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Design of Monopole Antenna Integrated with an CSRR-SIW band-pass Filter using a Cascaded Approach

Fatma Zohra Hamrioui [1*], Rachida Touhami [1,2], Mustapha C.E. Yagoub [3]

[1] Laboratoire des Dispositifs de Communication et de Conversion Photovoltaïque (LDCCP), Département d'Electronique, Ecole Nationale Polytechnique, 10 Rue des Frères OUDEK, El Harrach 16200, Algiers, Algeria, fatma_zohra.hamrioui@g.enp.edu.dz

[2] Instrumentation laboratory, Electronics and Informatics faculty, USTHB university, Bp32,El Alia ,Bab Ezzouar, Algiers, Algeria, rachida.touhami@g.enp.edu.dz

[3] ELEMENT laboratory, School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, Canada, myagoub@uottawa.ca

*Corresponding author: (Fatma Zohra Hamrioui), *Email Address*: fatma_zohra.hamrioui@g.enp.edu.dz

Abstract

In this paper, a butterfly-shaped monopole antenna is integrated with a CSRR-SIW band-pass filter using a cascaded approach. Initially, the design of the monopole antenna was suggested and studied. The bandwidth of this monopole antenna was extended by inserting a L-Shaped DGS into the partial ground plane, where the extended bandwidth ranges from 2.49 to 6.53 GHz . The design of an SIW band-pass filter based on extended split rectangular CSRRs is suggested to operate within the Wi-Fi 5 GHz band. The proposed band-pass filter operates at 5.47 GHz with -3dB fractional bandwidth of 13.52% (i.e., 5.07 GHz -5.81 GHz). The observed insertion loss is around 0.24 dB and the return loss is 32.23 dB. To validate the SIW-CSRR filter performance, it was cascaded with the previous wideband monopole antenna to cover the 5 GHz WI-Fi band. The resulting filtenna successfully achieves the primary goal of sharply defining the operating frequency band while maintaining good impedance matching within that band. Moreover, the suggested filtenna provides an omnidirectional radiation pattern over the desired band with a realized gain of 2.93 dB_i.

Keywords: Antenna; Filter; SIW; Filtenna.

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1. Introduction

Band pass filters and antennas are essential components in most RF front-ends, and their performance is critical to the overall system operation [1]. Compact size, low cost, light weight, robustness, and excellent filtering and radiating characteristics are the key properties driving an exponential surge in research focused on RF front-end system development [2]. In this context, Substrate Integrated Waveguides (SIW) have piqued the interest of researchers in microwave circuits due to their inherent benefits such as a higher quality factor, low radiation losses, compact size, and high power handling capacity [3]. Substrate integrated waveguide is a popular guided-wave configuration, intermediate between regular bulky waveguides and planar structures. It is synthesized on a planar dielectric substrate using linear, periodic arrays of metalized vias to form the sidewalls. This arrangement creates a discontinuity of the metal sidewall, which prevent the propagation of transverse magnetic TM mode wave [4].

Different technological approaches have been employed to realize high-performance filtennas. In [2], the integration utilized a synthesis approach where an inverted L-shaped monopole antenna replaced the second resonator of the band-pass filter. The antenna was integrated into the filter structure via a coupled line admittance inverter, resulting in a compact module that exhibits near-zero insertion loss within the operating frequency band. In [1], a compact integrated filtering antenna was proposed. This design utilized a microstrip structure combining a square ring resonator and a capacitor-loaded microstrip line filter, which was connected to the feeding line of a conventional patch antenna without adding extra space. In [5], a compact, wideband circularly polarized planar filtenna based on filter synthesis methodology was proposed for 5 GHz WLAN applications. The design integrates a third-order hairpin line resonator filter with a circularly polarized hexagonal radiating element. The high level of integration resulted in a wide impedance bandwidth, good stop-band gain rejection, and high selectivity at the band edges.

In this paper, a butterfly-shaped monopole antenna is integrated with a CSRR-SIW band-pass filter using a cascaded approach. The objective of this work is to demonstrate the ability of SIW structures to integrate with other microwave components by designing a band-pass filter based on this technology. The first component is a wideband monopole antenna that covers N77,N78 and N79 5G bands, and WIFI bands with large bandwidth more than 4 GHz. and the second component is a SIW-CSRR band-pass filter that operates at WIFI 5GHz band with minimum insertion loss.

