DESIGN AND PERFORMANCE ANALYSIS OF FREQUENCY RECONFIGURABLE PLANAR MONOPOLE ANTENNAS FOR WIRELESS APPLICATIONS

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ABSTRACT

This work presents the design and detailed performance analysis of a frequency-reconfigurable planar monopole antenna, where we choose to reconfigure the antenna in hexa-band operation to meet the requirements of modern multi-standard wireless communication systems. The proposed antenna is developed using a compact planar monopole structure integrated with reconfigurable switching elements that dynamically modify the surface current paths, enabling selective activation of six distinct resonant bands without altering the physical footprint. The design methodology includes optimization of the radiating patch geometry, ground structure, feed configuration, and switch placement to ensure stable impedance matching and efficient mode switching across all six bands. Extensive simulations were carried out to examine S-parameters, VSWR, gain, radiation efficiency, bandwidth behavior, and far-field patterns under each switching state. A prototype was fabricated to experimentally validate the simulated outcomes, demonstrating close alignment in terms of resonant frequency shifts, return loss improvement, and radiation performance for all configurations. The hexa-band reconfigurable planar monopole antenna thus exhibits adaptable frequency behavior, consistent radiation characteristics, and strong suitability for applications such as WLAN, LTE, Wi-Fi, Bluetooth, and sub-6-GHz 5G, making it a promising solution for compact and flexible next-generation wireless devices.

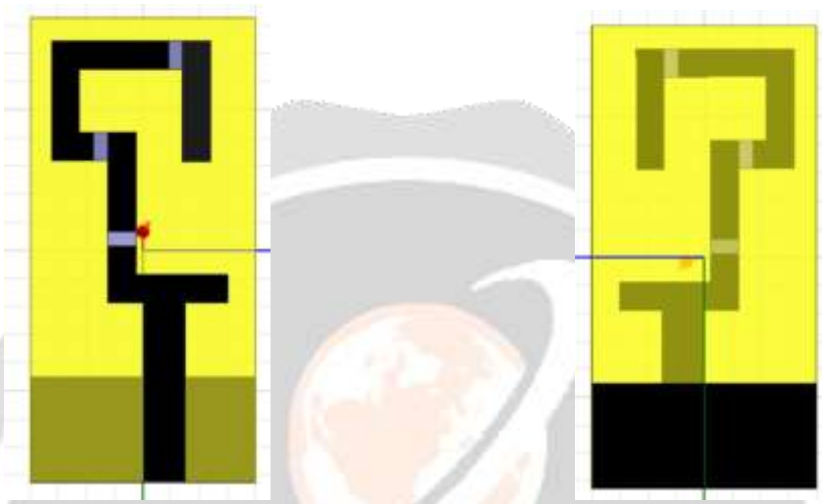
Keyword : - Reconfigurable antenna, Hexa band operation, Frequency switching,, Wireless communication, Multiband communication, Impedance bandwidth, Radiation pattern stability, Antenna miniaturization, communication systems, Antenna performance analysis, Adaptive wireless systems.

INTRODUCTION

With the rapid growth of wireless communication technologies, modern communication devices are required to support multiple frequency bands within a compact platform. Conventional fixed-frequency antennas are unable to efficiently meet the increasing demand for multi-standard operation, spectrum flexibility, and reduced hardware complexity. As a result, frequency reconfigurable antennas have emerged as a promising solution due to their ability to dynamically alter operating bands using electronic, mechanical, or material-based switching mechanisms.

A frequency reconfigurable antenna allows a single radiating structure to operate at several frequency bands, thereby improving system adaptability and reducing the need for multiple antennas in wireless devices. Such reconfigurability enhances spectrum utilization, minimizes interference, and enables support for evolving communication standards like GSM, LTE, Wi-Fi, WiMAX, and emerging broadband networks. In this context, hexa-band reconfigurable antennas have gained significant attention due to their capability to cover six distinct frequency bands using a single compact design. By integrating switching elements such as PIN diodes, the antenna can tune its resonant frequencies based on different configurations, providing high flexibility for multi-band wireless applications. The design of these antennas demands careful optimization of geometry, switching placement, and material selection to ensure stable radiation characteristics, good impedance matching, and adequate gain across all operating states.

