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Bandwidth-Enhanced Pentagon-Shaped Microstrip-Based Planar Monopole Antenna with Harmonic Rejection

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Abstract

Microstrip patch antennas' two primary limitations are narrow bandwidth and harmonic interference, restricting their application for 2.4 GHz systems. Standard microstrip patch antennas typically only provide a fractional bandwidth between 2 % and 5 %. Because of the higher-order harmonic emissions from microstrip patch antennas, other wireless services may also experience interference from these devices. The proposed design, a pentagon-shaped patch antenna, handles both limitations through geometric innovation rather than complex multi-layer construction. When the base of pentagonal patch is positioned opposite the feed location, surface currents are distributed more uniformly than conventional rectangular geometries, thereby creating a broader resonant response. Strategic ground plane defects produce transmission nulls at harmonic frequencies and introduce additional resonances within the operating band. The introduction of a partial ground plane modifies the conventional cavity-backed radiation mechanism, resulting in monopole-like behavior that contributes to the observed wide impedance bandwidth. ANSYS HFSS 13 electromagnetic simulation verifies that the design provides a 1.85 GHz operational bandwidth between 1.32 GHz and 3.17 GHz, i. e. 82.22 % fractional bandwidth. The integrated defected ground structure forms wide 4.0 GHz to 12.0 GHz stop band. This modification disturbs ground plane current, which results in effective suppression of higher-order harmonics. The aforementioned combination, which is made on an inexpensive single-layer substrate, provides an ideal solution for spectrally pure, wideband wireless systems by doing away with the need for external decoupling components.

Keywords: defected ground structure, microstrip patch antenna, harmonic suppression, bandwidth enhancement, pentagonal antenna

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Плоская пятиугольная антенна-монополь на основе микрополосковой структуры с расширенной полосой пропускания и подавлением гармоник

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Двумя основными недостатками микрополосковых патч-антенн являются малая ширина полосы пропускания и гармоническая интерференция, что ограничивает их применение диапазоном 2,4 ГГц. Стандартные микрополосковые патч-антенны, как правило, обеспечивают относительную ширину полосы пропускания в диапазоне от 2 % до 5 %. Высокий уровень высших гармоник в излучении микрополосковых патч-антенн создаёт помехи для сторонних беспроводных устройств. Предлагаемая конструкция пятиугольной патч-антенны позволяет преодолеть оба этих ограничения за счёт использования инновационной геометрической формы вместо сложной многослойной структуры. При расположении основания пятиугольника противоположно месту подвода мощности обеспечивается более равномерное распределение поверхностных токов, чем при традиционной прямоугольной геометрии антенны, благодаря чему увеличивается ширина резонансной кривой. Целенаправленно сформированные дефекты заземляющей плоскости создают провалы в передаточной характеристике на частотах высших гармоник и вводят дополнительные резонансные частоты в пределах рабочей полосы частот. Компьютерное моделирование в среде ANSYS HFSS 13 подтвердило достижение рабочей ширины полосы пропускания в диапазоне от 1,32 ГГц до 3,17 ГГц на частоте 1,85 ГГц, т. е. относительную ширину полосы пропускания 82,22 %. Интегрированная дефектная структура заземления позволила сформировать широкую полосу подавления в диапазоне от 4,0 до 12,0 ГГц. Введённая модификация нарушает протекание тока в плоскости заземления, что приводит к эффективному подавлению гармоник более высоких порядков. Комбинация упомянутых решений, реализуемая на недорогой однослойной подложке, является оптимальным решением для спектрально чистых широкополосных беспроводных систем, устраняющим необходимость во внешних развязывающих компонентах.

Ключевые слова: дефектная структура заземления, микрополосковая патч-антенна, подавление гармоник, расширение полосы частот, пятиугольная антенна

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Introduction

Today's wireless communication systems are continuously evolving towards higher data rates and more and more sophisticated functionality; however these systems remain restricted by basic antenna limitations that have remained largely unchanged for decades. Microstrip patch antennas have become a major choice and need of many wireless systems, mainly because their physical structure can easily be accommodated by today's electronic design [1]. Since the radiating element is printed onto a substrate, it forms part of the circuit itself rather than acting as an external component. This contributes to the simplicity of the construction, the inexpensive production of the product, as well as the ability to reliably produce in mass production with standard printed circuit board processes. Their compact size is a useful feature, especially for the applications requiring a slim profile, such as mobile handheld devices, sensors, and automotive communication units. Although these are suitable for many applications, designers must consider their inherent performance limitations that are still imposed on the R&D of this field.

