Compact in-line triplet SIW bandpass filter using etched GCPW line resonator

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Abstract: This paper presents a novel compact in-line triplet substrate integrated waveguide (SIW) bandpass filter. The filter is composed of two SIW cavity resonators and an etched one-half wavelength grounded coplanar waveguide (GCPW) line resonator. The GCPW line resonator is etched between two SIW cavity resonators to obtain more compact size. A transmission zero on the upper stopband is created by the cross coupling, which allows the filter implementation in in-line with sharp upper cut-off skirts. Finally, a compact third-order 15 dB return loss filter with a fractional bandwidth (FBW) of 7% at 5.5 GHz is designed, fabricated and measured. The experimental results show good agreement between the simulated and measured results.

Keywords: etched GCPW line resonator, in-line, triplet, cross coupling, substrate integrated waveguide (SIW)

Classification: Microwave and millimeter wave devices, circuits, and systems

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1   Introduction

Modern wireless communication systems are in constant need of filters with high performance and compact size. By building frequency-dependent coupling, the SIW filters with inline resonators [1, 2, 3] are gained considerable attention and many novel structures have been proposed. On the one hand, compared with the cross-coupled filters [4, 5], the inline filters can avoid isolation problems between the input and output. The frequency-dependent couplings allow the filter to generate one or more transmission zeros in an inline topology [2, 6]. On the other hand, the SIW passive components have many advantages, including low loss, high Q-factor, and easy integratation with other planar circuits [7].

Among these SIW filters with inline resonators, there are two typical methods to realize frequency-dependent couplings. One method is implemented via open and short stubs [1, 8]. Although the stub can generate new transmission zeros, its circuit sizes are very large. Moreover, the structure formed by stub and two SIW cavity resonators generates new resonant frequency in the lower stopband to deteriorate the stopband response. Another method is to etch lines on the upper face of H-plane iris which can introduce the electric coupling, such as the short-ended strip line [2], inter-digital slot-line (ISL) [9], meander line [10] and GCPW line [3, 11]. The etched line has no increase in circuit size, but the filter exhibits a poor stopband response due to the spurious passband generated by the etched line resonator. And most of the frequency-dependent filters can only achieve less than 5% FBW.

In this paper, a compact in-line triplet SIW bandpass filter is presented. It consists of two SIW cavity resonators and an etched one-half wavelength GCPW line resonator. The dominant resonant frequency generated by the GCPW line is adjusted and works together with the resonant frequencies of two coupled SIW cavity resonators to form a third-pole filter. Different from the frequency-dependent filters, the GCPW line is used as a resonator rather than to introduce electric coupling. The filter structure is attractive, since the reduction of the resonator number results in a compact in-line filter configuration. A transmission zero in the upper-stopband is created due to the cross coupling. Finally, a filter with a 15 dB

return loss FBW of 7% at 5.5 GHz is designed, and good agreement can be obtained between the experimental and simulated results.

2 In-line triplet SIW filter design

Fig. 1 illustrates the top view of the proposed in-line triplet SIW filter which consists of two SIW cavity resonators (length: l_1 and width: $2w_2 + w_1$) and an one-half wavelength GCPW line (length: l_2, width: w_3 and gap: g_1) with $50\,\Omega$ CPW (length: $l_{p1} + l_{p2}$ and width: w_p) as its I/O. The sizes of the SIW cavity are determined by the corresponding TE_{10} resonant frequency

$$f_0 = \frac{c_0}{2\sqrt{\epsilon_r}} \sqrt{\frac{1}{w_{eff}^2} + \frac{1}{l_{eff}^2}}, \tag{1}$$

$$w_{eff} = w - \frac{d^2}{0.95s}, \quad l_{eff} = l - \frac{d^2}{0.95s}. \tag{2}$$

