Antenna Design Project Report

Submitted to

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Abstract

The abstract presents a circular microstrip patch antenna designed for optimal performance. This antenna is unique in its ability to simultaneously excite both the fundamental TM01 mode and higher-order TM0n modes, resulting in omnidirectional azimuthal coverage. Two annular ring slots have been intricately etched onto the circular patch to achieve this, effectively coupling with the first three resonating modes. The abstract also outlines a method that allows for precise control over the coupling among these modes. This control is key to defining the antenna's bandwidth and filtering characteristics, which are crucial for signal reception and transmission. The study includes a fabricated prototype tailored for X-band applications, showcasing impressive features. The antenna offers a substantial 28% impedance bandwidth at 10.2 GHz, ensuring broad frequency coverage. Additionally, its gain variation remains remarkably stable, with fluctuations within a mere 1% margin around 7dBi across the entire passband. Furthermore, this antenna excels in out-of-band signal suppression, demonstrating suppression levels greater than 22 dB. This design represents a remarkable achievement in antenna engineering, combining multi-mode capabilities, wide bandwidth, and consistent performance in filtering and gain stability.

Brief Explanation and Advantages

The circular microstrip patch antenna plays a crucial role in modern communication systems, offering an attractive solution with its quasi-omnidirectional radiation patterns. This feature is especially valuable in applications like Wireless Local Area Networks (WLANs) and vehicle telematics, ensuring reliable signal coverage over a wide range of angles.

In traditional communication systems, the standard approach involves the utilization of bandpass filters subsequent to the antenna. However, this can result in undesirable consequences, including heightened insertion loss, increased system expenses, and additional bulk. As a remedy to this challenge, the concept of filtering antennas has emerged, presenting an innovative fusion of filtering functionality within the antenna design. Although various filtering antennas have been explored, they often come at a price—the efficiency of the antenna itself may be compromised due to the insertion loss incurred by the filtering unit preceding the radiator.

In this paper, we present a novel approach. By feeding a circular microstrip patch antenna at its center, we can efficiently excite the TM0n modes, resulting in nearly omnidirectional radiation patterns across a broad bandwidth. The unique aspect of this design is its ability to control the antenna's impedance bandwidth through intermodal coupling among the first three modes.

This filtering antenna exhibits radiation nulls at the band edges, effectively rejecting unwanted bands. To validate its performance and understand its working principles, we conducted comprehensive full-wave simulations using ANSYS HFSS. Furthermore, we discovered that even with a ground plane size 100% larger than the circular patch, the antenna maintains its remarkable performance characteristics.

This research opens up promising possibilities for a variety of applications where filtering and radiation pattern control are essential. The compact design ensures minimal insertion loss and cost-effectiveness, making it an attractive solution for modern communication systems.

Brief Explanation:

Components and Significance of a Coaxial Feed Circular Patch Antenna:

1. Circular Patch: The circular patch is the radiating element of the antenna. It plays a central role in producing the antenna's radiation pattern, which is typically quasi-omnidirectional. The significance lies in its ability to provide reliable signal coverage over a wide angular range.

2. Coaxial Cable: The coaxial cable serves as the feed line for the antenna. It consists of an inner conductor and an outer conductor separated by an insulating dielectric material. The inner conductor is connected to the circular patch, while the outer conductor acts as the ground plane. The coaxial cable's significance is in efficiently delivering the electromagnetic signals to and from the antenna.

3. Ground Plane: The ground plane, often the outer conductor of the coaxial cable, acts as a reference point for the antenna's radiation. It helps control the antenna's radiation pattern and impedance. The significance lies in its role in minimizing signal interference and providing a stable reference for the antenna's operation.

4. Simplicity: The coaxial feed circular patch antenna is relatively simple in its design, making it easy to manufacture and implement. Its straightforward structure contributes to ease of installation and maintenance.

5. Impedance Control: The use of a coaxial feed allows for precise impedance matching, ensuring that the antenna operates at the desired impedance level. This control is crucial for optimizing the antenna's performance and signal quality.

6. Compact Design: The antenna's compact design is significant, especially in applications where space is limited. It can be integrated into various communication systems without adding significant bulk.

7. Signal Quality: The coaxial feed configuration helps minimize signal loss and interference, resulting in improved signal quality. This is of particular significance in high-frequency applications, such as microwave communication, where signal integrity is essential.

8. High-Frequency Applications: The antenna is commonly used in microwave and RF applications, including microwave communication, satellite communication, and radar systems. Its ability to maintain signal quality at higher frequencies makes it a preferred choice in these fields.

9. Omnidirectional Radiation: The circular patch's ability to generate quasi-omnidirectional radiation patterns is significant in applications that require signal coverage over a wide angular range. This feature ensures reliable communication in diverse scenarios.

Advantages:

1. **Wide Frequency Coverage:** One of the primary advantages is the wideband operation, allowing the antenna to cover a broader range of frequencies. This versatility is essential for modern communication systems that utilize different frequency bands for various services like data, voice, and video transmission.

2. **Compact Design:** Circular patch antennas are known for their compact and low-profile design, making them suitable for applications where space is limited. The use of slots in the circular patch adds flexibility to the design without significantly increasing its physical footprint.

3. **Coaxial Feed Efficiency:** Coaxial feed is a well-established and efficient method for connecting antennas. It ensures minimal signal loss during transmission, resulting in improved overall performance.

