# Compact Modified Quarter Mode Substrate Integrated Waveguide Resonator and Its Application to Filters Design

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***Abstract*** **─** A novel compact modified quarter mode substrate integrated waveguide (QMSIW) resonator is proposed. The dominant resonant mode of the proposed resonator is $TE_{101}$ mode. Using modified QMSIW resonator can reduce 97.3% in size with respect to its corresponding substrate integrated waveguide (SIW) counterpart. With the new coupling structures, the miniaturized cavity can be properly arranged in the filter design to minimize the footprint of the circuit. Two novel filters using compact modified QMSIW cavity are designed, and these proposed compact filters are fabricated to prove the predicted results in experiments, in which good agreement is obtained.

***Index Terms*** **─** Filter, substrate integrated waveguide, $TE_{101}$ mode.

## I. INTRODUCTION

Substrate integrated waveguide (SIW) circuits have many advantages such as low cost and high quality factor, so they are well suited to realize passive components in microwave and millimeter wave integrated circuits. Nevertheless, the biggest drawback of SIW is that the physical dimension may be too large for lower microwave integrated circuits [1-4].

In 2006, the concept of half mode substrate integrated waveguide (HMSIW) was proposed, which can reduce the size of SIW components by half [5-6]. The field distribution of the HMSIW remains almost unchanged compared with that of the original SIW. The center symmetrical plane of the HMSIW is equivalent to a quasi-magnetic wall for some particular modes. The HMSIW can be further bisected into two parts again along the symmetrical plane. As a result, a quarter mode substrate integrated waveguide (QMSIW) can be achieved and its size is only the half of HMSIW resonator cavity [7-9]. An eighth-mode SIW (EMSIW) resonator cavity has been realized by bisecting the QMSIW. The cavity is only one-eighth the size of the SIW [10,11].

Another size miniaturization approach is folding in its thickness direction [12-19]. In 2005, folded SIW (SIFW) concept has been proposed [13]. SIFW exhibits similar cutoff frequency and propagation characteristics while only occupies half the room of its SIW equivalent structure, and then the double-folded SIW (DFSIW) [14-17] has been proposed. This DFSIW resonator cavity has the footprint only a quarter of the original SIW cavity, but still keeps similar high Q property. In [18,19], compared with classical SIW resonant cavity, the circuit area of the quadruple folded SIW (QFSIW) resonant cavity can be decreased to 89%.

Meanwhile, folded HMSIW (FHMSIW) has been applied in designing microwave devices. FHMSIW [20] and double folded HMSIW (DFHMSIW) [21] can be properly arranged in the filter design to minimize the footprint of the circuit. DFQMSIW are able to reduce the dimension of SIW components by approximately 94% [22,23].

In this paper, a compact modified QMSIW resonator is proposed and used to design high performance microwave filters in the paper. The compact modified QMSIW resonator is operated at $TE_{101}$ mode, with more than 97.3% size reduction in contrast with the traditional SIW filter. Two novel filters using compact modified QMSIW cavity are designed, including single bandpass and dual bandpass filters. The results of the simulation and experimentation matched very well. Thus, the proposed method has been proved to be feasible.

## II. COMPACT MODIFIED QMSIW CAVITY

Figures 1 (a) and (b) show the structure of a compact modified QMSIW cavity, which is composed of a bottom conductor plane, two dielectric layers, a middle metallic conductor plate with a C-shaped slot, and a top conductor plane. The top conductor plane and bottom conductor plane are united through the C-shaped slot as a whole. Its height is two times of the original SIW, because it has two layers of substrate with height of h. The length ($L^{'} = 2(L_1 + L_2)$) of the C-type slot obviously affects the miniaturization of the QMSIW cavity.

A conventional SIW cavity with $36 \times 36\,mm^2$ area is designed on Rogers RT/Duriod 5880 substrate with the relative permittivity of 2.2 and the height of 0.508 mm.

