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V-Slot Microstrip Patch Array Antenna for 5G Applications

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***Abstract*—The primary aim of this work is to design and analyze a microstrip patch array antenna for usage in 5G communication systems. Array antennas are extensively employed in 5G applications due to their high gain and directivity, which enhance signal strength, coverage and directional control. The microstrip patch is fabricated on FR-4 materials and configured in a 1×2 array. The antenna is engineered to comply with the frequency range of 3.4 GHz to 3.6 GHz that is regulated by the Malaysian 5G applications. The microstrip patch antenna array operates at a frequency of 3.5 GHz. The FR-4 substrate has a height of 1.6 mm and a dielectric constant of 4.7. The microstrip patch antenna array has been designed with the appropriate dimensions through theoretical analyses and computations. The principal software for modelling and simulating results is the CST Microwave Studio 2021. Gain, directivity, voltage standing wave ratio (VSWR), radiation pattern, bandwidth, and the reflection coefficient are among the critical parameters that must be analysed.**

Keywords*—*Microstrip array antenna, V-Slot, 5G, Return loss

I. Introduction

The wireless communication technology of the fifth generation (5G) is a transformative advancement that serves as the backbone of next-generation connectivity. It provides high-speed data transfer rates, minimized latency, and the capacity to connect hundreds of millions of devices effortlessly. The capabilities enable a wide range of applications, including autonomous vehicles, automation in industries, augmented reality (AR), smart city development, and advanced health care systems [1-2]. By utilizing electromagnetic waves across multiple frequency bands, 5G transforms traditional communication networks into highly efficient, responsive systems.

5G functions within three main frequency ranges: low-band (600 MHz–1 GHz), mid-band (1 GHz–6 GHz), and high-band or millimeter-wave frequencies (26 GHz–60 GHz). The mid-band frequency range of 3.4 GHz to 3.6 GHz is essential, with an operating frequency of 3.5 GHz, as it provides a balance between high data speeds and adequate coverage, rendering it especially appropriate for urban and suburban applications [3-4]. For instance, Malaysia has adopted this mid-band spectrum for its 5G networks, reflecting its significance in delivering reliable connectivity [5].

To maximize the performance of 5G systems, external antennas play a crucial role by enhancing signal quality, gain, and coverage. These antennas ensure robust and reliable communication, especially in high-density and high-demand environments [6]. Microstrip patch antennas (MPAs) have become common in 5G applications owing to their lightweight design, compact dimensions, and economical production methods. Fabricated using printed circuit boards (PCBs), MPAs are well-suited for integration into portable devices and compact wireless systems [7-8].

Conventional microstrip antennas encounter inherent problems, including limited bandwidth, reduced gain, and inadequate impedance matching, which restrict their efficacy in high-frequency 5G applications. To overcome these limitations is by using array techniques, which improve gain, directivity, and overall radiation efficiency [9].

An antenna array consists of multiple radiating elements arranged together to enhance performance in terms of signal strength, beam direction, and coverage [10]. Each antenna element has its own radiation pattern, and when placed close to each other, their signals combine in a way that strengthens the overall radiation [11]. Feedlines are used to link these antennas to a transmitter or receiver, which provide power to each element in a controlled manner [12]. By carefully adjusting the phase of the signals, the radiated waves from all elements combine to form a stronger and more focused beam, resulting in higher gain, better signal coverage and strength, and reduced interference [19]. Because of these advantages, antenna arrays are widely used in 5G applications, where fast data transmission and reliable signal quality are essential [20].

To further enhance antenna performance, additional techniques such as incorporating slots into the patch design, using high-performance substrates, and optimizing the array configuration can be implemented [21]. Among these, the 1×2 array configuration is particularly effective in improving gain and directivity by combining the radiation patterns of multiple elements. This enhances energy transfer efficiency and

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reduces power loss, making it suitable for mid-band 5G communication systems.

