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Wideband Tunable Filter of Dual-path Microstrip Coupled-lines with Varactor Tuned Circuit

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ABSTRACT: This study presents a compact and tunable microstrip of dual-path wideband filter that employs coupled-lines and varactors to address the needs of 4G/sub-6 GHz 5G communication systems. This work integrates tunable methods inspired by wideband parallel coupled line-based topologies to realize a reconfigurable solution achieving a 34% frequency tuning range (1.13–1.51 GHz) while maintaining a low insertion loss of approximately below 1 dB. Specifically, the proposed microstrip-based filter, which is designed, uses parallel coupled-line resonators with a quarter-wavelength length, enabling a broad tuning range between 1.27–1.54 GHz. Adjusting the coupling strengths of both adjacent and non-adjacent resonators, the filter can be shifted within this frequency band without compromising performance. Therefore, to achieve the desired level of control, two identical varactor diodes and biasing circuitry are meticulously selected for their stable and repeatable capacitance-voltage characteristics to adjust the filter's resonant frequency. The optimal positions for these tuning circuits are determined based on the resulting capacitance, which is crucial for achieving a wide tuning range. Simulation and measurement confirm that this reconfigurable microstrip filter, implemented on a $60.7 \times 35.4\,\mathrm{mm}^2$ footprint, benefits not only from a reduced footprint but also from the ability to target multiple frequency bands with minimal hardware modifications, delivering the intended performance for modern wireless front ends.

1. INTRODUCTION

The field of microwave filters has undergone significant advancements, driven by the rapid progress in communication systems. This tunable filter is deemed to be one of the most important factors in performing the function of multi-band and multifunctional applications. Notably, tunable filters are often found in today's wireless communication systems due to their selectivity. These enable devices to precisely define the frequencies that can traverse their passband for effective signal processing and interference suppressions [1–3]. These filters can be tuned to be bandstop, low-pass, high-pass, or Bandpass Filter (BPF) types [4–6]. Vast applications are observed for tunable BPFs, which can be grouped based on their attributes. Meanwhile, some designs maintain a constant absolute bandwidth while shifting the center frequency (f_c), others preserve a fixed f_c but vary the operating bandwidth, and a further category offers full reconfigurability of both bandwidth and frequency [7, 8]. Considering the tunability in a BPF, the tunable BPFs can be realized by various methods such as varactors, PIN diodes [9, 10], and Micro-Electro-Mechanical Systems (MEMS) devices [11]. Tunable filters based on coupled-lines structures have particularly been rapidly developed, with multiple configurations available to involve varactors, including modified parallel-coupled lines [12, 13], interdigital [14, 15], comb lines [9, 16] and the insertion of coupled line resonators. However, the specific area of tunability in parallel coupled-lines has received relatively limited attention. This is due to adding each additional resonator requiring its own tuning circuitry and biasing components, resulting in larger filter sizes as the number of coupled-lines increases.

While significant progress has been made in developing tunable filters based on coupled-line structures, the aspect of tunability in parallel coupled-lines remains relatively unexplored [17–19]. This limitation stems from practical constraints where each additional coupled line necessitates further varactor-based tuning circuits, leading to larger filter sizes and design complexities. Hence, this necessity inevitably expands the filter's overall footprint and complicates its design — an especially critical issue considering that miniaturization is a major priority in modern microwave applications. Nonetheless, the proposed filter design demonstrates efficiency and holds promise for wideband frequency tuning applications [20–22].

Moreover, in [23], two independent Transmission Zeros (TZs) that can be adjusted were introduced to decouple the control of the f_c and bandwidth across a wide tuning range. By incorporating loaded short-ended resonators within a tuned TZ, the design enhanced the response symmetry and the selectivity of the lower band in a tunable BPF. In addition, by precisely managing the TZ near the lower or higher passband skirt, incorporating a modified coupled line and a varactor-loaded stub enabled a broad bandwidth tuning range [24].

