INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

OPEN ACCESS

Received: 27-11-2023

Accepted: 19-12-2023

Published: 13-01-2024

Citation: Chetan S, Chandrappa DN, Yogesh GS, Jagadeesha S, Sreedharamurthy SK (2024) Design and Performance Analysis of Multiband Patch Antenna with Metamaterial for Wireless Applications. Indian Journal of Science and Technology 17(3): 270-276. https://doi.org/10.17485/IJST/v17i3.3022

* **Corresponding author**.

chetansjmit@gmail.com

Funding: None

Competing Interests: None

Copyright: © 2024 Chetan et al. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Design and Performance Analysis of Multiband Patch Antenna with Metamaterial for Wireless Applications

S Chetan[1]*, D N Chandrappa[2], G S Yogesh[3], S Jagadeesha[4], S K Sreedharamurthy[5]

1 Assistant Professor, E&CE, SJMIT, Visveswaraya Technological University, Belagavi, Karnataka, India
2 Professor, E&CE, EPCET, Visveswaraya Technological University, Belagavi, Karnataka, India
3 Professor & Head, E&CE, EPCET, Visveswaraya Technological University, Belagavi, Karnataka, India
4 Professor, E&CE, AMCEC, Visveswaraya Technological University, Belagavi, Karnataka, India
5 Professor, E&CE, UBDTCE, Visveswaraya Technological University, Belagavi, Karnataka, India

Abstract

Objectives: The objective of this study is to design and construct a patch antenna with frequency configurability by integrating metamaterial components. **Method:** To achieve frequency configurability in the patch antenna, a method is employed whereby a PIN diode is strategically placed within the metamaterial gap. **Findings:** The findings of this study indicate that when the diode is in the OFF state, the frequency-configurable patch antenna can operate within two distinct frequency bands, specifically at 4.3GHz and 7.7GHz. However, when the diodes are switched ON, the antenna is capable of operating within three distinct frequency bands, namely 4.3GHz, 5.7GHz, and 7.7GHz. **Novelty:** The novelty of this work lies in the unique method employed to achieve frequency configurability in the patch antenna, which involves the strategic placement of a PIN diode within the metamaterial gap. This innovative approach allows for the antenna to switch between different frequency bands, enhancing its versatility and performance compared to conventional designs.

Keywords: Frequency reconfiguration; PIN diodes; Metamaterial; HFSS

1 Introduction

5G technology, known for its high speed and low latency, is revolutionizing mobile communication. To address the space constraints posed by multiple antennas, reconfigurable antennas offer a breakthrough solution. These antennas, whether single-band or multi-band, consolidate capabilities within a single unit, saving both space and costs. The adoption of frequency-reconfigurable antennas proves pivotal, enhancing device performance across diverse communication bands.

Several studies have explored frequency-reconfigurable patch antennas for diverse applications. Mahlaoui et al. [1] developed a patch antenna with a fluctuating lower band and constant upper band, achieving frequency reconfiguration through varactor diodes.

Another design [2] focused on L-Band applications, incorporating PIN diodes for frequency switching and concentric rings as a Defected Ground Structure. Additionally, a hexagonal patch antenna [3] employed PIN diodes and an H-Tree fractal slot for frequency reconfiguration in L and S bands. Further, a WiMAX and WLAN antenna [4] utilized two substrates and PIN diodes to achieve frequency agility. Navarajan et al. [5] presented a microstrip patch antenna with Shunt-series MEMS switches for wideband frequency switching. Lastly, a microstrip patch antenna [6] with RF PIN diodes strategically placed in slots achieved six reconfigurable modes, suitable for 5G, WLAN, and Wi-Fi. In [7], a microstrip patch antenna was designed for upcoming wireless applications, incorporating slots, slits, and a defective ground construction. The antenna demonstrated versatility across multiple frequency bands, showcasing potential for cognitive radio applications with both narrowband and broadband elements.

While these studies contribute significantly to the field of reconfigurable antennas, there is a notable absence of exploration into the incorporation of metamaterials for frequency reconfiguration. The unique strategy of employing metamaterials in antenna design for frequency tuning is not extensively covered in the reviewed literature. Addressing this research gap could lead to innovative approaches and advancements in the development of frequency-reconfigurable antennas.

