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A Novel Circular Ring Microstrip Patch Antenna for Bandwidth Enhancement and Harmonic Suppression

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Abstract

The study presented aims to design a new patch antenna with improved bandwidth and effective rejection of spurious modes and harmonics. This design contains two λ/4 resonators that are closely connected to a circular ring patch. The proposed antenna exhibits wide bandwidth due to dual resonances created by means of a novel ring-shaped radiating patch with a decagonal-shaped inner ring and non-radiating λ/4-length resonators. The decagonal shape's unique geometry optimizes electromagnetic field distribution, enhancing control over radiation patterns and impedance matching. This design choice distinguishes the antenna from traditional circular patch antennas, as it effectively addresses the challenge of spurious modes and harmonics. This dual-resonance patch antenna design is distinctive because it does not require an electrically thick substrate. The resonators and the proximity feeding system are essential in efficiently minimizing the emission of harmonic radiating modes. This decrease is important for today's requirements for the level of integration with various types of communication systems. A prototype antenna was designed and fabricated to work at 2.4 GHz. The simulated and measured results of the designed and fabricated antenna show that the antenna's bandwidth is seven times greater than that of a traditional circular patch antenna. Additionally, it efficiently reduces the emission of unwanted radiation from higher-order modes. This antenna will be utilized in devices designed for the purpose of capturing RF energy and wireless power transfer.

Keywords: Circular Patch Antenna, Decagonal Shape, Harmonic Suppression, Microstrip Patch Antenna, Partial Ground Plane, $\lambda/4$ Resonator.

Introduction

Mirostrip patch antennas have gained a very significant position in today's modern communication systems due to their unique characteristics and versatile operations (1). These antennas are preferred for their small size and flattened structure and can be fitted in almost all communication gadgets, like smart phones, tablets, IoT gadgets, and wireless sensors (1). Microstrip patch antennas are popular for use and preferred for mass production because they are easy to fabricate using PCB. This makes it possible to design and correspond depending on the designs required for a certain organization or system (2). One advantage of such antennas is their ability to achieve extended frequency tunability, due to which a single small form factor antenna can support a variety of the frequency bands and communication standards (3). In addition, such antennas can also be designed to obtain an end fire radiation pattern, which allows the transmitted signal to be directed in a given direction only. This increases the reach of the communication signals as well as their amplitude (4). Polarization ability can be varied in different manners so that linear, circular, or elliptical antennas can be formed to satisfy the needs of the communication system. Also, multi-frequencies can be easily achieved by microstrip patch antennas through the modification of patch size and orientation as well as feed structure (5). This makes it possible for the radio to respond to several aspects of communication standards and different frequencies. Some of these antennas can also be integrated together with other RF devices, such as filters, amplifiers, and matching networks, using the said substrate. This means that small and efficient RF front-end designs can be developed. Fortunately, by using complicated design methods, the presence of harmonics and unwanted radiation in microstrip patch antennas can be reduced, thus leading to an efficient signal in communication systems (6). The significance of microstrip patch antennas in today's communication networks is due to factors such as size, ease of fabrication,

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operating frequency range, directive nature, polarization, frequency selection, integration, and harmonic control features. These properties make them excellent entities that are commonly used in several wireless communication systems (7).

To reduce harmonics and improve bandwidth, various techniques have been proposed in the literature. An example of such a technique, described in (8), employs microstrip patch inset feed along with defective ground structure. This antenna was designed for a 2.45GHz resonance frequency. The microstrip line used in this research has the substrate material selected as FR4. Inclusion of single or additional slots at the foremost edges of the antenna ground plane removes higher order harmonics, hence eliminating additional unnecessary circuits. These modifications in the dimensions of the circular patch antenna design optimize the performance of such an antenna and do not require additional components. The reflection coefficient obtained at 2.45 GHz was -38.75 dB; the described antenna effectively suppressed higher-order harmonics from -38.04 dB to -2.61 dB at 4.54 GHz and from -13.08 dB to -1.38 dB at 5.76 GHz (8). In the study by Wanli Ma (9), a microstrip patch antenna was developed that operated at a fundamental frequency of approximately 2.45 GHz. This antenna successfully suppressed the second, third, and fourth harmonics of the fundamental frequency. The attenuation was achieved by incorporating two impaired ground structures designed in the shape of dumbbells, which were strategically positioned beneath the feed line.

In another study, researchers proposed a U-shaped defect in the micro-strip patch antenna feed line to suppress second harmonic frequencies for a 3.55 GHz antenna. The proposed design incorporates two U-shaped DMSs; the first, a long U-shape DMS, aims to minimize the second harmonic, while the second, a short U-shape DMS, attempts to suppress the third harmonic. Upon comparing the return loss profiles of the first, second, and third harmonic frequencies, it becomes apparent that the proposed patch antenna has better harmonic suppression than conventional microstrip patch antennas (10).