The result of this cascading is a successful filtenna that achieves a sharply defined operating frequency band while maintaining good impedance matching within that band and provides an omnidirectional radiation pattern over the desired band with a realized gain of 2.93 dB_i. Therefore, this approach demonstrates the ability to utilize a single, high-performance wideband antenna for diverse applications, either in its unfiltered state for wideband capability or in its filtered state for narrow-band communication, with the latter being the primary focus and core contribution of this paper. To thoroughly cover the methodology, implementation, and performance of the proposed design, the paper is organized into several sections: Section 2 details the methodology used to design the wideband antenna with L-shaped defected ground structure (DGS). Section 3 focuses on the design of the SIW band-pass filter by loaded extended Complementary split Ring Resonators (CSRRs), including its S-parameters and current distribution. Section 4 describes the final cascaded implementation, presenting the resulting simulated performance, such as the sharp input reflection coefficient response and omnidirectional radiation pattern. Finally, Section 5 provides the conclusion of the paper.

2. Design and analysis of the proposed monopole antenna

One category of antenna used in wireless technology is the monopole antenna due to their wide bandwidth, light weight and small size. In this section, a butterfly-shaped monopole antenna is designed. This proposed antenna is printed on Rogers RT/Duroid 5880 substrate having a thickness of 0.79 mm , permittivity of 2.2 and dielectric loss tangent of 0.0009. The proposed structure is illustrated in figure 1 and the geometric dimensions are given in table 1. Note that the partial ground plane is etched with an L-shaped defected ground structure (DGS) to extend the operating band. To illustrate the effect of the DGS on the input reflection coefficient, the design evolution of the proposed antenna, evolving from prototype 1 to prototype 2, is depicted in figure 2. The input reflection coefficients of these antennas are shown in figure 3.

The design of the proposed antenna starts with a butterfly-shaped patch antenna with a partial ground plane (Prototype I, Figure 2). The antenna resonates at 5.28 GHz with -10 dB bandwidth spanning from 3.71 GHz to 5.83 GHz. To enhance bandwidth performance, two L-shaped DGS elements are etched onto the partial ground plane (Prototype 2, Figure 2). Consequently, the bandwidth expands from 2.49 to 6.53 GHz with maximum return loss of 29.12 dB.

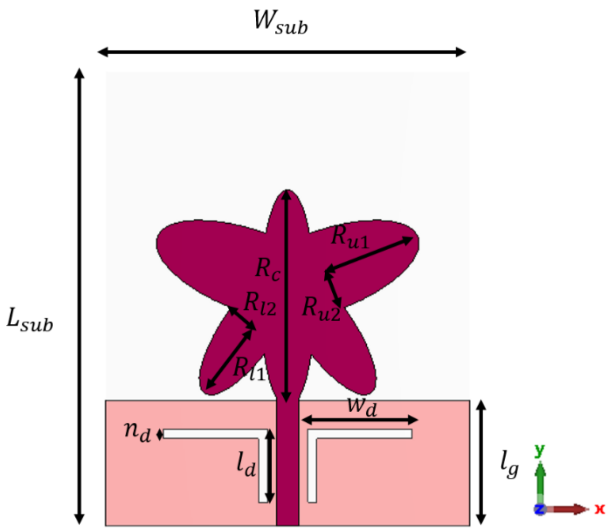


Figure 1. Geometric structure of the proposed butterfly monopole antenna.

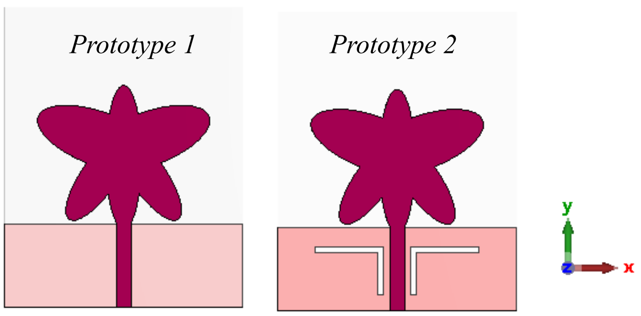


Figure 2. The design evolution of the suggested monopole antenna.

