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A High-Gain Slotted Rectangular Microstrip Patch Antenna for 5G Millimeter-Wave Applications

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Abstract

The fifth generation (5G) of telecommunications has been a compelling subject for several academics in recent years. A patch antenna has recently been used for 5G technology, which demands a communication connection with a high data rate and low latency. This article proposes a high-gain slotted microstrip patch antenna for 5G applications at the resonant frequency of 38 GHz. Rogers RT5580 material, with a dielectric permittivity of 2.2 and a loss tangent of 0.009, has been used as a substrate for the antenna. The antenna in concern has a compact construction with dimensions of 8×5.2×0.324 mm^3. The slotted antenna's dimensions are optimized with the CST Studio Suite software simulator. The proposed antenna design achieved a reflection coefficient of -49.9 dB, a gain of 9.233 dBi, and a wide operational bandwidth of 1.84 GHz, which is the main objective of this study. The suggested antenna also demonstrated favorable performance at 37 GHz and 39 GHz by changing the length of the radiation patch. In comparison to previous similar designs reported in the literature, the proposed antenna has significantly higher bandwidth, return loss, beam gain, and radiation efficiency; therefore, it is a viable alternative for 5G communication.

Keywords: 5G, Microstrip Patch Antenna, High-Gain, Rogers RT5580

هوائي رقعة مستطيل ذو فتحات عالي الكسب لتطبيقات الموجات المليمترية في الجيل الخامس

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الخلاصة

يعتبر الجيل الخامس (5G) من الاتصالات موضوعًا مثيرًا للاهتمام للعديد من الأكاديميين في السنوات الأخيرة. تم استخدام هوائي الرقعة مؤخرًا في تقنيات الجيل الخامس، التي تتطلب اتصالًا بمعدل بيانات مرتفع وزمن استجابة منخفض. يقترح هذا المقال هوائي رقعة ذو فتحات وعالي الكسب لتطبيقات الجيل الخامس عند تردد رنيني يبلغ 38 جيجاهرتز. تم استخدام مادة Rogers RT5580 ، التي تتمتع بموصلية عازلة تبلغ 2.2 و خسارة تبلغ 0.009 كركيزة للهوائي. الهوائي المعني له تصميم مدمج بأبعاد 8×5.2×0.324 مم³. تم تحسين أبعاد الهوائي المقترح باستخدام برنامج المحاكاة (CST Studio Suite). حقق الهوائي المقترح معامل انعكاس قدره 49.9- ديسيبل، وكسب قدره 9.233 ديسيبل، وعرض نطاق تشغيلي واسع يبلغ 1.84 جيجاهرتز. أظهر الهوائي المقترح أيضًا أداءً جيدًا عند تردد 37 جيجاهرتز و39 جيجاهرتز من خلال تغيير طول رقعة الإشعاع. بالمقارنة مع التصاميم المماثلة السابقة المذكورة في الأدبيات، فإن الهوائي المقترح يتمتع بعرض نطاق أعلى بشكل ملحوظ، وخسارة عائدة أقل، وكسب شعاعي أفضل، وكفاءة إشعاعية أعلى، مما يجعله بديلاً قابلاً للتطبيق في اتصالات الجيل الخامس.

1. Introduction

In recent decades, there has been a substantial surge in the need for mobile subscriptions, data rates, and mobile data transfer frequencies for 5G networks [1], [2]. The exponential expansion of the 5G network will significantly influence many sectors, such as artificial intelligence, blockchain, ultra-high definition, and Internet of Things (IoT) services, including intelligent transportation, smart grids, and smart cities. These industries will see substantial improvements with the introduction of 5G technology [3], [4]. An essential prerequisite for the deployment of 5G is to guarantee the availability of appropriate frequency resources. In order to enhance significantly spectral efficiency and, as a result, the throughput provided to the client, it is imperative to deploy dense networks, which are characterized by a large number of short-range base stations [5]. 5G networks replace massive cell-based solutions with networks made of many tiny cells[6]. 5G technology operates at high-frequency ranges that are significantly affected by the antenna performance, namely in terms of return loss, bandwidth, and gain. To address these issues and fulfill user requirements, it is crucial to manufacture and design antennas that possess very desirable properties in terms of gain, return loss, and bandwidth [7], [8].

Microstrip patch antennas (MPA) are well-suited for utilization in 5G applications, which make use of higher frequency bands. In addition, microstrip patch antennas are economically efficient, lightweight, physically simple to produce, and provide integrated functionality [9]. Microstrip antennas are offered in a diverse range of radiating patch configurations, such as rectangular, square, circular, elliptical, triangular, and more. Patch antennas characterized by square and rectangular forms are often used because of their comparatively simple construction and analysis. [10].

