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Design and Optimization of a 1x2 Rectangular Array Antenna with U-Slot for 5G Application at 26 GHz Millimeter Wave

Fitri Amillia[1], Mulyono[2]
[1.2] Department of Electrical Engineering, Faculty of Science and Technology,
Universitas Islam Negeri Sultan Syarif Kasim Riau
Jl. HR. Soebrantas No. 155 Simpang Baru, Panam, Pekanbaru, 28293
Email: fitriamillia@uin-suska.ac.id, mulyono@uin-suska.ac.id

ABSTRACT

5G technology utilizes millimeter wave frequencies, particularly 26 GHz, to enable high-speed and low-latency communication services. However, the use of high frequencies presents challenges such as limited coverage area and signal penetration, requiring innovative antenna designs. This study aims to design and optimize a 1×2 rectangular array antenna with a U-slot for 5G applications operating at 26 GHz. The design process involves analytical calculations and simulations using CST Studio Suite software. The performance parameters evaluated are return loss, bandwidth, VSWR, and gain. The simulation results show that the designed antenna has a achieves a bandwidth of 3.51 GHz and a gain of 5.46 dB, which meets the desired specifications for 5G applications. In addition, the integration of U slots improves bandwidth efficiency, while the array configuration significantly improves the gain of the antenna. This antenna is expected to provide effective support for 5G networks, along with the increasing demand for robust and efficient wireless communication systems.

Keywords: *Antenna array, microstrip, U-slot, millimeter wave, 5G*

Introduction

5G technology, the latest generation of wireless communication, offers more reliable connectivity, higher data speeds, and lower latency compared to previous generations. The use of millimeter wave (mm-Wave) frequencies, spanning 24 GHz to 100 GHz, is a critical component in the implementation of 5G. In Indonesia, 5G broadband cellular networks operate at frequencies of 700 MHz, 3.5 GHz, 26 GHz, dan 28 GHz [1]. Especially, the 26 dan 28 GHz mm-Wave frequencies are utilized due to their higher data capacity and faster transmission speeds [2].

5G networks frequently employ mm-Wave frequencies to support high-speed services such as streaming video, virtual reality (VR), augmented reality (AR), dan low-latency communication. Additionally, the enable connectivity for up to 100 billion mobile devices and Internet of Things (IoT) application [3][4]. Other communication applications, such as high-definition television (HDTV) and ultra-high-definition-video (UHDV) require wide bandwidth and achieve data speeds nearing 10 Gbits/s [5]. However, utilizing mm-Wave frequencies presents technical challenges, including limited range and signal penetration, which necessitate innovative antenna designs.

Microstrip antennas are widely used in wireless communication systems due to their compact size, simplicity, low cost, and ease of integration with devices. However, their primary limitation lies in their narrow bandwidth [6]. In 5G applications, microstrip antennas arranged in arrays are well-regarded for their ability to direct signals more efficiently, increase gain, and reduce interference. The incorporation of U-slots into the patch design enhances the antenna's bandwidth. Utilizing a 1×2 U-slot array antenna can improve system performance by enhancing the radiation pattern and gain at the 26 GHz frequency, a mm-Wave used in 5G application.

Related studies demonstrate that U-slot wideband designs support 5G performance [7],[8],[9]. To further improve gain, radiation quality, and frequency stability, array configurations are commonly employed. For instance, rectangular patch antennas with U-slot arrays 1×2 have been designed for 15 GHz and 28 GHz frequencies [10],[11]. However, research rectangular patch antennas with U-slot at the 26 GHz frequency remains limited [12].

Building on previous research, rectangular patch antennas with a U-slot have been shown to enhance bandwidth at 26 GHz mm-Wave frequencies, with single element designs achieving a gain of 4.01 dB [12]. This study aims to advance and enhance gain performance using an array method and coaxial probe feeding. Therefore, this research proposes the design and optimization of a 1x2 rectangular patch array antenna with U-slot operating at 26 GHz. The objective is to support 5G applications by improving gain, bandwidth, and achieving stable performance.

Research Methods

This employs simulation and experiments to determine the specification required for 5G and the antenna material. Analytical calculations from equations (1) – (9) are used to design a single rectangular element without a slot, utilizing coaxial probe feeding. Subsequently, equations (10) – (14) are applied to calculate the dimensions of the U-slot. The results meet the 5G requirements as reported in [12].