Numerous technologies such as Wi-Fi, Bluetooth, Zigbee, and microwave heating systems operate in this relatively narrow spectral allocation. Therefore, 2.4 GHz industrial, scientific, and medical (ISM) band represents a clear example these challenges.

Standing wave patterns with different resonances are obtained when electromagnetic energy couples into a rectangular patch antenna [1]. Excellent impedance matching is produced at the centre frequency by this resonant behaviour but as the frequency gets away from the design point, steep impedance variations are produced. As Internet of Things deployments continue to increase over a multitude of applications requiring compact 2.4 GHz antennas, each system is required to operate reliably despite increasing levels of electromagnetic congestion and interference from both intentional and unintentional radiators [2].

The biggest obstacle is probably bandwidth limitations. Fractional bandwidths typically fall between 2 % and 5 %, or roughly 50 to 120 MHz at 2.4 GHz operation. This limited bandwidth means that a single antenna cannot be used to support multiple communication standards and results in much lower rates of data transmission. The methods adopted in traditional approaches for bandwidth enhancement generally lead to a physical size increase, higher manufacturing cost, or higher system complexity [3]. Although the bandwidth can be extended by employing multi-layer configurations and metamaterial superstrates, the benefits that make microstrip antennas attractive are lost [4].

Another important limitation is harmonic generation. The physics behind this is the same as that which leads to energy at integer multiples of the fundamental frequency just ending up with a small bandwidth. Such spurious emissions can lead to non-compliance with the emission requirements, electromagnetic interference, and degradation of signal quality. In communications systems, harmonic interference within ISM band can degrade system performance, potentially rendering devices unreliable or even non-functional. As a result of this, harmonic suppression typically requires additional filtering components that complicate integration, add insertion loss, and increase cost. These drawbacks emphasize the need for analyzing the microstrip patch antennas used in several applications and to resolve what large efforts have been made.

However, most existing methods focus either on bandwidth broadening or harmonic filtering independently, rather than designing a solution to tackle these two issues at the same time. This antenna designing work investigates whether non-traditional polygon shapes simultaneously provide bandwidth enhancement and harmonic suppression requirements through characteristic of the shape, use of defected ground structure (DGS), and stub.

According to Zhang et al. [5] and Shah et al. [6], defected ground structures were used to generate new modes or resonators in a microstrip antenna by disturbing the current distribution from a smooth surface via the appropriate placement of strategic defects while maintaining the same radiating efficiency. Experimental results verified harmonic suppression of 25.3 dB at the second harmonic and 18.7 dB at the third harmonic, while suppression of 31 dB at 4.54 GHz was also reported.

Expanding these, Al-azzawi [7] proposed a rectangular patch antenna that involved the utilization of active radiators and a defected ground structure for harmonic suppression; however, resulting bandwidth was limited to 85 MHz. To extend the suppression range, Kaplesh et al. incorporated into the ground plane an H-shaped defect, an indirect feed mechanism. Using this design reflected the unwanted signals to a frequency of 16 GHz with high gain retained [8].

Alternative geometrical approaches have considered how different patches shapes affect the electromagnetic characteristics of a patch. Prasad looked at semicircle shapes and determined that patches with curved edges will have inherently wider frequency ranges and will have harmonic suppression as a result of their natural configuration [9]. Awan et al. utilized fractal-shaped geometries and a rectangular conducting stub on an ultra-thin (very low mass) substrate in their designs [10] to dramatically reduce the overall size (miniaturize) of the antennas while also rejecting harmonics at a frequency of up to 11 GHz. These findings further supported the premise that conventional geometries may be modified strategically to produce significant performance benefits. Their research clearly demonstrated that even traditional rectangular shapes could have significant performance increases with careful design modifications.

Application-specific antenna design research provided more insights into maximizing the performance of the antenna for the given set of operating frequencies. A compact, circularly polarized antenna with cross-shaped slots for harmonic suppression is developed by Sarkar et al. 11], yielding a 10 MHz (-10 dB) bandwidth of antenna at 2.4 GHz with good harmonic suppression with no filtering loss. A circular shaped patch with a quarter-wave resonator with a partial ground plane was proposed by Markad and Mahadik [12]. With this configuration, the resulting ultra-wide bandwidth was over 52 % with harmonic suppression to 12 GHz.