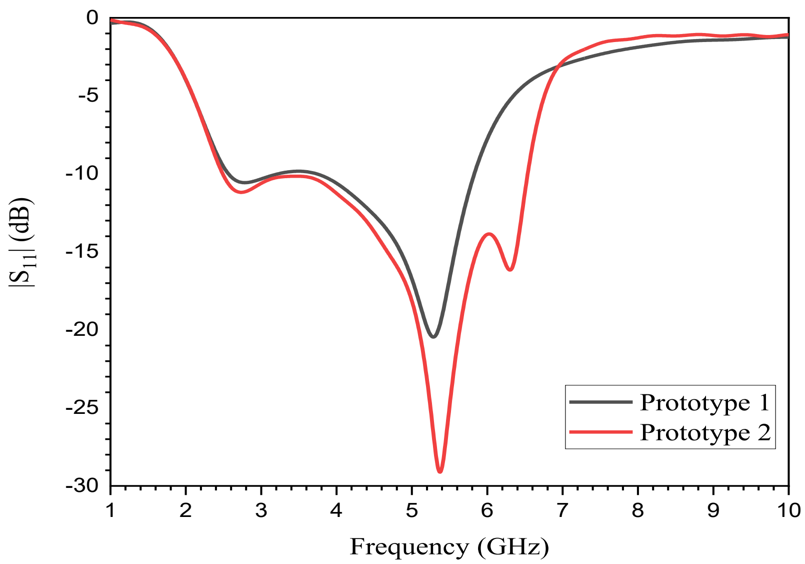
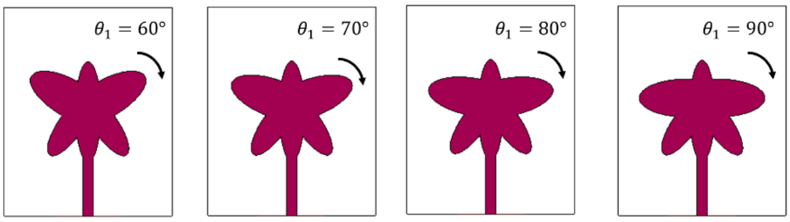


Figure 3. the input reflection coefficient for each prototype.

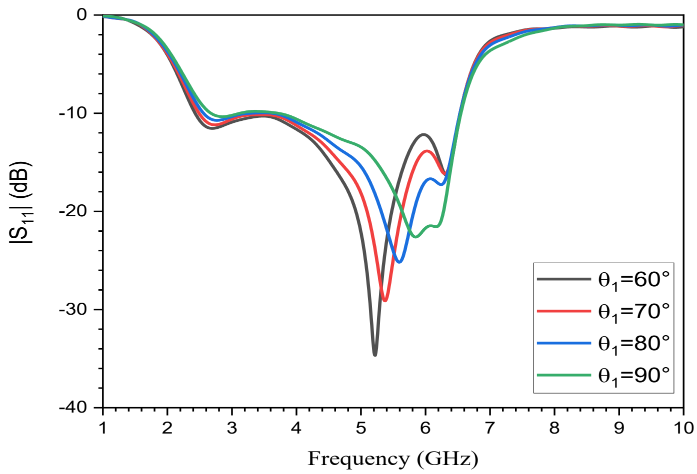
Table 1. Detailed dimensions of the proposed monopole antenna.

W_{sub}	L_{sub}	W_d	L_d	L_g
50.00 mm	40.00 mm	11.50 mm	8.00 mm	13.80 mm
n_d	R_{u1}	R_{l1}	R_c	h
1.00 mm	11.00 mm	9.00 mm	24.00 mm	0.79 mm
R_{u2}	R_{l2}	Θ_1	Θ_2	
4.50 mm	3.00 mm	-70°	-35°	

Next, the effect of the parameters Θ_1 and Θ_2 on the upper and lower wings are shown in figures 4 and 5, respectively. As Θ_1 is increased, the return loss is reduced and the primary resonant frequency is moved toward a higher frequency .Whereas, as Θ_2 is increased from 15° to 45°, the primary resonant frequency shifts to a higher frequency and the bandwidth is extended except that as Θ_2 exceeds 45° ,the bandwidth is reduced. Therefore, Θ_2 is a sensitive tuning parameter for the antenna's operating frequency. Changing Θ_2 effectively changes the antenna's geometry, which directly dictates its resonant frequency and the operating bandwidth . These results suggest that Θ_2 = 35° is the optimal design point for this antenna within the tested range, as it provides the best and the widest impedance bandwidth.