4. **Applications:** Antennas with wideband and coaxial feed capabilities find applications in various fields, including wireless communication, satellite communication, radar systems, and more. These antennas can adapt to different frequency requirements in diverse scenarios.

5. **Research Significance:** Research in this area contributes to the development of advanced antenna technologies, which are essential for evolving wireless communication standards, such as 5G and beyond. It addresses the need for antennas that can handle complex frequency arrangements and offer reliable performance.

ANTENNA DESIGN AND ANALYSIS

Design Description for without slot Circular ring Antenna:

Figure 1(a): The design presents a circular patch antenna, where various critical parameters are specified. This antenna design is intended to operate efficiently in the given conditions and requirements.

Substrate and Material:

- *Substrate:* The antenna is constructed on a Roger RO4003C substrate. This substrate is selected for its specific electrical properties and is crucial for the antenna's overall performance.

- *Relative Permittivity (εr):* The substrate has a relative permittivity (dielectric constant) of $\varepsilon r = 3.55$. This parameter determines the ability of the material to store electrical energy and significantly influences the antenna's impedance and radiation characteristics.

- *Thickness (h):* The substrate has a thickness of $h = 0.813$ mm. The thickness is a critical dimension that affects the antenna's radiation pattern and impedance matching.

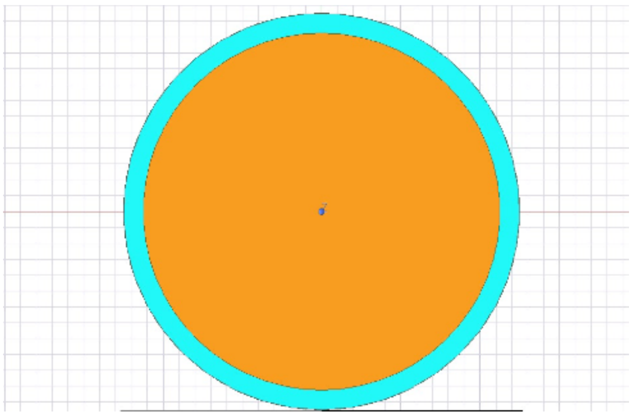
Patch Specifications:

- *Patch Shape:* The antenna's radiating element is a circular patch with a specific radius.

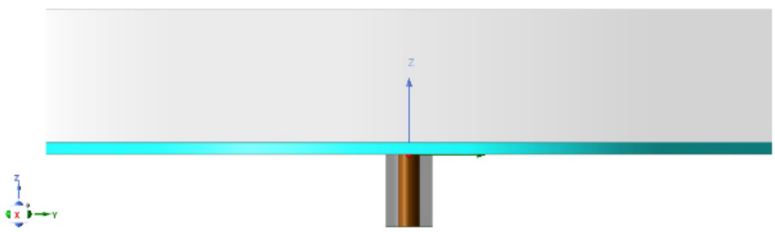
- *Radius (Rp):* The circular patch has a radius of $Rp = 22.5$ mm. The choice of the circular shape and its dimensions determines the antenna's radiation pattern and resonant frequency.

Ground Plane:

- *Ground Plane Radius (Rg):* The ground plane, which acts as the outer conductor of the coaxial feed structure, has a radius of $Rg = 25$ mm. The ground plane plays a crucial role in the antenna's radiation characteristics and impedance control.



Top View



Side View

Figure 1(a)

Design Description for Slotted Center-Fed Circular Patch Antenna:

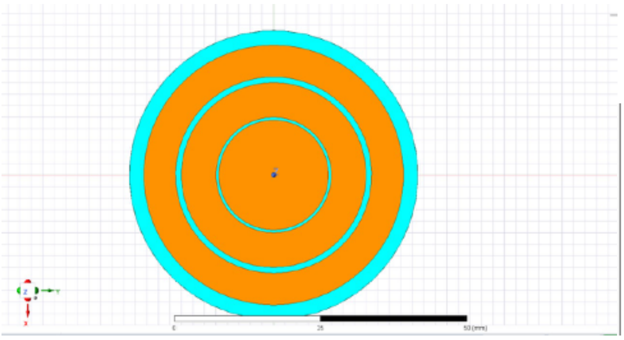
Figure 1(b): The design features a slotted center-fed circular patch antenna, emphasizing its physical structure and key dimensions. The antenna design aims to provide optimal performance based on specific parameters.

Antenna Structure:

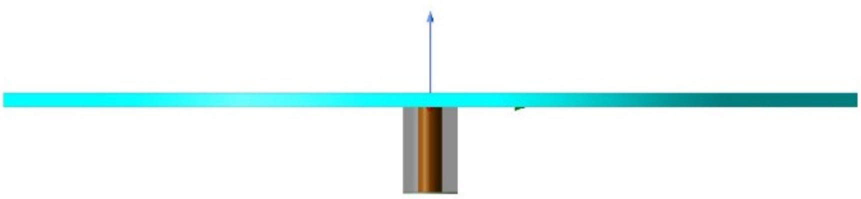
- *Fabrication:* The antenna is fabricated to include a centre-fed circular patch. This central feeding mechanism is designed for efficient signal transmission and reception.
- *Slot Configuration:* The circular patch features slots, which play a crucial role in controlling the antenna's radiation pattern and impedance matching.

