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Design and Performance Analysis of Hexagonal MIMO Antenna and Dual Band Notched MIMO Antenna for Microwave and Millimeter Wave Communications

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Abstract: Microwave antennas play a crucial role in satellite communication and radar systems, while millimeter-wave antennas are indispensable for advancing high-speed telecommunications and radar technologies, especially with the emergence of 5G networks. This research focuses on the development and evaluation of two distinct Multiple Input Multiple Output (MIMO) antennas tailored for Ultra-Wideband (UWB) and millimeter-wave network applications using High Frequency Solution Setup (HFSS) software. The Hexagonal MIMO antenna, measuring 40 x 36 x 1.6 mm^3, and the Dual Band Notched MIMO antenna, measuring 35 x 23 x 1.6 mm^3 both utilize double-port MIMO technology and operate at frequencies of 7.5 GHz and 30 GHz. Performance parameters including Gain, Directivity, Radiation Efficiency, Return loss, Reflection Coefficient, and Beam Area are examined, with a comparative analysis conducted at both frequencies. The findings reveal the consistent superiority of the Dual Band Notched MIMO antenna, exhibiting higher gain and directivity across both frequencies. Specifically, at 7.5 GHz, gains of 24.97 dB and 33.17 dB, directivities of 6.05 dB and 5.10 dB, radiation efficiencies of 18.9 dB and 28.07 dB, beam areas of 4.94 sq. deg and 5.89 sq. deg, reflection coefficients below -12 dB, and return loss values exceeding 12 dB are observed for the Hexagonal and Dual Band antennas, respectively, while at 30 GHz, gains are 32.49 dB and 24.92 dB, directivities are 6.79 dB and 7.9 dB, radiation efficiencies are 16.41 dB and 24.57 dB, beam areas are 4.20 sq. deg and 3.07 sq. deg, and reflection coefficients and return loss values show similar trends for Dual Band and Hexagonal antennas, respectively. This study provides valuable insights for optimizing MIMO antenna designs to enhance performance in UWB and millimeter-wave network applications.

Index Terms: Dual Band Antenna, Hexagonal Antenna, High Frequency Solution Setup(HFSS) Software, MIMO Antennas, Ultra-Wide Band, Millimeter Wave Networks

1. Introduction

Antennas developed for Ultra-Wideband (UWB) applications and Millimeter-wave (mm Wave) technology in 5G networks serve distinct roles within modern wireless communication. UWB antennas operate across a wide frequency spectrum, enabling high-speed data transfer without requiring extensive tuning. Their compact and discreet design makes them ideal for integration into portable electronic devices, ensuring adaptability across various applications. Additionally, their omnidirectional radiation pattern provides consistent signal coverage in diverse environments. On the other hand, mm Wave antennas in 5G networks focus on enhancing signal strength and mitigating propagation losses. By utilizing narrow beamforming, these antennas efficiently direct energy, reducing interference and maximizing network efficiency. Techniques such as phased arrays and large-scale MIMO configurations further enhance signal directionality, capacity, and performance, making both UWB and mm Wave antennas critical to the advancement of wireless communication systems.

MIMO antennas [1] are fundamental to modern wireless networks, leveraging spatial diversity to increase data throughput, improve reliability, and expand system capacity. By facilitating multiple simultaneous data streams within the same frequency band, MIMO technology meets the growing demand for high-speed connectivity and robust network performance. Whether used in UWB systems or 5G mm Wave networks, MIMO antennas are instrumental in optimizing spectral efficiency and addressing propagation challenges [2,3]. Their ability to enhance communication links through spatial multiplexing and interference suppression makes them indispensable in next-generation wireless technologies.

Hexagonal Multiple-Input Multiple-Output (MIMO) antennas [4] introduce an advanced design approach, featuring a hexagonal array structure that improves spatial coverage, minimizes interference, and enhances signal stability. These benefits make them particularly effective in high-data-rate applications, such as 5G networks and UWB communication systems [5,6]. The improved performance and adaptability of hexagonal MIMO antennas position them as promising solutions for future wireless communication networks.

Dual Band Notched antennas [7] are designed to efficiently function across two distinct frequency bands while suppressing interference from unwanted signals. By incorporating notch structures at specific frequencies, these antennas filter out interference while maintaining optimal performance in their intended operating bands. They are widely used in various wireless communication systems [8], particularly where interference reduction is crucial, including multi-functional devices such as smartphones and network routers. With their ability to support multiple frequency bands and selectively filter signals, Dual Band Notched antennas improve connectivity and optimize communication performance across different environments [9].

Although significant progress has been made in designing and evaluating Hexagonal MIMO and Dual Band Notched antennas for UWB and 5G networks through HFSS simulations [10,11], there remains a need for comparative analysis in real-world conditions. While this study focuses on the performance of the Dual Band Notched antenna in terms of gain and radiation efficiency across different frequencies, its behavior under varying environmental factors and deployment conditions requires further investigation. Additional research is essential to evaluate the reliability and robustness of these antennas in practical UWB and 5G applications. Moreover, exploring optimization techniques to enhance their efficiency can provide valuable insights for future antenna design. Addressing these gaps will contribute to a more comprehensive understanding of the performance and practical implementation of Hexagonal MIMO and Dual Band Notched antennas, supporting informed decisions for advanced wireless communication systems [12,13].

This study introduces structural improvements in Hexagonal MIMO and Dual Band Notched antennas to enhance impedance matching, radiation efficiency, and gain. Compared to traditional designs, the proposed antennas incorporate optimized slot arrangements, advanced feeding techniques, and refined geometric configurations to achieve superior performance. These enhancements improve signal transmission and reception while maintaining compactness. By addressing design limitations and integrating targeted optimizations, this research provides valuable insights into antenna design and its application in UWB and 5G communication systems.

The research aims to achieve the following objectives:

1. Develop 2×2 Hexagonal and 2×2 Dual Band Notched MIMO antennas optimized for UWB and mm Wave applications at 7.5 GHz and 30 GHz using simulation-based analysis.
2. Evaluate and compare key performance parameters, including gain, directivity, efficiency, and impedance matching, to determine their suitability for wireless communication systems.
3. Analyze the effects of structural modifications on antenna performance and identify potential challenges for real-world deployment.

2. Literature Review

The study of hexagonal-shaped and dual-band notched MIMO antennas has become highly significant due to their wide-ranging applications in contemporary communication systems like WLAN, WiMAX, LTE, and 5G. Research highlights the advancements in their design and performance, emphasizing their practical advantages.

Abdulhussein et al. (2023) [14] investigated the design and analysis of hexagonal-shaped antennas with multi-band capabilities suited for WLAN, WiMAX, and LTE applications. Their findings highlighted that the hexagonal design provides a compact size and enhanced multi-directional radiation patterns, making it effective across various wireless communication standards. The study emphasized the antenna's efficiency in operating across multiple frequency bands, contributing to its versatility in contemporary wireless systems. Singh et al. (2022) [15] introduced a hexagonal microstrip patch antenna optimized for ultra-wideband (UWB) applications. Their research focused on refining the hexagonal shape to achieve wideband performance while maintaining a compact form factor. This design demonstrated improved bandwidth and gain, proving to be a viable choice for UWB communication systems.

In another research, Singh et al. (2022) [16] examined a hexagonal slot-loaded antenna for ISM band applications. Their study highlighted the antenna's effective performance in the ISM band, achieved through slot-loading techniques that enhance impedance matching and bandwidth. This design is particularly suitable for industrial, scientific, and medical (ISM) frequency applications. Rana (2018) [17] explored the design and fabrication of hexagonal antennas for various wireless applications. The research underscored the benefits of hexagonal geometries, such as compactness and consistent performance. It also discussed fabrication techniques that enhance the antenna's reliability and effectiveness.

Keshri et al. (2022) [18] introduced a compact UWB MIMO antenna equipped with dual-band notch filters designed to mitigate interference from specific frequency bands while preserving broad-band performance. This design enhances the antenna's effectiveness in complex frequency environments. Likewise, el Omari el Bakali et al. (2021) [19] developed a dual-band notch UWB MIMO antenna for 5G and Wi-Fi 6E applications using a hybrid method. Their integration of notch filters helps to suppress interference from neighboring frequency bands, thereby improving signal quality and overall system performance. Nan et al. (2021) [20] studied a UWB-MIMO antenna with dual-band notched features, focusing on the efficiency of notch filters in blocking unwanted frequencies while maintaining the desired bandwidth. This design proves particularly useful for high-frequency applications where effective interference management is crucial. Additionally, Lu et al. (2023) [21] designed a miniaturized UWB MIMO antenna with dual-band notch capabilities, noting its compact form and effective interference suppression. This design is ideal for advanced communication systems requiring high-performance and efficient interference control.

Recent advancements in hexagonal and dual-band notched MIMO antennas highlight an increasing emphasis on improving performance for microwave and millimeter-wave applications. Researchers are exploring hybrid designs, new materials, and optimization techniques to address the latest challenges in communication systems. Enhanced filtering methods and miniaturization efforts are driving improvements in antenna efficiency, bandwidth, and interference management. These developments are paving the way for more efficient, adaptable, and high-performance antennas, suited for a broad range of modern communication needs, from WLAN and LTE to 5G.

