the dielectric constant of the substrate material has a direct influence on antenna efficiency, particularly in terms of gain, bandwidth, and directivity. Additionally, the dielectric constant significantly affects the physical size of the antenna. The antenna designed with Alumina had the smallest size, owing to the slower propagation of electromagnetic waves within the high-permittivity material, which increases electric field density and reduces the required physical dimensions for achieving similar radiation characteristics. Therefore, increasing the dielectric constant is a known method for reducing antenna size.

Reference

[1] Mishra, S. N., and J. K. Sharma. "Microstrip Patch Antenna: A Review of Recent Developments." *International Journal of Electronics and Communication Engineering & Technology (IJECET)* , vol . 7 , no . 5 , 2016 , pp . 10–18.

[2] Koul, Anil, et al. "Design and Optimization of Microstrip Patch Antennas for Wireless Communication." *International Journal of Microwave and Wireless Technologies*,vol.9,no.7,2017,pp.1569–1577.

[3] Paul, L. C., Hosain, M. S., Sarker, S., Prio, M. H., & Sarkar, A. K. *"*The Effect of Changing Substrate Material and Thickness on the Performance of Inset Feed Microstrip Patch Antenna.*" American Journal of Networks and Communications*, vol. 4, no. 3, 2015, pp. 54–58.

[4] Hsu, C. H., C. H. Lai, and Y. S. Chang. "A Compact Planar Microstrip-Fed Feed Patch Antenna Using High Permittivity Substrate." *Electromagnetic Research Symposium Proceedings*, 12 Sept. 2011, Suzhou, China.

[5] Nel, Ben A. P., Skrivervik, Anja K., and Gustafsson, Mats. "Radiation Efficiency and Gain Bounds for Microstrip Patch Antennas." *IEEE Transactions on Antennas and Propagation*, vol. 73, no. 2, 2025, pp. 873–883.

[6] Khan, Muhammad Umar, et al. "Microstrip Patch Antenna Miniaturization Techniques: A Review." *IET Microwaves, Antennas & Propagation*, vol. 9, no. 9, 2015, pp. 913–922.

[7] Fadehan, Gabriel A., et al. "Influence of Substrate Materials on the Performance of a Triple-Band Notched Frequency UWB Antenna." *Journal of Engineering Advancements*, vol. 3, no. 2, 2024, pp. 1–12.

http://www.doi.org/10.62341/mmes1069

[8] Kumar, Manoj, and Anil Sharma. "Effect of Dielectric Constant on the Design of Rectangular Microstrip Antenna." *International Journal of Electronics and Communication Engineering & Technology (IJECET)*, vol. 6, no. 6, 2015, pp. 1–8.

[9] A. El Hasnaoui and T. Mazri, "Effect of Substrate Permittivity on the Performance of Microstrip Patch Antenna for 5G Applications." *Journal of Electromagnetic Waves and* Applications, vol. 34, no 18, 2020, pp. 2382-2396.

[10] A. Saeidi, H. Oraizi, and M. Khalaj, "Performance Enhancement of Microstrip Patch Antennas Using Composite Substrates and Substrates." *Optical and Quantum Electronics*, vol. 55, no 13, 2023, pp. 1-12.

[11] Sulwan Dase, Irawati Razak, " Optimization of an inset-fed calculations for rectangular microstrip antenna." *Computer Science and Information Technologies*, Vol. 4, No. 2, July 2023, pp. 143~148.