Fifth-generation (5G) technologies have been developed in response to the growing need for expanded data speeds, enhanced network capacity, and reduced latency communication. To fulfill these criteria, wireless communication systems have started to use the millimeter-wave (mmWave) radio spectrum, which covers frequencies ranging from 30 GHz to 300 GHz [11]. The use of this frequency range offers broader bandwidths, therefore facilitating accelerated data transfer and improved network performance in comparison to the sub-6 GHz bands usually employed in previous cellular technologies [12]. Within the millimeter wave (mmWave) bands, the 38 GHz frequency band has attracted significant attention in 5G systems because of its capacity to provide very high data rates while accommodating a substantial number of interconnected devices. This frequency is deliberately placed inside the bandwidth designated for 5G services, and its usage offers significant benefits like fast data transfer rate, little interference, and effective use of spectrum resources.

Much study is dedicated to the investigation and development of millimeter range antennas for 5G technologies, particularly in the 38 GHz frequency range, which provides optimal performance for 5G networks. In order to achieve this objective, it is essential to develop novel types of antennas that are appropriate for fifth-generation technologies. This undertaking presents a formidable and noteworthy challenge for experts in antenna design. In one of these studies[13], the researchers proposed a rectangular patch antenna designed to operate at 38 GHz using a substrate of FR-4 and cylindrical notches with a return loss of − 24 dB, directivity of 2.37 dBi, and overall bandwidth of 1.021 GHz. Similarly, the researchers of [14] present a compact size circular MPA with a return loss of -20.6 dBi and gain of 7.25 dBi. This design produces a bandwidth of 640 MHz. Another rectangular patch antenna with two elements array was produced in [15]. This design achieved a gain of 7.6 dBi, a bandwidth of 767 MHz, and

90% radiation efficiency. In [16], the authors proposed an inverted F, dual-band antenna work at 28/38 GHz frequency bands. This antenna was designed using FR4 substrate with a relative permittivity of 4.4 and thickness of 0.2 mm. The overall size of the antenna was 5.5×4 mm^2 and achieved a bandwidth of 1.23 GHz and a gain of 6.61 dBi at 38 GHz. Similarly, a dual-band antenna with triangular stubs was introduced using Rogers RT4003 with a height of 0.203 mm. This design produced two bands (from 26 GHz to 30.45 GHz) and (from 36.4 GHz to 40.25) with an overall gain of 4.5 dBi and 4.2 dBi in the first and second bands, respectively. This work is proposed in reference [17]. In another work [18], An HP-shaped antenna was introduced using the Rogers RT5880 substrate, which has a thickness of 0.51 mm. The antenna achieved a maximum bandwidth of 3.17 GHz and a low reflection coefficient of -33 dB. The gain and radiation efficiency of this design was 6.5 dBi and 80%. In addition, in [19] a single band fork-shaped antenna is designed for 38.6 GHz. The design utilizes Rogers RT5880 substrate with an overall size of 10×6×0.254 mm^3 and achieved a reflection coefficient of -30 dB. The gain of the design was 7.6 dBi, and good bandwidth was achieved at 1.9 GHz. A compact U-shaped antenna fed by a transmission line using Rogers RT5880 substrate was presented in the study [20]. It achieved a bandwidth of around 1 GHz at a frequency of 37 GHz and a reflection coefficient of -20 dB with a good gain of 6.81 dBi. In reference [21] The researchers introduced a dual-band MPA with overall dimensions of 15×25×0.25 mm3. The proposed design operates at 38/60 GHz and is designed on Rogers RO3003TM substrate. It achieved bandwidths of 2 GHz and 3.2 GHz at 38 GHz and 60 GHz, respectively. The total gain was 6.5 dBi at 38 GHz and 5.5 dBi at 60 GHz. This design achieved a decent return loss value of -42 dB at 38 GHz and -47 dB at 60 GHz.

This study introduces the design of a patch antenna designed for operation at a frequency of 38 GHz. The antenna has the distinctive capability to change its operating frequency to either 37 GHz or 39 GHz by adjusting the length of the radiating patch. This technique provides a streamlined but efficient means of attaining frequency reconfigurability, hence improving the antenna's flexibility for different mmWave communication situations without requiring extra switching electronics. The design presented in this study showcases the feasibility and effectiveness of making physical modifications to the patch length as a method to alter the operating frequency of the antenna within the crucial mmWave bands for 5G networks. The paper is organized into six sections; in addition to this section, the paper includes an explanation of the antenna design process in the second section and a presentation of simulation results at a frequency of 38 kHz in the third section, the fourth section includes the antenna operation at frequencies of 37 and 39 GHz. A comparison between the proposed work and previous studies is mentioned in the fifth section, and the research is concluded by presenting a conclusion of the proposed work in the sixth section.

2. Design of the proposed antenna

This section discusses the design procedure of a microstrip patch antenna designed for 5G applications operating at a resonance frequency of 38 GHz. Given the widespread usage of patch antennas in various forms [22], the antenna was designed using a rectangular patch with symmetrical multi-rectangular slots. The antenna was constructed on a Rogers RT5880 substrate material (5.2 mm in width, 8 mm in length, and 0.254 mm in thickness) with a relative dielectric permittivity (εreff) of 2.2 and loss tangent (tan(δ)) of 0.0009. More information on the RT 5880 substrate is available in the reference [23]. The inset feed method was chosen among the many feeding strategies for microstrip patch antennas to get optimal matching impedance between the feed line and the radiation patch. Figure 1 shows a flowchart of the design process of the proposed work. Figure 2 illustrates the proposed design of the antenna.

