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Research Article

Electronically Reconfigurable HM-SIW Band-pass Filter Based on New CSRR Design Using PIN Diodes

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Abstract. In this paper, a novel and original reconfigurable *half-mode substrate integrated waveguide* (HM-SIW) *band-pass filter* (BPF) is proposed. The proposed BPF is composed of two different size new design complementary split-ring resonators to achieve the compact size, and two PIN diodes to achieve the reconfigurability. This filter can function in three different cases according to the ON/OFF combination states of the PIN diodes. The operating state can either be a dual-band-pass filter with resonant frequencies 2.5 GHz and 3.6 GHz that have measured *return loss* (RL) less than −23 dB and −25 dB, respectively. Or it can operate as a single-band-pass filter in two other cases. The resonant frequency of the first is 2.6 GHz that has a measured RL of −20 dB, and for the second one, the resonant frequency is 3.35 GHz that has −35 dB as a measured RL. Moreover, the measured *insertion loss* (IL) is better than 1 dB for all the cases. The size of this filter design is 26.3 mm × 12 mm which makes it a very compact device considering that it functions in the S-band compared to publish work that targets the same frequency band.

Keywords. HM-SIW; Metamaterial; CSRR; PIN diode; Reconfigurable

Mathematics Subject Classification (2020). 78A50

1. Introduction

In the past few years, wireless communication systems' demand on having multiple applications in one compact size device has been increasing. Where each application has a different operating band with different characteristics. Usually, a system like this requires multiple filters. Thus, this will significantly increase the size, complexity, and cost of this system. For these reasons, the concept of reconfigurable filters is having more and more attention. This attention is owed to the many merits of reconfigurability, such as the compact size, the facility in integrating with other systems, the low cost along with its multifunctional applications.

The *substrate integrated waveguide* (SIW) technology is a very favorable choice for implementing power dividers [4], antennas [2, 11], resonator [1], planar waveguide [10], and filters [5, 19]. The choosing of this technology is based on a list of advantages compared to traditional guided wave structures like the less complexity, the ability of mass Production, the high-quality Factor, the low loss, with better retune loss and high-power handling. On the other hand, *half mode substrate integrated waveguide* (HM-SIW) is an enhanced SIW structure, by reducing its surface size by almost 50%. Where the open size is playing the role of a magnetic wall, combining that with the vias row on the other side will allow the wave propagation in a mode like TE_{10} of a full-size SIW. Therefore, the HMSIW has a compact size, and low radiation/insertion losses compared to that of SIW [19].

Metamaterials-based *complementary split-ring resonators* (CSRR) introduce in [8, 13] as sub-wave-length planar structure, which can be considered as an electric dipole. This structure has the *same characteristic as split-ring resonators* (SRRs). CSRR will create a stopband behavior, which can stop the electromagnetic waves effectively from passing through. For filters based on microstrip, CSRRs are normally imprinted in the middle of the transmission band or the defect structure, which will sustain the size of the circuit. Additionally, the CSRR is excited by the electric field of the microstrip. Meanwhile, SIW and HM-SIW are very suitable for engraving the CSRR on the waveguide surface. By applying no change regarding the passing from microstrip to SIW or HM-SIW, the SIW/HM-SIW loaded with CSRR are considered a proper choice for implementing band-pass filters [3, 12].

As mentioned before, and along with the development of cognitive radios, broadband, and multiprotocol. The traditional communication standard of one designated purpose device that has a fixed bandwidth and central frequency is no longer felling the requirement of the new wireless transceivers. The alternative option will be developing devices that are reconfigurable and multimode, which will significantly reduce the interference, increase communication, and expand spectrum utilization and the *quality of service* (QoS) [7, 20]. For these reasons, researchers over the last few years have proposed several types and ideas for reconfigurable microwave components, and specifically tunable BPF, such as using diodes [3, 5, 6, 25] or *radio frequency microelectromechanical systems* (RF MEMS) [16, 24]. In addition, several filter structures applying metamaterial are proposed in order to change their characteristics [26], and adding reconfigurability to the metamaterial studied in [21, 23], while SIW based switchable filters are proposed in [27].