Research more specific to pentagons has also developed more recently as researchers realized the special characteristics of five-sided geometries. En-Naghma et al. came up with a pentagon-based array in wireless power transfer system applications, and it was shown to have better impedance matching compared to defected ground techniques [13]. The pentagonal, microstrip patch array of antennas at 2.45 GHz with broadband and circularly polarized characteristics was more effective in enhancing gain and impedance. This work, however, only concentrated on the performance of arrays and not on single-element performance, so it was not possible to determine the performance of pentagons in single elements. Ramineni and Nimmala studied patch antennas with a polygonal arrangement of DGS at 4 GHz, and improved return loss and impedance matching properties were demonstrated [14]. The study highlighted advantages of the combination of unconventional shapes and substrate-level defect structures as a theoretical basis of the combination of geometric and ground plane innovations. The usefulness of pentagonal geometry in a variety of antenna designs became clear when Arora and co-authors developed miniaturized pentagon-shaped planar monopole antenna designs to operate in ultra-wideband modes [15].

In the same way, Deshmukh and Chavali [16] have investigated polygon structures and exhibited that a pentagonal design with rectangular openings offers over 700 MHz bandwidth. Zhang and Huang [17] employed a dual-point feeding structure as an alternating method to control higher order modes, but with another strategy, thereby contributing to impedance bandwidth enhancement.

Similarly, application-oriented antenna designs also address bandwidth and harmonic suppression requirements. Rectenna-based and slotted antenna designs reported by Kang et al. [18] incorporate compact resonant and modified slot structures and Polaiah [19] produced compact slotted antennas based on symmetrical configurations with modified slot structures to achieve harmonic suppression.

These studies collectively demonstrate that geometric modifications can significantly influence impedance bandwidth and harmonic behavior without relying on external filtering components.

When compared to the circular geometries which have symmetrical current distribution and sharper resonance behavior, the polygonal shapes induce edge discontinuities which change current paths and quality factor. Among polygon shapes, a pentagon is asymmetrical but not excessively so. Hence, many resonance paths are available without much overlapping of modes. This improves its impedance bandwidth and controls harmonic response. On the other hand, the use of higher-order polygons such as hexagons or octagons produces more complex mode interactions, leading to unstable spectral behavior.

This study adopts a systematic approach to overcome fundamental performance limitations inherent in conventional microstrip patch antenna configurations. The research methodology integrates two primary objectives: first, bandwidth enhancement within 2.4 GHz ISM band; second, suppression of spurious harmonic radiation that can degrade system performance in densely populated electromagnetic environments.

Methodology

Design strategy overview

The design methodology for proposed antenna consists of two steps. A traditional circular microstrip patch antenna at a frequency of 2.4 GHz serves as basis for performance comparison. Secondly, the basic circular geometry of the antenna is converted into a pentagon-shaped radiating patch along with a partial ground plane integrated using a small rectangular stub, thereby transforming behaviour of antenna towards planer monopole configuration with improved bandwidth and harmonic suppression characteristics. Both structures are realized on a single-layer FR4 substrate with relative permittivity $\varepsilon_r = 4.4$, substrate thickness $h = 1.6$ mm and loss tangent $\tan\delta \approx 0.02$. The dimensions of the radiating element and ground plane are covered with copper cladding of 35 μm thickness.

Circular patch design

The reference circular patch antenna as shown in Figure 1 is designed to resonate at 2.4 GHz using the cavity model for the dominant TM11mode.

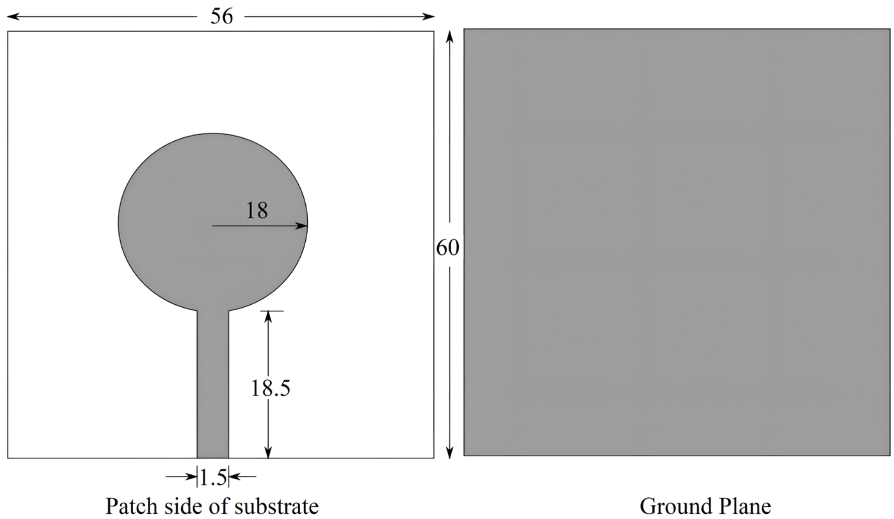

Figure 1 – Circular patch antenna

The effective radius aeff is expressed as [20]:

$$a_{eff} = a\sqrt{1+\frac{2h}{\pi a \varepsilon_r}\left[\ln\left(\frac{\pi a}{2h}\right)+1/7726\right]}. \quad (1)$$

The resonant frequency for dominant mode is expressed as:

$$f_r = \frac{1.8412c}{2\pi a_{eff}\sqrt{\varepsilon_r}}, \quad (2)$$

where c is the speed of light in free space; 1.8412 is the first zero of the derivative of the Bessel function J_1.