Dimensions (unit: mm):

- *Ground Plane (Rg):* The radius of the ground plane is Rg = 25 mm. The ground plane's size influences the antenna's radiation characteristics and helps establish the desired radiation pattern.
- *Patch Radius (Rp):* The circular patch's radius is Rp = 22.5 mm. The size of the patch directly affects the antenna's resonant frequency and radiation characteristics.
- *Slot Dimensions (R1 and R2):* The slots in the circular patch have specific dimensions. R1 = 9.5 mm and R2 = 16 mm. These slot dimensions are carefully chosen to influence the antenna's radiation pattern and impedance properties.
- *Slot Widths (w1 and w2):* The widths of the slots are also specified. w1 = 0.5 mm and w2 = 1 mm. These dimensions play a vital role in shaping the antenna's performance characteristics.



Top View



Side View

Figure 1(b)

Simulation Result and Discussion

S11 Response of without slot Circular ring Antenna:-

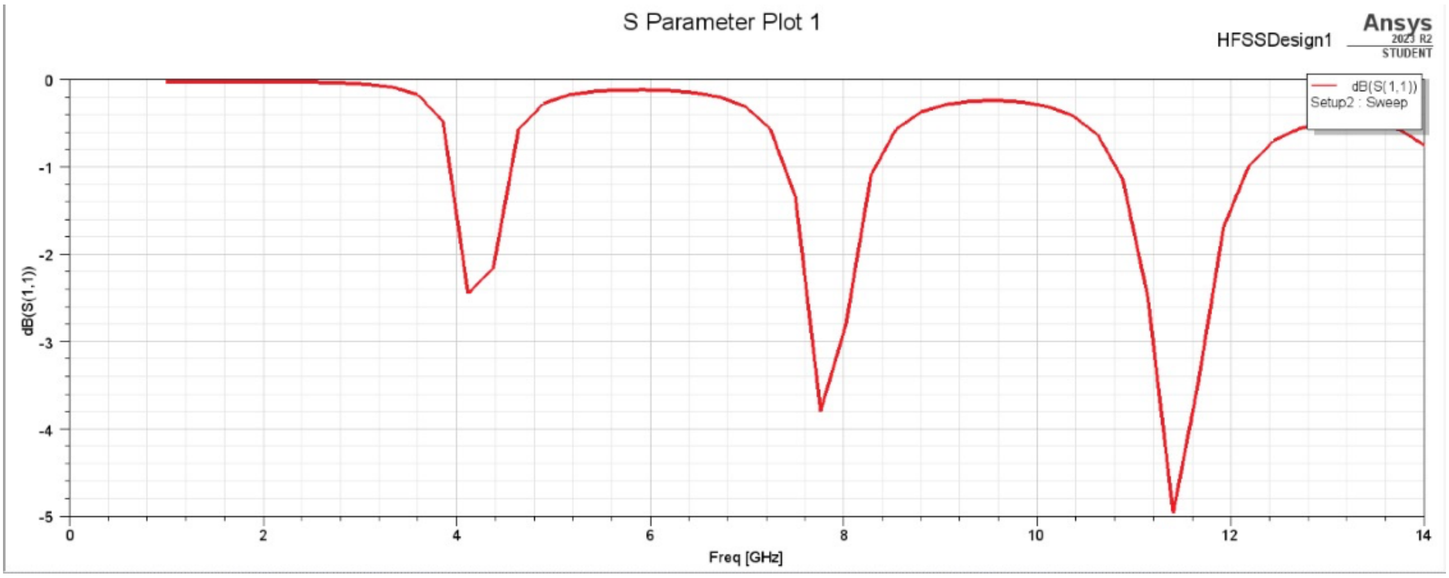


Figure 1(c)

Discussion:

In Figure. 1(c), we observe three dips in the |S11| plot, each associated with distinct modes: TM01, TM02, and TM03. These dips result from the interaction of electromagnetic waves with the circular patch antenna.

- **TM01 Mode:** The first dip signifies the fundamental resonance of the circular patch antenna. High input impedance at this frequency is due to a strong electric field and a weak magnetic field at the patch centre, resulting in poor matching with the transmission line.
- **Higher-Order Modes (TM02 and TM03):** The second and third dips correspond to higher-order modes with similar matching challenges.

These dips impact antenna performance:

- Poor impedance matching results in signal reflection, reducing antenna efficiency and gain.
- Designers must consider these modes, either avoiding them or using matching techniques for improved performance based on application requirements.

