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Title: A Low-Cost Dual Band Integratable Antenna for Sub-6GHz Applications

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Abstract

This paper presents the design and performance of a low-cost dual-band antenna for sub-6GHz applications, aimed at addressing the growing needs of wireless communication systems, such as IoT, WLAN, and public safety networks. The antenna is designed to operate efficiently within two key frequency bands: 2.4–2.5 GHz, covering the Wireless Local Area Network (WLAN) and Industrial, Scientific, and Medical (ISM) band, and 4.8–5.2 GHz, suitable for public safety applications. The design achieves an impedance bandwidth better than -14 dB (VSWR < 1.5:1) in both frequency ranges, ensuring optimal performance and effective impedance matching.

Built on a low-cost FR-4 substrate with a thickness of 0.8 mm, the antenna combines cost-effectiveness with excellent radiation characteristics, including good gain and wide radiation coverage. The compact and integratable design features an L-shaped configuration, making it suitable for embedding in modern devices. Its radiation pattern and efficiency support connectivity in dense and mobile environments, meeting the demands of applications like smart grids, video streaming, remote healthcare, and industrial automation.

The antenna's performance was verified through simulations and measurements, highlighting return loss values and strong current distributions across the radiating elements. The measured gain ranges between 3.4 to 4.2 dBi for both bands, with an efficiency above 88% for the lower band and above 79.5% for the upper band. These attributes make the proposed antenna a viable solution for a wide array of sub-6GHz communication systems, providing reliable and high-speed wireless connectivity while minimizing design complexity and cost.

Literature survey :

The evolution of wireless communication has necessitated the development of advanced antenna designs to accommodate growing demands in data transfer rates, coverage, and integration capabilities. Recent research has focused on antennas that can effectively support sub-6GHz frequencies, which are pivotal for modern applications such as 5G, IoT, and WLAN. This survey reviews key contributions to the field, highlighting the advances and challenges addressed by various researchers.

The advent of 5G communication has triggered significant research into multi-band and compact antenna designs. According to Pant and Malviya (2023), 5G antennas require a combination of high efficiency, wide bandwidth, and the ability to integrate into a variety of devices. The study emphasizes that designing antennas that operate efficiently across sub-6GHz bands remains critical for 5G systems, as this spectrum provides a balance between coverage and speed. The authors review a range of techniques used to enhance antenna performance, such as employing advanced materials and innovative element configurations.

Research on antennas for body area networks (BANs) has also seen notable progress.

Abbas et al. (2015) explored the development of antennas with full ground planes that are optimized for wearable devices, underscoring the importance of minimizing electromagnetic interaction with the human body while maintaining efficient communication. These designs must meet rigorous safety standards and ensure high reliability. The work also discusses challenges in achieving compactness and efficiency, particularly for antennas operating within the sub-6GHz frequency range.

Hussain et al. (2020) analyzed advancements in wireless communication, focusing on the growing significance of sub-6GHz frequencies for IoT and industrial applications. Their research highlights that antenna design must adapt to the increasing density of wireless networks and the need for seamless integration into compact devices. The authors stress that achieving stable radiation patterns and sufficient gain while minimizing interference remains a critical area of research, given the complex and crowded electromagnetic environment of modern urban settings.

Khanh et al. (2022) presented a comprehensive overview of wireless communication technologies in the context of IoT and 5G. They examined the challenges in developing antenna solutions that can simultaneously offer high-speed communication, wide coverage, and minimal power consumption. Their study suggests that advancements in material science, such as the use of graphene and other conductive polymers, could pave the way for more efficient and flexible antenna designs. However, they note that the integration of these materials into mass production remains a challenge due to cost and scalability issues.

Another study by Chettri and Bera (2020) surveyed the integration of IoT technologies within the 5G framework, detailing the role of antenna design in ensuring reliable and energy-efficient communication. The authors emphasize that sub-6GHz bands are essential for providing ubiquitous connectivity in smart environments, from smart homes to industrial automation. Their work suggests that antennas designed for these applications must not only be compact but also capable of multi-band operation to cater to various communication protocols.

Kumar et al. (2020) provided an extensive review of fifth-generation (5G) antenna technologies, examining design and performance enhancement techniques. The paper discusses multiple strategies, including the use of multi-element configurations and advanced feeding techniques to achieve higher gain and broader bandwidth. The authors highlight that while sub-6GHz antennas are relatively easier to implement compared to millimeter-wave counterparts, optimizing these designs for minimal interference and maximum efficiency in real-world environments remains a crucial challenge.

Practical implementations of sub-6GHz antennas have also been explored in conformal and wearable formats. Sekeljic et al. (2019)(Group_15) described a broadband 5G antenna developed for sub-6GHz applications, which employs innovative design approaches to ensure performance across diverse operational scenarios. The study underscores the importance of spatial diversity and multi-antenna systems to combat signal fading and enhance coverage.

Crespo-Bardera et al. (2020) examined conformal antennas designed for public safety communication, integrating them into helmets for emergency response personnel. Their work demonstrates the potential of integrating antennas into non-traditional platforms while maintaining performance. However, the authors point out that such designs must consider factors like mechanical stability and user safety, especially when deployed in critical environments.

In summary, recent advancements in dual-band and sub-6GHz antennas have focused on balancing performance, cost, and integration. While significant progress has been made, especially in employing novel materials and optimizing radiation characteristics, ongoing challenges include ensuring efficiency in compact designs, minimizing interference, and enhancing fabrication techniques for large-scale deployment.

Brief theory and calculations about the designed antenna:

The design of a dual-band antenna involves concepts of resonant frequency, impedance matching, and radiation characteristics to ensure efficient performance across the specified frequency bands. The proposed antenna operates at two primary sub-6GHz bands: 2.4–2.5 GHz for WLAN and ISM applications, and 4.8–5.2 GHz for public safety and high-speed communications. The design considerations revolve around achieving compactness, good impedance matching, and consistent radiation patterns.