In this paper, A novel reconfigurable tunable HM-SIW band-pass filter is proposed. To enhance the properties of this device as long as monetarizing its size, a new metamaterial CSRR is used. Also, we will implement two PIN diodes in this BPF to achieve three different cases that can be easily switched depending on the diodes' states ON or OFF.

The organization of this paper is done as follows: Second 2 presents the theory of half-mode SIW and complementary-SRR. Section 3 introduces the original filter design investigated in this work. Section 4, a thorough interpretation of the obtained results is conducted.

2. Theory of SIW BPF and CSRR

2.1 Substrate Integrated Waveguide

SIW structure normally consists of a dielectric substrate and two metallic conductive layers, one on the top and the other on the bottom of the substrate. These layers are connected with lines of periodically set vias on the sidewalls Figure 1, where d is the diameter of the metallic via holes and p is the periodical distance between two consecutive vias. Moreover, a_d is the waveguide dimension in a dielectric-filled waveguide [10, 21].

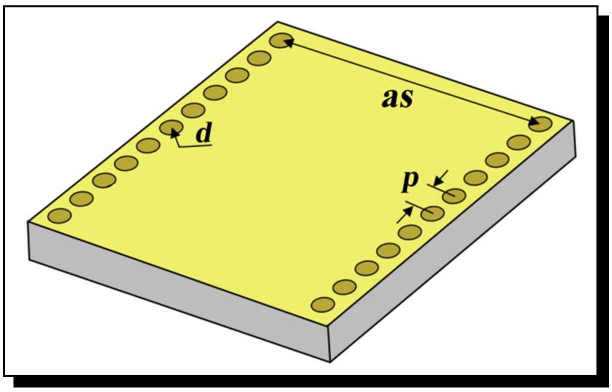


Figure 1. Based structure of Substrate integrated waveguide

The cut-off frequencies of each propagating mode are given by [18]:

$$f_{cmn} = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}. \tag{2.1}$$

The TE_{10} mode, for $m = 1$, $n = 0$, and c is the speed of light in free space.

By considering the fundamental mode to be TE_{10} and f_c to be the cut-off frequency, the following equations can be writing: From (2.1) and [5, 18].

$$a = \frac{a_d}{\sqrt{\varepsilon_r}}, \tag{2.2}$$

$$f_c = \frac{c}{2a_d} \tag{2.3}$$

and the width of the SIW can be calculated using equation (2.3):

$$a = as - \frac{d^2}{0.95p}. \tag{2.4}$$

Two conditions are meant to be respected in order to avoid the radiation, and return loss that can be caused due to field leakage from the gaps between vias: $p \le 2d$ and $d < \frac{\lambda_g}{5}$, where λ_g is the guided wavelength defined by:

$$\lambda_g = \frac{\pi}{\sqrt{\frac{(2\pi f)^2 \varepsilon_r}{c^2} - \left(\frac{\pi}{a}\right)^2}}. \tag{2.5}$$

2.2 Complementary Split Ring Resonators

The based CSRR usually comprised of two open-loop resonators loaded on a metallic surface. The rings are placed one inside the other with opposite openings direction. The distance between the loops is set with a determent gap, as shown in Figure 2. On the other hand, the edge capacitance effect between the two rings is what makes the CSRR resonate. The transmission characteristic of the transmission line will be affected, following the change in the electric field caused by printing the defect pattern or the rings on the ground plane. This is also known as defected ground structure (DGS) [14].