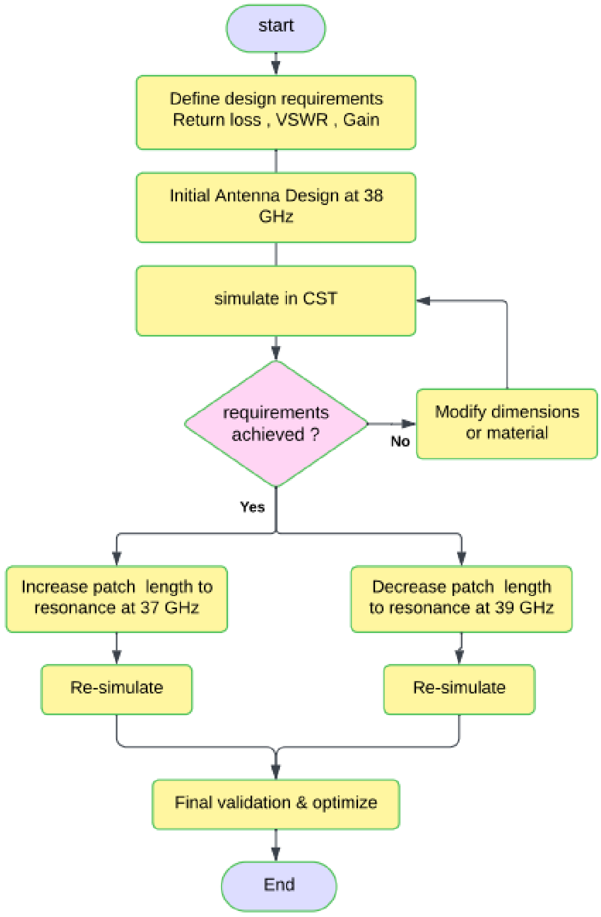

Figure -1 Flowchart of the design process of the proposed work.

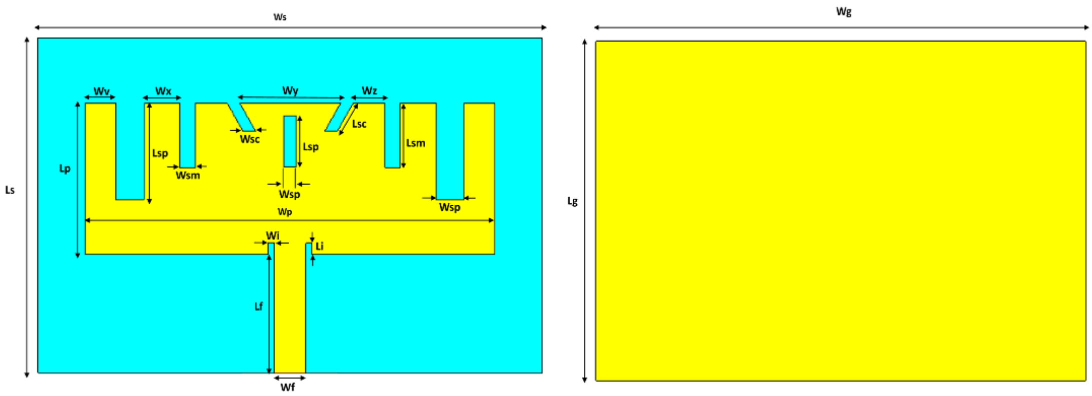

Figure -2 Proposed MPA design.

The initial dimensions of the rectangular patch were determined by formulas given in [24], [25], considering the intended working frequency (38 GHz), substrate characteristics, and specific size needs. In the beginning, we will compute the length and width of the radiating patch. Where Wp and Lp represent the width and length of the radiation patch, c is light speed, εr is the relative permittivity of the dielectric substrate material, εreff is the effective permittivity, and ΔL refers to the Superfluous length of the radiated part.

$$W_p = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

$$\varepsilon reff = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\sqrt{\frac{1}{1+12\frac{h_s}{w_p}}} \tag{2}$$

$$\Delta_L = 0.412h_s\frac{(\varepsilon_{reff}+0.3)(\frac{Wp}{h_s}+0.264)}{(\varepsilon_{reff}-0.258)(\frac{Wp}{h_s}+0.8)} \tag{3}$$

$$Lp = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta_L \tag{4}$$

After the initial parameters of the radiating patch are calculated, the width and length of the dielectric substrate material are computed using the following formulas where Ws refers to substrate width and Ls to the substrate length.

