Indonesian Journal of Electrical Engineering and Computer Science
Vol. 40, No. 3, December 2025, pp. 1337∼1344
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v40.i3.pp1337-1344

Miniaturized reconfigurable metamaterial based bandstop filter for wireless applications

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Article Info

Article history:

Received Jan 22, 2025
Revised Aug 5, 2025
Accepted Oct 15, 2025

Keywords:

Bandstop filter
Metamaterial resonator
Microwave filter
Reconfigurable
Wireless application

ABSTRACT

The design of compact size and high efficiency metamaterial based reconfigurable microstrip bandstop filter for IEEE 802.11 WLAN applications is developed. This paper presents a switchable dual-mode filter, it resonant at 2.4 GHz and 3.6 GHz. The hexagonal metamaterial resonator inserted switch as PIN diode which form reconfigurable filter. By changing the DC bias of the diode, the filter can be reconfigured with a controlled precision, resulting in the frequency reconfigurable. The CST simulator used to simulate filter design, measuring a return loss over -29.12 dB and a low insertion loss less than -0.2 dB, which is a great performance. The filter is compact at the size of 8 mm×12 mm×1.6 mm design using Rogers RT Duroid 5880 substrate.

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1. INTRODUCTION

The advancement of wireless technologies has necessitated the development of compact, high-performance radio frequency (RF) components that can support various standards such as long-term evolution (LTE), wireless fidelity (Wi-Fi), and wireless local area network (WLAN). The research [1]-[7] microstrip filters have become critical in minimizing interference and enhancing signal quality. Recently, designs based on metamaterials have gained attention for their distinctive electromagnetic properties, which facilitate the creation of filters that are both smaller and more efficient [8]-[10]. This paper introduces a reconfigurable bandstop filter that employs a novel hexagonal metamaterial resonator [11]-[17]. The design utilizes the adaptability of PIN diodes for frequency reconfiguration, catering to the increasing demand for reconfigure solutions in wireless applications [13], [18]-[21]. Metamaterials, especially resonators such as split ring resonators for their ability to control electromagnetic waves in innovative ways [9], [11], [16], [22]. The proposed filter integrates a hexagonal metamaterial structure with a microstrip line to establish highly selective rejection bands at 2.4 GHz and 3.6 GHz. The use of PIN diodes for reconfigurability presents an efficient and practical approach, simplifying the traditional tuning processes while ensuring high performance [23]-[25].

For modern wireless communication systems, this work presents a novel, miniature, reconfigurable bandstop filter inspired by metamaterials. The proposed design uses a combination metamaterial structure made up of a complementary ring resonator (CSRR), split ring resonator (SRR) arranged in a special configuration, in contrast to conventional bandstop filters that have limited tuning flexibility and size efficiency [9]. The primary reason behind this integration is the ability to use electronic switching to enable changing frequency reconfiguration while achieving unique size reduction and improved stop band performance.

The design of compact size and high efficiency metamaterial based reconfigurable microstrip bandstop filter for IEEE 802.11 WLAN applications is developed. PIN diode is inserted across the novel hexagonal metamaterial cell (NHMC) structure to provide reconfigurability, enabling the filter to function in two different modes: passband and stopband. This switching behavior gives the filter design adaptability, allowing it to be used in many different frequencies [12]. This paper presents a switchable dual-mode filter, it resonant at 2.4 GHz and 3.6 GHz. The hexagonal metamaterial resonator inserted switch as PIN diode which form this reconfigurable filter. By changing the DC bias of the diode, the filter can be reconfigured with a controlled precision, resulting in the frequency reconfigurable. The CST simulator used to simulate filter design, measuring a return loss over -29.12 dB and a low insertion loss less than -0.2 dB, which is a great performance. The filter is compact at the size of 8 mm$\times$12 mm$\times$1.6 mm design using Rogers RT Duroid 5880 substrate.

Figure 1 illustrates the evolution of compact and reconfigurable metamaterial unit cells. The initial design Figure 1(a), the hexagonal split ring resonator (HSRR) [13], features two concentric hexagonal rings with splits. Though effective, it occupies more space. To improve compactness, design Figure 1(b), the hexagonal metamaterial cell (HMC) [12], replaces the dual rings with a single split ring, reducing inductance and simplifying the structure. Further refinement leads to Figure 1(c), the proposed NHMC [15], which includes an extended inner cut for frequency tuning and a C-shaped loop for enhanced miniaturization. This results in a highly compact and effective structure. The final version Figure 1(d) integrates a PIN diode (BAR 64002) on the inner arm, enabling reconfigurability and dual-mode operation by varying the diode bias. This optimized design functions as an adaptable bandstop filter, supporting switchable filtering modes. The work represents a key advancement in reconfigurable metamaterial design for wireless applications.

