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Compact Wideband Microstrip Bandpass Filter for 5G Millimeter-Wave Applications

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Abstract: This paper presents the design and analysis of a compact microstrip wideband bandpass filter tailored for 5G sub-6 GHz and millimeter-wave (mmWave) communication systems. The proposed filter is realized on a Rogers RO4003C substrate, featuring a relative permittivity (ε_r) of 3.5, a loss tangent (tan δ) of 0.02, and a compact overall footprint of 10 × 10 × 0.4 mm³, making it suitable for integration into space-constrained RF front-ends. To ensure design robustness and performance validation, the structure is comprehensively modeled and simulated using three industry-standard electromagnetic tools: ANSYS HFSS, CST Microwave Studio, and Keysight ADS. The simulated S-parameter responses—including return loss, insertion loss, and bandwidth characteristics—exhibit excellent mutual agreement across all three platforms, confirming the filter's reliability and reproducibility. Owing to its miniature form factor, cost-effective substrate choice, and wideband passband characteristics, the proposed filter is well-suited for operation in the unlicensed frequency spectrum, which is increasingly exploited for high-data-rate, low-latency 5G and beyond-5G wireless applications.

Keywords: Microstrip filter,5G, band pass filter,I Shaped, Millimeter-wave.

1. Introduction

In recent years, the exponential growth of wireless data traffic and the proliferation of ultra-wideband communication systems have significantly increased the demand for high-performance, reliable, and cost-effective radio-frequency (RF) front-end components [1]. Among these, microwave bandpass filters play a critical role in transceiver architectures, as they are tasked with selectively transmitting signals within a designated frequency band while effectively attenuating out-of-band interference and spurious responses [2]. With the advent of fifth-generation (5G) and emerging millimeter-wave (mmWave) technologies, stringent requirements have been imposed on filter design, including wide fractional bandwidth, low insertion loss, sharp selectivity, and compact form factor, all of which are essential for integration into densely packed portable and base-station equipment [3, 4].

To meet these evolving specifications, various planar filter topologies have been extensively investigated in the literature. Conventional architectures such as combline, hairpin, parallel-coupled lines, stepped-impedance resonators, and stub-loaded configurations have been widely adopted, each offering distinct trade-offs between electrical performance, physical size, and manufacturing complexity [5–8]. However, at higher

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frequency bands (e.g., 24–40 GHz), parasitic effects, substrate losses, and electromagnetic coupling become more pronounced, necessitating rigorous full-wave electromagnetic modeling and optimization. Consequently, miniaturization techniques have emerged as a key research focus, aiming to reduce the dimensions of distributed elements while preserving or enhancing filter selectivity and insertion loss characteristics [9, 10].

In this context, this paper presents the design, simulation, and comparative analysis of a miniaturized microstrip wideband bandpass filter specifically targeted for 5G new radio (NR) and mmWave applications. The proposed structure is realized on a Rogers RO4003C substrate and is meticulously modeled using three independent simulation platforms : ANSYS HFSS (High-Frequency Structure Simulator), CST Microwave Studio, and Keysight ADS (Advanced Design System). This multi-tool approach ensures cross-validation of electromagnetic performance and enhances design reliability. The simulated results exhibit a wide passband spanning from 22 to 35 GHz, with a return loss better than 3 dB across the operating band. Furthermore, the overall filter footprint is exceptionally compact, measuring only 10 × 10 × 0.4 mm^3, rendering it highly suitable for integration into modern compact communication systems, including 5G small cells, phased-array antennas, and Internet-of-Things (IoT) gateways operating in unlicensed millimeter-wave spectra..

2. Design and Configuration of the Proposed Filter

The geometrical layout of the proposed bandpass filter is illustrated in Figure 1. The structure is realized on a single-layer Rogers RO4003C substrate, which exhibits a relative permittivity (ε_r) of 3.5, a loss tangent (tan δ) of 0.02, and a thickness of 0.4 mm. This substrate choice offers a favorable trade-off between low dielectric loss, mechanical stability, and cost-effectiveness, making it well-suited for high-frequency millimeter-wave applications.

The filter topology consists of a compact I-shaped resonator, which is directly excited by a 50 Ω microstrip feed line terminated at both input and output ports. This direct coupling scheme simplifies the feeding network and minimizes additional mismatch losses. On the bottom side of the substrate, a continuous ground plane is printed to ensure proper electromagnetic field confinement and signal return path integrity.