$$W_s = W_p + 6h_s \tag{5}$$

$$L_s = L_p + 6h_s \tag{6}$$

Finally, the dimensions of the feed line are determined using these formulas, where Wf and Lf represent the width and length of the feed line.

$$L_f = 3.96W_f \tag{7}$$

$$B = \frac{377\pi}{2Z_O\sqrt{\varepsilon_O}} \tag{8}$$

$$W_f = \frac{2h_s}{\pi}\left(B - 1 - \ln(2B-1) + \frac{\varepsilon_r-1}{2\varepsilon_r}\left(\ln(B-1) + 0.93 - \frac{0.61}{\varepsilon_r}\right)\right) \tag{9}$$

Next, the inset feed gap (Wi) may be calculated using the following formula, where fr is the resonance frequency.

$$W_i = \frac{4.65\times10^{-18}cf_r}{\sqrt{2\varepsilon_{reff}}} \tag{10}$$

The design process is segmented into three steps, with the first step being the acquisition of the fundamental design via the use of mathematical models at the resonant frequency of 38 GHz. The second step involves improving the alignment between the feed line and the radiating patch, leading to an observed increased return loss; this is done by inserting two rectangular slots at the ends of the patching part. The final step involves optimizing the design by reducing its dimensions, adjusting its resonance at 38 GHz, and further improving its return loss and gain by insertion five slots in the middle of the patching part. Figure 3 illustrates each step of the design process for the proposed antenna.

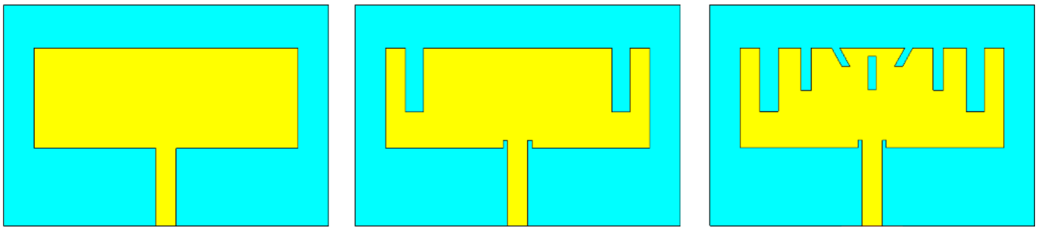

Figure -3 Design process steps of proposed MPA (a) first step, (b) second step, (c) third step

The variables are adjusted manually, and the resulting impacts are verified using the simulator. When adjusting the dimensions of the antenna parameters, every performance factor for the specific design is taken into account to assess its effect on all performance metrics. The optimized dimensions of the designed antenna are shown in Table 1.

Table 1. Optimized dimensions of the proposed antenna

Parameter	*Value (mm)*	*Parameter*	*Value (mm)*
Wg	8	Wsp	0.45
Lg	5.2	Lsp	1.5
Ws	8	Wsm	0.25
Ls	5.2	Lsm	1.05
hs	0.254	Wsc	0.22
hg	0.035	Lsc	0.51
Wf	0.51	Wsp	0.2
Lf	1.82	Lsp	0.83
Wp	6.51	Wv	0.49
Lp	2.35	Wx	0.56
Wi	0.1	Wy	1.6
Li	0.19	Wz	0.5

The simulated coefficients of reflection (S11 parameter) for the suggested antenna through the three steps of design are shown in Figure 4. It is a vital indication used to evaluate the matched impedance between the transmission line and the radiation patch.

