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# Performance Comparison of Circular Patch Antennas Using Three Different Substrates at mmWave for 5G Systems

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# مقارنة الأداء لهوائيات دائرية شريطية باستخدام ثلاثة ركائز مختلفة عند الأمواج فوق المليمترية لأنظمة الجيل الخامس

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**Abstract**

This study presents the design and analysis of three inset-fed circular patch antennas using different substrate materials with unique dielectric constants, namely Polycarbonate, Preperm 260 LDS, and Rogers RT-5880 to compare their performance. The proposed designs utilize copper material for the radiating patch on the top side of the dielectric substrate and the ground plane on the bottom side of the same dielectric substrate. These structures resonate at a frequency of 28 GHz, and the dimensions of the three antenna structures were computed for the three different substrate materials. The performance of the three designs was simulated using the Computer Simulation Technology (CST) software to compare their performances. The performance parameters utilized to evaluate and compare the proposed designs include return loss, gain, radiation efficiency, bandwidth, radiation pattern, and voltage standing wave ratio. The proposed structures provide a return loss ($S_{11}$) less than -10 dB, and their VSWR was very close to the ideal value, which is less than two for practical wireless applications. Moreover, Preperm 260 LDS exhibited better results in terms of $S_{11}$ and VSWR, with values of -61.038 dB and 1.0017, respectively. In terms of gain, it increases when low-dielectric constant materials are employed.

***Keywords:*** *Antenna performance indexes, Circular patch antenna, Dielectric constant, Fifth-generation (5G).*

**الملخص**

في هذه الدراسة، يتم تقديم تصميم وتحليل ثلاثة هوائيات دائرية للأمواج فوق المليمترية المُغذّاة من الداخل باستخدام خامات قاعدة مختلفة تتميز بثوابت كهربائية فريدة، وهي Polycarbonate وPreperm 260 LDS وRogers RT-5880، لمقارنة أدائها. تستخدم التصاميم المقترحة مادة النحاس لتشكيل الهوائي الإشعاعي على الجانب العلوي من قاعدة العازل الكهربائي وأرضية على الجانب السفلي من نفس قاعدة العازل الكهربائي. تتردد هذه الهياكل عند تردد 28 غيغاهرتز، وقد تم حساب أبعاد الهوائيات الثلاثة بناءً على الخامات الثلاثة المختلفة للقاعدة. تمت محاكاة أداء الهياكل الثلاثة المقترحة باستخدام برنامج تكنولوجيا المحاكاة الحاسوبية (CST) لمقارنة أدائها. تم استخدام معايير الأداء التالية لتقييم ومقارنة أداء التصاميم المقترحة: فقدان العودة، والكسب، وكفاءة الإشعاع، والعرض الترددي، ونمط الإشعاع، ومعامل الجهد الموجي الواقف. توفر التركيبات المقترحة فقدان إرجاع ($S_{11}$) أقل من -10 ديسيبل، وكان VSWR قريب جدًا من القيمة المثالية، والتي تقل عن اثنين للتطبيقات اللاسلكية العملية. علاوة على ذلك، أظهر Preperm 260 LDs نتائج أفضل من حيث $S_{11}$ و VSWR، مع قيم -61.038 ديسيبل و 1.0017، على التوالي. من حيث الكسب، يزداد عند استخدام المواد ذات ثابت عزل منخفض.