One method of mitigating harmonic generation in microstrip patch antennas involves integrating a spur line filter into the design. This method was utilized in the creation of a 2.45 GHz microstrip antenna, wherein the feed line design was altered to incorporate spur line filters for the attenuation of second and third harmonic frequencies. The antenna also utilizes an inset feed technique coupled with a quarter-wavelength transformer to achieve impedance matching. This approach has proven highly effective in suppressing higher-order harmonics, leading to improved antenna performance (11).

In recent years, a key strategy for reducing harmonics in array antennas for wireless power transfer (WPT) has been the use of defective ground structures (DGS). One notable technique involved an array antenna operating at 2.45 GHz, which had the capability to reduce or block the first four harmonics of the base frequency. This was achieved by the integration of rectangular slot-defective ground structures (12).

In their work Li *et al.* (13) proposed a radiating element with a square ring slot and two side slots. In addition, their antenna design incorporated a transverse opening at the bottom, aligned parallel to the microstrip feed line, serving as a unit for harmonic control. Another advantage is that the microstrip feed line extends through the slot ring, thereby reducing harmonic levels. Another approach to achieving adequate bandwidth and harmonic suppression involves incorporating quarter-wavelength stepped impedance resonators at the antenna interface (14). Similarly, two $\lambda/4$ length micro-strip line resonators were used and positioned adjacent to the rectangular patch with a view to obtaining capacitive coupling (15). Evaluation of the two resonances associated with the radiating rectangular patch and non-radiating $\lambda/4$ resonators enables the realization of wideband characteristics. Consequently, it was found that the return loss of the antenna effectively controlled the bandwidth, which was 2.7 times higher than its counterpart antenna (15).

Along with the above techniques, many efforts have been made to obtain efficient harmonic rejection and improvements in bandwidth. A few of the methods suggested in the literature for bandwidth improvement are aperture coupling feed (16) and proximity coupling feed (17), along with the use of stacked patches (18–20). But these methods require multiple layers of substrates, and hence the fabrication unit is more complicated and costly. Instead of using a stacked multiplayer substrate, the single-layer substrate is most likely preferred for enhancing the patch antenna bandwidth. When analyzed, patch antennas can be pictured as resonators with certain losses. If another resonator resonates besides the patch radiating element, this could lead to an improvement in bandwidth. There is a substantial increase in bandwidth if additional resonance is introduced with the main resonating patch. Some methods commonly advanced by researchers include different fed (21–23) and creating different shapes in radiating patches (24–25). A low-profile monopole antenna design with a double-crescent-shaped patch and a partial ground plane attained a notable 38% bandwidth (1.91 GHz to 2.81 GHz), rendering it appropriate for diverse wireless communication applications (26). A study examined the implementation of a cross-dumbbell-shaped defective ground structure to mitigate the intrinsic narrow bandwidth restrictions of a bow-tie microstrip patch antenna (27). The implemented DGS technique resulted in a significant improvement in bandwidth, increasing the fractional bandwidth from 2.6% to 10.45% for a center frequency of 3.67 GHz.

A study demonstrated a novel technique to enhance both the bandwidth and gain of a rectangular microstrip patch antenna. By incorporating slots into the rectangular patch, a significant bandwidth improvement from 425.2 MHz to 920 MHz was achieved, resulting in a 494.8 MHz enhancement (28).

To decrease antenna size and increase bandwidth, a coaxial feed patch antenna with a thumb-shaped defected ground structure (DGS) is suggested (29). The DGS produces two resonant frequencies flanking the operational frequency, hence minimizing the antenna's dimensions.

One study developed a circularly polarized microstrip patch antenna using a stacking technique, incorporating two slots on the primary radiating patch and one cross slot on the near-field resonating parasitic patch. The antenna featured an altered Hilbert shape that resonates at 900 MHz and 1890 MHz and provided an impedance bandwidth of 265 MHz and 120 MHz at respective frequencies (30).

Similar to bandwidth improvement, for harmonic suppression, different techniques are proposed, such as the use of a filer with a patch (31), but this leads to additional losses and size. EBG, PBG, and DGS are among the typical methods focused on harmonic rejection (32,33).

A novel rectangular patch antenna design achieved harmonic suppression by strategically placing differential signals at specific locations, resulting in an 8.6% impedance bandwidth without the need for traditional filtering techniques. This design effectively suppressed harmonics around 3.4 times the center frequency (34).