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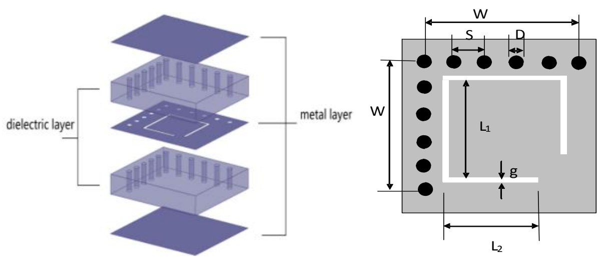
Its $\tan\delta = 0.0009$. As a result a fundamental $TE_{101}$ mode exists around 3.9 GHz. For a fixed QMSIW cavity resonator size, inserting C-type slot into the structure will reduce the resonance frequency. The miniaturization factor for a particular miniaturized resonator operating at a lower frequency of $f_0$ is computed using miniaturization factor (MF):

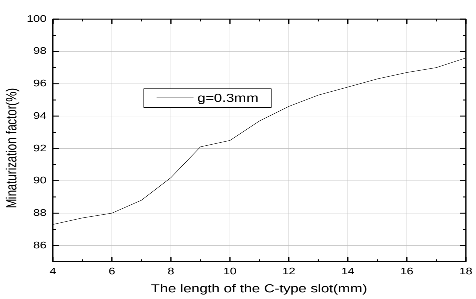
$$MF = \frac{A_{siw,f0} - A_c}{A_{siw,f0}} \times 100\% , \quad (1)$$

where $A_{siw,f_0}$ is the area of a conventional SIW resonator, which fundamentally operates at $f_0$ and $A_c$ is the area of the proposed modified QMSIW cavity resonators. This miniaturization factor contribution for each element is mentioned in the caption of Fig. 2 (a).

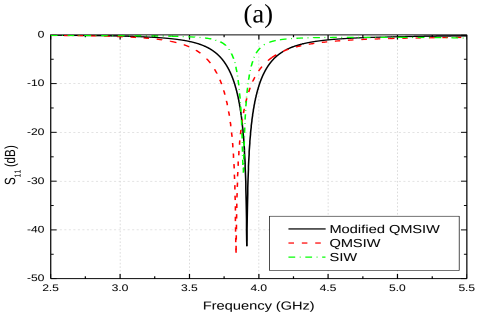



(a) (b)

Fig. 1. The structure of a compact modified QMSIW cavity. (a) 3D configuration and (b) middle metal layer.




(a)




(b)

Fig. 2. (a) Miniaturization factor of the proposed modified QMSIW resonator for different C-type slot dimensions, and (b) simulated results of the compact modified QMSIW and SIW resonator.

Conventionally, the length of square SIW cavity with a dominant resonant mode of $TE_{101}$ is of half wavelength. The resonant frequency of the $TE_{101}$ mode is calculated usinEg equation (2) [24]:

$$f_{101}^{SIW} = \frac{C}{2\pi\sqrt{u_r\varepsilon_r}}\sqrt{(\frac{\pi}{W_{eff}^{SIW}})^2 + (\frac{\pi}{W_{eff}^{SIW}})^2} , \quad (2)$$

$$W_{eff}^{SIW} = W - 1.08\frac{(d)^2}{S} + 0.1\frac{(d)^2}{W} , \quad (3)$$

where $u_r$ is the relative permeability of the substrate and $\varepsilon_r$ is the permittivity of the substrate. $C$ stands for the velocity of light in vacuum. $W_{eff}^{SIW}$ represents the equivalent width of the corresponding original square SIW structure. $W$ is the length and width of the original square SIW cavity resonator. d and $s$ are the diameter of via and the distance between adjacent vias, respectively. The fundamental resonant mode in the compact modified QMSIW structure is still the $TE_{101}$ mode, and its resonant frequency is given by Equation (4) [25]:

$$f_{101}^{Modeifed} = \frac{C}{p\sqrt{2u_r\varepsilon_r}W_{eff}^{Modified}} , \quad (4)$$

$$W_{eff}^{Modified} = W_{eff}^{SIW} / p + \Delta W , \quad (5)$$

where $W_{eff}^{Modified}$ is the equivalent width of compact modified QMSIW. P is the multiple of the length of the original substrate integrated waveguide with respect to the length of the proposed modified QMSIW substrate integrated waveguide. The value of P is mainly determined by the length of the C-type slot, which is between 2 and 6. $\Delta W$ is the additional width and achieved because of the change in feeding position. In fact, the magnetic walls are not ideal on account of fringing fields [25].

