Progress In Electromagnetics Research C, Vol. 147, 153-159, 2024

PIER C

(Received 29 July 2024, Accepted 22 August 2024, Scheduled 8 September 2024)

Reconfigurable SIW-Based Bandpass Filter Using Open Ring Resonators for Ku/K-Band Application

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ABSTRACT: This manuscript introduces an advanced architecture for a reconfigurable band-pass filter, utilizing substrate-integrated waveguide (SIW) technology. To induce a transmission zero in the passband response of the filter, the design involves coupling two identical open-loop ring resonators in a back-to-back configuration on top of the SIW cavity. The work includes a comprehensive investigation of the variation in notch frequency with respect to the ring diameter. Further incorporating PIN diodes into the structure enabled the realization of a reconfigurable filter that can be switched between a broad passband and two narrow passbands with a notch. Also, a planar DC biasing network has been specifically designed to bias the diodes. Additionally, a prototype has been developed to validate the concept and the performance in terms of reflection and transmission coefficients. The miniaturized reconfigurable filter design presented is well suited for the use in both Ku- and K-band applications due to its specific performance characteristics.

1. INTRODUCTION

In the realm of satellite, mobile, and other communication systems, microwave filters are essential components. These devices are specifically engineered to discern between the frequencies of signals that are intended to be transmitted or received and those that are not, ensuring seamless and interference-free communication [1]. Substrate-integrated waveguide (SIW) filters are favored for designing and implementing radio frequency (RF) systems due to their planar structure, compact size, relatively low loss, and high-quality factor, as documented in [2]. SIW technology offers greater cost-effectiveness and is more suitable for mass production than conventional waveguide technology. The reduction in size, cost-effective fabrication, and reduced signal losses in SIW (Substrate Integrated Waveguide) devices establish this technology as an attractive alternative to non-planar waveguides, offering advantages in terms of compactness, affordability, and performance.

In electromagnetic spectrum, there is a dense proliferation of wireless signal frequencies. This has led to a significant need for microwave and mm-wave filters that can effectively capture desired signals while filtering out unwanted ones. Band-pass filters play a crucial role in various applications, particularly in communication systems. They are highly popular due to their effectiveness in isolating a specific range of frequencies, but their intricate design and construction make them a challenging component to create and implement successfully. RF filter designers are faced with the demanding task of reconciling conflicting requirements in order to create effective and efficient filters. For example, to achieve high selectivity, RF filter designers may need to incorporate a larger number of resonators. However, this can lead to a corresponding increase in insertion loss. Balancing these competing factors is a crucial aspect of designing effective RF filters. Essential design parameters, such as insertion loss, return loss, group delay, quality factor, and cost, are critical considerations for RF filter designers. Balancing and optimizing these parameters is vital to ensure high performance while effectively managing the overall costs of the design.

Selecting an appropriate transmission line or waveguide technology plays a crucial role in the development of a filter. For instance, a planar microstrip filter, although lighter than a waveguide filter, generally demonstrates a lower quality factor. Conversely, a non-planar rectangular waveguide filter, characterized by its three-dimensional structure and enclosed metal walls that guide electromagnetic signals, presents a superior quality factor and higher power handling capacity. However, it is heavier and larger in size than a planar microstrip filter, making it more suitable for applications where space and weight considerations are less critical. The integration of these technologies by Wu et al. culminated in the innovative advancement known as substrate-integrated waveguide (SIW) technology [1, 4]. SIW filters are meticulously developed by strategically inserting two rows of metallic via posts into a dielectric substrate, ensuring advanced performance with top and bottom metal linings for enhanced electromagnetic capabilities. A comprehensive analysis of SIW band-pass filters, encompassing various methods and designs, is presented in [3]. The SIW structure exclusively facilitates the transmission of the transverse electric mode, similar to the TE_{n0} mode found in rectangular waveguides. SIW's lack of a transverse magnetic mode makes it an excellent choice for designing bandpass filters. Additionally, establishing proper interconnections between SIW and other planar circuits is essential. Tapering

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doi:10.2528/PIERC24072903

Published by THE ELECTROMAGNETIC ACADEMY

serves as the primary interconnection method and, when being executed accurately, can achieve excellent return loss.