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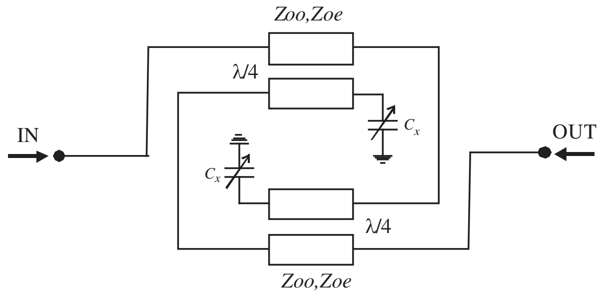

FIGURE 1. Proposed tunable dual-path coupled-lines topology integrating the tuning capacitors, C_x.

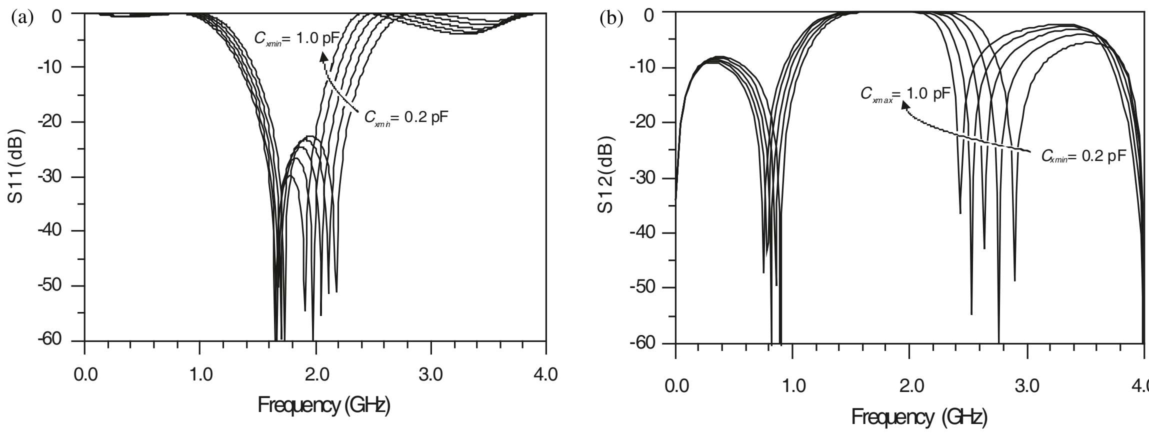

FIGURE 2. Response of the proposed filter illustrating how varying C_x between minimum 0.2 and maximum 1.0 pF adjusts the f_c and affects overall passband characteristics: (a) Passband return loss (simulated values in dB) and (b) passband insertion loss (simulated values in dB).

In this paper, a tunable microstrip dual-path wideband BPF proves highly compatible for deployment in 4G/sub-6 GHz 5G systems, where versatile frequency tuning capabilities are essential. We are exploiting the varactor-tuned circuit in developing the tunable microstrip of a dual-path wideband filter to achieve a broad tuning range. The filter spans a wide tuning range of 34% (1.13–1.51 GHz) while preserving a low insertion loss (< 1 dB). The design integrates varactor diodes, selected for their stable and repeatable capacitance-voltage characteristics, to enable frequency agility across multiple bands with minimal hardware modifications. The optimal integration points for the tuning circuits were determined based on the resulting capacitance for achieving precise tuning and stable performance. Note that this capacitance is critical in determining the degree of tuning. In particular, this design paradigm can reduce costs and increase reliability while making it suitable for the next generation.

Therefore, we experimentally implemented the tunable filter to verify the design concept and examined its performance through detailed measurements. These results validate our design and tuning approach to achieve the desired performance for modern communication systems and demonstrates the practical relevance of the design approach. The proposed BPF addresses the increasing demand for compact, tunable, and reconfigurable filters in next-generation of multiband communications. and wireless front-end applications, as the ability to target multiple frequency bands, reduces costs and enhances system reliability.

