Design of an ultra-miniature substrate integrated waveguide filter

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\textbf{Abstract:} An ultra-miniature modified quarter mode substrate Integrated waveguide (QMSIW) resonator is proposed. The dominant resonant mode of the proposed resonator is TE\textsubscript{101} mode. The area of the modified QMSIW resonator is reduced by nearly 97.3\% compared with the conventional full-mode SIW resonator. With the new coupling structures, the miniaturized resonator can be properly arranged in the filter design to minimize the footprint of the circuit. A novel filter using compact modified QMSIW cavity is designed, the proposed compact filter is fabricated to prove the predicted results in experiment, and good agreement is obtained.

\textbf{Keywords:} QMSIW, filter, resonator, coupling

\textbf{Classification:} Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Compared with the microstrip structures, Substrate integrated waveguide (SIW) circuits have higher quality factor, therefore they are suitable for realizing passive components in MMICs. However, the physical dimension of SIW blocks may be too large for certain applications, especially for lower microwave frequency band.

Half-mode substrate integrated waveguide (HMSIW) concept has been proposed, which can reduce the size of SIW components by half [1]. The HMSIW can be further bisected into two parts again along the symmetrical plane. Hence, a quarter mode substrate integrated waveguide (QMSIW) is realized and its size is only a quarter of SIW resonator cavity [2]. An eighth-mode SIW (EMSIW) cavity is formed by bisecting the QMSIW. The structure only occupies eighth of the SIW [3]. On the other hand, to reduce the footprint of SIW resonator, folded SIW (FSIW) concept [4, 5], defected-ground-structure (DGS) and ring gaps [6, 7] have been applied to design SIW filters. A quadruple folded SIW (QFSIW) cavity is introduced to decrease the circuit area of conventional SIW cavity to be 89% [8], but DGS and ring gaps are limited by the geometrical dimensions of the employed loading structures and the area available on the top/bottom walls of the SIW cavity. Meanwhile, various miniaturization technologies have been combined to design microwave devices. Double folded QMSIW [9, 10] and QMSIW with ramp-shaped slots [11] can reduce the size of SIW components by nearly 94% and 95%, respectively.

To further decrease the size of filters in substrate integrated waveguide, an ultra-miniature modified QMSIW resonator is proposed and exploited to design a high performance microwave filter in the paper. The modified QMSIW resonator is operated at TE101 mode, and it has more than 97.3% size reduction compared with the conventional SIW resonator. A filter using the modified QMSIW cavity is designed. Good agreement between simulated and measured results demonstrates the validity of the proposed method.
2 Analysis of the resonator

Fig. 1(a), (b) shows the structure of the modified QMSIW cavity, which consists of a bottom conductor plane, two dielectric layers, a middle metal conductor plate with a slot, and a top conductor plane. The up cavity and down cavity are grouped through this C-type slot as a whole. Its height is two times of that of the original SIW, because it has two substrates with height of \( h \). In fact, the modified double layer QMSIW cavity is that a metal plane with the C-type slot is inserted in the middle layer of a conventional QMSIW cavity with height of \( 2h \). The C-type slot introduces additional capacitance effect. The capacitance value can controlled by the location and the size of C-type slot. The increase of capacitance leads to the decrease of resonant frequency. Therefore, the length \( L' = 2(L_1 + L_2) \) of the C-type slot obviously affects the miniaturization of the QMSIW cavity. A modified QMSIW cavity with \( 6 \times 6 \text{ mm}^2 \) area is designed on Taconic TLY substrate with the relative permittivity of 2.2 and the height of 0.508 mm. Its \( \tan \delta = 0.0009 \), \( g \) is fixed to 0.3 mm. For a fixed QMSIW cavity resonator size, inserting C-type slot into the structure will reduce the resonance frequency, and the simulation results from Ansoft HFSS are shown in Fig. 2(a). As can be seen, increasing the length of
the C-type slot results in lower fundamental TE\textsubscript{101} frequency. The frequency downshift due to this capacitive loading is mainly limited by the size of the C-type slot. At the same time, because of the existence of the open boundary, the variation of capacitance is not completely continuous, the relationship between the length of C-type slot and frequency is not a smooth curve in Fig. 2(a). A conventional single layer SIW cavity with $36 \times 36 \text{mm}^2$ area and a conventional single layer QMSIW cavity with $18 \times 18 \text{mm}^2$ are designed in the same condition. In Fig. 1(b), $L'$ is 17.6 mm. Fig. 2(b) shows the simulated S-parameter curve of the modified QMSIW cavity, the conventional QMSIW cavity and the conventional SIW cavity. It should be pointed that the TE\textsubscript{101} mode resonant frequency of the proposed modified QMSIW almost remains unchanged compared with that of the corresponding SIW cavity. However, the width of the modified QMSIW is nearly 1/6 of that of the original SIW. The modified QMSIW cavity can be used for the circuit size reduction with its footprint about 2.7% of the conventional TE\textsubscript{101} mode. The unloaded $Q$ factor ($Q_u$) of the proposed modified QMSIW is smaller than that of the conventional SIW in the same condition, since the two open edges are not perfect magnetic walls and some amount of radiation may happen. Meanwhile, the influence of the C-type slot may cause the radiation. In our design, simulated $Q_u$ is about 203. Under the same conditions, the $Q_u$ of the corresponding SIW resonator and QMSIW resonator are around 500 and 320, respectively.