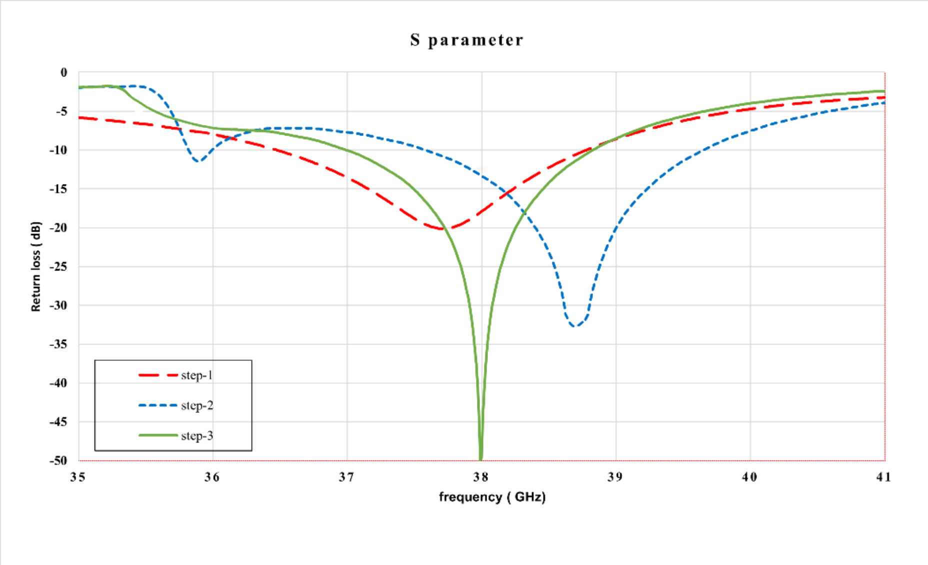

Figure - 4. Return loss results of steps of the design process

3. Simulation results

The following section presents the simulation findings of the antenna that was developed with the CST simulation software. Table 2 presents the detailed results of the radiation parameters used in this study to assess the performance of the designed MPA. The parameters specified include resonance frequency, return loss (S11), VSWR, bandwidth, gain, directivity and, radiation efficiency. The findings demonstrate that the antenna developed exhibits high performance across all analyzed parameters in the research. In particular, the return loss at the resonance frequency was measured to be -49.9 dB. The very low return loss value significantly affects both gain and directivity, both of which achieved very high performance. This design attained a commendable bandwidth of 1.84 GHz. In addition, the value of VSWR in this frequency band is very close to 1, suggesting a strong alignment between the feeding equipment and the antenna. Figure 3 displays the return loss parameter with the resonance frequency. The graph displays the annotated resonance frequency and measured bandwidth at the specified operating frequency. Figure 6 shows the VSWR result of the designed antenna.

Table 2- Simulation results of the proposed antenna

Resonance Frequency	***Return Loss***	***VSWR***	***Bandwidth***	***Directivity***	***Gain***	***Radiation Efficiency***
38	*-49.9 dB*	*1.006*	*1.84 GHz*	*9.51 dBi*	*9.233 dBi*	*93.5%*

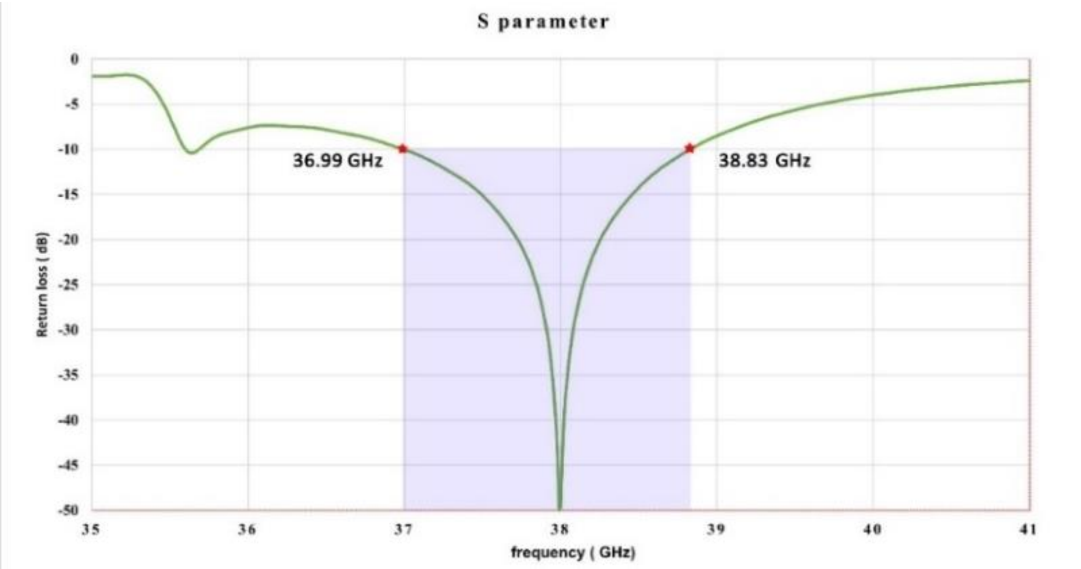

Figure -5 Return loss parameter result of the designed antenna

Furthermore, the antenna efficiency surpassed 93.5% within the specified spectrum. Moreover, the bandwidth of the suggested antenna within the frequency range is suitable for 5G applications. The antenna produced a high gain of 9.233 dBi. The substantial increase in value is outweighed by the very modest bandwidth attained, which was the primary aim of this research. As previously stated, gain takes precedence over bandwidth in the development of 5G antennas, provided that the bandwidth remains sufficiently broad to accommodate 5G services. The radiation pattern of the proposed antenna at resonance frequency is shown in Figure 7.

