Enhancing Gain and Bandwidth of Microstrip Antennas Through Optimized 3D Printing: A Study on Design and Implementation

Kaustubh K. Shukla[1], Hari M. Rai[2], Abdul Razaque[2], Saule Amanzholova[2] and Bagdat Kozhakhmetova[2,3]

[1]*Dronacharya Group of Institutions, APJ Abdul Kalam Road, 27, Greater Noida, India*
[2]*International Information Technology University, Manas St. 34/1, Almaty, 050040, Kazakhstan*
[3]*Almaty University of Power Engineering and Telecommunications named after G.Daukeev, Baytursynuli St. 126/1, Almaty, 050013, Kazakhstan*

Abstract

The design of antennas plays a pivotal role in advancing wireless communication technology. An antenna's design can have a substantial impact on the performance of a wireless communication link. Among the various types of antennas, the microstrip antenna, also known as the printed antenna, has gained significant popularity for its applications in microwave frequencies. Researchers have explored ways to enhance the gain and bandwidth of microstrip patch antennas. In this study, we focus on investigating a rectangular microstrip patch antenna with the aim of improving its gain and bandwidth. Through experimentation, it has been discovered that increasing both the substrate height and the patch length can effectively augment the bandwidth and gain of the rectangular microstrip patch antenna. The research process involved several stages, starting with the conceptualization and optimization of the microstrip antenna. Notably, 3D printing technology was employed to create the final structure of the antenna. Subsequently, the printed antenna underwent rigorous testing in an antenna laboratory, utilizing a Vector Network Analyzer. The results of this comprehensive analysis and testing demonstrate the development of a highly suitable and dependable microstrip antenna optimized for microwave frequencies. This antenna has the potential to significantly contribute to the field of wireless communication technology.

Keywords

3D Printing, gain, HFSS, microstrip antenna, microwave

1. Introduction

A microstrip antenna is a specialized type of radio frequency (RF) antenna commonly used in various wireless communication and radar applications. What sets microstrip antennas apart is their planar and compact design, making them particularly well-suited for integration into electronic devices and systems. These antennas primarily operate within the microwave frequency range and are favored for their ease of fabrication, low profile, and versatility. The fundamental structure of a microstrip antenna consists of several key components, including a radiating patch, dielectric substrate, ground plane, and feed line. The radiating patch, usually made of conductive materials like copper or aluminum, serves as the antenna's main element, responsible for either radiating or receiving RF signals [1-4]. The dimensions and shape of the radiating patch, along with the dielectric properties of the substrate, play a crucial role in determining the antenna's operating frequency and characteristics. Mounted on a dielectric substrate, the radiating patch is situated above a conductive ground plane. The substrate, which provides mechanical support and electrical insulation, significantly influences the antenna's

DTESI 2023: Proceedings of the 8th International Conference on Digital Technologies in Education, Science and Industry, December 06–07, 2023, Almaty, Kazakhstan

kaustubh.shukla@gnindia.dronacharya.info (K. Shukla); r.hari@iitu.edu.kz (R. Hari); a.razaque@iitu.edu.kz (A. Razaque); s.amanzholova@iitu.edu.kz (S. Amanzholova); kozhahmetova.ba@gmail.com (B. Kozhakhmetova)
0000-0001-7308-5883 (K. Shukla); 0000-0001-7651-7338 (R. Hari); 0000-0003-0409-3526 (A. Razaque); 0000-0002-6779-9393 (S. Amanzholova); 0000-0002-9566-3629 (B. Kozhakhmetova)

© 2023 Copyright for this paper by its authors.
Use permitted under Creative Commons License Attribution 4.0 International (CC BY 4.0).

CEUR Workshop Proceedings ceur-ws.org ISSN 1613-0073

CEUR-WS.org/Vol-3680/S4Paper4.pdf

electrical properties. Different substrates with varying dielectric constants are chosen to achieve specific impedance and bandwidth requirements. To excite the radiating patch with an RF signal, a feed line (often a microstrip transmission line) is connected to it. Depending on the design, the feed line can be positioned on the same side as the patch (proximity-fed) or on the opposite side (aperture-fed). Microstrip antennas operate based on the principles of electromagnetic wave propagation [5-8]. When an RF signal is applied to the radiating patch through the feed line, electromagnetic fields are generated, causing the patch to either radiate the signal or receive incoming RF energy. The ground plane beneath the substrate acts as a reflector, shaping the antenna's radiation pattern and influencing its performance characteristics. There are various types of microstrip antennas, such as rectangular and circular patches, patch arrays, and microstrip antenna arrays [9-11]. Each type has unique characteristics and is suited to different applications. Rectangular microstrip antennas, for instance, are simple and common, offering omnidirectional radiation patterns but with moderate gain. Circular microstrip antennas, on the other hand, are used to achieve circular polarization or broader bandwidth. Microstrip antenna arrays are employed in phased-array radar systems and satellite communication, allowing for electronic beam steering, high gain, and directional control. While microstrip antennas offer numerous advantages, including their compact size, ease of integration, and cost-effective manufacturing, they do come with challenges such as limited bandwidth, susceptibility to surface waves, and impedance matching complexities. Nonetheless, microstrip antennas continue to play a crucial role in modern wireless communication systems due to their adaptability and versatility [11].