2. TUNABLE DUAL PATH COUPLEDLINES USING TUNING CAPACITORS

In this study, the resonator's frequency was tuned by varying its effective electrical length via capacitive loading through capacitive loading. This approach is proven effective for varactor-based microwave stub resonators by adjusting the tuning capacitors and the electrical length shifts, thereby altering the resonant frequency. In general, increasing the resonator's electrical length lowers its resonance frequency, a behavior widely noted in microwave systems. The equivalent capacitance C_x of the resonator can be expressed as:

$$C_x = \frac{\tan\theta_0}{2\pi f_0 Z_0} \tag{1}$$

Here, f_0 represents the resonance frequency while θ_0 denotes the electrical length of the filter. Tuning capacitors, such as C_x, are commonly employed to optimize the response of the resonator based on changes in capacitance. Increasing C_x results in a longer effective electrical length, which lowers the resonance frequency and shifts the passband characteristics. This makes tuning capacitors highly applicable for selecting varactor diodes with precision. The filter comprises two parallel quarter-wavelength coupled lines, totaling half a wavelength at f_0. Within one of these lines, two identical capacitors are placed at carefully chosen locations on the open-circuited side (see Figure 1).

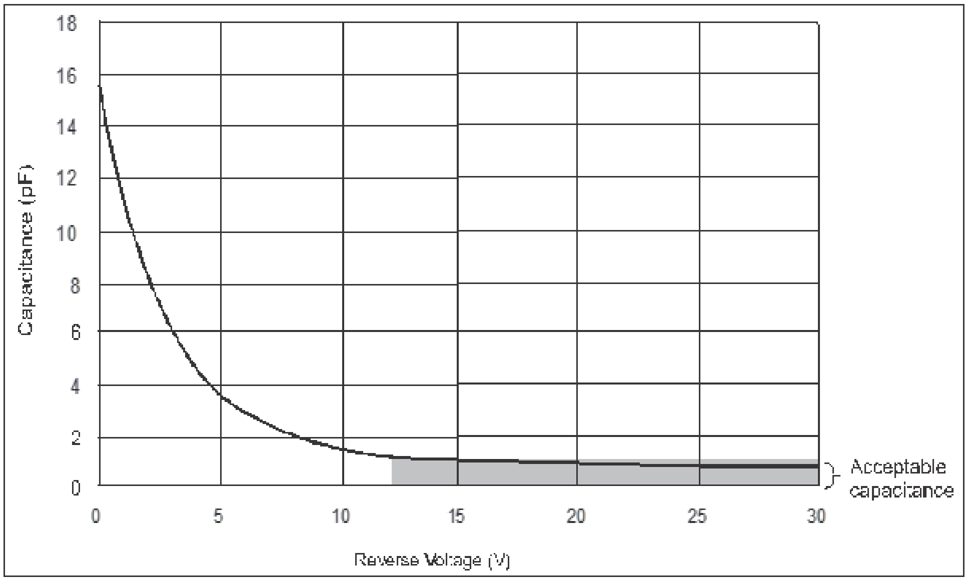

FIGURE 3. Variation of the varactor diode's capacitance under different reverse bias voltages.

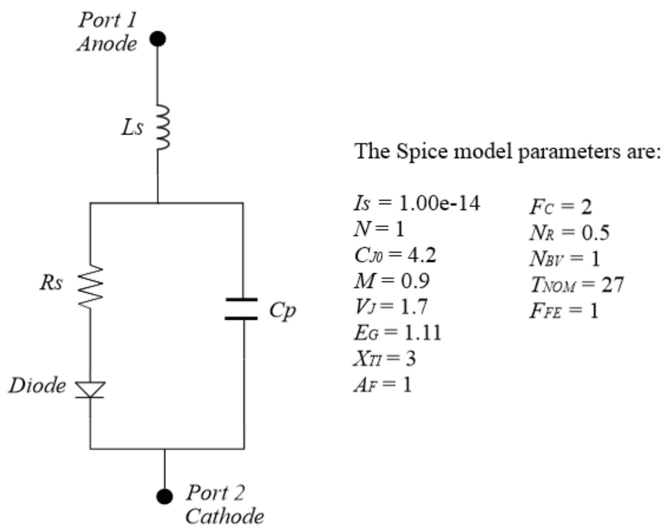

FIGURE 4. Varactor circuit model in SPICE software, highlighting the tunable junction capacitance and minimal parasitic elements.

