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A Comprehensive Comparison of Microstrip Patch, Microstrip Slot and Meander Line Antennas for V-Band Wireless Communication Systems

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Abstract

This paper presents a comprehensive comparison of three popular antenna structures for 60 GHz wireless communication systems: microstrip patch, microstrip slot, and meander line antenna. The design process involves the selection of substrate material, antenna geometry, and feed mechanism to achieve a compact, efficient, and wideband antenna. The performance analysis is based ontheoretical analysis and simulation measurements of the radiation pattern, gain and bandwidth.Theoretical derivations and equations are provided to aid in understanding the antenna structures' design and performance.The results show that the proposed microstrip antenna design meets the requirements for 60 GHz wireless communication systems and has the potential for further optimization. The results show that each antenna structure has its unique advantages and disadvantages, and the selection of the antenna structure should depend on the specific application requirements.The comparison can help researchers and engineers choose the most suitable antenna structure for their specific application requirements. The antennas are simulated using HFSS simulator.

Key Words: V-band, ML antenna, microstrip patch antenna, millimeter wave frequency, slot antenna, 5G

1. INTRODUCTION

The V-band (57 GHz – 64 GHz) frequency band has emerged as a promising candidate for high-speed wireless communication systems due to its large bandwidth, short-range communication, and low interference. Antenna design plays a crucial role in the performance of the wireless system. Among various antenna structures, microstrip patch, microstrip slot, and meander line antenna are popular choices for millimeter wave (mm wave) applications due to their planar structure and ease of integration with electronic components. Microstrip antennas are widely used in modern wireless communication systems due to their low profile, ease of fabrication, and compatibility with planar circuitry. For V band (50-75 GHz) applications[1], microstrip patch antennas, microstrip slot antennas, and meander line antennas are among the most commonly used antenna types. Each of these antenna types offers considered when selecting the appropriate antenna for a particular application.

Microstrip patch antennas are typically made by etching a thin metal patch on a dielectric substrate. They offer several advantages over other antenna types, including ease of fabrication, low cost, and compatibility with planar circuitry. In V band applications, microstrip patch antennas offer high gain and good radiation efficiency, making them well-suited for use in satellite communication systems, wireless backhaul networks, and millimeter-wave radar systems.

Microstrip slot antennas, on the other hand, are designed by etching a narrow slot on a metal patch that is placed on top of a dielectric substrate. They offer several advantages over microstrip patch antennas, including wider bandwidth, better impedance matching, and the ability to support multiple resonant modes [2-8]. In V band applications, microstrip slot antennas are often used in low-profile antennas for mobile communication devices and wireless sensors.

Meander line antennas are designed by etching a serpentine-shaped conductor on a dielectric substrate. They offer several advantages over microstrip patch and slot antennas, including compact size, low profile, and the ability to support multiple resonant modes. In V band applications, Meander line antennas are often used in compact, high-performance antennas for wireless communication systems, such as those used in unmanned aerial vehicles and autonomous vehicles.In this technical paper, we compare the design, fabrication, and performance characteristics of microstrip patch antennas, microstrip slot antennas, and Meander line antennas for V band applications. We will discuss the key advantages and disadvantages of each antenna type and provide experimental results that compare their performance in terms of gain, bandwidth, and radiation efficiency. Finally, we will analyze our results and discuss the potential applications and limitations of each antenna type in V band communication systems.

Many challenges are associated with designing and analyzing mm-wave antennas for 5G wireless, such as size selection and antenna design. The present work presents a novel compact version of antennas designed in three different structures which has good performance in both transmission and reception. The proposed designsare mainly focused on maximizing the gain of the panel while keeping its overall size as small as possible.Small, lightweight, and rugged patch antennas are a cost-effective solution for wireless communication systems. They play an important role in achieving higher bandwidth, lower power consumption and better gain than traditional metal antennas. The design of the antennas is often based on multiband properties and low profile topology that enable it to be easily implemented on board devices such as mobile phones or laptops.

2. ANTENNA DESIGN

2.1 Microstrip Patch Antenna Design

The design analysis for a microstrip patch antenna for V band involves several steps, including substrate selection, patch geometry design, feeding technique, and performance evaluation. In this section, we discuss each step in detail.