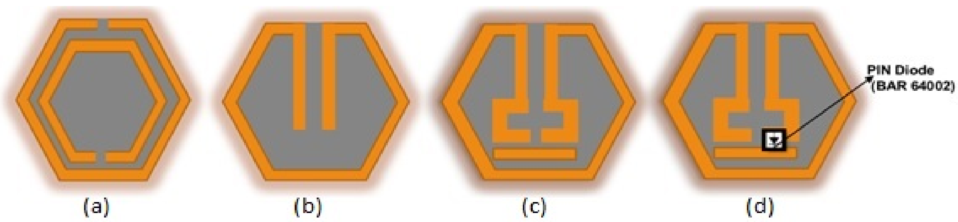


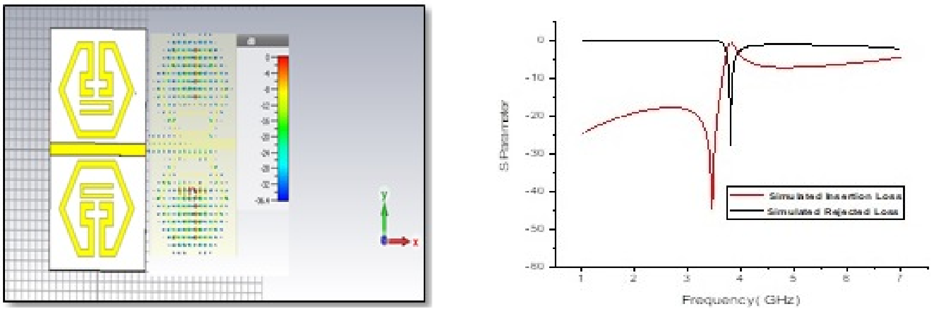
Figure 1. Different metamaterial resonator design; (a) HSRR, (b) HMC, (c) fundamental structure of innovative modified NHMC, (novel hexagonal metamaterial cell), and (d) reconfigurable structure of innovative hexagonal meta unit with PIN diode

2. BANDSTOP FILTER DESIGN

The proposed methodology includes the design, simulation, fabrication, and experimental validation of a miniaturized, reconfigurable metamaterial-based bandstop filter (BSF) for IEEE 802.11 WLAN applications. It is divided into two parts: (i) fixed bandstop filter design and (ii) frequency-reconfigurable BSF design. The design uses a microstrip line loaded with a metamaterial unit cell exhibiting single negative (SNG) properties—either negative permittivity or permeability—resulting in strong attenuation at resonance due to coupling effects. Placing the metamaterial resonator along the microstrip line induces a localized stopband, determined by the resonator's geometry and material [26] . For enhanced rejection, two identical resonators are symmetrically placed to improve coupling and depend the stopband through mutual interaction. Rogers RT Duroid 5880 is chosen for its low dielectric loss and stable permittivity ($\varepsilon_r = 2.2$), ensuring low insertion loss and high performance at microwave frequencies. The resonator is modeled in CST Microwave Studio and optimized to produce a sharp attenuation at 3.6 GHz, suitable for sub-6 GHz 5G communication. Its dimensions are fine-tuned to ensure strong rejection at the target frequency with minimal loss outside the stopband.

2.1. Design and simulation

Figure 2 presents the design and simulation results of the proposed BSF using a NHMC. The symmetric configuration of the NHMC unit cells ensures balanced electromagnetic field distribution and improved coupling efficiency. Figure 2(a) shows the CST-simulated surface current distribution on the microstrip line embedded with the NHMC structure, highlighting the effective interaction between the resonator and the line. Figure 2(b) depicts the simulated S-parameter response of the BSF, clearly demonstrating a stopband centered at 3.6 GHz with significant signal rejection. The structure consists of a hexagonal metamaterial resonator symmetrically placed on a 50-ohm microstrip line, generating a rejection band at 3.6 GHz. The resonator has a ring thickness of 0.8 mm, outer ring length of 4 mm, and inner ring size of 3.2 mm with 1.6 mm thickness. The feedline width is 1.2 mm. The microstrip is implemented on a Rogers RT Duroid 5880 substrate, known for its stability, low dielectric loss, and relative permittivity of 2.2.



