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Design and Analysis of a Reconfigurable Triangular Microstrip Patch Antenna for C-Band Television Applications

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Abstract: This paper describes an innovative approach to designing a microstrip patch antenna for television band applications that makes use of metamaterial structures. The antenna is specially designed with four strategically placed metamaterial unit cells on a triangle patch and thoughtfully placed rectangular slots on a portion of the ground plane. The feeding mechanism uses a microstrip line configuration. To evaluate performance, advanced simulations were performed using HFSS Software. The antenna exhibits remarkable bandwidth expansion, covering frequencies ranging from 3.07 GHz to 8 GHz, spanning the C band. With an S-parameter value of -40.04 dB and a gain of 3.056 dBi, this antenna is adaptable and offers solutions for a range of applications in modern communication systems. This antenna makes a significant contribution to the field due to its carefully designed choices and thorough evaluation. Its small form factor and wide frequency coverage enable it to meet the demands of modern communication technology. Additionally, the performance and suitability for real-world applications are further enhanced by the 1.6 mm-thick FR-4 antenna substrate.

Keywords: Microstrip Patch; Metamaterial Structures; Ground Plane; Microstrip Line; HFSS Software; Bandwidth Expansion; Modern Communication; Wide Frequency; Real-World Applications.

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1. Introduction

In the world of wireless communication, microstrip patch antennas have gained attention due to their compact size, low profile, and ease of integration with contemporary electronic devices. To create a transmission line structure, these antennas consist of a ground plane on one side and a metallic patch printed on the other side of a dielectric substrate. They are appealing for many applications, from satellite communication and radar systems to mobile phones and wireless networking devices, due to their straightforward design, low manufacturing cost, and flexibility in shape and size. Since modern consumer electronics are

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designed to be compact and aesthetically pleasing, researchers and engineers face considerable difficulty when it comes to the size of antennas used in TV applications. This challenge arises from the frequency bands that are designated for television broadcasting. Modern television sets are not designed to accommodate large, traditional TV antennas, such as Yagi-Uda or log-periodic antennas, as they are often huge and heavy [12]. Furthermore, because TV frequencies are typically located in the lower microwave and VHF/UHF bands, a large physical antenna size may be required for effective operation. This conflict between the need for small, aesthetically pleasing designs and the size specifications required for optimal performance presents a significant challenge [7]. Therefore, engineers are tasked with developing innovative antenna designs and methods.

Additionally, with the development of digital television technologies, there is an increasing need to address the size issue as the shift to higher frequency bands—such as the UHF and VHF bands—becomes more widespread. With the ability to address the physical limitations and design specifications imposed by contemporary TV sets, microstrip patch antennas have attracted growing interest for television (TV) applications. Regarding television reception, microstrip patch antennas can be configured to function effectively within the designated frequency ranges for terrestrial broadcast signals, primarily the VHF and UHF bands. Due to their small size, low profile, and ease of integration, they are a great fit for installation within the streamlined form factors of modern television designs, meeting customers' desire for visually appealing electronics. Marongiu et al. [1] employ meta-materials with a negative refractive index to overcome the low transmission power and limited range issues in Wireless Power Transmission (WPT) [5]. To address these problems, this publication presents a Ferrite-core metamaterial WPT model. Finite Element Analysis (FEA) in ANSYS demonstrates superior performance in terms of mutual inductance and received power compared to conventional designs [2].

Notably, increased efficiency is achieved through reduced core radii, which can lower the cost of material manufacture. Marongiu et al. [1] use an On-board Fast Charger (OBC) in an electric vehicle (EV) as a case study to compare Wide Band Gap (WBG) devices, specifically GaN HEMT and SiC MOSFET. EV batteries have a higher capacity than silicon-based OBCs due to their limited power density. The paper describes the differences in operating and performance constraints between SiC MOSFET and GaN HEMT for OBC applications. The GaN HEMT exhibits lower operating voltage and higher switching frequency, as demonstrated through 25 MATLAB simulations, making it suitable for low-power charging applications [8]. Marongiu et al. [1] present a novel approach to understanding and enhancing Wireless Power Transfer (WPT) devices using a reduced circuit model and a unique material known as metamaterial (MM). The researchers closely examined the effects of this MM-based technique on wireless power transfer efficiency using mathematical analysis and computer simulations. Their approach can, in fact, improve the performance of WPT systems, as they verify by testing their theories on actual prototypes [6].