The proposed antenna distinguishes itself from current designs aimed at enhancing bandwidth and suppressing harmonics through several innovative features and methodologies. The antenna features a unique circular ring structure with a decagonal inner ring, a design not previously utilized in any traditional circular ring microstrip patch antennas. This geometry enhances radiation characteristics and improves control over resonant modes, resulting in a significant increase in bandwidth. The integration of two $\lambda/4$ resonators next to the radiating patch is a key feature that introduces additional resonant frequencies, broadening bandwidth and effectively suppressing higher-order harmonics.

The proposed antenna uses a partial ground plane to reduce size while effectively suppressing harmonics. This approach contrasts with conventional designs that often require complex multi-layer substrates, leading to higher fabrication costs and complexity.

Methodology

The progressive evolution of antenna designs is illustrated in Figure 1, which demonstrates a sequence of modifications that result in enhanced designs. The development starts with a simple circular patch antenna and culminates in decagonal inner ring type circular patch. Each iteration adds significant improvements aimed at improving the performance of the antenna.

Figure 2 depicts a circular patch antenna, which is designed for 2.4GHz frequency using FR4 substrate having thickness of 1.6mm with dielectric constant of 4.4. The radius ‘a’ of the circular patch is calculated from the following formulae (Eq. [1]-[4], 35).

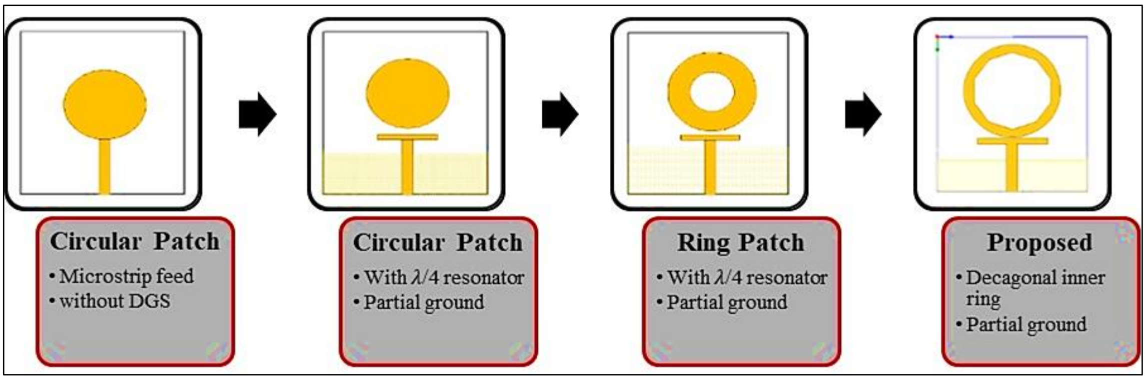

Figure 1: Progression of Proposed Antenna Design

$$a = F\left\{1 + \frac{2h}{\pi F \varepsilon_r}\left[ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{\frac{-1}{2}} \quad [1]$$

Where

$$F = \frac{8.791 \times 10^9}{f_r} \quad [2]$$

Here f_r is in GHz. h (height of substrate) in mm

$$a_e = a\sqrt{\frac{2h}{\pi a \varepsilon_r}\left[ln\left(\frac{\pi a}{2h}\right) + 1.7726\right]} \quad [3]$$

Here

a: circular patch radius, F: fringing field,

h: substrate thickness, ε_r : relative dielectric constant,f

a_e: effective radius,

Circular patch resonating frequency (fr)