3. Antenna Design

Designing Hexagonal 2X2 MIMO and Dual Band Notch 2X2 MIMO antennas in HFSS involves several essential stages. For Hexagonal MIMO antennas [22], this includes defining the operational frequency bands, creating individual antenna elements, arranging them in a hexagonal array layout, and refining the design to enhance performance metrics such as mutual coupling and spatial diversity. Similarly, in Dual Band Notch MIMO antenna design [23], comparable steps are followed, with an added emphasis on integrating notch filtering components to eliminate unwanted frequencies within each band. Both designs necessitate establishing simulation environments, conducting electromagnetic simulations, and iteratively adjusting the designs to meet the criteria for MIMO communication. Throughout this process, HFSS offers the necessary tools and features to assess antenna performance and ensure optimal functionality in real-world scenarios.

3.1 Hexagonal 2X2 MIMO Antenna Design and Geometry

The hexagonal MIMO antenna is specifically engineered for use in the microwave and millimeter-wave frequency ranges, aiming to provide a dual-band response suitable for a variety of applications. This design utilizes a hexagonal configuration, incorporating dimensions and slots that enable accurate tuning of the resonant frequencies and bandwidth. The hexagonal MIMO antenna comprises a hexagonal patch element mounted on a substrate. It includes two symmetrical arms of varying lengths to support dual-band functionality, allowing it to resonate at distinct frequencies.

Designing a hexagonal patch antenna entails several essential formulas and parameters that are influenced by the design objectives, such as the operating frequency, substrate material, and intended radiation pattern. The general design process involves the following steps and calculations:

A substrate material with an appropriate relative permittivity ($\boldsymbol{\varepsilon_r}$) is selected to match the operating frequencies. For example, FR4, with a relative permittivity of 4.4, is widely used due to its availability and mechanical stability. The effective dielectric constant (ε_{eff}) plays a significant role in determining the antenna's propagation characteristics by considering the combined influence of the dielectric substrate and the surrounding air. It is computed using the substrate's dielectric constant ($\boldsymbol{\varepsilon_r}$) and height (h), as defined in Eq. (1):

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}(1+12\frac{h}{s})^{\frac{-1}{2}} \quad (1)$$

Where,

S is the side length of the hexagon,

h is the height of substrate,

ε_r is the relative permittivity

The side length of the hexagonal patch (s) is a crucial design factor, as it determines the antenna's resonant frequency. It is derived using Eq. (2), which links the side length to the resonant frequency ($\boldsymbol{f_r}$) and the effective dielectric constant (ε_{eff}):

$$S = \frac{C}{2 f_r \sqrt{\varepsilon_{eff}}} \tag{2}$$

Where,
C is Velocity of light,
f_r is the resonant frequency,
ε_{eff} is the effective dielectric constant

This equation ensures that the patch is designed to resonate at the target frequency by appropriately selecting its dimensions.

Another important parameter influencing the radiation characteristics of the antenna is the effective radius R, which can be approximated using the side length(s) as given in Eq. (3):

$$R = s \text{ x } \sqrt{\frac{2}{3}} \tag{3}$$

Where,
S is side length of Hexagonal Patch

This relationship simplifies certain analytical calculations by approximating the hexagonal patch with an equivalent circular structure.

Ensuring proper impedance matching is essential for efficient power transfer between the antenna and the feedline, minimizing reflection losses. The characteristic impedance (Z_0) is generally set to 50 ohms, and matching is achieved by adjusting the feed position or employing additional matching networks.

The substrate dimensions must be sufficient to accommodate the hexagonal patches and their spacing. When two hexagonal patches are arranged side by side, the substrate width should be large enough to include both patches and the spacing between them, as determined by Eq. (4):

$$W_{sub} = 2 . (2s) + a \tag{4}$$

Where,
s is hexagon side length
a is horizontal spacing between two hexagonal patches

Similarly, the substrate length should be sufficient to fit the height of the hexagons along with any additional vertical spacing. The hexagon height(h) is calculated using Eq. (5):

$$h = 2 . s . \sqrt{3} \tag{5}$$

After calculating the height h, the length of the substrate can be determined. If additional vertical spacing (v) between rows or patches is needed, it should be added to the calculated height. The corresponding formula is given by Eq. 6 as:

$$L_{sub} = h + v \tag{6}$$

Where,
v is the vertical spacing between two patches

The values obtained from these equations define the physical dimensions of the hexagonal antenna, ensuring that it is optimized for the intended frequency bands while maintaining structural stability and efficient radiation performance. The specific dimensions used in the design are summarized in Table 1.

Table 1. Design parameters of Hexagonal MIMO antenna

Component	**Dimensions(mm)**
Width of the ground plane	15
Length of the ground plane	36
Hexagon side	6
Feed length	16.6
Width of feed	3
Length of the substrate	36
Width of the substrate	40
Radius of hexagonal patch	5
Internal slot Width	3
Height of substrate	1.6

The hexagonal antenna design in HFSS is defined by specific dimensions aimed at achieving optimal performance [24,25]. The antenna structure has dimensions of 40mm in length, 36mm in width, and 1.6mm in height, striking a balance between compactness and effectiveness as shown in Fig. 1. With a hexagon side size of 6mm, the antenna adopts a unique geometric layout. Moreover, the ground beneath the substrate is critical, featuring a length of 15mm and a width matching the antenna's width at 36mm as shown in Fig. 2. These precise specifications are tailored to attain the desired antenna characteristics within the HFSS tool, considering both geometric intricacies and substrate-related parameters.

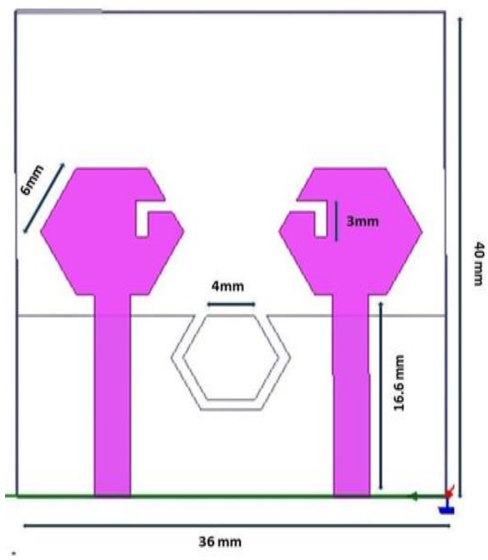


Fig. 1. Hexagonal Antenna: Front view

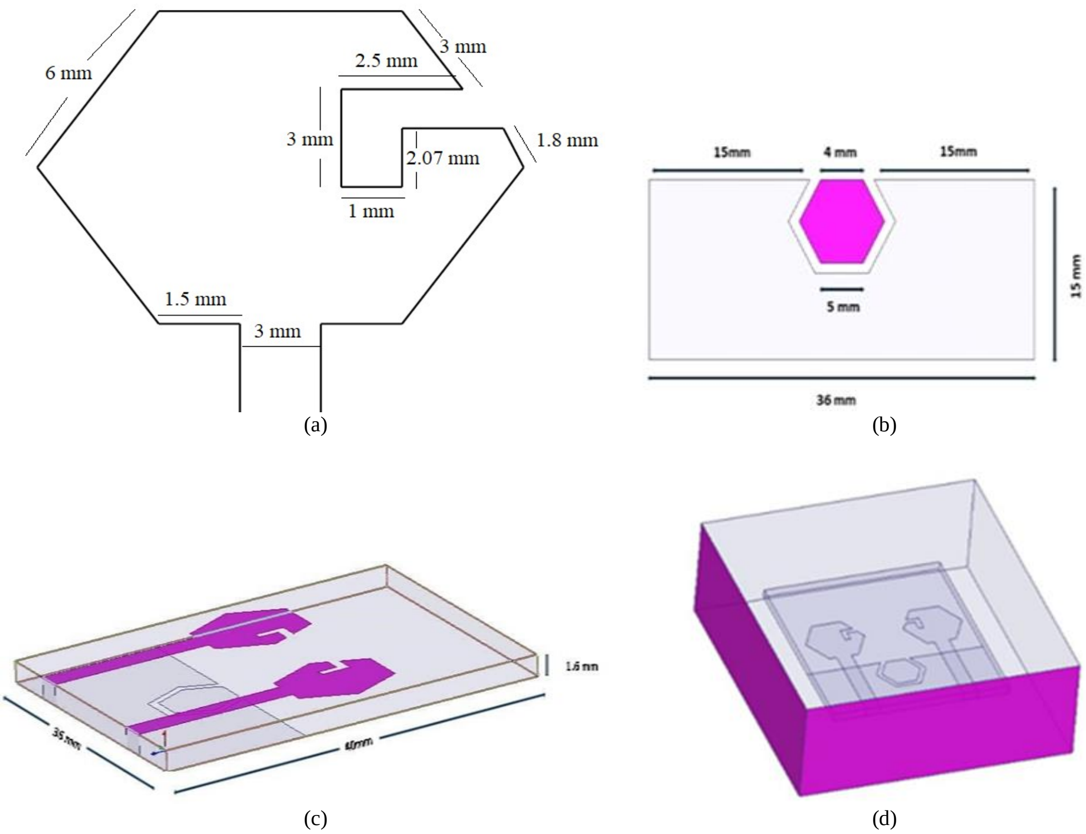


Fig. 2. (a). Hexagonal shape dimension (b). Ground for Hexagonal antenna (c). Designed Hexagonal Antenna (d). Antenna Radiation box

To facilitate practical implementation, an additional element is incorporated into the design: a radiation box surrounding the entire structure. This radiation box acts as a protective and controlling environment for the antenna, ensuring that emitted radiation is confined within a specified space.