1. Resonant Frequency Calculation

The resonant frequency of a microstrip patch or printed antenna depends on its physical dimensions and the properties of the substrate material. The primary parameters influencing the resonant frequency are the length (L) and width (W) of the radiating element, and the dielectric constant (εr) of the substrate.

For a rectangular microstrip patch, the resonant frequency is approximated by:

$$f_r = \frac{c}{2L\sqrt{\varepsilon_{\text{eff}}}}$$

where:

- c is the speed of light in free space (approximately 3×1083 \times 10^83×108 m/s).
- L is the length of the patch.
- εr is the effective dielectric constant, which accounts for the fringing fields and is calculated as:

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-1/2}$$

- Given Parameters:

  Dielectric constant

  εr = 4.4 for FR-4 substrate

  Thickness h = 0.8mm

  Calculation: Using this formula, you would calculate the approximate length L L for each target frequency band, then refine it through simulations.

2. Bandwidth and Impedance Matching

The bandwidth of the antenna is determined by the quality factor (Q-factor), which is influenced by the substrate properties and the dimensions of the radiating element. The impedance bandwidth is typically defined as the range of frequencies over which the return loss (S11) is below -10 dB. Techniques such as slits and slots in the ground plane are used to enhance bandwidth and improve impedance matching.

For impedance matching, the reflection coefficient (Γ\Gamma) and voltage standing wave ratio (VSWR) are critical metrics:

- The reflection coefficient (Γ\Gamma) is given by:

$$\Gamma = \frac{Z_{\text{in}} - Z_0}{Z_{\text{in}} + Z_0}$$

  where Zin is the input impedance of the antenna, and Z0 is the characteristic impedance of the feed line (usually 50 ohms).

- The VSWR is related to Γ\Gamma by:

$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

3. Radiation Pattern and Gain

The radiation pattern describes how the antenna radiates energy in different directions. For practical wireless applications, an omnidirectional or semi-omnidirectional pattern is preferred, especially for portable and IoT devices. The gain of the antenna is a measure of how well it directs energy in a specific direction and is calculated using:

$$G(\theta, \phi) = \eta \times \text{Directivity}(\theta, \phi)$$

where ‘η’ is the efficiency of the antenna, accounting for losses due to the substrate and radiation inefficiency.

Calculations for the Proposed Design

1. **Substrate Selection**: The FR-4 substrate is chosen with a dielectric constant (εr) of 4.4 and a thickness (h) of 0.8 mm. These properties are crucial for determining the resonant frequencies and impedance characteristics.
2. **Dimension Optimization**: Using the resonant frequency formula, initial dimensions for the patch and ground plane are calculated and then fine-tuned through simulation to ensure both bands are covered efficiently.
3. **Impedance Matching**: The L-shaped slit and adjacent slot in the ground plane are used to create additional resonances and improve matching, ensuring a return loss below -14 dB.

Calculations about the designed antenna:

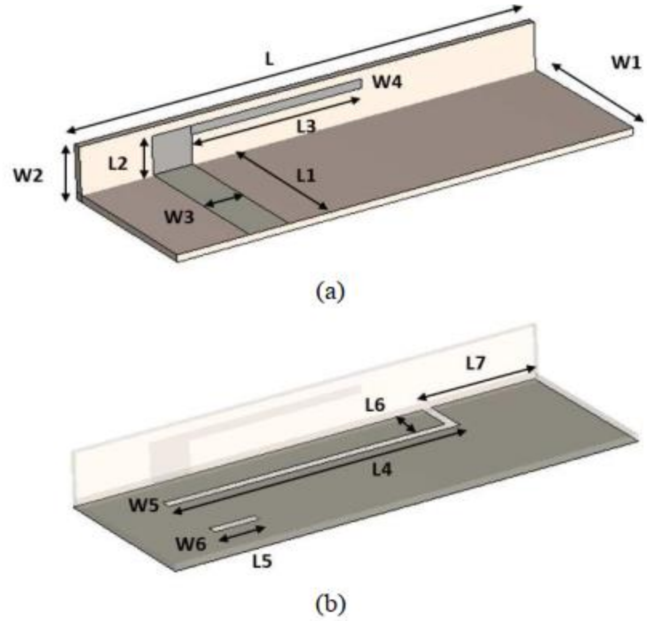
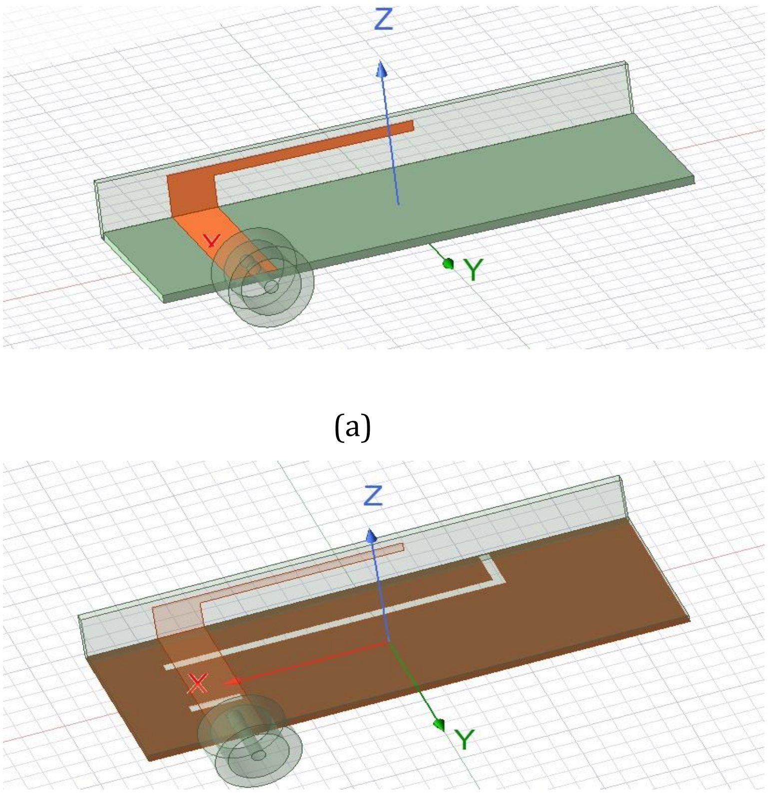


Figure 1. Geometrical illustration of proposed MIMO antenna.