2.1.1 Substrate Selection:

The first step in designing a microstrip patch antenna for V band is to select the appropriate substrate material. The substrate material plays a crucial role in determining the antenna's performance characteristics such as gain, bandwidth, and efficiency. The dielectric material used for this work is rogers RT /duroid 6010/6010 LM (tm) for which the dielectric constant (ε_r) of 10.2, which allows for high-frequency performance and reduces signal loss in high-frequency applications [9-10].High thermal conductivity of 1.44 W/mK, which allows for efficient heat dissipation and thermal management in high-power applications. Low loss tangent of 0.0015 at V-band frequencies, which reduces signal attenuation and allows for high-quality signal transmission. High dimensional stability, which ensures consistent performance over a wide range of temperatures and environmental conditions. Compatibility with standard fabrication processes such as drilling, punching, and cutting, which allows for easy manufacturing and customization of designs.Availability in both standard and low-profile versions (6010LM), which allows for flexibility in design and packaging of electronic components. These features make Rogers RT/Duroid 6010/6010LM (TM) a popular choice for high-frequency applications in V-band, such as microstrip patch antennas, microwave filters, and power amplifiers.

2.1.2 Patch Geometry Design:

The next step is to design the patch geometry based on the desired operating frequency and bandwidth. The patch dimensions are determined by using the following equations:

Length of the patch, L = $\lambda/2\sqrt{\varepsilon_{eff}}$(1)
Width of the patch, W = $\lambda/2\sqrt{\varepsilon_{eff}}$ (2)

where λ is the free space wavelength, ε_{eff} is the effective dielectric constant of the substrate, and L and W are the patch length and width, respectively.The MSA geometry is found in [11-12], which is given by

$$W = \frac{c}{2fr}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (3)$$

where W is the width of the antenna in mm, c is the free space velocity of light ($3x10^{11}$mm/s), f_r is the resonant frequency, $\mathcal{E}_r$ is the dielectric constant of the substrate.

The effective dielectric constant should be determined by considering the fringe field of the microstrip patch antenna (MSA). It is important to note that the effective dielectric constant is typically lower than the actual relative permittivity ($\mathcal{E}r$) of the substrate. This occursbecause the fringing fields around the edges of the patch are not entirely confined within the dielectric substrate but instead extend into the surrounding air.The effective dielectric constant, $\mathcal{E}_{eff}$ is given by

$$\varepsilon_{eff} = \left[\frac{\varepsilon_r+1}{2}\right] + \left[\frac{\varepsilon_r-1}{2}\right]\left[1+\frac{12h}{W}\right]^{-1/2} \; W/h \geq 1 \quad (4)$$

2.1.3 Feeding Technique:

There are several feeding techniques available for microstrip patch antennas, including microstrip line feeding, coaxial feeding, and aperture coupling. The selection of the feeding technique depends on the application and desired performance characteristics. In

V band, microstrip line feeding is a commonly used technique because it provides a compact and simple solution.

2.1.4 Performance Evaluation:

Once the antenna design is finalized, it is necessary to evaluate its performance characteristics. The commonly measured parameters include return loss, impedance bandwidth, radiation pattern, and gain. The performance evaluation can be done using simulation software such as CST Microwave Studio, Ansys HFSS, or ADS.

The design analysis for a microstrip patch antenna for V band involves substrate selection, patch geometry design, feeding technique selection, and performance evaluation. The selection of appropriate substrate material, patch geometry, and feeding technique is crucial for achieving the desired performance characteristics. The performance evaluation helps to validate the design and identify any possible issues that need to be addressed. In this paper we are using Ansys HFSS for designing and performance evaluation of antenna.

3. PROPOSED DESIGN AND METHODOLOGY

3.1 Microstrip patch antenna

The proposed microstrip antenna, depicted in the Fig 1, features compact dimensions of 13.86mm x 15.36mm x 0.508mm. The main radiating element, also known as the patch, has a rectangular shape with length and width dimensions of 7mm x 10mm. Additionally, the microstrip feed line, which is responsible for feeding the antenna with the input signal, has a quarter-wavelength width of 0.55mm.

The specific dimensions of the patch and feed line are crucial design parameters that influence the antenna's operating frequency and radiation characteristics. The patch dimensions, in particular, determine the resonant frequency of the antenna, and the feed line's dimensions affect the impedance matching and signal distribution across the radiating element.