The primary objective behind designing microstrip antennas lies in addressing the need for compact, efficient, and versatile radio frequency (RF) antennas for various applications. Microstrip antennas offer several advantages that make them a preferred choice in the world of RF and microwave communication. The design of microstrip antennas aims to create compact and planar RF antennas suitable for integration into electronic devices and systems. One of the key objectives is to achieve miniaturization without compromising on antenna performance, such as gain, bandwidth, and radiation characteristics. Microstrip antennas are engineered to be low-profile, making them ideal for applications where space is limited or where traditional bulky antennas are impractical. Additionally, these antennas are designed for specific operating frequencies, allowing engineers to tailor them to match the requirements of various wireless communication, radar, and satellite systems. Microstrip antennas find applications in a wide range of fields, including wireless communication (such as mobile phones, Wi-Fi, and Bluetooth devices), radar systems (for tracking and surveillance), satellite communication (for data transmission and reception), and even aerospace and defense (for communication between aircraft and ground stations). Their versatility extends to both commercial and military applications, where their compact size, light weight, and ease of integration prove invaluable. Whether enabling wireless connectivity in portable devices or facilitating long-distance data transmission in remote sensing systems, microstrip antennas play a pivotal role in modern technology.

Many researchers in the past few decades have done extraordinary work in the design of microstrip antenna for various applications.

[12] presented an X-band microstrip patch antenna designed to enhance bandwidth. This antenna, on a 40 mm×40 mm printed circuit board, utilized HFSS for analysis and included rectangular and circular slots to broaden its bandwidth within the X-band (8 GHz to 12 GHz). It achieved stable performance with 78.85% radiation efficiency, 4.31 dBi peak gain, and a 1.59 GHz impedance bandwidth. In [13] developed a neural network model to predict the properties of slotted microstrip patch antennas, such as resonance frequency, gain, and bandwidth. Their study focused on analyzing physical parameters of these antennas with specific dielectric and substrate properties. The results showed a significant increase in bandwidth, from 5.88 GHz to 8.28 GHz, compared to conventional unslotted microstrip antennas. Researches in [14] devised a method to enhance gain, bandwidth, and efficiency in a microstrip patch antenna. They successfully tested the antennas at X-band and 60 GHz band frequencies, meeting the requirements for high-data-rate wireless applications per IEEE standards. Simulation and measurement results aligned well.

In [15] presented a compact metamaterial antenna using a triangular complementary split ring resonator (TCSRR) for multiband performance. The antenna includes a trapezoidal radiating patch, a partial ground plane, and a loaded TCSRR to achieve multiple resonance frequencies. It covers various frequency bands and maintains good radiation patterns in both the E-plane and H-plane. [16] designed a broad-band patch antenna using split ring metamaterial, enhancing its bandwidth and performance. The antenna incorporated split ring resonator (SRR) metamaterial in a novel way, achieving an impedance bandwidth of 1.63–4.88 GHz and an average gain of 4.5 dB. Experimental results matched simulations, making it suitable for LTE, GSM, WiMAX, Bluetooth, and more wireless applications.

In [17] introduced a tooth-based metamaterial antenna with enhanced gain and directivity. They explored four antenna designs, conducted simulations, fabrication, and measurements across a broad frequency range (3 GHz to 9 GHz), and compared their performance with existing work. The innovative antenna offers seven operational frequency bands and achieves 8.57 dB of gain, making it suitable for various applications like radar, satellite communication, and wireless devices. At [18] introduced a novel spiral-shaped patch and ground-based MIMO antenna. Their design offers multi-band performance with low reflectance, wide bandwidth, high isolation, and strong gain. This antenna is suitable for applications like biomedical imaging, short-range communication, healthcare, and WBAN. Researches in [19] enhanced a W-shaped patch antenna for wireless communication at 6 GHz using CSRR metamaterial and FSS techniques. Initial results fell short, but the modifications significantly improved gain, bandwidth, and reflection coefficient. The antenna is suitable for WLAN and WiMAX applications at various frequencies.

The mentioned papers [1-10, 12-14, 16, 17, 19-24], have provided comprehensive insights into the design of patch antennas, specifically focusing on microstrip antenna designs. These papers encompass a wide array of applications where microstrip patch antennas have been employed. They serve as valuable references for understanding the intricacies of designing antennas for various purposes, such as wireless communication, radar systems, satellite communication, and more. Looking ahead, the field of antenna design is expected to witness a paradigm shift with the growing utilization of machine learning and deep learning models [25-36]. These advanced techniques offer powerful tools for optimizing microstrip patch antennas. Machine learning algorithms can assist in automating the design process, helping engineers find optimal antenna configurations more efficiently. Deep learning models, with their ability to handle complex data, can aid in fine-tuning antenna designs to meet specific performance requirements.

2. Features of microstrip antenna

High Gain: Increased Signal Strength: High gain antennas can transmit and receive signals over longer distances with improved signal strength. This is especially important for long-range communication, such as in wireless networks or satellite links, where maintaining a strong and reliable connection is essential. Antennas with high gain can provide broader coverage areas, which is advantageous in scenarios where signal coverage needs to span a wide geographic area, like in cellular networks or radio broadcasting. Signal loss occurs as radio waves propagate through the air or encounter obstacles. High gain antennas can compensate for this loss, allowing signals to penetrate obstacles and reach their intended destinations more effectively. High gain antennas can reduce interference and noise, resulting in a cleaner and more stable signal. This is particularly important in critical applications like military communications or medical telemetry. A high bandwidth microstrip antenna can transmit and receive data at faster rates. In applications like high-speed internet access or video streaming, a wide bandwidth is essential to support the transfer of large amounts of data. Antennas with broad bandwidth can support various communication protocols and frequency bands simultaneously. This versatility is valuable in multi-service networks where different services require different frequency ranges. High bandwidth antennas can adapt to different frequency bands, making them suitable for dynamic environments where frequency allocation may change over time. Broadband antennas are compatible with a wide range of devices and systems, reducing the need for specialized antennas for each application [17, 18].

Improved Directivity: Gain measures the capability of the antenna to focus energy in a particular direction. A high gain antenna can concentrate the transmitted or received energy more effectively in the desired direction, which can improve the communication range and signal quality [19, 20, 37].

Enhanced Signal-to-Noise Ratio (SNR): In communication systems, an improved SNR can lead to better data rates and more reliable communication. A higher gain often translates to a stronger signal relative to the background noise [21, 37, 38].