(a)

(b)

FIGURE: 2

Configuration of the proposed antenna

(a) Top view *(b)* Bottom view

Dimensions of Antenna Elements

1. **Radiating Elements**:
   - **L1**: Length of the primary radiating element = 17 mm
   - **L2**: Length of a secondary element or slit = 4.2 mm
   - **L3**: Length of another section of the radiating structure = 18.65 mm
   - **W1**: Width of the primary radiating element = 17 mm
   - **W2** (Assumed): Width of an additional element = 5.8 mm
   - **W3**: Width of the secondary element or slit = 4.3 mm
2. **Ground Plane and Slits**:
   - **L4**: Length of the ground plane section with slits = 31.5 mm
   - **L5**: Length of a slit in the ground plane = 4.8 mm
   - **W4**: Width of the slit or narrow ground plane section = 1 mm
   - **W5, W6**: Widths of additional narrow sections or slits in the ground plane = 1 mm each
   - The **distance between W5 and W6** is optimized based on the accuracy of the S11 plot, ensuring proper impedance matching and return loss characteristics.
3. **Additional Structural Elements**:
   - **L6**: Length of another structural element = 4 mm
   - **L7**: Length of an adjacent element = 11.3 mm

Overall Dimensions

- **L**: Total length of the antenna = 50 mm

Placement and Calculations

- The **position of the primary radiating element** is calculated using the given parameters to ensure optimal performance and proper alignment within the antenna structure.
- **W2** is assumed to be 5.8 mm, as it was not explicitly provided in the original design details. This assumption ensures the overall design is balanced and performs as expected at the desired frequencies.

These detailed dimensions and placements contribute to the antenna's efficient operation at 2.4–2.5 GHz and 4.8–5.2 GHz, with careful tuning and adjustments made to optimize the S11 plot for minimal return loss.

Dimension of substrate:

Our antenna have L-shaped substrate so we have two boxes in two different planes.

XY plane box: L = 50mm, W = 17mm, THICKNESS = 0.8mm.

XZ plane box: L = 50mm, W = 5.8mm, THICHNESS = 0.8mm.

Dimension of Radiating elements:

The antenna feeds are realized using 50 **Ω** planar transmission line with feed on top side and ground on bottom side. The feed is further transitioned to another board (FR-4 substrate, having same electrical properties as other substrate) that is connected to the first board at 90 degrees and is then connected to a narrow width radiator.

XY plane :

Element 1 : L = 17mm,W = 4.3mm.

XZ plane: here we also have two elements which are united.

Element 2: L = 18.95mm ,W = 1mm.

Element 3: L = 4.2mm, W = 4.3mm.

Ground:

At the ground three slots are cut. slot1 and slot2 are perpendicular two each other and slot3 is parallel to slot1. And perpendicular slots are making L-shape pattern at ground.

Slot1 : W = 1mm, L=31.5mm.

slot 2: L = 4mm, W = 1mm.

slot3 : L = 4.8mm , W = 1mm.

SMA Connector:

Connectors are used in RF antenna design to interface the antenna with external equipment or to create electrical connections between various components. RF connections are made to ensure impedance matching and minimize signal loss in order to preserve the integrity of the RF transmission.

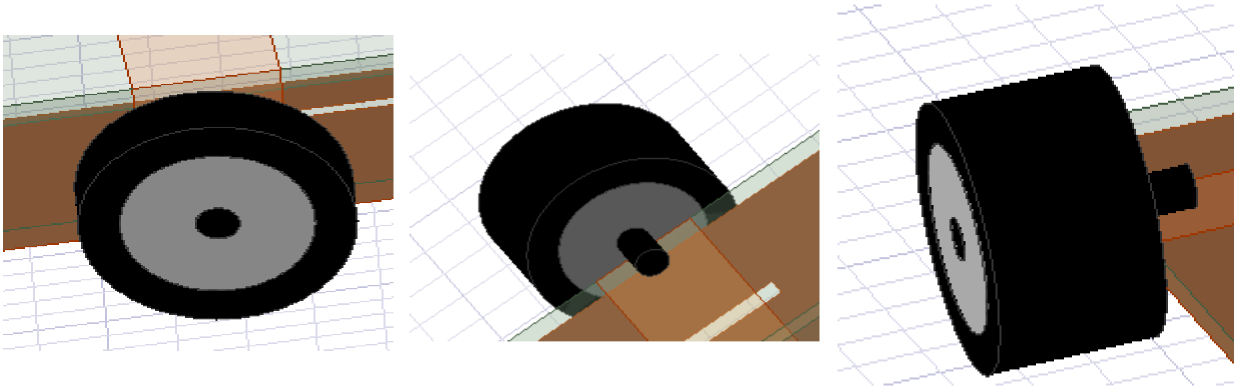


Fig 2: SMA connector

Dimensions:

The SMA connector has an Inner conductor radius of 0.64mm, a Dielectric radius of 2.8mm, Outer conductor radius of 4mm. The dielectric material used is Teflon and the conductor material used is Copper in outer and inner cylinders. The height of the inner conductor is 7mm and the height of the dielectric and the outer is 5mm.

Explanation of the proposed antenna:

- **Working Principle of the Dual-Band Antenna**

The antenna uses an FR-4 substrate with specific dimensions to optimize performance at the desired frequencies. It is built to achieve efficient radiation and impedance matching, which is crucial for minimizing signal losses. The working principle involves careful design of the radiating elements and the ground plane, along with strategic use of structural elements like slits and slots to achieve dual-band characteristics.