1.1 ANTENNA DESIGN



Front view **Rarer view**

Fig: Designed Hexa Band Frequency Reconfigurable Antenna

The proposed hexa-band frequency reconfigurable antenna is designed with a compact and efficient layout that supports multiple resonant paths for flexible frequency switching. The front and rear views show the patterned radiating structure integrated on an FR4 substrate, where the reconfigurable section is shaped to generate six distinct operating bands. The design uses switching elements placed along the radiating strip to alter the electrical length of the antenna, enabling smooth transitions between ON and OFF states. This geometry ensures wideband coverage, stable radiation, and omnidirectional performance suitable for modern wireless communication devices. Overall, the antenna structure is optimized for multi-band operation while maintaining a simple, lightweight, and low-profile design.

The proposed hexa-band frequency-reconfigurable antenna is developed on an FR-4 epoxy substrate of dimensions 33 mm × 16 mm with a thickness of 1.6 mm, as illustrated in the design layout. The radiating patch consists of multiple interconnected strips forming a compact geometry suitable for multiband operation. The top horizontal section has an overall width of 110.2 mm, with 10-mm extensions on both sides, followed by downward arms measuring 7.3 mm on the left and 8.0 mm on the right. These arms connect to an internal horizontal segment of 4 mm, which further links to the central vertical radiating structures. The inner left and right vertical arms measure 19.2 mm and 6.5 mm respectively, while a small central segment of 2.5 mm provides additional coupling between sections. The lower part of the antenna consists of two vertical strips of 32 mm length separated by a 3-mm gap, each joined to a 3-mm-wide feed region that transitions into a 12.75-mm extension forming the lower radiating branch. The ground plane is positioned with an offset of 7.5 mm in the x-direction and spans the full substrate width. This structured arrangement of horizontal and vertical arms enables the antenna to support six switchable frequency bands. Reconfigurability is achieved by strategically inserting switching elements within the patch and ground regions, allowing different current paths to be activated. The combined effect of these geometrical transitions, reactive loading, and switching states enables the antenna to operate across multiple resonant bands, realizing a compact and efficient hexa-band frequency-reconfigurable system.

DESIGN FORMULA AND EQUATION

The design of Hexa Band Frequency Reconfigurable antennas is based on the transmission line model, which provides closed-form expressions to determine essential parameters. For a given resonant frequency f, dielectric constant $\varepsilon r = 4.4$, and the speed of light c, the patch width W is given by:

$W = (c / 2f) * \text{sqrt}(2 / (\varepsilon r + 1))$

The effective dielectric constant εreff, which accounts for fringing effects, is calculated using:

$\varepsilon reff = (\varepsilon r + 1)/2 + (\varepsilon r - 1)/2 * [1 + 12*(h/W)] \wedge (-0.5)$

The effective length of the patch is:

$Leff = c / (2f * \text{sqrt}(\varepsilon reff))$

The fringing length extension ΔL is given by:

$\Delta L = 0.412h * [(\varepsilon reff + 0.3)\ (W/h + 0.264)] / [(\varepsilon reff - 0.258\ )(W/h + 0.8)]$

The actual patch length is:

$L = Leff - 2\Delta L$

To estimate the required substrate height h for a desired impedance bandwidth BW, the following approximation can be used:

$h = (BW * \lambda) / (2\pi * \text{sqrt}(\varepsilon r))$

For the slotted patch array, the resonant frequency fs is approximated by:

$fs = c / (2 * Lslot * \text{sqrt}(\varepsilon reff))$

Antenna efficiency η, which considers losses, is calculated using:

$\eta = Gr / (Gr + Gc + Gd + Gs)$

where:

- Gr = radiation conductance
- Gc = conductor loss conductance
- Gd = dielectric loss conductance
- Gs = surface wave loss conductance

RESULT AND DISCUSSION

The performance of the proposed hexa-band frequency reconfigurable antenna was evaluated through detailed HFSS simulations, with particular attention to how different switching states modify the antenna's operating frequencies. Instead of relying on multiple fixed resonant modes, the antenna achieves multiple distinct operating frequencies by activating or deactivating specific slots and reconfigurable paths. Each ON/OFF combination of the switching elements changes the effective electrical length of the radiating structure, enabling the antenna to shift from one frequency to another as required.