Less Power Consumption: Devices using high gain antennas can reduce their transmission power while achieving the same communication distance, leading to prolonged battery life, especially critical for mobile and battery-powered devices [18, 23].

High Bandwidth: Wide Frequency Range: A higher bandwidth means the antenna can operate efficiently over a broader frequency range. This versatility is crucial in applications where multiple communication standards or channels are used [38].

Reduced Inter-symbol Interference: For high data rate transmissions, having a wider bandwidth can help reduce inter-symbol interference and, therefore, enhance the quality of communication [22].

Adaptability: In dynamically changing environments or applications where frequency hopping is used for security, a broader bandwidth can be advantageous [12, 13].

Support for Multiple Services: In today's world, with the proliferation of wireless communication services, a single device might need to access various services such as GPS, Wi-Fi, Bluetooth, and cellular networks. An antenna with a broad bandwidth can potentially cater to multiple services, either individually at different times or simultaneously [14, 24].

Integration with Other Systems: Both high gain and high bandwidth can be essential when integrating the microstrip antenna with other RF systems, devices, or technologies. This integration is often necessary in modern devices, which might comprise multiple communication or sensing modules [23].

Futureproofing: As communication standards evolve, there's a push for higher data rates and broader bandwidths. Designing antennas with these characteristics in mind can make devices more adaptable to future changes [11, 23].

Regulatory and Coexistence: As the spectrum gets crowded, the ability to focus energy (high gain) in specific directions can help in mitigating interference with other systems. A broader bandwidth might help in quickly shifting between frequencies to avoid interfering with other systems [6, 8].

3. Microstrip antenna design

Various types of 3D printers have become widely available in the market, contributing to the transformation of manufacturing and design processes. These printers, as depicted in Figure 1 (a) - Types of 3D Printers, offer diverse capabilities and applications across different industries. One common and accessible option is Fused Deposition Modeling (FDM), where material is extruded layer by layer to create objects. Stereolithography (SLA) printers, on the other hand, use liquid resin solidified by UV light, providing high-resolution prints suitable for intricate designs. Selective Laser Sintering (SLS) utilizes lasers to fuse powdered materials, such as plastics and metals, delivering strong and functional parts. Binder Jetting binds layers of powder using a liquid binder and is valuable in metal and sand casting processes. Electron Beam Melting (EBM) specializes in high-temperature metal printing, while Digital Light Processing (DLP) printers use digital light sources to cure liquid resin rapidly. Multi-Jet Fusion (MJF) combines thermal and chemical processes for speedy and detailed part production [39, 40]. The choice of 3D printer depends on factors such as material, resolution, volume, and cost considerations, making this technology increasingly versatile and influential in numerous industries.

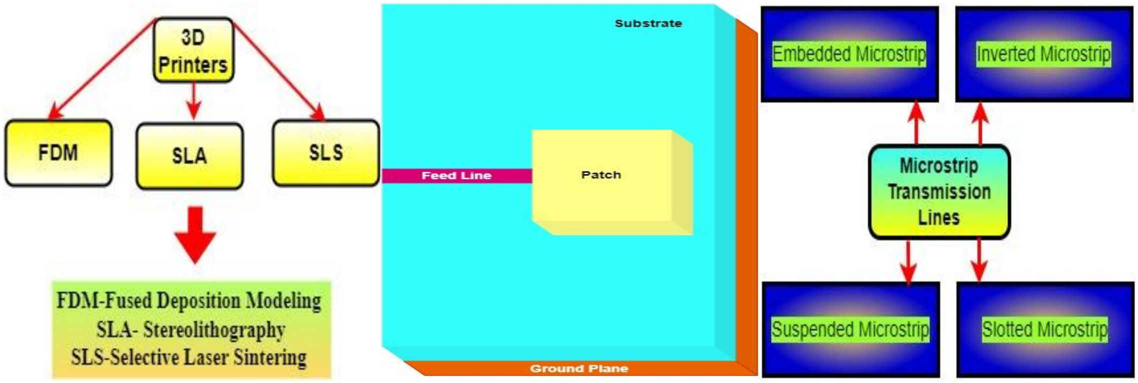


Figure 1: (a) Various Types of 3D Printers, (b) Basic Microstrip Structure, and (c) Types of Microstrip Transmission Lines

Microstrip antennas are fundamental components in the realm of wireless communication technology. These antennas are often fabricated on printed circuit boards (PCBs) through techniques such as microstrip or photolithography. A defining characteristic of microstrip antennas is their utilization of dielectric substrates. The most common structural design for microstrip antennas involves a rectangular metal patch placed on the surface of the dielectric substrate. These antennas operate by applying a voltage source across the base of the ground plane and the rectangular metal patch. This excitation generates electromagnetic radiation, allowing for the transmission and reception of wireless signals. Figure 1(b) illustrates the core components of a basic microstrip structure. It provides a visual representation of the essential elements that constitute a microstrip antenna. The depicted rectangular metal patch and the underlying dielectric substrate are key components that contribute to the antenna's functionality. Moreover, microstrip transmission lines play a pivotal role in microwave frequency communication. They are extensively employed for conveying microwave signals within electronic circuits. Figure 1(c) showcases various types of microstrip transmission lines, underscoring their diversity and utility. These transmission lines are indispensable in enabling the efficient transmission of microwave frequencies, serving as vital conduits within electronic systems. In summary, microstrip antennas are integral to wireless communication technology, and their design and performance rely on key components and transmission lines. These components, as highlighted in Figure 1, are critical in ensuring the effective operation of microstrip antennas and the seamless transmission of microwave signals in modern communication systems.