Several SIW-based band-pass filters have been documented, with efforts made to achieve a wider passband using methods such as defective ground structure (DGS), complementary split ring resonators (CSRRs), and others [5]. Furthermore, the validity of these concepts has been substantiated through the development of equivalent circuit models for these structures [6]. Innovations and concepts for creating SIW-based band-pass filters have been extensively deliberated in [7]. Moreover, in scientific literature, ultra-wideband (UWB) SIW-based band-pass filters featuring single, dual, and multiple notches to mitigate the impact of undesired bands have been successfully realized [8–16].

The current work presents a novel miniaturized band-pass filter (BPF) that exhibits high selectivity filtering characteristics by leveraging open ring resonators to suppress spurious passbands. Additionally, a reconfigurable band-pass filter is introduced, offering the flexibility to opt for either a wider passband or a wider passband with a notch (dual passbands with a notch). The upper cut-off of the band-pass filter is extended to create a wider passband through the incorporation of square-shaped ring slots and vias. Furthermore, the introduction of open ring resonators generates a transmission zero between the two passbands. This configuration enhances the rejection level between the passbands by leveraging the transmission zero produced by the open-loop resonators.

2. FILTER DESIGN

The substrate integrated waveguide (SIW) structure, as illustrated in Fig. 1, is composed of three distinct layers: a top metal plane, a substrate layer in the middle, and a bottom ground plane. Additionally, via holes are strategically etched in parallel positions along the edges of the structure. When examining the SIW resonant cavity at the TE$_{m0n}$ mode, the resonant frequency can be accurately determined using the provided formula [17], which takes into consideration the speed of electromagnetic waves in a vacuum (c_0) and the relative permittivity (ε_r).

$$f_{m0n} = \frac{c_0}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{l}\right)^2} \tag{1}$$

In the case of SIW cavities, the dominant mode ($m = n = 1$) is indicated as TE$_{101}$. In this dominant mode, the electromagnetic energy is primarily concentrated at the center of the SIW cavity. This concentration effectively suppresses radiation loss and improves the quality factor of the cavity. A substrate integrated waveguide (SIW) filter is implemented using the expression denoted as (1). The physical dimensions and layout of the filter are depicted in Fig. 1, providing a visual representation of its construction. The distance or gap between adjacent via connections is precisely set at 0.3 mm to ensure proper functionality. The SIW filter is constructed on a substrate made of RT/Duroid 5880 material, which is 20 mils thick and has specific electrical properties including a dielectric constant of 2.2 and a loss tangent of 0.0006. The overall dimensions of the filter's structure measure 26 × 13 mm^2, providing a comprehensive insight into its physical size.

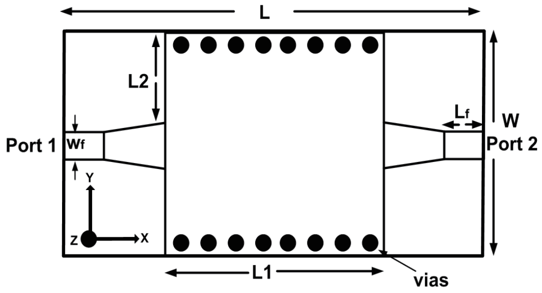

FIGURE 1. SIW Structure.

The graph in Fig. 2 shows the reflection coefficient, which is significantly below -10 dB, while the transmission coefficient is superior, measuring better than -1 dB. A resonator must be incorporated into the structure to create a band-pass response. The introduction of the resonator, as depicted in Fig. 3, successfully results in the desired band-pass response evident in Fig. 4. This approach also highlights the flexibility to modify the upper cut-off frequency of the band-pass filter by adjusting the inductance value, which can be accomplished by changing the diameter of the vias.

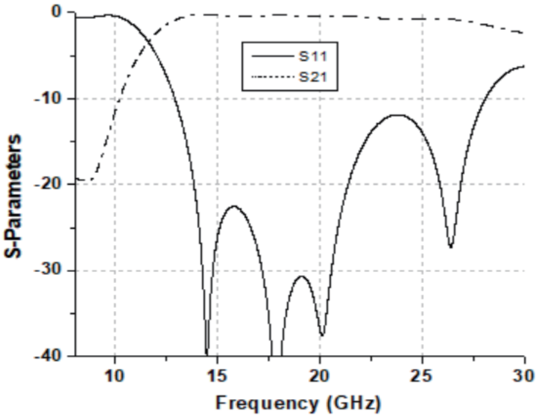

FIGURE 2. Reflection and transmission coefficients of the SIW structure shown in Fig. 1.