A compact modified QMSIW cavity with $6\times6$ mm$^2$ area is designed on Rogers RT/Duriod 5880 substrate. The relative permittivity and the height of the substrate is 2.2 and 0.508 mm, respectively. Its $\tan\delta = 0.0009$, $L^{'} = 17.6mm,\ L_1 = 4.8mm,\ L_2 = 4mm,\ s = 1.2mm,\ D = 0.8mm,$ $g$ is fixed to 0.3mm. A conventional SIW cavity with $36\times36$ mm$^2$ area and a conventional single layer QMSIW cavity with $18\times18$ mm$^2$ are designed in the same condition. Figure 2 (b) shows the simulated S-parameter curve of the modified QMSIW cavity, the conventional QMSIW cavity and the conventional SIW cavity. It is shown that the $TE_{101}$ mode resonant frequency of the proposed compact modified QMSIW almost remains unchanged compared with that of the corresponding original SIW resonator cavity. When the width of compact modified QMSIW is nearly 1/6 of the corresponding SIW, the compact modified QMSIW can preserve similar propagation and cutoff characteristics with the SIW structure, with the advantages of simple structure, compact size and the merit of low-loss.

Therefore, the compact modified QMSIW cavity can be used for the circuit size reduction with its footprint about 2.7% of the conventional $TE_{101}$ mode. However, the unloaded $Q$ factor ($Q_u$) of the proposed compact modified QMSIW is smaller than that of the corresponding SIW in the same condition, because the open edges are not perfect magnetic walls and a certain amount of radiation may happen. In our design, $Q_u$ is about 186. Under the same conditions, the $Q_u$ of the corresponding SIW resonator is around 270. The E-field distribution of the upper layer is the same as that of the down layer. The field distribution of the compact modified QMSIW in the fundamental mode is different from that of SIW. The maximum electric field does not concentrate on the center. Instead, it is focused on the C-shaped slot region, as shown in Fig. 3. Table 1 lists the comparative results among different compact SIW resonant cavities.

It is demonstrated that our configuration is the smallest structure.

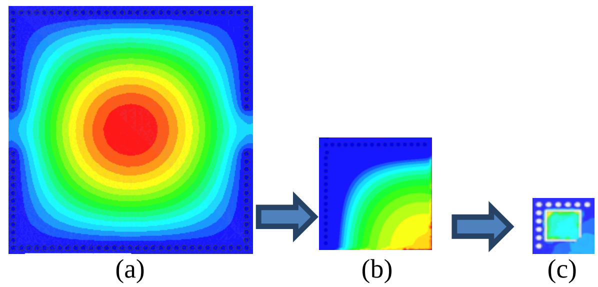



Fig. 3. Electric field distribution of different cavities. (a) SIW, (b) QMSIW, and (c) modified QMSIW.