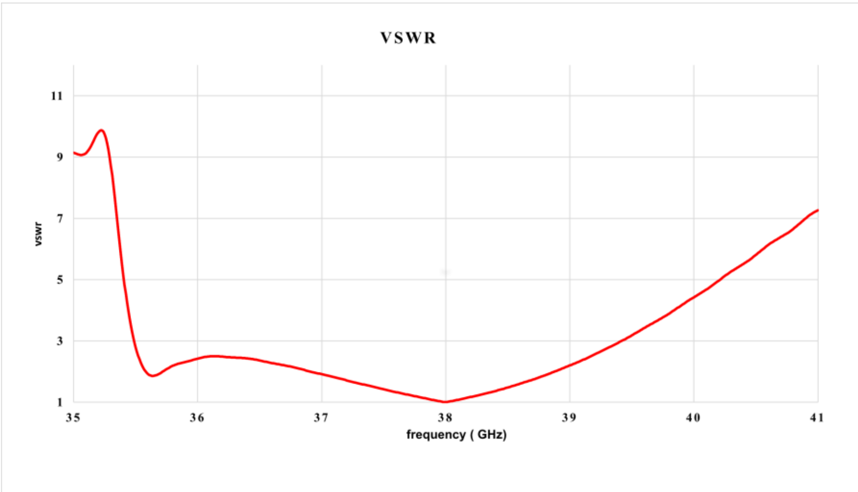

Figure -6 VSWR result of the designed antenna

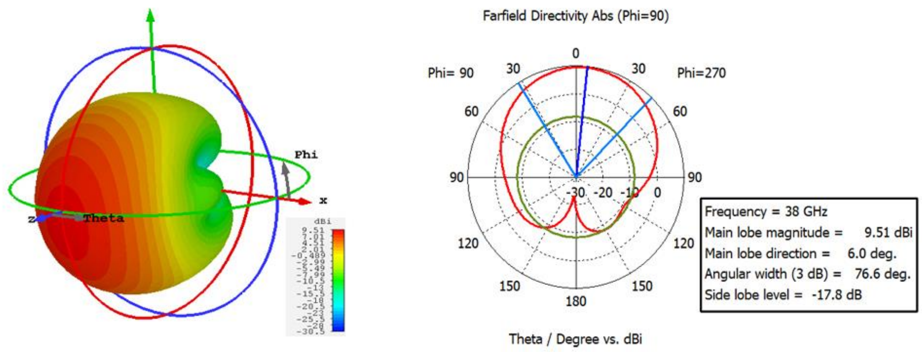

Figure -7 Far-field results of the proposed antenna at 38 GHz in (a) 3D form and (b) 2D form

4. Frequency Tuning at 37 and 39 GHz

Operational flexibility over many frequency bands is crucial in contemporary communication systems, especially in 5G mmWave applications, to optimize bandwidth and enhance signal efficiency [26]. Although the antenna is intended to operate at a main operating frequency of 38 GHz efficiently, it is often necessary to adjust the operating frequency to neighboring bands, such as 37 GHz and 39 GHz, in order to fulfill specific system needs or conform to various communication standards. One promising approach to do this is by changing the physical length of the patch antenna to optimize the frequency. By precisely adjusting the patch length, the resonant frequency of the antenna may be controlled to function at either 37 GHz or 39 GHz without substantial alterations to the overall construction. The current part investigates the influence of patch length adjustment on the operating frequency of the antenna and provides the simulation findings for both the 37 GHz and 39 GHz resonance frequencies.To get an ideal performance at a frequency of 38 GHz, the patch length is configured to be 2.35 mm. To decrease the frequency to 37 GHz, the patch length is marginally increased to 2.44 mm, but for 39 GHz, the length is diminished to 2.29 mm. This adjustment is derived from the fundamental relationship between patch dimensions and resonance frequency, wherein an augmentation in patch length results in a reduction in resonant frequency, while a reduction in length causes an increase in frequency. The return loss of the proposed antenna is illustrated in Figure 8 for each length of the antenna patch.