Figure 4 displays the equivalent circuit for the resonator. Notably, a substantial variation becomes apparent as the diameter of the vias (shunt inductor) is altered. A thorough investigation has been carried out to examine the influence of varying the via diameter [18].

$$\begin{aligned} L_{wire} &= 2l\left\{ \ln\left[\left(\frac{2L}{D}\right)\left(1+\sqrt{1+\left(\frac{D}{2L}\right)^2}\right)\right] \right. \\ &\quad \left. -\sqrt{1+\left(\frac{D}{2L}\right)^2}+\frac{\mu}{4}+\left(\frac{D}{2L}\right)\right\} \end{aligned} \tag{2}$$

where L_{wire} = Inductance of a straight wire in henries (H), D = diameter of the wire in cm, L = length of the wire in cm, μ = permeability.

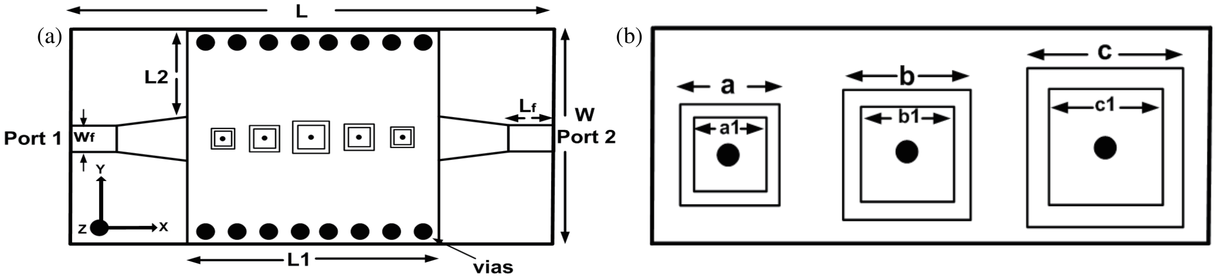

FIGURE 3. (a) Geometry of the SIW band-pass filter (b) geometry of the different-sized resonators. Dimensions: $a = 2.1$; $a1 = 1.8$; $b = 2.3$; $b1 = 1.9$; $c = 2.7$; $c1 = 2.2$; all units are in mm.

TABLE 1. Upper cut-off frequency of the SIW-based filter.

Diameter (mm)	Inductance (nH)	Upper Cut-off frequency (GHz)
0.1	0.240	19
0.3	0.145	21
0.5	0.110	23
0.7	0.092	25
0.9	0.078	27

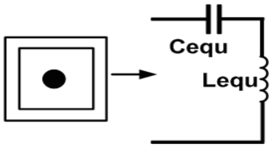

FIGURE 4. Equivalent circuit of the resonator.

3. RESULTS AND DISCUSSIONS

By adjusting the wire diameter, the upper cut-off frequency of the band-pass filter can be controlled. Since the substrate thickness is fixed, the wire's length remains constant. Extensive analysis has been conducted to determine the impact of diameter variations on the bandpass filter's upper cut-off frequency as shown in Fig. 5.

In Table 1, various values are presented. The reflection and transmission coefficients of the filter, with the alteration in wire diameter (inductor), are visually depicted in Fig. 5. To authenticate the analysis, a prototype with a 0.5 mm diameter was employed. Furthermore, the upper cut-off frequency of the bandpass filter is clearly illustrated to be 23 GHz in Fig. 6.

The obtained bandwidth of the filter is notably broad, suggesting that it can potentially cover the 12–27.5 GHz range, encompassing both the Ku- and K-bands, by varying the diameters of the shorted wire (via). In anticipation of the growing electromagnetic pollution in the near future, a filter offering the flexibility to select a wider passband or a passband with notches becomes crucial. This would enable the filtering out or reduction of spurious or unwanted signals. Reconfigurable filters hold the potential to offer the freedom to choose different filter characteristics based on specific needs [19, 20].