where d and s are the diameter of metallic via and the space between adjacent vias, respectively. c is the velocity of light and ϵ_r is the relative dielectric constant. w_{eff} and l_{eff} are the effective width and length of SIW cavity. The substrate used is RT/Duroid 5880 with a thickness of 0.508 mm, permittivity of 2.2 and loss tangent 0.0009. The sizes of the SIW cavity and the $50\,\Omega$ feed line centred at 5.5 GHz are determined as [12]: $w_1 = 1.588\,\text{mm}$, $w_2 = 12.5\,\text{mm}$, $w_3 = 0.15\,\text{mm}$, $l_1 = 22.8\,\text{mm}$, $d = 0.6\,\text{mm}$, $s = 1\,\text{mm}$.
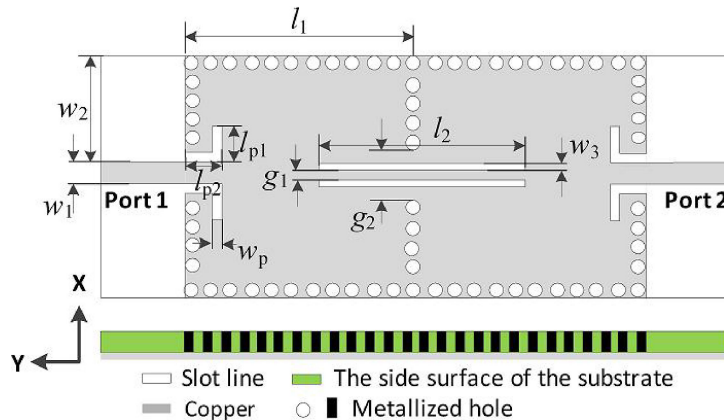

Fig. 1. Schematic of in-line triplet SIW filter using the etched GCPW line resonator.

A conventional inductive window between two SIW cavities introduces the magnetic coupling. An etched GCPW line in [3, 11], which mainly introduces electric coupling, is combined with the inductive window to build the frequency-dependent coupling. Fig. 2 gives the insertion losses of the filter with varied the length l_2 of the GCPW line in the weak coupling case. When the resonant frequency f_{m3} generated by the GCPW line is lower than the resonant frequencies f_{m1} and f_{m2} of two coupled SIW cavity resonators, a frequency-dependent SIW filter can be designed with a transmission zero near the lower passband edge. The formation reason of the transmission zero T_z can be interpreted as the frequency-

dependent coupling (also called: mixed coupling). The resonant frequency f_{m3} of the GCPW line is far from the central frequency, so that the GCPW line does not affect the performance of the filter.
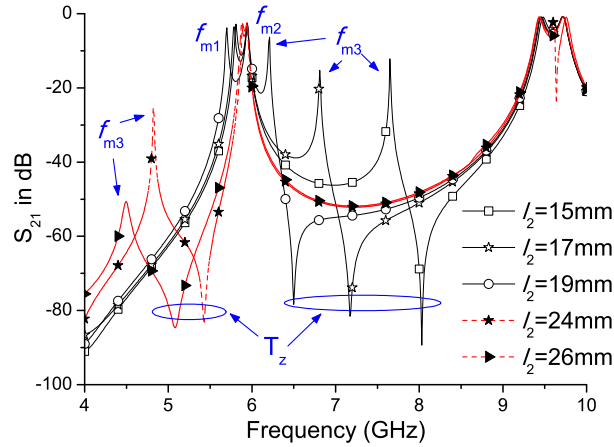

Fig. 2. The insertion losses of the filter with varied l_2 in the weak coupling case. (The other dimensions of the GCPW line and external coupling are: $g_1 = 0.3\,\text{mm}$, $w_3 = 0.15\,\text{mm}$, $l_{p1} = 1\,\text{mm}$, $l_{p2} = 1\,\text{mm}$, $w_p = 0.3\,\text{mm}$)
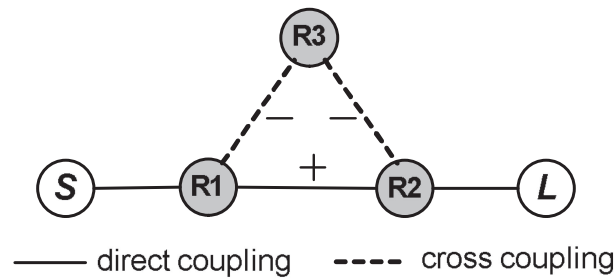

Fig. 3. Coupling scheme of the in-line triplet SIW filter.

From another point of view, the GCPW line can be considered as non-resonant node (NRN) [13, 14]. In this design, the GCPW line is used as a resonator rather than to introduce electric coupling. The resonant frequency f_{m3} can be adjusted near the f_{m1} and f_{m2} and works together with them to form a compact third-pole filter which increases the passband width. Fig. 3 illustrates the coupling scheme of the new SIW filter. R3 represents the GCPW line resonator, and R1 and R2 represent two SIW cavity resonators. The main coupling between two SIW cavity resonators is positive (magnetic coupling), whereas the cross coupling between the GCPW line and SIW cavity resonator is negative (electric coupling). The formation reason of the transmission zero T_z can be interpreted as the cross coupling. The transmission zero are always on the right side of f_{m3}.