This study has the potential to improve the effectiveness and dependability of wireless charging in various scenarios [4]. The growing popularity of wireless charging has created a need for effective Wireless Power Transfer (WPT) systems with extended transmission ranges. Especially important for EV charging on the go and mobile chargers. However, problems at high frequencies cause power loss and component stress in current WPT designs that use metamaterials (MM) [15]. This study reviews the current state of MM-based WPT research, examining different technologies and how MM designs might improve performance by addressing issues such as size reduction and prototyping obstacles, modeling techniques, and operating frequencies. Rahman and Saifullah [5] utilize metamaterials in our new WPT model, which combines a multilayer coil with ferrite core metamaterials to increase power output above traditional designs. Better performance is achieved by fine-tuning the coil size and layer spacing.

Using smaller ferrite cores also keeps costs down without compromising power output. Our method is optimized for optimal efficiency using MATLAB software and rigorous computer simulations. The results show a good match with the data collected via experiment [1]; [14]. The Modified Comb Patch Antenna (MCPA), a novel microstrip antenna, is presented in this paper. It is constructed by joining several parallel wires to a single microstrip. Scientists used computers to verify the mathematical technique they had devised to comprehend and design it. When they tested the antenna's performance with signals, they discovered that adding more conductors enhanced the antenna's ability to process and strengthen the signals. They constructed and tested one with eighty conductors to validate their findings, and the outcomes closely matched their predictions [7].

This study examines a novel type of antenna that offers multidirectional signal transmission capabilities. With rectangular unit cells oriented at a 45-degree angle on a square foundation, it features a special type of ground structure known as an artificial ground structure (AGS). This configuration, known as a diamond-shaped AGS (DAGS), helps reduce undesired signal interference. Compared to conventional antennas, this one has a wider frequency range of operation and a more stable signal strength. Vithanawasam et al. [8] examine how the effective dielectric constant of the substrate is altered by periodic microstrip rampart lines to enhance the gain of conventional microstrip patch antennas. It proposes a high-gain microstrip antenna design that achieves a significant gain of 10.0 dBi, a 2.55 dB or 79.9% improvement over conventional antennas at 5.8 GHz, and introduces a method to estimate the frequency of gain augmentation. Both simulated and measured outcomes confirm the consistency of the conclusions.

The goal of this paper is to develop a small microstrip antenna with increased bandwidth and better indoor reception quality for digital TV [3]. With a frequency range of 2.402 GHz to 2.480 GHz, Bluetooth technology is utilized by the antenna to enhance reception and provide users with more programming options. The antenna, measuring 18 cm by 18 cm, exhibits exceptional performance with a bandwidth of 236.97 MHz, a VSWR of 1.0799, a gain of 4.1 dBm, and a return loss value of -28.31 dB, thanks to careful design and testing [4]. In this study, a novel three-ring microstrip circular patch antenna is presented. It is intended to operate in the 470MHz–806MHz white space TV band, which is currently unoccupied due to modifications to TV transmission. In contrast to conventional antennas, this one features three circular rings added to the patch and replaces the infinite ground plane with a finite one, enabling operation across the entire TV band (420 MHz to 810 MHz). With a gain of 1.3 dBi and a radiation efficiency of 92%, this enables the antenna to effectively utilize the white space TV band frequency.