4. Fabrications and testing

The research conducted in this study involved a systematic and comprehensive approach to enhance the performance of a microstrip antenna. The process commenced with an extensive literature survey, wherein existing research and analysis of microstrip antennas were thoroughly reviewed. This literature review served as the foundational step to gain insights into the design and optimization of microstrip antennas. Subsequently, to gain a deeper understanding and assess the antenna's performance, simulation was carried out using HFSS software. This simulation phase was crucial in obtaining a preliminary understanding of the antenna's behavior and characteristics. It allowed for the fine-tuning of design parameters in preparation for the physical fabrication of the microstrip antenna. The practical aspects of the research, including fabrication and testing, were conducted in the Antenna Laboratory at NITTTR, Chandigarh. These experimental phases were instrumental in validating the simulation results and evaluating the antenna's real-world performance. The key steps involved in this research endeavor are elucidated in Figure 2. The initial phase involved the design of the microstrip antenna using HFSS software, tailored to the specific application requirements. Subsequently, there was a need to delve into the realm of 3D printing, where aspects such as size, resolution, and material selection played a pivotal role in ensuring the successful creation of the microstrip antenna using a 3D printer. This phase marked the bridge between the virtual design and the physical realization of the antenna. Finally, the research culminated in the testing phase, wherein the microstrip antenna's performance was rigorously examined using a vector network analyzer. This step provided empirical data on the antenna's operational characteristics, confirming its suitability for microwave frequency applications. In essence, this research journey involved a meticulous blend of theoretical analysis, simulation, practical fabrication, and rigorous testing, all aimed at optimizing the microstrip antenna's performance for microwave frequency usage.

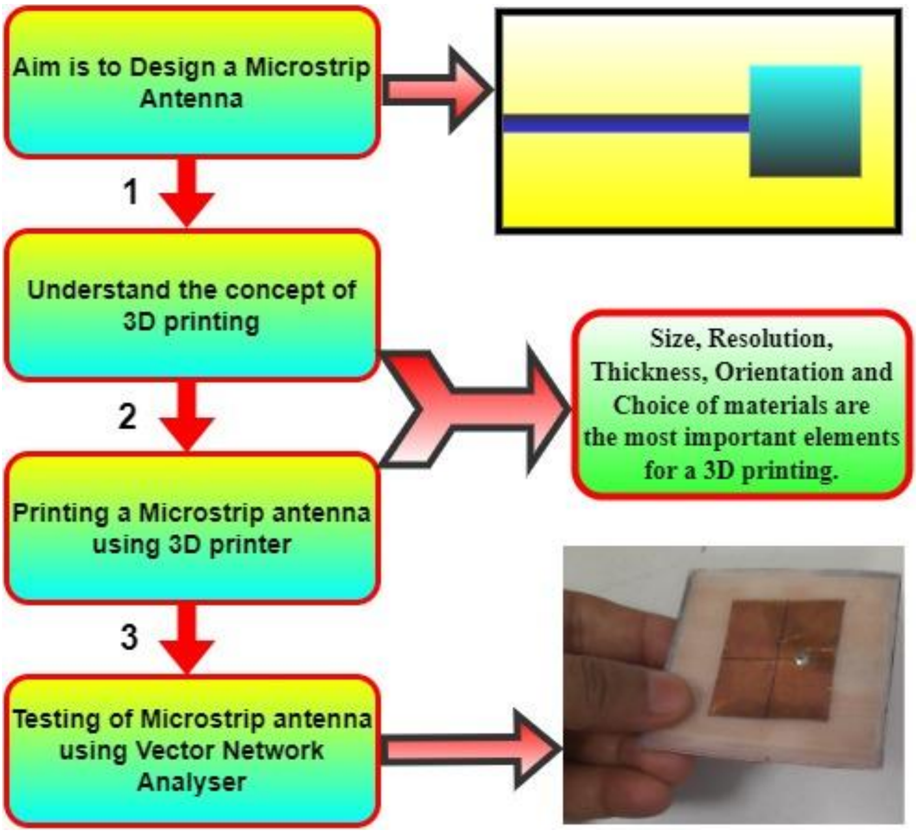


Figure 2: Workflow of Design and Testing of Microstrip Antenna

4.1 Design of microstrip antenna using HFSS software

In the initial phase of this research, the design of the microstrip antenna was meticulously crafted using HFSS (High-Frequency Structure Simulator) software. HFSS is a widely-used electromagnetic simulation tool that allows engineers and researchers to model and analyze high-frequency structures, including antennas. During this phase, the primary objective was to tailor the microstrip antenna's design to meet the specific requirements of the intended application. This involved making critical design decisions such as choosing the substrate material, determining the dimensions of the radiating patch, and selecting the optimal location for the feed point. Simulation software like HFSS enables engineers to create a virtual prototype of the antenna, providing insights into its expected performance characteristics. Parameters such as impedance matching, radiation pattern, and bandwidth were examined through simulation.

4.2 Understanding 3D printing concepts

The next crucial step was to delve into the realm of 3D printing, a technology that would be employed to fabricate the microstrip antenna. 3D printing, also known as additive manufacturing, involves creating three-dimensional objects layer by layer based on a computer-generated design. In this phase, researchers needed to acquire a comprehensive understanding of 3D printing concepts and methodologies. This included grasping the principles of layer-by-layer construction, printer capabilities, and the types of materials suitable for 3D printing. Critical considerations included determining the size of the antenna, specifying the printing resolution (layer thickness), and carefully selecting appropriate printing materials. These factors were instrumental in ensuring the successful realization of the microstrip antenna using a 3D printer.