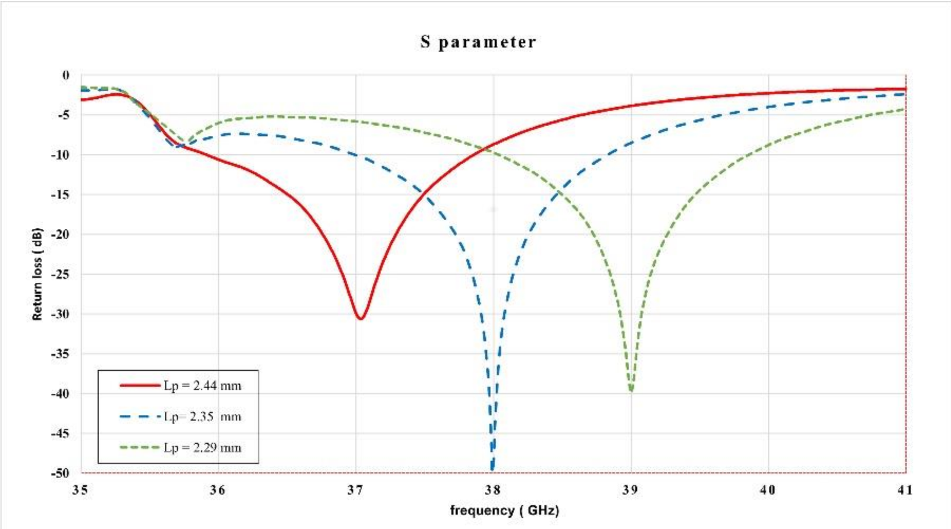

Figure -8 Return loss results in various lengths of the patch of antenna

The simulation findings for the patch antenna at operating frequencies of 37 GHz and 39 GHz illustrate the successful tuning of frequency by adjusting the length of the patch. Operating at a frequency of 37 GHz and with a patch length of 2.44 mm, the return loss (S11) achieves a remarkable value of -30.6 dB, which suggests exceptional impedance matching. The design incorporates a bandwidth of 1.94 GHz and covers the frequency range from 35.91 GHz to 37.86 GHz. At a frequency of 39 GHz, the antenna was able to produce a return loss of -39.9 dB with a patch length of 2.29 mm, demonstrating consistent performance across the tuning range. The proposed design specifies a bandwidth of 1.06 GHz, ranging from 38.01 GHz to 39.87 GHz. The Voltage Standing Wave Ratio (VSWR) maintains a value near one within the resonant frequencies, therefore providing further evidence of effective impedance matching. Table 3 provides a concise overview of the primary simulation outcomes for all three frequencies. Figure 9 displays the VSWR findings for each matching patch length, showcasing the antenna's consistent performance across the tuned frequencies.

Table 3- Simulation results of different lengths of patch of antenna

Patch length	*Resonance Frequency*	*Return Loss*	*VSWR*	*Bandwidth*	*Directivity*	*Gain*	*Radiation Efficiency*
2.44 mm	37 GHz	-30.6 dB	1.06	1.94 GHz	9.3 dBi	8.976 dBi	92.6%
2.35 mm	38 GHz	-49.9 dB	1.006	1.84 GHz	9.51 dBi	9.233 dBi	93.5%
2.29 mm	39 GHz	-39.9 dB	1.02	1.85 GHz	9.59 dBi	9.303 dBi	93.4%

All of the radiation patterns exhibit directional behavior that is constant across all frequencies, with just a small amount of change occurring in the beamwidth and the direction of the main lobe. The gain values are likewise consistent throughout the frequencies, with the antenna obtaining roughly 8.97 dBi at 37 GHz and 9.303 dBi at 39 GHz. They are equivalent across the frequencies. The findings demonstrate that the antenna continues to exhibit excellent efficiency and consistent radiation characteristics despite the fact that the patch length has been slightly altered throughout the study. Figure 10 illustrates the radiation pattern of the antenna at 37 GHz and 39 GHz.