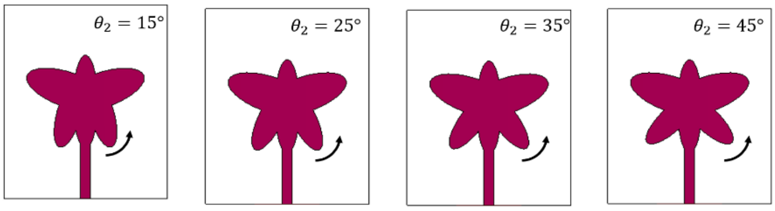


(a)

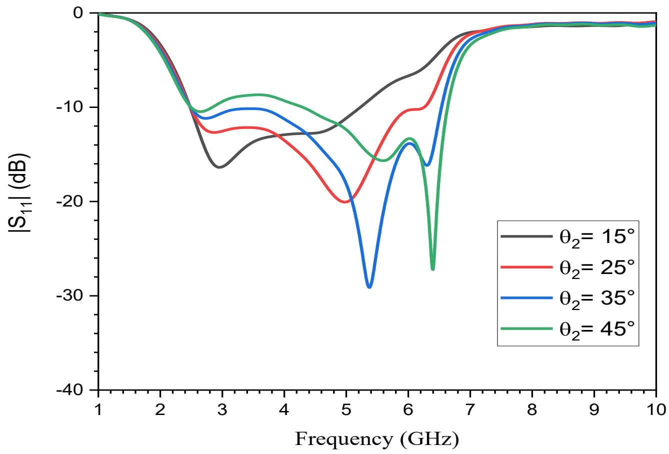


(b)

Figure 4. Input reflection coefficient of the proposed monopole antenna by varying Θ_1, (a) Varying Θ_1 (b) the input reflection coefficient for each Θ_1.



(a)



(b)

Figure 5. Input reflection coefficient of the proposed monopole antenna by varying Θ2, (a) Varying Θ2 (b) the input reflection coefficient for each *Θ2* .

The simulated 3D radiation patterns of the proposed monopole antenna at 5.37 GHz is shown in figure 6. From this figure, we can see that the antenna exhibits almost broadside omnidirectional radiation pattern at this operating frequency with maximum realized gain of 2.92 dB_i and directivity of 3.01 dB_i.

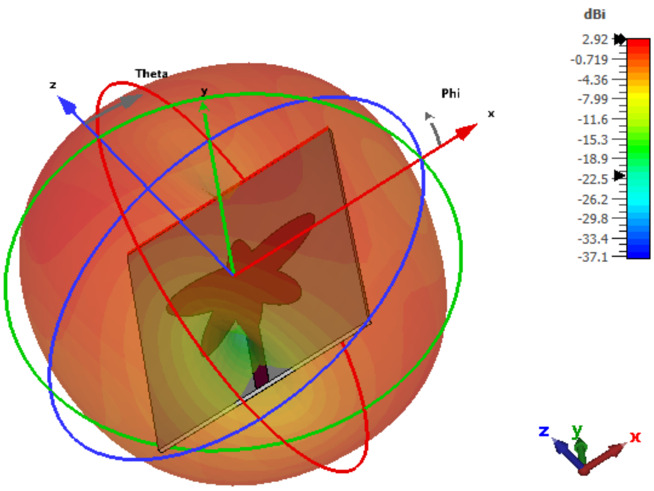


Figure 6. Simulated 3D radiation patterns of the proposed filtenna at 5.37 GHz.

3. Design of the proposed CSRR-SIW band-pass filter

The design structure of the suggested SIW band-pass filter based on CSRRs is shown in Figure 7. Two rows of metallic via holes are inserted on the waveguide's two long sides, to form the waveguide's metal walls. The diameter d of the via is fixed to 0.60 mm and pitch s of via holes is fixed to 1.10 mm. a face-to-face extended split rectangular resonators are etched on the top of the metal plane of the SIW cavity to provide a pass-band below the waveguide cutoff in accordance with the theory of evanescent-mode propagation[6].

