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Design of Compact, Single-layered Modified Substrate Integrated Waveguide Filtenna with Passive Patch

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Abstract

This article presents a compact planar filtering antenna that integrates radiation and filtering functions within a single-layer structure, providing an efficient solution for modern wireless systems. The proposed filtenna is based on a modified semi-hexagonal half-mode substrate-integrated waveguide (SH-HMSIW), which serves as the primary resonant cavity, enabling size reduction while preserving stable electromagnetic performance. To further enhance antenna characteristics, a via-loaded passive patch composed of two pairs of metallic vias is introduced as a secondary resonator. This resonator contributes to bandwidth enhancement and produces sharp filtering behaviour with improved frequency selectivity. By embedding the filtering functionality directly into the antenna structure, the requirement for external filtering circuits is eliminated, resulting in a compact configuration with reduced system complexity and fewer components. The inclusion of metallic vias enhances out-of-band attenuation and improves rejection performance, resulting in a well-defined passband and stable radiation characteristics. Measured results demonstrate that the proposed antenna achieves a high-realized gain of 8dBi along with a fractional bandwidth of 4.6%, confirming its suitability for contemporary wireless communication applications. The proposed design is novel in its integration of a modified SH-HMSIW cavity and a via-loaded passive patch within single-layer architecture, providing inherent filtering characteristics without the need for additional circuitry. Compared with existing filtenna designs, the antenna offers reduced physical size, enhanced gain, improved frequency selectivity, and simplified fabrication. The antenna performance is validated through electromagnetic simulations using ANSYS HFSS 2020, with simulated and measured results showing good agreement, demonstrating its potential for advanced wireless communication systems.

Keywords: Filtering Antenna, High Gain, Metallic Vias, SH-HMSIW, Substrate-Integrated Waveguide.

Introduction

The increasing need for miniature, high-performing, and multipurpose antennas in daily wireless communication devices has evoked interest in integrated antenna-filter structures (1). Conventional antenna designs tend to need independent filtering circuits to suppress out-of-band signals, which may make design more difficult and increase size, complexity, and insertion loss. Filtering antennas that integrate both radiation and filtering functions in a single structure offer a viable solution to these problems. Substrate-integrated designs are preferred among different technologies because they provide low-loss, compact, and planar elements ideal for use in high-frequency applications (2, 3). Half-mode configurations, especially modified geometries, allow even more miniaturisation with excellent performance (4-6). This work proposes a novel planar filtering antenna that employs a modified semi-hexagonal half-mode cavity as the primary resonator. A passive patch with two pairs of metallic vias acts as the secondary resonator, improving bandwidth and introducing sharp filtering behaviour. The use of metallic vias improves frequency selectivity and contributes to size reduction and gain enhancement. Unlike traditional designs, this antenna does not require external filtering components, resulting in a simplified and efficient solution. Simulation and measurement results confirm that the antenna performs a high gain of 8 dBi and a fractional bandwidth of 4.6%, making it well-suited for integration into compact wireless and RF front-end systems. HMSIW have become a go-to platform for compact, PCB-friendly microwave filters and "filtering antennas" radiators with built-in selectivity. Together, these results trace the path from classic microwave and antenna fundamentals

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to current dual-band, dual-polarised, and low profile designs ready for 4G/5G (7).

Foundations and Design

Two classic texts anchor nearly all later designs: Pozar lays out system-level microwave/RF design constraints (impedance matching, noise/linearity allocations, and integration trade-offs) that ultimately shape what a “good” filter/antenna looks like in a real wireless link (8). A practical synthesis of microstrip/planar filters—coupling coefficients, shallow Q, and topology transformations—methods is routinely adapted to SIW/HMSIW implementations (9). For the radiation side, Balanis remains the reference on crack/patch behaviour, polarisation, and pattern control that filtering-antenna papers build upon to hit selectivity and pattern targets simultaneously (10).

Filtering innovation of core SIW

A substrate integrated waveguide (SIW) filter employing hexagonal resonator geometry is demonstrated, showing that non-rectangular cavity shaping can draw the footprint while keeping high Q and low loss by leveraging dense via walls and controllable yoke windows. The method is a planar SIW cavity with hexagonal geometry and tuned inter-resonator apertures; the improvement is a more compact, PCB-integrable filter with competitive passband performance (11).

HMSIW Compactness without Giving Up Waveguide Benefits

An HMSIW bandpass filter is demonstrated in which essentially halving the SIW along a magnetic wall to shrink the width while retaining waveguide-like custody. Their method is a half-width SIW cavity chain with adapted coupling/feeding; the gain is substantial size reduction with manageable radiation/leakage, paving the way for slim, embeddable filters (12). HMSIW propagation (dispersion, loss, fields) is described, providing design rules that subsequent HMSIW filters/antennas rely on. Their contribution is methodological — modal/ measurement characterisation—yielding clear procedures for cutoff, effective permittivity, and leakage control in half-mode structures (13).

