Compact filter based on a hybrid structure of substrate integrated waveguide and coplanar waveguide

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Abstract: This letter presents a compact bandpass filter using a hybrid structure of quarter-mode substrate integrated waveguide (QMSIW) and coplanar waveguide (CPW). The hybrid structure is realized by inserting a CPW resonator into the two side-coupled QMSIW resonators. The CPW structure not only works as a resonator but also introduces extra electric coupling between the two magnetically coupled QMSIW that generates additional transmission zero. Also, the CPW does not occupy additional circuit size which further reduces the whole circuit size of the filter. To validate the proposed concept, a prototype filter is fabricated and measured. Good agreement is achieved between simulation and measurement.

Keywords: compact bandpass filter, coplanar waveguide, hybrid structure, quarter-mode substrate integrated waveguide

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

[1] D. Deslandes and K. Wu: “Single-substrate integration technique of planar circuits and waveguide filters,” IEEE Trans. Microw. Theory Techn. 51 (2003) 593 (DOI: 10.1109/TMTT.2002.807820).

[2] J. N. Hui, et al.: “Balun bandpass filter based on multilayer substrate integrated waveguide power divider,” Electron. Lett. 48 (2012) 571 (DOI: 10.1049/el.2012.0479).

[3] L.-S. Wu, et al.: “A novel multilayer partial H-plane filter implemented with folded substrate integrated waveguide (FSIW),” IEEE Microw. Wireless Compon. Lett. 19 (2009) 494 (DOI: 10.1109/LMWC.2009.2024825).

[4] B. Liu, et al.: “Half mode substrate integrated waveguide (HMSIW) 3-dB coupler,” IEEE Microw. Wireless Compon. Lett. 17 (2007) 22 (DOI: 10.1109/
1 Introduction

With fast development of wireless and mobile communication, bandpass filters (BPFs) with high performance and low cost are highly demanded. Substrate integrated waveguide (SIW) technology provides a promising candidate to fulfill this as it earns advantages of low loss, high quality factor, low fabrication cost and easy integration with other planar circuits [1]. However, due to cutoff frequency property, SIW occupies a relatively larger circuit size when compared with its counterparts of micro-strip line and coplanar waveguide (CPW).

To realize miniaturized circuit size of SIW filter, lots of methods have been proposed by researchers in literature. In [2, 3], multilayer technique is applied to design compact filter by vertically arranging the SIW or folded SIW (FSIW) resonators on different layers of the substrate through aperture or slot coupling. In [4, 5, 6], half-mode substrate integrated waveguide (HMSIW), quarter-mode substrate integrated waveguide (QMSIW) and even eighth-mode SIW (ESIW) are utilized to do miniaturization based on symmetrical field distribution of the SIW cavity. In [7, 8], compact SIW filters are realized by loading complementary split ring resonator (CSRR) or defected grounded structure (DGS). In [9, 10], compact filters are designed by combining different planar structures with QMSIW.

In this letter, a third-order triplet BPF using hybrid QMSIW and CPW structures is presented. The hybrid structure is implemented by embedding a CPW resonator across the coupling region of two QMSIW resonators. The embedded CPW structure works in resonating mode and it produces additional in-band pole of the filter. Simultaneously, it also generates additional electric...
coupling between the two QMSIW resonators, which introduces extra transmission zero (TZ). Consequently, the proposed filter gets a compact size and high stop band rejection.

2 Hybrid structure of QMSIW and CPW

Fig. 1(a) illustrates the 3D view of the proposed hybrid structure of QMSIW and CPW. It is composed of a CPW resonator and two magnetically coupled QMSIW resonators. The CPW resonator is realized by etching two slots across the neighboring region of the QMSIW without occupying extra layout. The QMSIW resonators are formed by top and bottom metal planes that fenced by two rows of metallized vias. Its dominant resonant frequency can be calculated as [5]:

\[ f_{\text{QMSIW}}^{101} = \frac{c}{2\pi\sqrt{\mu_r\epsilon_r}} \sqrt{\left(\frac{\pi}{2W_{\text{QMSIW}}^{\text{eff}}}\right)^2 + \left(\frac{\pi}{2L_{\text{QMSIW}}^{\text{eff}}}\right)^2} \]  

(1)

Where \( c \) denotes the speed of light in free space, \( \mu_r \) and \( \epsilon_r \) denote the relative permeability and relative permittivity of the substrate. \( W_{\text{QMSIW}}^{\text{eff}} \) and \( L_{\text{QMSIW}}^{\text{eff}} \) are the effective width and length of QMSIW resonator, they can be estimated as [5]:

\[ W_{\text{QMSIW}}^{\text{eff}} = \frac{1}{2} W_{\text{SW}}^{\text{eff}} + \Delta W, \quad L_{\text{QMSIW}}^{\text{eff}} = \frac{1}{2} L_{\text{SW}}^{\text{eff}} + \Delta L \]  