TABLE I. OPTIMUM PARAMETER FOR ARRAY ANTENNA

Parameter	Ref. [10]	Ref. [11]	Ref. [12]	Ref. [14]	Ref. [16]	Ref. [21]
Size (mm)	33.5 x 32.5 x 4	12.2 x 12.2 x 1.6	45 x 45 x 6	80 x 80 x 1.6	48 x 25.2 x 1.6	48 x 25.2 x 1.6
Frequency (GHz)	3.41–3.62	3.5	3.3–3.5	3.5	3.5	3.5
FBW (%)	6.0	7.1	5.8	1.9	4.54	Null
Peak Gain (dBi)	5.61	5.1	5.5	5.5	2.5	5.01
Array Technique	Yes	Yes	Yes	Yes	No	No
Radiation Pattern (dBi)	9.36	14.3	Null	9.32	Null	5.15

Table I compares the Design Size, Frequency (GHz), FBW (%), Peak Gain (dBi), Array Technique, and Radiation Pattern (dBi) with an with those of previous studies. It is clear that, despite its larger size, the suggested array antenna have a good working bandwidth and a high realised gain. In this work, the FBW is 10% and peak gain 6.36 dBi.

The design and analysis of a V-slotted microstrip patch antenna array operating at 3.5 GHz are analysed in this work within the frequency range of 3.4 GHz to 3.6 GHz. The introduction of V-shaped slots into the 1×2 array configuration creates additional resonant modes, leading to improved gain, bandwidth and matching of impedance. The utilisation of a FR-4 substrate featuring a dielectric constant of 4.7 and a thickness of 1.6 mm facilitates economical manufacturing while maintaining performance standards. The design's essential performance metrics, such as voltage standing wave ratio (VSWR), gain, bandwidth, and reflection coefficient (S11), are determined through simulation studies conducted with the CST Studio Suite [13-14].

The proposed V-slotted 1×2 array design addresses the challenges associated with conventional microstrip antennas by achieving high gain, efficient radiation patterns, and stable impedance matching. This study contributes to the development of compact, high-performance antennas for 5G communication systems, enhancing network speed and reliability. The proposed antenna design is particularly well-suited for deployment in wireless routers and portable 5G devices, meeting the stringent requirements of modern communication networks [15-16]. By improving the key performance metrics of the antenna, this work aims to facilitate robustness and efficient 5G connectivity, ensuring seamless integration into diverse applications such as industrial IoT, smart homes, and telemedicine [17-18].

II. ANTENNA GEOMETRY AND DESIGN.

The geometry and dimensions of the modified rectangular patch antenna that was initially proposed for single-band operation are shown in Fig. 1 and Fig. 2. The antenna in dispute is constructed on a FR-4 substrate that is distinguished by a thickness of 1.6 mm, a dielectric constant (ε_r) of 4.7, and a loss tangent of 0.019. Copper, with a thickness of 0.035 mm, was chosen for the patch and ground plane due to its superior electrical conductivity.

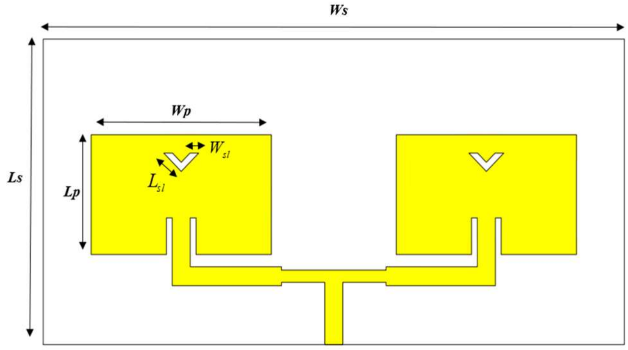

Fig. 1. The front view of the proposed antenna's geometric design.