Cavity-Backed Slots for 5G Dual-Band Arrays

A dual-band SIW cavity-backed slot array is constructed that excites the TM [020] and TM [120] modes in the same cavity to realise two well-separated operating bands with a single low-profile aperture. Method: SIW cavities feeding slots, with deliberate multimode excitation and arraying. Revision: accurate dual-band operation with array-grade performance (efficiency, scanning/pattern control) suitable for 5G while conserving manufacturability on PCB (14).

Filter + antenna to filtering antenna

A key trend is combining selectivity into the radiator so that out of band (OOB) suppression and steep skirts come “for free” from the system.

A compact printed filtering antenna is designed that integrates resonant traps/structures into the radiator and feed, yielding good suppression of upper harmonics without external filters. Method: co-design of radiator plus embedded resonators; improvement: smaller footprint and cleaner spectrum (harmonic/OOB rejection) with minimal insertion loss (15).

A compact broadband dual-polarized filtering dipole antenna for base stations is developed. Method: dual-pol dipoles augmented with integrated filtering sections and carefully controlled coupling; improvement: high selectivity at the band edges with wide impedance bandwidth and strong port isolation—meeting operator specs for co-existence and EMC in congested sites (16).

A single-patch antenna that can realize broadside and conical patterns for pattern diversity in 3G/4G is demonstrated. Method: modal control within one patches (exciting different modes or loading to re-shape fields). Improvement: diversity gain (mitigating fading) without multiple discrete antennas—compact and practical for terminals (17).

Hybrid and Low Profile SIW Cavity Radiators

Pushing height and integration even further, two lines of work hybridize cavities and patches or lean on HMSIW to keep profiles thin:

Low-profile patch + semi-circular SIW cavity hybrid antennas are proposed. Method: combining

a resonant SIW cavity (semi-circular) beneath or alongside a patch to reinforce radiation and bandwidth. Improvement: thinner form factor with cavity-assisted gain/bandwidth, all in planar technology amenable to mass production (18).
A single-layer low-profile HMSIW filtering antenna is presented using a shorted parasitic patch and defected ground structure (DGS). Method: HMSIW cavity feeding a radiator with parasitic short, while the DGS engineers the current return to sculpt the filtering response. Improvements: single-layer PCB, strong OOB suppression, and profile/size reduction—an elegant, fabrication-friendly filtering antenna for modern front-ends (19).

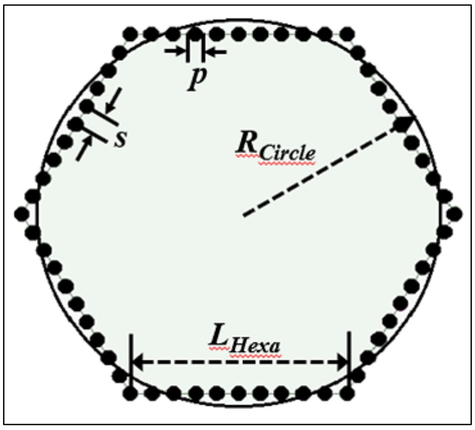


Figure 1: The Hexagonal Cavity and Its Equivalent Circle with the Same Area

Methodology

Antenna Configuration

In order to represent the geometric domain, a hexagonal cavity was initially considered due to its structural relevance in many engineering and physical systems. However, for the purpose of analytical modeling and computational efficiency, this hexagonal geometry was transformed into an equivalent circle of the same area, as shown in Figure 1. The hexagon is defined by its characteristic side length L_{Hexa}, while the equivalent circular domain is represented by a radius R_{circle} that preserves the approximately same cross-sectional area given in Equation [1]. The resonant frequency of the hexagon cavity is determined using empirical Equations [2-4].

$$R_{Circle} = 0.909\ L_{Hexa} \qquad [1]$$

$$f(TM_{mn0}) \approx \frac{c\rho_{mn}}{2\pi \cdot 0.909 \cdot L_{eff} \cdot \sqrt{\mu_r \varepsilon_r}} \qquad [2]$$

$$R_{eff} = R_{circle} - \frac{s^2}{0.95p} \qquad [3]$$

$$L_{eff} \approx 1.1\ R_{eff} \qquad [4]$$

Where c is the speed of light, and ρ_{mn} denotes the root of the nth order ordinary Bessel functions and μ_r, ε_r is the relative permeability and permittivity of the substrate.