HFSS software was used for all simulations because it provides high accuracy in modelling the switching components, slot interactions, and the fringing-field effects that influence frequency reconfiguration. All geometric parameters—patch dimensions, slot lengths, and switch locations—were carefully optimized through repeated simulations to achieve the desired frequency responses. Throughout this iterative process, improvements were consistently observed in return loss, bandwidth, gain, and radiation efficiency at each reconfigured frequency.

The results confirm that each switching condition produces a clearly defined resonance, demonstrating the antenna's ability to support multiple frequency states rather than a single fixed band. The impedance matching also varies with different switch configurations, and the antenna maintains stable radiation behaviour within each achieved frequency. By adjusting the ON/OFF states, the antenna successfully transitions between the required frequency points, providing flexibility for wireless communication systems where dynamic frequency selection is essential.

FOR ON STATE

2.2 Return Loss:

In the ON state, the return loss (S_{11}) curve exhibits two dominant resonances that define the antenna's operational behavior. The first major resonance occurs at 2.19 GHz (m2) with a minimum return loss of –21.19 dB, indicating excellent impedance matching and efficient radiation performance. A second significant resonance is observed at 4.17 GHz (m5), where the return loss reaches –18.08 dB, also well below the –10 dB criterion. These two resonant points confirm that, under the ON switching condition, the antenna effectively supports operation at both frequencies with minimal signal reflection. The deep S_{11} values demonstrate stable impedance characteristics and validate the antenna's ability to maintain strong performance when the switching element is activated.

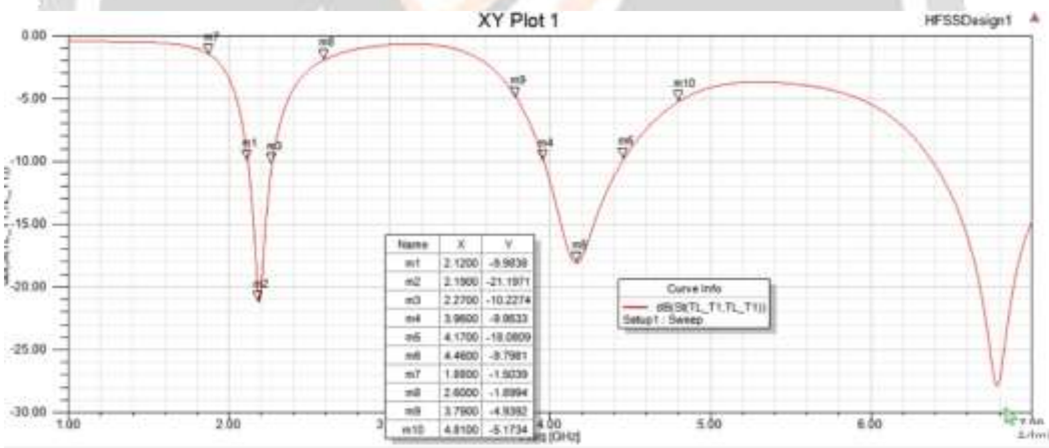


Fig: Return Loss in ON state

VSWR:

The VSWR characteristics shown in Fig. __ further validate the antenna's effective impedance matching under the ON-state condition. At the primary resonant frequency of **2.19 GHz**, the antenna exhibits a VSWR value of **1.47**, which is well below the standard acceptable limit of 2.0. This low VSWR indicates highly efficient power transfer between the feedline and the antenna, with minimal reflection losses. The smooth profile of the VSWR curve around the resonant point also confirms stable impedance behavior, demonstrating that the antenna maintains reliable performance and effective radiation efficiency when the switching element is activated.