Reconfigurable band-pass filters utilizing Substrate-Integrated Waveguide (SIW) technology have become a highly versatile solution for meeting the intricate demands of contemporary wireless communication systems. By leveraging the unique properties of SIW technology, including compact form factor, high-quality factor, and low insertion loss, these filters offer a sophisticated mechanism for dynamically adjusting their operational characteristics to suit varying environmental and performance constraints. This adaptability not only enhances the overall flexibility of the communication systems but also contributes to optimizing their efficiency in diverse operational scenarios.

The reconfigurable SIW-based bandpass filters offer a compact and efficient design, making them a highly desirable option. SIW technology facilitates a compact filter design that seamlessly integrates with planar circuits, resulting in space saving and reduced system weight. Achieving high performance akin to traditional waveguides is possible with a significantly smaller footprint. Reconfigurability can be realized through various methods, such as integrating PIN diodes [21, 22], varactor diodes [23], microelectromechanical systems (MEMSs) [24], or mechanical tuning by capacitors [25]. For instance, in the case of PIN diodes, two states (ON and OFF) can be attained by supplying the appropriate bias. With varactor diodes, adjusting the bias voltage alters the capacitance, thereby modifying the filter's resonance frequency. The precise control of reconfigurable elements is typically accomplished through external control circuits. Therefore, the design must carefully consider control signal routing and the potential impact on overall filter performance.

The adaptability and improved selectivity offered by reconfigurable SIW-based bandpass filters make them well suited for applications in cognitive radio, multi-band communication systems, and adaptive signal processing. These filters represent a notable advancement in filter technology, providing the necessary flexibility and performance for next-generation wireless communication systems. Hence, a reconfigurable SIW filter

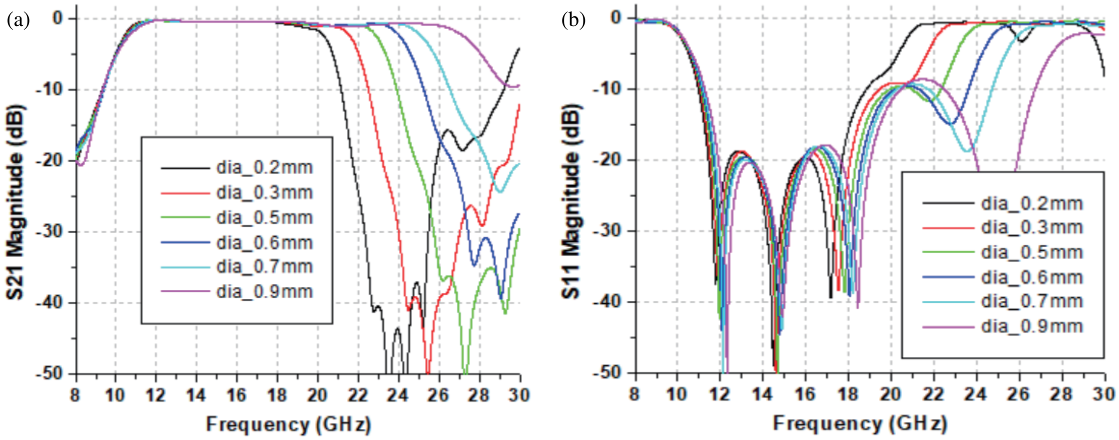

FIGURE 5. Plots showing variations with diameter of the wire (a) transmission coefficient (b) reflection coefficient.

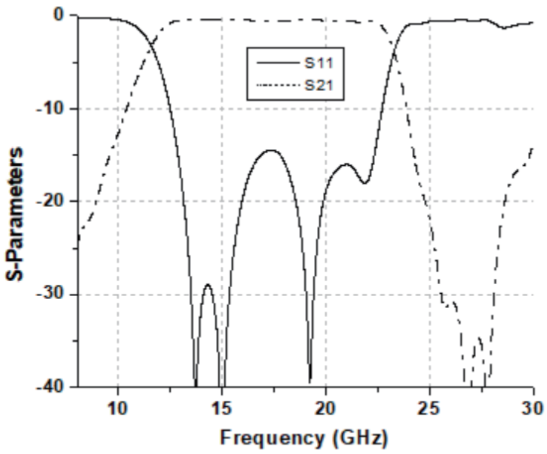

FIGURE 6. Simulated S-parameters of the SIW-based band-pass filter after incorporating resonators with a wire diameter of 0.5 mm.