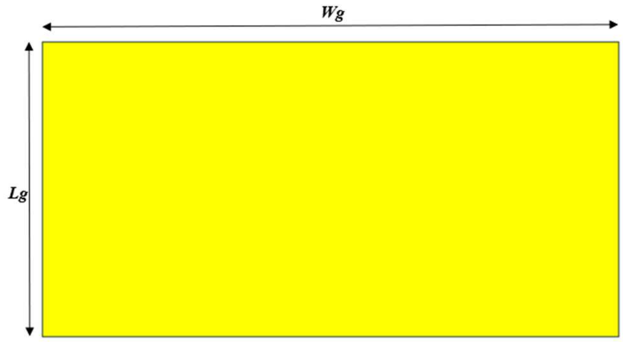

Fig. 2. The Back view of the proposed antenna's geometric design.

The following mathematical equations are evaluated to determine the length (L) and breadth (W) of the Rectangular Patched Microstrip antenna [19-20].

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \quad (1)$$

where;

W represents the patch's width, c represents the speed of light in free space, f_r represents the resonant frequency, and ε_r represents the substrate's dielectric constant.

The fringing effect and the propagation of waves in the field line necessitate the calculation of the effective dielectric constant. Equation (2) can be employed to ascertain the effective dielectric constant (ε_{eff}) from the value of W:

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + \frac{12h}{W}}} \quad (2)$$

where;

The substrate's height is denoted by h. The calculation that determines the effective length, denoted as Leff, is as follows:

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} \tag{3}$$

As follows is the expression for the length extension ΔL:

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{reff}-0.238)(\frac{W}{h}+0.8)} \tag{4}$$

The precise measurement of the patch length is defined as follows:

$$L = L_{eff} - 2\Delta L \tag{5}$$

For the feedline dimension, when (w/d)>2. It can be calculated using:

$$\frac{w}{d} = \frac{2}{\pi}\left[\begin{array}{l} B-1-\ln(2B-1) \\ +\frac{\varepsilon_r-1}{2\varepsilon_r}\times\left[\ln(B-1)+0.39-\frac{0.61}{\varepsilon_r}\right] \end{array}\right] \tag{6}$$

$$B = \frac{377\pi}{2Z_o\sqrt{\varepsilon_r}} \tag{7}$$

TABLE II. DIMENSION OF THE ANTENNA

Parameter		Label	Dimension (mm)
Patch	Width	W_p	19.6
	Length	L_p	31
Slot	Width	W_{sl}	1.5
	Length	L_{sl}	4.24
Ground	Width	W_g	100
	Length	L_g	50
Substrate FR-4	Width	W_s	100
	Length	L_s	50
	Thickness	h	1.6
	Dielectric Constant	ε_r	4.7
SMA	Impedance	Ω	50

The array antenna features V-slots that are imprinted into a metallic dielectric material substrate. The ground plane exerts partial control over the dielectric area, preventing direct placement underneath the monopoles. The microstrip antenna interfaces with the patch, substrate, and ground plane via a SMA connector, which is attached through soldering techniques. TABLE II provides specifics on the antenna's ideal geometrical specifications, and the manufactured microstrip array antenna is shown in Fig. 3 and Fig. 4.

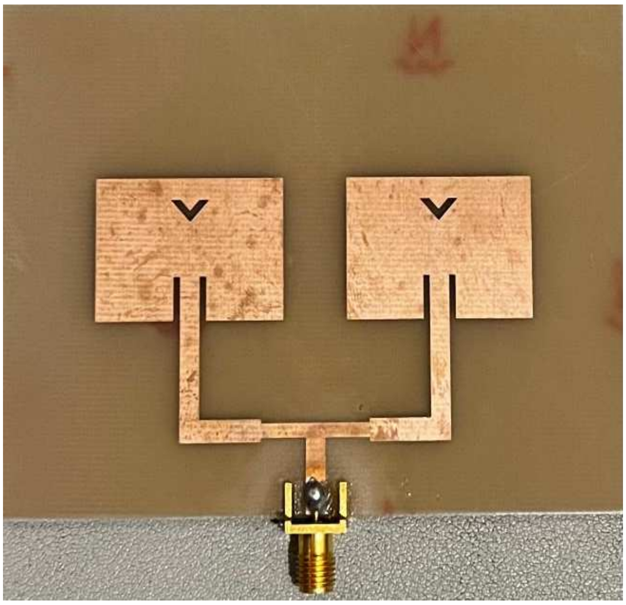

Fig. 3. The antenna's upper view geometry that has been suggested.