The physical radius of the circular patch is calculated using a target frequency of 2.4 GHz. To reduce dielectric loss and other fabrication tolerances, a full-wave simulation is used to modify an analytical estimate of this radius.

A 50-Ω microstrip stripline feed is designed using standard transmission line equations. The feed width W_f is calculated using the following equation [20]:

For $W_f/h>1$:

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}}\left[W_f/h+1.393+0.667\ln(W_f/h+1.444)\right]}. \quad (3)$$

The feed position relative to the patch center is optimized to achieve impedance matching at the fundamental resonance. Since input impedance varies radially in a circular patch, the feed is placed at an offset location along the *x*-axis where the real part of the input impedance approximates 50 Ω.

For the reference design, a full ground plane is first considered to provide a baseline performance. The dimensions of ground plane are chosen as at least six times that of the substrate height beyond the edge of the patch to reduce truncation effects and obtain stable radiation characteristics [20]. The baseline configuration (without DGS) allows comparative evaluation of the bandwidth, return loss, radiation efficiency, and harmonics before modification of the ground plane. For the reference design, a full ground plane is first considered to provide a baseline performance.

Pentagon-shaped radiator

The proposed pentagon-shaped antenna modifies the reference geometry to overcome the limitations of narrow bandwidth and harmonic interference of the reference geometry. The structural evolution consists of two important modifications: geometrical modification of the radiating element and truncation of the ground plane. The circular patch was reconfigured in a pentagonal geometry, as is visualized in the front and back views of proposed design shown in Figure 2.

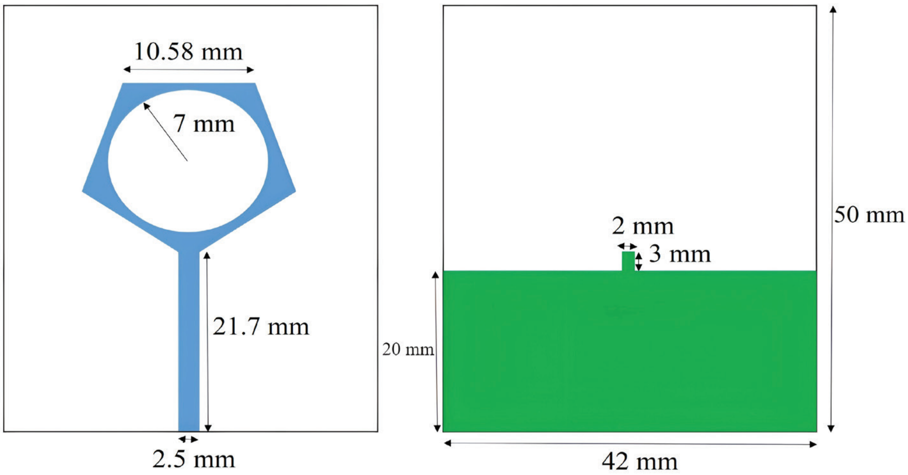

Figure 2 – Proposed pentagon shaped antenna

Radiating element

The circular patch is converted into s pentagonal shape to reduce the symmetry and perturb the dominant mode, while preserving approximately equal radiating area.

$$A_{circle} = A_{pentagon}. \quad (4)$$

The side length of the regular pentagon is derived as:

$$A_{pentagon} = \frac{5s^2}{4} ctg\left(\frac{\pi}{5}\right) = \pi a^2. \quad (5)$$

The expressions above can be used to provide an approximate estimate of the side length (s) providing the effective electrical dimensions of the approximated radiating element remain virtually unchanged, with the dominant frequency of resonance being at or close to 2.4 GHz before running a full-wave optimization. Final dimensions are refined via electromagnetic simulation to account for fringing fields and substrate effects not fully taken into consideration by simple area equivalence.

A conventional pentagonal patch antenna resonating at 2.4 GHz with FR4 substrate requires an approximate 24 mm side length, however, by introducing carefully tuned circular slot etched at the centre of reverse pentagon, the proposed antenna resonates at the required frequency with reduced pentagon edge length of 10.58 mm. This reduces the required substrate area of 42×50 mm, i. e. reduction of 37.5 % substrate area obtained compared with circular patch antenna.