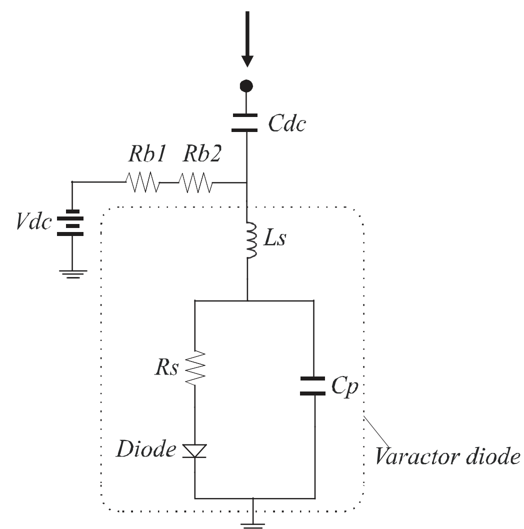

FIGURE 5. Bias circuit for the varactor-based tuning system.

By varying the capacitive load at these points, the resonator's effective electrical length and, thus, its resonant frequency can be accurately tuned. The ideal filter responses incorporate the C_x are depicted in Figure 2, using the specified coupled-line impedances, for even and odd modes.

They are denoted by Z_{0e} and Z_{0o} impedances respectively of 50 Ω and 22 Ω. These impedance values were chosen to optimize the coupling strength between the resonators while enabling practical implementation with standard microstrip lines. Although the odd and even mode impedances are not both typically matched to 50 Ω, the selected values ensure a balance between wideband performance, minimal insertion loss (below 1 dB), and a broad frequency tuning range. As the capacitance increases between 0.2–1.0 pF, the center frequency (f_c) shifts accordingly, which in turn affects the passband insertion loss.

The Skyworks SMV1800 varactor diode was selected for its ability to provide the required capacitance range and integration flexibility, aligning with Skyworks' wider family of varactor diodes that produce a wide tuning range, which is essential for achieving consistent performance in tunable microwave filters. This diode can be integrated into the coupled- line filter at two specific locations on the upper side of the filter. This placement ensures that each varactor introduces the required capacitance variation without compromising the filter's passband integrity or unnecessarily increasing insertion loss.

As displayed in Figure 3, this filter design requires a capacitance between 0 and 1.5 pF. A parasitic-free varactor diode equivalent circuit usually includes only a parallel capacitance (C_p), a series inductance (L_s), and a series resistance (R_s). In this design, the values are $C_p = 0.9$ pF, $L_s = 0.8$ nH, and

TABLE 1. Varactor's capacitance at different reverse voltage.

Reverse Voltage (V)	Capacitance (pF)
0	15.78
2	7.87
4	4.85
6	3.07
8	2.17
10	1.72
12	1.51
15	1.26
20	1.06
25	0.93
28	0.88
30	0.84

TABLE 2. Design parameters of the SPICE model.

Parameters	Values
I_S	1.00e-14
N	1
C_{JO}	4.2
M	0.9
V_J	1.7
E_G	1.11
X_{TI}	3
A_F	1
F_C	2
N_R	0.5
F_{FE}	1
T_{NOM}	27
N_{BV}	1

$R_s = 2.5\,\Omega$, respectively, as introduced by the diode package. Table 1 provides further details on the capacitance values. Figure 4 details the varactor diode's equivalent circuit model parameters, which are simulated in SPICE software, ensuring accurate high-frequency simulations by accounting for these packaging-related effects. Additionally, the data of the equivalent values from the simulation result can be described in Table 2.

To prevent DC effects from flowing directly to the dual path design filter, the bias circuitry predominantly relies on a high-value DC-feed resistor network (R_{b1} and R_{b2}) and a DC-blocking capacitor (C_{dc}). As explained, such arrangements are designed to minimize the RF signal path from the DC supply line while ensuring negligible signal leakage into the bias circuitry. The varactor diode with these bias components reduces parasitic influences (see Figure 5).