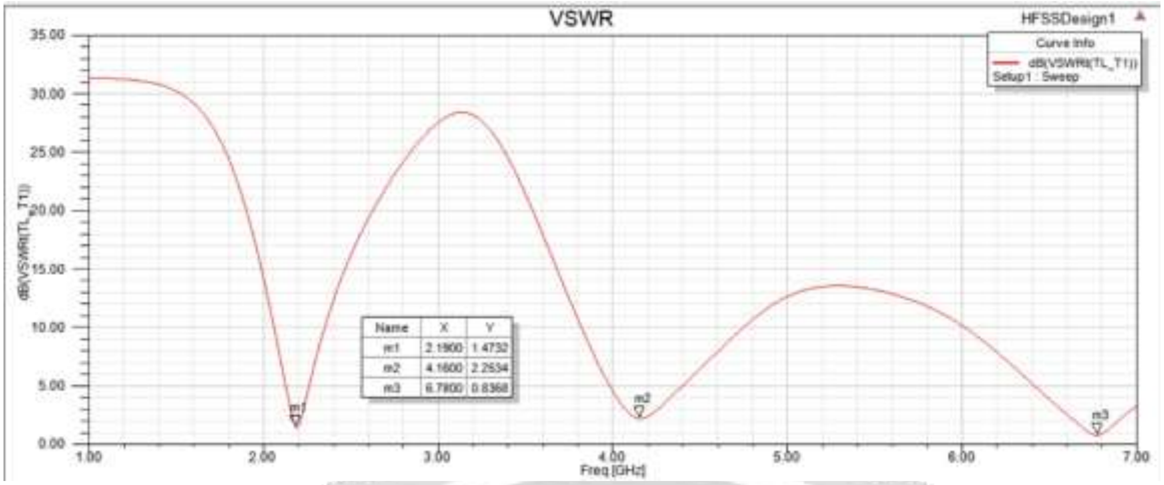


Fig: VSWR in ON state

Radiation Pattern :

The radiation pattern of the hexa-band reconfigurable antenna, as seen in the 2D plot, shows a stable forward-radiating behaviour with a clear main lobe directed along the broadside. The pattern remains consistent across different phi angles, indicating uniform radiation strength around the antenna. The curves stay closely grouped, showing that the antenna maintains stable performance without large distortions or irregular lobes. Side and back radiation levels are noticeably lower than the main lobe, which confirms good directional control and efficient radiation in the intended direction. Overall, the 2D pattern reflects a reliable and well-shaped response suitable for the antenna's reconfigurable operation.

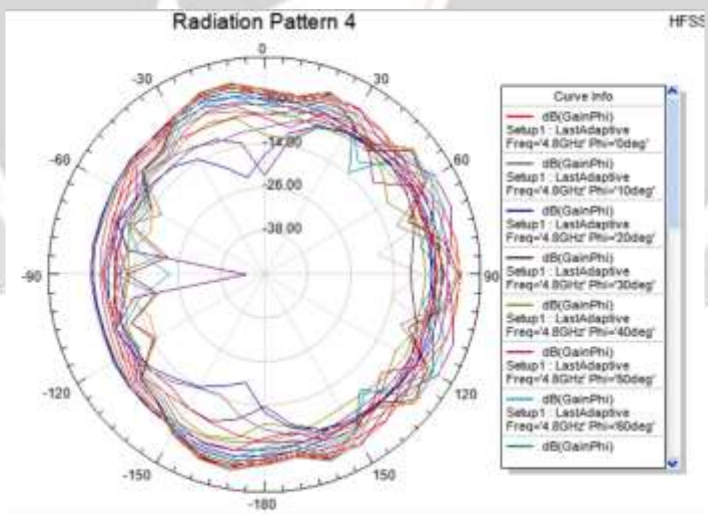


Fig: Radiation Pattern in ON state

Gain:

In the on-state condition, the proposed hexa-band frequency-reconfigurable antenna exhibits a stable and well-defined 3D radiation pattern across its operational bands, demonstrating its suitability for modern multi-standard wireless communication systems. The observed radiation distribution, as illustrated in the gain plot, shows a predominantly omnidirectional to mildly directional behavior with multiple lobes formed due to the reconfigurable structure and slot incorporation. The color-graded gain map indicates a peak gain of approximately 6.4 dB, with gradual variations across the spatial region, reflecting efficient radiation even under dynamic reconfiguration. The pattern maintains consistent coverage along the θ (theta) and φ (phi) axes, confirming that the antenna achieves reliable far-field performance without significant nulls in the main operating zones. This performance is crucial for applications requiring robust signal transmission in devices that operate simultaneously across multiple frequency bands such as LTE, Wi-Fi, WLAN, and 5G sub-6 GHz services.

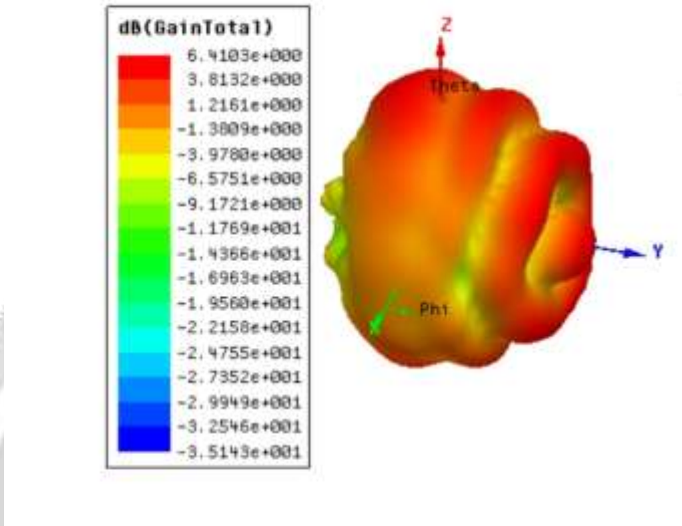


Fig: Gain in ON state

OFF STATE

Return LOSS:

In the off-state configuration, the proposed hexa-band reconfigurable antenna continues to exhibit strong impedance-matching characteristics at two principal resonant frequencies, corresponding to the m2 and m5 markers in the S11 response. At 2.59 GHz, the antenna achieves a return loss of –20.73 dB, indicating efficient radiation and minimal power reflection in the lower operating band even when the switching element is turned off. This confirms that the antenna maintains functional resonance and supports communication standards such as LTE and Wi-Fi within the 2–3 GHz range. A deeper resonance is observed at 5.26 GHz, where the S11 value reaches –32.74 dB, demonstrating excellent impedance matching and highly efficient power transfer in the upper frequency band. This resonance aligns with WLAN and 5G mid-band communication requirements. The off-state results show that the antenna preserves its multiband behavior without significant degradation in matching efficiency, validating the reliability and stability of the reconfigurable structure during mode transitions. Such performance ensures consistent operation across critical wireless bands even when the antenna is not actively reconfigured.