3.2 Dual Band Notched 2X2 MIMO Antenna Design

The design of the dual-band notched antenna [26,27] includes precise dimensions, with the antenna structure measuring 23mm in length, 35mm in width, and 1.6mm in height. The ground width matches the antenna's width at 35mm. Integration of two patch antennas enables dual-band functionality. To ensure controlled testing and analysis, the entire antenna structure is encased within a radiation box. This addition of a radiation box confines emitted radiation within a specified area, enabling a controlled assessment of the dual-band notched antenna's performance and characteristics.

Designing a dual-band patch antenna involves defining the patch dimensions to resonate at two different frequencies. These dimensions are influenced by the chosen frequencies and the properties of the dielectric substrate. The following steps outline the design process:

Step-1: Determine the two operational frequencies for the antenna, labeled as f_1 and f_2.

Step-2: The effective dielectric constant(ε_{eff}) is derived from the substrate's relative permittivity (ε_r) and the patch's dimensions. It can be estimated by using equation 1.

Step-3: The length and width of the patch antenna in a dual-band notch antenna are calculated using Eq.7 and Eq.8, respectively.

$$W_p = \frac{c}{2f_r\sqrt{\frac{\varepsilon_r+1}{2}}} \quad (7)$$

Where,
f_r is the resonant frequency,
ε_r is the substrate's relative permittivity

$$L_p = \frac{C}{2f_r\sqrt{\varepsilon_{eff}}} - 2\,\Delta L \quad (8)$$

Where,
ε_{eff} is the effective dielectric constant,
ΔL is the extension in length due to the fringing effect

The patch length and width in a dual-band notch antenna are crucial for defining its resonant properties. Since the width influences radiation conductance and impedance bandwidth, fine-tuning may be necessary to optimize the antenna's performance for dual-band operation.

The extension in length due to the fringing effect, which can be calculated using Eq. 9 given as:

$$\Delta L = 0.412h\left(\frac{\varepsilon_{eff} + 0.3}{\varepsilon_{eff} - 0.258}\right)\left(\frac{W + 0.264h}{W + 0.8h}\right) \quad (9)$$

Where,
h is the height of substrate, w is the width of the patch

The fringing effect, results from electromagnetic fields extending beyond the patch edges. This phenomenon significantly impacts the resonant frequency and depends on both the patch width and substrate height.

Adjustments to the width might be necessary to fine-tune the design for dual-band operation. The width of the substrate must be large enough to fit the width of the patch plus any additional spacing (a). The width of the substrate(W_{sub}) can be determined using Eq. 10 as:

$$W_{sub} = W_p + a \quad (10)$$

Where,
W_p is width of the patch
a is any additional spacing

The length of the substrate must be adequate to accommodate both the length of the patch and any vertical spacing (v). The length of the substrate L_{sub} can be calculated by Eq. 11 as:

$$L_{sub} = L_p + v \quad (11)$$

Where,
L_p is length of the patch

Step-4: To optimize for dual-band performance, consider incorporating extra slots or extensions into the patch to generate multiple resonant frequencies and using detailed patch designs or layered structures to effectively support both frequency bands.

The values required for designing a dual-band notch antenna are detailed in Table 2. This table provides essential parameters and design specifications needed to achieve the desired dual-band functionality. It includes values such as, dimensions of the patch and slots, and other critical design metrics.

Table 2. Design parameters of Dual Band Notched MIMO antenna

Component	Dimensions(mm)
Length of the ground plane	35
Width of ground plane	6.3
Width of patch	14
Length of patch	9
Width of feed	1
Feed length	8.8
Width of slot(a)	0.5
Length of slot(a)	2.8
Width of slot(b)	1.3
Length of slot(b)	7.7
Width of slot(c)	0.3
Length of slot(c)	8
Width of slot(d)	0.4
Length of slot(d)	9.4
Length of the substrate	35
Width of substrate 23	

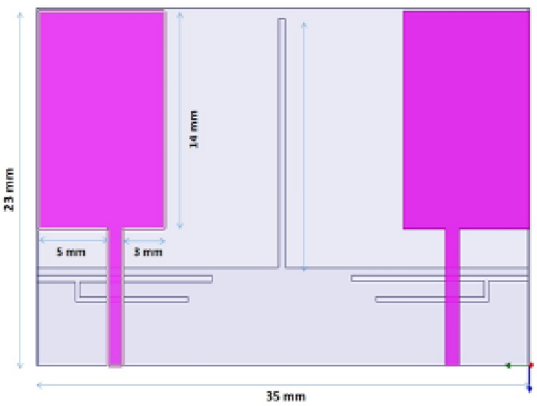


Fig. 3. Dual Band Notched Antenna: Front View

The dual-band notched antenna has been designed with the dimensions detailed in Table 2. These specific dimensions have been carefully selected to achieve the desired dual-band performance and notched characteristics. The corresponding designed antennas, which reflect these dimensions, are illustrated in Fig. 3 and 4. These figures provide visual representations of the antenna designs, showcasing the structural layout and the integration of the notched features essential for dual-band operation.

3.3 Simulated Antenna Parameters

The simulated antenna parameters for the Hexagonal 2X2 MIMO [28-30] antenna and the Dual Band Notch 2X2 MIMO antenna [31-34] designs are outlined as follows:

Operating frequency: It denotes the range of frequencies within which the antenna efficiently transmits and receives signals. Ensuring alignment between antenna design and system requirements is crucial. In this case, the operating frequency ranges from 7.5GHz to 30GHz.

The frequencies of 7.5 GHz and 30 GHz were selected as they correspond to important communication bands in modern wireless systems. The 7.5 GHz frequency is within the Ultra-Wideband (UWB) range, commonly used for high-speed, short-range applications such as radar and imaging. On the other hand, 30 GHz is part of the millimeter-wave (mm Wave) spectrum, which plays a key role in 5G networks due to its ability to support high-capacity and low-latency communications. These frequencies were chosen to evaluate the antenna's performance in different use cases, ensuring its relevance for both UWB and 5G applications.

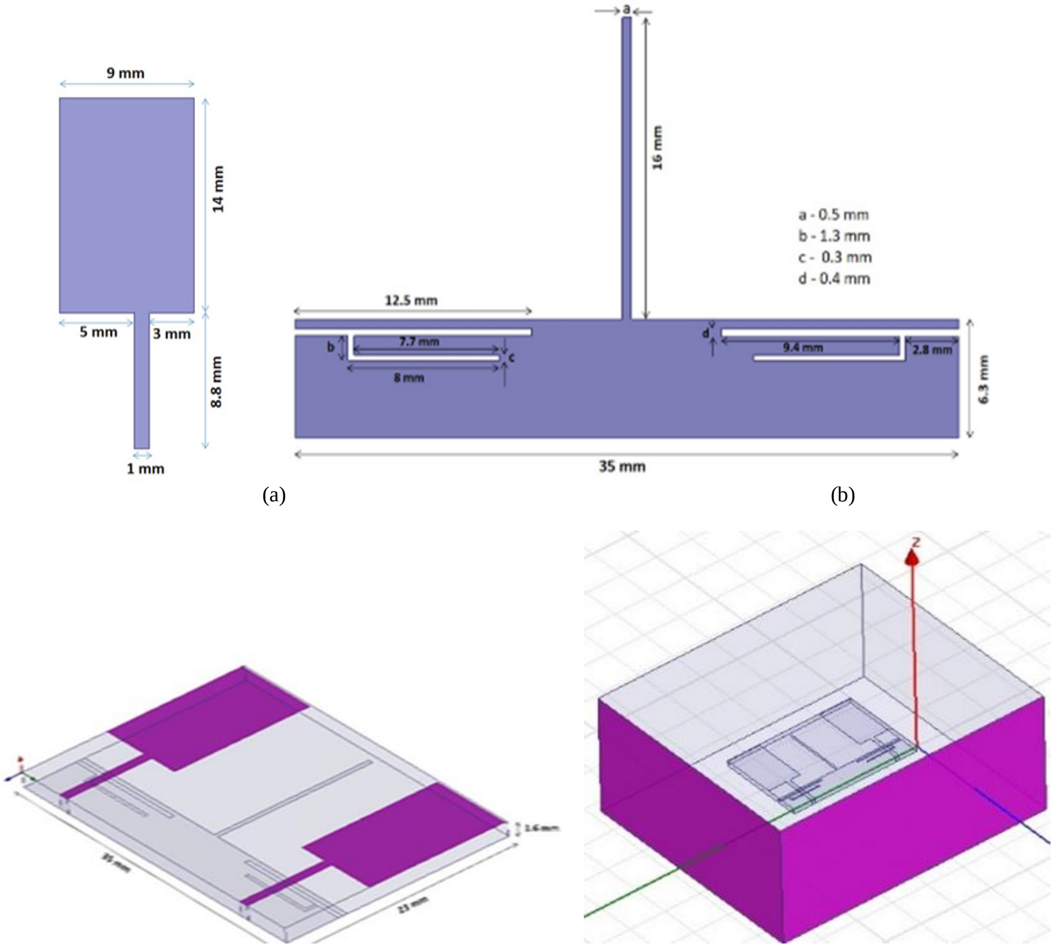


Fig. 4. (a). Patch dimensions of Dual Band Notched antenna (b). Dual band Notched antenna ground (c). Designed Dual Band Notched antenna (d). Antenna Radiation box

Antenna Gain and Directivity: Gain measures how effectively an antenna concentrates electromagnetic energy compared to an isotropic radiator, factoring in losses. Directivity assesses the antenna's ability to focus electromagnetic energy in a specific direction without considering losses. The difference lies in gain accounting for losses, while directivity does not, thus offer an idealized measure of antenna performance. High gain and high directivity are typically preferred attributes for antennas as they play pivotal roles in enhancing communication effectiveness and dependability.