Our research presents a novel approach to microstrip patch antenna design, tailored specifically for C-band satellite communication systems, including television dish applications. In our innovative design, both the radiating element (triangular patch) and the ground plane are co-located within the same plane. This configuration offers several significant advantages for antenna performance and connectivity. Furthermore, integrating the ground plane within the same plane as the antenna simplifies signal propagation and enhances signal integrity, which is critical for maintaining high-quality reception of television broadcasts in C-band frequencies. Additionally, the compact and streamlined nature of our antenna design makes it well-suited for integration into television dish systems, addressing space constraints while providing users with enhanced connectivity and improved performance for receiving satellite television broadcasts. Overall, our innovative microstrip patch antenna design signifies a significant advancement in antenna technology for C-band satellite communication systems, promising enhanced connectivity, performance, and reliability for television dish applications [9].

2. Antenna Design Methodology

The antenna structure presented features two ground surfaces on the same substrate plane, which enhances radiation pattern control while minimizing mutual coupling. A triangular patch divided into two slots also accommodates pin diodes for dynamic tuning, making it suitable for various wireless communication applications. The antenna is built from a FR4 substrate with a dielectric constant of 4.4 [10]. This material selection ensures that the antenna design performs well and remains stable. The equation is used to determine the width and length of the patch.

$$W_s = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

Where c is the velocity of light, f_r is the resonant frequency, and ε_r is the dielectric constant of the substrate.

$$L_s = L_{eff} - \Delta L$$

Where $L_{"eff"}$ is the effective length of the patch as follows.

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

Where $\varepsilon_{"eff"}$ is the effective dielectric constant given as follows

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

and ΔL is the extended incremental length given as follows

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

Analyzing transmission lines in microstrip using εreff's relative effective permittivity. With the use of εr value equations, the relatively effective permittivity magnitude may be used in place of space, which is made up of a mixture of air and dielectric [11]. The dimensional component values are then applied to the antenna design in HFSS simulation software. Create using the computation as a guide. Design based on the calculation results.

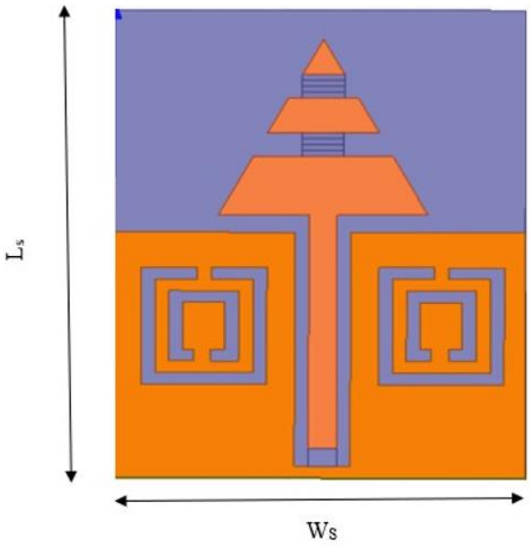

Figure 1: Structure of triangular patch

Figure 1 depicts the geometrical layout of the triangular slotted microstrip patch antenna. The antenna's substrate (FR4) dimensions are 59 mm in width (W) and 80 mm in length (L), and the substrate thickness is 1.6 mm with a dielectric constant of 4.3. It is composed of a triangular patch, which is divided into three sub-patches. Between the patches, there are slots (Figure 2).

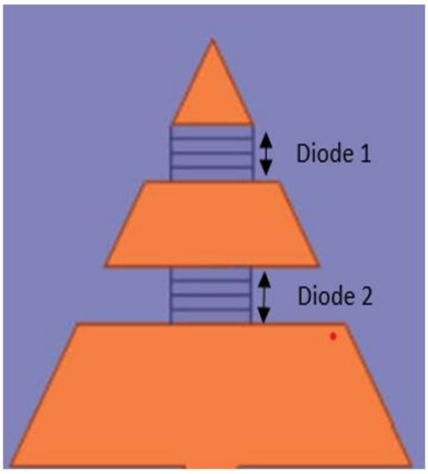

Figure 2: Step-graded varactor diode structure showing depletion regions (diode one and diode 2)

Each slot contains a PIN diode. The PIN diode is used for reconfiguration. The ground plane has a width of 25mm (WG) and a length of 42 mm (LG). There are two identical ground planes, which are placed in the same plane as the patch. The antenna consists of feedlines that are used to transfer radio frequency (RF) signals. The parameters are shown in Table 1.