(a) (b)

Figure 2. Bandstop filter design and simulation results, (a) NHMC-based BSF structure and current distribution simulated in CST, illustrating symmetric current flow on the microstrip and (b) simulated S-parameter response of the BSF showing a sharp stopband centered at 3.6 GHz with significant return loss

This configuration permits the resonator to effectively absorb the unwanted frequency band at 3.6 GHz when the 50-ohm microstrip line is energized. CST simulation results, illustrated in Figure 2(b). It validate the resonance occurring at 3.6 GHz, achieving significant rejection with a return loss (S21) of -29.12 dB. The insertion loss at this frequency is minimal, recorded at -0.15 dB, indicating low power dissipation and efficient operation. This design methodology promotes a compact and reliable filter, making it suitable for advanced wireless applications operating at 3.6 GHz.

2.2. Fabricated bandstop filter prototype based on metamaterial

The fixed BSF prototype is fabricated using Rogers RT Duroid 5880 substrate with dimensions 8 mm$\times$12 mm$\times$1.6 mm shown in Figure 3. After fabrication, the filter is tested using a vector network analyzer (VNA) to validate the S-parameter performance. The Roger RT Duroid 5880 material was used to develop the NHMC-based BSF prototype, which is shown in Figure 3(a). A VNA included of the measurement setup to evaluate the prototype's performance shown in Figure 3(b) shows the connections. Figure 3(c) presents the results of the experiment for the NHMC-based BSF, correctly illustrating the insertion loss and return loss.

(a) (b) (c)

Figure 3. NHMC metamaterial-based bandstop filter; (a) fabricated prototype, (b) measurement setup (VNA Agilent 8722ES 50 MHz-40 GHz), and (c) measured result of the BSF at 3.6 GHz

Figure 4 presents a comparison between the simulated and fabricated results of the metamaterial BSF. The Figure 4 shows simulated NHMC-based BSF shows resonance at 3.6 GHz, with a measured return loss of -28.12 dB, compared to the simulated value of -29.12 dB. Correspondingly, the measured insertion loss at 3.6 GHz is -0.2 dB, whereas the simulations indicated -0.15 dB. These minor variations, as highlighted in the accompanying results, underscore the practical challenges encountered when transitioning from simulation to fabrication.

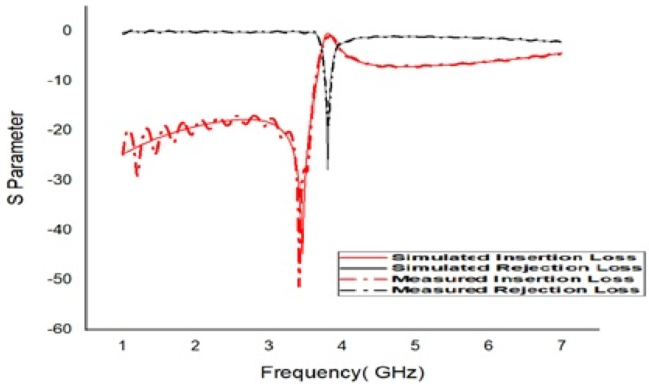


Figure 4. NHMC-based bandstop filter- simulated and measured results

The difference in result observed can be attributed to several factors. Fabrication tolerances, including minor variations during the etching process and slight misalignments during assembly. The measurement setup may also introduce potential inaccuracies due to connector losses and calibration errors within the VNA. Despite these variations, the NHMC-based BSF exhibits excellent rejection characteristics and low insertion loss, confirming its reliable and efficient operation in real-world applications.