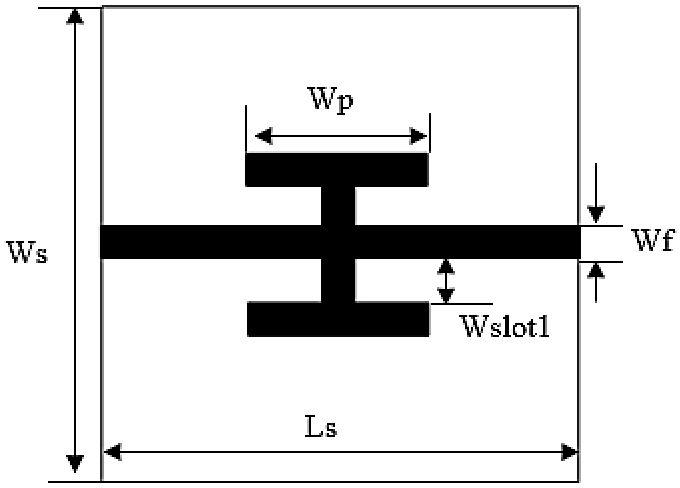

Figure.1 Geometrical configuration of the proposed microstrip bandpass filter

The overall filter footprint is remarkably compact, measuring only 10 × 10 mm^2, owing to the optimized folding of the resonator structure. The key geometrical parameters governing the resonant behavior and coupling characteristics—including line widths, gaps, stub lengths, and inter-element spacings—are comprehensively listed in Table 1. These dimensions were meticulously tuned through iterative full-wave electromagnetic simulations to achieve the desired wideband passband response centered around the 28 GHz band, while maintaining low insertion loss and high return loss across the operating spectrum.

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Table 1. The Optimized dimensions of the proposed microstrip bandpass filter

parameters	Value (mm)
Ws	10
Ls	10
Hs	0.4
Wf	1
Wp	4.6
Lp	4.6
Wslot1	1
Lslot1	1.7
Wslot2	1
Lslot2	1.7

3. Results and discussion

To achieve optimal performance of the proposed bandpass filter, a comprehensive parametric study was conducted to investigate the influence of each geometrical parameter on the frequency response, particularly the bandwidth and return loss characteristics. This was accomplished by varying one design parameter at a time while keeping all others fixed, using three independent full-wave electromagnetic simulation tools: ANSYS HFSS (High-Frequency Structure Simulator), CST Microwave Studio, and Keysight Advanced Design System (ADS). These software platforms are extensively validated in the RF and microwave engineering community for the design and analysis of antennas, waveguides, planar circuits, and filter structures. They enable accurate extraction of scattering parameters (S-parameters), including return loss (S_{11}), insertion loss (S_{21}), and other critical performance metrics such as group delay and voltage standing wave ratio (VSWR).

The simulated frequency responses of the proposed filter, focusing on the magnitude of S_{11} and S_{21}, are illustrated in Figure 2. Specifically, Figure 2(a) presents the results obtained from HFSS, Figure 2(b) from CST Microwave Studio, and Figure 2(c) from ADS. This multi-tool simulation strategy not only validates the design robustness but also highlights any discrepancies arising from different numerical methods (e.g., finite element method in HFSS, finite integration technique in CST, and method of moments in ADS).

As observed from Figure 2(a), the HFSS simulations reveal a wide 3-dB fractional bandwidth spanning from 21.8 GHz to 34.7 GHz, corresponding to an absolute bandwidth of 12.9 GHz centered around 28.0 GHz. The return loss reaches an excellent minimum value of −52.02 dB at the center frequency, indicating near-perfect impedance matching and minimal reflected power. Similarly, the CST results shown in Figure 2(b) demonstrate a slightly shifted passband from 22.35 GHz to 35.33 GHz, with a bandwidth of 12.98 GHz and a center frequency of 27.45 GHz. The minimum return loss in this case is −29.2 dB, which remains well within acceptable limits for practical applications. Meanwhile, the ADS simulations (Figure 2(c)) yield a passband extending from 21.5 GHz to 33.0 GHz, with a bandwidth of approximately 11.5 GHz, centered at 29.0 GHz, and a minimum S_{11} of −27 dB.

Across all three simulators, the insertion loss (S_{21}) remains close to 0 dB (i.e., near-zero attenuation) throughout the entire operational bandwidth, confirming the filter's low-loss transmission characteristics. Minor variations in the center frequency and bandwidth among the three simulation tools can be attributed to differences in meshing strategies, convergence criteria, and numerical computation techniques employed by each software. Nevertheless, the overall responses are in good qualitative and quantitative agreement, particularly between HFSS and CST, which exhibit highly consistent passband shapes and roll-off characteristics. This cross-validation reinforces the reliability of the proposed design and confirms its suitability for 5G millimeter-wave front-end modules

In summary, the simulated results demonstrate that the proposed filter successfully achieves a wideband response covering the 28 GHz band, with excellent return loss performance, low insertion loss, and compact footprint, making it a promising candidate for next-generation wireless communication systems