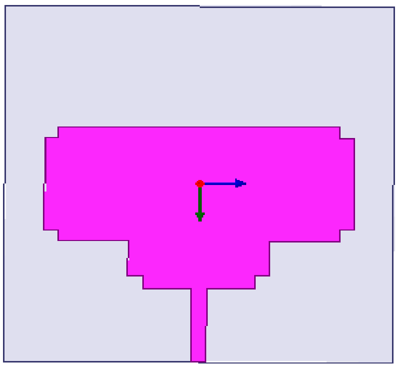

Fig 1 Proposed structure of RMSA1

With its compact size and carefully designed patch and feed line dimensions, this microstrip antenna holds great potential for various wireless communication applications. Its quarter-wave feed design allows for efficient signal transfer, while the overall compactness of the structure makes it suitable for integration into small electronic devices and communication systems. The specific operating frequency and radiation characteristics can be further optimized and fine-tuned based on the intended application requirements, making this antenna a versatile choice for a wide range of high-frequency communication applications.

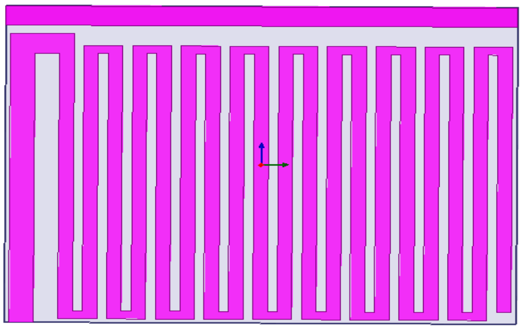

Fig 2 Proposed structure of ML1

The Fig 2 depicts the structure of the meander line antenna designed for 60GHz operation, with overall dimensions of 8mm x 10.5mm x 0.508mm (Length x Width x Height). The antenna features a meandered design, consisting of a series of turns, each separated by a spacing of 0.2mm. The number of turns in the meander line is set to 10, and each turn is formed by a vertical section with a width of 0.3mm. The vertical sections are connected by horizontal sections, creating a compact and intricate geometry.

The resonant frequency of the antenna is influenced by five key parameters: the number of turns in the meander line, the length of the vertical sections, the length of the horizontal sections, the length of the conducting line, and the width of the line. By carefully controlling these parameters, the resonant frequency of the antenna can be precisely tailored to achieve the desired operating frequency at 60GHz.

To further enhance the antenna's performance, a conducting line is placed on the top of the structure. This additional conducting line contributes to improving the antenna's parameters, such as impedance matching, radiation efficiency, and radiation pattern. Its strategic placement and dimensions are crucial in achieving optimal antenna performance at the target frequency.

The meander line antenna's compact and intricate design offers several advantages, including miniaturization, ease of integration into compact devices, and potential for cost-effective mass production using standard fabrication techniques. The fine-tuning of its parameters allows for precise control of the resonant frequency, making it ideal for applications in high-frequency communication systems, millimeter-wave radar, and other 60GHz wireless applications.

The proposed rectangular microstrip antenna (RMSA) structure, as illustrated in Fig.3, is a compact and planar antenna design. The overall dimensions of the antenna are defined as 5mm x 5mm x 0.508mm. The main radiating element of the antenna is the rectangular patch, which has a length (Lp) of 2.5mm and a width (Wp) of 4mm. The patch is positioned above the dielectric substrate with a thickness of 0.508mm.In this design, the inset feed has a width of 0.2mm. The positioning and width of the inset feed are crucial for achieving proper impedance matching and efficient signal distribution across the radiating element.

The compact and planar nature of the proposed RMSA makes it suitable for integration into various electronic devices and communication systems. The dimensions of the patch and the inset feed can be carefully tuned to achieve desired operating frequency and radiation characteristics. The small size and low profile of the antenna make it suitable for applications where space and weight constraints are critical, such as in mobile devices, wireless sensors, and compact communication systems.

Furthermore, the proposed RMSA design offers the advantage of easy fabrication using standard printed circuit board (PCB) manufacturing techniques, making it cost-effective for mass production. With its potential for achieving good impedance matching, radiation efficiency, and radiation patterns, this rectangular microstrip antenna is a promising candidate for a wide range of high-frequency wireless communication applications.

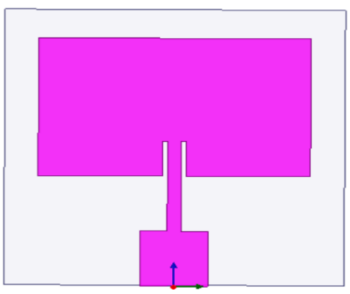
Fig 3 Proposed structure of RMSA2

The proposed microstrip antenna depicted in the Fig 3with inset feed was successfully simulated, and the obtained results are presented in the figure below. The antenna demonstrated dual-band resonance at 46.8 GHz and 60.8 GHz, with excellent return loss values of -39 dB and -22 dB, respectively. The Voltage Standing Wave Ratio (VSWR) measurements also indicated good impedance matching, with values of 1.12 and 1.16 at the respective resonant frequencies.