This equivalence ensures that the physical properties dependent on area, such as flow capacity, stress distribution, or electromagnetic field interaction, remain consistent despite the geometric simplification. The parameter p and s indicate the via diameters and spacing between two vias respectively. The parameters p and s indicate discretization spacing along the boundary, where uniformly distributed nodes (depicted as black dots) capture the geometry for numerical simulation. By adopting this equivalent-circle approximation, the complexity of polygonal modelling is reduced without compromising the accuracy of area-based calculations. This approach provides a balance between geometric fidelity and computational tractability, making it particularly effective for subsequent analysis and simulations.
In Figure 2, the dimensions are in millimetre: (*Wp* = 19, *Lp* = 12.54 *Wg* = 10, *Lg* = 15, *d* = 5, d_1 = 7.5, *g = 0.4, a* = 1, *p* = 1, *s* = 1.5, *m* = 0.55, *fw* = 1.65, *fb* = 4.95, *fa* = 3, *fl* = 8, *h* = 0.508).

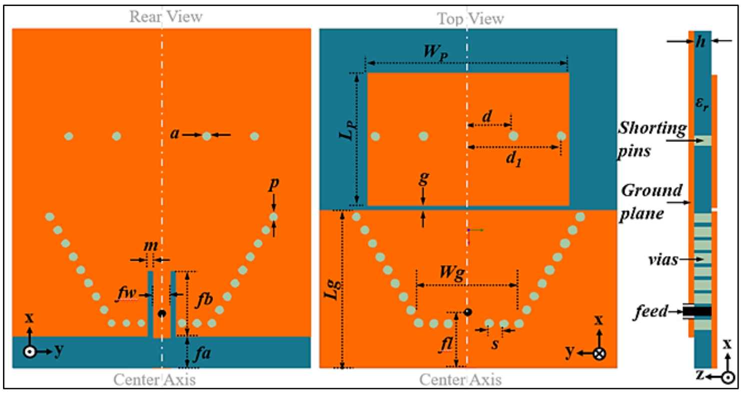


Figure 2: Novel Proposed Filtenna Design

The proposed design combines filtering and antenna functionalities in a single compact structure, commonly referred to as a filtenna. As shown in Figure 2, the configuration consists of a radiating patch integrated with ground vias and shorting pins to enhance impedance matching and suppress undesired harmonics. The rear view illustrates the arrangement of vias and slots that define the filtering characteristics, while the top view highlights the rectangular patch of width Wp and length Lp along with ground plane extensions (Wg, Lg) for stable resonance. The passive patch is designed to operate in its TM_{01} mode. Its dimensions W_p and L_p are computed as Equations [5, 6].

$$W_p = \frac{c}{2f_p}\sqrt{\frac{2}{\varepsilon_r+1}} \qquad [5]$$

$$L_p = \frac{c}{2f_p\sqrt{\varepsilon_{reff}}} - 2\Delta L \qquad [6]$$

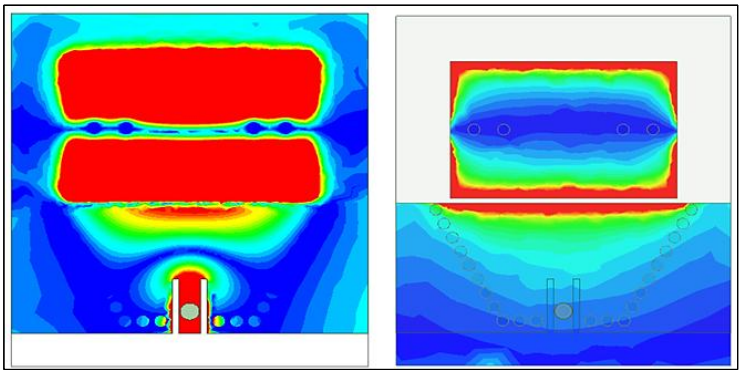
where f_p is the patch's resonant frequency ε_{eff} , is the effective dielectric constant, and ΔL accounts for fringing fields.

The effective permittivity and length correction are given by below Equations [7, 8], where h is the height of the substrate.

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r+1}{2}\left[1 + 12\,\frac{h}{W_p}\right]^{-1/2} \qquad [7]$$

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{reff}+0.3)\left(\frac{W_p}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W_p}{h}+0.8\right)} \qquad [8]$$

The parameters d and d1 correspond to the spacing and offset of vias, ensuring proper current distribution across the patch. Feed dimensions (fa, fw, fb, m) regulate the excitation, while the gap (g) and spacing parameters (s, m) optimize coupling and radiation efficiency. The side view demonstrates the substrate thickness (h) and dielectric constant (εr), which govern the propagation characteristics. Overall, this integrated design approach ensures both band pass filtering and efficient radiation in a compact form, making the proposed filtenna suitable for modern wireless communication systems.