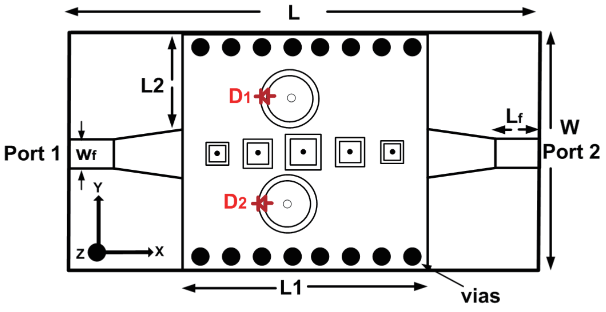

FIGURE 7. Reconfigurable SIW-based band-pass filter. Dimensions: $L = 26$; $W = 13$; $Wf = 1.8$; $Lf = 2.5$; $L1 = 13$; $L2 = 4.4$; all units are in mm.

is considered a strong contender for cognitive radio and multiband communication systems.

In current work, reconfigurability is achieved through the use of PIN diodes, as illustrated in Fig. 7, where 2 PIN diodes are employed. Two identical open-loop circular ring resonators are inserted on the top of the SIW cavity to create transmission zero in the passband response of the filter. The outer diameter of the ring dictates the lowest frequency of the notch, while the inner diameter determines the upper resonance frequency of the notch. An analysis was conducted by varying the inner diameter of the ring across a range of 0.5–1.1 mm, resulting in the variation of the notch resonance frequency from 14 to 22 GHz. It should be noted that integrating a PIN diode becomes challenging when the inner diameter of the ring is less than 0.5 mm. The reflection and transmission coefficients depicted in Fig. 8 illustrate the impact of different inner diameters of the circular ring, with all four rings being identical.

The reconfigurable SIW structure featuring PIN diodes is depicted in Fig. 7 and is designed with a consideration for a 0.9 mm inner diameter of the circular rings. Two PIN diodes, namely $D1$ and $D2$, have been integrated into the design. The insertion of circular rings within the structure serves to create a notch in the passband response with the aid of PIN diodes. Notably, the frequency of the notch can be altered by adjusting the diameter of the ring slots. When all diodes are in the OFF state, a wider passband ranging from 12 to 25 GHz is achieved. The measured return loss was better than -15 dB, and the insertion loss was less than 1 dB for the entire passband. while turning all diodes ON results in the creation of a single-notch band in the passband response of the filter. When the PIN diodes are in the ON state, they perturb the surface current of the structure, causing the rings to function as resonators.

An equivalent circuit of the PIN diode is depicted in Fig. 9(a), with a series resistor of 5 Ω being used to represent the ON state in simulations, and a parallel combination of a 40 Ω resistor and a 0.035 pF capacitor being used to characterize the OFF state of the diode. A prototype was constructed to validate the analysis, as in Fig. 9(c) depicting a photograph of the fabricated SIW-based bandpass filter. Biasing was implemented through a 50 nH lumped inductor, with 100 pF capacitors integrated at the feed ports to block DC flow within the equipment. Small, thin wires were soldered to provide DC to the diodes via a DC power supply, as illustrated in the biasing circuit shown in Fig. 9(b).