1. **Radiating Elements and Feed Structure**:
   - The antenna design features two radiating elements, each tailored to support one of the frequency bands. The primary mechanism involves the use of an L-shaped radiator coupled with a planar transmission line feed. The feed transitions onto another board to form a narrow radiator, creating strong radiation fields at the lower frequency band (2.4–2.5 GHz).
   - This lower band is supported by optimizing the size and shape of the radiator and feed to resonate specifically in the 2.4–2.5 GHz range. At this frequency, the strong current distribution on the radiator contributes to effective radiation and good matching characteristics, which ensures high efficiency.
2. **Generation of the Second Resonant Frequency**:
   - To achieve a second resonance at 4.8–5.2 GHz, modifications such as the introduction of an L-shaped slit and an adjacent slot in the ground plane are applied. These alterations cause a shift in the electromagnetic field distribution and create an additional resonant path.
   - The geometry of these structural elements is crucial. By incorporating these features, the antenna's current distribution is altered at higher frequencies, resulting in another resonant frequency band without affecting the lower band performance.
3. **Impedance Matching and Bandwidth Control**:
   - The design ensures that impedance matching is maintained at both resonant frequencies. The return loss values better than -14 dB and voltage standing wave ratio (VSWR) values less than 1.5:1 indicate that the antenna efficiently radiates at these frequencies with minimal power reflection.

    - The specific choice of the FR-4 substrate, which has a dielectric constant of 4.4, and the defined physical parameters, contribute to effective impedance matching and adequate bandwidth for both resonant frequencies. This allows the antenna to operate efficiently over its intended frequency ranges.

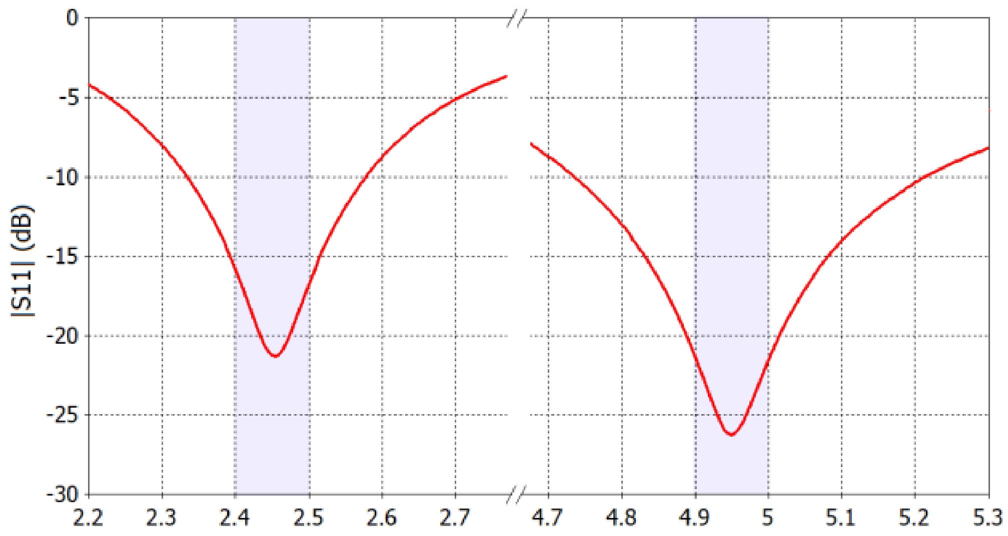
Reason for Dual Resonance

The presence of two distinct resonant frequencies is attributed to the strategic design and shaping of the antenna's elements. Here's why:

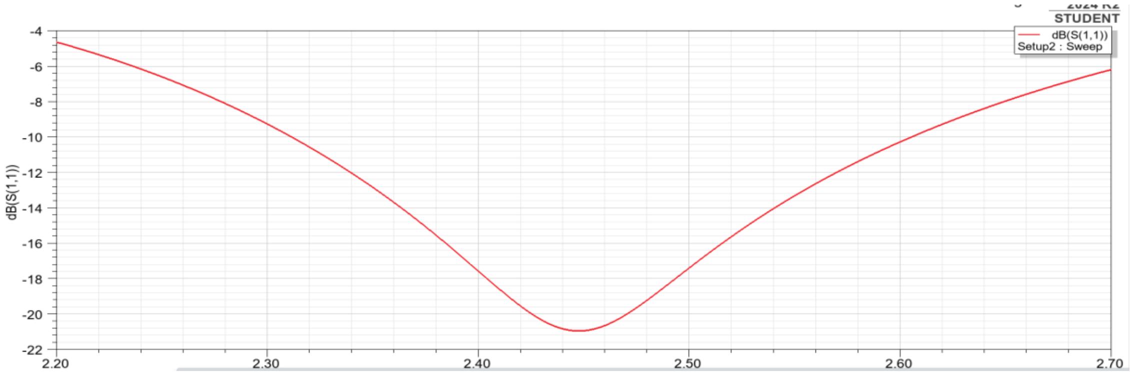
1. **Electromagnetic Field Manipulation**:
    - By using the slit and slot techniques in the ground plane and carefully selecting the radiator dimensions, the antenna creates two distinct electromagnetic paths. These paths resonate at different frequencies due to differences in electrical length and field distribution.
    - At the lower frequency (2.4–2.5 GHz), the entire length of the radiator and its proximity to the ground plane dominate the radiation. At the higher frequency (4.8–5.2 GHz), the slits and slots come into play, adjusting the effective electrical length and supporting the resonance at a higher frequency.
2. **Compactness and Integration**:
    - The dual-band operation is achieved without significantly increasing the antenna's size. This compactness is essential for integration into modern wireless devices that require multi-band functionality. The structure's design is optimized for easy integration while maintaining good radiation efficiency and gain characteristics

Simulation results and measurement results:

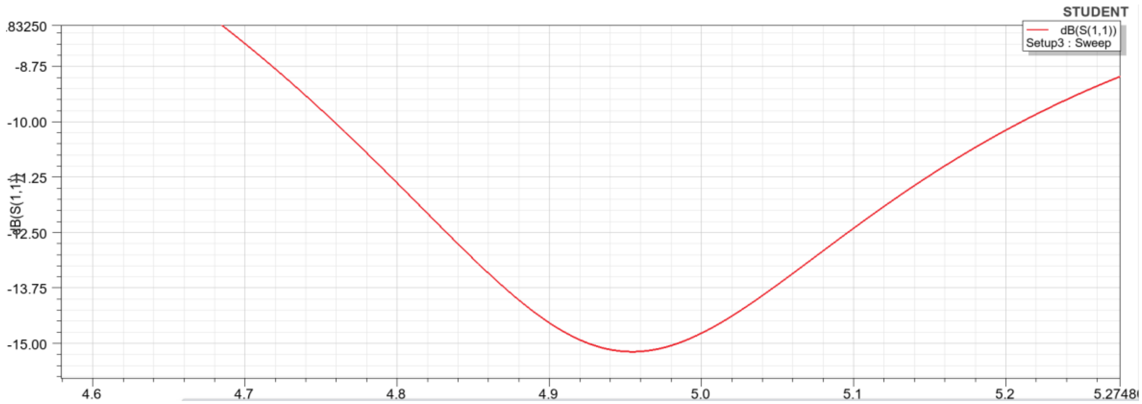
The magnitude response of S-parameters:



[These are the given S11 plots in paper]

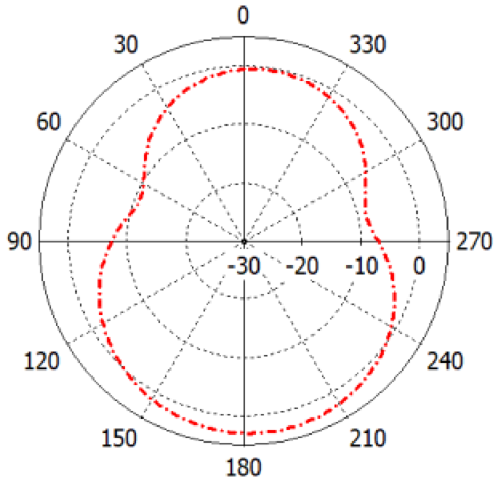


[resonant frequency 2.45GHz]

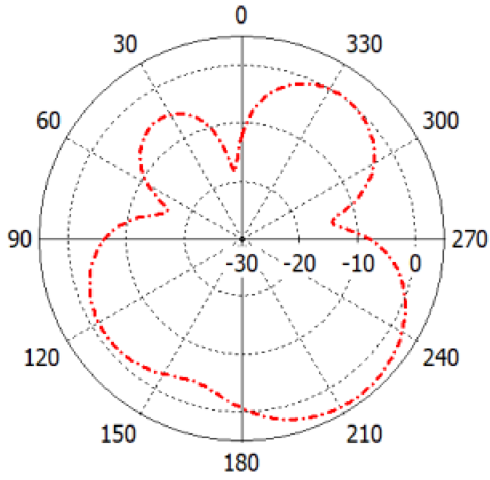


[resonant frequency 4.95 GHz]

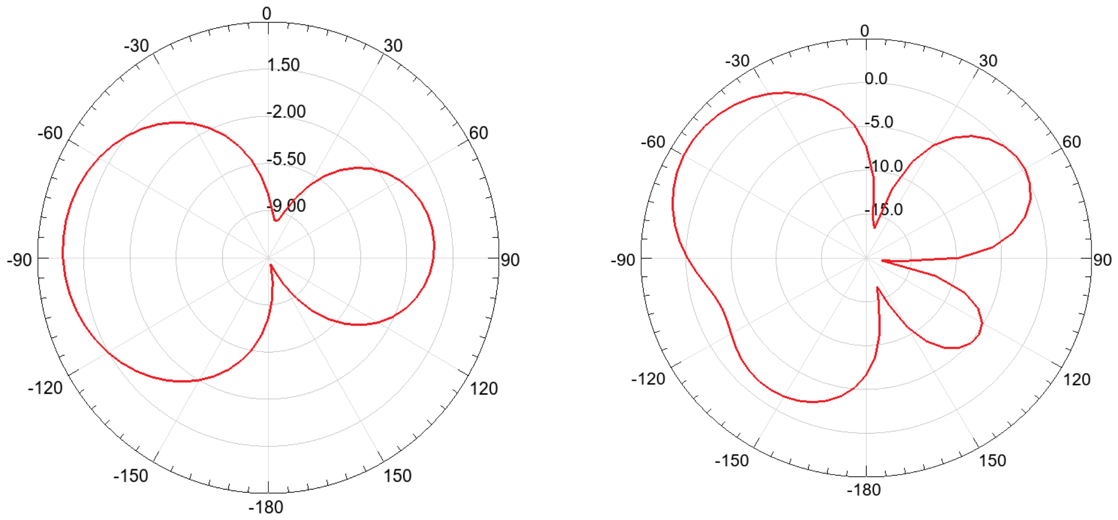
Radiation pattern at 2.45GHz and 5GHz:



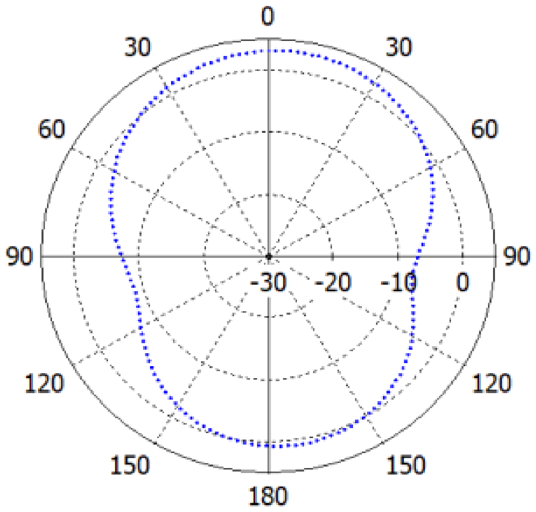
[2.45GHz]