(A) (B)

Figure 3: Electric Field Magnitude Distribution of the Designed Filtering Antenna (Filtenna): (A) Bottom Layer View and (B) Top Radiating View

Figure 3 explain the simulated electric field distribution of the proposed filtenna at resonance (bottom and top views). The left panel (a. Bottom view) illustrates strong TM01 field distribution around the SH-HMSIW cavity and shorting vias, confirming efficient excitation of the radiating patch. The red regions correspond to maximum field intensity, gradually decreasing to blue in low-field zones. The right panel (top view) shows uniform field distribution across the patch surface, indicating stable mode excitation. The surrounding via fence effectively confines the fields within the radiating region, minimizing surface wave leakage and enhancing both radiation efficiency and filtering performance.

Second-Order Band pass Filter Prototype

The filter behaviour of the filtering antenna is designed based on a second-order Chebyshev bandpass response. The filter exhibits a centre frequency of 7.6 GHz, fractional bandwidth (FBW) of 4.6%, and in-band return loss of 14.6 dB. The generalized coupling matrix is given Equation [9]:

$$M = (S\ 1\ 2\ L\ S\ 0\ 1.0224\ 0\ 0\ 1\ 1.0224\ 0\ 1.2620\ 0\ 2\ 0\ 1.2620\ 0\ 1.0224\ L\ 0\ 0\ 1.0224\ 0\ ) \quad [9]$$

The demoralization of the matrix elements yields Equations [10, 11].

$$k_{12} = FBW \cdot M_{12} \quad [10]$$

$$Q_e = \frac{1}{FBW \cdot M_{S1}^2} \quad [11]$$

For the design specifications, the calculated values are coupling coefficient$k_{12} = 0.058$, and external quality factor $Q_e = 28.5$. Figure 4 shows the variation of coupling coefficient k12 with gap (g). The plot demonstrates that as the gap between SH-HMSIW cavity resonator and passive patch increases from 0.2 mm to 2.0 mm, the coupling coefficient decreases steadily from approximately 0.2 to 2. This inverse relationship indicates that tighter spacing between resonators enhances electromagnetic coupling, whereas larger separation reduces interaction. The result highlights the importance of gap optimization in achieving the desired bandwidth and filtering performance for the proposed filtenna design.

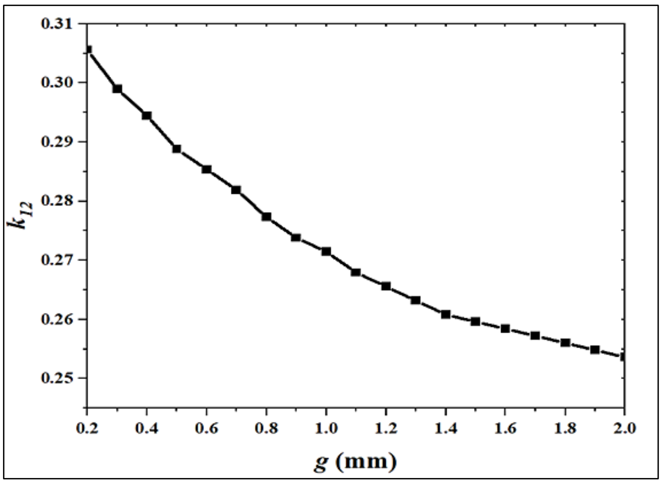


Figure 4: Coupling Coefficient between SH-SIW Cavity and Passive Patch as Function of Gap-g

Parametric Study

Figure 5 presents the Realized gain of the proposed filtenna for different gap values (g). The plot shows that the antenna maintains a stable gain across the passband (6.5–8 GHz) while introducing a sharp notch around 6.0 GHz. As the gap decreases from 0.6 mm to 0.2 mm, the notch depth increases significantly, with the deepest suppression (−18 dBi) occurring at g=0.2 mm. This behaviour confirms that a smaller gap enhances coupling between resonating elements, resulting in stronger filtering performance, while larger gaps reduce the notch depth but provide smoother gain variation across the band.