**الكلمات الدالة:** الثابت الكهربائي للعازل، الجيل الخامس G5، هوائي دائري الشكل، مؤشرات أداء الهوائي.

## 1. Introduction

The advancements in mobile wireless technology from zero generation (0G) to fourth generation (4G) have driven a revolution in mobile communications. Although 4G has offered several benefits, it is still not able to address some issues such as low coverage, low quality, inadequate interconnectivity, connections lost, excessive energy consumption, and congested channels (Kumar and Kumar, 2019). Therefore, the fifth-generation (5G) systems have been introduced to meet the user's desires. The International Telecommunication Union (ITU) has designated for the 5G systems frequency range in the mm-wave spectrum, spanning from 24 GHz to 80 GHz (Prachi *et al.*, 2020; and Almazok, 2022). The 5G is anticipated to significantly increase communication capacity by utilizing a large unlicensed bandwidth, primarily in the millimeter-wave range. Additionally, 5G will be able to connect a large number of devices, minimize end-to-end delay by about 5 times, prolong battery life for lower battery communication equipment, and provide higher data rates than current systems (Almazok, 2022; and Gemeda *et al.*, 2021). Therefore, the 5G network requires a challenging replacement concerning antenna design to fulfill these anticipated services (Almazok, 2022). Any communication system's objective is to transmit and receive information between transmitter and receiver through electromagnetic waves; hence, to do this, the system requires an antenna that can both send and receive electromagnetic waves (Almazok, 2022; and Ngoc, 2020). However, an antenna in such an advanced 5G communication system needs to be able to transmit and receive electromagnetic waves at the mm-wave frequency band, along with the following features: compactness, small and portable profiles, cheaply manufactured, easily installed, and suitability for both planar and non-planar surfaces (Almazok *et al.*, 2023; Almazok, 2022; Gemeda *et al.*, 2021; and Kaur et al., 2016). Microstrip patch antennas at mm-wave frequencies can be a potential option for 5G to meet all of the aforementioned requirements (Almazok, 2022; Ngoc, 2020; and Darboe *et al.*, 2019). The three layers that make up the construction of a microstrip patch antenna from the bottom to the top are the ground plane, a dielectric substrate layer, and the top layer, which represents the radiating metallic patch element (Almazok, 2022). A variety of configurations are possible for microstrip patch elements, the rectangular patch element is the most prevalent, while the circular patch element is the second most well-known (Huque *et al.*, 2011). In many fields of science and engineering, however, circular geometry plays an important role, and antenna design is one of them (Altufaili *et al.*, 2022). A circular patch antenna is straightforward to construct and simple to utilize with an implanted device, additionally, the physical dimension of the circular patch antenna is up to 16 percent less than the rectangular antenna at the same design frequency (Samad & Rahman, 2021). Also, there are two degrees of control freedom for rectangular patch components while there is only one degree of control freedom for circular patch elements. Consequently, it is simpler to design a circular patch structure and manage its radiation pattern (Huque *et al.*, 2011). In terms of feeding, there are three ways to feed a microstrip antenna, including coaxial probe, aperture coupling, and microstrip line, which are the most popular methods (Almazok *et al.*, 2023). This is because of their easy impedance matching and their bandwidth achievement with impedance matching of 2-5% (Mohammed *et al.*, 2019; and Kumar & Verma, 2017). This paper investigates and compares the performance of circular patch antennas employing three different substrate materials in circular patch antenna design.

A microstrip patch antenna for 5G technology has been proposed and published in a variety of studies in the literature. Colaco and Lohani (2020) have introduced a circular patch antenna at 28.5 GHz using a Rogers RT/Duroid 5880-based substrate with a height of 0.6 mm, a dielectric constant of $\mathcal{E}_r$=2.2, a loss tangent of 0.0010, and a microstrip feed line, the proposed design shows a good return loss of -32.86 dB, enhanced bandwidth of 1.6369 GHz, high gain of 10 dB, and outstanding antenna radiation efficiency of about 100% which is crucial for 5G applications and equipment that supports 5G, such as smartphones.

Kumar and Kumar (2019) conducted a study on the design of circular patch antennas for 5G applications operating at 28 GHz. The authors aimed to simulate and compare the performance of two types of circular patch antennas: one with a coaxial micro-feed line feed and the other with a linear feed, both constructed using RT/Droid 5880 substrate material. The results of the study showed that the coaxial feed circular antenna outperformed the linear feed circular antenna, with a bandwidth of 0.792 GHz compared to 0.660 GHz for the microstrip line feed antenna.