(2)

\[ W_{\text{SW}}^{\text{eff}} = 2W - 1.08 \frac{D^2}{S} + 0.1 \frac{D^2}{2W}, \]  

(3)

\[ L_{\text{SW}}^{\text{eff}} = 2L - 1.08 \frac{D^2}{S} + 0.1 \frac{D^2}{2L} \]

Where \( W_{\text{SW}}^{\text{eff}} \) and \( L_{\text{SW}}^{\text{eff}} \) are the effective width and length of the corresponding SIW resonator, \( D \) is the diameter of the vias, \( S \) is the center-to-center distance of the two adjacent vias. And \( \Delta W/\Delta L \) are the additional width and length, which correspond to non-ideal magnetic walls of the QMSIW resonators caused by fringe filed along the open sides. And \( W_{\text{QMSIW}}^{\text{eff}} \) and \( L_{\text{QMSIW}}^{\text{eff}} \) are the effective width and length of the
corresponding SIW resonator. They can be calculated based on formulas (4) and (5), where \( h \) is the thickness of the substrate [5].

\[
\Delta W = h \left( 0.05 + \frac{0.3}{\varepsilon_r} \right) \ln \left[ \frac{0.79 W_{QMSIW}^{\text{eff}}}{4h^3} + \frac{52 W_{QMSIW}^{\text{eff}}}{h^2} - 261 + \frac{38}{h} + 2.77 \right] \tag{4}
\]

\[
\Delta L = h \left( 0.05 + \frac{0.3}{\varepsilon_r} \right) \ln \left[ \frac{0.79 L_{QMSIW}^{\text{eff}}}{4h^3} + 52 L_{QMSIW}^{\text{eff}} + \frac{38}{h} + 2.77 \right] \tag{5}
\]

In order to investigate the resonant characteristics of the proposed hybrid structure, eigen-mode simulations with perfect electric conductor boundary condition have been conducted using full-wave electromagnetic simulator HFSS. Fig. 1(b)–(d) depict the calculated electric field distributions of the first three resonant modes in the substrate of the hybrid structure. The first and second modes are even and odd TE101 modes of the two coupled QMSIW resonators with maximum electric fields at their open sides. The third mode is quasi-TEM mode of CPW with electric field focuses at its central part. The calculated eigen-mode resonant frequencies are 7.9, 8.9 and 9.2 GHz and the corresponding quality factors are 224, 268 and 202, respectively. The substrate is Rogers 5880 (\( \varepsilon_r = 2.2, \tan\delta = 0.001 \)) with thickness of 0.254 mm and dimensions of: \( W = 7, L = 7, l_c0 = 5.9, g_c0 = 0.8, g0 = 0.2, w01 = 2.4, \) and \( w02 = 3 \) (unit: mm). Here, the length and width of QMSIW is calculated from formulas (1)–(5) with frequency of 8.2 GHz. And the length of CPW is chosen as half wavelength at 8.2 GHz, while its width is fixed as 0.8 mm for simplicity and its slot width is minimized as 0.2 mm according to fabrication limitation. It can be seen from Fig. 1(b) that the coupling between QMSIW and CPW is magnetic as the coupling occurs at the region with minimum electric field. From Fig. 1(c) and Fig. 1(d), it can be seen that the coupling between the two QMSIW resonators is magnetically dominant. Then the TZ will be expected to locate at the upper stop band.

3 Filter design

In this section, a third order bandpass filter with triplet configuration is designed based on the proposed hybrid structure of QMSIW and CPW. Fig. 2(a) shows the top view of the proposed filter and Fig. 2(b) shows the coupling diagram. The couplings of \( M_{12} \) and \( M_{23} \) are magnetic (solid lines), while the coupling of \( M_{13} \) is mixed coupling (dashed line). The filter is designed to work at center frequency of 8.2 GHz with 20 dB in-band return loss bandwidth of 1.2 GHz. Two imaginary TZs are placed at normalized angular frequency (\( \omega \)) of \( j1.4 \) and \( j3.7 \). With these specific parameters and the triplet topology, the normalized coupling matrix can be synthesized based on the technique presented in [11]:

\[
M = \begin{bmatrix}
S & 1 & 2 & 3 & L \\
S & 0 & 1.2735 & 0 & 0 & 0 \\
1 & 1.2735 & 0.1137 & 0.8143 & 1.1069 - 0.2516\omega & 0 \\
2 & 0 & 0.8143 & -0.7763 & 0.8143 & 0 \\
3 & 0 & 1.1069 - 0.2516\omega & 0.8143 & 0.1137 & 1.2735 \\
L & 0 & 0 & 0 & 1.2735 & 0
\end{bmatrix} \tag{6}
\]
To design the filter, it is first needed to determine its physical dimensions of the resonators according to the pre-defined center frequency. For the two QMSIW resonators, their lengths and widths are initially designed based on formulations (1)–(5) at frequency of 8.2 GHz. For the CPW resonator, its length is initially chosen as half-wavelength at 8.2 GHz, while its width controls the coupling coefficient of $M_{12}$ and $M_{23}$ which controls the bandwidth of the filter. It can be properly tuned to satisfy required coupling strength between QMSIW resonator and CPW resonator. And in order to minimize the slots effect on the QMSIW resonators, the widths of the CPWs two slots are fixed at 0.2 mm due to fabrication limitation.

Then the external quality factor and internal coupling coefficients are determined according to the procedure described in [11]. Finally, the dimensions of the whole structure are optimized by electromagnetic (EM) simulation tool. The optimized values are: $L_1 = 7$, $L_2 = 8.2$, $W_1 = 2.4$, $W_2 = 3$, $L_c = 5.9$, $g_c = 1$, $g_0 = 0.2$, $w_f = 3.2$, $w_{50} = 0.76$, (unit: mm).

### 4 Fabrication and measurement

To validate the proposed design, the proposed filter is fabricated on a substrate of Rogers 5880 with thickness of 0.254 mm. Its photograph is shown in Fig. 3. The circuit size excluding the feed lines is 8.2 mm × 14 mm and the effective circuit size normalized by guided wavelength ($\lambda_{g}$) at center frequency is $0.13 \lambda_{g}$. Then it is measured on a universal test fixture with two 2.92 mm SMA connectors by the

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**Fig. 2.** (a) Top view of the proposed filter, (b) coupling diagram (Numbers 1, 2 and 3 denote resonators, S and L present source and load).

**Fig. 3.** Photograph of the fabricated filter.
exposed circumstance. Before the measurement, the vector network analyzer (Keysight N5245A) was calibrated using standard short-open-load-thru (SOLT) method.

The simulated and measured results are illustrated in Fig. 4 which shows a good agreement. The measured center frequency \(f_0\) is 8.2 GHz and the 3-dB bandwidth is 1.7 GHz. The fractional bandwidth (FBW) is 21%. The measured insertion loss (IL) at center frequency is 1.3 dB. And the measured return loss (RL) is better than 16.5 dB within the pass-band. Meanwhile, two transmission zeros (TZs) can be observed at 9.08 and 10.68 GHz and the upper roll-off skirt is calculated as 150 dB/GHz. The second TZ gets a frequency shift of 0.2 GHz to lower frequency band which can be attributed to the fabrication tolerance.

![Simulated and measured results of the proposed filter.](image)

Table I compares the performance and circuit size of the proposed filter with some previously published works in reference with similar circuit topologies [5, 7, 8, and 10]. It can be seen that the proposed filter gets a relatively more compact circuit size. What’s more, the proposed filter owns more TZs which indicates that the proposed filter gets a better stop band rejection.

| Ref.  | Order | \(f_0\) (GHz) | FBW  | IL (dB) | RL (dB) | Num. of TZ | Topology            | Size (\(\mu^2\)) |
|-------|-------|--------------|------|---------|---------|------------|---------------------|-----------------|
| [5]   | 3     | 5.2          | 38%  | 0.7     | 10      | 1          | Triple-mode QMSIW   | 0.25            |
| [7]   | 4     | 60.5         | 12%  | 2.5     | 15      | 0          | QMSIW+CSRR          | 0.17            |
| [8]   | 4     | 8.79         | 9.5% | 2.2     | 12      | 0          | QMSIW+DGS           | 0.19            |
| [10]  | 3     | 4            | 16%  | 2.1     | 17      | 0          | QMSIW+CPW           | 0.34            |
| This work | 3     | 8.2          | 21%  | 1.3     | 16.5    | 2          | QMSIW+CPW           | 0.13            |
5 Conclusion

A compact bandpass filter based on hybrid structure of QMSIW and CPW is presented in this letter. By incorporating the CPW into the QMSIW, the proposed filter not only gets a compact circuit size but also obtains a mixed EM coupling between the two QMSIW resonators. The mixed coupling introduces extra TZ that leads to a better upper stop-band rejection performance. The experiment results have validated the effectiveness of the design. The proposed filter gets a promising potential for low cost and high integration microwave applications.

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