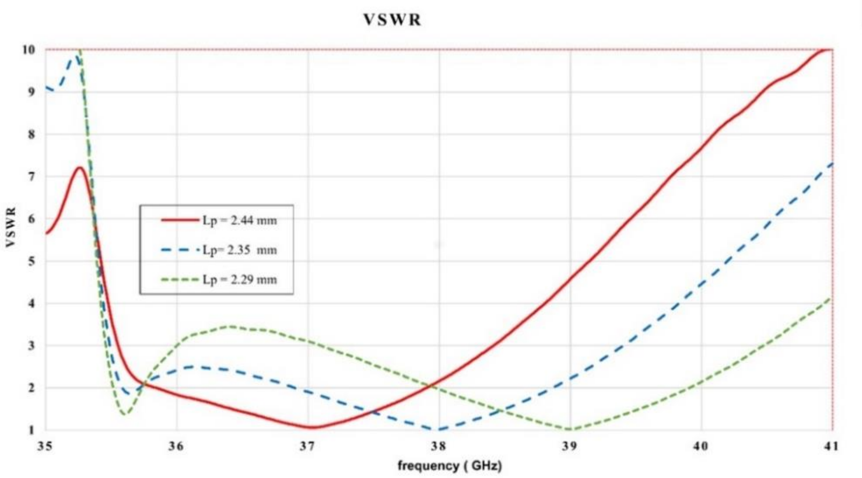

Figure -9 VSWR results in various lengths of patch of antenna

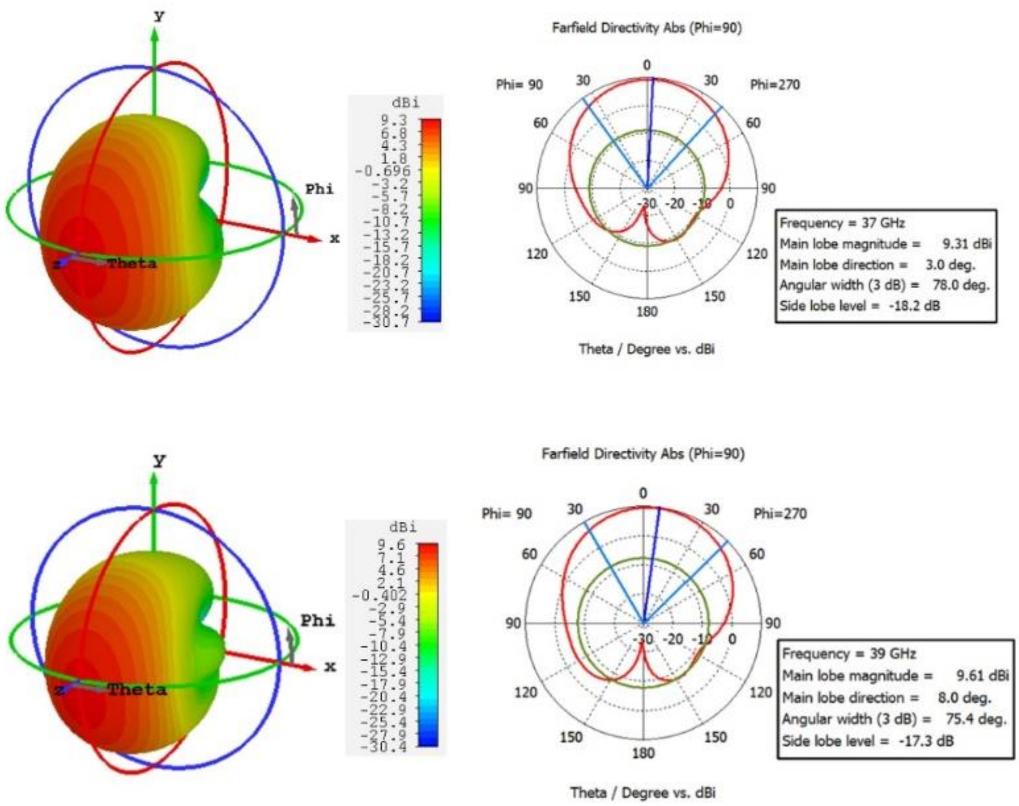

Figure -10. Far-field result at resonant frequencies (a) 3D far field results at 37 GHz, (b) 2D far field results at 37 GHz, (c) 3D far field results at 39 GHz, (d) 2D far field results at 39 GHz

5. Comparison with other works

Table 3 compares the designed antenna with recently published research. The suggested antenna's advantageous radiation properties include a low return loss, steady gain, compact design, and high radiation efficiency. These features provide evidence that the design is compatible with communication systems that function within the millimeter wavelength range.

Table 3- Simulation results of different lengths of patch of antenna

Ref.	*Operating frequency (GHz)*	*Design dimensions (mm^2)*	*Substate material*	*Return loss (dB)*	*Bandwidth (GHz)*	*Gain (dBi)*	*Radiation efficiency*	*Remarks*
[13]	38	5.9×8	FR-4	- 24	1.021	1.26	-	low gain
[14]	38	6×7.8	FR-4	-20.6	640	7.25	91%	Narrow bandwidth
[15]	38	5×5	Rogers RT5870	-12.8	767	7.67	90%	High return loss and limited bandwidth
[16]	38.49	5.5×4	FR4	-42	1.23	6.61	92%	Low bandwidth
[17]	38	12×12	Rogers RT4003	-43.8	4.54	4.2	96.6%	wide bandwidth but not efficient gain
[18]	38	23.7×8.8	Rogers RT5880	-33	3.17	6.5	80%	wide bandwidth but low radiation efficiency
[19]	38.6	8×8	Rogers RT5880	-30	1.9	7.6	-	Not compact design
[20]	37	10×6	Rogers RT5880	-20	1	6.81	85%	High return loss and limited bandwidth
[21]	38	15×25	Rogers RO3003	-42	2	6.5	89.57%	Large design for mm-wave range
This work	38	8×5.2	Rogers RT5880	-49.9	1.84	9.233	93.5%	Low return loss, high gain, and wide bandwidth

6. Conclusion

This paper presents the design of a slotted microstrip patch antenna for wireless communication applications. The main objective is to reduce power loss and enhance performance, specifically at a frequency of 38 GHz. An analysis was conducted on many criteria to assess the efficiency of the antenna. The design successfully attained a bandwidth of 1.84 GHz, a return loss of -49.9 dB, a VSWR of 1.006, a high gain of 9.233 dBi, and a radiation efficiency of 93.5%. By modifying the patch length, the antenna can work at frequencies of 37 GHz and 39 GHz while continuing to exhibit excellent radiation performance over these ranges. This antenna attained a radiation efficiency of 92.6% at 37 GHz by extending the length of the antenna patch while minimizing the length of the patch, and the antenna reached a radiation efficiency of 93.4% at 39 GHz. The findings emphasize notable improvements in performance, such as increased gain, decreased VSWR, enhanced bandwidth, and reduced return loss. These improvements demonstrate greater power transfer efficiency, impedance matching, and directionality of radiation patterns. To further improve the performance of the antenna, the researcher proposes that future studies should examine different techniques and materials. This may include various design configurations, substrate materials, or manufacturing methods. The results obtained from the simulation conducted in this work indicate that the microstrip patch antenna design under consideration has considerable promise as a viable option for wireless communication systems. The next stage would include the fabrication of the proposed antenna and the execution of experimental measurements to contrast the actual outcomes with the simulated findings, thus assuring the practical viability and efficiency of the antenna.

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