Radiation Efficiency: Radiation efficiency measures how well an antenna converts supplied power into radiated electromagnetic energy, excluding losses. It represents the ratio of emitted power to total input power, reflecting the antenna's effectiveness in converting input power into useful radiation. Higher efficiency indicates more effective power conversion, while lower efficiency suggests greater losses within the antenna system. Assessing radiation efficiency is essential for evaluating antenna performance, directly affecting its ability to transmit or receive signals efficiently.

Beam area: The beam area of an antenna defines where most of its radiated electromagnetic energy is concentrated and represents the coverage area defined by its primary radiation pattern. A condensed beam area implies concentrated radiation, while a broader area suggests wider signal coverage. Understanding beam area is critical in antenna design as it influences the antenna's range and spatial signal distribution. It plays a pivotal role in determining antenna performance, with a larger beam area indicating broader signal coverage and improved communication range and reliability, suitable for applications requiring extensive coverage. Conversely, a smaller beam area may be preferred for precise communication, offering higher gain and signal strength in specific directions. Ultimately, the choice of beam area depends on specific application requirements such as coverage area, communication range, and interference considerations.

Scattering Parameters(S-Parameters): In microwave antenna design, S-parameters characterize the propagation of RF signals within a network, measuring the fraction of the input signal that is transmitted or reflected at various ports. Among these, s_{11} is widely used in antenna analysis as it represents the reflection coefficient at the input port, while s_{22} indicates the reflection at the second port. These parameters play a crucial role in assessing impedance matching and determining the overall performance of the antenna.

Reflection coefficient: In the realm of antenna design, the reflection coefficient finds expression through S-parameters. Γ_1 , the reflection coefficient, corresponds to s_{11} , an S-parameter signifying the reflection coefficient observed at the antenna's input port. This representation facilitates a direct evaluation of the antenna's interaction with the transmission line or free space, as well as its impedance matching with the surrounding medium, usually determined via experimental measurement or simulation. The antenna design under consideration features two ports, resulting in the presence of two reflection coefficients, as outlined below.

Reflection coefficient at Port 1 represented as Γ_1 given as $\Gamma_1 = s_{11}$
Reflection coefficient at Port 2 represented as Γ_2 given as $\Gamma_2 = s_{22}$

The values of s_{11} *and* s_{22} offer valuable information about the antenna's impedance properties. When these values are low (typically below -10 dB), impedance matching is improved, leading to minimal signal reflection and optimal power transfer. Conversely, inadequate impedance matching increases the reflection coefficient, diminishing the antenna's ability to effectively transmit and receive signals. Although S-parameters primarily assess impedance behavior, they also have an indirect impact on radiation efficiency, as mismatched impedance causes power to be reflected rather than radiated.

Return loss: Return loss in antenna design measures the signal loss resulting from the reflection of electromagnetic waves at the interface between the antenna and the transmission line or free space. It gauges the extent of power reflected back from the antenna due to impedance mismatch. A greater return loss signifies enhanced impedance matching and diminished signal loss, thereby enhancing antenna efficiency. The calculation of return loss can be derived from the reflection coefficient, as outlined in Eq. 12.

$$\text{Return loss(dB)} = -20\log_{10}(\Gamma) \quad (12)$$

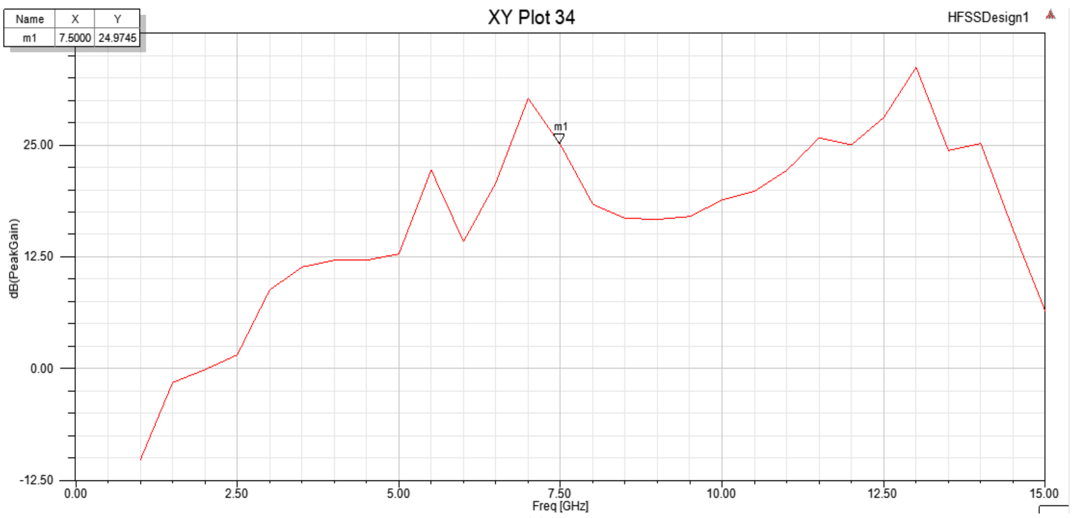
Where, Γ is Reflection coefficient

Return loss and reflection coefficient have an inverse relationship: when return loss increases, reflection coefficient decreases, and vice versa. In practical antenna designs, a return loss exceeding 10 dB is deemed sufficient, indicating that the majority of the input power is effectively transmitted with minimal reflection.

4. Results and Discussions

The designed 2X2 hexagonal antenna and 2X2 dual-band notch antenna's performance has been evaluated at frequencies of 7.5 GHz and 30 GHz, utilizing HFSS software, which is applicable for ultra-wideband and millimeter-wave applications. The assessment criteria include gain, directivity, radiation efficiency, beam area, reflection coefficient, and other pertinent metrics.

The gain of both the hexagonal antenna and the dual-band notched antenna at a frequency of 7.5GHz is depicted in Fig. 5. Likewise, Fig. 6 showcases the gain of the dual-band notched antenna and the hexagonal antenna at a frequency of 30 GHz.



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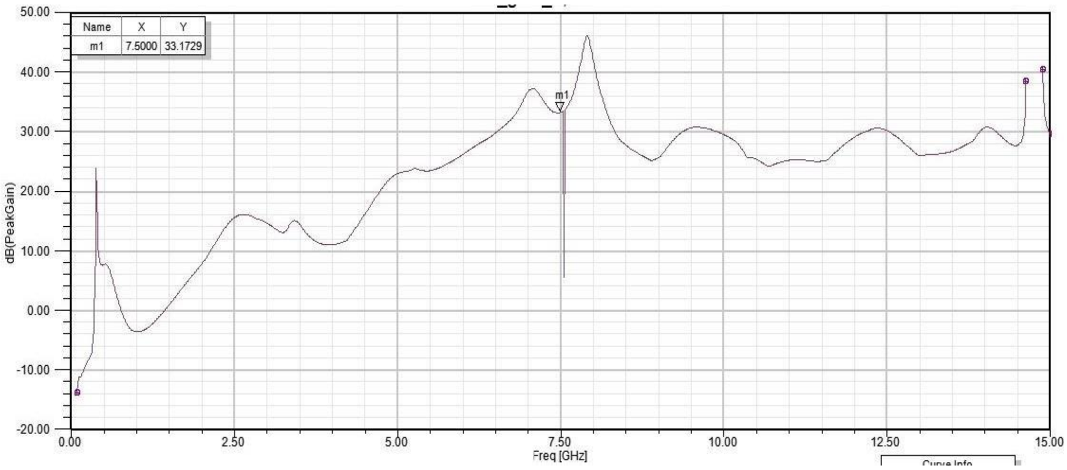
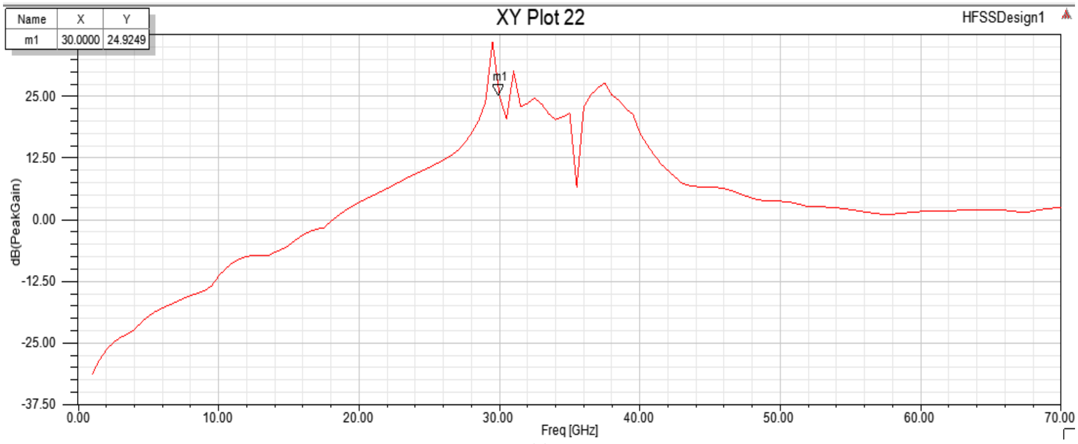