Table 1: Parameters of the triangular patch antenna

Parameters	Description	Values(mm)
Ls	Length of substrate	22
Ws	Width of substrate	16
Lg	Length of ground	13.5
Wg	Width of the ground	2.3
Lp	Length of patch	13
Wp	Width of patch	10.6

2.1. Design of Antenna Patch

Patches are crucial in microstrip patch antennas, serving as compact and efficient radiating elements. The triangular patch is divided into two slots [13]. Each slot contains a PIN diode. The total length of the patch is 30 mm, and the width of the patch is 30 mm. The slot is incorporated with a PIN diode (Figure 3).

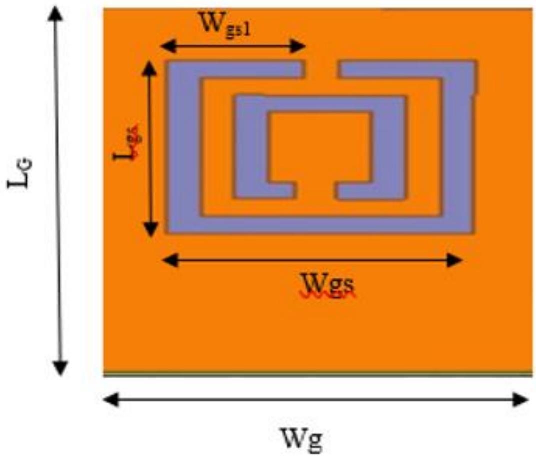

Figure 3: Structure of the ground plane

The integration of pin diodes within the slots of the triangular patch antenna design allows for dynamic tuning and reconfiguration of the antenna's operational characteristics (Figure 4).

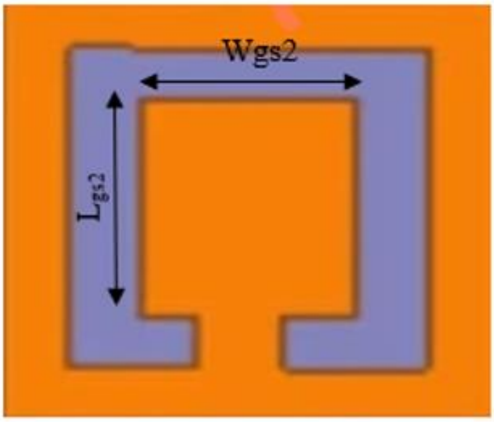

Figure 4: U-shaped slot geometry with labeled dimensions W_{gs2} and L_{gs2}

Pin diodes enable real-time adjustments to meet changing communication needs by giving precise control over the antenna's radiation pattern and resonant frequency. The dimensions of the antenna are further specified in Table 2.

Table 2: Parameters of the patch

Parameters	Description	Dimension(mm)
Lp1	Length of patch-1	6
Wp1	Width of patch-1	8
Lp2	Length of patch-2	6
Wp2	Width of patch-2	16
Lp3	Length of patch-3	10
Wp3	Width of patch-3	30

2.2. Designing of Ground Plane

The ground state is present on the same surface as the patch. There are two ground surfaces. Each is identical to the others. Antenna performance is improved by this configuration, which minimizes mutual coupling and reduces radiation losses. The fabrication and integration processes are made simpler by placing the grounds on the same surface. The proximity of the grounds to the patch enhances the impedance matching and overall antenna efficiency. This design strategy ensures a compact and efficient antenna solution for various wireless communication applications. The parameter is listed in Table 3.

Table 3: Structure of the ground plane

Parameters	Description	Dimension(mm)
L_g	Length of ground	42
W_g	Width of the ground	25
L_{gs}	Length of ground slot	20
W_{gs}	Width of the ground Slot	18
L_{gs1}	Length of ground slot	8
L_{gs2}	Length of ground slot 2	12
W_{gs2}	Width of ground slot 2	10

3. Stimulation Result and Analysis

3.1. Reflection Coefficient

An important factor in determining an antenna's performance is the reflection coefficient, also referred to as return loss and represented by (S11) (Figure 5).

