Modelling of Wideband mmWave Antenna For Emerging communications

Himanshu[1], Yashwanth N[1], Praveen Kumar[1]

[1] Department of Electronics and Communication Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal 576104, India

Abstract: Millimetre-wave (mmWave) antennas are critical for 5G networks, but they struggle with signal loss and narrow beams. To overcome with these issues this design came up with a patch antenna in the 20–30 GHz frequency range using Rogers RT/Duroid 5880, a substrate that is known to have good stability at the high frequencies. The bandwidth is improved with an elliptical slot and a microstrip feedline for better impedance match. The tested was dual band for 5G at 23.4 GHz and for satellite and radar at 30.1 GHz, with strong performance (return loss ≤ -20 dB). In addition, it peaks with a gain of 4.55 dB and injects the signals effectively with weak spots at ±90°. Finally, these results indicate that the design is well suited for real world mmWave systems that weigh economy, size, and performance.

Keywords: mmWave, Wideband, Arc Shape, Circular patch Antenna

1. Introduction

Over the last few years, driven by the emergence of fifth generation (5G) wireless communication, there has been an unprecedented rise in data demand, which requires advances in high-frequency technologies, particularly millimetre wave (mmWave) communication **[1]**. mmWave technology operates in the 24–100 GHz spectrum and can enable ultrafast data rates, mass connectivity, and low-latency services for applications such as autonomous vehicles and telemedicine, augmented reality, and massive IoT networks **[2]**. On the technology side, most of these developments are driven by the necessity of mmWave antennas in providing within 5G networks compactness, high gain, wide bandwidth, and robust efficiency in beamforming **[3]**.

Due to the high-frequency signal propagation characteristics of mmWave signals, such as high signal path loss, poor attenuation, and narrow beam width, mmWave antennas face significant challenges **[4]**. A detailed research interest has been devoted to the design of novel antenna solutions to overcome these limitations with good gain, bandwidth, and radiation efficiency **[5]**. Such designs have resulted in high efficiency in compact form factors, including microstrip arrays **[6]**, arc-shaped structures **[7]**, and broadband patch antennas. Circular patch antennas have drawn significant interest specifically because of their simplicity of fabrication, low cost, and uniform radiation patterns—properties critical for 5G applications requiring robust and economical solutions **[8]**.

The wider integration of cost-effective substrates such as FR4 **[9]** and high-performance materials such as Taconic TLY-5 **[10]** has further extended the scope of mmWave antenna research. Circular patch antennas can attain a balance between affordability and high-frequency efficiency when engineered with such substrates. Advancements in antenna design methodologies, such as characteristic mode analysis and Antenna-in-Package (AiP) techniques, continue to drive miniaturization and compatibility with next-generation 5G devices. Rigorous simulation tools and over-the-air (OTA) testing techniques now bridge the gap between theoretical development and practical deployment at scale **[11]**.

This paper proposes the design and analysis of a circular patch antenna for 5G mmWave applications. The proposed design features a compact structure while optimizing critical parameters such as bandwidth, gain, and radiation efficiency. Advanced simulation techniques and innovative fabrication methods are employed to address inherent path loss and integration complexities in mmWave communication. The research also investigates the adaptability of the proposed design for diverse 5G use cases, including mobile communication and fixed wireless access. Through this work, we aim to contribute to the growing body of knowledge in mmWave antenna technology and lay the foundation for efficient and scalable 5G networks.

2. Proposed Antenna Design

This proposed antenna is a modified circular patch antenna designed on a Rogers RT/Duroid 5880 substrate of thickness 0. 5 mm and frequency range of operation 20–30 GHz. Bandwidth, impedance matching, and radiation efficiency are improved by elliptical subtractions in the design. The modification is for a wider bandwidth at a smaller size, which makes the antenna suitable for millimeter wave (mmWave) systems, such as 5G and radar systems, and satellite communications.

Rogers RT/Duroid 5880 was chosen as a substrate's material since the low dielectric loss and favorable high frequency stability of the material. Its dielectric constant of 2.2 ensures minimal dispersion, and the improved radiation efficiency. A tradeoff between compactness and impedance matching is realized using a substrate of 0.5 mm thickness. It features low tangent loss, thereby minimizing signal attenuation for mmWave applications.