In this investigation, a patch antenna tailored for wireless applications is innovatively designed to exhibit frequency configurability through the incorporation of metamaterials. The integration of metamaterials induces a shift in the antenna's frequency, and this reconfiguration is achieved by strategically placing PIN diodes on the metamaterial structures. This approach effectively addresses the previously identified research gap by introducing metamaterials as a unique strategy for achieving frequency tunability in patch antenna designs.

2 Methodology

The structure of single cell circular shaped metamaterial unit cell is as shown in Figure 1. The gap width g=1mm and the thickness of the ring is 0.2mm. The ring is realized using HFSS on FR4 epoxy substrate with thickness 1mm.

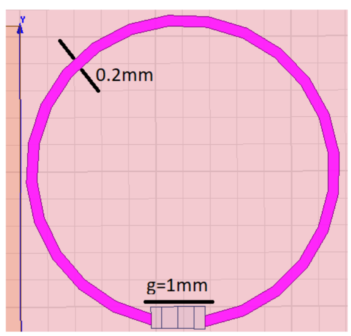


Fig 1. Split Ring Resonator

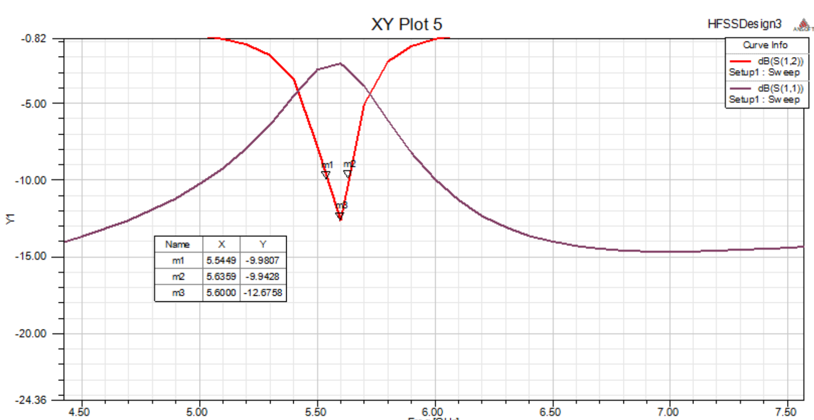


Fig 2. Return Loss Plot of Circular Split Ring Metamaterial

According to Figure 2, the unit cell structure, which consists of a circular split ring resonator, has a bandwidth of 0.65 GHz (5.2 GHz–5.85 GHz), where electromagnetic waves are reflected, leading to undesirable material characteristics. At 5.5 GHz, a circular metamaterial unit cell resonates. According to Figure 3, the operating frequency of the circular split ring-based metamaterial unit cell[8] increases as the gap width grows. According to Figure 4, a square split ring resonator runs at a higher frequency when the thickness is decreased.