Accordingly, the selected component values are C_{dc}, R_{b1}, and R_{b2}, respectively, at the value of 1 µF and 10 kΩ, which offer effective DC isolation and help maintain consistent device performance across the operating band. Figure 6 illustrates the complete tunable microstrip of a dual-path wideband filter fabricated on an FR-4 substrate, chosen for its practicality, with a parameter of dielectric constant (ε_r) of 4.1, a loss tangent (d) of 0.02, and a thickness (h) of 1.5 mm.

Such filters are commonly implemented in microwave systems to pass or reject specific bands in the gigahertz range. In this design, the SMV1800 varactor diode is selected to achieve the desired capacitance range, enabling voltage-controlled tuning of the filter passband. As the DC bias voltage is adjusted between 8–30 V (see Figure 7(a) and Figure 7(b)), the simulated f_c shifts between 1.27–1.54 GHz. Moreover, the passband insertion loss remains below 1 dB across this tuning range, indicating excellent passband performance. Such tunable approaches have proven effective in microwave applications requiring frequency agility and compact form factors. The details of the simulated result of the tunable dual path coupled-lines filter are presented in Table 3.

3. FABRICATION AND MEASUREMENT

The tunable microstrip of dual-path wideband filter, with a dimension footprint of $60.7\,\text{mm} \times 35.4\,\text{mm}$, is displayed in Figure 8, illustrating the physical layout of the designed filter. Silicon hyper-abrupt junction varactor diodes used in this design SMV1800-079LF are integrated to provide the required tunability, featuring nominal parameters C_{jo},V_j,M, C_p, R_s, and L_s, respectively, at the value of 14.5 pF, 16 V, 6, 0.9 pF, 2.5 Ω, and 0.8 nH. It is important to note that the junction potential (V_j) of 16 V is a nominal parameter provided by the manufacturer and is intrinsic to the SMV1800-079LF varactor diode. This value reflects the built-in potential rather than the externally applied reverse bias voltage. The higher V_j value showed that the characteristic of hyper-abrupt junction varactors, which enables a substantial change in capacitance over a small voltage range. This characteristic is critical for achieving the wide tuning range of the filter. The biasing circuitry includes a DC-blocking capacitor (C_{dc}) and two bias resistors (R_{b1}, R_{b2}), respectively, at the value of 1 µF and 10 kΩ, ensuring stable tuning control while minimizing interference with the RF signal path.

Table 4 summarizes the tunable nominal parameters of the dual-path coupled-lines filter. Following assembly, the filter's S-parameters were characterized using a Vector Network Analyzer (VNA), a standard practice in evaluating the proposed filter performances. Such parallel coupled-line configurations are well-established in microwave applications and can be readily adapted for various frequency-agile systems.

Figure 9 depicts the measured passband response of the tunable microstrip of a dual-path wideband filter in terms of return and insertion losses, measured in unit dB In Figure 9(a), the filter's return loss demonstrates a tuning range of about 34% around its f_c, shifting between 1.13–1.51 GHz when the bias voltage is adjusted between 8–30 V. Figure 9(b) illustrates that the measurement of the passband insertion loss remains below 1 dB. Table 5 summarizes the performance metrics of recently developed tunable microstrip filters designed for 4G and sub-