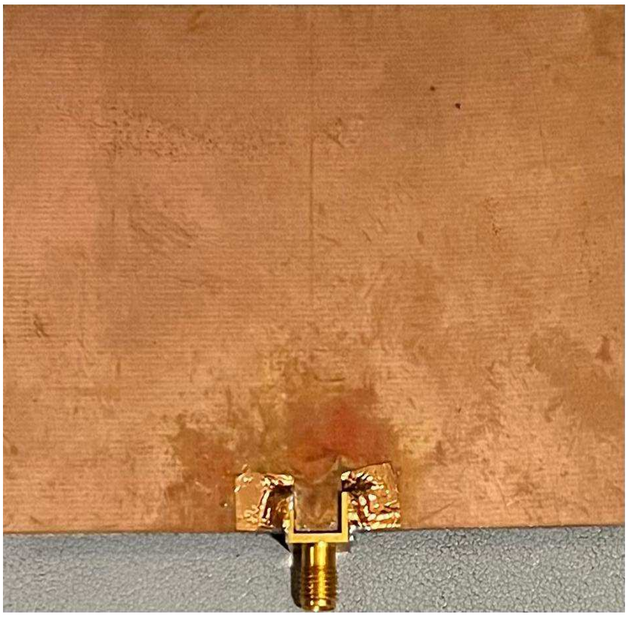

Fig. 4. The antenna's bottom view geometry that has been proposed.

III. RESULTS AND DISCUSSION

A. Simulation results for the proposed antenna

Following antenna testing, the comparison of the S-Parameters between the real antenna (VNA) and the simulated antenna (CST) is shown in Fig. 5. Both the computed and measured antennas have bandwidths of 0.18 GHz (3.4–3.58 GHz) and 0.36 GHz (3.42–3.78 GHz), respectively.

The intended centre frequency however was slightly moved from 3.50 GHz (simulation) to 3.55 GHz (measured), which also caused the |S11| values to alter from -26.9330 dB (simulation) to -30.70 dB (measured).

The fractional bandwidth (FBW) for the simulated antenna is calculated to be 5.16%, while the measured antenna exhibits a wider FBW of 10%, confirming that the fabricated antenna provides a broader impedance bandwidth compared to the simulation.

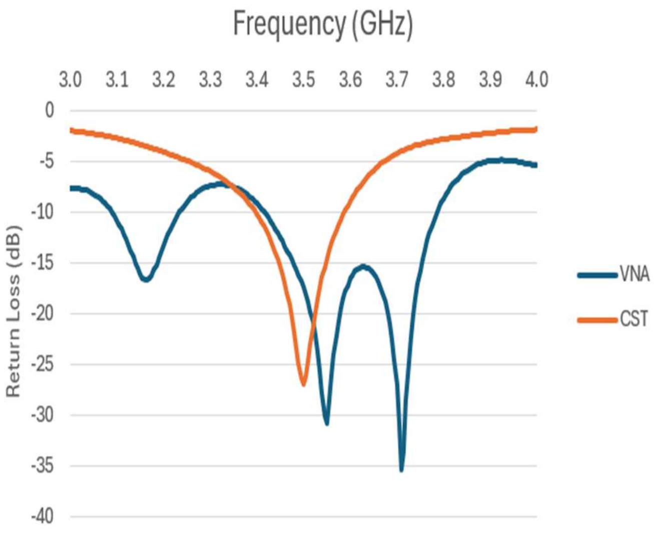

Fig. 5. Simulated |S11| versus frequency

The antenna's VSWR is simulated. and shown in Fig. 6. The frequency of 3.5 GHz has a VSWR value of less than 2, which is adequate to cover the whole frequency range that Malaysia has been allocated.