4.3 3D Printing of microstrip antenna

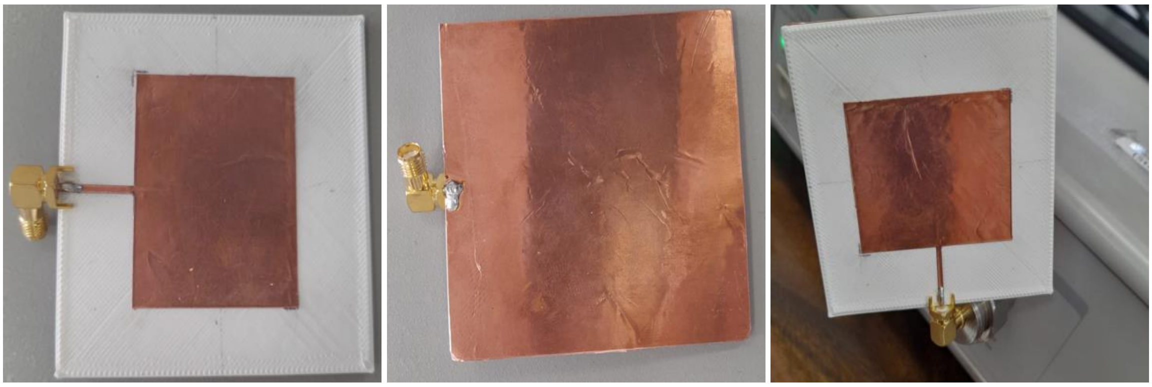
Building upon the knowledge acquired in the previous step, the researchers proceeded to physically fabricate the microstrip antenna. This involved the actual construction of the antenna structure based on the optimized design parameters obtained from the HFSS simulation. One of the distinctive aspects of this research was the utilization of 3D printing technology to create the microstrip antenna. The 3D printer employed layer-by-layer deposition to construct the antenna structure precisely according to the computer-generated design. The choice of materials for 3D printing was crucial, as it directly influenced the antenna's physical properties and performance. Researchers needed to ensure that the printed antenna retained the desired structural integrity and electrical characteristics.

4.4 Testing using Vector Network Analyzer (VNA)

The culmination of the research involved rigorous testing of the fabricated microstrip antenna to assess its real-world performance. This critical phase was conducted in the dedicated Antenna Laboratory at NITTTR, Chandigarh. A Vector Network Analyzer (VNA) played a central role in the testing process. The VNA is a sophisticated instrument used for measuring and characterizing the electrical behavior of antennas and other RF (radio frequency) devices. Various performance parameters were evaluated using the VNA, including return loss, impedance matching, bandwidth, and radiation efficiency. These empirical measurements provided concrete data on how well the antenna performed in practical applications. Any disparities or variations between the simulated results from HFSS and the actual measurements from the VNA were meticulously analyzed. Any discrepancies were addressed to ensure that the physical antenna closely matched the design specifications.

In essence, this research journey encompassed a systematic progression from virtual design and simulation to the physical realization of the microstrip antenna using 3D printing technology. Rigorous testing and measurement of the antenna's performance using advanced equipment completed the process, ultimately leading to the development of an innovative and high-performing microstrip antenna for microwave frequency applications.

Fig. 3 provides a comprehensive view of the fabricated microstrip antenna and its associated testing setup. In (a), the upper view of the fabricated microstrip antenna is depicted. This angle offers a clear perspective of the antenna's top surface, showing the arrangement of the radiating element and other essential components. Moving on to (b), the back view of the fabricated microstrip antenna is showcased. This perspective allows us to examine the antenna's rear surface, which typically contains the ground plane and other elements that play a crucial role in its operation. Finally, (c) illustrates the microstrip antenna in action, connected to a Vector Network Analyzer (VNA). This setup demonstrates how the antenna is integrated into the testing environment, where it undergoes rigorous evaluation and measurement to assess its performance characteristics, including impedance, gain, and bandwidth. The VNA is a critical tool for analyzing the antenna's behavior and ensuring it meets the desired specifications.



a) b) c)

Figure 3: (a) Upper and (b) back view of fabricated microstrip antenna, (c) microstrip antenna connected to vector network analyzer

Figure 4: Sequential process for acquiring results using a Vector Network Analyzer (VNA)

Figure 4 illustrates the crucial process of obtaining and optimizing the response of the microstrip antenna when it is connected to the Vector Network Analyzer (VNA). This step is vital in assessing the performance of the antenna and ensuring that it meets the desired specifications. In the image, you can see the microstrip antenna, which has been designed, fabricated, and printed as described in previous steps. The antenna is connected to the VNA through a probe, allowing for precise measurements of its characteristics. As the connection is established, the VNA begins to analyze the antenna's response to different frequencies. This response is visualized on the screen in real-time, providing valuable data about the antenna's behavior. The optimization process involves adjusting various parameters, such as the antenna's dimensions or impedance matching, to fine-tune its performance. This iterative process aims to achieve the best possible results, optimizing factors like gain, bandwidth, and resonance frequency. The data obtained from the VNA is instrumental in evaluating the antenna's effectiveness for its intended application. Researchers can use this information to make necessary adjustments or validate the antenna's suitability for specific microwave frequencies or communication purposes. In summary, Figure 4 showcases the critical phase of assessing and optimizing the microstrip antenna's response when connected to the Vector Network Analyzer, a fundamental step in ensuring its functionality and efficiency in real-world applications.

4.5 Graphs and analysis

The major response of the designed microstrip antenna is displayed in Figure 5(a) to 5(c), which includes three distinct cases. In Case-1, the figure showcases the overall response of the microstrip antenna, encompassing various performance parameters such as return loss, bandwidth, and radiation pattern. This analysis provides a comprehensive view of how well the antenna performs in its intended application. Moving to Case-2, the microstrip antenna's response is explored within a four-port configuration. This suggests a more complex testing scenario where the antenna's behavior is assessed when interacting with multiple ports or possibly in a system with additional components. Case-3 presents an even more detailed examination involving the utilization of a single-ended two-port vector network analyzer (VNA) and HYPERLABS ultra-broadband baluns for measuring differential S-parameters. This approach is likely employed to gain insights into the antenna's behavior in a differential signal environment, a crucial consideration for certain applications. Additionally, comparisons with measurements obtained from a four-port VNA offer valuable data for evaluating the antenna's suitability in scenarios requiring differential signaling.