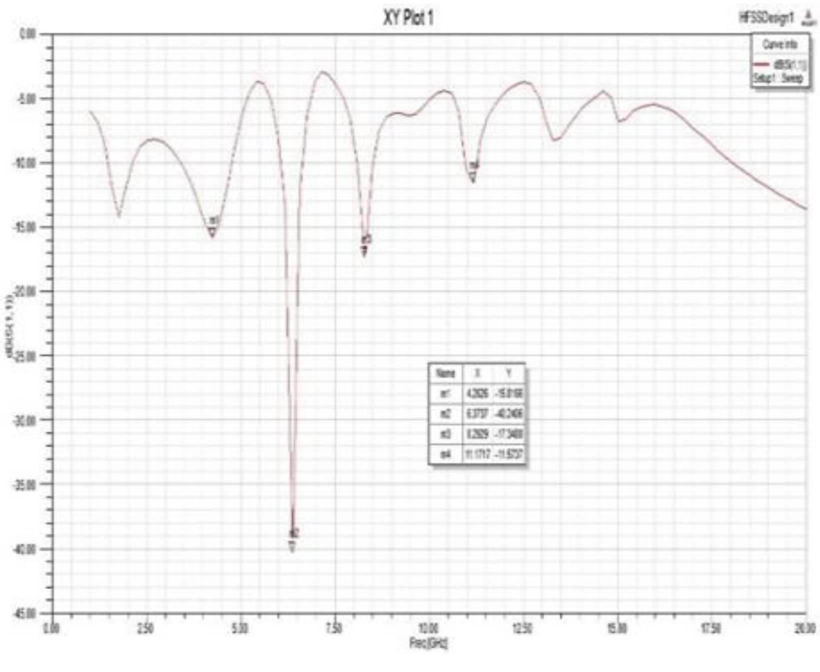

Figure 5: Return loss (diode-1 is off)

An effective antenna must have a high reflection coefficient, which is commonly expressed in dB. A return loss of at least -10 dB or greater than -15 dB is generally regarded as desirable, as it indicates that the antenna reflects the least amount of power back to the source (Figure 6).

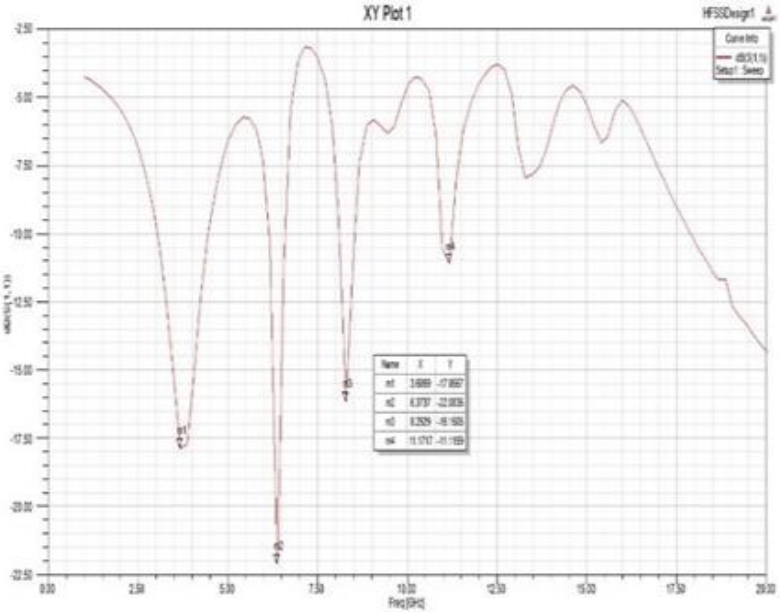

Figure 6: Return loss (diode-2 is off)

In our analysis, as shown in Figure 5, we found a return loss of -40.84dB, indicating that the antenna performed very effectively. An antenna that effectively radiates the majority of the incident power and ensures high-quality signal transmission is suggested by such a substantial return loss (Figure 7).