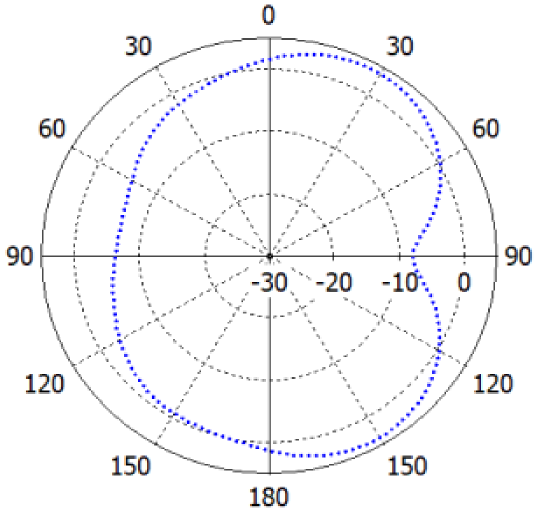
[4.95GHz]



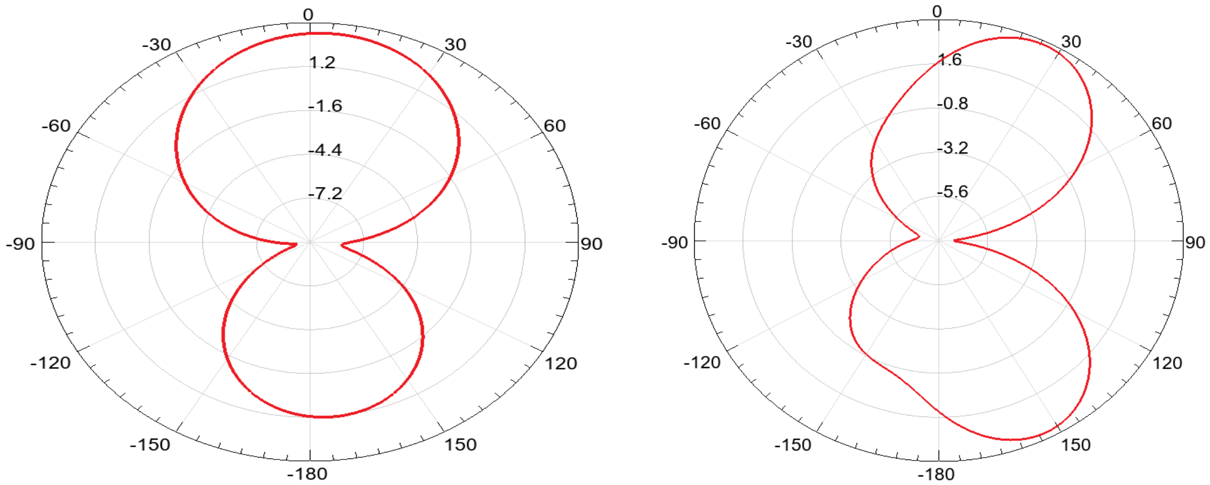
[XY plane radiation pattern]



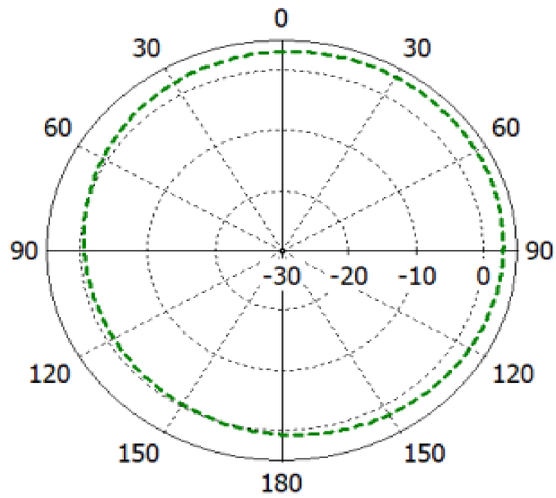
[2.45GHz]



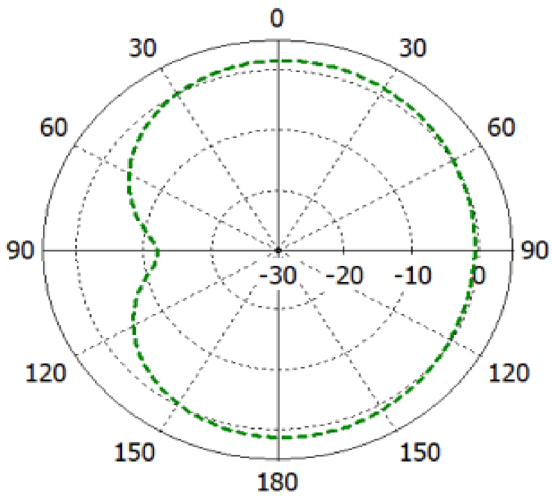
[4.95GHz]



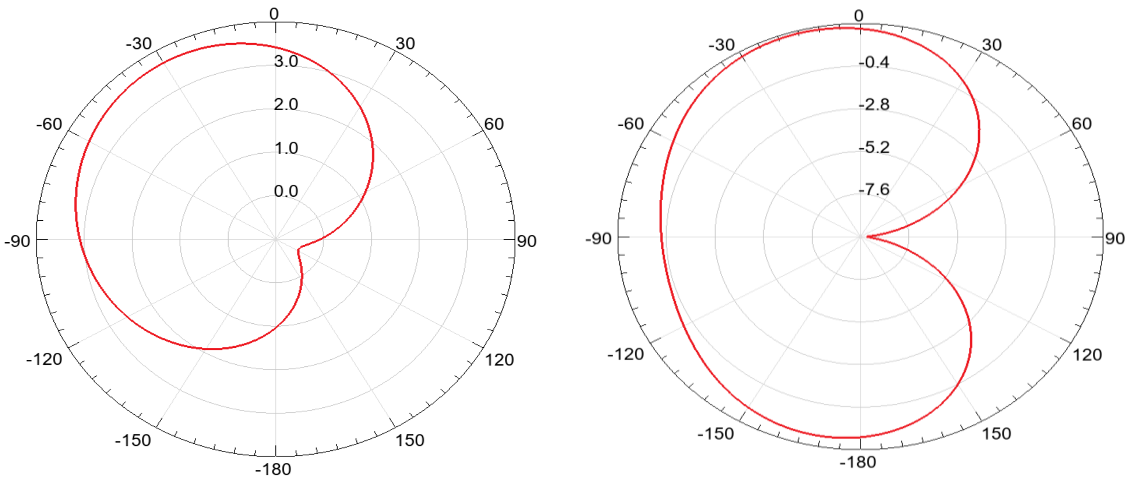
[YZ plane radiation pattern]