S11 Response for Slotted Center-Fed Circular Patch Antenna:-

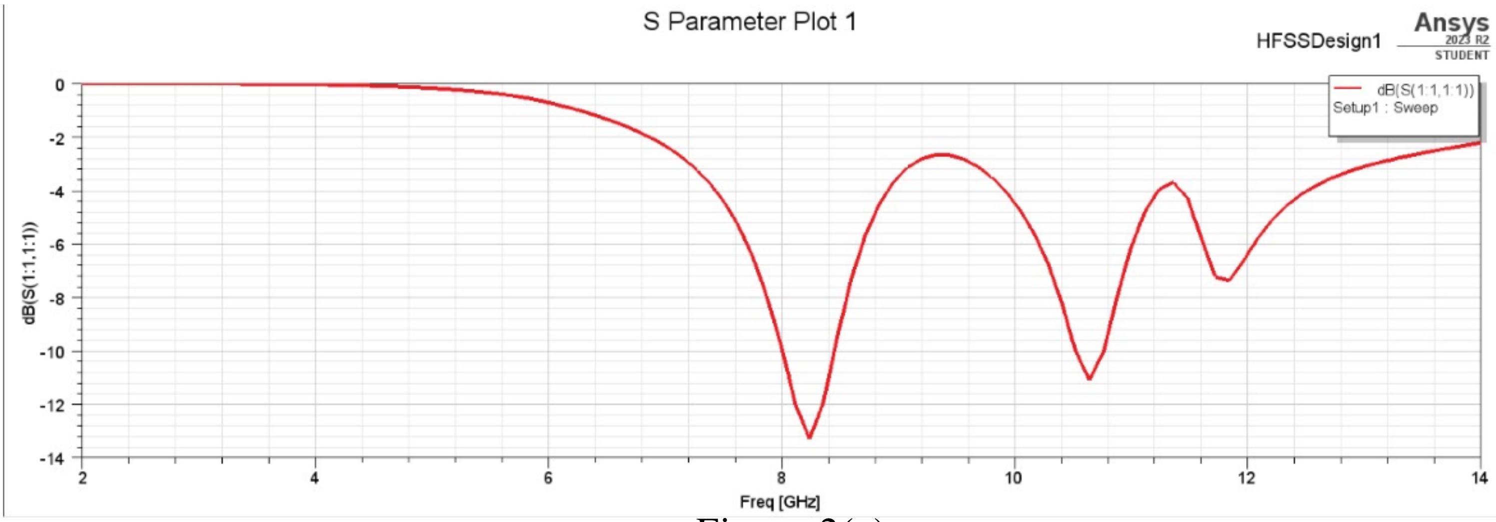


Figure 2(a)

Discussion:

In Figure 2(a), it is evident that the introduction of slots has a notable effect on the resonant modes of the circular patch antenna. The observation is that the slots serve to compress the first two modes (TM01 and TM02) towards the centre of the patch without altering the field patterns associated with these modes. Consequently, this compression results in a reduction of the effective radiating area for these modes.

- **Resonant Frequency Upshift:**
  The reduction in effective radiating area leads to an upshift in the resonant frequencies of the TM01 and TM02 modes. This means that these modes resonate at higher frequencies compared to the original, unaltered circular patch antenna.

- **Coupling of TM03 Mode:**
  Interestingly, the resonant frequency of the TM03 mode remains unchanged despite the presence of slots. This unique behaviour leads to a crucial outcome: the TM01 and TM02 modes become coupled to the TM03 mode. In other words, energy from the TM01 and TM02 modes is shared with the TM03 mode.

- **Enhanced Bandwidth:**
  The coupling of TM01 and TM02 to the TM03 mode results in a larger bandwidth for the antenna. This increased bandwidth is valuable in practical applications, especially when the antenna needs to operate over a wider range of frequencies. It provides greater flexibility in tuning the antenna for various communication needs.

Bandwidth control using mode coupling with variation in W2:-

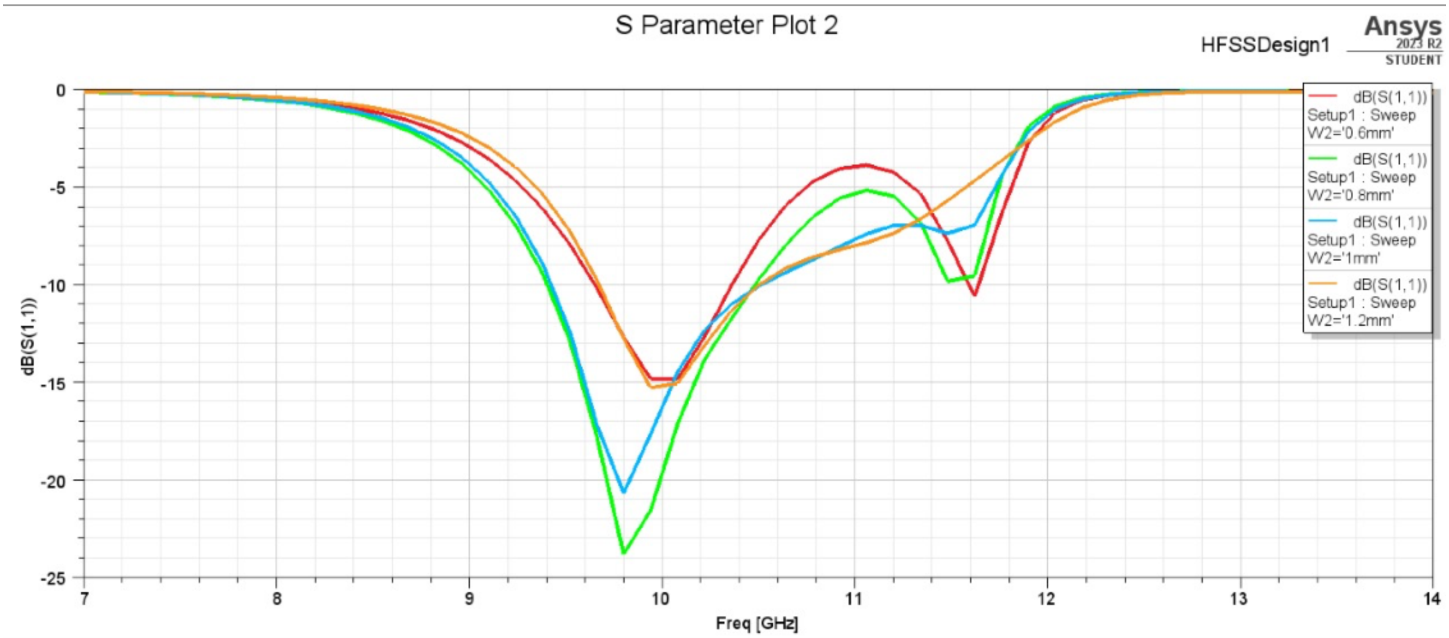


Figure 2(b)