(b)

Fig. 5(a). Gain of Hexagonal antenna and at 7.5GHz frequency (b). Gain of Dual band notch antenna and at 7.5GHz frequency



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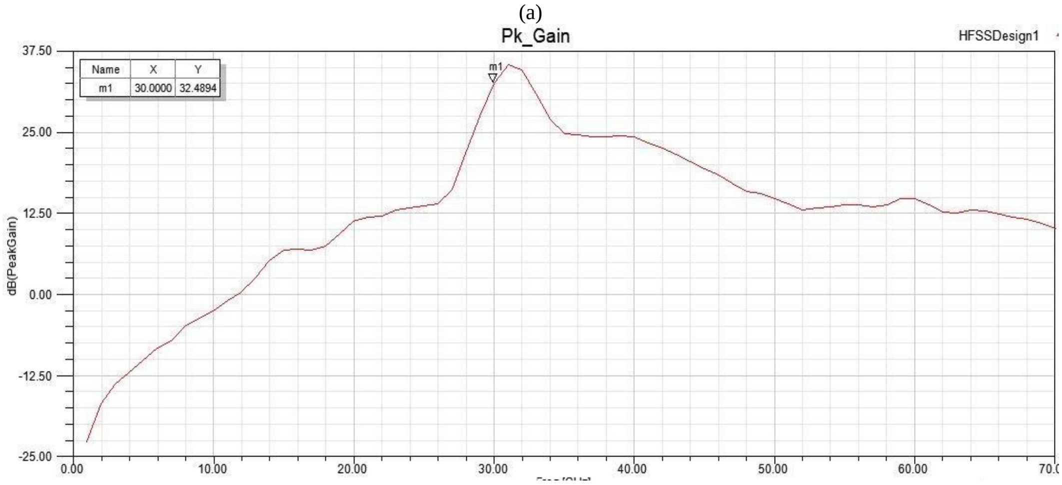
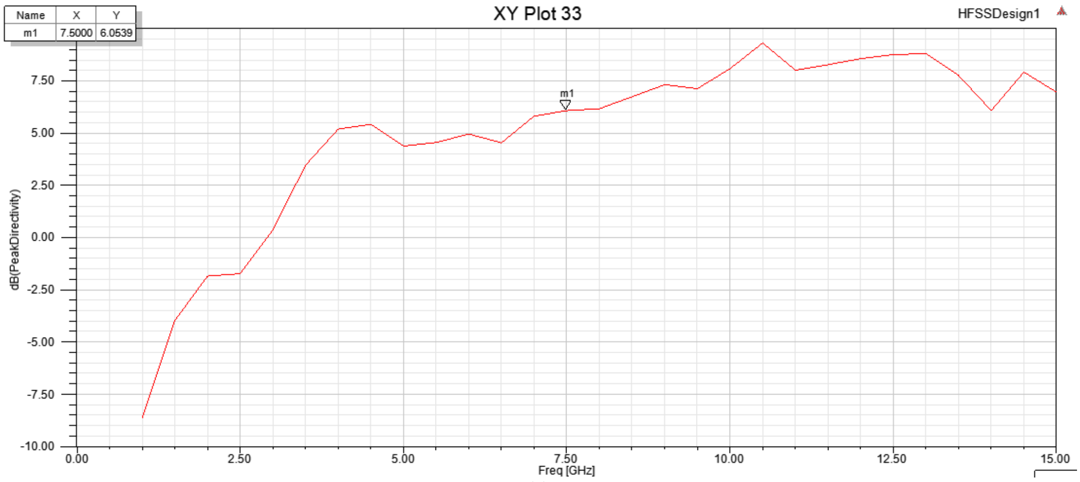


(b)

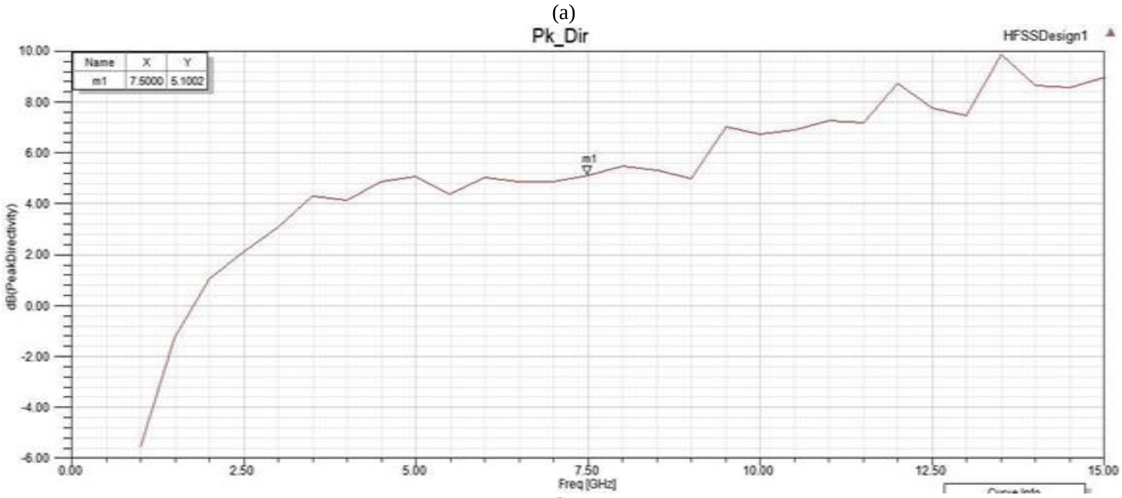
Fig. 6(a). Gain of Hexagonal antenna and at 30GHz frequency (b). Gain of Dual band notch antenna and at 30GHz frequency

At a frequency of 7.5GHz, the hexagonal antenna achieves a gain of 24.53 dB, while the dual-band notched antenna achieves a gain of 33.17 dB. Similarly, at 30GHz, the hexagonal antenna attains a gain of 24.92 dB, whereas the dual-band notched antenna achieves a gain of 32.49 dB. These results indicate that the dual-band notched antenna consistently outperforms the hexagonal antenna in terms of gain across both frequencies.

The directivity of both the hexagonal antenna and the dual-band notched antenna at a frequency of 7.5GHz is depicted in Fig. 7. Likewise, Fig. 8 showcases the directivity of the dual-band notched antenna and the hexagonal antenna at a frequency of 30 GHz.



(a)

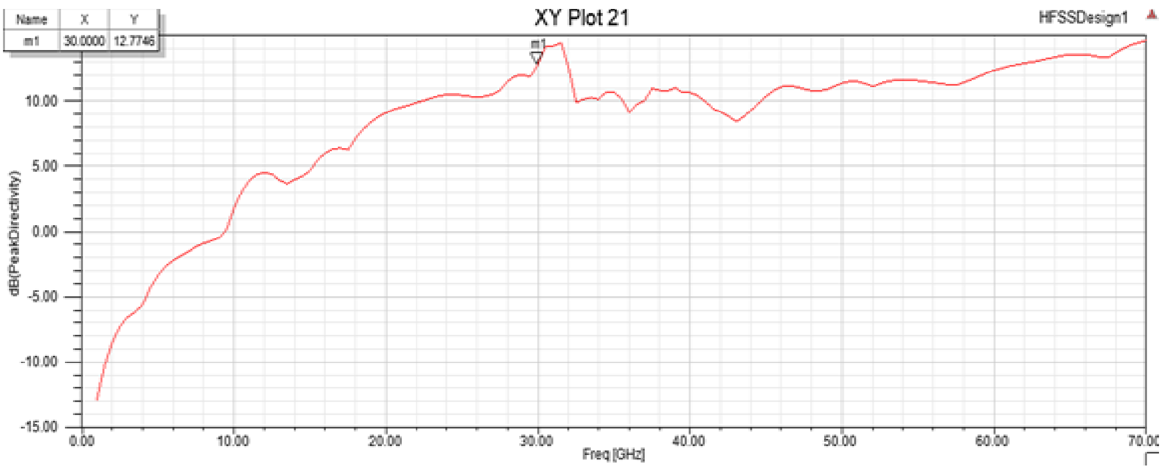


(b)