Table 1: Comparison with different compact SIW resonant cavities

| Type | $f_g$ | $Q_u$ | Dimensions(L×W×H) | $\varepsilon_r$ |
|---|---|---|---|---|
| HMSIW in [5] | 9.88 GHz | 250 | $0.52\lambda_0 \times 0.26\lambda_0 \times 0.008\lambda_0$ | 2.94 |
| QMSIW in [7] | 5.85 GHz | 172.8 | $0.195\lambda_0 \times 0.195\lambda_0 \times 0.005\lambda_0$ | 2.94 |
| EMSIW [10] | 3.29 GHz | Not calculated | $0.5\times(0.197\lambda_0 \times 0.197\lambda_0 \times 0.017\lambda_0)$ | 2.2 |
| SIFW in [13] | 10.03 GHz | 206 | $0.32\lambda_0 \times 0.16\lambda_0 \times 0.013\lambda_0$ | 5.9 |
| DFSIW in [14] | 30 GHz | 94 | $0.253\lambda_0 \times 0.253\lambda_0 \times 0.088\lambda_0$ | 7.8 |
| QFSIW [19] | 3.2 GHz | 232 | $0.128\lambda_0 \times 0.128\lambda_0 \times 0.01\lambda_0$ | 3.5 |
| FHMSIW in [21] | 5.5 GHz | Not calculated | $0.179\lambda_0 \times 0.258\lambda_0 \times 0.019\lambda_0$ | 2.2 |
| DFHMSIW in [21] | 5.5 GHz | Not calculated | $0.138\lambda_0 \times 0.147\lambda_0 \times 0.019\lambda_0$ | 2.2 |
| QFQMSIW in the paper | 3.19 GHz | 186 | $0.06\lambda_0 \times 0.06\lambda_0 \times 0.01\lambda_0$ | 3.5 |

$f_g$ is resonating frequency; is resonating frequency; $\lambda_0$ is the wavelength in vacuum at $f_g$

## III. COMPACT MODIFIED QMSIW FILTERS DESIGN

### A. Design of three-order bandpass filter

In this section, the filter has a fractional bandwidth of 12.8% at 4.62 GHz. A three order Chebyshev filter with 20 dB of passband return loss is regarded as the prototype. The coupling coefficient and the external quality factor can be calculated by [26]:

$$M_{12} = 0.125; M_{23} = 0.125; Q_{e1} = 7.01; Q_{e3} = 7.01,$$

where $M_{i,i+1}$ represents the coupling coefficient between resonator i and resonator i+1, while $Q_{e1}$ and $Q_{e3}$ stand for the external quality factors of the input and output.

The schematic coupling topology of the proposed bandpass filter is depicted in Fig. 4. Because compact modified QMSIW cavity is not strictly symmetrical, $M_{12}$ (the coupling between cavity 1 and cavity 2) and $M_{23}$ (the coupling between cavity 2 and cavity 3) can't be realized in the same way. The layout of the proposed cascaded compact modified QMSIW filter is shown in Fig. 5. The magnetic coupling is achieved through the coupling window between cavity 1 and cavity 2. The coupling characteristic and coupling strength can be flexibly controlled and modified by adjusting the size (Lp) of the window. Meanwhile, a coupling slot and metallic via hole printed between cavity 2 and cavity 3 can produce mixed electric and magnetic coupling. The value of mixed coupling is mainly under the control of the slot size (Lt) and the number of the metallic via holes.

The filter is realized by using the substrate with Rogers RT/Duriod 5880, with thickness of 0.508 mm, and the dimensions are given as below: La=18mm, Wm=6.75mm, Ws=1.35mm, Ls=4.1mm, L1=3.95mm, L2=3.9mm, L3=3.5mm, Wp=1.9mm, Lp=4mm, Lt=4mm, s1=0.2mm. The proposed filter is shown in Fig. 6.

The data are measured by Agilent E5071C vector network analyzer (VNA). Figure 7 depicts the simulated and measured frequency responses. The measured bandwidth of the filter is 12.8% in the center frequency of 4.62 GHz. The measured return loss in the passband is more than 14 dB, while the measured minimum insertion loss is approximately 1.4 dBin the passband. Because $TE_{102}$ mode of the square SIW resonator is not generated in compact modified QMSIW cavity, the proposed filter has a very good suppression characteristic in the out-off-band, and the $S_{21}$ parameter is better than 20 dB in relatively wide-band. The energy loss of the proposed filter mainly comes from the material and SMA connectors. The good agreement between measured and simulated results demonstrates that the presented method is effective. For modified QMSIW, the predicted resonance for $TE_{202}$ mode is excited at 7.35 GHz, so there appears a ripple at around 7.35 GHz.