Discussion:

In Figure 2(b), the bandwidth variation with the parameter w2, while keeping w1 fixed at 0.5 mm, is examined. The study demonstrates that the antenna's performance is significantly influenced by the separation between slots (w2). A similar trend is observed when the width of the first slot (w1) is altered while keeping w2 constant.

- **Strong Coupling with Small w2 (< 0.8 mm):** For very small values of w2 (below 0.8 mm), all three resonant modes (TM01, TM02, and TM03) exhibit strong coupling. However, this coupling is not matched, resulting in poor impedance matching. Consequently, the individual poles associated with each mode are not well-defined, and the overall bandwidth is limited. This scenario is characterized by a small, indistinct bandwidth due to the lack of clear resonance peaks.

- **Increase in w2 (Up to 1 mm):** As w2 increases, up to a value of 1 mm, the poles corresponding to each resonant mode become more prominent and clearly visible. This leads to an increase in the antenna's bandwidth. The stronger coupling between the modes at this stage allows for a more effective transfer of energy and a broader range of frequencies over which the antenna can operate efficiently.

- **Decrease in Bandwidth with Further Increase in w2 (> 1 mm):** Beyond a certain threshold value of w2, the coupling between the first two modes (TM01 and TM02) and the third mode (TM03) starts to weaken. As a result, the bandwidth decreases. At this stage, the TM03 mode is no longer coupled to the pre-coupled TM01 and TM02 modes. Consequently, the antenna's bandwidth is now primarily controlled by the width w1 of the first slot.

It's worth noting that the bandwidth from the coupled TM01 and TM02 modes is less than that of the bandwidth from the coupled TM01, TM02, and TM03 modes. However, this particular scenario is not illustrated in this specific figure.