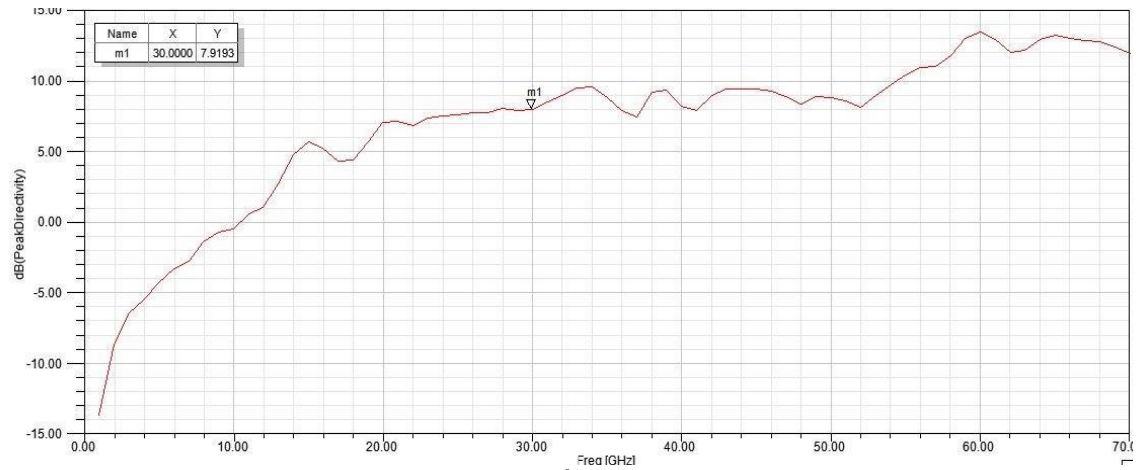
Fig. 7(a). Directivity of Hexagonal antenna at 7.5GHz frequency (b). Directivity of Dual band notch antenna at 7.5GHz frequency

At a frequency of 7.5GHz, the hexagonal antenna exhibits a directivity of 6.05 dB, while the dual-band notched antenna registers 5.10dB. Similarly, at 30 GHz, the hexagonal antenna records a directivity of 6.79 dB, whereas the dual-band notched antenna achieves 7.9dB. These findings suggest that the dual band notched antenna consistently surpasses the hexagonal antenna in terms of directivity across both frequencies.

The radiation efficiency of both hexagonal antenna and the dual band notched antenna at a frequency of 7.5 GHz is depicted in Fig. 9. Similarly, Fig. 10 showcases the radiation efficiency of these antennas at a frequency of 30 GHz.

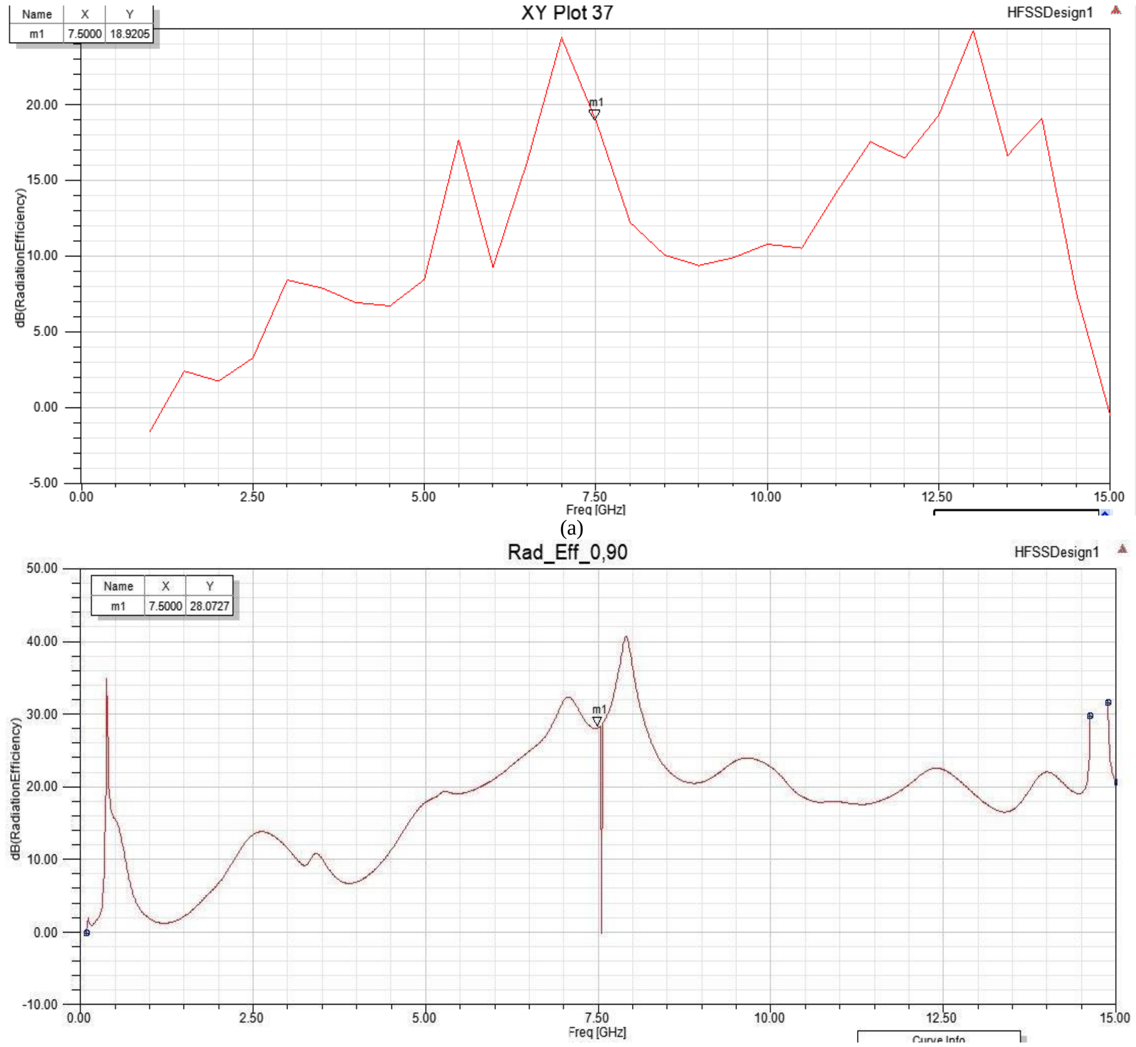


(a)



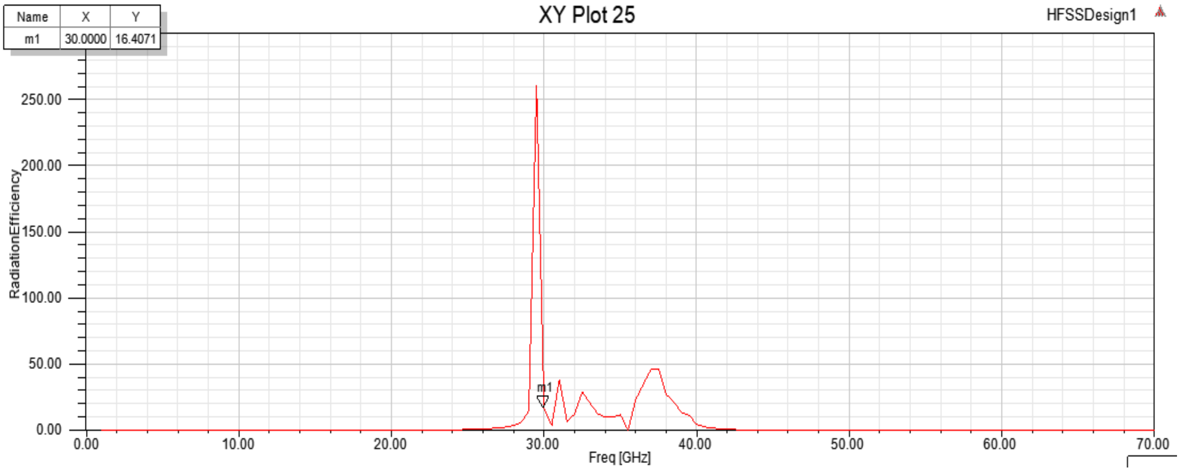
(b)

Fig. 8. (a). Directivity of Hexagonal antenna at 30GHz frequency (b). Directivity of Dual band notch antenna at 30GHz frequency