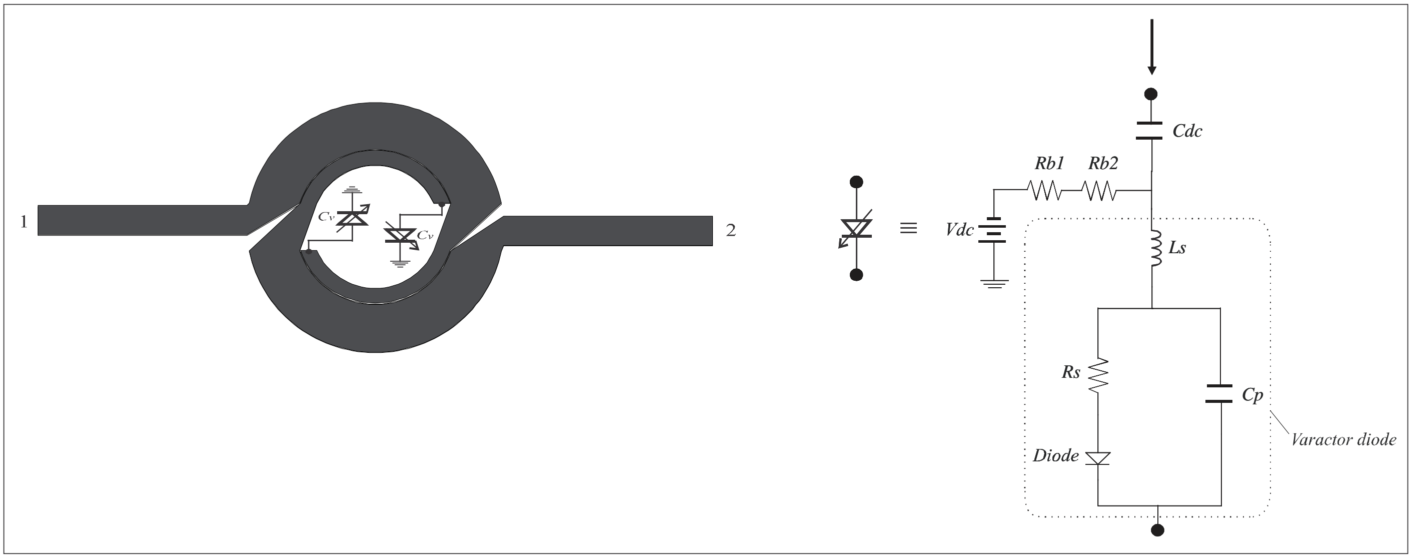

FIGURE 6. Proposed topology of the tunable microstrip of a dual-path wideband filter using a varactor-tuned circuit.

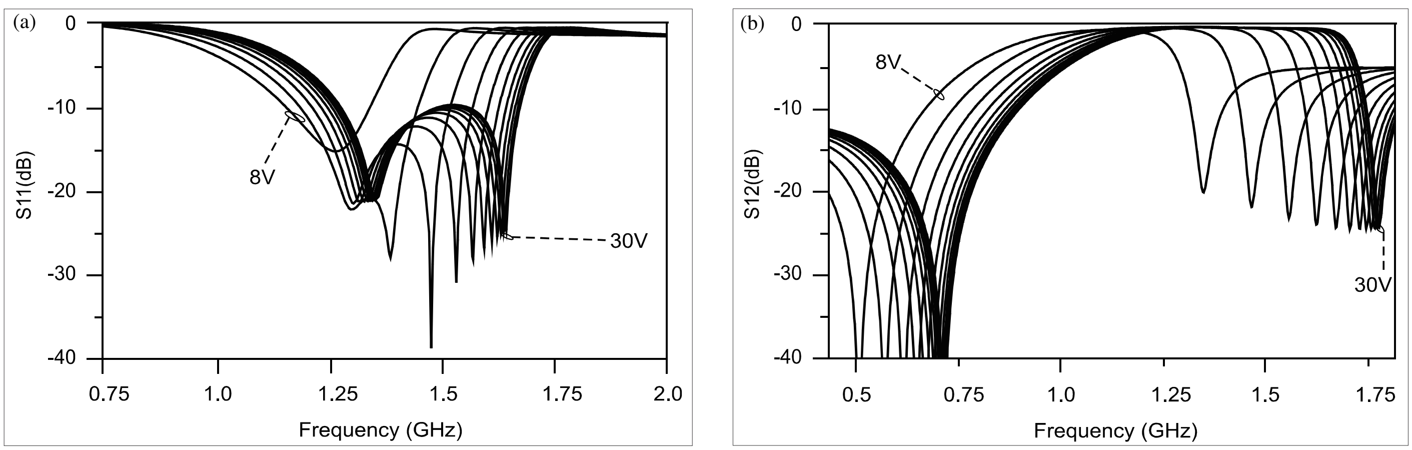

FIGURE 7. Simulation filter responses of a pair S_{11} and S_{12} parameters, showing (a) passband return loss (simulated in dB) and (b) passband insertion loss (simulated in dB).

TABLE 3. Data of simulated result of the tunable dual path coupled-lines filter.