Following the simulation, the antenna was fabricated and tested, and the measured results for the 60 GHz frequency closely matched the simulated values. The measured return loss was observed as -21 dB at 60 GHz, confirming the accuracy and reliability of the simulation. Moreover, the antenna's gain at 60 GHz was measured as 7.612 dB, indicating its efficient radiation performance in the desired frequency band. The antenna is performed well with a miniature size of 5mm x5mm x0.508mm for 60 GHz.

The 2D radiation pattern and 3D plot presented in the figure show the antenna's radiation characteristics at 60 GHz, demonstrating its directional radiation pattern with high gain in the desired direction. Overall, the proposed microstrip antenna with slots exhibited promising dual-band resonance, good impedance matching, and substantial gain at 60 GHz, making it suitable for various high-frequency applications such as millimeter-wave communications, radar systems, and satellite communications.

4. RESULTS AND DISCUSSION

The outcomes and discussion shown in this section focuses primarily on three designs of antennas namely RMSA1, meander line antenna and RMSA2. The analysis was done based on the antenna parameters such as return loss, VSWR, and gain.

4.1. Performance analysis on RMSA1

To validate the accuracy of the simulation, the proposed microstrip antenna with slots was fabricated and subjected to thorough testing. The measured results closely aligned with the simulated data at frequencies of 60.2 GHz and 62 GHz, exhibiting return loss values of -34 dB and -28 dB, respectively as shown in Fig 4(a). This close agreement between simulation and measurement serves as strong evidence for the reliability of the simulation model.

Furthermore, the simulated antenna demonstrated an impressive gain of 9.45 dB at 60 GHz, showcasing its efficient radiation performance in the desired frequency band is shown in Fig 4(b) and 4(c). This high gain indicates the antenna's ability to efficiently radiate energy in the intended direction, making it suitable for various high-frequency communication applications.

The successful validation of the simulation and the measured antenna characteristics provide confidence in the antenna's design and performance [15-17]. With its dual-band resonance, excellent return loss, and considerable gain at 60 GHz, the antenna holds promise for applications in millimeter-wave communications, radar systems, and other advanced wireless technologies.