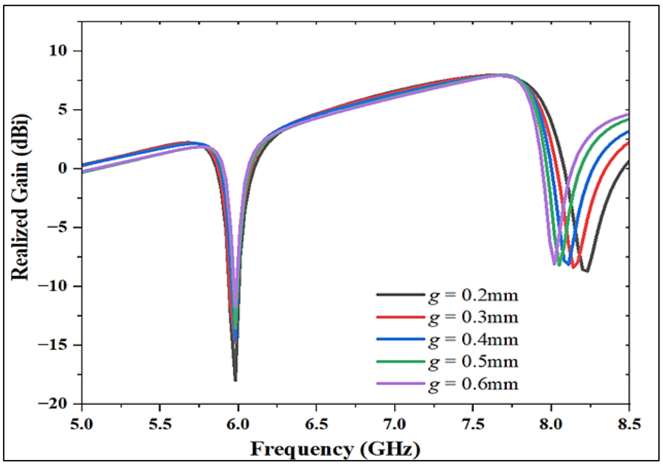


Figure 5: Effect of Coupling Gap *g* on the Realized Gain of the Proposed Filtering Antenna

Figure 6 presents the Realized gain of the proposed filtenna for different via spacing values (d). The results show that varying (d) between 3 mm and 6 mm significantly alter the position of the lower rejection notch. For d=3 mm, the notch appears near 5.8 GHz, while increasing d shifts the rejection band upward in frequency, with d=6 mm producing a notch around 6.7 GHz. The depth of suppression also varies, with smaller (d) yielding sharper and deeper notches. Across all cases, the realized gain remains stable in the passband region (6.8–8 GHz), confirming that via placement is a key tuning parameter for controlling notch frequency and harmonic suppression without degrading the antenna's radiation performance.

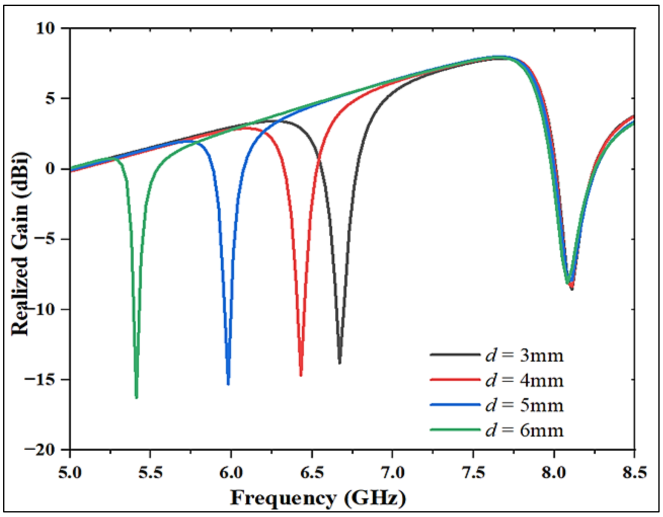


Figure 6: Effect of Geometrical Parameter *d* on the Realized Gain of the Proposed Filtering Antenna

Figure 7 illustrates the Realized gain response of the proposed filtenna for different values of parameter (a). The plot highlights how adjusting (a) directly affects the filtering behaviour of the antenna. For smaller values of a (1.0–1.4 mm), strong notches appear in the lower frequency range near 6–6.5 GHz, showing effective suppression of unwanted signals. As (a) increases, these notches gradually shift toward higher frequencies, with narrower rejection bands observed around 7.2–8.5 GHz for a=2.2 mm. Interestingly, when a=0 mm, the antenna behaves almost like a conventional radiator with little filtering effect, producing a relatively flat gain response. These results confirm that a is a powerful tuning parameter, enabling precise control over where and how strongly the antenna rejects interference, while still maintaining a good realized gain in the passband. To better understand the behaviour of the proposed filtenna, a detailed parametric study was carried out by varying three key structural parameters: the gap g, the via spacing d, and the slot offset a. These parameters directly influence the coupling strength, resonance control, and filtering response of the antenna, as reflected in the realized gain characteristics.

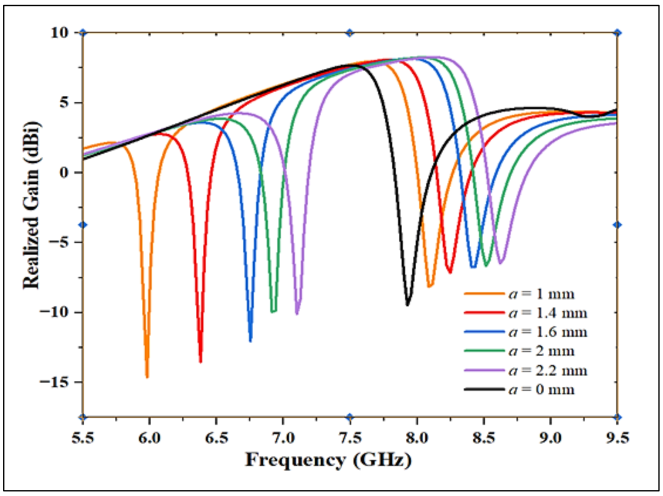


Figure 7: Effect of Geometrical Parameter *A* on the Realized Gain of the Proposed Filtering Antenna