Ground plan

To further enhance impedance bandwidth and to achieve harmonic suppression, the proposed design utilizes the partial ground configuration by truncating the ground plane. This partial ground plane modifies the boundary conditions of the electromagnetic fields and increases fringing effects at the substrate-air interface. This modification transitions the antenna operation from a purely resonant cavity mode toward a planar monopole-like radiation mechanism, which plays a key role in bandwidth enhancement. Along with partial ground, a small reactive stub is incorporated at top edge of partial ground plane. This stub alters shield current distribution, and acts as an integrated band-stop filter. This stub's dimensions are tuned such that it creates high impedance at higher-order harmonic frequencies.

Although, the suggested structure started as microstrip patch configuration, the truncation of ground plane produces monopole-like radiation characteristics while keeping the benefits of the microstrip implementation.

Result and discussion

Electromagnetic performance of proposed reverse pentagonal antenna was evaluated using finite element method in Ansys high frequency structure simulator. The design strategy specifically targeted the resolution of two inherent limitations in conventional patch antennas: restricted impedance bandwidth and the presence of out-of-band harmonic radiation. To validate the efficacy of the proposed geometric modifications and the DGS, the simulated parameters of the proposed architecture are systematically benchmarked against a standard circular microstrip patch antenna.

The basic operation of a circular patch is based on a high-Q cavity built between solid radiator and continuous ground plane. The S11 plot of the circular patch antenna is shown in Figure 3.

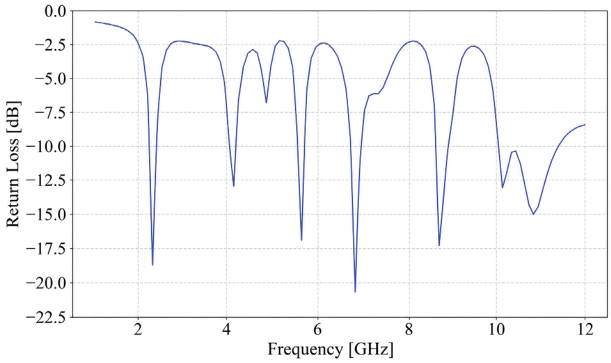

Figure 3 – S11 plot of circular patch antenna

This response shows a fundamental resonance frequency approximately 2.4 GHz (-19 dB). However, higher-order modes heavily pollute the spectral response, with multiple resonances appearing between 4.2 and 11 GHz. Specifically, there are distinct parasitic resonant peaks located at frequency components corresponding to -13 dB at 4.2 GHz, -17 dB at 5.7 GHz, -20 dB at 6.0 GHz, -18 dB at 8.7 GHz, -15 dB at 11 GHz. Based on these results, it is evident that typical patch shapes radiate spurious harmonic signals with very small bandwidths (2.33 GHz – 2.48 GHz) within the intended frequency range; therefore, these do have the capability to operate as a single-mode cavity but are influenced greatly by higher-order mode interactions.

The limitations of a baseline antenna can be addressed by using a slotted reverse pentagon-shaped patch along with a partial ground plane and a stub shown in Figure 2. The frequency response of modified antenna differs completely from the baseline antenna shown in Figure 4.

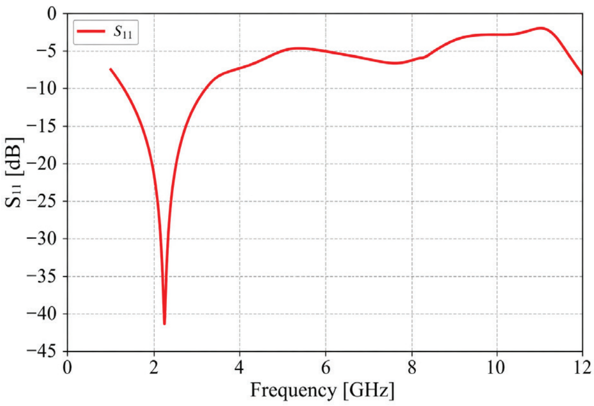

Figure 4 – S11 plot of proposed pentagon shaped antenna

The proposed antenna resonates at 2.25 GHz with a return loss of -41.25 dB. More significantly, the -10 dB impedance bandwidth is expanded by wide margin from 1.32 GHz to 3.17 GHz. These wideband characteristics are obtained from weakening the Q-factor of the cavity by truncation of the ground plane up to a 20 mm height, which makes the radiation mechanism transform to a monopole-like form.