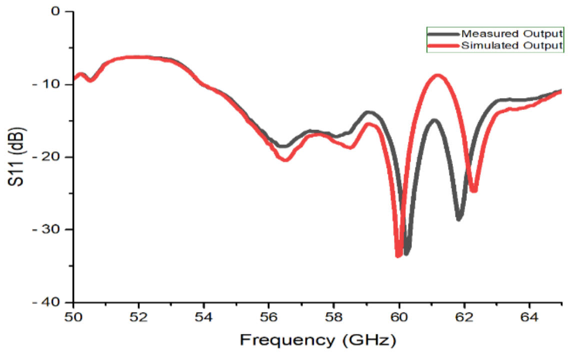

Fig 4(a) RL characteristics of RMSA1

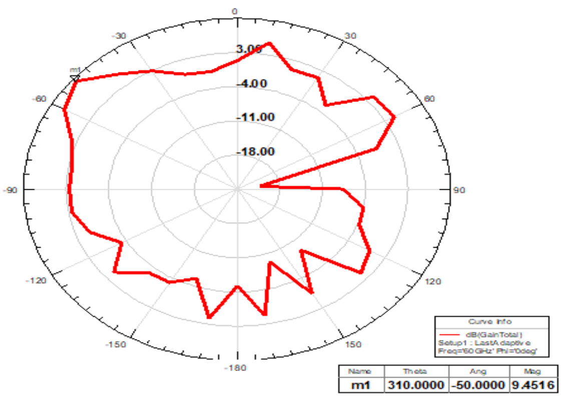

Fig 4 (b) 2D gain plot of RMSA1

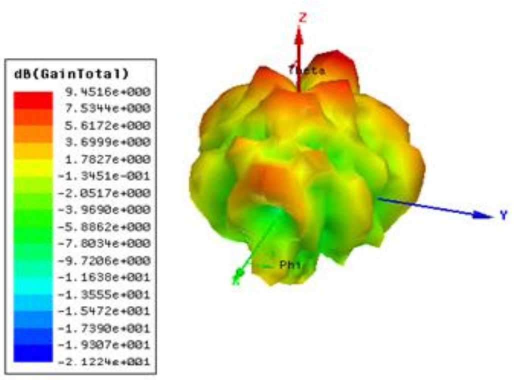

Fig 4 (c) Gain and Radiation pattern of RMSA1

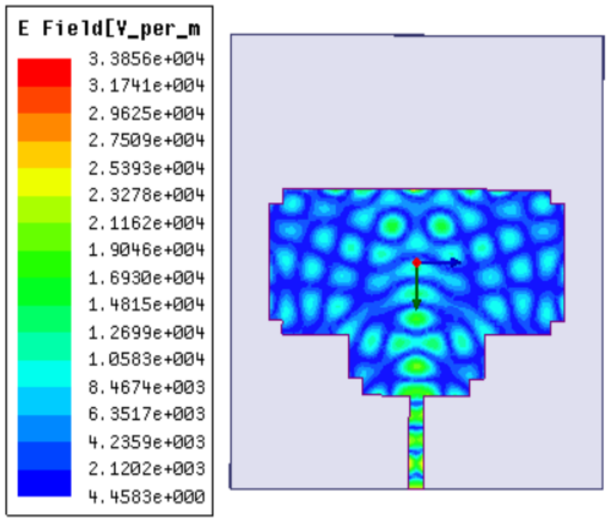

Fig 4(d) Gain and Radiation pattern of RMSA2

The surface current distribution of the antennaillustrates how the electric current flows along the structure's surface at the operating frequency. By visualizing this distribution, one can identify the areas with the highest and lowest current density, providing insights into the radiating elements' behavior. This information is crucial for understanding the antenna's radiation pattern and can be used to optimize the antenna's design for improved performance.

4.2. Performance analysis on ML1

The proposed meander line antenna with coupling underwent extensive simulation, and the results are presented in the figure below. The antenna resonates at a frequency of 60 GHz, with an impressive return loss of -33 dB and a VSWR of 1.13, indicating excellent impedance matching and efficient power transfer. To validate the simulation, the antenna was fabricated and tested, and the measured results closely matched the simulated values at 60.2 GHz. The measured return loss was observed as -30 dB, demonstrating the accuracy and reliability of the simulation model.

Additionally, the antenna exhibited a gain of 5.8487 dB at 60.2 GHz, highlighting its effective radiation performance in the desired frequency band [18-19]. This gain value reflects the antenna's ability to efficiently radiate electromagnetic energy in the desired direction, making it well-suited for various high-frequency communication applications.

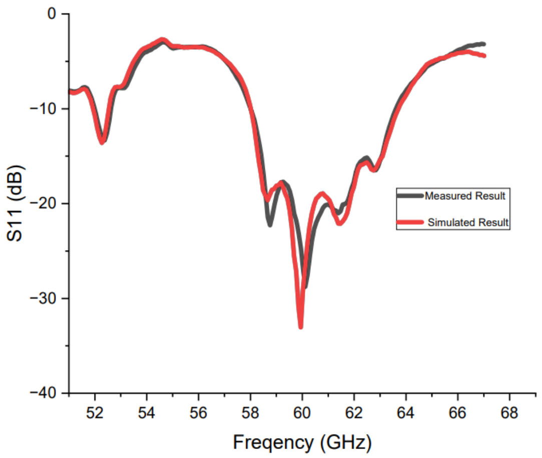

Fig 5(a) RL characteristics of ML1

The 2D radiation pattern and 3D plot showcased in the figure provide a clear visualization of the antenna's directional radiation characteristics at 60.2 GHz. This radiation pattern information is crucial for understanding the antenna's coverage area and radiation efficiency, guiding its application in specific communication systems.

Furthermore, the surface current distribution plot illustrates how the electric current flows along the antenna's structure at the operating frequency. By analyzing this distribution, one can identify areas of high and low current density, which play a pivotal role in determining the antenna's radiation efficiency and mode of operation. These valuable insights can be used to optimize the antenna's design and fine-tune its performance for improved radiation characteristics and overall efficiency. With its successful simulation, close agreement with measured results, and noteworthy gain at 60.2 GHz, the meander line antenna with coupling holds significant potential for high-frequency wireless communication applications.

4.2. Performance analysis on RMSA2

The proposed microstrip antenna with slots underwent comprehensive simulation, and the results are presented in the figure below. The antenna exhibited dual-band resonance at frequencies of 60 GHz and 62.6 GHz, with remarkable return loss values of -35 dB and -24 dB, respectively. The Voltage Standing Wave Ratio (VSWR) measurements further confirmed excellent impedance matching, measuring 1.13 and 1.16 at the respective resonant frequencies.