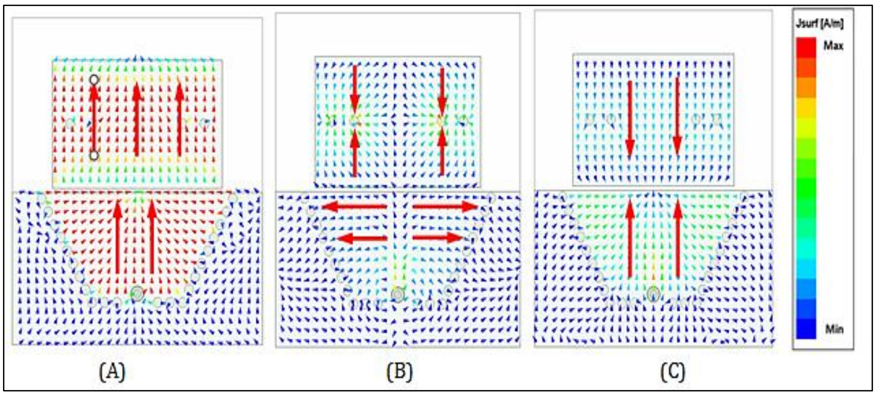


Figure 8: The Current Distributions on the SH-SIW Cavity and Passive Patch at (a) Operational Centre Frequency (7.6 GHz), (b) Lower Radiation Null Frequency (6 GHz), and (c) Upper Radiation Null Frequency (8 GHz)

Figure 8 depicts the surface current distributions on the proposed SH-HMSIW cavity integrated with a passive patch at three distinct frequencies: the operational center frequency of 7.6 GHz, the lower radiation null frequency at 6 GHz, and the upper radiation null frequency at 8 GHz. At the center frequency (Figure 8a), the surface currents are strongly concentrated along the passive patch and are symmetrically extended into the cavity region, confirming effective cavity–patch coupling. This constructive resonance supports efficient radiation and leads to the observed maximum gain of 8 dBi. In contrast, at 6 GHz (Figure 8b), the surface currents on the patch and cavity exhibit opposite orientations, resulting in destructive interference and the formation of a lower radiation null. A similar destructive distribution is observed at 8 GHz (Figure 8c), producing the upper radiation null. The presence of these dual radiation nulls enhances the selectivity of the design by suppressing out-of-band radiation, thereby allowing the antenna to function as a bandpass filtenna centered at 7.6 GHz. These results validate that the integration of the passive patch with the semi-hexagonal SIW cavity provides not only efficient radiation but also inherent filtering characteristics within a compact single-layer configuration.

Results and Discussion

The proposed filtenna structure is fabricate on a rectangular dielectric substrate with a relative permittivity of 2.2, a loss tangent of 0.0009, and a thickness of 0.508-mm. Figure 9 comparison of simulated and measured results for the proposed filtenna. The plot shows the reflection coefficient S11 and boresight realize gain across the 5.5–8.5 GHz frequency range. The black solid lines represent simulation results, while the red dashed lines indicate measurements. The measured 10 dB bandwidth is 4.6%, ranging from 7.40 to 7.75 GHz with Anritsu 2037C Network Analyzer. The measured peak gain is 7.9 dBi, which is obtained by comparing with a standard horn antenna. The results confirm that the proposed antenna achieves dual notches around 6.0 GHz and 8.0 GHz, with stable gain maintained across the passband. The measured frequency selectivity at the lower and upper edges is 27 and 42 dB/GHz, indicating moderate frequency selectivity. The simulated radiation efficiency is above 90% in the passband. The measured data closely follow the simulated curves, validating the accuracy of the design. Minor discrepancies, such as slight shifts in notch frequency and reduced suppression depth, are attributing to fabrication tolerances, dielectric constant variations, and connector losses during measurement. Importantly, both simulation and measurement confirm the effectiveness of the SH-HMSIW cavity and passive patch configuration in producing controllable notches while sustaining high radiation efficiency.