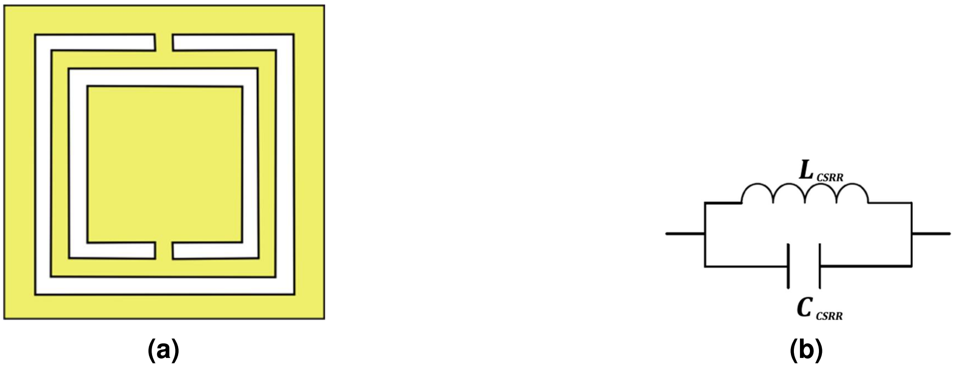


Figure 2. (a) Based structure of a CSRR, (b) The equivalent circuit diagram of this CSRR

To fully benefit from CSRR, and its metamaterials advantages, the best way is to engrave it on a SIW or HM-SIW structure. Because they are shown to have much more acceptable results compare to traditional metallic wave-guides [12].

3. Filter Analysis and Design

In this article, an original CSRR shape is proposed. This new CSRR consists of a C-shape ring located on the inside and one ring with two arms sticking and pointing toward the C-shape ring, as presented in Figure 3. This design will not only increase the electric length, and as a result, we have more miniaturization, but also the arms of the ring provide a better way to place the PIN diodes and control the reconfigurability.

Two of the new designs CSRRs are loaded on the top of the HMSIW structure to realize the band-pass filter, by using the resonance characteristics of the CSRR. The two CSRR cells are having different sizes and diameters. In other words, each will have a different cut-off frequency.

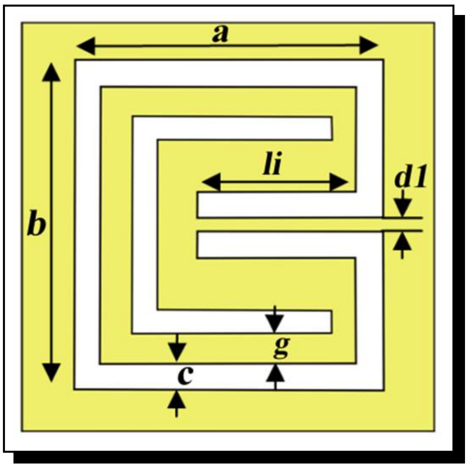
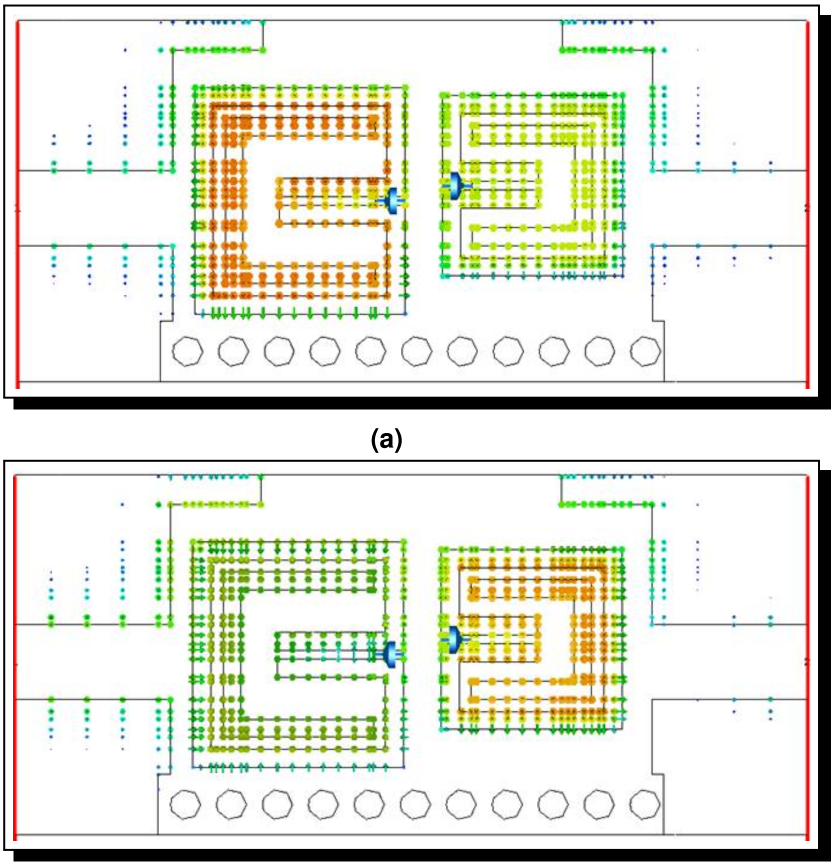