The research then advances to the development and optimization stage to enhance gain by designing a 1x2 linear horizontal array antenna using CST Studio Suite software. To achieve mutual coupling within the desired antenna specification of less than -20 dB, a spacing of 0.8λ equivalent to 9.23 mm in simulations, is used between the two elements. Following this, simulation parameters are analyzed to evaluate return loss, bandwidth, VSWR, and gain.

The design is further optimized until it meets the 5G specification requirement, with the results summarized in the table form for easier data analysis. Finally, the research concludes with a summary of the antenna simulation analysis and provides recommendation for future research development.

Specification of Proposed Antenna

Table 1 shows the desired antenna specifications that can meet 5G requirements. The dielectric material used as the substrate is FR4-epoxy, with a relative permittivity of 4.3 and a substrate thickness of 1.6 mm.

Table 1. Specification Antenna

Parameter	Value
Frequency	26 GHz
Bandwidth	≥ 600 GHz
Return loss	≤ 10 dB
Gain	> 3 dB
VSWR	< 2
Mutual Coupling	-20 dB

Design of Rectangular Microstrip Antenna

As shown in Figure 1, the structure of a rectangular microstrip antenna using a coaxial probe feed consists of a rectangular patch, a substrate, and a ground line. Since this type of antenna is easier to analyze, its dimensions are width (h), width (W), and length (L).

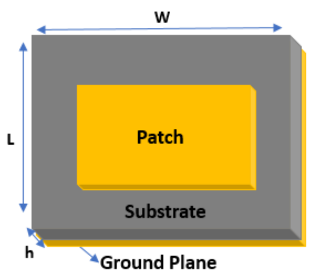

Figure 1. Structure of Rectangular Microstrip Antenna

The length (L) and width (W) parameters are the measurements that must be known when designing a rectangular microstrip patch antenna. To obtain the dimensions of length (L) and width (W), equations (1) to (4) are used [13],[6], as follows:

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

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

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$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} \quad (3)$$

$$\Delta L = 0.412\,h\,\frac{\left(\varepsilon_{reff} + 0.3\right) + \left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{reff} + 0.258\right) + \left(\frac{W}{h} + 0.8\right)} \quad (4)$$

Description of symbols for equations (1) to (4) for f_r the antenna operating frequency (Hz), c is the speed of light of 3.10^8 m/s, h is substrate thickness (mm).

The length and width of ground plane are calculated using equation (5) and (6) [14], [6], as follows:

$$L_g = xh + L \quad (5)$$

$$W_g = xh + W \quad (6)$$

Description of symbols for equations (5) to (6) L_g is the length of ground plane (mm), W_g is the width ground plane and substrate (mm), dan x is a multiplier factor with minimum value of 6.

The location of the antenna feeding point affects the performance of the antenna, equations (7) to (9) can be used to calculate the location of the antenna feeding point. [15],[6], as follows:

$$\varepsilon_{reff} = \frac{(\varepsilon_r+1)}{2} + \frac{(\varepsilon_r-1)}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \quad (7)$$

$$X_f = \frac{L}{2\sqrt{\text{å}_{reff}}} \quad (8)$$

$$Y_f = \frac{W}{2} \quad (9)$$

Description of symbols for equations (7) to (9), the substrate thickness is h, the patch width is W, X_f is the length side feeding point, dan Y_f is the wide side feeding point. The effective dielectric constant is ε_{reff}, and the substrate dielectric constant is ε_r.

U-slot Method

The technique of making slots in patch antennas to increase bandwidth. The capacity of the U-slot shape reduces the inductance on the feeding and adds new resonant frequencies. If the resonant frequency of the patch is added, the bandwidth becomes wider. The U-slot method can be used to achieve wideband and broadband condition [16].

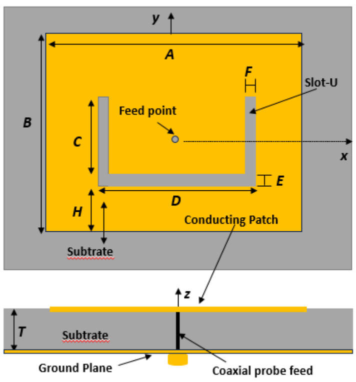

Figure 1. U-slot Geometry on Rectangular Patch Microstrip Antenna [17]

The U-slot technique has the ability to extend the bandwidth of a microstrip antenna from 10% to 40%, depending on how the antenna is configured. The U-slot schematic for a microstrip antenna is shown in Figure 2. The calculations for the U-slot design from previous studies [17], as follows:

1. Calculate the thickness of slots E and F:

$$E = F = \frac{\lambda}{60} \quad (10)$$

2. Calculate the width of slot D:

$$D = \frac{v_o}{\sqrt{\varepsilon_{reff}\, f_1}} - 2(L + 2\Delta L - E) \quad (11)$$

3. Determine the length of slot C:

$$\frac{C}{D} \geq 0.75 \quad (12)$$

4. Calculate the distance H:

$$\varepsilon_{reff(pp)} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12h}{D - 2E}\right]^{-1/2} \quad (13)$$

$$H = L - E + 2\Delta L - \frac{1}{\varepsilon_{reff(pp)}}\left(\frac{v_o}{f_u} - (2C + D)\right) \quad (14)$$

5. Determine whether C+E+H is less than B. If not, change the value of C according to the ratio in equation 2.42 until the design can be physically implemented.

Design of Microstrip Rectangular Patch Array 1x2 Antenna

After designing a single element with U-slot that meets the 5G requirement specifications that have been reported [12].The calculation of the dimensions of the single element uses equations (1) - (9). and the dimensions of the U-slot with equations (10) - (14), then the dimensions of the single element with U-slot are optimized, the results are summarized in Table 2 and the geometry in Figure 3. The results of the single element were in accordance with the antenna specifications. The dimensions of the single element patch are 6.35 mm × 5.56 mm ×1.6 mm.

Tabel 2. Dimension of Single Element [12]

Parameter	Value (mm)
Width of Patch (A)	6.35
Length of Patch (B)	5.56
Slot C	1.85
Slot D	4.00
Slot E	0.40
Slot F	0.35
Length of H	3.03
Width of Substrate Ground Plane (Ws)	8.32
Length of Substrate Ground Plane (Ls)	6.61
Length of the coordinate feeding (xf)	2.15

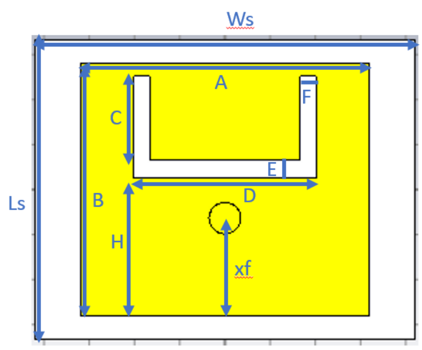

Figure 3. The single element with U-slot [12]

Next, design a 1x2 array antenna arranged linearly horizontally as shown in Figure 4. The mutual coupling meets the desired antenna specifications of less than -20 dB, with elements spaced of 0.8 or 9.23 mm. The patch antenna has dimensions of 17.55 mm × 6.61 mm ×1.6 mm.

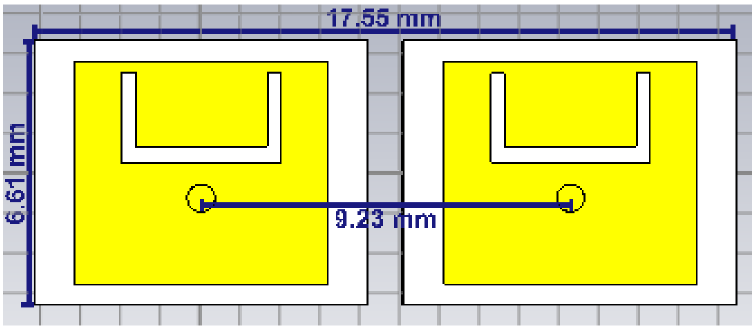

Figure 4. Antenna of Array 1×2

Results and Discussion

This section describes the simulation of 1x2 array antenna design and analyzes its parameter performance, including return loss, bandwidth, VSWR, and gain. The results are summarized in a table for easy data analysis. Next, see the desired antenna specifications to meet 5G requirements.

Return Loss and Bandwidth

The antenna satisfies the expected performance specifications, as shown by the performance simulation of the S-parameter of the 1×2 array antenna in Figure 5, as the return loss value is less than -10 dB. S11 and S22 both have measured return losses of -26.05 dB. The antenna bandwidth of 3.51 GHz, or 3510 MHz, with a fractional bandwidth of 13.50% is determined by taking the return loss value below -10 dB in the operate frequency range of 23.55 - 27.06 GHz. As a result of this bandwidth exceeding 600 MHz, the results demonstrate that the antenna satisfies the required antenna performance requirements.