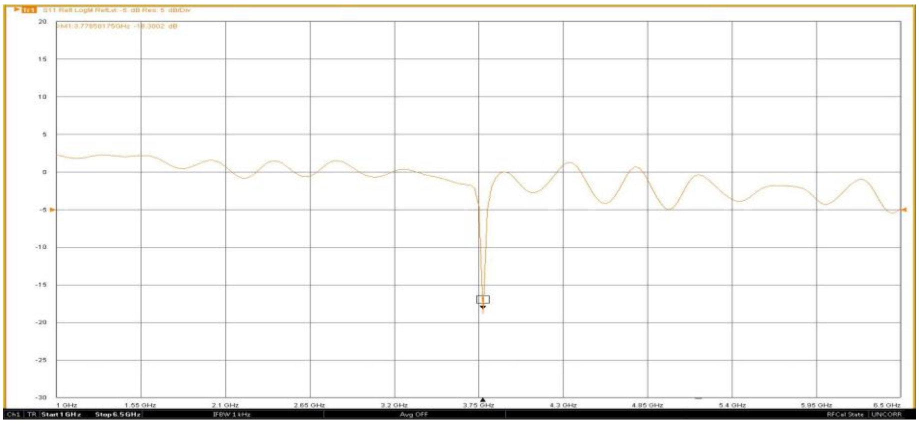


Figure 5(a): Case-1: Response of the microstrip antenna

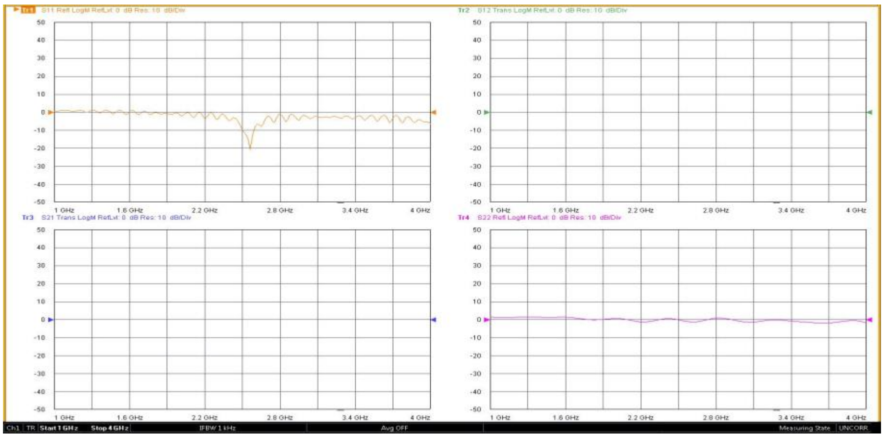


Figure 5(b): Case-2: Response of the microstrip antenna

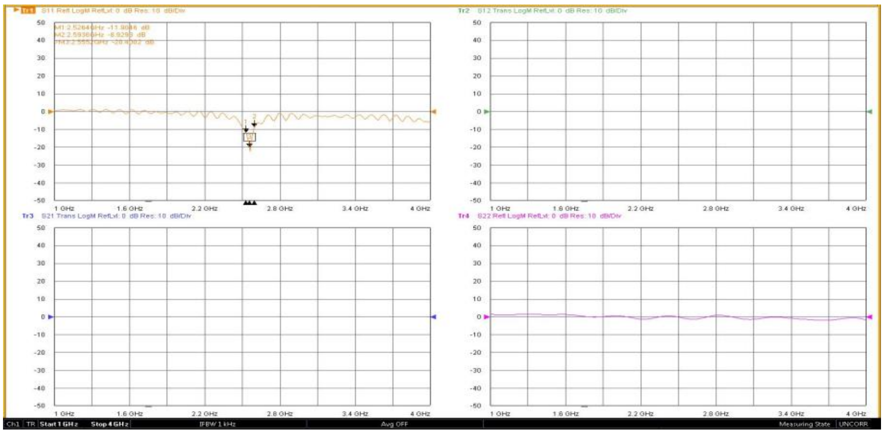


Figure 5(c): Case-3: Response of the microstrip antenna

5. Conclusion

The key outcome of this research endeavor culminates in the successful design of a novel and highly dependable microstrip antenna, tailored to cater to various microwave frequency-related applications. It emphasizes the versatility of microstrip antennas when it comes to adapting to specific requirements. It is worth highlighting that the antenna's performance can be significantly improved by meticulous selection of dimensions, shape, and suitable materials, all of which were rigorously tested in the antenna laboratory. While both high gain and high bandwidth are indeed advantageous, it's important to acknowledge the inherent design trade-offs that make achieving both simultaneously in a microstrip antenna a challenging feat. However, through the application of advanced design methodologies and innovative materials, many of these challenges can be effectively addressed and mitigated, paving the way for improved microstrip antenna performance in diverse applications.

6. Acknowledgement

The authors of this paper wish to express our heartfelt gratitude to the research team at NITTTR, Chandigarh for generously providing us with the opportunity to fabricate and test the microstrip antenna within their Antenna Laboratory during the STC on "Antenna Design and Fabrication using Additive Manufacturing Techniques." This event, held from 20/03/2023 to 24/03/2023, was conducted under the auspices of the Department of Electronics and Communication Engineering at NITTTR, Chandigarh. Their support and access to the laboratory facilities greatly contributed to the successful execution of our research work, and we extend our sincere appreciation for their assistance.

7. References

[1] A. Jadhav, N. Biradar, H. Bhaldar, M. Mathpati, R. Wadekar, and M. Deshmukh, Multiband (2023). Circular Microstrip Patch Antenna for Wireless Applications, in: Wirel Pers Commun, vol. 128, no. 1, pp. 173–186, doi: 10.1007/s11277-022-09948-9.