The comparison plot shown in Figure 5 validates harmonic suppression capability of proposed antenna.

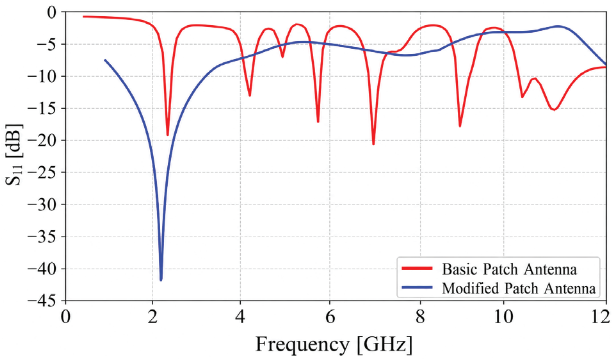

Figure 5 – Comparison of S11output characteristics

The basic patch, which produces fairly sharp voltage standing wave ratio spikes at the higher end of the frequency scale, has a highly reflective stop band from 4.0 GHz to 12.0 GHz for the modified antenna (S11 levels are primarily between -3 dB and -7 dB). The 2×3 mm stubs provided with a partial ground plane act as a parallel LC band-stop filter and thus do not require the complex lossy external decoupling networks.

Parametric optimization of the radiator and ground

Sequential parametric analysis was used to establish the final physical dimensions.

1. Ground plane truncation (*gl*)

The partial ground plane length determines the impedance matching and lower cutoff frequency. The sensitivity of system to this parameter is shown in Figure 6. When length is increased beyond 30 mm (almost full ground configuration), the band established becomes wide since the spectrum has a deteriorated appearance, with spurious harmonics re-entering at frequencies higher than before. The best value of 20 mm results in the perfect capacitive coupling to cause the very deep resonance occurring at 2.25 GHz and -41 dB, while still ensuring that an impedance mismatch exists capable of blocking the 4 GHz to 12 GHz band.

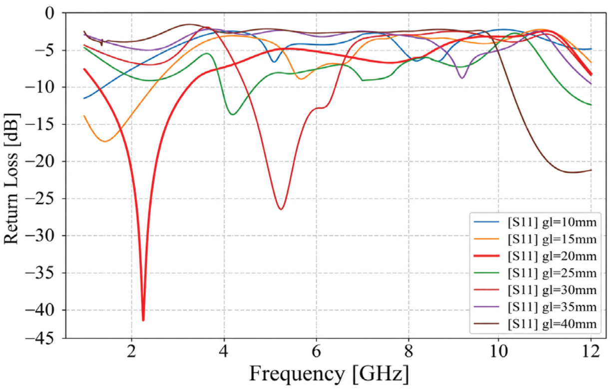

Figure 6 – Parametric sweep of ground plane length *gl*

2. Inductive slot loading (*r*2)

At 2.25 GHz, the physical footprint of the pentagonal patch (42×50 mm) is considered electrically small. In order to create a more resonant, reactive load on the patch, a circular slot has been added as shown in Figure 7. As described previously, increasing the size of the slot from 2 mm to 4 mm results in an increasing frequency shift up the frequency spectrum. When increasing the slot size to 7 mm, the surface current density vectors will have to navigate around the slot, which will increase the total electrical length around the pentagonal patch and increase the inductance of the total electrical path. This will effectively lower the fundamental frequency to the desired band without increasing the total area of the substrate.

Figure 8 shows that the optimized design has an absolute minimum voltage standing wave ratio of 1.02 at 2.25 GHz, but it begins to rise rapidly in the suppressed harmonic regions (>4.5 GHz). This confirms that the absence of higher-order resonances in the plots is driven by active power reflection at the feed point, rather than parasitic absorption within the dielectric substrate.