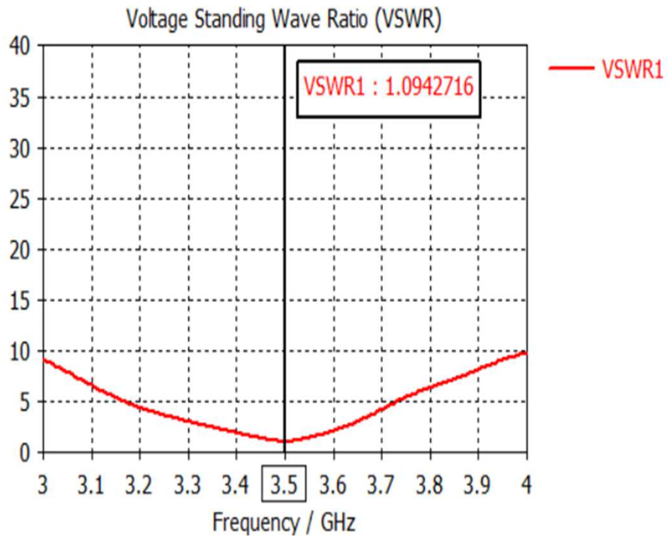

Fig. 6. Simulated Voltage Standing Wave Ratio

A mathematical function or graphical representation that shows the antenna's radiation properties in respect to spatial coordinates is used to characterize an antenna pattern of radiation. The two or three dimensional spatial distribution of radiated energy, which changes depending on the observer's position along a predetermined path or surface of constant radius, is the main focus of radiation properties. The constructed antenna's three-dimensional radiation pattern, which shows a gain of 6.36 dBi at a frequency of 3.5 GHz, can be seen in Fig. 7.

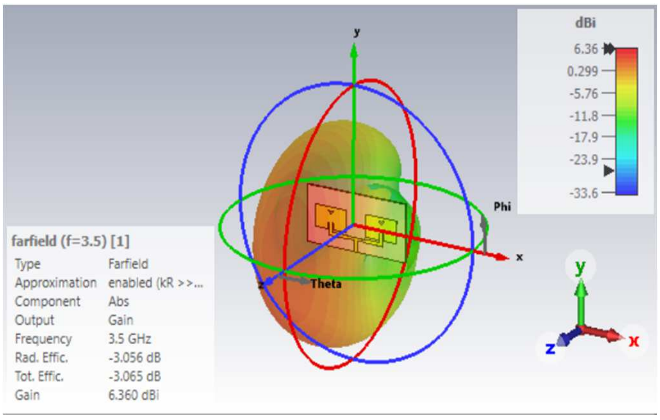

Fig. 7. Farfield view 3D radiation pattern simulation

Gain is a useful measurement that describes what the antenna's performance is like in a different way. The antenna's directivity and gain are directly correlated. It is determined by considering the antenna's directional capabilities in addition to its efficiency.

The antenna shown in Fig. 8 has an average simulated gain of 6.37 dBi, and the polar plot of the suggested antenna shows that the side lobe level at -15.4 dBi. Thus, it shows the characteristic of directional antennas with minimal side lobes and a weak back lobe to reduce interference.