Figure 3. The proposed CSRR cell design

The current distribution obtained by CST of the simulated design is display in Figure 4. By observing the outcome, the current concentrates and distributes mainly around the CSRR cells that correspond to the targeted frequency. This outcome is mainly because the electric field is perpendicular to the metallic layers. On the other hand, the magnetic field is perpendicular to the sidewalls of the vias and parallel with the surface.



(a)

(b)

Figure 4. Current density of the HM-SIW BPF at: (a) 2.5 GHz, and (b) 3.65 GHz

In order to achieve reconfigurability, two PIN diodes are been employed in the filter [15]. The PIN diode does function as a variable resistor at radio frequencies, and microwave frequencies, which are controlled mainly by its bias voltage. In a direct polarization, those diodes offer an extremely low impedance, but when it is polarization in the reverse Direction the impedance will go higher, and with a very low capacity. Each PIN diode will be placed between the two arms of each CSRR cell as shown in Figure 5. Consequently, the diodes will connect the conductive surface inside the cell with the rest of the structure conductive.

The HM-SIW filter designed proposed in this article functions within the S-band. This prototype is loaded with two CSRR, and two PIN diodes (Figure 5). The choosing substrate is RT/Duroid 5880, that its relative permittivity and loss tangent are 2.2 and 0.0009, respectively, and its thickness is $h = 0.508$ mm. The total size of the filter is 26.3 mm × 12 mm. This filter is considered to be positively small considering its functioning band.

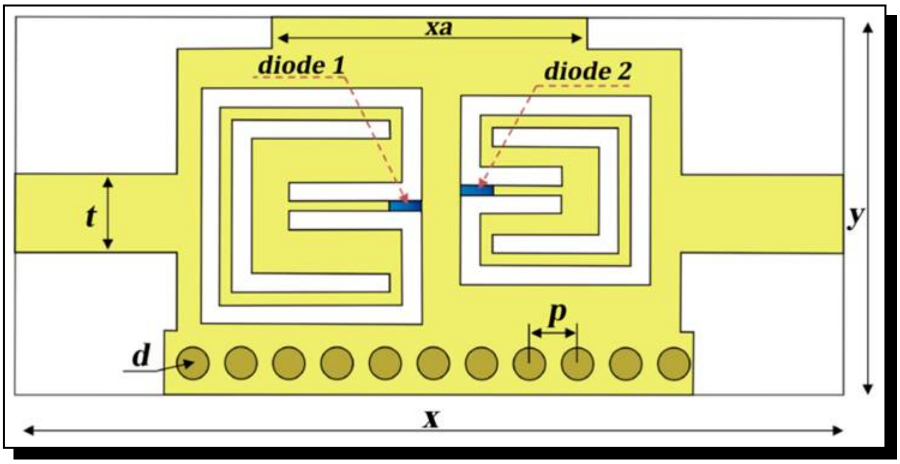


Figure 5. The top layer of the half- mode SIW filter lauded with two CSRR and two PIN diodes