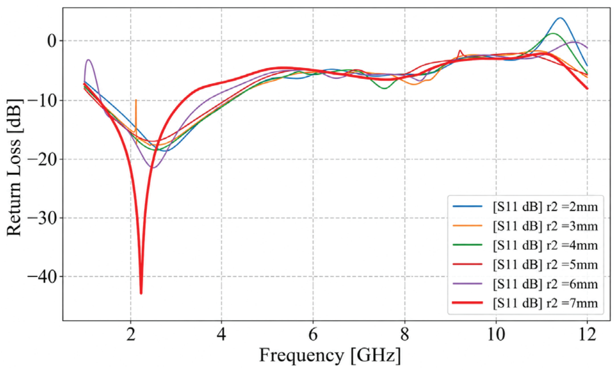

Figure 7 – Parametric sweep of the circular slot radius *r*2

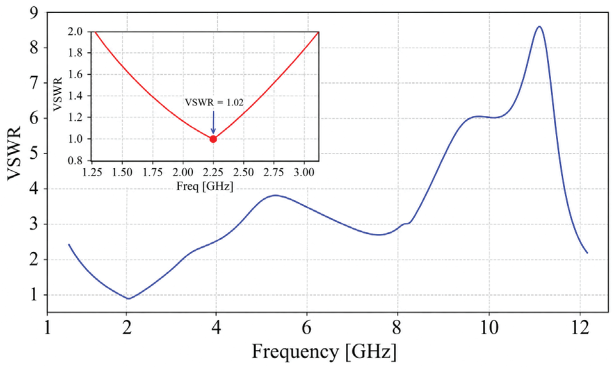

Figure 8 – Voltage standing wave ratio of the proposed antenna

Signal integrity was verified via polarization purity analysis. As detailed in E-plane and H-plane polarizations shown in Figure 9 and Figure 10, cross-polarization remains highly isolated from the co-polarization main lobes. Specifically, E-plane cross-polarization levels remain suppressed by an average of 20 dB relative to the main lobe peak. The H-plane maintains a near-omnidirectional co-polarized footprint, which is highly advantageous for portable ISM-band devices and IoT sensor nodes where spatial orientation relative to the receiver cannot be predetermined.

To experimentally validate the simulated electromagnetic characteristics, a physical prototype of proposed pentagonal antenna was fabricated, as shown in Figure 11. The antenna uses a standard low-cost, single-layer FR-4 dielectric substrate with an overall spatial footprint of 42×50 mm. The top conductive copper layer was patterned to define the reverse pentagon- shaped patch radiator with a 7 mm circular slot and the 2.5 mm wide microstrip feed line, whereas the bottom layer was etched to realize the 20-mm truncated partial ground plane and the integrated 2×3 mm DGS stub. A standard 50 Ω subminiature version A connector was subsequently soldered to feed terminal to interface with a vector network analyzer for empirical reflection coefficient and bandwidth measurements.

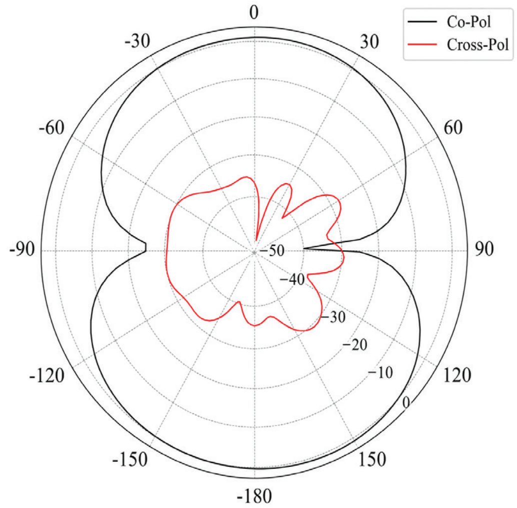

Figure 9 – E-plane Co-Cross Polarization patterns

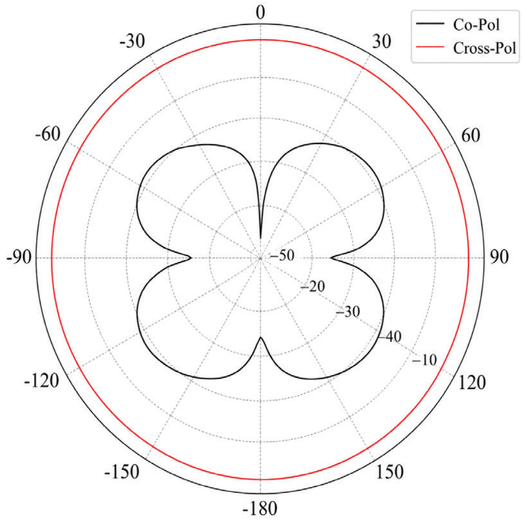

Figure 10 – H-plane Co-Cross Polarization patterns

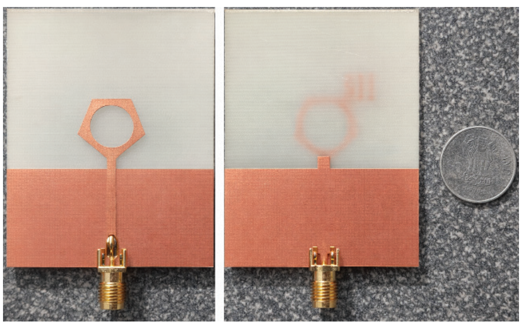

Figure 11 – Fabricated proposed antenna

The plot of simulated and measured shown in Figure 12, exhibit similar resonance behaviour around the fundamental frequency. The variation in return loss and variation in curve shape may result from fabrication tolerances and measurement conditions during antenna characterization.