[2] Y. H. Parakoti, S. L. Praveena Jallipalli, A. S. Y. Krishna, and A. J. Rani (2023). Design of Two Element Array Microstrip Patch Antenna for Wi-Max Applications, in: 2023 International Conference on Recent Advances in Electrical, Electronics, Ubiquitous Communication, and Computational Intelligence, RAEEUCCI 2023, Institute of Electrical and Electronics Engineers Inc. doi: 10.1109/RAEEUCCI57140.2023.10134309.

[3] M. M. R. Hire and M. C. S. Ahire, A Review on Microstrip Patch Antenna Design and its Applications [Online]. Available: https://ssrn.com/abstract=4043696.

[4] H. El-Hakim and H. A. Mohamed (2023). Synthesis of a Multiband Microstrip Patch Antenna for 5G Wireless Communications, in: J Infrared Millim Terahertz Waves. doi: 10.1007/s10762-023-00937-y.
[5] S. Elangovan, R. Gokul Raj, M. Vethaprasath, and K. Mahendran (2023). Design and analyzing of hexagon-shaped microstrip patch antenna for biomedical applications, in: 2023 International Conference on Computer Communication and Informatics, ICCCI 2023, Institute of Electrical and Electronics Engineers Inc. doi: 10.1109/ICCCI56745.2023.10128199.
[6] R. Sharma, N. S. Raghava, and A. De (2022). Design and Analysis of Circular Microstrip Patch Antenna for White Space TV Band Application, in: Wirel Pers Commun, vol. 126, no. 4, pp. 3333–3344, doi: 10.1007/s11277-022-09867-9.
[7] P. Kaur, S. K. Aggarwal, and A. De (2016). Performance enhancement of rectangular microstrip patch antenna using double H shaped metamaterial, in: Radioelectronics and Communications Systems, vol. 59, no. 11, pp. 496–501. doi: 10.3103/S0735272716110030.
[8] T. R. Kumar and M. Madhavan (2022). Design and Optimization of Wearable Microstrip Patch Antenna using Hybrid Fuzzy Flamingo Swarm Optimization Algorithm for RF Energy Harvesting, in: Iranian Journal of Science and Technology - Transactions of Electrical Engineering. doi: 10.1007/s40998-021-00470-5.
[9] D. Kaushal and T. Shanmuganantham (2018). Design of a Compact and Novel Microstrip Patch Antenna for Multiband Satellite Applications. [Online]. URL: www.sciencedirect.comwww.materialstoday.com/proceedings.
[10] S. Ihlou, H. Tizyi, A. Bakkali, A. El Abbassi, and J. Foshi (2020). Design and development of a microstrip patch antenna array for rectenna system, in: ACM International Conference Proceeding Series, Association for Computing Machinery, pp. 323–328. doi: 10.1145/3419604.3419766.
[11] U. Sharma, J. A. Ansari, and P. K. Mishra (2023). Closed Envelop Shaped Microstrip (CESM) Antenna with DGS for X and Ku Band wireless Applications, in: International Conference on Microwave, Antenna and Communication, MAC 2023, Institute of Electrical and Electronics Engineers Inc. doi: 10.1109/MAC58191.2023.10176336.
[12] M. M. Islam, M. T. Islam, M. R. I. Faruque, and W. Hueyshin (2013). Design of an X-band microstrip patch antenna with enhanced bandwidth. 2013 2nd International Conference on Advances in Electrical Engineering (ICAEE), IEEE, pp. 313–317. doi: 10.1109/ICAEE.2013.6750355.
[13] C. S. Roy and P. S. Roy (2015). Design of slotted Microstrip patch Antenna with enhanced bandwidth in C- band applications. 2015 IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT), IEEE, pp. 1–4. doi: 10.1109/ICECCT.2015.7226186.
[14] M. S. Rabbani and H. Ghafouri-Shiraz (2016). Improvement of microstrip patch antenna gain and bandwidth at 60 GHz and X bands for wireless applications. IET Microwaves, Antennas and Propagation, vol. 10, no. 11, pp. 1167–1173. doi: 10.1049/iet-map.2015.0672.
[15] R. Rajkumar and U. K. Kommuri (2018). A Triangular Complementary Split Ring Resonator Based Compact Metamaterial Antenna for Multiband Operation. Wirel Pers Commun, vol. 101, no. 2, pp. 1075–1089. doi: 10.1007/s11277-018-5749-7.
[16] P. Kaur, S. Bansal, and N. Kumar (2022). SRR metamaterial-based broadband patch antenna for wireless communications. Journal of Engineering and Applied Science, vol. 69, no. 1. doi: 10.1186/s44147-022-00103-6.
[17] K. Aliqab, S. Lavadiya, M. Alsharari, A. Armghan, M. G. Daher, and S. K. Patel (2023). Design and Fabrication of a Low-Cost, Multiband and High Gain Square Tooth-Enabled Metamaterial Superstrate Microstrip Patch Antenna. Micromachines (Basel), vol. 14, no. 1. doi: 10.3390/mi14010163.
[18] A. A. Althuwayb et al. (2023). Broadband, high gain 2 × 2 spiral shaped resonator based and graphene assisted terahertz MIMO antenna for biomedical and WBAN communication. Wireless Networks. doi: 10.1007/s11276-023-03494-3.