Realized gain vs frequency in the main beam direction:-

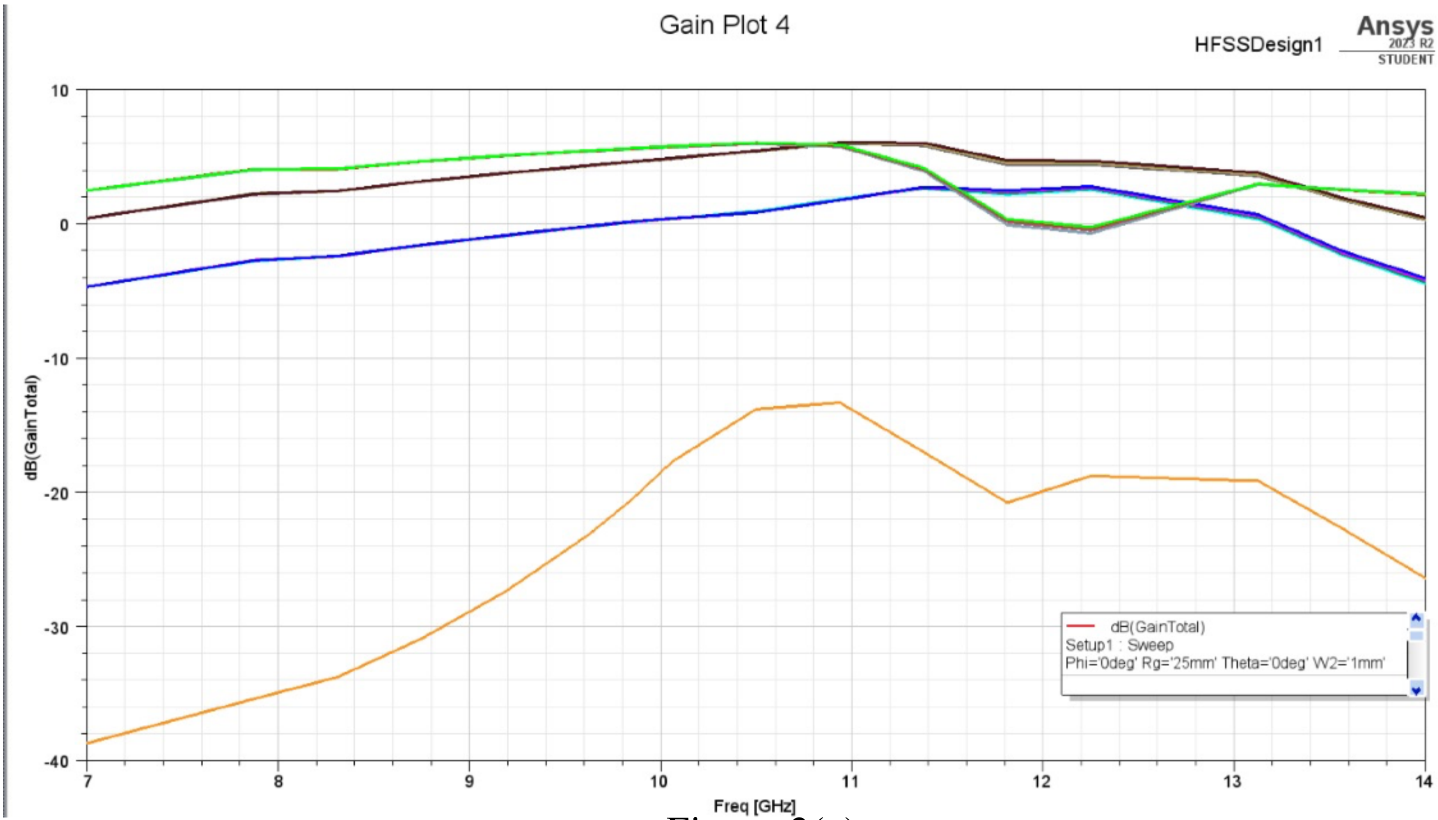


Figure 2(c)

Discussion:-

Figure 2(c) presents a crucial aspect of antenna performance: the gain versus frequency plot in the direction of the main beam, with a focus on the variation of parameter w2. These plots provide insight into the controllable gain bandwidth through the coupling between different resonant modes, as previously discussed. In addition, Fig. 4(b) demonstrates how specific design modifications can lead to bandpass filter-like characteristics in the antenna's performance.

- **Bandpass Filter-Like Characteristics at w2 = 1 mm:** A noteworthy observation is that when w2 equals 1 mm, the gain plot exhibits two radiation nulls at the edges of the passband. This occurrence imparts a bandpass filter (BPF))-like characteristic to the antenna. The presence of these radiation nulls can be attributed to the interaction of the various modes within the antenna structure, particularly due to the coupling of these modes.

- **Suppression of Gain at Lower Stopband Frequency:** A critical consequence of this behaviour is that, as there are no resonant frequency modes below the TM01 mode, the gain is significantly suppressed at the lower stopband frequency. This is a crucial feature for applications requiring the isolation of specific frequency ranges. The ability to control the lower stopband is vital for filtering applications and allows the antenna to effectively block unwanted signals.

- **Upshifting TM04 for Upper Stopband:** Another interesting effect observed in Figure 2(c) is the upshifting of the TM04 mode due to the presence of ring slots. Importantly, this upshift occurs without significantly affecting the TM03 mode. As a result, this design modification provides the upper stopband of the filtering antenna.

This dynamic control over the upper and lower stopbands is highly advantageous in applications where precise frequency isolation is required.

Response with variation in ground plane size Rg (in mm):-

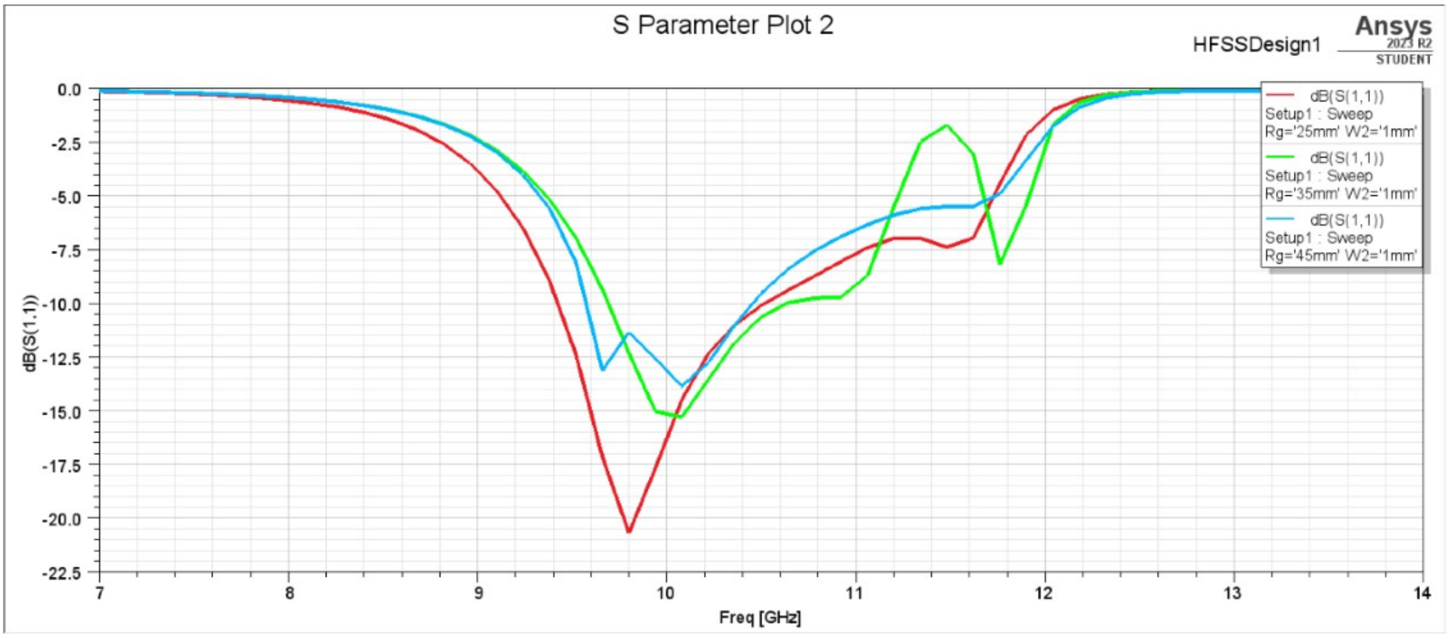


Figure 3(a)

Discussion:-

Figure 3(a) displays the S11 response of the antenna as a function of ground plane size (Rg) in millimetres. It's evident from the plot that there is no significant change in the bandwidth of the S11 response with variations in the ground plane size. This observation has important implications for the design and performance of the antenna.