According to Altufaili *et al.*, (2022), a design and simulation are made for a microstrip circular patch antenna. The antenna consists of two circles, with the first circle having a compact structure and a radius of

2.5 mm, and the second circle having a radius of 1 mm and a thickness of 0.35 mm. The introduced antenna exhibits three resonant frequencies: 41.08 GHz (-12.4 dB return loss), 47.4 GHz (-18.86 dB return loss), and 54.4 GHz (-24.3 dB return loss). The bandwidths associated with these frequencies are 150 MHz, 222 MHz, and 219 MHz, respectively. The gain at the three resonant frequencies is measured to be 6.16 dB, 9.89 dB, and 5.54 dB, with an overall efficiency of 98%. To ensure proper matching between the 50 $\Omega$ microstrip feed line and the radiating patch, an inset feed transmission line technique was employed. The chosen substrate for the antenna design is Roger RT Duroid 5880, which possesses a loss tangent of 0.0009, a height of 0.5 mm, and a dielectric constant of 2.2. The computational analysis of the proposed design was carried out using computer simulation technology microwave studio.

Sahoo *et al.* (2020) developed a circular patch antenna for 5G applications. In this study, HFSS software is used for the design and simulation. The frequency at which the antenna resonates is 3.5 GHz. The antenna shows $S_{11}$ value of -40.2827 dB, a bandwidth value of 200 MHz, and an impedance value of 50.99 – 0.15 $\Omega$. The maximum power transfer theorem is satisfied by the superb impedance matching. In addition, it has an efficiency of 88.40% and a maximum gain of 5.8263 dB. The VSWR value is 1.02, which is considered almost perfect. As a result, there will be reduced reflection and maximum signal transmission possible. This introduced structure is considered appropriate for a variety of 5G applications because of its straightforward design, small size, acceptable radiation characteristics, appropriate impedance matching, and superior gain.

Based on the literature reviewed, previous studies have focused on the development of 5G circular patch antennas using commonly employed substrate materials such Roger RT Duroid 5880. This present study, however, introduces a design consisting of three inset-fed rectangular patch antenna structures operating in the 28 GHz mm-wave frequency band. These proposed structures utilize three different dielectric constant substrate materials, namely Rogers RT-5880, Preperm 260, and Polycarbonate. The main contribution of this article lies in proposing and comparing the performance of these three diverse dielectric constant substrate materials as a potential substrate for microstrip patch antenna design. To simulate and assess the performance of the proposed structures, the Computer Simulations Technology (CST) program is employed, as mentioned in the reference (CST Studio Suite, 2019).

## 2. Materials and Methods

The design process consists of the following steps:

- Selecting 28 GHz as the resonant frequency.
- Identifying three different substrate materials, namely Rogers RT-5880, Preperm 260LDS, and Polycarbonate.

- Selecting copper material for the ground plane and patch element.
- Choosing a suitable substrate height that is standardized for all three structures.
- Employing the inset-fed method for feeding the three antennas.
- Determining the dimensions of the three structures based on the design equations using Matlab code.
- Constructing each design in CST software based on the obtained dimensions from MATLAB code
- Saving the three constructions and simulating each of the designs.
- Saving the results of structure simulation if they meet the requirements.
- Applying optimization techniques to improve the performance if the results are not satisfactory
- Comparing the results of the three structures.

These steps are followed systematically to design and simulate the proposed structures, and the results are compared to evaluate the performance of the three circular patch antennas using different substrate materials for 5G systems.

## 3. The Proposed Antennas Design

The design process of the proposed circular patch is divided into several stages. Firstly, the initial stage involves designing the patch itself, which primarily involves the computation of the patch's radius. This is accomplished by considering parameters such as the resonance frequency ($f_r$), the height of the substrate (h), and the dielectric constant of the substrate ( $\varepsilon_r$). Secondly, the dimensions of the substrate and the ground plane are determined. Finally, the inset feeding method parameters are calculated to complete the design process.