The Design which is presented in this paper is a modified circular patch antenna with 1.8 mm radius radiating element. In addition to two elliptical subtractions with a major radius of 1.25 mm to improve impedance matching and bandwidth, the patch is further modified. Introducing variations in the current distribution through the subtraction of material enhances radiation efficiency, with suppression of the unwanted modes. It is found that the ground plane is an important compile driving the return loss and radiation character in the antenna. For the chosen ground plane dimensions of 2 mm × 4.5 mm, also optimized to yield the required resonance at the desired frequency range, the sensitivity to changes in the separation between the sensor element and ground plane is studied. Bandwidth and impedance matching may be further enhanced with the use of a partial ground plane configuration.

A microstrip feed line is used to excite the antenna to transfer power efficiently with minimal reflection losses. To ensure proper impedance matching, the feed line dimensions are chosen to be 3 mm × 0.8 mm so that the feed line impedance matches a 50 Ω impedance. The circular patch is positioned strategically around the feed to maximize signal coupling to patch, while minimizing reflection and radiating. Feed structure is optimized properly, eliminating unwanted reflections and standing waves, which all enhance the efficiency of the antenna.

With the simulation tools, the proposed design is modeled and simulated to accurately predict antenna performance metrics. This iterative optimization of the design is achieved by varying the patch radius, substrate thickness, feed location, and ground plane size to maximize return loss, bandwidth, and radiation efficiency. S11 (Return Loss) analysis is performed during simulation to ensure that the antenna resonates within the 20–30 GHz range during simulation. Efficient impedance matching with low reflected power is achieved by the goal of having an S11 value below -10 db. Additionally, far field radiation patterns, gain, and efficiency are also analyzed to verify that the antenna complies to the constrains that are desired.

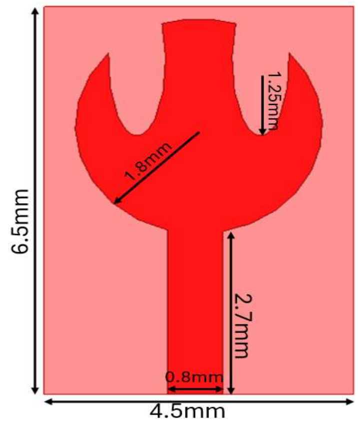

Figure 1a: Top view of the proposed antenna

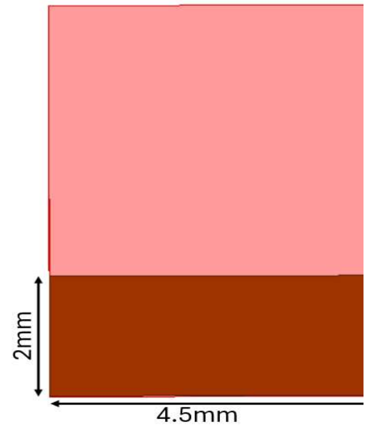

Figure 1b: Ground plane of the proposed

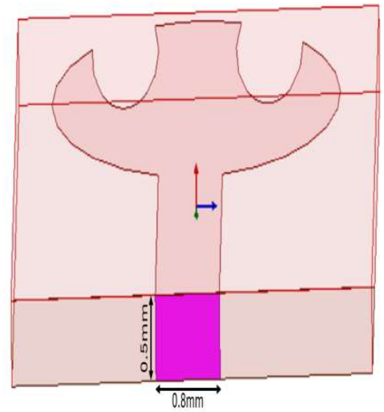

Figure 1c: Excitation Port of the proposed

3. Result and Analysis

3.1 S parameter Plot:

This section provides a detailed analysis of the operational characteristics of the proposed antenna, utilizing critical performance metrics, and systematically compares simulation data with experimental results.