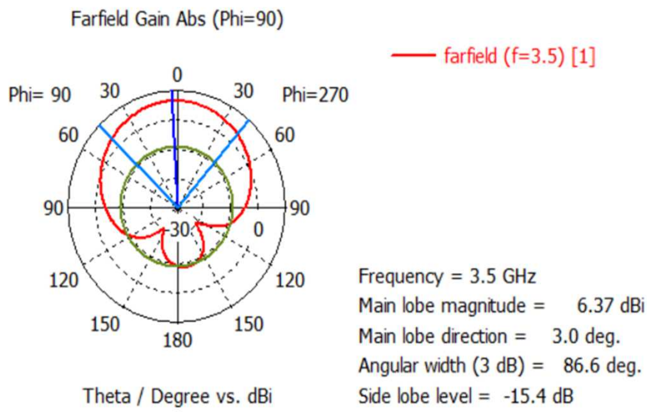

Fig. 8. Simulated Polar plot for Gain

B. Effects of Parametric Studies on Return Loss S11

1) Substrate Thickness , h

The parametric study to evaluate the antenna's performance included varying the substrate thickness while keeping all other parameters constant. Fig. 9 illustrates the effect of substrate thickness variations on the S11 value and operating frequency of the proposed 1×2 array antenna. The initial substrate thickness of 1.6 mm (red) exhibited an S11 value of -26.9330 dB at 3.5 GHz. Reducing the thickness to 1.5 mm (green) resulted in an S11 value of -24.1500 dB and a shift in the operating frequency to 3.515 GHz. Further reduction to 0.8 mm (blue) increased the operating frequency to 3.57 GHz, with the S11 value declining to -7.4725 dB. Finally, a thickness of 0.4 mm (orange) caused a further frequency shift to 3.61 GHz and an S11 value of -6.8104 dB. In summary, decreasing the substrate thickness leads to an increase in operating frequency and a significant reduction in S11 performance.

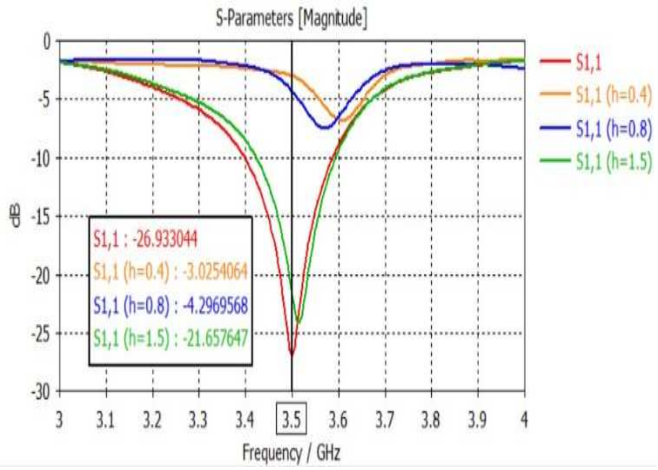

Fig. 9. Substrate Thickness vs. Return Loss S_{11}

2) Symmetrical Slot Width, Ws

Fig. 10 illustrates the impact of varying the symmetrical slot width on the antenna's performance, focusing on return loss (S11) and operating frequency. The original slot width of 1.5 mm (red) achieved an S11 value of -26.9330 dB at 3.5 GHz and cater targeted frequency from 3.4 GHz to 3.6 GHz. Increasing the slot width to 2.0 mm (green) reduced the operating frequency to 3.4924 GHz and improved the S11 to -28.9275 dB. A further increase to 2.5 mm (blue) lowered the frequency to 3.4826 GHz and enhanced the S11 to -32.6549 dB. Conversely, reducing the slot width to 1.0 mm (yellow) raised the frequency to 3.5057 GHz and slightly decreased the S11 to -25.42 dB. A further reduction to 0.5 mm (purple) resulted in an operating frequency of 3.5103 GHz and an S11 of -24.3416 dB. In summary, increasing the symmetrical slot width lowers the operating frequency and slightly improves the S11, while reducing the slot width has the opposite effect. The optimal symmetrical slot width for the proposed antenna design is determined to be 1.5 mm.