### 3.1. Radiating Circular Patch

To determine the radius (a) of a circular microstrip patch antenna, the following equation is used for computation (Rahma *et al.*, 2020):

$$a = \frac{F}{\left\{1+\frac{2h}{\pi\varepsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{\frac{1}{2}}} \quad \text{...... (1)}$$

where F represents the logarithmic function of the radiating patch (Rahmawati *et al.*, 2021). The computation of F can be obtained by using the following formula (Rahma *et al.*, 2020):

$$F = \frac{8.791*10^9}{f_r\sqrt{\varepsilon_r}} \quad \text{...... (2)}$$

**3.2. Feed-Line Dimensions**

In the context of designing a microstrip transmission line, several computations are required to determine the dimensions of various components. Specifically, the transmission line length ($T_L$), the inset feed depth (Fi), the feed line width ($W_f$), and the notch gap (g) are calculated using Eqns. (3) to (8).

The transmission line length ($T_L$) is determined according to the following equation (Przesmycki *et al.*, 2020; and Almazok *et al.*, 2023):

$$T_L = 3 \times h \qquad \text{...... (3)}$$

The inset feed depth ($F_i$) is calculated to be the same inset feed depth of a rectangular patch antenna based on the following formula (Darboe *et al.*, 2019; and Almazok *et al.*, 2023):

$$F_i = 10^{-4}\big[0.001699\varepsilon_r{}^7 + 0.13761\varepsilon_r{}^6 - 6.1783\varepsilon_r{}^5 + 93.187\varepsilon_r{}^4 - 682.69\varepsilon_r{}^3 + 2561.9\varepsilon_r{}^2 - 4043\varepsilon_r + 6697\big](Lp/2) \qquad \text{...... (4)}$$

Where $Lp$ represents the actual rectangular patch length in the case of rectangular patch geometry (Almazok *et al.*, 2023).

The feed line width ($W_f$) required to obtain a 50Ω characteristic impedance (Zo) can be determined by computing the feed line width-to-height ratio ($W_f$ /h) using the following formula (Przesmycki *et al.*, 2020; Kaeib *et al.*, 2019; and Almazok *et al.*, 2023):

$$\frac{Wf}{h} = \begin{Bmatrix} \frac{8e^A}{e^{2A}-2} & when\ A \geq 1.52 \\ \frac{2}{\pi}\left\{B - 1 - \ln(2B-1) + \frac{\varepsilon_{r-1}}{2\varepsilon_r}\left[\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right]\right\} & when\ A < 1.52 \end{Bmatrix} \qquad \text{...... (5)}$$

where;

$$A = \frac{Z_O}{60}\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \qquad \text{...... (6)}$$

$$B = \frac{60\pi^2}{Z_O\sqrt{\varepsilon_r}} \qquad \text{...... (7)}$$

Finally, the notch gap (g) is determined using the following equation (Matin & Sayeed, 2010; and Almazok *et al.*, 2023):

$$g = \frac{c_0}{\sqrt{2*\varepsilon_{reff}}}\frac{4.65*10^{-12}}{f_r(in\ GHz)} \qquad \text{...... (8)}$$

It is important to note that these computations play a critical role in the design process, and accurate determination of the dimensions is essential for optimal performance of the microstrip transmission line.

In this study, the design parameters of three structures were computed at a frequency of 28 GHz using Matlab code. The three different substrate materials considered were Rogers RT-5880, Preperm 260 LDS, and Polycarbonate, with corresponding dielectric constant values of 2.2, 2.6, and 2.9, respectively. To optimize the performance of the three structures, the calculated dimensions were refined using the trial and error method

(Mukta *et al.*, 2021). This approach enabled the identification of optimal design parameters, ultimately resulting in improved performance results. Figure (1) displays the design parameters that were taken into consideration during the design process of the three circular patch antennas.

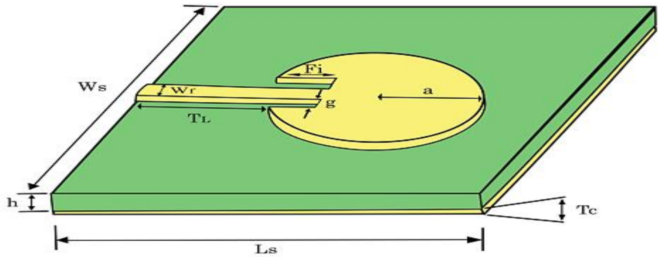


**Figure 1. Proposed circular patch antenna structure.**

The design parameters for the proposed designs have been compiled and presented in Table (1).