3. RECONFIGURABLE BAND STOP FILTER

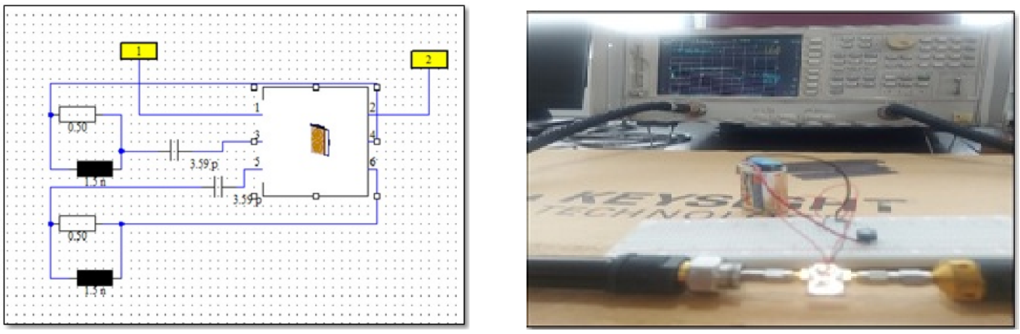
To achieve frequency reconfigurability [14], [27]-[30], a novel HMC with a C-shaped inner arm cut is designed. This introduces additional capacitance by modifying the current path and enhancing electric field concentration. A PIN diode placed across the slit acts as a switch, and its bias controls the filter's stopband frequency. The structure is simulated in CST Design Studio, incorporating the diode's equivalent circuit (Rs, Ls, Cp). In the OFF state, it resonates at 3.6 GHz; in the ON state, increased capacitance shifts the frequency to 2.4 GHz. This dual-mode operation supports 5G (3.6 GHz) and 4G/WLAN (2.4 GHz) within a single design. The filter is fabricated on a Rogers RT Duroid 5880 substrate, with PIN diodes integrated and biased via RF chokes and bias tees for signal isolation. Reconfigurability is enabled by the PIN diodes in the inner arm, which alter the resonator's frequency response based on applied DC bias. Simulated current distribution in Figure 5 shows concentration along the inner cut and slit, emphasizing the gap's role in enabling frequency switching.

3.1. Simulation design

In Figure 5 shows the reconfigurable BSF. In Figure 5(a) illustrates the simulation configuration using CST Design Studio for modeling and analyzing the reconfigurable BSF. CST Design Studio allows for the integration of equivalent inductance and capacitance values to replicate the behavior of the BAR 64002 PIN diode. By incorporating the diode's equivalent parameters, the design can alternate between ON and OFF states to operate at the specified frequencies of 2.4 GHz and 3.6 GHz. The software's ability to simulate PIN diodes provides an accurate representation of the reconfigurable characteristics of the BSF.

3.2. Measurement setup for reconfigurable BSF

Figure 5(b) shows the measurement setup for the NHMC-based reconfigurable BSF, where a PIN diode is placed between the inner cut arm and an added segment to enable reconfigurability. The diode is connected through a decoupling network to isolate DC and RF signals effectively. Measurements using a VNA are taken with the diode in both ON and OFF states. In the OFF state, the stopband appears at 3.6 GHz, while switching the diode ON shifts it to 2.4 GHz, demonstrating frequency reconfigurability. The filter maintains acceptable return and insertion losses in both modes. Two PIN diodes (Switch 1 and Switch 2) enable dual-mode operation: both OFF – operates at 3.6 GHz and both ON – operates at 2.4 GHz. Jumper wires connect the diodes to RF chokes and resistors, ensuring isolation between RF signals and DC bias. The BAR 64002 diode, chosen for its low 1.35-ohm forward resistance at 100 mA, is biased using a 9V battery, 1 kohm resistor, and a 2.2 mH RF choke (RL873S-222K-RC) as shown in Figure 5(b).

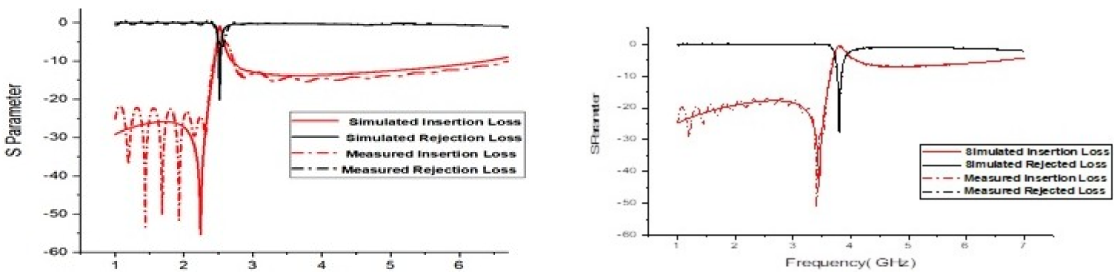


(a) (b)