Bias voltage (V)	f_0 (GHz)	Simulated S_{11}, S_{12} (dB)
8	1.27	-27.10, -0.41
10	1.32	-31.66, -0.35
12	1.38	-28.24, -0.25
14	1.44	-17.85, -0.25
16	1.47	-17.41, -0.25
18	1.50	-16.91, -0.25
20	1.51	-16.65, -0.25
22	1.52	-16.35, -0.25
24	1.52	-15.96, -0.25
26	1.53	-15.47, -0.25
28	1.53	-15.22, -0.25
30	1.54	-15.10, -0.25

TABLE 4. Tunable nominal parameters of dual path coupled-lines filter.

Parameters	Values
Zero-Bias Junction Capacitance (C_{jo})	14.5 pF
Junction Potential or Built-In Voltage (V_j)	16 V
Grading Coefficient or Junction Grading Exponent (M)	6
Parasitic Capacitance (C_p)	0.9 pF
Series Resistance (R_s)	2.5 Ω
Parasitic Inductance (L_s)	0.8 nH
R_{b1}	1 µF
R_{b2}	10 kΩ

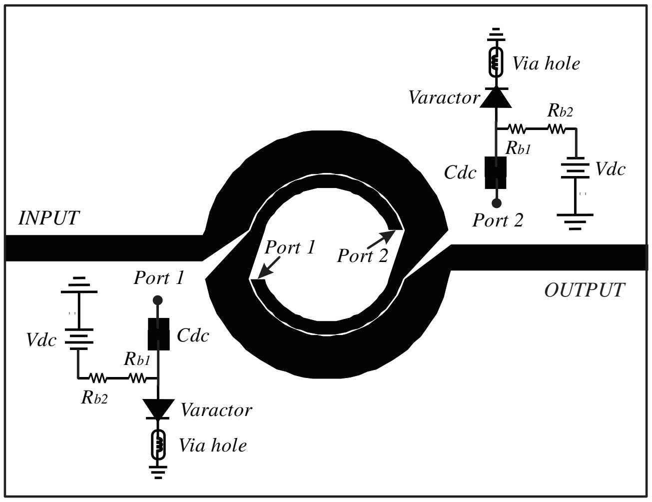

FIGURE 8. Layout of the fabricated filter, demonstrating a wideband dual path coupled line-based design.

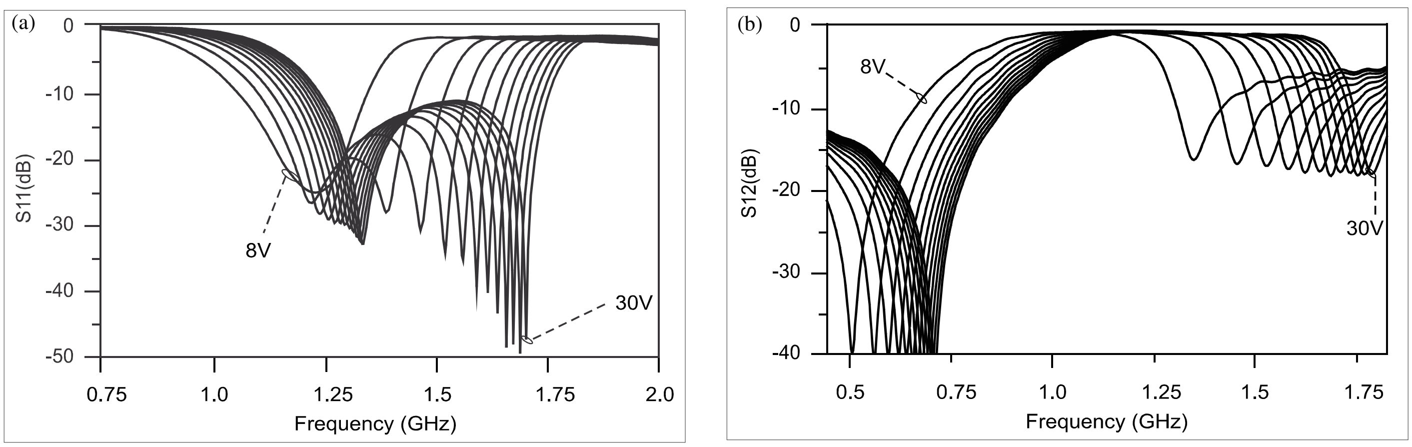

FIGURE 9. Measured filter responses of a pair S_{11} and S_{12} parameters, demonstrating a wide tuning range: (a) passband return loss (measured in dB) and (b) passband insertion loss (measured in dB).