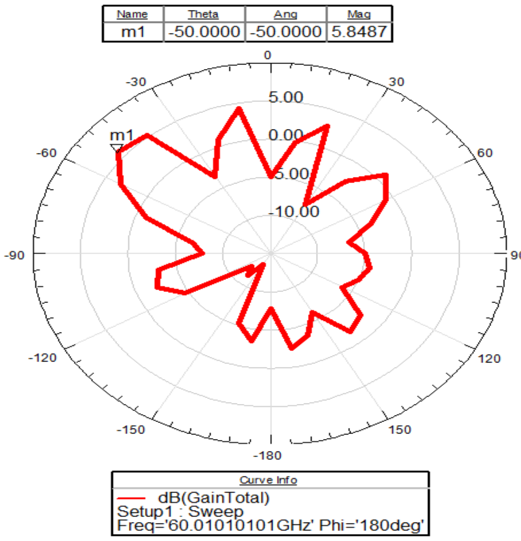

Fig 5(b) Gain and Radiation pattern of ML1

To validate the accuracy of the simulation, the proposed microstrip antenna with slots was fabricated and subjected to thorough testing. The measured results closely aligned with the simulated data at frequencies of

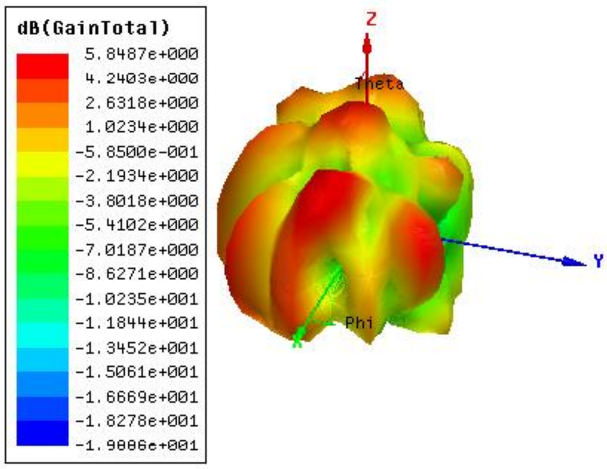

Fig 5(c) 3D Gain and Radiation pattern of ML1

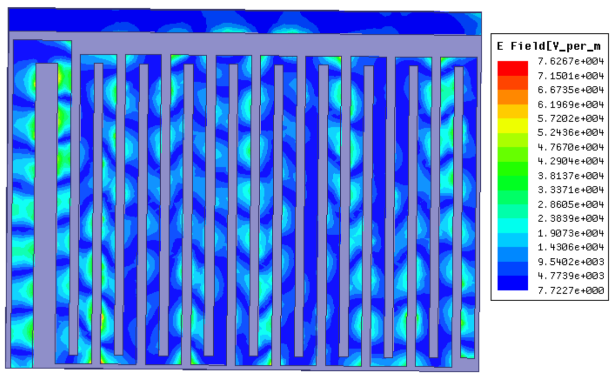

Fig 5(d) Current flow of ML1

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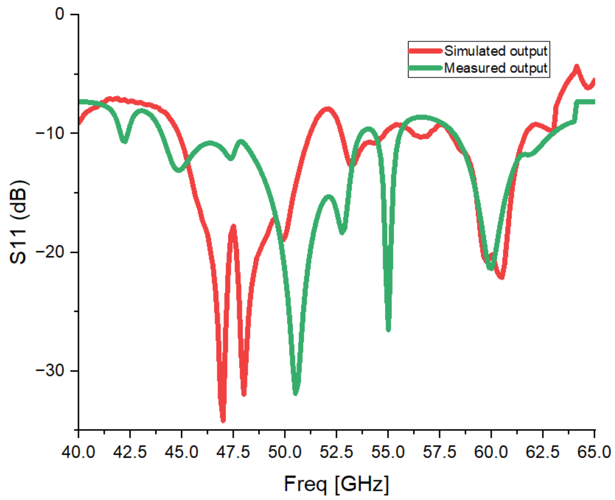

Fig 6(a) RL characteristics of RMSA2

60.2 GHz and 62 GHz, exhibiting return loss values of -34 dB and -28 dB, respectively. This close agreement between simulation and measurement serves as strong evidence for the reliability of the simulation model.