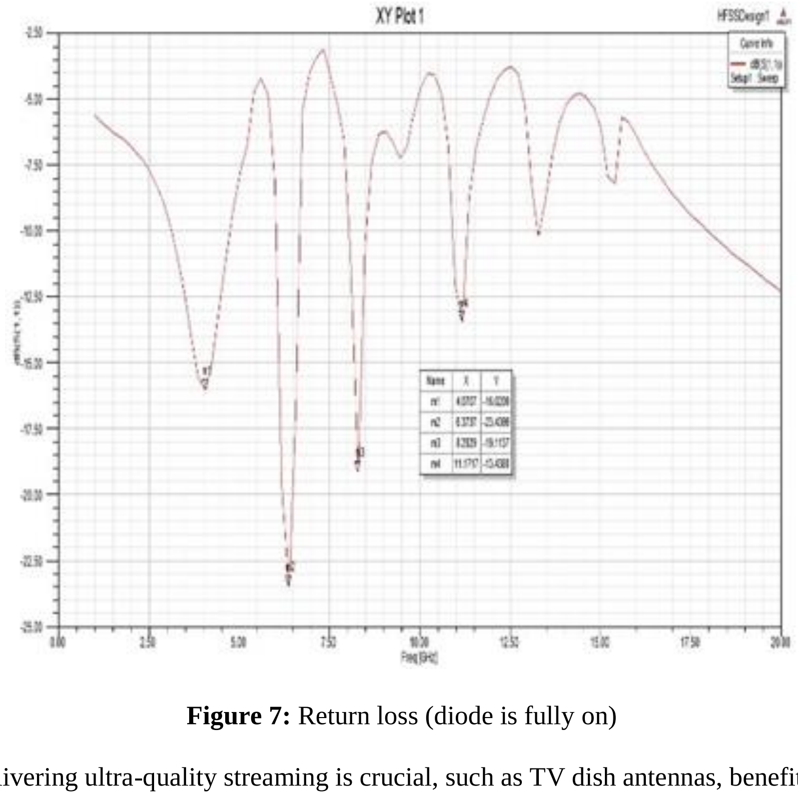

Figure 7: Return loss (diode is fully on)

Applications in which delivering ultra-quality streaming is crucial, such as TV dish antennas, benefit greatly from this level of return loss (Table 4).

Table 4: Return loss

Switch	Frequency	Return loss
Diode-1 is ON	4.2626	-15.81
	6.373	-40.24
	8.29209	-17.3488
	11.1717	-11.5737
Diode-2 is OFF	3.6869	-17.8567
	6.3737	-22.085
	8.2929	-16.150
	11.1717	-11.159
The diode is fully ON	4.0707	-16.0209
	6.3737	-23.4399
	8.2929	-19.1137
	11.1717	-13.4388

3.2. VSWR

Obtaining a VSWR value of 1 at 6.373 GHz demonstrates the perfect impedance matching achieved by our antenna system, as described in our journal paper. VSWR is a crucial metric for determining matching efficiency, with a value of 1 indicating optimal power transfer from the source to the load with no reflections. By minimizing signal loss and optimizing overall antenna performance, this result indicates maximum power transfer (Figure 8).