FIGURE 10. Photograph of the fabricated filter on a FR4 substrate.

TABLE 5. Summarize performance of recent filter with dual path coupled-lines filter.

	Reference [10]	Reference [7]	Reference [27]	Reference [5]	Our proposed design
Tuning Range (GHz)	2.5–3.8	0.9–2.2	0.5–1.5	0.79–1.59	1.13–1.51
Fractional Tuning Range (%)	41	37	35.6	22	34
Insertion Loss (dB)	< 1	< 1	1.6–3.9	< 2.1	< 1
Substrate Material	Rogers RO3010	Rogers RO4003	Rogers RO3003	Rogers AD300C	FR-4
Filter Size (mm^2)	13×8	43.1×43.1	25×28	26×18	60.7×35.4

6 GHz 5G applications. The proposed filter demonstrates practical relevance by combining cost-effective design features with achievable performance, rendering it well-suited to real-world applications. This comparison indicates that, although the proposed filter achieved a noteworthy fractional tuning range of 34% while maintaining low insertion loss, it employs a cost-effective FR-4 substrate. Despite its affordability, FR-4 exhibits insertion loss characteristics similar to most Rogers substrates, with the exception of Rogers RO3010. Additionally, the filter's physical dimensions surpass than some recent designs, suggesting further opportunities for miniaturization and performance enhancements.

Figure 10 demonstrates a photograph of the fabricated filter by integrating varactor diodes for frequency tuning. The minor discrepancy between the measured and simulated results are due to the varactor diode's parasitic elements, such as series resistance (2.5 Ω), inductance (0.8 nH), and package capacitance (0.9 pF) These parasitic elements affect both the tuning range and insertion loss, they were nonetheless incorporated into an equivalent-circuit model to enhance simulation accuracy. Strategies such as optimizing the biasing network were adopted to mitigate these effects. The proposed filter demonstrates practical relevance by combining cost-effective design features with achievable performance, rendering it well-suited to real-world applications in 4G and sub-6 GHz 5G systems. However, its performance is partially constrained by the parasitic elements of the varactor diodes.

Future improvements may involve incorporating varactor diodes with lower parasitic values or utilizing advanced packaging to further enhance tunability. In addition, we will explore alternative low-loss substrates such as Rogers 4350B or Taconic materials, which have the potential to improve overall filter efficiency and reduce insertion loss. To enhance the filter's competitiveness, future investigations will compare its performance metrics specifically tuning range, insertion loss, and implementation cost with existing designs. Moreover, alternative tuning mechanisms, such as Micro-Electro-Mechanical Systems (MEMS) and PIN diodes will be explored to assess the respective advantages and limitations. While MEMS components typically provide broader tuning ranges, lower insertion loss, and superior linearity, they often incur higher fabrication complexity and cost. Conversely, PIN diodes offer faster switching speeds but may exhibit higher insertion loss. Comparing these tuning mechanisms will be crucial for identifying the most effective approach to dual-path wideband filters. In conclusion, although the current design achieved its target specifications, future research will focus on real-world applications, substrate alternatives, and advanced tuning methods, ensuring continued enhancements in both practicality and relevance for modern wireless systems.

4. CONCLUSION

In conclusion, this study demonstrates the effective realization of a varactor-based tuning approach successfully implemented in a dual-path parallel coupled-lines structure microstrip. This is where each open-circuited coupled-lines resonator is embedded with a varactor diode to change its electrical length. Moreover, this is consistent with previous efforts on varactor-tuned microwave resonators, where a diode's voltage-dependent capacitance is utilized to shift the resonant frequency. Furthermore, experimental results reveal that f_c is tunable by as much as 34%. In addition, simulated and measured results closely match each other, confirming the proposed filter performance in multiband and multifunction applications.

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