**Table 1. The Design Parameters for the Proposed Structures**

| *parameter* | *symbol* | *Rogers RT-5880 substrate* | | *Preperm 260 LDS substrate* | | *Polycarbonate substrate* | |
|---|---|---|---|---|---|---|---|
| | | *Cal. values (mm)* | *Opt. values (mm)* | *Cal. values (mm)* | *Opt. Value (mm)* | *Cal. values (mm)* | *Opt. Values (mm)* |
| Circular patch radius | $a$ | 1.99541 | 2.112 | 1.84549 | 1.9533 | 1.7532 | 1.915 |
| Feed lineWidth | $W_f$ | 0.616213 | 0.6 | 0.553184 | 0.6 | 0.514404 | 0.6 |
| Transmission line length | $T_L$ | 0.6 | 0.341 | 0.6 | 0.263 | 0.6 | 0.218 |
| Feed line inset distance | $F_i$ | 0.84354 | 1.58 | 0.820106 | 1.525 | 0.808877 | 1.457 |
| Substrate Length | $L_s$ | 4.70504 | 4.906 | 4.43327 | 4.4333 | 4.26611 | 4.266 |
| Substrate Width | $W_s$ | 5.43519 | 5.221 | 5.19298 | 5.193 | 5.03633 | 5.036 |
| Notch Gap | g | 0.0244307 | 0.071 | 0.022589 | 0.068 | 0.0214592 | 0.07 |
| Substrate height | h | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Copper Thickness | $T_c$ | 0.035 | 0.035 | 0.035 | 0.035 | 0.035 | 0.035 |

In terms of calculated substrate length and width, (Almazok et al., 2023) provide these values based on the rectangular patch designs, and the same values were applied to the proposed structures.

## 4. Simulation Results Analysis, Comparison and Discussion

The evaluation and comparison of the performance of these proposed designs are based on several performance parameters, including return loss($S_{11}$), bandwidth (BW), voltage standing wave ratio VSWR, radiation pattern, gain G, and radiation efficiency ($\eta rad$ %).

### 4.1. Performance Assessment Metrics

The Return Loss ($S_{11}$): is a performance parameter that is expressed in decibels (dB) and represents the ratio of the reflected power to the incident power (Almazok, 2022; and Almazok *et al*., 2023). A reference value of -10 dB is commonly utilized in the evaluation of this parameter, as it indicates that only 10% of the incident power is reflected while the remaining 90% is received, which is considered an acceptable level for mobile communication (Gemeda *et al.,* 2021; and Almazok *et al*., 2023). A small $S_{11}$ value of -10 dB or less is an indication of superior performance (Almazok *et al.,* 2023).

The bandwidth (BW): It refers to the frequency range, where the return loss is less than -10 dB, as reported by (Gemeda *et al.,* 2021; and Almazok *et al*., 2023).

Voltage Standing Wave Ratio (VSWR): It is a metric that measures the amount of power reflected from the antenna toward the transmitter (Fante & Gemeda, 2021; and Almazok *et al.,* 2023). The values of both $S_{11}$ and VSWR indicates an impedance mismatch between the antenna and transmission line (Almazok *et al.,* 2023). While $S_{11}$ is defined as the ratio between the incident power and reflected power (Almazok *et al.,* 2023). VSWR is calculated as the ratio between the highest and lowest voltage values on the standing waveform along the length of the transmission line (Almazok *et al.,* 2023). For patch antennas, an acceptable VSWR value falls between 1 and 2 throughout the bandwidth, with the optimal value being 1 (Almazok *et al.,* 2023).