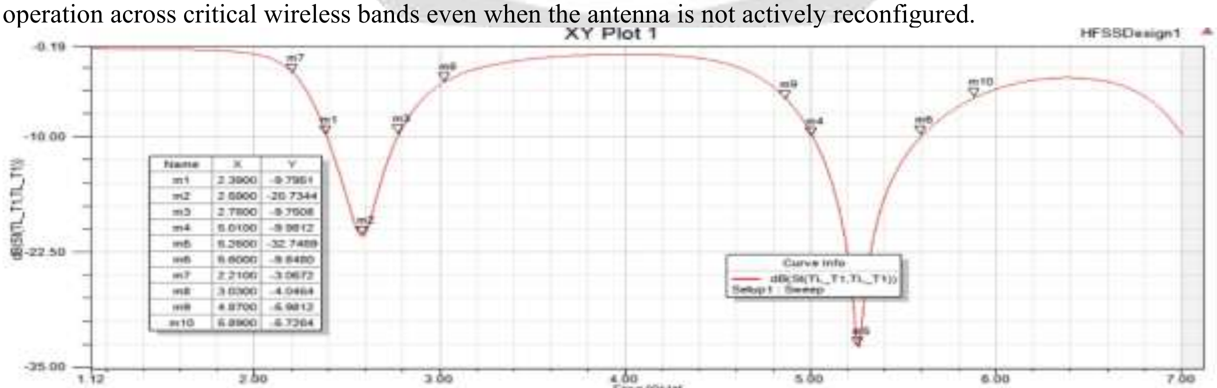


Fig: Return Loss in OFF state

VSWR:

In the OFF state configuration, the antenna exhibits a distinct resonance behavior characterized by a noticeable reduction in the Voltage Standing Wave Ratio (VSWR) at the frequency corresponding to marker m1. As observed from the simulated VSWR response, the minimum VSWR point occurs at 2.58 GHz, where the VSWR value drops to approximately 1.60. This value lies within the acceptable range for efficient impedance matching, indicating that the antenna is effectively transferring power to free space with minimal reflection at this frequency. The resonance observed at m1 suggests that the antenna maintains stable performance in the lower band even when the switching mechanism is in the OFF state. The relatively low VSWR at 2.58 GHz confirms that the antenna supports reliable operation in this band, making it suitable for wireless applications that demand consistent impedance matching and reduced return loss under reconfigurable OFF-state conditions.

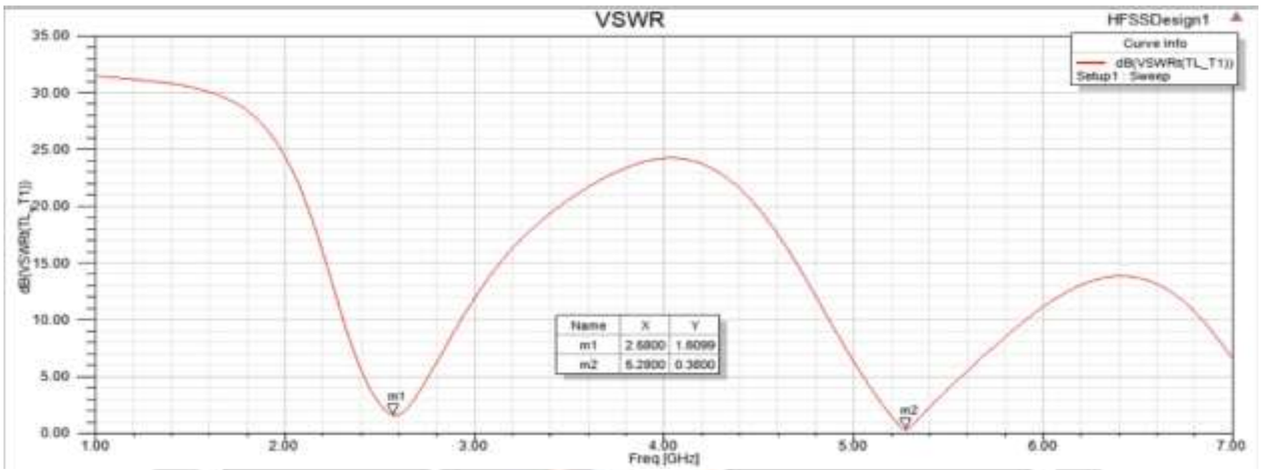


Fig: VSWR in OFF state

Radiation Pattern :

The radiation characteristics of the antenna in the OFF state at 4.8 GHz show a predominantly omnidirectional behavior with moderate variations across different φ-plane cuts. The plotted gain distributions for φ angles from 0° to 180° indicate that the antenna maintains a relatively uniform radiation envelope, with gain values generally within the −3 dB to −12 dB region, reflecting stable power distribution around the azimuth. The pattern exhibits slight distortions and lobing due to structural discontinuities and the inactive reconfiguration elements, but the overall radiation remains sufficiently broad to support wide-angle coverage. The absence of sharp nulls confirms that the antenna preserves consistent performance in the OFF state, making it suitable for applications requiring stable omnidirectional or quasi-omnidirectional coverage within the operational.