The 50Ω microstrip lines are directly connected to the cavity at input/output ports. This suggested filter is designed using 0.79mm thick Rogers RT/Duroid 5880 substrate having a permittivity of 2.22 and dielectric loss tangent f 0.0009.The geometric dimension are : l_p=*4.40 mm* and w_p=*10.00 mm.*

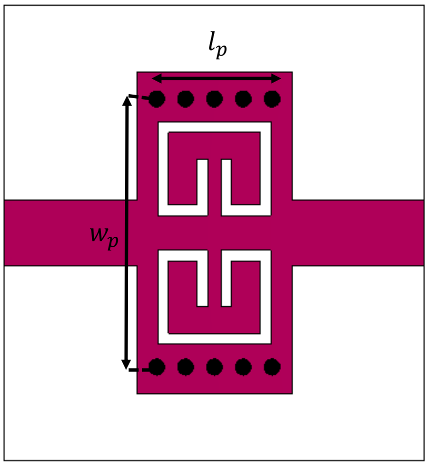


Figure 7. Geometric structure of the proposed SIW-CSRR band-pass filter

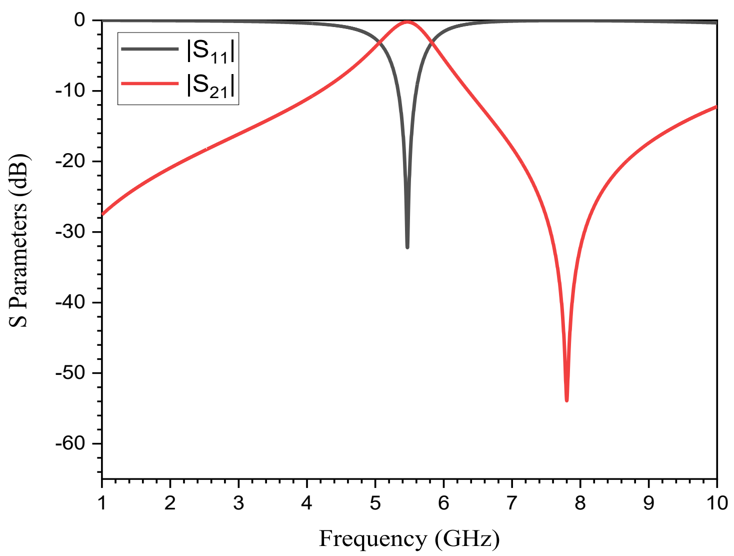


Figure 8. Simulated S-Parameters of the suggested SIW-CSRR band-pass filter.

The simulated results of the proposed band-pass filter are shown in figure 8. It is seen that the proposed filter operates at 5.47 GHz with -3dB fractional bandwidth of 13.52 % (i.e., 5.07 GHz-5.81 GHz) covering the 5 GHz Wi-Fi band. The observed insertion loss is around 0.24 dB and the return loss is 32.23 dB. One transmission zero around 7.80 GHz is detected at upper stop-band with high attenuation of 53.91 dB.

The electric field distribution of the proposed SIW-CSRR band-pass filter is shown in figure 9. The electric field distribution is concentrated around the CSRRs as indicated by the color ramps, demonstrating that the pass-band created below the waveguide cutoff frequency is caused by loading the CSRRs into the SIW.

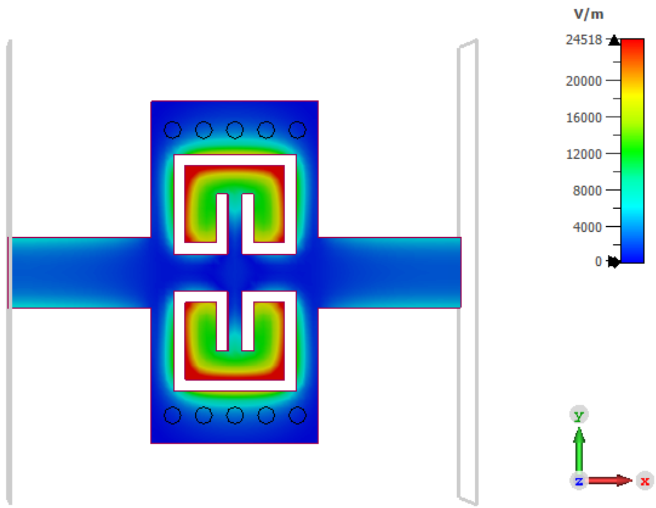


Figure 9. Simulated E field distribution of the proposed SIW-CSRR band-pass filter.

4. Design and analysis of the proposed filtenna

To achieve a filtering response, the proposed butterfly monopole antenna is cascaded with the suggested SIW-CSRR band-pass filter. The resulting filtenna from this cascaded structure is shown in figure 10. The geometric dimensions are: W_{sub}= *40 mm* and L_{sub}= *66 mm.*

The input reflection coefficient versus frequency is depicted in figure 11. It can be seen that the suggested design successfully achieves the primary goal of a filtenna: sharply defining the operating frequency band while maintaining good impedance matching within that band. The suggested filtenna resonates at frequency of 5.41 GHz with a minimum input reflection coefficient of -25.38 dB, indicating a near-perfect impedance match where virtually all power is delivered to the antenna .A−10 dB impedance bandwidth from 5.27GHz to 5.54 GHz is obtained around the resonant frequency. Outside the desired band, the return loss rises sharply and approaches 0 dB.