Radiation Pattern and Gain (G): These two parameters are also used for evaluating the antenna's performance. The radiation pattern of an antenna illustrates the amount of energy it radiates (Colaco & Lohani, 2020; and Almazok *et al.,* 2023). On the other hand, antenna gain is the ratio of the antenna power density at a specific point to the isotropic antenna power density at the same point when both antennas are supplied with the same amount of power (Almazok, 2022; and Almazok *et al*., 2023). This gain excludes mismatching and efficiency losses; however, realized gain considers that the antenna has some efficiency loss and mismatching loss; therefore, realized gain is smaller than gain. (Fishyxl, 2006; and Why Is There a Big Difference Between Realize Gain and Gain in My Design? Research Gate, 2018)

Radiation Efficiency ($\eta rad$ %): It is a performance metric that defines the ratio of the total power radiated by an antenna to the total input power injected into it (Almazok *et al.,* 2023). This parameter signifies the antenna's effectiveness in radiating and receiving electromagnetic waves. Therefore, higher values of radiation efficiency are desirable for better antenna performance (Almazok *et al.,* 2023).

### 4.2. Comparative Analysis of Simulation Results for Three Proposed Circular Patch Structures

In this section, comparisons have been made between the performance parameters of the three proposed designs as illustrated in Figures 2 to 6. Furthermore, Table (2) presents a concise overview of the simulation results, highlighting the differences between the three structures.