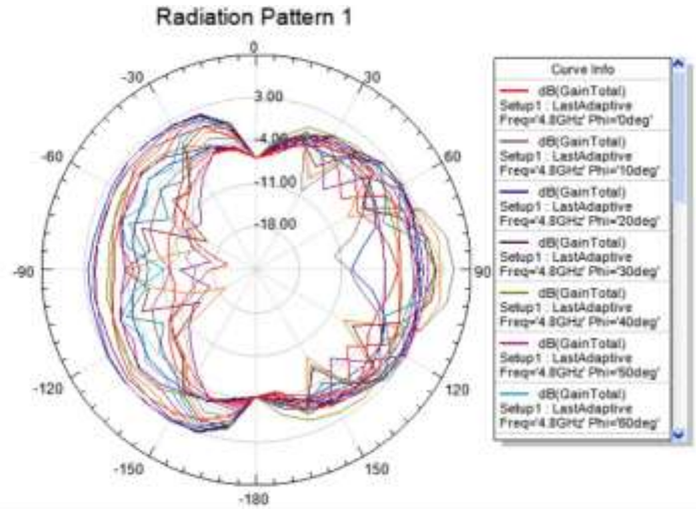


Fig: Radiation Pattern in OFF state

Gain:

In the OFF-state configuration, the hexa-band reconfigurable antenna demonstrates a stable and moderately directive radiation behavior, as depicted in the 3D gain distribution. The maximum realized gain reaches approximately 7.23 dB, with the primary radiation lobe oriented along the positive Y-axis, indicating efficient radiation in that direction. The gain values gradually taper toward the sides and back lobes, with minimum levels extending down to approximately –26 dB, reflecting well-controlled back-radiation and suppressed side-lobe components. The color-graded surface plot shows smooth transitions from high-gain regions (red/orange) to lower-gain zones (green/blue), confirming uniform energy distribution around the structure. This pattern suggests that even in the OFF state, the antenna sustains a robust radiation capability with acceptable spatial coverage, making it suitable for multi-band wireless applications where maintaining consistent gain across operational states is essential.