This value in the stop-band confirms the functionality of the suggested filter, which effectively rejects unwanted signals and interference.

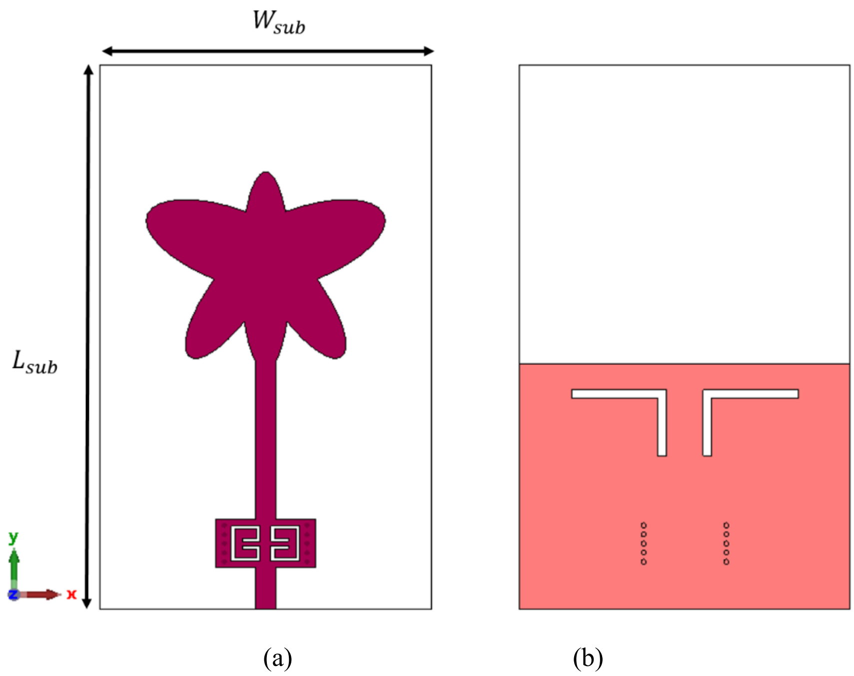


Figure 10. Geometric structure of the proposed filtenna, (a) Top view, (b) back view.

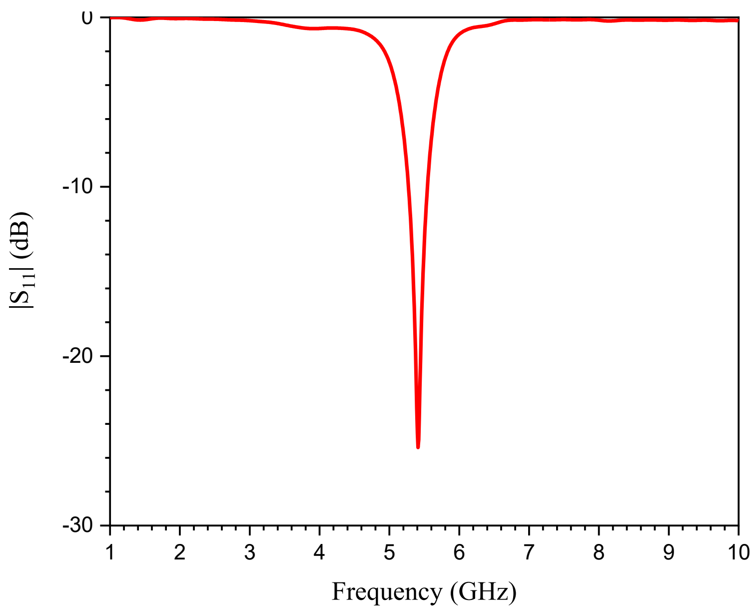


Figure 11. Input reflection coefficient of the proposed filtenna.

The E plane (φ = 90°) and H plane (φ = 0°) radiation patterns at 5.41 GHz of the proposed filtenna are illustrated in figure 12. It can be seen that this filtenna exhibits broadside ,omnidirectional pattern similar to radiation pattern of the monopole antenna at the same operating band .The realized gain is around 2.93 dB_i and the directivity of 3.23 dB_i.