Table 1. Dimensions of the HM-SIW proposed tunable filter with two CSRRs (unit: mm)

Symbol	p	d	x	y	h	t	c	g	$d1$	xa
Quality	1.5	1	12	26.3	0.508	2.5	0.6	0.4	0.3	10

Table 2. The dimensions are different between the two CSRRs (unit: mm)

CSRR unit	Unit 01	Unit 02
a	7	6
b	7.5	6
li	4.2	3.2

4. Results and Discussion

Designing and optimizing the parameters, along with the simulated results of the HM-SIW metamaterial prototype are all performed using CST microwave studio. Figures 6, 7 and 8, display the simulated S11 (return loss), and S21 (transmission coefficient) for the spiral structure filter, with the different cases depending on the different PIN diode states. The simulated results evidently show that the prototype can function as a dual-band -pass filter if the two diodes are activated (Case 1 in Table 3). Meanwhile, if one of the diodes is activated while the other stays deactivated (Case 2 and Case 3 in Table 3), it can be seen that the prototype act as a single-band-pass filter. The resonant frequency is shifted to 2.6 GHz for Case 2 when diode 1 (D1) is activated and diode 2 (D2) is deactivated. In an opposite event or Case 2 where D1 is deactivated and D2 is activated the resonance frequency is 3.35 GHz. Compared to the first case where diode 1 and diode 2 are both activated and the pass-bands are 2.5 GHz and 3.6 GHz. Table 3 summarize the performance and the different simulation parameters of the HM-SIW tunable filter for all three PIN diode combinations.

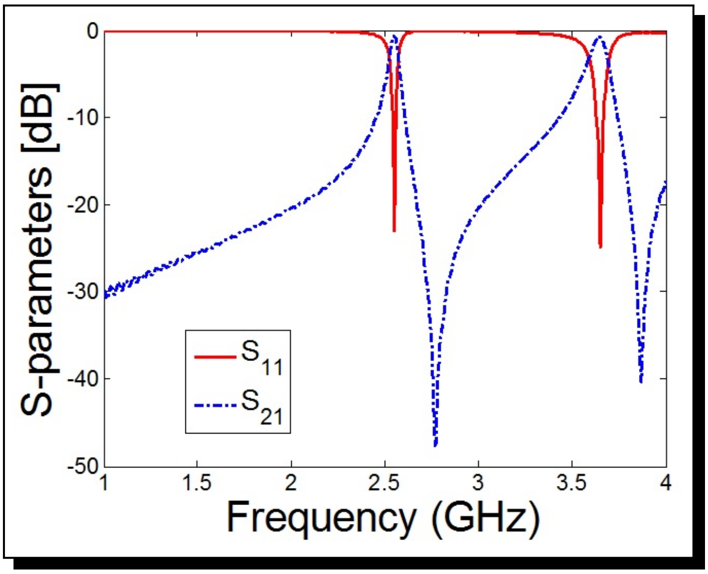


Figure 6. The simulated S-parameters of the filter in a dual-band-pass state, Case 1 where diode 1 is ON and diode 2 is ON

Table 3. The different states of the filter and their properties

Cases	Case 1	Case 2	Case 3
diode 1 (D1)	ON	ON	OFF
diode 2 (D2)	ON	OFF	ON
Resonant frequency (GHz)	2.5/3.6	2.6	3.35
Return loss (dB)	−23/−25	−20	−35
Insert loss (dB)	> −1	> −1	> −1
Function of the filter	Dual-band	Single-band	Single-band