$$f_r = \frac{1.8412\, v_0}{2\pi a_e \sqrt{\varepsilon_r}} \quad [4]$$

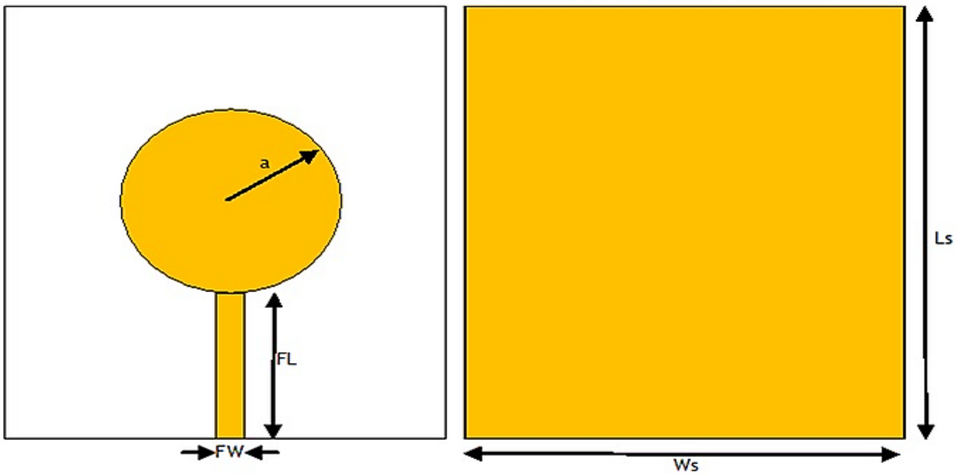

Figure 2: Basic Circular Patch Antenna

Table 1: Circular Patch Antenna Design Values

Design Parameter	Optimized Dimension in mm
Substrate length (Ls)	60
Substrate width (Ws)	56
Feed line width (FW)	1.5
Feed line length (FL)	18.5
Radius of patch (a)	18

The major disadvantage of basic patch antennas results from the need to use a thin substrate, which contributes to formation of a limited bandwidth. An improvement in bandwidth can be obtained by creating multiple resonances, and using structures that provide dual resonance can improve the bandwidth of a simple patch. Table 1 summarizes the design values for basic circular patch antenna. Figure 3 shows a modified circular patch antenna utilizing two non-radiating $\lambda/4$ resonators arranged near the circular patch antenna. To ensure a balanced enhancement in the antenna's operation, place the resonators completely symmetrically. This modified antenna uses capacitive coupling among the circular radiating patch and the $\lambda/4$ resonators. These resonators introduce additional resonant modes that work in tandem with the main radiating element, allowing for a broader operational bandwidth while simultaneously suppressing unwanted harmonic frequencies. The careful spacing between the $\lambda/4$ resonators and the radiating patch is crucial, as it optimizes the capacitive coupling, which is instrumental in reducing harmonic radiation. To accomplish this, the resonators are positioned at a particular length (represented as $d1$) away from the patch to facilitate the transfer of power through an electric field. The gap between the patch and resonators $d1$ mainly affects the levels of coupling and overall performance boosting.

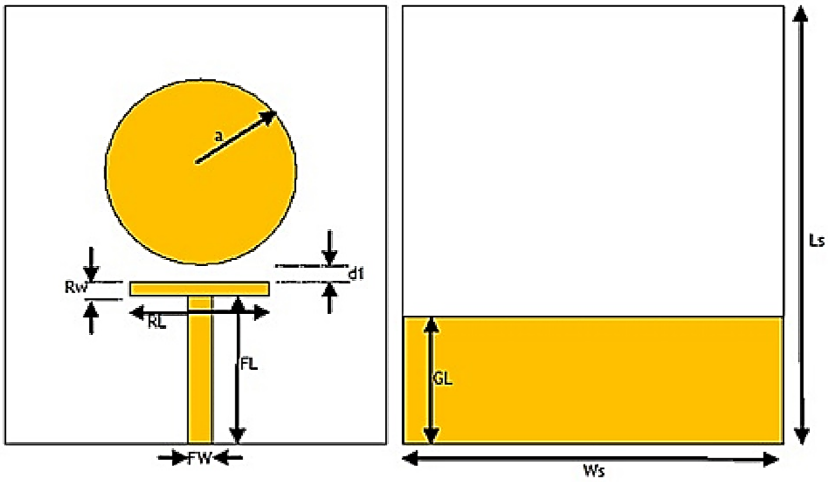

Figure 3: Circular Patch Antenna with $\lambda/4$ Resonators and Partial Ground

The coupling gap width 'd1' should be carefully considered in the evaluation of broad band performance because it corresponds to two very significant frequencies. Thus, the gap's size can be modified to decrease the space between two frequencies that resonate. So, it is possible to get wider pass bands by combining two narrow ones. This feeding technique also enhances the bandwidth and eliminates the unwanted higher-order mode in the patch radiator efficiently. In addition to bandwidth, for the purpose of improving impedance matching, the antenna shown in Figure 3 is structured with partial ground. Employing a partial ground plane mitigates the antenna's tendency to radiate surface waves. These surface waves can contribute to the excitation of higher-order modes, which are associated with undesirable harmonics. A reduced ground plane restricts the propagation of these waves, thereby diminishing harmonic radiation. This alteration enables better travel of power from an antenna to the feed line by enhancing voltage standing wave ratio (VSWR) and return loss (15). Figure 4A depicts further modified versions of the antenna shown in Figure 3. The deployment of the two $\lambda/4$ resonators technique remains unchanged, except that a circular ring patch has been used in place of the circular microstrip patch. When this modification is made together with a plane that is partly grounded, it helps in matching the impedance and general performance of the working antenna. The proposed design, which replaces the inner circular ring with a decagonal-shaped inner ring, is shown in Figure 4B. This design increases the bandwidth and provides better radiation characteristics than the circular ring design.