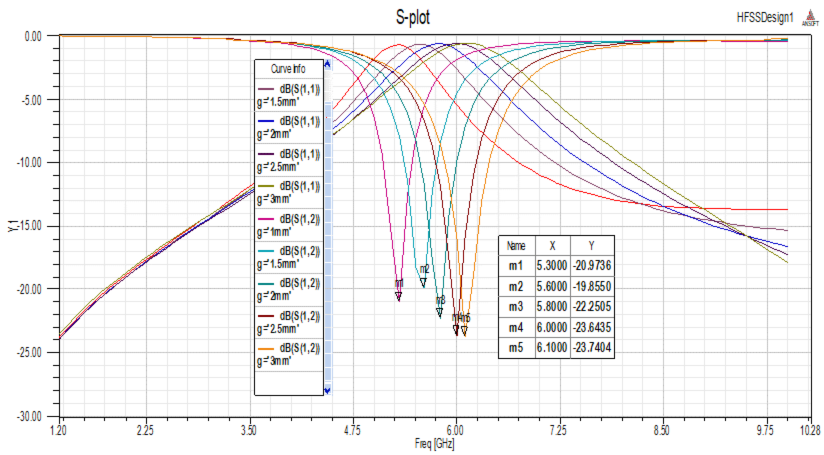


Fig 3. RL plot for Varying gap

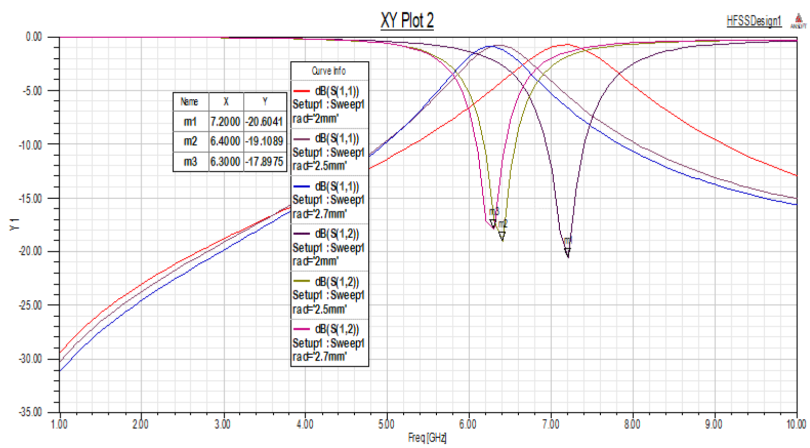
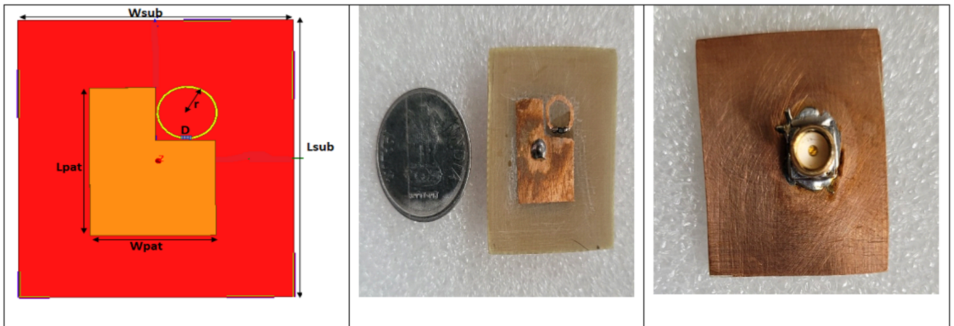


Fig 4. RL plot for Varying thickness

In Figure 5**a**, we can see a schematic representation of the construction of a frequency-reconfigurable antenna that utilizes metamaterials. The detailed information about the antenna's physical dimension is shown in Table 1. In this particular antenna, there is a squared slot located in the upper right corner of the patch. This slot is used to obtain good impedance matching. Within this squared slot, there is a unique element known as a "split-ring metamaterial." "Metamaterials are artificially engineered materials designed to have properties that are not found in nature". In this case, the metamaterial takes the form of a circular structure made up of split rings. The specific arrangement and geometry of these rings are crucial for the antenna's functionality. The antenna is fed using a technique called "probe feeding." This means that electromagnetic energy is introduced into or extracted from the antenna using a probe, which is a small, electrically conductive element that makes direct contact with the antenna structure. The location of the feed is optimized to achieve low return loss. The entire antenna structure is built on a substrate made of FR4 epoxy. This substrate material has a dielectric constant of 4.4 and a height of 1.6mm. Within the gap of the metamaterial structure, a PIN diode (represented as 'D') is inserted. A PIN diode is a type of semiconductor device that can be controlled to act as a switch. In the context of this antenna, the PIN diode serves as a controllable element that can be turned on or off. Its presence in the antenna's gap has a significant impact on the antenna's resonance and operating frequency.

The fabricated prototype is seen in Figure 5 **b** and **c**.



5a.Proposed Antenna Schematic	5b.Fabricated Antenna Prototype – Top view	5c.Fabricated Antenna Prototype – Rear view

Fig 5. Proposed Antenna

Table 1. Antenna Specifications

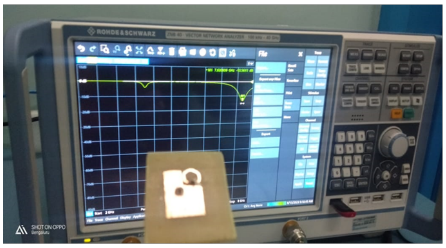
Parameters	Dimensions in mm
Lsub	30
Wsub	26
Lpat	15
Wpat	12
r	3