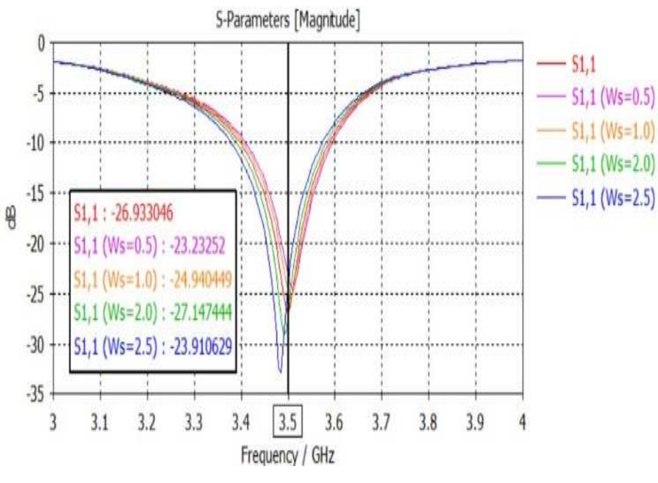

Fig. 10. Symmetrical Slot Width vs. Return Loss S_{11}

3) Symmetrical Slot Length, Ls

Fig.11 demonstrates the effect of varying the symmetrical slot length on the return loss (S11) and operating frequency. The initial slot length of 4.24 mm (red) achieved an S11 value of -26.9330 dB at 3.5 GHz. Increasing the slot length to 5.24 mm (green) reduced the operating frequency to 3.485 GHz while improving the S11 to -30.0398 dB. Further extending the length to 6.24 mm (blue) lowered the operating frequency to 3.4627 GHz and enhanced the S11 to -35.5354 dB. Conversely, reducing the slot length to 3.24 mm (yellow) raised the frequency to 3.51 GHz but decreased the S11 to -25.4130 dB. A further reduction to 2.24 mm (purple) increased the frequency to 3.5158 GHz and decreased the S11 to -23.9704 dB. In summary, increasing the symmetrical slot length decreases the operating frequency while improving the S11 value, with 4.24 mm identified as the optimal length for the proposed antenna design.

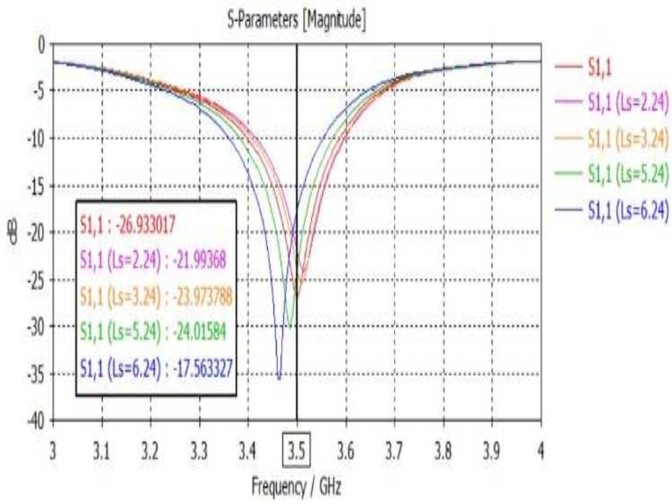

Fig. 11. Simulated Symmetrical Slot vs Return Loss S_{11}

IV. Conclusion

An effective V-slot microstrip patch antenna array with a 4.7 dielectric constant and a 1.6 mm thickness has been created on a FR4 substrate. An 100 mm × 50 mm × 1.6 mm are the antenna's overall dimensions. This antenna is powered by a 50 Ω SMA connector. Several changes have been made to the measurable dimensions in order to investigate the antenna's return loss. After an in-depth study of the acquired simulation results, it has been concluded that the antenna operates as a directional antenna and is suitable for implementation in the 5G applications in Malaysia, which explicitly allows frequency bands of 3.4 GHz to 3.6 GHz with a reflection coefficient of less than -10 dB, that is widely accepted as a benchmark for acceptable antenna performance. Finally, after analyzing and comparing the antenna's radiation patterns, a gain of 6.36 dBi at 3.5 GHz was obtained, which is relatively good compared to those reported in previous studies, as shown in Table I.

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