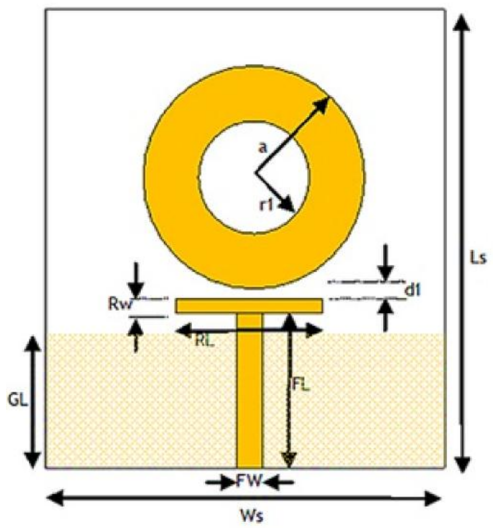

Figure 4A: Circular Ring Patch Antenna

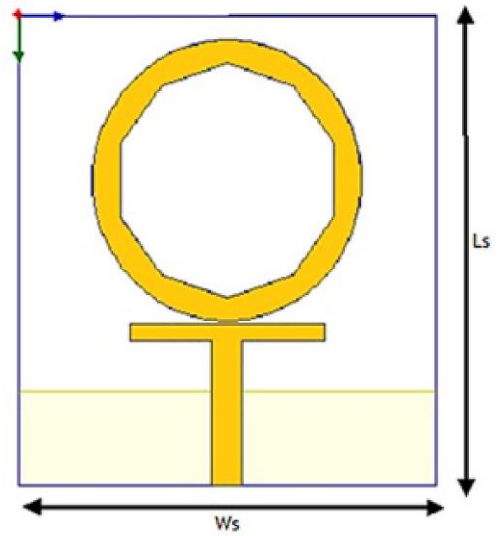

Figure 4B: Proposed Antenna

Table 2: Optimized Proposed Antenna Specifications

Design Parameter	Optimized Dimension in mm
Substrate thickness (h)	1.6
Substrate length (Ls)	60
Substrate width (Ws)	56
Feed line width (FW)	1.5
Feedline length (FL)	18.5
Radius of patch (a)	18
λ/4 resonators width (RL)	26
λ/4 resonators length (Rw)	2
Spacing between patch and resonator (d1)	0.5
Length of ground plane (GL)	12
Radius of inner circle (r1)	15

The decagonal shape's geometric complexity allows for more effective control over the current distribution helps in minimizing the emission of higher-order modes. The proximity feeding system integrated into the antenna design further aids in efficiently managing the energy distribution, thereby reducing the likelihood of harmonic generation. Table 2 shows optimized dimensions of the circular ring and modified decagonal inner ring antenna.

Results and Discussion

Traditional Circular Patch Antenna

The outcomes pertaining to the simulated circular patch antenna shown below were simulated with the help of HFSS V15. Figure 5 shows the reflection coefficient obtained after simulation of the circular-shaped patch antenna. Several peaks of harmonics and spurious modes are present in the graph. The simulation also confirms and highlights the narrow bandwidth characteristics of the traditional circular-shaped patch. The obtained bandwidth after simulation for 2.4 GHz circular shape patch antenna is around 158 MHz.

The simulated data show that for the patch radius a = 17 and the fundamental mode frequency of f = 2.4 GHz, the output consists of multiple low points. These dips are higher-order mode and spurious modes. Compared to the fundamental mode, higher-order modes are electromagnetic modes that take place at a higher frequency in microstrip patch antennas. These arises due to patch geometry and dielectric substrate and additional resonances in the frequency response or multiple dips and peaks.