3 Results and Discussions

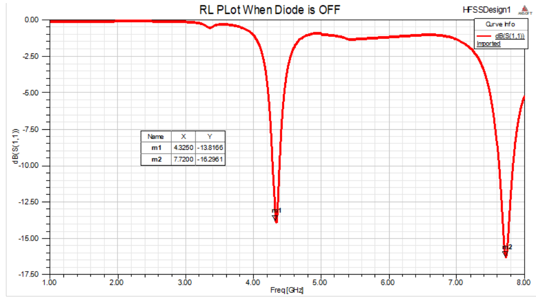
The High-Frequency Structure Simulator (HFSS) served as the primary tool for modeling the envisioned antenna, enabling a comprehensive analysis of its performance characteristics. This simulation was crucial in understanding how the antenna behaves under different conditions. Figures 6 and 7 provide valuable insights into the simulation results, illustrating the reflection coefficient for two distinct states of the PIN diode: ON and OFF.

The antenna is tested using ZNB40 vector network analyser and its experimental setup is shown in Figure 6**a**. In Figure 6**b**, it is evident that when the PIN diode, situated across the metamaterial antenna, is in the OFF state, the simulation reveals the presence of two resonant frequencies at 4.3GHz and 7.7GHz. These frequencies represent the antenna's operational points when configured for specific applications or frequency bands. However, Figure 7 showcases the impact of switching the PIN diode ON, resulting in a shift in the antenna's resonance behaviour. In this state, the antenna exhibits three distinct resonance frequencies, specifically at 4.3 GHz, 5.7 GHz, and 7.7 GHz. This remarkable capability to alter resonance frequencies through the control of the PIN diode underscores its pivotal role in facilitating frequency switching within a broad range spanning from 4 to 8 GHz. Such versatility makes this antenna design well-suited for a wide spectrum of wireless communication applications where adaptability to different frequency bands is essential. Figure 6 **c** shows measured results of antenna when PIN diode is OFF. While there is a notable alignment between the simulated and measured results, discrepancies in the fabricated antenna outcomes in comparison to the simulated ones primarily arise from manufacturing tolerances, imperfections in components, and variations in the soldering of the PIN diode.

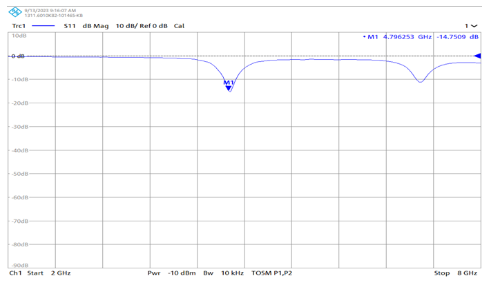
In Figure 8, the surface current plots of the designed antenna provide valuable insights into its electromagnetic behaviour. Figure 8**a**, representing the OFF state of the diode, shows that the majority of the surface currents are concentrated along the edges of the patch and the metamaterial ring. Notably, the presence of current on the metamaterial ring [9] is a result of its coupling effect with the patch. This coupling effect plays a crucial role in the antenna's functionality, allowing for the modification of the patch's resonant frequency. By appropriately designing the metamaterial ring, it becomes possible to control and fine-tune the antenna's resonance characteristics.



a. Experimental set up



b. Simulated Return Loss plot when PIN diode is OFF



c. Measured Return Loss plot when PIN diode is OFF

Fig 6. a) Experimental set up, b) Simulated Return Loss plot when PIN diode is OFF, c) Measured Return Loss plot when PIN diode is OFF