The plot presented in Fig. 10 provides a visual comparison between the reflection and transmission coefficients obtained from simulation and measurement processes, offering valuable

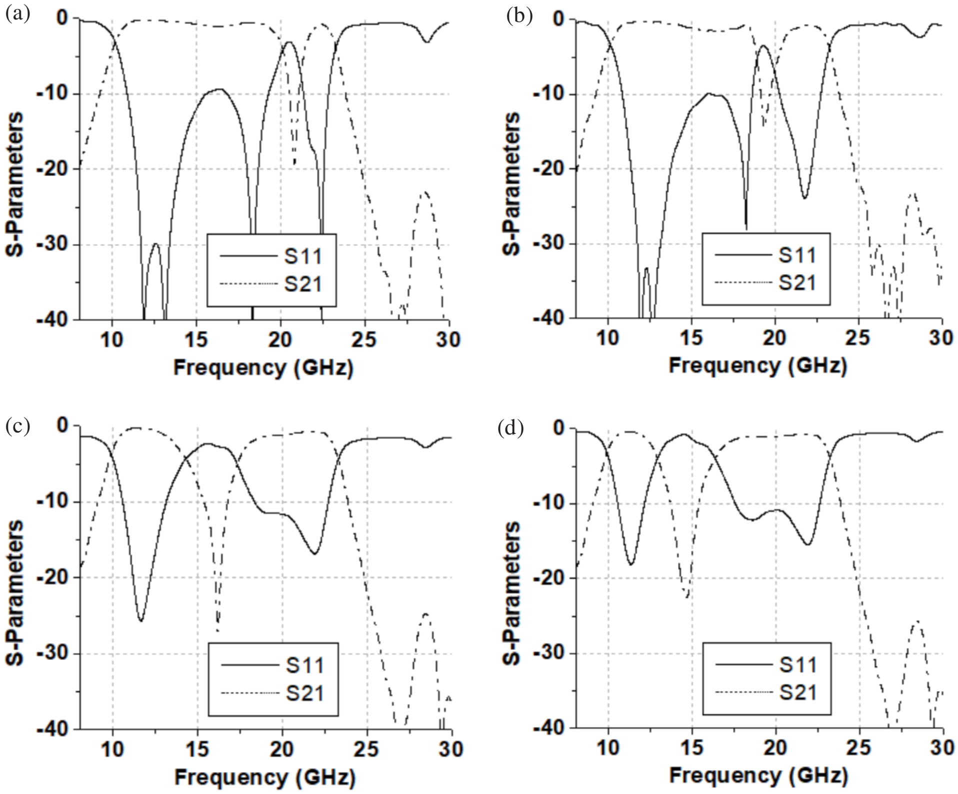

FIGURE 8. Simulated reflection and transmission coefficients showing effects of variations in the inner diameter of the circular rings (a) inner diameter $= 0.5\,\mathrm{mm}$ (b) inner diameter $= 0.6\,\mathrm{mm}$ (c) inner diameter $= 0.9\,\mathrm{mm}$ (d) inner diameter $= 1\,\mathrm{mm}$.

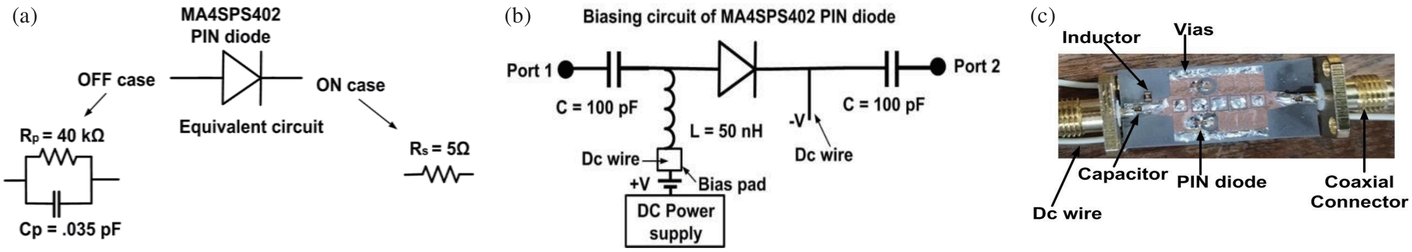

FIGURE 9. (a) Equivalent circuit of the PIN diode. (b) Biasing circuit for the PIN diode. (c) Photograph of the fabricated reconfigurable SIW-based band-pass filter.