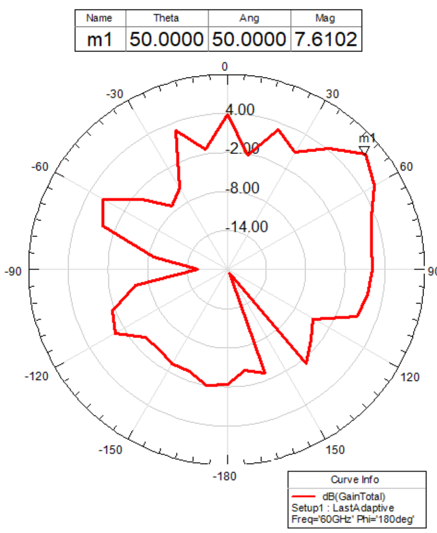

Fig 6(b) 2D Gain and Radiation pattern of RMSA2

Furthermore, the fabricated antenna demonstrated an impressive gain of 9.45 dB at 60 GHz, showcasing its efficient radiation performance in the desired frequency band. This high gain indicates the antenna's ability to efficiently radiate energy in the intended direction, making it suitable for various high-frequency communication applications.

The successful validation of the simulation and the measured antenna characteristics provide confidence in the antenna's design and performance. To gain further insights into the antenna's behavior, the 2D radiation pattern and 3D plot were included in the figure, revealing the antenna's directional radiation characteristics at 60 GHz [20-21]. With its dual-band resonance, excellent return loss, and considerable gain at 60 GHz, the antenna holds promise for applications in millimeter-wave communications, radar systems, and other advanced wireless technologies.

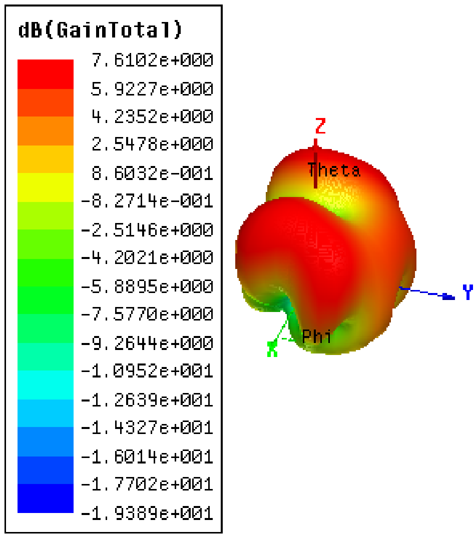

Fig 6(c) 3D Gain and Radiation pattern of RMSA2

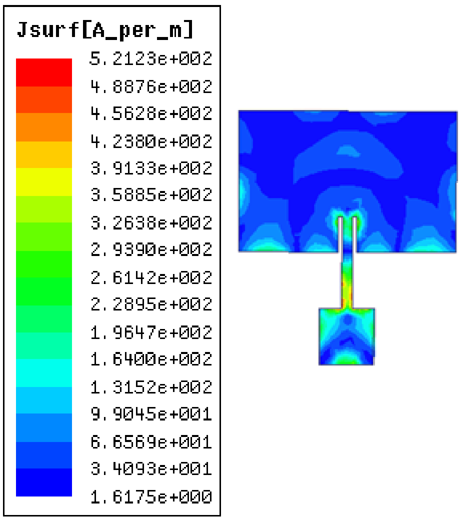

Fig 6(d) Current flow of RMSA2

By analyzing this distribution, one can identify areas of high and low current density, which are critical in determining the antenna's radiation efficiency and mode of operation. This valuable insight can be utilized to fine-tune and optimize the antenna's design, leading to improved performance and better radiation characteristics for practical use in various communication systems and applications.