Figure 5. Reconfigurable BSF design, (a) simulation structure using CST design studio, and (b) measurement setup of reconfigurable BSF using VNA

3.3. Simulated and measured results

In Figure 6 shows the simulates mesured result for both cases. Figure 6(a) shows the case-1 (when both diode ON) condition , the BSF operate at 2.4 GHz. The results display the simuaed result. The simulated result return loss -20.2 dB with insertion loss -0.2dB. The measured result -19.5 dB and insertion loss -0.24 dB. The strong correlation between simulation and measurement, confirming the design's effectiveness. The filter achieves significant rejection at the intended frequencies while maintaining minimal insertion loss, making it suitable for wireless applications. Figure 6(b) shows case-2, where both diodes are OFF and the BSF operates at 3.6 GHz. The simulated return loss is -29.12 dB and insertion loss is -0.2 dB, while measured results show -28.12 dB and -0.24 dB, respectively, confirming the NHMC-based filter's functionality and reconfigurability for dual-frequency use.



(a) (b)

Figure 6. Simulation result for reconfigurable filter design (a) case 1 (Diodes D1 and D2 in the ON state) operating at 2.4 GHz and (b) case 2 (Diodes D1 and D2 in the OFF state) operating at 3.6 GHz

Table 1 compares the proposed filter with recent designs. Although previous works used PIN diodes for reconfigurability, their performance varied, with return losses of -34.39 dB and -15 dB, and larger sizes of 15×15 mm^2 and 10×8 mm^2. In contrast, the proposed filter is more compact (8×12 mm^2), with low insertion loss (less than -0.2 dB) and high return loss (greater than -29 dB), making it ideal for modern wireless systems.

Table 1. Comparison of metamaterial-based bandstop filters in recent literature and the proposed design

Paper no. (Ref.)	Year of publication	Band	Size of filter (mm)	Insertion loss (dB)	Return loss (dB)	Reconfigurable
[14]	2024	SB	1.21 λ g $\times$0.69 λ g	-3.5 dB	-22.5 dB	Yes
[15]	2023	SB	$15\times15\times1.57$ mm^3	-0.22, -0.39	-34.39, -21.52	Yes (PIN Diode)
[16]	2022	SB	10 mm$\times$8 mm	-0.3 dB	-15 dB	Yes (PIN Diode)
[17]	2021	DB	12 mm$\times$12 mm	-	-18 dB	Yes (PIN Diode)
[18]	2019	SB	10 mm$\times$10 mm	-0.5 dB	-20 dB	No
	Proposed design	SB	8 mm$\times$12 mm	-0.2 dB	-29.12 dB	Yes

The reconfigurable feature of the novel hexagonal resonator enables precise switching between 2.4 GHz and 3.6 GHz, supporting both 4G and 5G applications. Its compact size and dual-frequency operation make it suitable for future wireless front-end modules requiring flexibility and performance. The proposed dual-band filter operates at 2.4 GHz and 3.6 GHz, offering versatility for WLAN and wireless systems. With dimensions of $8\times12\times1.6\,\text{mm}^3$, it is more compact than many existing designs and exhibits improved return and insertion loss compared to previous works.

4. CONCLUSION

This paper presents an innovative approach for developing reconfigurable metamaterial-based diodes. The proposed filter achieves single-band operation with dual-mode reconfigurability, effectively switching between two frequencies at 2.4 GHz and 3.6 GHz. The design is notable for its compact size of $8\times12\times1.6$ mm^3, which is smaller than many existing filters reported in the literature. It demonstrates excellent electrical performance, meeting the IEEE 802.11 standards for WLAN and wireless applications. Simulation results show a high return loss of more than –29.12 dB and a very low insertion loss of less than –0.2 dB, indicating superior performance compared to previous works. The filter is fabricated using a Rogers RT Duroid 5880 substrate, further contributing to its high efficiency and compactness. Overall, the successful implementation highlights the potential of metamaterial-based designs in overcoming the challenges of modern wireless communication systems.

FUNDING INFORMATION

The authors state no funding is involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Khyati Chavda	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				✓
Ashish K. Sarvaiya	✓			✓		✓				✓	✓	✓		
Mehul K. Vala	✓					✓	✓			✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal Analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject Administration
Fu : **Fu**nding Acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [Khyati Chavda].

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