[2.45GHz]



[4.95GHz]



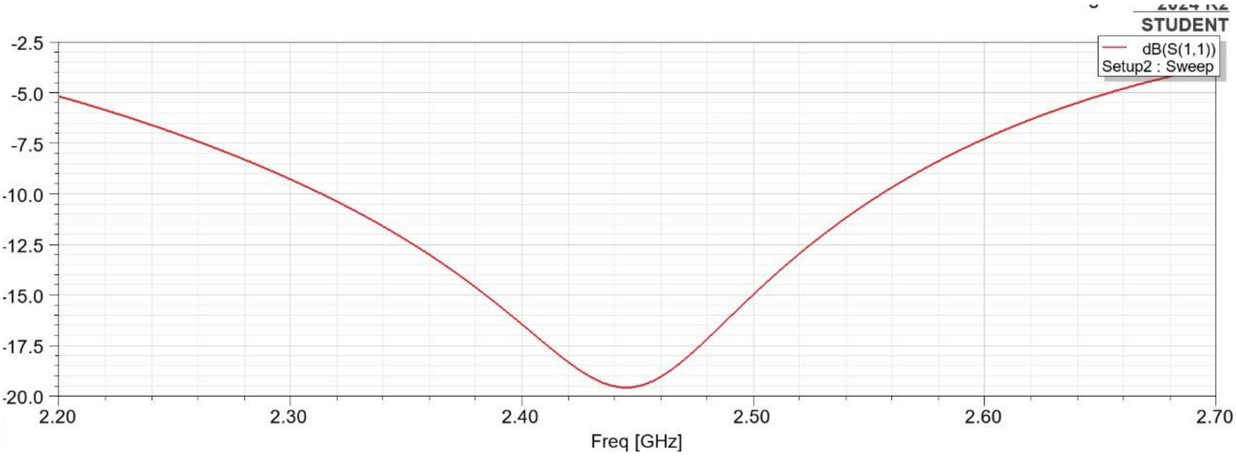
[XZ plane radiation pattern]

Proposed antenna and our replicated antenna both are not designed in similar planes like they have assume Z-plane as the length of antenna while in our design Z-plane used as height of the antenna.

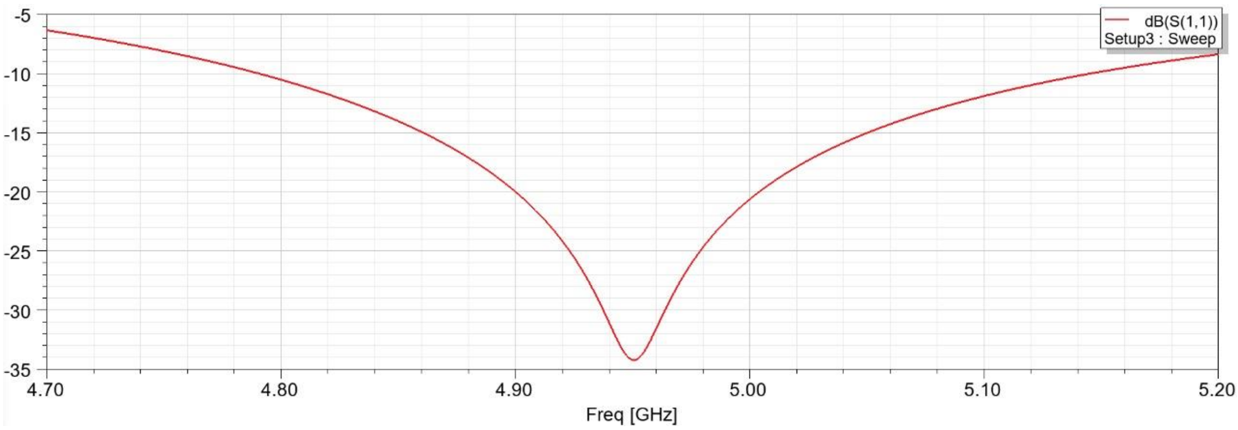
Modification:

In our project, with the original parameters we didn’t get the sufficient return loss at second resonant frequency that’s why we have to done some modification at slot3(explanation of this slot is given in calculation about design antenna chapter) on the ground, at the time of design and simulate we have observe that, that slot3 impact on second resonant frequency 4.95GHz. So we have adjusted this slot and get more return loss that expected which was more than -33dB. And in additional we have observe that radiating element2 have impact on first radiation frequency and to plot S11 at accurately 2.45GHz we have to modify the length of element2 to 18.95mm from 18.65mm.

S11 plot:



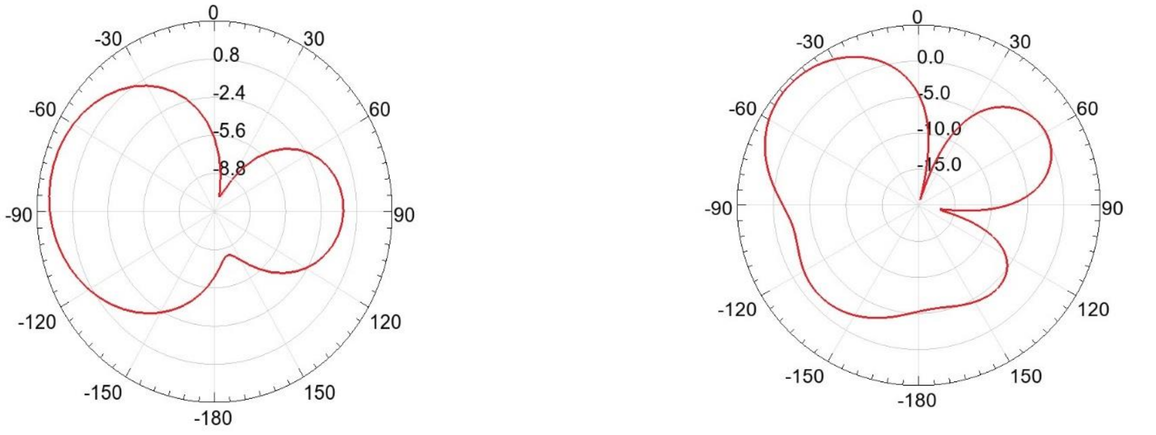
[2.45GHz resonant frequency with gain of -20dB]