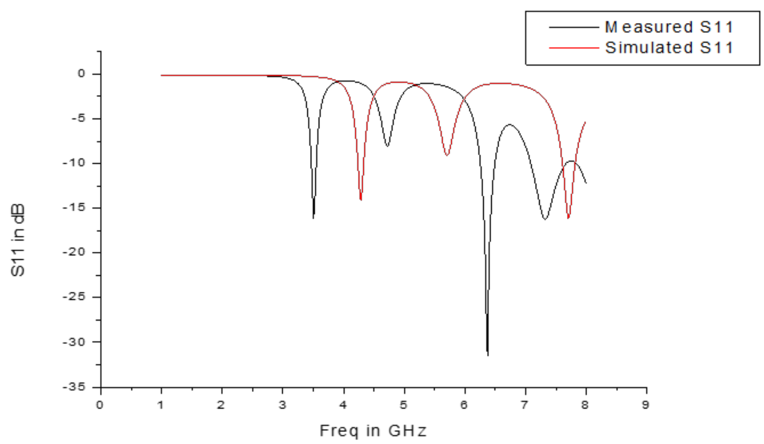
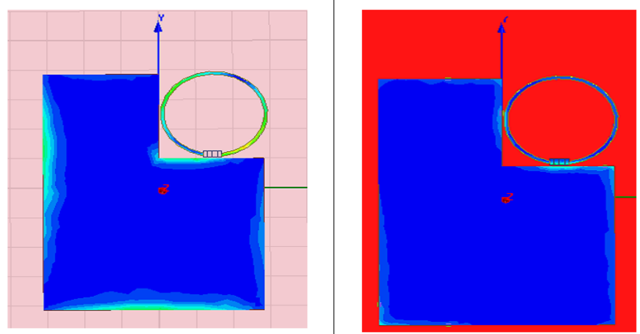


Fig 7. Measured and Simulated Return Loss plot when PIN diode is ON

However, when the diode is switched ON, as illustrated in Figure 8**b**, a significant transformation occurs in the metamaterial ring. It adopts a closed ring configuration, effectively resembling a slotted circular patch antenna. This transformation leads to an additional resonance phenomenon, now occurring at 5.5 GHz when the diode is in the ON state. This shift in resonance behaviour highlights the versatility of the antenna design, where the state of the diode allows for dynamic alterations in the antenna's operating frequencies. This capability to switch between resonance modes by controlling the diode state is pivotal in adapting the antenna's performance to various communication requirements and frequency bands.

The proposed work introduces a frequency-configurable patch antenna with metamaterial technology and PIN diode integration, demonstrating potential for versatile operation in 5G mobile communication, portable Wi-Fi, Wi-MAX, and WLAN. The innovative design aligns with the multifaceted demands of modern wireless communication, offering adaptability across diverse applications and showcasing promise for enhanced functionality in advanced communication systems. In



(a) *Surface current when Diode is OFF* (b) *Surface current when Diode is ON*

Fig 8. Surface current Plots

Table 2. Comparative study

References	Antenna Design	Reconfigurability	Applications
(10)	Metamaterial concept with truncated and SRR-etched patch	Three PIN diode switches	5G mobile, portable Wi-Fi, WiMAX, WLAN
(11)	reconfigurable monopole antenna with wide-band, dual-band, and single-band operation	Two p-i-n diodes for wide-band, dual-band, and single-band operations	WiMAX, WLAN, WAVE, 5G, multi-mode communication systems
(12)	Frequency diversity microstrip antenna inspired by a metamaterial structure	Two ideal PIN diodes inserted in the metamaterial portion	WiMAX, WLAN
Proposed Work	Frequency-configurable patch antenna with metamaterial technology	PIN diode integration within metamaterial gap	5G mobile, portable Wi-Fi, WiMAX, WLAN

alignment with our exploration of proposed antenna design, our study references key works (references[10–12]) in the field. Table 2 provides a concise summary of the comparative analysis conducted, offering insights into metamaterial concepts, reconfiguration techniques, and application scope

4 Conclusion

In conclusion, this study successfully presented the design and implementation of a frequency-configurable patch antenna incorporating metamaterial technology. The integration of a PIN diode within the metamaterial gap allowed for easy frequency adjustments. When the diode was in the OFF state, the antenna exhibited two distinct frequency bands at 4.3 GHz and 7.7 GHz. However, by activating the diode, an additional frequency band at 5.7 GHz was achieved. The antenna designs were developed using the HFSS software, ensuring accurate modelling and analysis. The successful implementation of the frequency-configurable patch antenna with metamaterial integration opens up new possibilities for advanced wireless communication systems. The compact design and flexible frequency tuning capabilities make these antennas promising candidates for future applications. Further research and development in this field could explore optimization techniques and explore additional features to enhance the performance and versatility of frequency-configurable antennas. Future work in this area may focus on optimizing the metamaterial configuration for even wider frequency tuning ranges and exploring advanced materials for enhanced antenna performance. Additionally, investigating the integration of multiple frequency-configurable antennas within a single system for increased versatility and adaptability in diverse communication scenarios could be a promising direction.