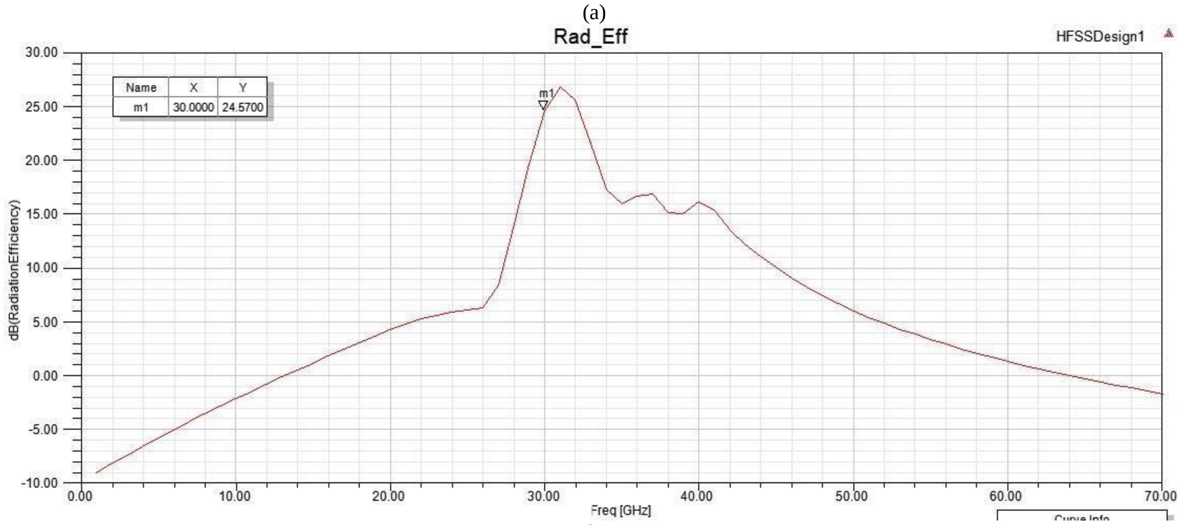


(b)

Fig. 9(a). Radiation efficiency of Hexagonal antenna at 7.5 GHz frequency (b). Radiation efficiency of Dual band notch an antenna at 7.5 GHz frequency



(a)



(b)

Fig. 10. (a). Radiation efficiency of Hexagonal antenna at 30 GHz frequency 10(b). Radiation efficiency of Dual band notch an antenna at 30 GHz frequency

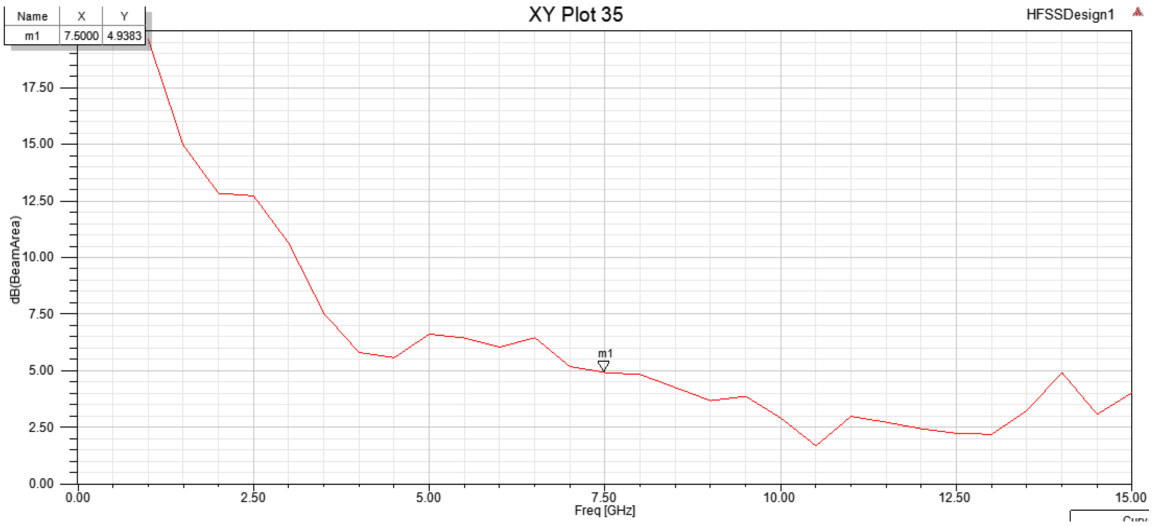
The hexagonal antenna demonstrates a radiation efficiency of 18.9 dB at 7.5GHz, while the dual-band notched antenna exhibits a higher efficiency of 28.07 dB. Similarly, at 30GHz, the hexagonal antenna shows a radiation efficiency of 16.41 dB, whereas the dual-band notched antenna achieves a higher efficiency of 24.57 dB. This consistent trend across both frequencies indicates that the dual-band notched antenna consistently surpasses the hexagonal antenna in terms of radiation efficiency. It suggests that the dual-band notched antenna is more proficient in converting input power into radiated electromagnetic waves compared to the hexagonal antenna across the tested frequencies.

Gain and radiation efficiency are key factors that influence overall antenna performance. While gain improves signal direction and strength, it doesn't always mean better efficiency, which measures how well the antenna radiates the input power. Increasing gain can sometimes reduce efficiency due to material losses or impedance mismatches. Likewise, antennas with high efficiency but lower gain may lack strong signal focus. The proposed Hexagonal MIMO and Dual Band Notched antennas achieve a good balance between the two, ensuring reliable performance for UWB and 5G systems.

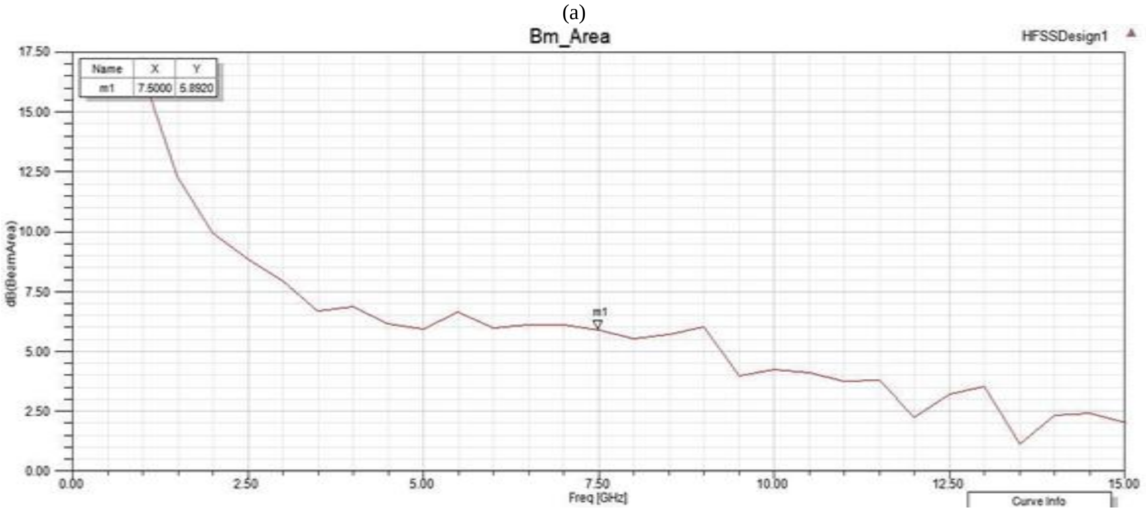
Design enhancements, including optimized geometry and feed structures, help maintain this balance, making the antennas suitable for high-frequency communication environments.

The beam area of both the hexagonal antenna and the dual-band notched antenna at a frequency of 7.5GHz is depicted in Fig.11. Similarly, Fig. 12 showcases the beam area of these antennas at a frequency of 30 GHz.

The hexagonal antenna displays a beam area of 4.94 square degrees at 7.5GHz, whereas the dual-band antenna has a larger beam area of 5.89 square degrees. Likewise, at 30GHz, the beam area of the hexagonal antenna is 4.20 square degrees, whereas the dual-band antenna exhibits a smaller beam area of 3.07 square degrees. In terms of the dual-band antenna at 30GHz, it exhibits a smaller beam area of 3.07 square degrees compared to the hexagonal antenna's beam area of 4.20 square degrees. This indicates that the dual-band antenna provides a more focused and directional radiation pattern at 30GHz compared to the hexagonal antenna.

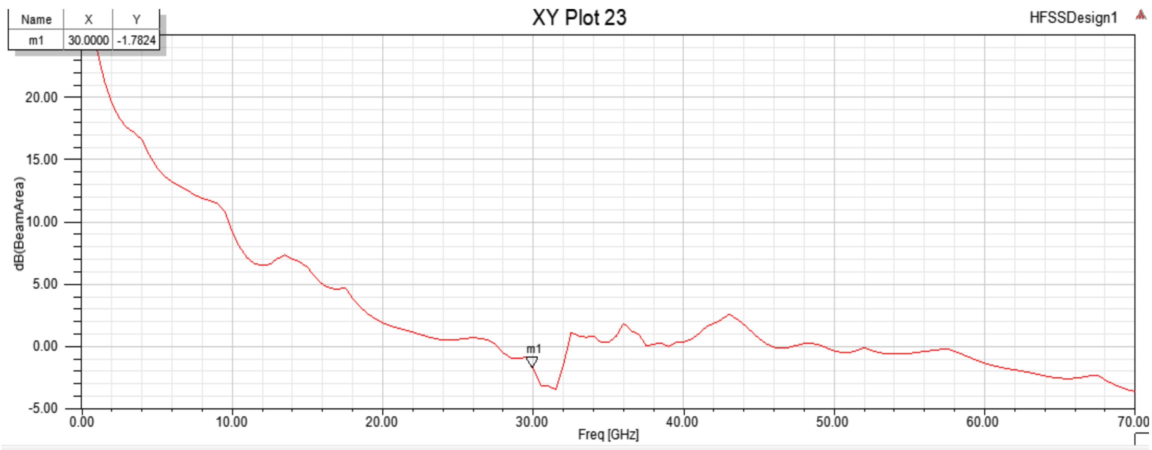


(a)