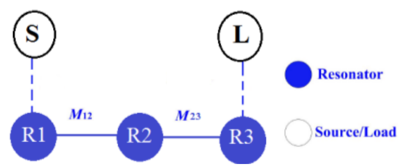



Fig. 4. Coupling scheme of the proposed three-cavity filter.

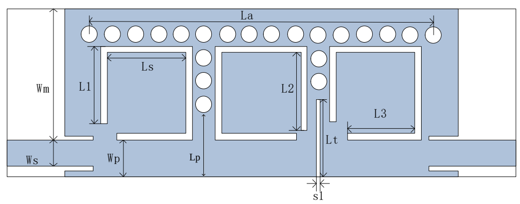
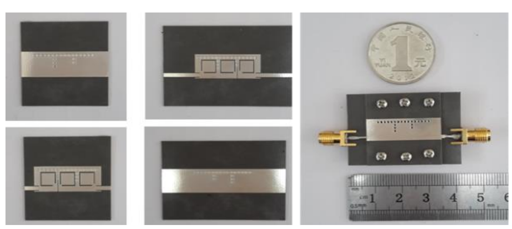



Fig. 5. Configuration of the middle conductor layer in the proposed three-cavity filter.



(a) (b) (c)

Fig. 6. Photograph of the proposed three-cavity filter prototype. (a) Top and bottom metal layer of the first substrate, (b) top and bottom metal layer of the second substrate, and (c) assembled filter prototype.

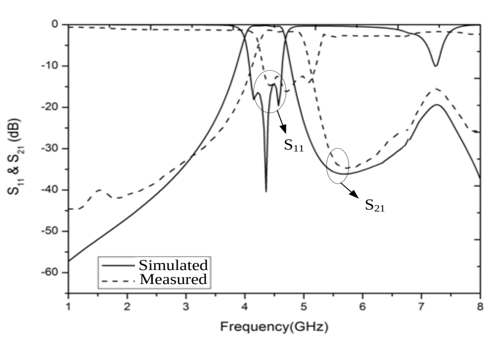



Fig. 7. Simulated and measured results of the three-cavity filter.

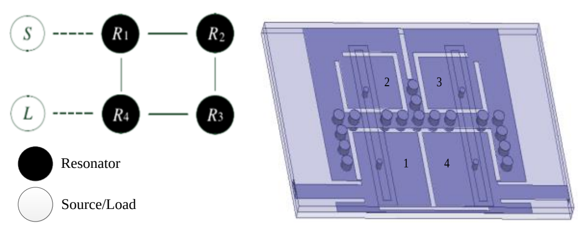
**B. Design of four-cavity dual-band filter**

In this section, a four-cavity dual-band filter is designed. The central first band frequency is $f_1$=3.6 GHz, the central second band frequency is $f_2$=4.8 GHz, and the corresponding bandwidths are BW=0.4 GHz and BW=0.3 GHz, respectively. The return loss is 20 dB in the both bands. The coupling matrix is obtained as follows:

$$\begin{bmatrix} 0 & 1.082 & 0 & 0 & 0 & 0 \\ 1.082 & 0 & 3.418 & 0 & -0.569 & 0 \\ 0 & 3.418 & 0 & -0.661 & 0 & 0 \\ 0 & 0 & -0.661 & 0 & 3.418 & 0 \\ 0 & -0.569 & 0 & 3.418 & 0 & 1.082 \\ 0 & 0 & 0 & 0 & 1.082 & 0 \end{bmatrix}$$

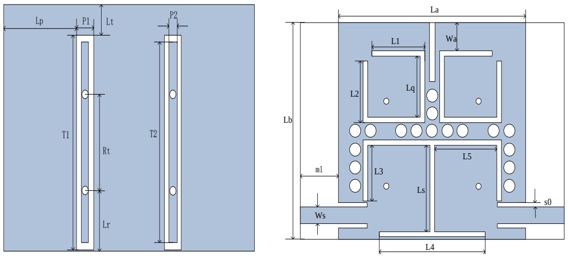
Here, the dual-band characteristic has been achieved by adjusting the position of the microstrip-probe coupling. The schematic coupling topology of the proposed four-cavity dual-band filter is shown in Fig. 8 (a). The physical model of the proposed compact modified QMSIW dual-band filter is shown in Fig. 8 (b).