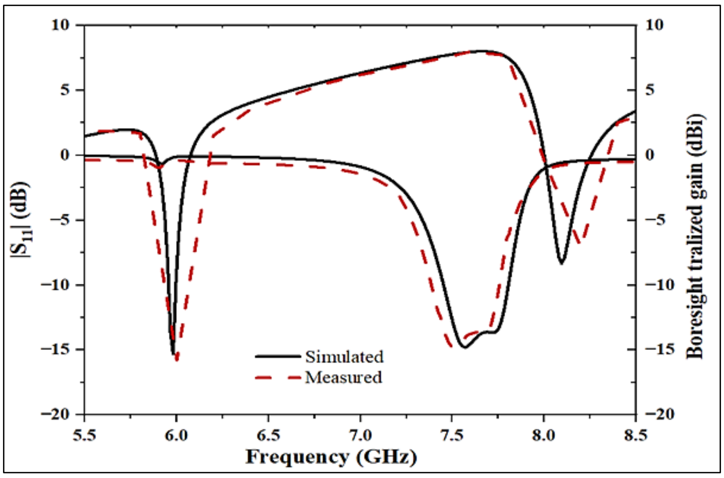


Figure 9: Simulated and Measured Reflection Coefficient ($|S_{11}|$) and Corresponding Boresight Gain of the Proposed Filtering Antenna as a Function of Frequency

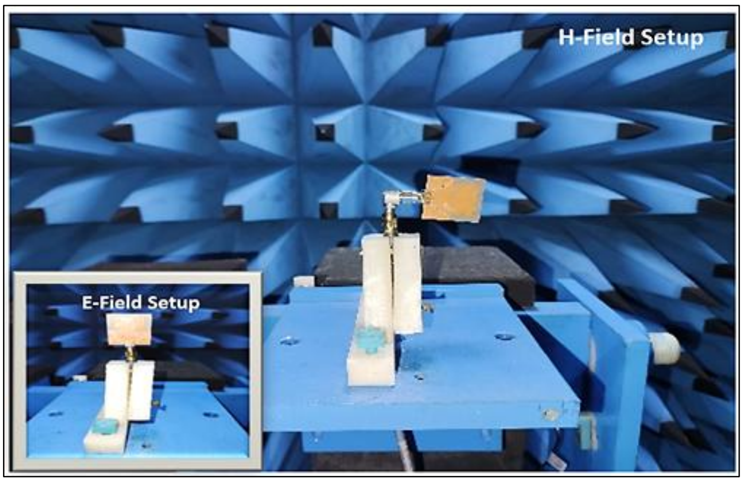


Figure 10: Experimental Measurement Setup of the Fabricated Filtenna in an Anechoic Chamber, The Main View Displays the H-field (Magnetic Field) Measurement Configuration, While the Inset shows the E-Field (Electric Field) Measurement Configuration

The fabricated filtenna prototype is teste in a standard anechoic chamber, as shown in Figure 10. The setup allowed precise measurement of return loss, gain, and radiation patterns under controlled conditions. The supporting fixture ensured stable alignment of the antenna, while the absorbers surrounding the chamber provided a reflection-free environment. This measurement arrangement validates the simulated results and confirms the practical feasibility of the proposed design. The results that the antenna maintains a stable and directional radiation pattern in both planes shown in Figure 11 (a) and (b). The co-polarization levels dominate significantly over the cross-polarization, confirming good polarization purity. In the E-plane, the pattern exhibits a broad main lobe with low side-lobe levels, while in the H-plane, a near-omnidirectional response is observed, typical for cavity-backed designs. The agreement between simulated and measured results is strong, with only minor deviations due to fabrication and alignment tolerances during measurement. These results verify that the proposed structure provides consistent radiation behaviour and is well suited for practical applications requiring stable gain and good polarization control. Table 1 clearly shows that the proposed filtenna outperforms several recent designs. It achieves a higher peak gain (8 dBi), very compact thickness (0.012λ0), flat gain in pass band and two controllable radiation nulls, while keeping a competitive footprint. Unlike earlier works that rely mainly on parasitic patches or defected grounds, our design combines an SH-SIW cavity with a passive patch, giving both strong filtering and tenability. This makes the antenna not only efficient but also compact and adaptable for modern wireless applications.