Fig. 3. Coupling scheme of the proposed two-cavity filter

Fig. 4. Configuration of the middle conductor layer in the proposed filter
3 Filter design

Based on above analysis, a two-order bandpass filter implemented with modified QMSIW cavity is designed. The schematic coupling topology of the proposed bandpass filter is shown in the Fig. 3. In the coupling structure, the input (S) and output (L) are coupled to both resonators and there is one direct coupling between adjacent resonators, denoted by $K_{12}$. This coupling between the adjacent modified QMSIW resonators 1 and 2 is realized through the coupling window.

The proposed filter has the central frequency of 4.05 GHz and fractional bandwidth of 4.5%, a finite-frequency transmission zero (TZ) on high side of the passband is located at 5.40 GHz, its passband return loss is 20 dB, the coupling matrix is obtained as follows [12]:

$$
\begin{bmatrix}
0 & 1 & 0.042 & 0 \\
1 & 0 & 1.1 & 0.042 \\
0.042 & 1.1 & 0 & 1 \\
0 & 0.042 & 1 & 0
\end{bmatrix}
$$

$Q_{e1} = Q_{e2} = 1$, where $Q_{e1}$ and $Q_{e2}$ represent the input and output external quality factors.

![Fig. 5.](image)

**Fig. 5.** (a) Simulated response with different values of $L_3$, (b) Simulated response with different values of $L_5$.

The layout of the proposed filter is shown in Fig. 4. It is built on the Tacnoic TLY substrate with dielectric permittivity $\varepsilon_r = 2.2$ and thickness $h = 0.508 \, \text{mm}$. The magnetic coupling is achieved through the coupling window between resonator 1 and resonator 2. The coupling characteristic and coupling strength can be flexibly controlled and modified by adjusting the length ($L_4$) of the window, so $L_4$ mainly controls the numerical value of $K_{12}$. The transmission zero is achieved because of the cross coupling $K_{S2}$ and $K_{L1}$. As shown in Fig. 5(a), $L_3$ mainly controls location of the transmission zero because it affects the numerical values of $K_{S2}$ and $K_{L1}$, which will shift toward the bandpass when the value of $L_3$ decreases. In Fig. 5(b), it can be noticed that $L_5$ mainly controls the center frequency of the filter, but the transmission zero is almost unchanged.
The dimensions of the two-cavity filter are given below: \( W = 6 \text{ mm}, \ L_1 = 4.8 \text{ mm}, \ L_2 = 4 \text{ mm}, \ L_3 = 2.3 \text{ mm}, \ L_4 = 2.5 \text{ mm}, \ L_5 = 1.7 \text{ mm}, \ t = 0.25 \text{ mm}, \ g = 0.3 \text{ mm}, \ W_C = 1.4 \text{ mm}, \ S = 1.2 \text{ mm}, \ D = 0.8 \text{ mm}. \) The center frequency of the filter is determined by the resonant frequency of the modified QMSIW resonator, while the bandwidth is mainly affected by the coupling strength \((K_{12})\). A photograph of the filter is given in Fig. 6. The measured frequency responses of the filter are shown in Fig. 7, agreeing well with the simulated ones. The measured central frequency is 4.05 GHz, and 3 dB bandwidth is about 430 MHz. The in-band insertion and return loss is better than 1.3 dB and 15 dB, respectively. The transmission zero is located at 5.10 GHz, resulting in an asymmetrical frequency selectivity. The measured transmission zero shifts toward the lower frequency, because \(K_{S2}\) and \(K_{L1}\) are easily influenced by the SMA connectors. The insertion loss is higher because the upper and lower two layers of substrate is fixed using screw, rather than sintering. There is a very small gap between the upper and lower layer.

![Fig. 6. Photograph of the proposed two-cavity modified QMSIW filter prototype. (a) Top, middle and bottom metal layer of the filter; (b) Assembled filter prototype](image)

![Fig. 7. Simulated and measured results of the proposed two-cavity filter](image)
4 Conclusion

A novel modified QMSIW resonator is proposed, the modified QMSIW cavity has good performance, while the size reduction is even up to 97.3% area compared with the conventional SIW cavity. Therefore, it is suitable in the design of miniaturization circuit. The design of the proposed filters are based on full-wave electromagnetic simulation. The simulated performance of these filters have been validated by the experiment.

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