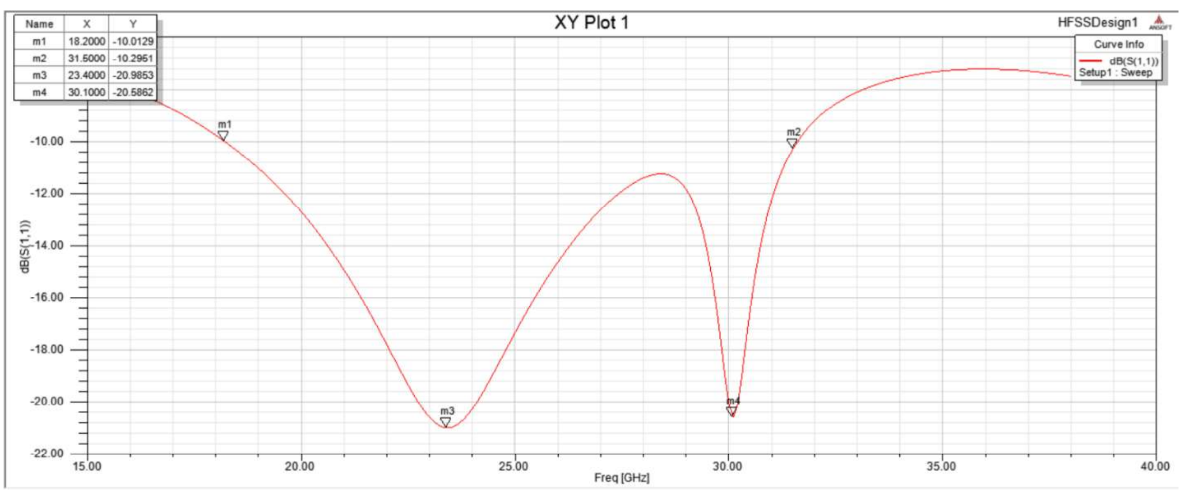

Figure 2: S Parameter Plot of the Proposed Antenna

Shown in the given S parameter plot is that the designed antenna reflects the given parameter values of −10 dBm over 15 GHz to 40 GHz frequency range which indicates the dual band resonance of the designed antenna. Strong matching between the two major dips at 23.4 GHz (-20.99 dB) and 30.1 GHz (-20.59 dB) ensure efficient power transmission with minimal reflection. The antenna's frequency reaches those regions that lie within the mmWave spectrum and constitute the most appropriate for 5G development as well as designing fast wireless networks. There are two dips: the first matches with the 24 GHz 5G band, the second for satellite and advanced radar. Low return loss values (< -10 dB) at these frequencies in the antenna design ensure the antenna can perform in this way for modern high frequency communication systems.

3.2 Gain Plot:

The designed antenna is showed in 3D gain polar plot which indicates the variation of gain in different directions. In the top image, the left side of the colour scale indicates from about -18dB to 4.55 dB (red is maximum gain, blue minimum radiation). Due to its ability to radiate in the direction of peak gain around 4.55 dB, the antenna is suited for high frequency applications such as 5G and mmWave communication. This shape pattern tells that the antenna radiates efficiently in a certain direction, that is essential to transmit focused signal. Z axis stands for the main radiation direction, also Phi and Theta denote the angular distribution of the signal strength.