References

1) Mahlaoui Z, Antonino-Daviu E, Latif A, Ferrando-Bataller M. Design of a Dual-Band Frequency Reconfigurable Patch Antenna Based on Characteristic Modes. *International Journal of Antennas and Propagation*. 2019;2019:1–12. Available from: https://doi.org/10.1155/2019/4512532.
2) Kumar S, Khandekar R, Tupe-Waghmare P. Frequency Reconfigurable Patch Antenna for L band Applications. *International Journal of Engineering and Advanced Technology*. 2019;9(1):4775–4784. Available from: https://www.ijeat.org/wp-content/uploads/papers/v9i1/A2097109119.pdf.
3) Ahmad KS, Aziz MZAA, Abdullah NB. A Dual-Band Frequency Reconfigurable Antenna Array Based on Reconfigurable Defected Ground Structure. In: 2020 IEEE International RF and Microwave Conference (RFM). IEEE. 2021;p. 1–4. Available from: https://doi.org/10.1109/RFM50841.2020.9344790.
4) Lokeshwar B, Venkatasekhar D, Sudhakar A. A High Gain Frequency Reconfigurable Microstrip Patch Antenna for Wireless Local Area Network Applications. *Journal of Computational and Theoretical Nanoscience*. 2019;16(4):1651–1655. Available from: https://doi.org/10.1166/jctn.2019.8092.
5) Navarajan J, Jebarani MRE, Krishnan VG. Frequency Reconfigurable Microstrip Patch Antenna for Multiband Applications with Shunt-Series MEMS Switch. *International Journal on Recent and Innovation Trends in Computing and Communication*. 2022;10(12):125–132. Available from: https://doi.org/10.17762/ijritcc.v10i12.5893.
6) Saikia B, Borah K. A compact frequency reconfigurable patch antenna with asymmetric armed U and reversed L slots for handheld wireless devices. *International Journal of Microwave and Wireless Technologies*. 2023;15(4):623–631. Available from: https://doi.org/10.1017/S1759078722000575.
7) Deshmukh V, Chorage S. Frequency reconfigurable patch antenna using slot, slits and defected ground structures: parametric analysis. *Australian Journal of Electrical and Electronics Engineering*. 2022;19(2):171–184. Available from: https://doi.org/10.1080/1448837X.2021.2023077.
8) Dwivedi S, Gupta U. Frequency Reconfigurable Antenna Using Metamaterial Split Ring Resonators for Smart Applications. In: 2021 International Conference on Electrical, Communication, and Computer Engineering (ICECCE), 12-13 June 2021, Kuala Lumpur, Malaysia. IEEE. 2021. Available from: https://doi.org/10.1109/ICECCE52056.2021.9514067.
9) Salih RM, Jassim AK. Design of Unit Cell for Metamaterials to Enhancement the Characteristic of the Microstrip Antenna. In: 2021 1st Babylon International Conference on Information Technology and Science (BICITS). IEEE. 2021;p. 11–15. Available from: https://doi.org/10.1109/BICITS51482.2021.9509894.
10) Patel SK, Surve J, Katkar V, Parmar J. Machine learning assisted metamaterial-based reconfigurable antenna for low-cost portable electronic devices. *Scientific Reports*. 2022;12(1):1–13. Available from: https://doi.org/10.1038/s41598-022-16678-2.
11) Awan WA, Naqvi SI, Ali WAE, Hussain N, Iqbal A, Tran HH, et al. Design and Realization of a Frequency Reconfigurable Antenna with Wide, Dual, and Single-Band Operations for Compact Sized Wireless Applications. *Electronics*. 2021;10(11):1–10. Available from: https://doi.org/10.3390/electronics10111321.
12) Mirzaei H, Eleftheriades GV. A Compact Frequency-Reconfigurable Metamaterial-Inspired Antenna. *IEEE Antennas and Wireless Propagation Letters*. 2011;10:1154–1157. Available from: https://doi.org/10.1109/LAWP.2011.2172180.