The coupling between cavity 2 and cavity 3 can be flexibly controlled and modified by adjusting the position of the slot and the number of the metallic via holes. The coupling between cavity 1 and cavity 4 is produced by the common-slot. The coupling between cavity 1 and cavity 2 and the coupling between cavity 3 and cavity 4 can't be realized by the coupling window, because the structure makes transmission of energy hard. The coupling is achieved through the microstrip-probe between resonator 1(3) and resonator 2(4). The probe can generate higher mode, so dual-band characteristics can be obtained by adjusting the position and size of microstrip-probe. The dual-band filter is realized by using the substrate with Rogers RT/Duriod 5880 with the thickness of 0.508 mm. The configuration size of the proposed filter is shown in Fig. 9. By simulation and optimization, the dimensions are given as follows: La=14.6, Lb=14.6, m1=3, L1=4.1, L2=4.1, Lq=4.1, Wa=1.9, L3=3.75, L4=8.25, L5=4.88, Ls=5.8, Ws=1.1, s0=0.3, Lr=3.6, T1=12.7, P1=1.4, T2=11.9, P2=0.6, Lp=6, Lt=1.8, Rt=5.7 (all in mm).




(a) (b)

Fig. 8. (a) Schematic coupling topology of the proposed filter (S: source, L: load, R: resonator), and (b) 3D configuration of the proposed compact cross-coupled dual-band filter using compact modified QMSIW resonators.




(a) (b)

Fig. 9. The configuration size of the proposed filter. (a) Top metal layer, and (b) middle metal layer.

Figure 10 shows a photograph of the filter. A HP network analyzer is chosen to measure the performance of the fabricated filter. In Fig. 11, the simulated and measured results are shown. The simulated and measured frequency responses demonstrate that an excellent agreement is obtained. A 3 dB fractional bandwidth of approximately 14% in the measured lower passband where the central frequency is about 3.62 GHz is presented, and the insertion loss in the lower passband is about 1.2 dB at the central frequency. Meanwhile, a 3 dB fractional bandwidth of approximately 6.25% in the measured upper passband where the central frequency is approximately 4.82 GHz is presented, and the insertion loss is about 2.1 dB at the central frequency. The return losses are better than 15 dB in the passband. It seems that the higher measured insertion loss at the higher passband is due to unfavorable coupling. There's something a little bit different between the passband bandwidths and the asymmetrical frequency response. It may be caused by certain minor cross coupling and structural difference.

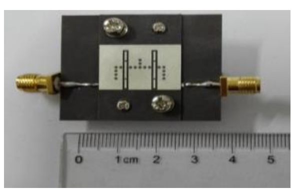



Fig. 10. Photograph of the proposed four-cavity filter.

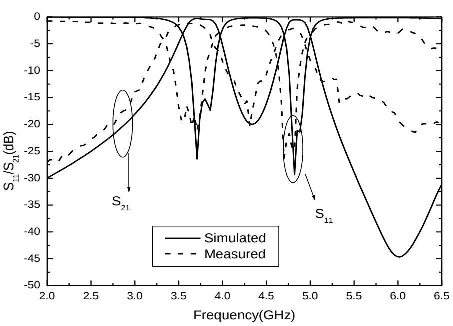



Fig. 11. Simulated and measured results of the four-cavity filter.

## IV. CONCLUSION

A novel compact modified QMSIW resonator is designed, and the proposed compact modified QMSIW cavity has good performance, while the size reduction is up to 97.3% compared with the conventional SIW cavity. Thus, it is well suited for designing miniaturization circuit. Several novel filters using compact modified QMSIW cavity are designed, including single passband and dual passband filters. The designs of the proposed filters are based on full-wave electromagnetic simulation. The measured performance of these filters is in good agreement with the simulated ones.

## ACKNOWLEDGMENT

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