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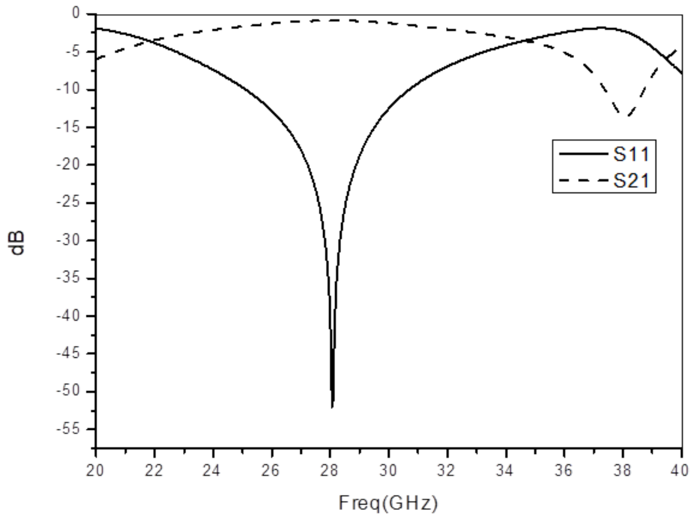
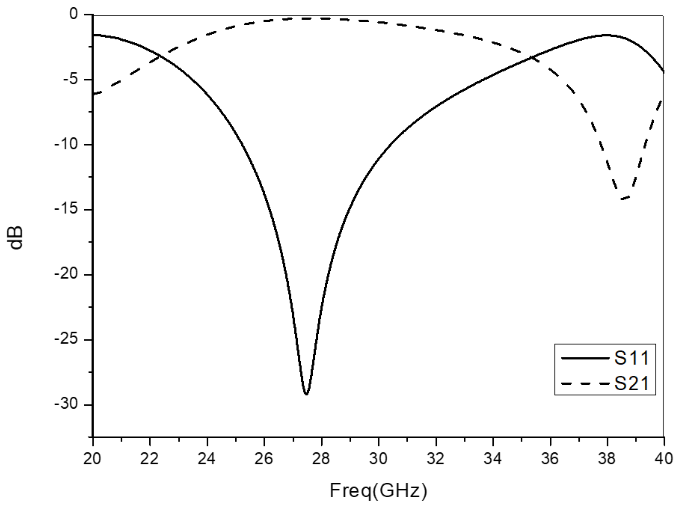
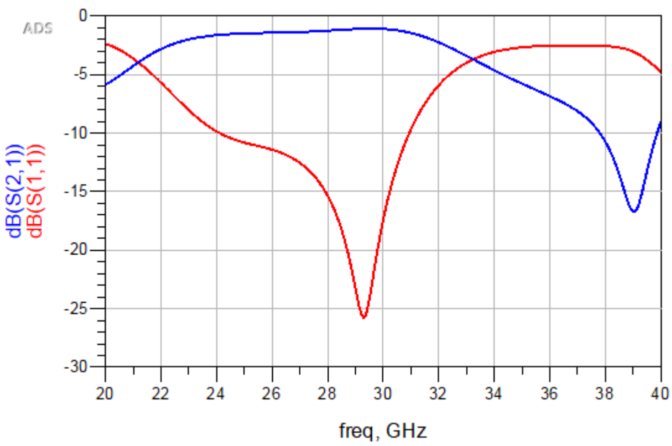


(a)



(b)



(c)

Figure.2 The return loss and the insertion loss: (a) HFSS, (b) CST and (c) ADS

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4. conclusion

In this paper, a miniaturized microstrip wideband bandpass filter has been designed, numerically investigated, and optimized for 5G new radio and millimeter-wave communication systems. The proposed structure, realized on a Rogers RO4003C substrate, was comprehensively analyzed using three independent full-wave electromagnetic simulation tools—ANSYS HFSS, CST Microwave Studio, and Keysight ADS—to ensure cross-validation and design reliability.

The simulated results demonstrate that the proposed filter achieves a wide 3-dB fractional bandwidth extending from approximately 22 GHz to 35 GHz, with a return loss better than −3 dB and an insertion loss superior to −3 dB across the entire passband. The multi-tool simulation approach yielded consistent responses, with minor discrepancies attributed to differences in numerical methods and meshing strategies, thereby confirming the robustness and reproducibility of the design.

Notably, the filter topology features a simple and compact configuration, occupying an overall footprint of only $10 \times 10 \times 0.4$ mm^3. This miniature form factor, combined with its planar structure and straightforward fabrication process, renders the proposed filter highly suitable for integration into dense RF front-end modules, including 5G small cells, phased-array antennas, and portable wireless terminals.

In summary, the proposed bandpass filter offers a compelling trade-off between wideband performance, compactness, and manufacturing simplicity, positioning it as a promising candidate for emerging high-data-rate millimeter-wave applications. Future work will focus on experimental validation through prototype fabrication and measurement, as well as further optimization to enhance selectivity and out-of-band rejection, potentially through the incorporation of defected ground structures (DGS) or cascaded resonator stages.

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