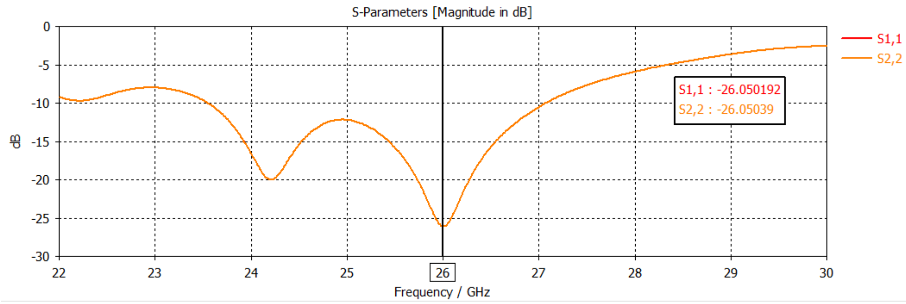

Figure 4. Return Loss and Bandwidth

VSWR

The VSWR of the 1x2 array antenna, namely VSWR1 of 1.105 and VSWR2 of 1.105, indicates that the antenna has achieved the desired performance as shown in Figure 5.

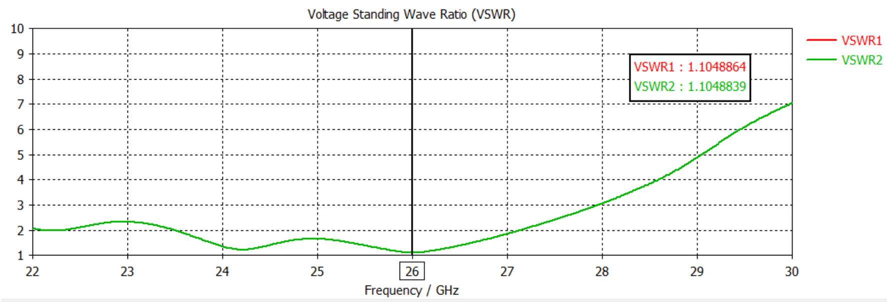

Figure 5. VSWR

Mutual Coupling

Mutual coupling of less than -20 dB is produced by the distance between two elements, namely S21 and S12, each of -21.31 dB, which shows that the antenna is in accordance with the desired performance, as shown in Figure 6.

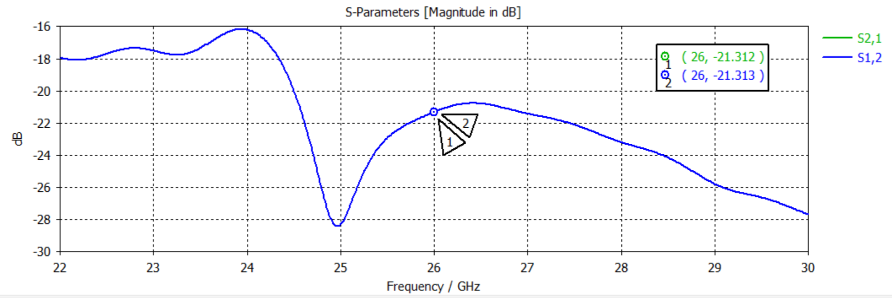

Figure 6. Mutual Coupling

VSWR

Figure 7 shows a gain of 5.46 dB as a result of the 3D radiation pattern.