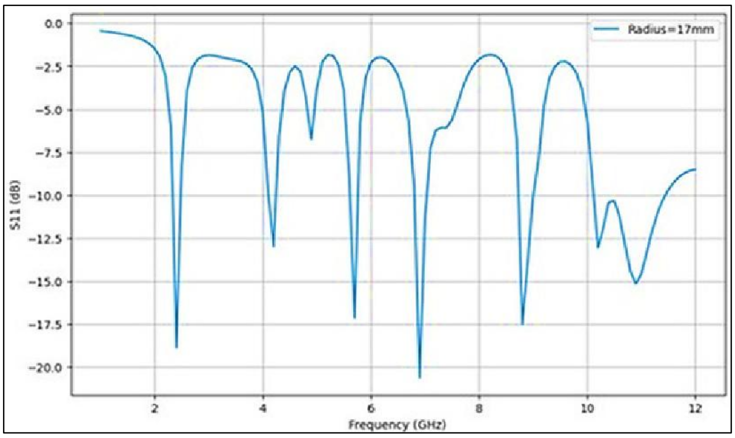

Figure 5: Reflection Coefficient of Circular Patch Antenna

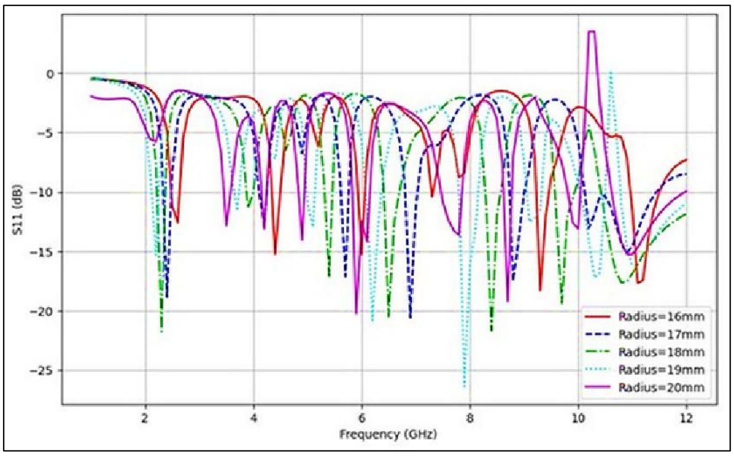

Figure 6: Patch Dimension Effect on Resonance Frequency and Reflection Coefficient

The simulation result for the change in radius 'a' of the circular patch is depicted in Figure 6. The above results reveal an inverse relationship between the antenna's radius and its resonance frequency. Therefore, for a decrease in radius, the point of resonance will increase, and when the radius of the patch increases, the center frequency also reduces or goes towards the left side.

Circular Ring Type Patch Antenna with λ/4 Resonator

The design shown in Figure 4, has a smoothing circular ring which in general offers very sharp peak of resonant frequency. This is confirmed by the simulation findings shown in Figure 7. For this type of patch antenna, resonant frequency can be calculated precisely, and also have less complex current distribution. The suppression of harmonics is quite beneficial in designing the antenna since it seeks to reduce radiation at harmonic frequencies, thus enhancing the performance of the developed antenna and reducing undesirable interference. The S11 plot has been shown in Figure 7. It indicates harmonics of order fourth successfully suppressed by ring circular and decagonal inner ring circular patch antennas. The microstrip line-fed patch has higher order radiating modes in addition to the fundamental modes. However, most of these were absent from the simulation characteristics of the proposed patch antennas depicted in Figure 6, thus justifying the rejection of harmonic radiation.

From the simulation results of a circular ring type patch antenna, it is observed that the degree of partial grounding can significantly affect both the resonance frequency and the radiation characteristics of circular patch antennas. This method may be used to strengthen some of the parameters, such as antenna radiation patterns, bandwidth, and proper impedance matching. It further involves creating a ground plane beneath the antenna, but not a full ground plane.

A decagonal shape is used to form the inner circle of a ring-type patch antenna instead of a smooth circle. The resonance frequency gets slightly shifted as the electrical current flow is changed due to different sides of the decagon from the full circle. Since this shape has some extra resonant modes, bandwidth is affected too.

The new geometry of the decagonal inner ring has decagonal nodes, which means new modes of resonance are likely to be introduced, and this may have an impact on the bandwidth. The complex geometry leads to a slightly wider bandwidth due to the added edge effects and different fringing fields.

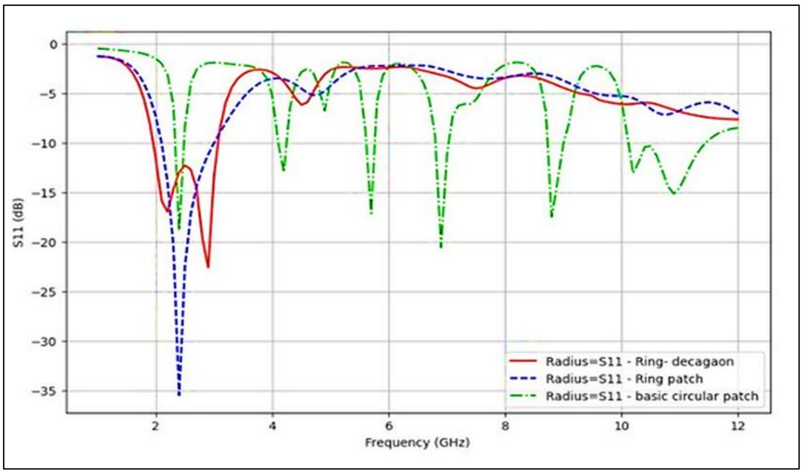

Figure 7: Comparison of Return Loss of Basic Circular Patch, Ring Circular and Modified Ring Circular Path