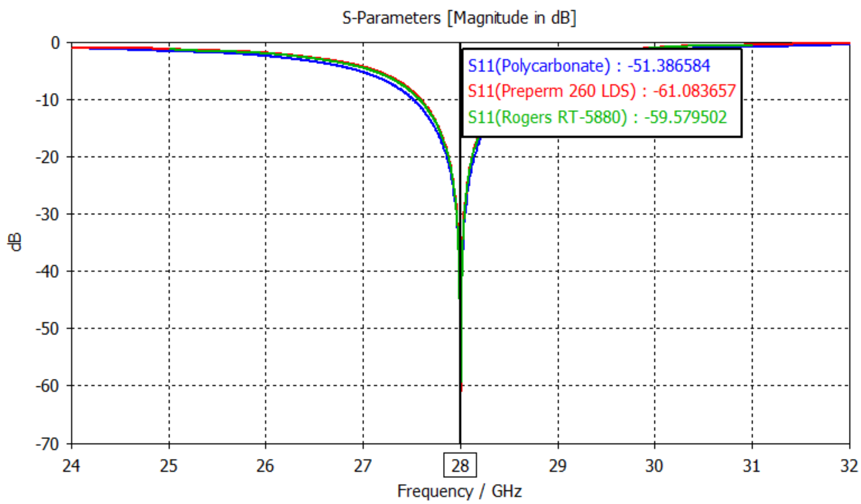


**Figure 2. $S_{11}$ plot of the three proposed structures**

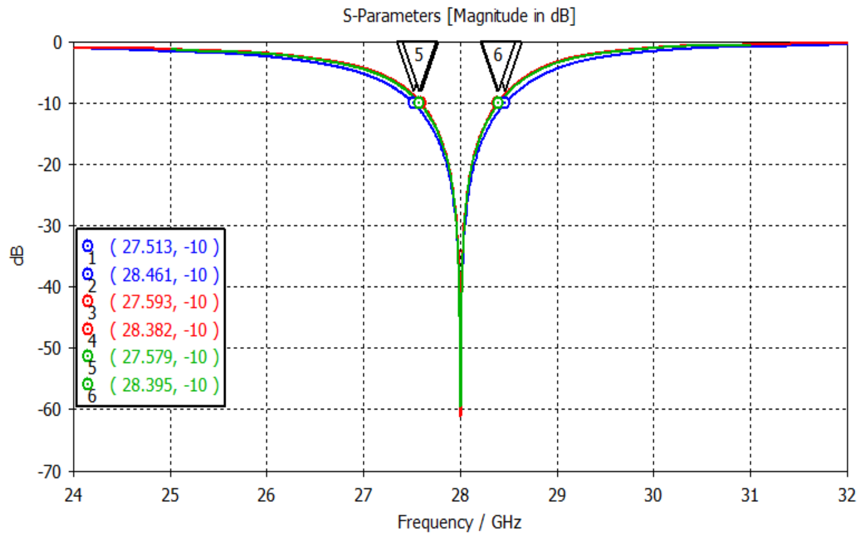


**Figure 3. BW plot of the three proposed structures**

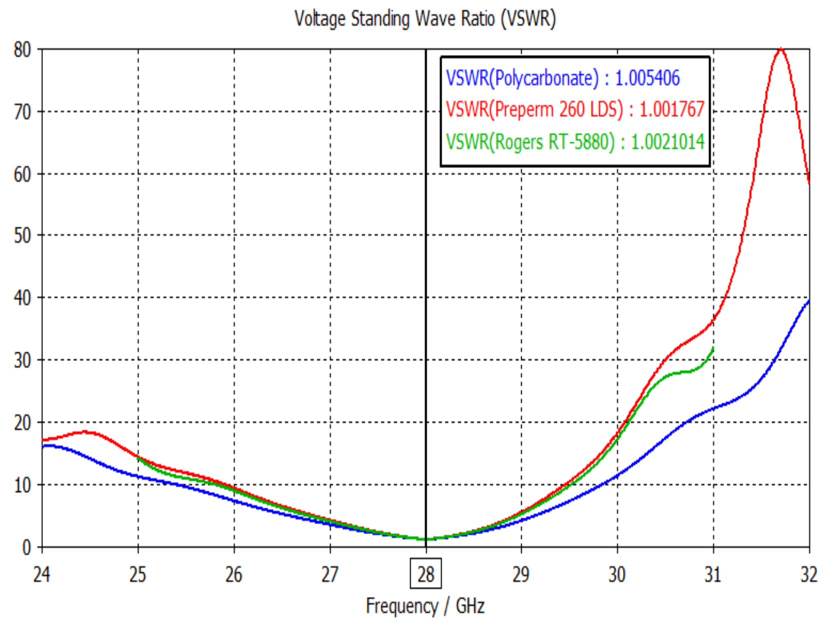


**Figure 4. VSWR plot of the three proposed structures**

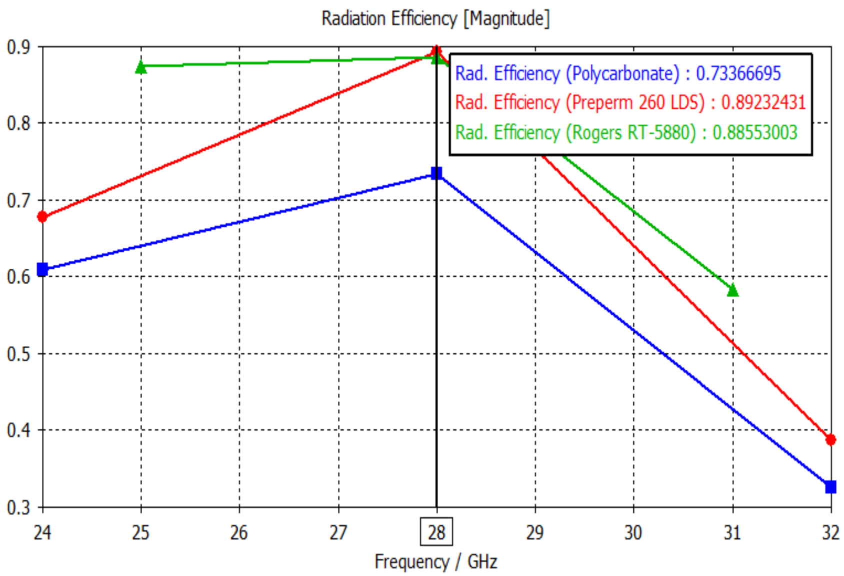


**Figure 5.** $\eta rad$ **% plot of the three proposed structures**

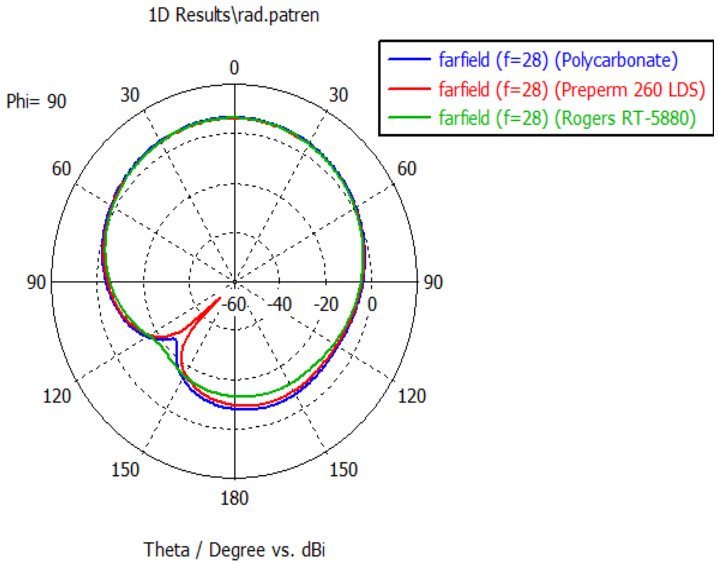


**Figure 6. 2-D radiation pattern plot of the three proposed structures.**

**Table 2. Comparison between proposed circular patch structures using Rogers RT-5880, Polycarbonate, and Preperm 260 LDS.**

| *Parameters* | *Rogers RT-5880* | *Polycarbonate* | *Preperm 260 LDS* |
|---|---|---|---|
| $S_{11}(dB)$ | -59.579 | -51.386 | -61.083 |
| VSWR | 1.0021 | 1.0054 | 1.0017 |
| Realized gain (dBi) | 6.260 | 5.187 | 6.093 |
| HPBW (deg) | 87.5 | 92.3 | 91.7 |
| Bandwidth (MHz) | 816 | 948 | 789 |
| $\eta rad$ % | 88.55% | 73.37% | 89.2% |

It can be noticed from Figure (3) and Table (2) that Rogers RT-5880 achieved a realized gain of 6.260 dBi with a bandwidth of 816 MHz, while Polycarbonate exhibited a realized gain of 5.187 dBi with a bandwidth of 948 MHz, and Preperm 260 LDS demonstrated a realized gain of 6.093 dBi with a bandwidth of 789 MHz. Notably, it can be observed from Figure (4) and Table (2) that the values of the VSWR did not exhibit significant changes with varying substrate materials, and their values are close to the ideal value. Additionally, Rogers RT-5880 and Preperm 260 LDS exhibited higher radiation efficiency values than polycarbonate, at 88.55% and 89.2%, respectively, as shown in Figure (5) and Table (2). In terms of $S_{11}$ ,it