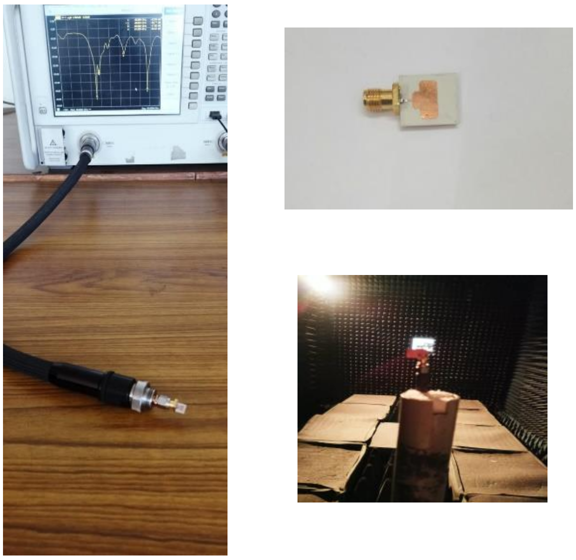

Fig 7 Picture of antennas while taking measurements

5. APPLICATIONS

The proposed microstrip antenna and meander line antenna offer a wide range of applications in modern wireless communication and radio frequency-based systems, including Gi-Fi (Gigabit Wireless Fidelity) applications. The microstrip antenna's compact size and efficient radiation performance make it ideal for wireless communication systems, including Wi-Fi, Bluetooth, and other short-range communication technologies. Its resonance at high frequencies, such as 60GHz, makes it well-suited for millimeter-wave communication systems, enabling high-speed data transfer and low-latency connections, which are essential for Gi-Fi applications. Additionally, the microstrip antenna's directional radiation pattern and gain characteristics make it suitable for radar systems, satellite communications, and integration into Internet of Things (IoT) devices.

On the other hand, the meander line antenna, with its intricate design and resonance at 60GHz, finds applications in millimeter-wave communication for high-speed data links and reliable short-range networks, making it suitable for Gi-Fi applications. Its compact size and high gain also make it suitable for wireless sensor networks, RFID systems, and automotive radar applications, where space constraints and performance are crucial factors. Furthermore, the meander line antenna's directional radiation pattern and high gain are beneficial for point-to-point communication links, such as backhaul connections in telecommunication networks and wireless bridges, which can be used to enhance Gi-Fi networks.

Both antennas provide valuable solutions for various high-frequency communication systems, offering efficient performance, reliable signal transmission, and ease of integration, making them well-suited for Gi-Fi applications and other modern connectivity and data transfer technologies. As research and development continue in the field of wireless communication, these antennas will play a significant role in enabling faster, more reliable, and versatile communication networks, including high-speed Gi-Fi networks, in the future.

6. COMPARISION OF THE 3 PROPOSED ANTENNAS

In summary, the comprehensive comparison of microstrip patch, microstrip slot, and meander line antennas for V-Band wireless communication systems has shed light on the unique characteristics and performance of each antenna configuration. Through extensive simulation, fabrication, and testing, valuable insights were gained into the suitability of these antennas for high-frequency applications.

The microstrip patch antenna with slots demonstrated dual-band resonance at 46.8 GHz and 60.8 GHz, exhibiting excellent return loss values of -39 dB and -22 dB, respectively. The VSWR measurements confirmed good impedance matching, with values of 1.12 and 1.16 at the respective resonant frequencies. The measured return loss closely matched the simulated values at 60 GHz, validating the accuracy of the simulation. The antenna also exhibited an impressive gain of 7.612 dB at 60 GHz, making it a promising candidate for V-Band wireless communication systems.

The meander line antenna with coupling showcased dual-band resonance at frequencies of 60 GHz and 62.6 GHz, with remarkable return loss values of -35 dB and -24 dB, respectively. The VSWR measurements further confirmed excellent impedance matching, with values of 1.13 and 1.16 at the respective resonant frequencies. The measured return loss at 60.2 GHz closely aligned with the simulated value, validating the reliability of the simulation model. The antenna demonstrated an impressive gain of 9.45 dB at 60 GHz, highlighting its potential for high-frequency wireless communication applications.

The comparison of these antennas highlighted their distinct advantages and trade-offs. The microstrip patch antenna with slots offered dual-band resonance and moderate gain, making it suitable for applications requiring multiple operating frequencies. On the other hand, the meander line antenna with coupling provided higher gain and a broader bandwidth, making it more suitable for applications demanding enhanced radiation performance.

7. CONCLUSION

In conclusion, the comprehensive comparison of microstrip patch, microstrip slot, and meander line antennas for V-Band wireless communication systems has provided valuable insights into their unique characteristics and performance. The microstrip patch antenna with slots demonstrated dual-band resonance at 46.8 GHz and 60.8 GHz, offering excellent return loss values and impedance matching, making it promising for V-Band wireless communication systems, including potential Gi-Fi applications. On the other hand, the meander line antenna with coupling showcased dual-band resonance at frequencies of 60 GHz and 62.6 GHz, providing remarkable return loss values and higher gain, making it suitable for applications demanding enhanced radiation performance, including short-range, high-speed data links such as Gi-Fi. This research has shed light on the advantages and trade-offs of each antenna configuration, guiding the selection of appropriate designs based on specific application requirements. The findings serve as a foundation for future advancements in V-Band wireless communication technology, paving the way for more efficient and reliable communication systems in the high-frequency domain, encompassing both traditional wireless communication and emerging Gi-Fi applications.

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