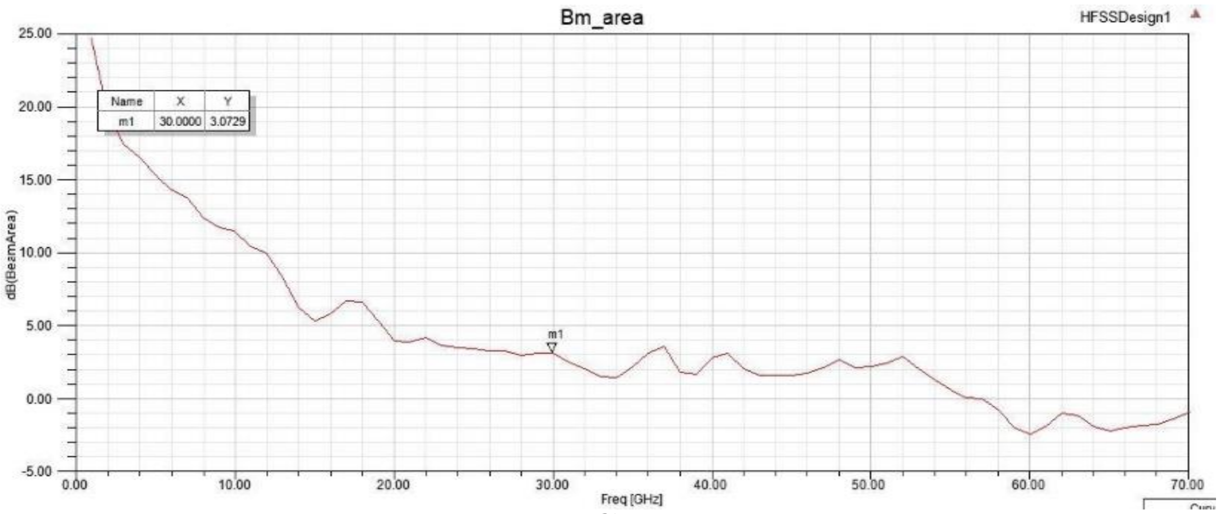


(b)

Fig. 11(a). Beam area of Hexagonal antenna at 7.5 GHz frequency (b). Beam area of Dual band notch antenna at 7.5 GHz frequency



(a)



(b)

Fig. 12(a). Beam area of Hexagonal antenna at 30 GHz frequency (b). Beam area of Dual band notch antenna at 30 GHz frequency

The determined S-parameters for both the Hexagonal 2X2 MIMO antenna and the Dual-band notched 2X2 MIMO antenna at frequencies of 7.5 GHz and 30 GHz are provided in Table 3 below.

Table 3. S-Parameters of Hexagonal and Dual band notch antenna

Antenna	Operating Frequency	s_{11} Parameter	s_{12} Parameter	s_{21} Parameter	s_{22} Parameter
Dual band Notched antenna	7.5 GHz	-7.31	-24.65	-24.65	-7.55
	30 GHz	-3.62	-29.80	-29.80	-3.83
Hexagonal antenna	7.5 GHz	-10.76	-33.24	-33.24	-11.36
	30 GHz	-26.85	-17.04	-17.04	-20.16

Analysis of Table 3 indicates that both antennas demonstrate reflection coefficients below -12 dB at both 7.5 GHz and 30 GHz frequencies, suggesting minimal reflection. Return loss values for both antennas can be computed using Equation 12. Upon closer inspection, it is observed that the return loss values for both the hexagonal and dual-band antennas at both frequencies exceed 12 dB, indicating lower reflection coefficients. This attribute suggests effective impedance matching and efficient transmission of electromagnetic waves, thereby signifying favourable antenna performance.

The evaluated parameters of the hexagonal and dual-band notched antennas at frequencies 7.5 GHz and 30 GHz are presented in the Table 4 below.

Table 4. Performance analysis of Hexagonal and Dual band notch antenna

Antenna	Operating Frequency(GHz)	Gain (dB)	Directivity (dB)	Radiation Efficiency(dB)	Beam area (Squ. deg.)	Reflection coefficient	Return loss(dB)
Dual band notched antenna	7.5	33.17	5.10	28.07	5.89	-7.31	2.61
	30	32.49	7.9	24.57	3.07	-3.62	8.25
Hexagonal antenna	7.5 (20 Passes)	24.97	6.05	18.9	4.94	-10.76	10.51
	7.5 (70 Passes)	24.53	5.67	18.86	5.32		
	30 (20 Passes)	13.59	6.79	6.80	4.20		
	30 (50 Passes)	17.85	12.05	5.79	-1.06		
	30 (70 Passes)	24.92	12.77	16.41	-1.78	-26.85	13.55

The performance of the hexagonal and dual-band notched antennas varies across different frequencies, reflecting their distinct design attributes and operational characteristics.

At 7.5 GHz, the hexagonal antenna performs well with good directional focus and effective impedance matching, though some losses are observed, likely due to design factors. At 30 GHz, the antenna shows improved gain and directivity with more passes, but its radiation efficiency slightly decreases, suggesting challenges in maintaining consistent performance across frequency ranges.

On the other hand, the dual-band notched antenna exhibits robust performance across its frequency ranges. At 7.5 GHz, it provides high gain and effective impedance matching, while at 30 GHz, it remains efficient but indicates a need for better impedance matching. These performance variations are due to the design complexity, material properties, and the necessity to optimize impedance matching for different frequency bands.

The antenna parameters, such as gain, directivity, and efficiency, offer valuable insights into its practical application. The high gain and directivity suggest that the antenna can effectively focus signals, which is advantageous for long-range communication and minimizing interference in high-frequency systems like 5G and UWB. However, the observed drop in efficiency at higher frequencies highlights potential challenges in real-world implementation, including material losses and fabrication tolerances. These factors need to be considered when incorporating the antenna into practical communication systems.

The results emphasize the effectiveness of the proposed structural modifications in enhancing gain and directivity while preserving a compact design. Compared to traditional antenna models, the optimized configurations exhibit better impedance matching and beam control, making them well-suited for UWB and 5G applications. However, the slight decline in radiation efficiency at higher frequencies suggests the necessity for further improvements in material selection and design refinement. Future research could focus on additional optimization strategies to achieve more consistent impedance matching across a broader frequency range, ensuring reliable performance in high-frequency communication systems. Although this study focuses on theoretical analysis and simulations, validating the design through fabrication and real-world testing remains a direction for future work. Assessing the effects of fabrication tolerances and environmental conditions would enhance the practical applicability of the proposed antenna.

5. Conclusion

This study aimed to evaluate the performance of 2X2 hexagonal and 2X2 dual-band notched antennas across various frequencies. We found notable differences between these antenna types, with the dual-band notched antenna consistently demonstrating superior gain, directivity, and radiation efficiency compared to the hexagonal antenna. Additionally, the dual-band notched antenna exhibited heightened radiation efficiency, highlighting its effectiveness in converting input power into radiated electromagnetic waves. These findings emphasize the importance of antenna design considerations for optimizing performance in specific frequency bands and applications.

Furthermore, the comparative analysis across 7.5 GHz and 30 GHz frequencies consistently favored the dual-band notched antenna in terms of gain, directivity, radiation efficiency, and beam area. Minimal reflection and effective impedance matching were observed for both antennas, offering valuable insights for antenna design. Overall, the dual-band notched antenna emerges as the preferred choice for ultra-wideband applications and millimeter wave applications due to its superior performance characteristics and focused radiation pattern.

The structural enhancements introduced in both antenna designs, such as optimized slot arrangements, improved feeding techniques, and refined geometric configurations, set this study apart from conventional designs. These modifications enhance impedance matching and radiation efficiency while also improving beam control and gain, demonstrating their suitability for real-world applications.

Although these improvements lead to better performance, slight reductions in radiation efficiency at higher frequencies indicate areas for further refinement. Future studies could investigate advanced material selection, the incorporation of reconfigurable components, or hybrid design approaches to improve the adaptability of these antennas across a wider frequency spectrum. Moreover, experimental validation and real-world implementation could provide further evidence of the proposed designs' effectiveness in practical communication systems, reinforcing their relevance for next-generation wireless technologies.

This research underscores the critical role of antenna design in achieving optimal performance metrics and addressing emerging technological challenges in wireless communication systems. Further exploration of novel design approaches may lead to advancements in antenna technology and enhanced performance in various applications.

Acknowledgements

Dr. Ramineni Padmasree was responsible for developing the design of the Hexagonal and Dual Band Notched MIMO antenna. Laxmi Prasanna Kumar contributed to the study by extensively studying HFSS software, implementing the designed antenna, and evaluating various antenna parameters. Combined efforts ensured a comprehensive exploration of the antenna's performance characteristics and its suitability for Microwave and Millimeter applications.

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