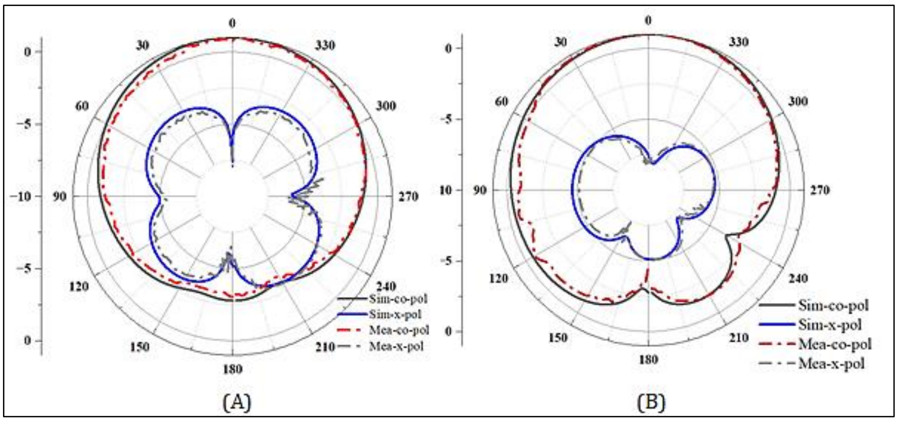


Figure 11: Radiation Patterns of the Proposed Filtenna at the Center Frequency (A) E-Plane (Φ=0°), (B) H-Plane (Φ=90°) The Solid Lines Represent Simulations, While Dashed Lines Indicate Measurements, Co-Polarization and Cross-Polarization are Denoted in Black/Red and Blue/Gray, Respectively

Table 1: Performance Comparison with Recently Reported Filtenna

Parameter Ref	Centre Frequency (GHz)	FBW (%)	Gain (dBi)	Thickness (λ_0)	Size ($\lambda_0 \times \lambda_0$)	Radiation Null	Feed Type	Key Features
(20)	3.2	7.90	7.34	0.017	0.29	2	Coax probe	SC-SIW + parasitic patch
(21)	3.5	5.1	7	0.018	0.53×0.81	2	Coax probe	Multimode SIW + patch
(22)	9.5	2.53	5.8	0.015	0.53×0.72	2	50Ω Micro strapline	SIW with electric + magnetic mixed coupling
(23)	2.8	4.2	6.76	0.014	0.18	2	GCPW	HMSIW + dual parasitic patches
(24)	3.52	9.14	7.4	0.037	0.74x0.74	2	Coax probe	HMSIW + dual parasitic patches
(25)	8	5.6	6.65	0.014	0.307x0.307	2	Coax probe	Wideband patch + SIW cavity
Proposed work	7.6	4.6	8	0.012	0.81x0.633	2	Coax probe	SH-SIW + Passive patch

Conclusion

In this work, a compact single-layer filename based on a modified SH-HMSIW cavity with a via-loaded passive patch has been proposed, designed, and validated. The antenna successfully integrates radiation and filtering functions within the same structure, eliminating the need for external filters. Simulation and measurement results confirm a high realized gain of 8 dBi, a fractional bandwidth of 4.6%, and effective dual radiation nulls, demonstrating good frequency selectivity and stable pass band performance. Compared to existing designs, the proposed antenna offers reduced thickness, enhanced gain, and improved rejection characteristics while maintaining structural simplicity. Looking ahead, the concept can be further extended to meet the demands of emerging wireless technologies. Potential directions include reconfigurable designs using reactor diodes or RF MEMS to enable tunable notches and multi-band operation, integration with MIMO systems for higher capacity, and adaptation for millimetre-wave frequencies to support 5G and beyond. Moreover, compact array configurations based on the proposed structure could be explored for high-gain directional applications. These developments would make the design even more versatile, ensuring its suitability for next-generation wireless and RF communication systems.

Future Scope

The proposed filename design can be further extended in several helpful directions. Reconfigurable components such as PIN diodes, reactor diodes, or RF MEMS may be incorporated to enable frequency tuning, switchable band rejection, and multi-band operation. The design can also be applied to MIMO configurations to improve system capacity and data throughput. Furthermore, the structure can be modified for operation at millimetre-wave frequencies, making it suitable for 5G and future wireless technologies. The development of compact filename arrays based on this concept can also provide higher gain and improved directional performance, enhancing their applicability in next-generation RF and wireless communication systems.

Abbreviations

ANSYS HFSS: Ansys High-Frequency Structure Simulator, DGS: Defected Ground Structure, ELARC: Electromagnetic and Antenna Research Centre, FBW: Fractional Band Width, HMSIW: Half-Mode Substrate Integrated Waveguide, OOB: out of band, PCB: Printed Circuit Board, SH-HMSIW: Semi Hexagonal–Half Mode Substrate Integrated Waveguide, TEQIP – III: Technical Education Quality Improvement Programme – III.

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Author Contributions

Parul H Panchal: conceptualization of the idea, the design of the SH-SIW cavity, conducting simulations, performing performance analysis, validating experimental results, preparing the manuscript, Falguni Raval: proofreading of the manuscript, provided approval as the supervising guide for the document.

Conflict of Interest

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

Declaration of Artificial Intelligence (AI) Assistance

Generative AI tools were used only for language editing and improving clarity in this manuscript. All technical content, analysis, and results are the authors' original work, and the authors take full responsibility for the accuracy and integrity of the paper.

Ethics Approval

This research did not involve human participants or animal subjects; therefore, ethical approval was not required for this study. All experimental procedures adhered to established guidelines for research integrity and ethical standards within the field.

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