can be observed from Figure 2 and Table 2 that Rogers RT-5880 and Preperm 260 LDS substrate structures show better values compared to the polycarbonate substrate design. Furthermore, the polycarbonate substrate structure provides the highest Half Power Beam Width HPBW (deg) as shown in Figure (6) and Table (2).

In general, it can be noticed that Rogers RT-5880 and Preperm 260 LDS, which have lower dielectric constant values of 2.2 and 2.6, respectively outperform polycarbonate substrates with 2.9 dielectric constant in VSWR, realized gain, and $\eta rad$ %. The proposed designs resonate at a frequency of 28 GHz with a return loss $S_{11}$ (below -10 dB), while their VSWR was very close to the ideal value. In higher-frequency applications, the lower dielectric constant value is recommended (Almazok *et al.,* 2023). As 5G mobile communication antennas require high gain and efficiency (Faisal *et al.*,2018), it is noteworthy that the three proposed designs meet the requirements of 5G mobile communications and can be utilized based on the specific application.

## 5. Conclusion

The primary objective of this paper was to investigate the performance of circular microstrip patch antennas concerning the requirements of 5G technology. To achieve this objective, three distinct dielectric substrate materials namely Rogers RT-5880, Polycarbonate, and Preperm 260 LDS were utilized in the design of the antennas. It was observed that the gain of the antenna increases when low dielectric constant materials are employed. In conclusion, all designs in this project meet the 5G mobile communication standards and can be implemented depending on the specific application.

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