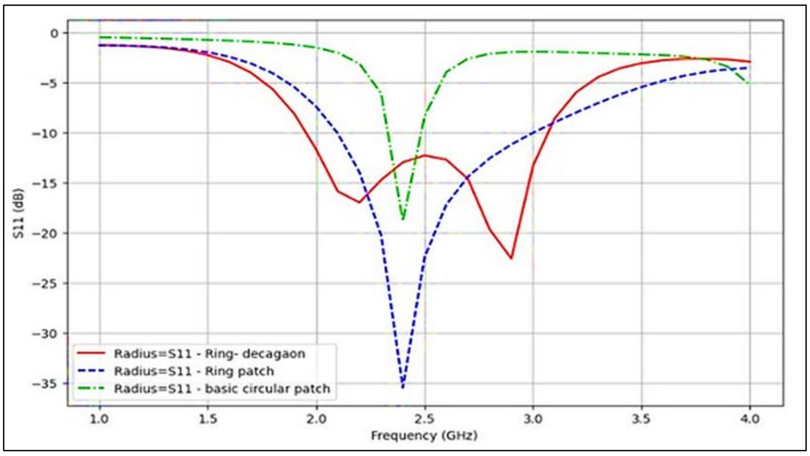

Figure 8: Comparison of Bandwidth and Return Loss

Table 3: Bandwidth Comparison of All Three Antennas

Antenna Design	BW (MHz)	Freq. Range (GHz)	% BW
Circular Patch Antenna	158	2.333-2.4906	6.53
Ring Circular Patch Antenna	903	2.1000-3.0027	35.38
Decagonal Inner Ring Circular Patch	1156	1.9442-3.0999	45.82

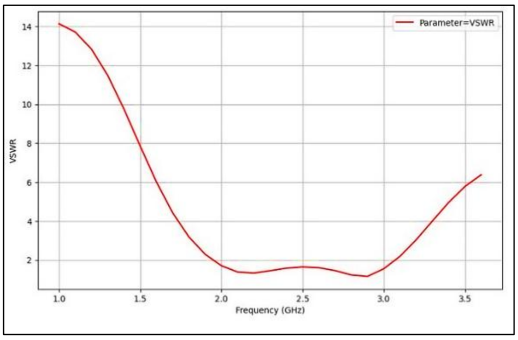

Figure 9A: VSWR Plot of Proposed Antenna

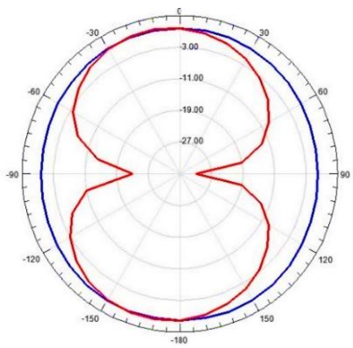

Figure 9B: Radiation Pattern of Proposed Antenna

Figure 8 and Table 3 shows that bandwidth of proposed decagonal inner ring circular patch antenna has been enhanced by 7 times than that of simple circular micro strip line feed antenna.

Figure 9A presents the Voltage Standing Wave Ratio (VSWR) plot, which illustrates the impedance matching between the designed antenna and the feed line. Additionally, Figure 9B plot provides insights into the antenna's radiation characteristics, highlighting the directionality and spatial distribution of the emitted electromagnetic waves. The proposed antenna demonstrates a bandwidth, defined by the VSWR, ranging from 1.94 GHz to 3.07 GHz, corresponding to a fractional bandwidth of 45.11%. This wide bandwidth indicates the antenna's capability to operate effectively over a broad frequency range, making it suitable for various communication applications.