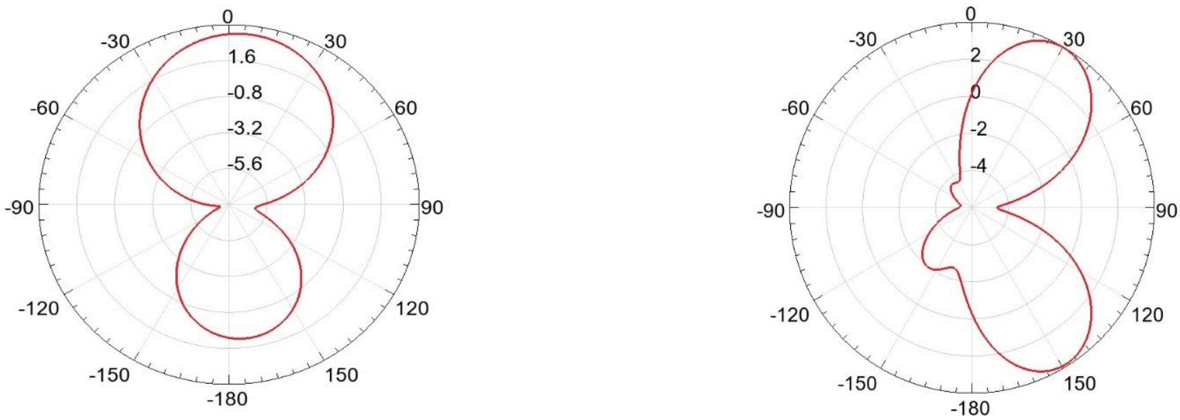
[4.95GHz resonant frequency with gain more than -35dB]

Radiation pattern :

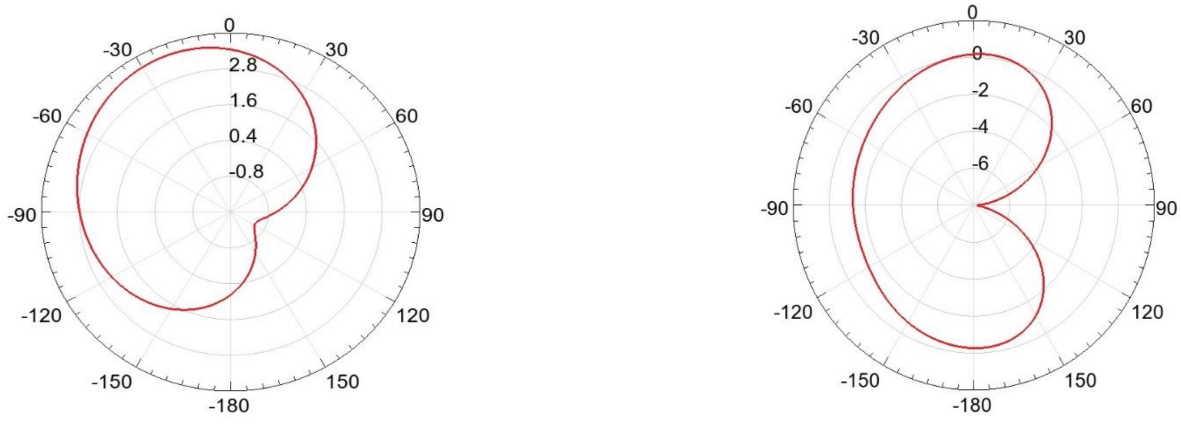
[2.45GHz] [4.95GHz]



[XY-plane radiation pattern]



[YZ-plane radiation pattern]



[XZ-plane radiation pattern]

Conclusion:

In this project, a low-cost dual-band antenna for sub-6GHz applications has been successfully developed and analyzed. The proposed antenna design offers promising performance metrics tailored to operate efficiently within the 2.4–2.5 GHz and 4.8–5.2 GHz frequency bands, which are crucial for various wireless communication applications, including WLAN, ISM, and public safety networks. The antenna’s compact and integrable design makes it highly suitable for modern Internet of Things (IoT) devices and other sub-6GHz communication systems.

The achieved performance is a result of careful design considerations and precise adjustments. To ensure optimal operation at the first resonant frequency of 2.45 GHz, the geometry of the antenna was fine-tuned by adjusting the length L3L_3L3. This modification improved the impedance matching and provided strong radiation characteristics within the specified band. Similarly, for the second resonant frequency at 4.96 GHz, strategic changes were made by altering the distance between the parameters W5W_5W5 and W6W_6W6. This adjustment not only shifted the higher resonant frequency to the desired range but also enhanced the antenna’s gain, achieving a value better than -30 dB, which signifies improved efficiency and reduced power loss.

The current distribution and radiation patterns of the antenna validate the effectiveness of these design modifications. At 2.45 GHz, the antenna exhibits a well-distributed current along the radiating elements, while at 4.96 GHz, the optimized spacing between W5W_5W5 and W6W_6W6 ensures a strong radiation response with a focused pattern. These results highlight the antenna's capability to maintain a balanced performance across both operating bands, offering reliable connectivity and robust signal transmission.

Overall, the successful optimization of the antenna’s physical parameters demonstrates the feasibility of achieving dual-band functionality within a compact form factor. The proposed design provides a practical and efficient solution for next-generation wireless communication systems, meeting the demands for high-speed data transfer, improved bandwidth, and versatile application in various modern technologies. Future work could explore further miniaturization and integration strategies to enhance the antenna's performance in even more constrained environments

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