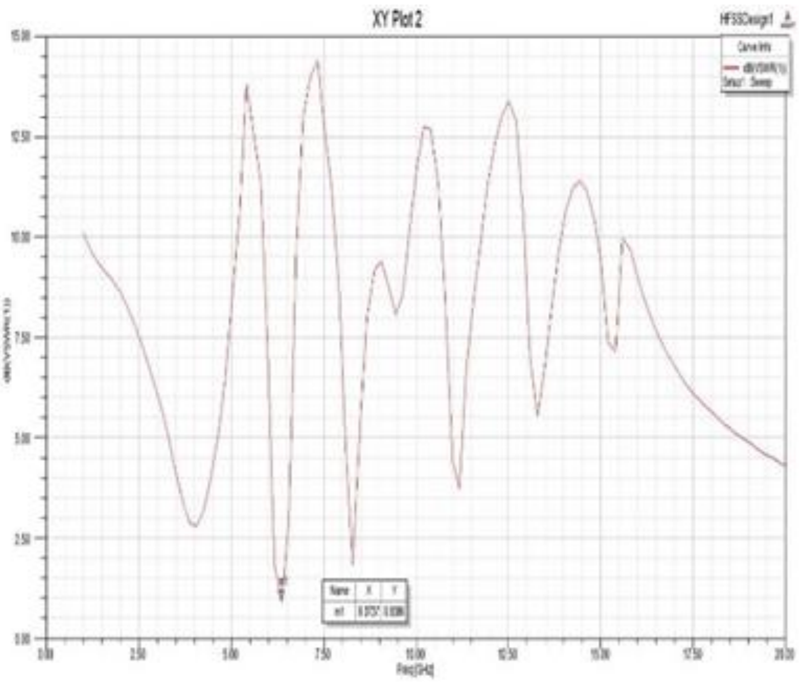

Figure 8: VSWR

In the context of our research, the precise impedance matching at 6.373 GHz demonstrates the antenna's ability to efficiently transmit and receive electromagnetic waves within this frequency range. For high-frequency applications, such as satellite communication and radar systems, this level of accuracy is crucial. Our findings on the VSWR value of 1 at 6.373 GHz underscore the careful design and optimization of our antenna system, paving the way for enhanced performance and reliability in various applications.

3.3. Radiation Pattern

Figures 9, 10, and 11 illustrate the 3D radiation patterns, respectively, showcasing gains of 3.149 dB, 3.128 dB, and 3.056 dB.

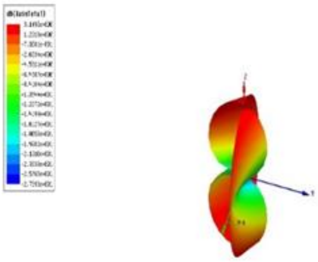

Figure 9: Radiation pattern diode-1 off

Gain of the antenna is crucial for TV dish systems because it is directly related to the amount of power the antenna radiates.

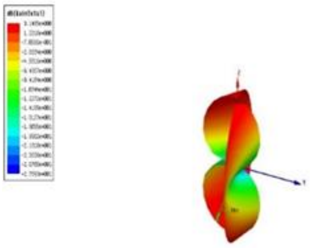

Figure 10: Radiation pattern diod-2 off

These radiation patterns are crucial for optimizing the performance of TV dish systems, as they provide valuable insights into the antenna's ability to efficiently send and receive signals.

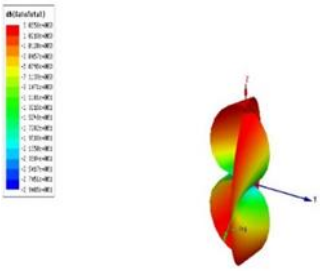

Figure 11: Radiation pattern of the diode fully on

Table 5 illustrates how the gain varies with the diodes' state. For example, when Diode-1 is OFF, the gain is 3.149 dB, when Diode-2 is OFF, it is 3.284 dB, and when both diodes are fully ON, it is 3.055 dB.

Table 5: Gain at different modes

Switch	Gain
Diode -1 OFF	3.149 dB
Diode - 2 OFF	3.284 dB
Diode fully ON	3.055 dB

4. Result and Discussion

Advanced simulations using HFSS Software demonstrate that the antenna exhibits remarkable bandwidth expansion, covering frequencies ranging from 3.07 GHz to 8 GHz. Its broad bandwidth coverage makes it suitable for a range of communication systems, ensuring compatibility with various communication standards and applications across the C-band.