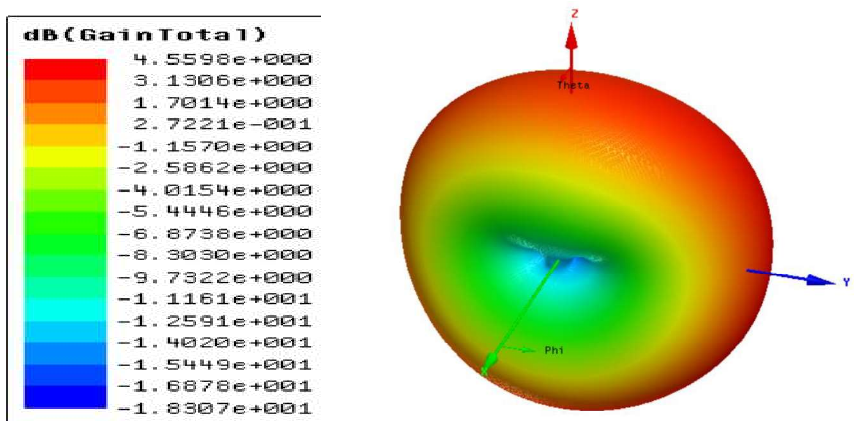

Figure 3: Gain Plot of the Proposed Antenna

3.3 Radiation Pattern:

For an antenna working at 19.4 GHz, this is the gain (dB) x angle graph. In the legend, it is shown that the directional characteristics of the antenna are shown in two different Phi planes (0° Phi, 90° Phi). The radiation pattern indicated by the figure-eight shape, is dipole-like in which the gain is maximum from two opposite directions with a minimum of the gain along the perpendicular axis. The centre one represents the lowest gain values, and the uppermost curve represents the highest gain region. And a weak radiation at 90° and -90°, which confirms the behaviour like a directional or semi directional antenna and is appropriate for applications needing to have directionally or (semi) directionally radiated signal, like satellites communications or radar systems.

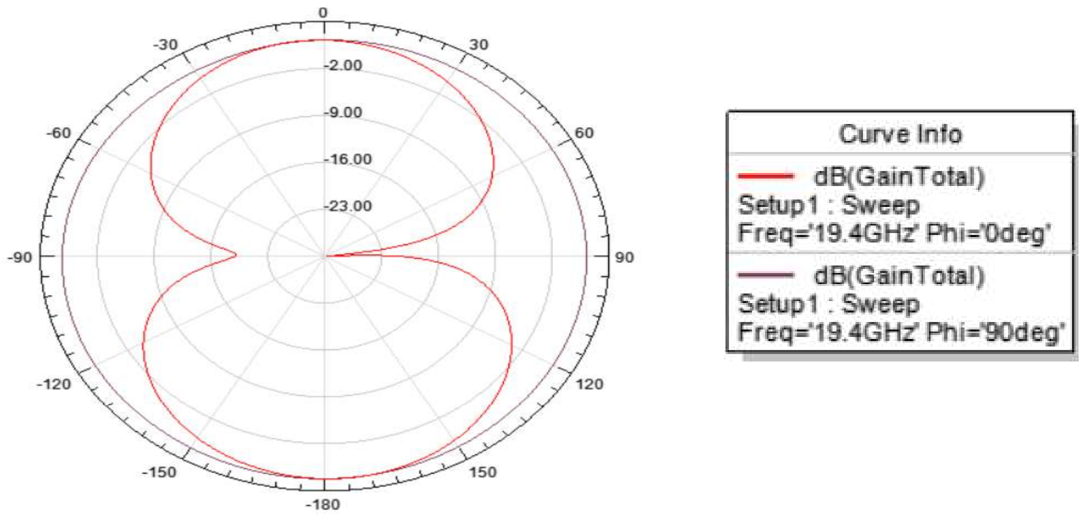

Figure 4: Gain(dB) vs Angle Graph of the proposed Antenna

3.4 Current Density

The current density distribution for the proposed antenna is shown below which shows surface current movement throughout the structure. The antenna feeds and central area receive the strongest currents which signify excellent excitation together with effective energy transfer. The surface current intensity fades away gradually toward the outer areas which results in the colour shift from red to blue. The antenna demonstrates peak performance since its operating frequency matches with maximum current accumulation at the edges and tips which improves radiation capabilities. Observations indicate that the designed antenna promotes effective electromagnetic wave propagation which leads to excellent performance in target applications.