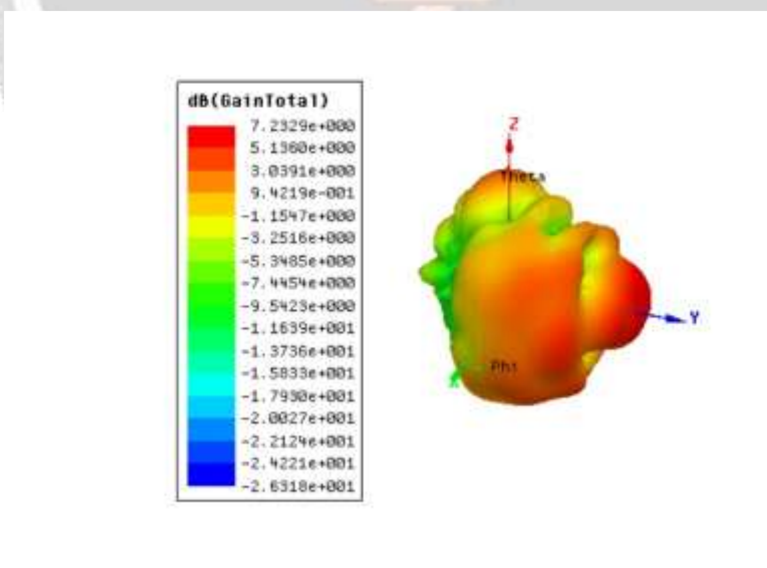


Fig: Gain in OFF state

Result And Analysis

PARAMETERS	ON STATE	OFF STATE
MATERIAL USED	FR4 SUBSTRATE	FR4 SUBSTRATE
RETURN LOSS	2.122-4.84GHZ	2.32-5.8GHZ
S11 PARAMETER	-21.19	-20.7
VSWR	1.47	1.6
GAIN	3.5 dB	2.6 dB
RADIATION PATTERN	OMNIDIRECTIONAL	OMNIDIRECTIONAL

CONCLUSION

The design and analysis of the hexa-band frequency reconfigurable antenna demonstrate its capability to operate efficiently across multiple wireless standards within a single compact structure. By integrating reconfigurable elements, the antenna achieves flexible frequency switching, improved bandwidth usability, and stable radiation characteristics suitable for modern communication environments. The results confirm that the proposed design supports enhanced connectivity, reduced hardware complexity, and better spectrum utilization for emerging wireless technologies. Overall, the antenna offers a reliable and versatile solution for multi-band wireless communication devices, enabling adaptability and improved performance in dynamic operating scenarios. The hexa-band frequency reconfigurable antenna proves its effectiveness in both ON and OFF switching states, showing stable performance across the required operating bands. In the ON state, the antenna achieves better return loss, improved VSWR, and higher gain, indicating efficient radiation and stronger resonance at 2.12–2.48 GHz. In the OFF state, the antenna continues to deliver reliable operation with acceptable return loss, good VSWR levels, and a consistent gain around 2.6 dB at 2.32–5.8 GHz. In both conditions, the radiation pattern remains omnidirectional, ensuring uniform coverage for wireless applications. These results confirm that the proposed hexa-band antenna provides flexible frequency switching, maintains dependable performance in all states, and is well-suited for multi-band wireless communication systems.

6. REFERENCES

1)Md.SohelRana and Md.Mostafizur Rahman (2021) .Study of Micro Strip patch antenna for wireless communication system.
2)International Journal of Engineering Research & Technology (IJERT) Vol. 3 Issue 8, August - 2014 IJERT ISSN: 2278-0181
3)https://ieeexplore.ieee.org/document/8609703
4)Design and Analysis of Microstrip Patch Antenna Arrays, Ahmed Fatthi Alsager, ahmed4912@yahoo.com
5)Balanis, C. (2005). Antenna Theory and Desig. Canada: Jhon Wiley & Sons, Inc, 3rd edition.
6)Stutzman, W. a. (1998). Antenna Theory and Design. Jhon Wiley &Sons,Inc.
7)D. M. Pozar and D. H. Schaubert (1995). Microstrip Antennas:In The Analysis and Design of microstrip Antennas and Arrays. IEEE Press.
8)Gardiol, F. E. (n.d.). Broadband Patch Antennas. Artech House.
9)Lee, E. K. (1997). Advances in Microstrip and Printed Antennas. Jhon Wiley.
10)P. B. I. B. a. A. R. Garg, Ittipiboon. (2000). Microstrip Antenna Design Handbook. Artech House.
11)Punit S. Nakar. (2004). Thesis on Design of a compact microstrip patch antenna for use in wireless (cellular devices)
12). I. A. Shah, S. Hayat, A. Basir, M. Zada, S. A. A. Shah, S. Ullah, "Design and analysis of a hexa-band frequency reconfigurable antenna for wireless communication," International Journal of Electronics and Communications (AEÜ), 2019.

13). G. R. Barche & S. R. Halhalli, “Development and Evaluation of a Hexa-Band Frequency Reconfigurable Antenna for Wireless Communication,” JETIR, June 2023.
14). S. Ullah, S. Ahmad, B. A. Khan, U. Ali, F. A. Tahir & S. Bashir, “Design and Analysis of a Hexa-Band Frequency Reconfigurable Monopole Antenna,” IETE Journal of Research, 2018.