4.1. Pin Diode

To facilitate reconfiguration, pin diodes are carefully integrated into the triangular patch of the microstrip antenna. This allows for dynamic control and modification of the antenna's performance characteristics at the radiating element level. We can change the electrical characteristics of the triangular patch and enable different reconfiguration functionalities across different frequency bands, such as the C band, by selectively biasing these pin diodes. Pin diodes specifically allow reconfiguration by changing the effective electrical dimensions and features of the triangle patch. This capability enables several critical functions, including beam steering, frequency tuning, pattern reconfiguration, and multiband operation. By incorporating pin diodes directly into the triangular patch of the microstrip antenna, we achieve a compact and efficient reconfigurable antenna design suitable for C-band applications. The antenna is ideally suited for contemporary communication systems that require dynamic adaptation to changing operating conditions and frequency bands, thanks to its flexibility, versatility, and optimized performance.

4.2. Ground

The ground structure in our antenna design is situated on the same plane as the patching elements. This means that the ground plane is level with the antenna's other components, such as the triangular patch and metamaterial unit cells. To achieve the best performance characteristics, we ensure uniformity and symmetry in the antenna's structure by positioning the ground plane on the same plane as the patch elements. To enhance the antenna's performance, we have also incorporated rectangular slots into the ground plane. To achieve specific goals, such as enhancing impedance matching, modifying the radiation pattern, and reducing surface wave propagation, these slots are strategically placed and designed with a purpose. The positioning of these slots on the same plane maximizes the efficiency of these design elements. The ground structure ensures that the electromagnetic fields produced by the antenna interact. In general, we maximize the antenna's performance in the C band, as well as in other required frequency bands, by placing the ground structure on the same plane as the patching parts and adding rectangular slots. Due to the continuous impedance characteristics, radiation patterns, and signal transmission/reception efficiency guaranteed by this design technique, the antenna is suitable for a wide range of communication applications.

4.3. Gain (dBi)

In comparison to an ideal isotropic radiator, gain is the antenna's capacity to concentrate radiation in a certain direction. The gains attained in the antenna design based on three modes are 3.149 dB, 3.284 dB, and 3.055 dB. With a maximum gain of 3.284 dBi in this instance, the antenna can focus radiation more effectively in specific directions. Greater gain indicates superior directivity, which is particularly important in communication systems where signal strength and coverage need to be optimized. With a gain of 3.284 dBi, the antenna exhibits efficient radiation properties, thereby enhancing its ability to transmit and receive signals effectively within the C-band.

4.4. S-parameter Value (dB)

The S-parameter value, or S11 in this case, measures the antenna's reflection coefficient, which is the quantity of signal that is reflected to the source or transmission line. The S-parameter value for the antenna under discussion is -31.88 dB, which denotes minimal transmission losses and good signal transmission efficiency. Improved impedance matching between the transmission line and antenna reduces signal reflections and ensures effective power transfer, as indicated by a lower S-parameter value. In communication systems, this feature is crucial for maximizing signal transmission and reception, especially in the C band, where signal integrity and dependability are critical. Overall, the antenna's gain and parameter value highlight its effective radiating qualities and minimal transmission losses, which make it ideal for C-band communication systems that want to maximize signal transmission and reception. These qualities are necessary to guarantee high-performance and dependable communication over a wide frequency range.

5. Conclusion

Finally, we describe a unique microstrip patch antenna design optimized for direct-to-TV communication in the C-band frequencies. We have achieved a 3 dB gain through careful optimization, ensuring stable and dependable signal transmission and reception for television dish applications. This gain increase is crucial for enhancing the antenna's ability to capture and transmit TV signals effectively, especially in areas with challenging reception conditions. With a 3 dB gain, our antenna design improves signal strength and coverage, resulting in better picture and sound quality for TV viewers. Furthermore, our antenna design promises increased adaptability and agility in meeting changing communication needs by laying the groundwork for future advances in control and reconfigurability. By leveraging these capabilities, we aim to maintain our antenna at the forefront of innovation, delivering exceptional performance while addressing the evolving needs of TV communication systems. All things considered, our work advances the state of antenna technology for television communication and presents a viable method to enhance the quality of signals received and transmitted in the C-band.

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Ethics and Consent Statement: This research adheres to ethical guidelines, obtaining informed consent from all participants.

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