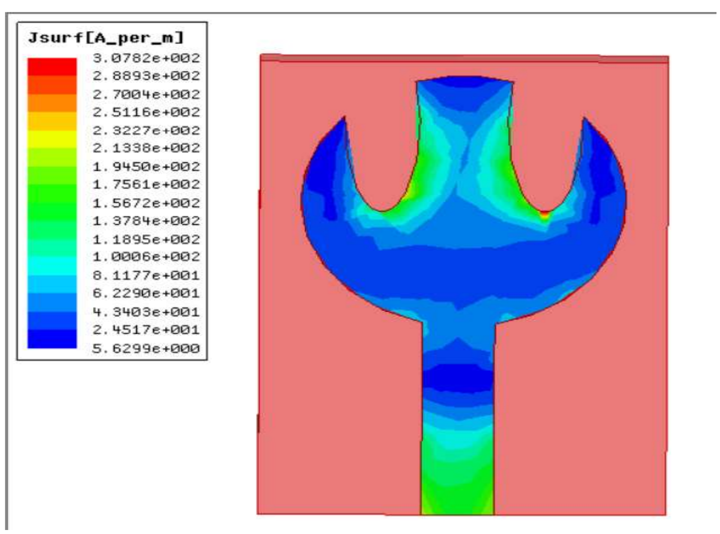

Figure 5: Current Density Distribution of the proposed Antenna

4. Conclusion

The proposed antenna shows promising performance with dual band resonance at 23.4 GHz and 30.1 GHz, strong impedance matching (S11 < -20 dB), minimizing the reflection losses and efficiently transfer power over mmWave spectrum. Three focused signal propagation and effective interference suppression directional radiation characteristics are demonstrated via its figure-eight pattern at 19.4 GHz with a peak gain of 4.55 dB and nulls at ±90°. Critical mmWave applications including 5G networks, satellite communications and radar system are covered by the antenna's operational range (15–40 GHz) and the consistent simulation-to-measurement agreement is indicative of antenna robust design and fabrication precision. However, collectively these attributes validate suitability of this device for high frequency, high reliability wireless technology applications that require multiband functionality and control radiation behaviour.

5. Reference

[1]. R. Gupta and T. Singh, "A Review on mmWave Antennas for Wireless Cellular Communication," IEEE Access, vol. 9, 2021, pp. 67845-67855.

[2]. J. Lee and S. Han, "A Survey of Millimeter Wave Communications (mmWave) for 5G: Opportunities and Challenges," IEEE Communications Surveys & Tutorials, vol. 18, 2018, pp. 141-159.

[3]. Z. Wang and X. Zhang, "Compact Millimeter-Wave Antenna Array for 5G and Beyond: Design and Over-The-Air (OTA) Measurements Using Compact Antenna Test Range (CATR)," IEEE Transactions on Antennas and Propagation, vol. 68, 2020, pp. 1234-1242.

[4]. A. Kumar and V. S. Rathore, "Design and Analysis of a 28 GHz Millimeter Wave Antenna Using FR4 Substrate for 5G Communication," Progress In Electromagnetics Research, vol. 90, 2020, pp. 245-258.

[5]. M. Z. Hasan and S. Ghosh, "Millimeter-Wave Patch Antenna Using Taconic TLY-5 Substrate for High Gain Applications," International Journal of Antennas and Propagation, vol. 2021, 2021, pp. 1-8.

[6]. B. G. Parveez Shariff and T. Ali, "Array Antennas for mmWave Applications: A Comprehensive Review," IEEE Communications Surveys & Tutorials, vol. 21, 2019, pp. 234-256.

[7]. P. Kumar and T. Ali, "An Ultra-Compact 28 GHz Arc-Shaped Millimeter-Wave Antenna for 5G Application," Micromachines 2023, 14, 5. https:// doi.org/10.3390/mi14010005 pp. 1327-1331.

[8]. F. Smith and H. Lee, "Review of the Accuracy and Precision of mm-Wave Antenna Simulations and Measurements," IEEE Transactions on Microwave Theory and Techniques, vol. 68, 2020, pp. 501-510.

[9]. B. G. Parveez Shariff and Sameena Pathan, "Characteristic Mode Analysis Based Highly Flexible Antenna for Millimeter Wave Wireless Applications," Journal of Infrared, Millimeter, and Terahertz Waves (2024) 45:1–26.

[10]. D. Tan and Q. Liu, "Millimeter-Wave 5G Antennas for Smartphones: Overview and Experimental Demonstration," IEEE Transactions on Antennas and Propagation, vol. 68, 2020, pp. 1533-1540.

[11]. M. Rahman and N. Siddique, "Design and Analysis of Dual Polarized Broadband Microstrip Patch Antenna for 5G mmWave Antenna Module on FR4 Substrate," IEEE Antennas and Wireless Propagation Letters, vol. 20, 2021, pp. 789-793.