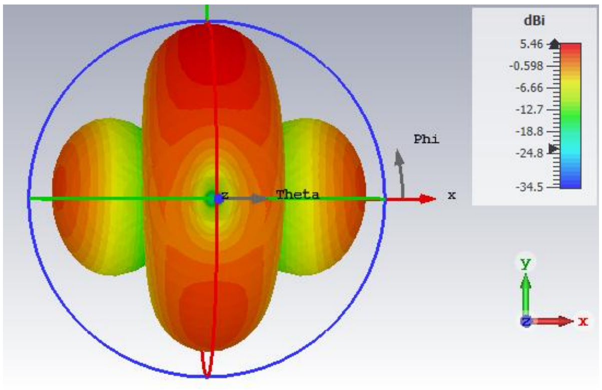

Figure 7. Gain

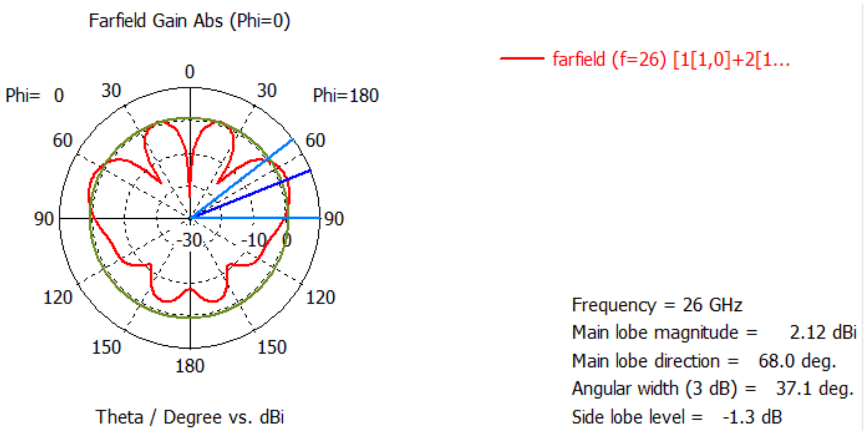

Figure 8. SLL and *Beamwidth* on H-Plane

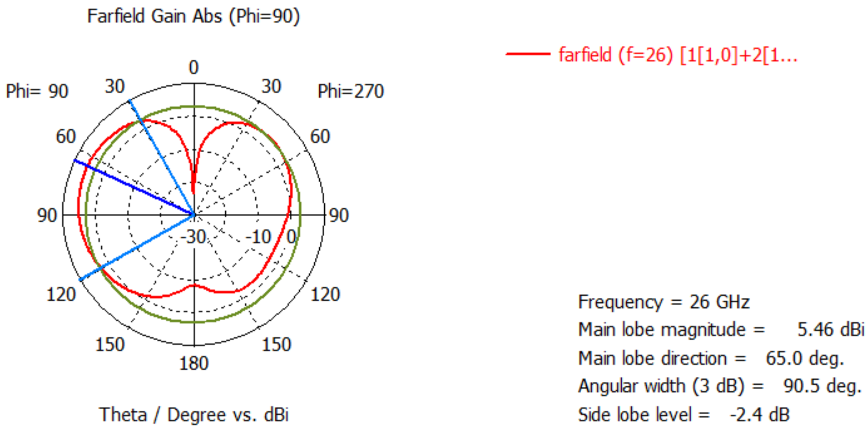

Figure 9. SLL dan *Beamwidth* pada E-Plane

Figure 8 shows the radiation pattern in 2D polar form for a 1x2 array antenna arranged horizontally on the H-Plane (azimuth) with parameters in the form of SLL and beamwidth. The results on the H-Plane show a main lobe magnitude of 2.12 dB, an angular beamwidth (3dB) of 37.1° and a Side lobe level (SLL) of -1.3 dB. Meanwhile, on the E-Plane (elevation), the results are a main lobe magnitude of 5.46 dB, an angular beamwidth (3dB) of 90.5° and an SLL of -2.4 dB, as shown in Figure 9. The resulting radiation pattern is bidirectional.

Comparison of Proposed Antenna

All performance results of single element rectangular slot-U antenna and 1×2 array antenna for ease of analysis is shown in Table 3.

Table 3. Performance Parameter Simulation Results for Antenna

Parameter	Single Element with Slot-U [12]	Antenna of Array 1x2
Return Loss (dB)	-28,09	-26,05
Bandwidth (MHz)	3550	3510
VSWR	1.08	1,10
Gain (dB)	4,01	5,46

Table 3 shows the simulation results of the parameter performance for single element with U-slot producing broader bandwidth. While the antenna of array 1x2 has an increase in gain. Overall, the simulation results of the antenna design performance are in accordance with the desired antenna specifications, and this antenna is recommended for 5G applications.

Tabel 4. Performance Comparison Between the Proposed of Antenna and the Reference Antenna

References	Antenna of U-slot	Operate Frequency (GHz)	Bandwidth (MHz	Gain (dB)
[10]	Array 1x2	15	375	9,89
[11]	Array 1x2	28	1620	7,52
[12]	Single Element	26	3650	4,01
The Proposed of Antenna	Array 1x2	26	3510	5,46

Table 4 compares the suggested antenna design with other works of literature in terms of operating frequency, bandwidth, and gain. When comparing various frequencies with the reference antenna, the comparison reveals that the proposed antenna can generate a broader bandwidth than the others and has a higher gain, indicating that it has fulfilled the required specifications and 5G requirements.

Conclusion

The design of the proposed 1x2 U-slot rectangular array antenna has been successfully completed. This design offers improved bandwidth and gain, meeting the required specification and fulfilling the demands for 5G applications. As a result, it is a strong candidate for 5G implementation. Future studies could explore the development of microstrip antennas using substrate material with higher permittivity and applying planar array techniques to enhance miniaturization, gain, and beamforming to further optimize performance.

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