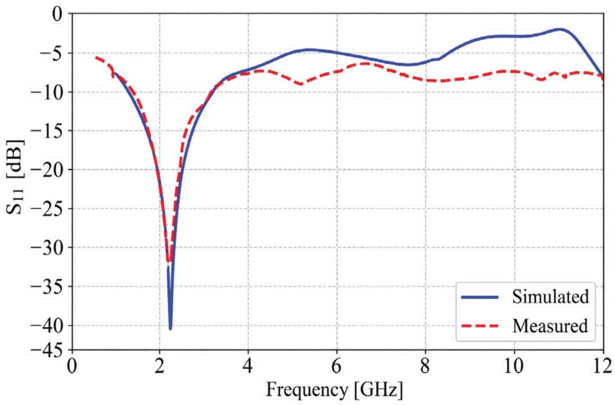

Figure 12 – Proposed antenna simulated vs measured result

Table describes comparison of the proposed pentagonal-shaped antenna with recent designs available in literature, highlighting parameters such as fractional bandwidth, harmonic suppression range, and physical size. The recent designs includes antennas based on circular, rectangular, fractal, and polygonal geometries.

Rectangular configurations when paired with DGS demonstrate effective harmonic suppression when, but provides limited bandwidth. Physical antenna size reduction achieved by using Multi-feed rectangular designs, but both bandwidth and harmonic suppression performance still limited. A comparatively larger bandwidth is obtained by the circular geometry, when used with resonant element which increases the antenna size.

Antennas with fractal geometry, ring, and square slot configurations have good harmonic suppression ranges, but their bandwidth characteristics remains limited. Unlike to all of these, the suggested pentagonal antenna maintains harmonic suppression up to 12 GHz, while achieving fractional bandwidth of 82.22 % with reduced physical size of the antenna. These results indicate that the pentagonal geometry provides both balanced combination of the bandwidth and harmonic suppression enhancement with structural simplicity.

Table

Comparison of proposed antenna with circular, rectangular, and polygonal geometries reported in recent literature

Ref No	Shape	Band-width (GHz)	Harmonic Suppression	Centre Freq (GHz)	Substrate	Method	Dimension
7	Rectangular	0.085	Up to 3rd Harmonic	2.4	RT/Duroid 5880	Active + DGS	84.7mm × 77.4 mm
8	Rectangular	0.08	Up to 16 GHz	5.8	Rogers 5880	H-Shaped DGS	$0.77\lambda_0 \times 0.67\lambda_0 \times 0.015\lambda_0$
10	Fractal	0.444	Up to 11 GHz	2.45	Rogers RO4835	Stub + Fractal	-
12	Circular	1.26	Up to 4th Harmonic	2.45	FR4	λ/4 Resonator	56 mm × 56 mm
16	Pentagonal	1.05	-	1.5	Air Sus-pended	Pair of Slots	Rad. r=49 mm
17	Rectangular	0.17	Up to 2.8f0	2.45	FR4	Dual-point Feed	~37 mm × 29 mm
18	Ring Slot	-	3.0 – 8.0 GHz	2.45	Taconic RF-35	CMRC	78 mm × 50 mm
19	Square Slot	-	Up to 10 GHz	2.08	FR4	Symmetrical Slots	40 mm × 40 mm
Pro-posed	Pentagonal	1.82	Up to 12GHz	2.25	FR4	Circular slot, DGS, stub	42 mm × 50 mm

Conclusion

A miniaturized harmonic-suppressed slotted pentagonal microstrip antenna has been synthesized and electromagnetically validated for 2.4 GHz industrial, scientific, and medical band utilizations. The impedance bandwidth was expanded to about 30 % by changing from a traditional full-ground cavity to a partial ground plane topology, thus overcoming the narrowband inadequacy of conventional planar radiators. The inductive loading for physical miniaturization is achieved using the geometric integration of a central circular slot. Simultaneously, an accurately sized defected ground structure stub considered the integrated LC band-stop filter. A full-wave analysis demonstrates a strong fundamental resonance at 2.25 GHz with peak return loss of -41.25 dB and active harmonic rejection (S11 > -10 dB) for a broad, continuous stopband from 4.0 GHz to 12.0 GHz. Combined with constant bidirectional and omnidirectional radiation profiles and very high cross-polarization isolation, this planar architecture offers a highly efficient integrated filter solution for spatially constricted IoT nodes where stringent out-of-band spectral purity is required.

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