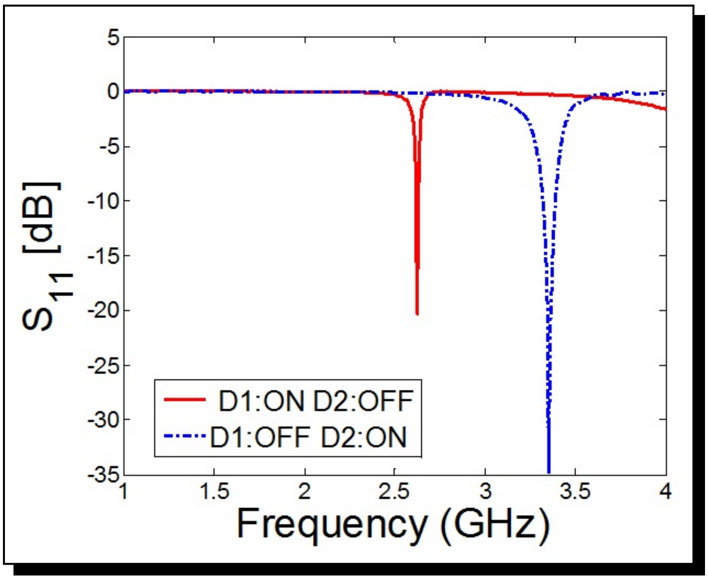


Figure 7. The simulated S11 of the filter in the single-band-pass states, Case 2 where D1 is ON and D2 is OFF, and Case 3 where D1 is OFF and D2 is ON

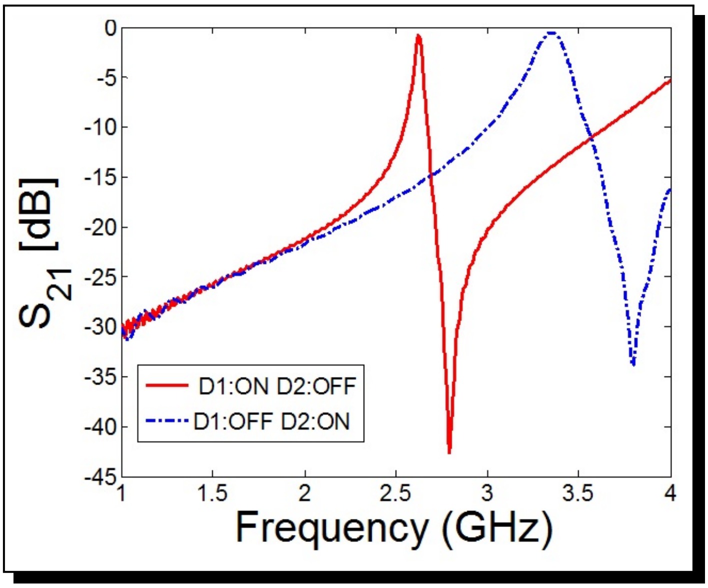


Figure 8. The simulated S21 of the filter in the single-band-pass states, which are Case 2 where D1 is ON and D2 is OFF, and Case 3 where D1 is OFF and D2 is ON

Table 3 clearly shows the good electromagnetic properties of the filter. The resonant frequencies of the three cases have a lower return loss than (more than -20 dB) which is very acceptable. Moreover, the insertion loss is excellent. On the other hand, and from the simulation Figures 7 and 8, the rejection levels outside of the filtering bands have reached very important levels. So, these simulation results have shown such good handling of the losses in both dual and single modes with less complexity on a compact sized structure.

5. Conclusion

This article presented a new technique for designing a frequency reconfigurable, tunable, and compact HM-SIW band-pass filter, based on PIN diodes. The overall compactness and selectiveness of this filter design were achieved using new CSRR units, loaded on the HM-SIW surface. The simulated results showed that the device has very good band-pass filter properties. The main limitation of this technique is the shifting in operating frequency when we change the filter state from single to dual-mode, which is happening because of the coupling effect between the CSRRs that has to be reduced. This promising technology can be more investigated. we can upgrade the number of possible cases. And target higher frequencies (mm-waves and 5G applications). This filter is suitable with modern communication systems, WALAN applications, and thanks to its compact size, and its reconfigurability it can be easily integrated with planar circuits and nowadays devices.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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