Therefore, the suggested filter does not change the physical structure of the radiator itself, thus the pattern is preserved. The 3D radiation pattern is illustrated in figure 13.

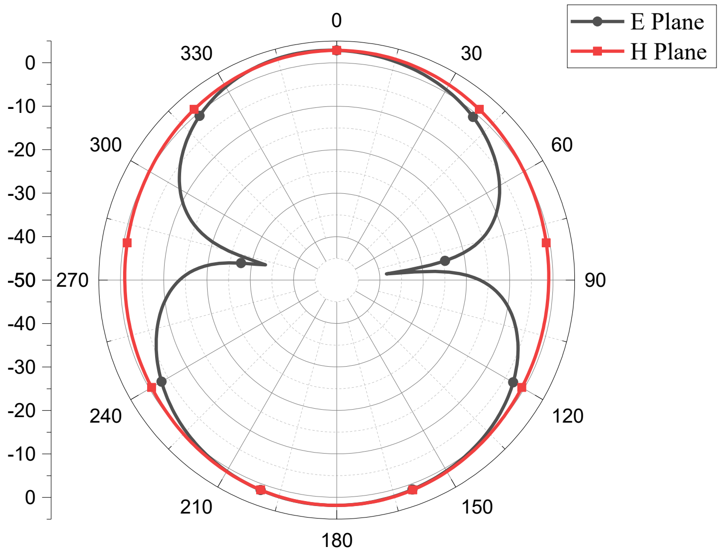


Figure 12. Simulated radiation patterns of the proposed filtenna at 5.41 GHz.

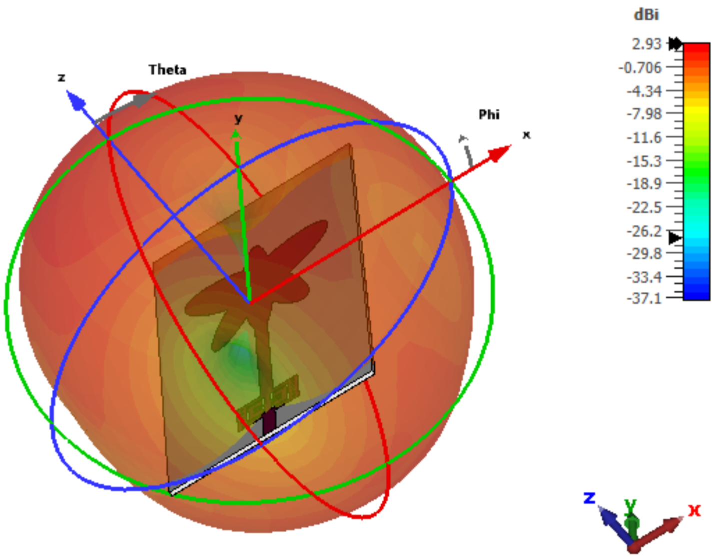


Figure 13. Simulated 3D radiation pattern of the proposed filtenna at 5.41 GHz.

To demonstrate the impact of the filter on the antenna's realized gain, figure 14 compares the realized gain of the standalone antenna and the proposed filtenna across the 1–10 GHz frequency range. The realized gain of the suggested antenna varied from 1.63 dB_i to 3 dB_i across the frequency band from 2.47 GHz to 5.45 GHz. Specifically, the gain reached a maximum of 5.17 dB_i at 6.28 GHz before decreasing to -1.70 dB_i at 10 GHz.

Whereas, the filtenna exhibits a selective gain response where the gain varies from 2.46 dB_i to 2.52 dB_i across the operating band, achieving a peak gain of 2.92 dB_i at the center frequency. Outside this band, the realized gain drops significantly, decreasing to -21.90 dB_i at 1.80 GHz on the lower side ,and further decreasing by -13.10 dB_i at 7.10 GHz on the higher side, before increasing again to -9.23 dB_i at 10 GHz.