[19] A. B. Devarapalli and T. Moyra (2023). Design of a Metamaterial Loaded W-shaped Patch Antenna with FSS for Improved Bandwidth and Gain. Silicon, vol. 15, no. 4, pp. 2011–2024. doi: 10.1007/s12633-022-02123-6.
[20] M. Boudjerda et al. (2022). Design and Optimization of Miniaturized Microstrip Patch Antennas Using a Genetic Algorithm. Electronics (Switzerland), vol. 11, no. 14. doi: 10.3390/electronics11142123.
[21] J. H. Chen, C. Y. Cheng, C. M. Chien, C. Yuangyai, T. H. Chen, and S. T. Chen (2023). Multiple Performance Optimization for Microstrip Patch Antenna Improvement, in: Sensors, vol. 23, no. 9. doi: 10.3390/s23094278.
[22] P. P. Chandran and S. Viswasom (2014). Gain and bandwidth optimization of a novel microstrip patch antenna, in: Proceedings - 2014 4th International Conference on Advances in Computing and Communications, ICACC 2014, Institute of Electrical and Electronics Engineers Inc., Sep. 2014, pp. 315–318. doi: 10.1109/ICACC.2014.80.
[23] R. Rashmitha, N. Niran, A. A. Jugale, and M. R. Ahmed (2020). Microstrip Patch Antenna Design for Fixed Mobile and Satellite 5G Communications, in: Procedia Computer Science, Elsevier B.V., 2020, pp. 2073–2079. doi: 10.1016/j.procs.2020.04.223.
[24] S. K. Noor et al. (2023). A Patch Antenna with Enhanced Gain and Bandwidth for Sub-6 GHz and Sub-7 GHz 5G Wireless Applications, in: Electronics (Switzerland), vol. 12, no. 12, Jun. 2023, doi: 10.3390/electronics12122555.
[25] H. M. Rai and K. Chatterjee (2019). Hybrid adaptive algorithm based on wavelet transform and independent component analysis for denoising of MRI images, in: Measurement (Lond), vol. 144, pp. 72–82. doi: 10.1016/j.measurement.2019.05.028.
[26] H. M. Rai and K. Chatterjee (2021). 2D MRI image analysis and brain tumor detection using deep learning CNN model LeU-Net, vol. 80, no. 28–29. Springer US. doi: 10.1007/s11042-021-11504-9.
[27] H. M. Rai and K. Chatterjee (2021). Hybrid CNN-LSTM deep learning model and ensemble technique for automatic detection of myocardial infarction using big ECG data. Applied Intelligence. doi: 10.1007/s10489-021-02696-6.
[28] H. M. Rai and K. Chatterjee (2020). Detection of brain abnormality by a novel Lu-Net deep neural CNN model from MR images. Machine Learning with Applications, vol. 2, p. 100004. doi: 10.1016/j.mlwa.2020.100004.
[29] H. M. Rai and K. Chatterjee (2018). A Novel Adaptive Feature Extraction for Detection of Cardiac Arrhythmias Using Hybrid Technique MRDWT & MPNN Classifier from ECG Big Data. Big Data Research, vol. 12, pp. 13–22. doi: 10.1016/j.bdr.2018.02.003.
[30] H. M. Rai and K. Chatterjee (2018). A unique feature extraction using MRDWT for automatic classification of abnormal heartbeat from ECG big data with Multilayered Probabilistic Neural Network classifier. Applied Soft Computing Journal, vol. 72, pp. 596–608. doi: 10.1016/j.asoc.2018.04.005.
[31] H. M. Rai, K. Chatterjee, and S. Dashkevych (2022). The prediction of cardiac abnormality and enhancement in minority class accuracy from imbalanced ECG signals using modified deep neural network models. Comput Biol Med, vol. 150. doi: 10.1016/j.compbiomed.2022.106142.
[32] H. M. Rai, K. Chatterjee, and S. Dashkevich (2021). Automatic and accurate abnormality detection from brain MR images using a novel hybrid UnetResNext-50 deep CNN model. Biomed Signal Process Control, vol. 66, no. January, p. 102477. doi: 10.1016/j.bspc.2021.102477.
[33] H. M. Rai, K. Chatterjee, and A. Nayyar (2021). Automatic Segmentation and Classification of Brain Tumor from MR Images Using DWT-RBFNN. Advanced Soft Computing Techniques in Data Science, IoT and Cloud Computing. pp. 215–243. doi: 10.1007/978-3-030-75657-4_10.
[34] H. M. Rai, K. Chatterjee, and C. Mukherjee (2020). Hybrid CNN-LSTM model for automatic prediction of cardiac arrhythmias from ECG big data. 2020 IEEE 7th Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON), IEEE. pp. 1–6. doi: 10.1109/UPCON50219.2020.9376450.

[35] H. M. Rai, K. Chatterjee, and D. Gupta (2020). Tumor detection from Brain Magnetic Resonance Images using MRDWTA-RBFNNC. 2nd International Conference on Information Management & Machine Intelligence (ICIMMI-2020), pp. 2–7.
[36] H. M. Rai, A. Trivedi, and S. Shukla (2013). ECG signal processing for abnormalities detection using multi-resolution wavelet transform and Artificial Neural Network classifier. Measurement, vol. 46, no. 9, pp. 3238–3246. doi: 10.1016/j.measurement.2013.05.021.
[37] A. Rajawat, K. M. Agrawal, and P. K. Singhal (2023). Design, implementation and analysis of wide-band antenna with novel DGS for RF energy harvesting. Mater Today Proc. doi: 10.1016/j.matpr.2023.03.456.
[38] K. Kamakshi, A. Singh, M. Aneesh, and J. A. Ansari (2014). Novel design of microstrip antenna with improved bandwidth. International Journal of Microwave Science and Technology, vol. 2014. doi: 10.1155/2014/659592.
[39] A. Kafle, E. Luis, R. Silwal, H. M. Pan, P. L. Shrestha, and A. K. Bastola (2021). 3d/4d printing of polymers: Fused deposition modelling (fdm), selective laser sintering (sls), and stereolithography (sla. Polymers, vol. 13, no. 18. MDPI. doi: 10.3390/polym13183101.
[40] S. F. Iftekar, A. Aabid, A. Amir, and M. Baig (2023). Advancements and Limitations in 3D Printing Materials and Technologies: A Critical Review. Polymers, vol. 15, no. 11. MDPI. doi: 10.3390/polym15112519.