- **Consistency in Bandwidth:** The lack of a substantial change in the S11 bandwidth with alterations in the ground plane size (Rg) indicates that this particular parameter has a relatively minor impact on the antenna's resonance and impedance characteristics. This consistency in bandwidth is advantageous for antenna design as it allows for more stable and predictable performance, regardless of variations in the ground plane size.

- **Predictable Performance:** In practical applications, the ability to maintain a consistent bandwidth is essential for ensuring the antenna's suitability across different operating environments and installation scenarios. The observed insensitivity to ground plane size simplifies the antenna design process, making it more robust and predictable.

Gain patterns at (a) 9.15 GHz, (b) 10.48 GHz and (c) 11.49 GHz:-

Figure 3(b)

Discussion:-

In Figure 3(b), we are presented with the measured and simulated gain patterns in both the E-plane (XZ-plane) and H-plane (XY-plane) at three specific dips in |S11|, occurring at 9.15 GHz, 10.48 GHz, and 11.49 GHz. These dips correspond to the TM01, TM02, and TM03 modes, respectively. This analysis of gain patterns is instrumental in understanding the antenna's radiation characteristics and its suitability for various applications.

- **Quasi-Omnidirectional Radiation Patterns:** One of the standout observations is that the field orientation remains strikingly similar across all three modes (TM01, TM02, and TM03). This uniformity in field orientation leads to the antenna exhibiting quasi-omnidirectional radiation patterns. Quasi-omnidirectional radiation means that the antenna radiates uniformly in almost all directions around its azimuth plane. This property is highly advantageous in scenarios where consistent, widespread coverage is essential, such as in-vehicle telematics and wireless communication systems.

- **20 dB Cross-Polarization Suppression:** The gain patterns also illustrate the antenna's remarkable ability to achieve a 20 dB cross-polarization suppression across the entire impedance bandwidth. This cross-polarization suppression ensures that the antenna predominantly radiates in its intended polarization state, minimizing unwanted radiation in orthogonal polarizations. This capability is essential in communication systems where minimizing interference and crosstalk is critical.

- **Steady Main Beam Direction:** Another noteworthy feature depicted in Fig. 6 is the consistent direction of the main beam, which remains fixed at θ = 25° throughout the antenna's impedance bandwidth. This steadiness in the main beam direction is pivotal for various applications, as it simplifies the deployment and alignment of the antenna. The fixed beam direction ensures that communication signals are reliably directed towards the intended target, whether it's a base station or another communication node.

Vector surface current distribution on the centre fed circular patch antenna for TM01, TM02 and TM03 modes (a) without slot (b) with slot.