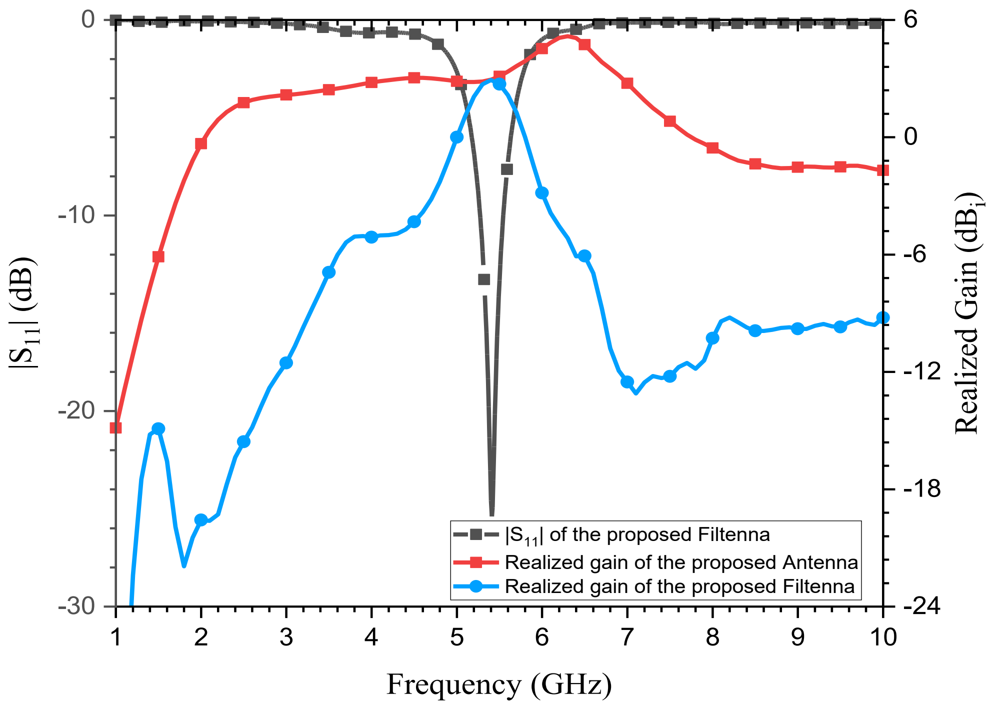


Figure 14. Simulated realized gain versus frequency.

The performance of the suggested filtenna compared to similar works is illustrated in table 2. The proposed filtenna achieves a maximum gain of 2.93 dB_i, which is the highest value compared to the cited works. This value is consistent with the gain of the standalone wideband antenna before integration. Therefore, this high gain is attributed to the effective integration of the low-loss SIW-CSRR band-pass filter. However, this high performance comes at the expense of footprint where the size of the proposed design is larger than the cited works.

Table 2. Performance comparison of the suggested filtenna with existing works (*: Simulated, **: Measured)

Works	f_r (GHz)	10 dB FBW (%)	RL (dB)	Gain (dB_i)	Size (mm^2)
[1] (**)	2.40	3.00	-	2.61	-
[2] (**)	2.40	7.50	-	0.74	$0.28\lambda_0 \times 0.24\lambda_0$
[7] (**)	2.45	10.00	-	0.65	$0.49\lambda_0 \times 0.49\lambda_0$
[8] (**)	2.45	-	-	1.20	$0.41\lambda_0 \times 0.41\lambda_0$
This work (*)	5.41	5.00	25.38	2.93	$0.72\lambda_0 \times 1.19\lambda_0$

5. Conclusion

This paper presents the cascaded integration of a butterfly-shaped monopole antenna and a CSRR-SIW band-pass filter. The proposed monopole antenna covers the (2.49 - 6.53 GHz). Its wide bandwidth is attributed to the L-shaped DGS etched into the partial ground plane. On the other hand, the design of a compact SIW CSRRs band-pass filter is suggested. The proposed filter covers the 5 GHz WI-Fi band with -3dB fractional bandwidth of 13.52 % (i.e., 5.07 GHz -5.81 GHz). To verify the functionality of the proposed filter, it is cascaded with the previous monopole antenna. The suggested filtenna resonates at frequency of 5.41 GHz with a minimum input reflection coefficient of -25.38 dB, indicating a near-perfect impedance match and $-10\ dB$ impedance bandwidth from $5.27GHz$ to 5.54 GHz is obtained around the resonant frequency. In addition, the suggested filtenna provides an omnidirectional radiation pattern over the desired band with a realized gain of 2.93 dB_i. These results prove that the suggested SIW-CSRR band-pass filter does not change the physical structure of the radiator and the monopole antenna's omnidirectional radiation pattern is preserved. Furthermore, because the antenna and filter are well-matched in the pass-band, the power delivered to the antenna is maximized. Consequently, the realized gain and the pattern form of the filtenna system is nearly the same as the original wideband monopole antenna's peak gain and pattern.

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