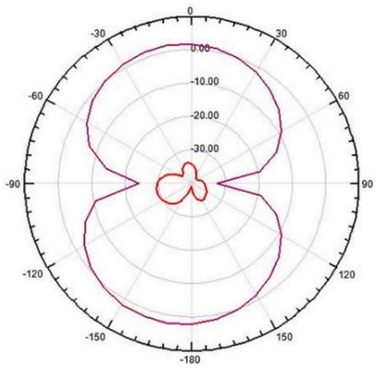

Figure 10A: Polarization Patterns in E Plane

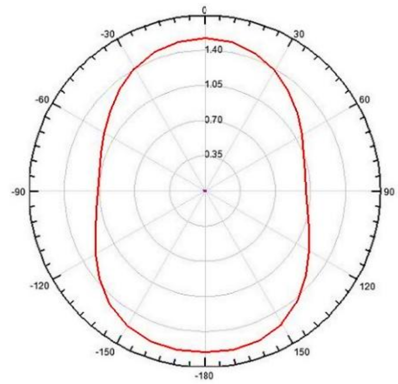

Figure 10B: Polarization Patterns in H Plane

The simulated co and cross polarization patterns of the proposed antenna in E-plane and H-plane at 2.4 GHz depicted in figure above. In the E-plane radiation pattern shown in Figure 10A reveals a bidirectional characteristic, while in Figure 10B co and cross polarization patterns in H-plane shows an omni-directional characteristic. For E-plane, cross polarization is much smaller (around 35dB) than the co polarization. For H-plane cross polarization almost absent. This indicates that antenna is very efficient in maintaining polarization purity in H-plane.

The proposed patch antenna was fabricated using FR4 substrate. The measured results of antenna are provided above in Figure 11.

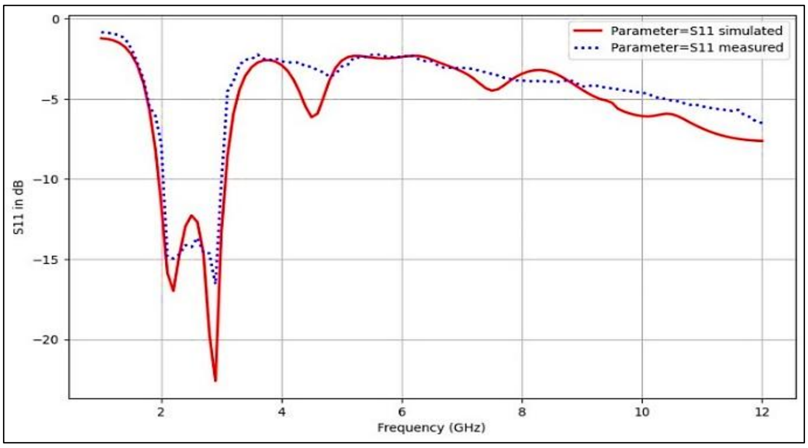

Figure 11: Propose Antenna Results - Simulated vs Measured

Table 4: Proposed Antenna Comparison with Other Designs

Ref No	Freq. (GHz)	BW (MHz)	Modes suppressed	Method
(8)	2.4	100	2	DGS
(9)	2.4	80	3	DGS
(10)	3.5	90	3	DMS

(11)	2.4	80	3	Spur-Line Filter
(12)	2.4	80	3	DGS
(13)	2.4	720	3	Slot
(14)	3.5	200	2	$\lambda/4$ SIR
(15)	4.9	410	4	rectangular patch and two $\lambda/4$ resonators in the feeding line sect
Proposed	2.4	1156	4	$\lambda/4$ resonator, decagonal shape inner ring

Table 4 provides a comparison summary of proposed antenna parameters with other antennas reported in the literature. The proposed antenna features a compact design that is perfect for space-constrained applications, such as mobile devices and IoT sensors. It offers improved bandwidth and minimizes interference, as well as easy integration into various communication systems. This significant enhancement in bandwidth is crucial for real-world applications, particularly in devices that require efficient RF energy capture and wireless power transfer. The antenna helps ensure energy-efficient operation by efficiently reducing the emission of higher-order modes. Additionally, its cost-effective fabrication enhances its practicality for a variety of applications, including Wi-Fi and Bluetooth.

Conclusion

This paper proposes a new type of radiating patch which takes the form of a ring with a decagonal inner ring and is used in conjunction with non-radiating $\lambda/4$ resonators. The use of $\lambda/4$ resonators and a partial ground approach effectively enhances harmonics and spurious mode rejection ability and also improves antenna bandwidth. The bandwidth of the proposed decagonal-shape antenna is 1156 MHz and enhanced by seven times. The findings presented in this paper exhibit a reasonably good correlation between the experimental and simulated values.

Abbreviations

DGS: Defected Ground Structure, DMS: Defected Microstrip Structure, EBG: Electromagnetic Band Gap, FR: Flame Retardant, HFSS: High Frequency Structure Simulator, IoT: Internet of Things, PBG: Photonic Band Gap, PCB: Printed Circuit Board, RF: Radio Frequency, SIR: Stepped-Impedance Resonators, VSWR: Voltage Standing Wave Ratio, WPT: Wireless Power Transfer.

Acknowledgment

None.

Author Contributions

Pravin Bhole: Conceptualization, methodology, simulation, experimental results, implementation, and drafting of the original manuscript. Pramod Deore: Review of the draft, investigation, and verification of results.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Ethics Approval

Not Applicable.

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