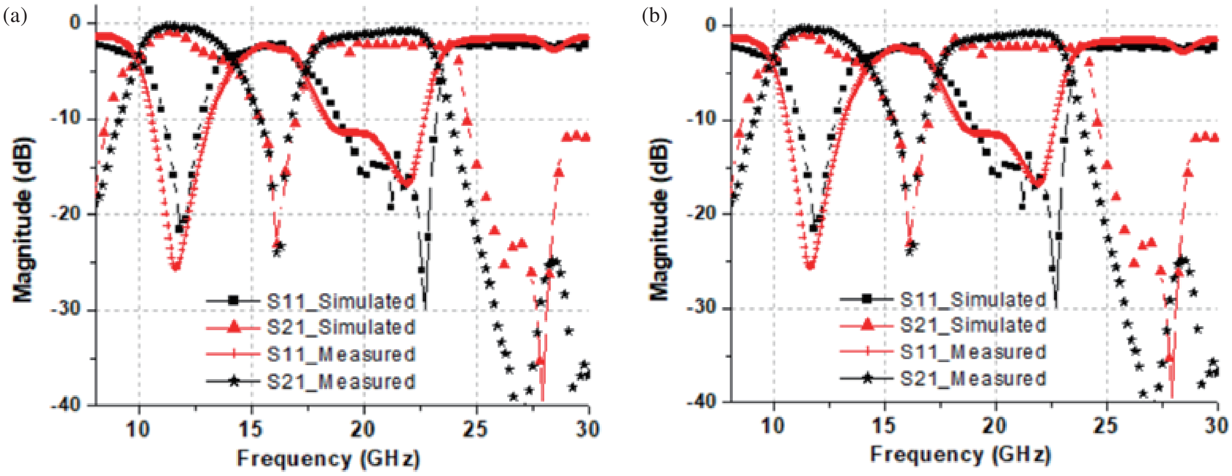

FIGURE 10. S-parameters of the reconfigurable SIW-based band pass filter. (a) when diodes are OFF and (b) When diodes are ON.

TABLE 2. Performance comparison between the previously published work & the work proposed.

Ref	CF (GHz)	FBW (%)	IL (dB)	RL (dB)	Size (λ_g)	Reconfigurable/No. of switches	Number of Notch	Type
22	17.7	72.3	NR	NR	2.32×0.94	Yes/4 (PIN Diode)	1/16.25–17.15	Hybrid SIW with SSPPs
26	9.25	44.02	2	> 12	4.57×0.91	No/NA	0	Hybrid SIW
27	14.74	76	< 1.5	> 17.6	1.25×0.72	No/NA	0	Hybrid SIW with DGS
28	16.73	57.5	< 1.5	> 10	11.11×1.78	No/NA	0	Hybrid SIW with SSPPs
29	6.85	NR	< 1.2	> 13	1.803×0.565	Yes/7 cells	1/NR	Hybrid SIW
30	17.8 / 18.8	61.7/76.4	NR	NR	2.92×0.79	No/NA	0	SIW with SSPPs
This Work	**18.5**	**70**	< 1	> 15	2.63×1.32	**Yes/2 (PIN Diode)**	**1/13.4–17.2**	**Hybrid SIW with open ring resonator**

Ref-Reference, CF-Center Frequency, FBW-Fractional Bandwidth, IL-Insertion Loss, RL-Return Loss, NR-Not Reported, NA-Not applicable, SSPPs-Spoof Surface Plasmon Polaritons.

insights into the performance of the system. A subtle difference is evident between the simulated and measured results, which is likely attributable to the manual fabrication process of the holes and the intricate nature of soldering wires and diodes. A performance comparison between the designed filter and previously published work [22, 26–30] is listed in Table 2.

4. CONCLUSION

This article introduces a cutting-edge reconfigurable band-pass filter based on the innovative substrate-integrated waveguide (SIW) technology, providing a unique solution to meet the intricate demands of modern wireless communication systems. The filter design incorporates two identical open-loop circular rings to introduce a notch within the passband. To facilitate the switching of the filter's characteristics from a wider passband to two passbands with a notch, a simple, planar, and compact biasing network is utilized to bias the diodes. Furthermore, it is noted that the filter's performance can be enhanced by integrating high-quality PIN diodes with reduced series resistance. This enhancement is expected to result in a more precise and refined signal filtration process, allowing for greater accuracy in isolating the desired frequencies. As a result, the overall performance of the filter is anticipated to be significantly improved, rendering it well suited for applications in the Ku and K band frequencies.

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