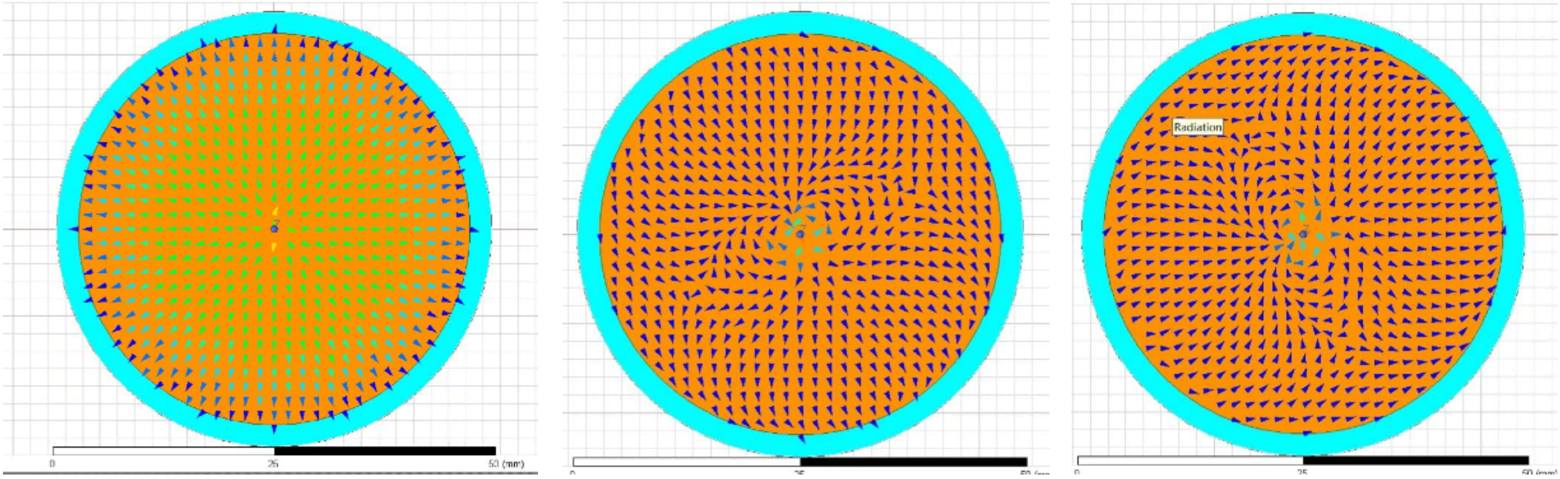


Figure 4(a) without slot

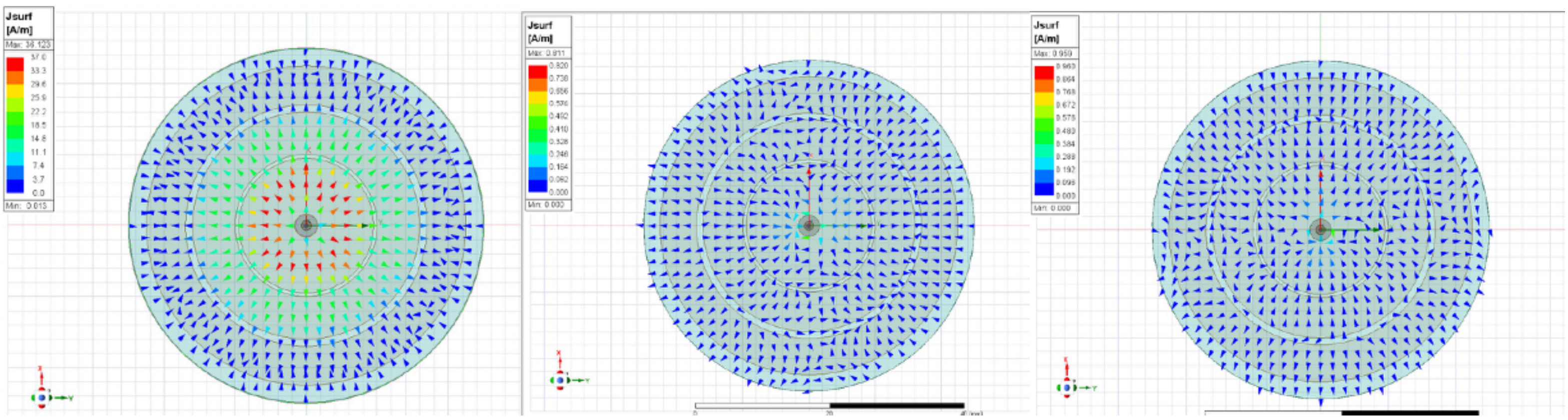


Figure 4(b) with slot.

Discussion:-

In Figure 4(a), we examine the current distribution of the antenna and observe intriguing characteristics related to the TM01, TM02, and TM03 modes. Specifically, we identify two distinct current minima circles associated with the TM03 mode, situated at radii R1 = 9.5 mm and R2 = 16 mm. These minima circles are noteworthy because they play a unique role in the antenna's behaviour and its interaction with other modes.

- **Role of TM03 Minima Circles:** The presence of the TM03 mode's current minima circles at R1 and R2 is intriguing. What's particularly interesting is that these minima circles do not correspond to the current minima for the TM02 or TM01 modes. This observation raises questions about how these minimum circles can be utilized to manipulate the antenna's behaviour without affecting other modes.

- **Effects of Slot Etching along TM03 Minima Circles:** To explore the impact of these TM03 minima circles, slots are etched along these circles. The interesting revelation is that when slots are introduced along these specific minima circles of the TM03 mode, the characteristics of the TM03 mode remain unaffected. This phenomenon is akin to treating the annular ring as an open-circuit plane for the TM03 mode.

- **Squeezing of TM01 and TM02 Modes:** Figure 4(b) provides a visual representation of the impact of these slots. They effectively squeeze the first two modes, TM01 and TM02, towards the centre of the patch without altering the field pattern. As a result, the effective radiating area for these modes decreases, leading to an upshift in their corresponding resonant frequencies.

- **Larger Bandwidth and Mode Coupling:** Critically, while the resonant frequency of the TM03 mode remains unaffected, this upshifting of TM01 and TM02 modes brings them closer to the TM03 mode in frequency space. As a result, these modes become coupled to the TM03 mode. This coupling results in a larger bandwidth for the antenna.

Conclusion

In this research, we have introduced a circular microstrip patch antenna equipped with annular slots, a novel design that exhibits remarkable performance attributes, making it a compelling solution for a wide range of applications. The antenna's quasi-omnidirectional radiation patterns and wideband filtering characteristics, extending across its entire impedance bandwidth, offer an ideal combination for addressing the specific requirements of various industries.

This multifrequency antenna, radiating at 8.15 GHz, 10.30 GHz, and 10.90 GHz, further underscores its adaptability to diverse communication and connectivity needs.

Reference

- **From the YouTube video:**

Name:- HFSS Tutorial 1- Microstrip Patch Antenna with coaxial feeding

Link:- https://www.youtube.com/watch?v=Me3mzL-sxO4

- **From the IEEE Xplore research paper:**

Link:- https://ieeexplore.ieee.org/document/8888485