For the third-order filter with coupling scheme in Fig. 3, the normalized position of the imaginary transmission zero is equal to 2.6 and a passband return loss of 15 dB. With the filter specification and topology defined, the normalized

coupling matrix can be obtained by Eq. (3) and the ideal filter response for the topology is shown in Fig. 4.

$$M = \begin{bmatrix} 0 & 0.9469 & 0 & 0 & 0 \\ 0.9469 & 0.0707 & 0.8371 & -0.3123 & 0 \\ 0 & 0.8371 & -0.3399 & -0.8371 & 0 \\ 0 & -0.3123 & -0.8371 & 0.0707 & -0.9469 \\ 0 & 0 & 0 & -0.9469 & 0 \end{bmatrix} \quad (3)$$

The coupling coefficient method is applied to determine the circuit dimensions of the filter to meet the specifications. For the third-order filter with 7% FBW at 5.5 GHz: $Q_{e1} = Q_{e2} = 16$. The external coupling with CPW feeding in Fig. 1 is controlled by the length l_{p1} and l_{p2} of coupling slot with a fixed slot width and post-wall iris width. Fig. 5 shows the calculated Q_e dependent on the length l_{p1} and l_{p2} by HFSS. Hence, the sizes of the CPW feeding are determined: $l_{p1} = 5$ mm, $l_{p2} = 1$ mm, $w_p = 0.3$ mm.
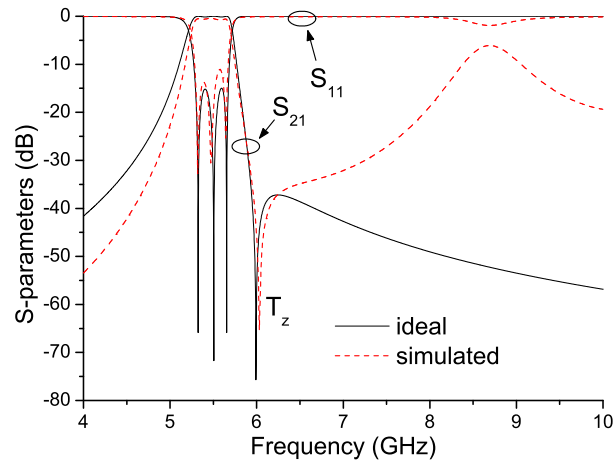

Fig. 4. Ideal filter response for the topology in Fig. 3 and corresponding simulated results.

The GCPW line passes through the H-plane iris between two SIW resonators as shown in Fig. 1. The length l_2 mainly determines the resonant frequency f_{m3} of the GCPW line, and simultaneously it has a great influence on f_{m1} and T_z. Hence, it is difficult to accurately extract the coupling coefficient between the GCPW line resonator and SIW resonator. Similarly, the width of the H-plane iris also has an influence on the cross coupling. Furthermore, the specific effects of the main coupling parameters g_1 and g_2 on the resonant frequency are separately investigated with other fixed parameter in the range from 4.5 to 8.5 GHz, where w_3 is equal to 0.15 mm.

In the weak coupling case, the resonant frequencies varied g_1 and g_2 are simulated by HFSS and illustrated in Fig. 6. From Figs. 2 and 6, it can be seen that the resonant frequency f_{m2} always remains stationary when varying g_1, g_2 and l_2. As g_1 increases, f_{m1} and f_{m3} move towards the lower frequency in Fig. 6(a).
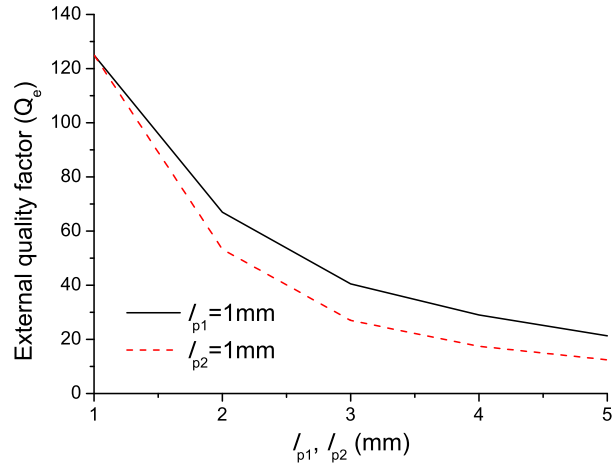
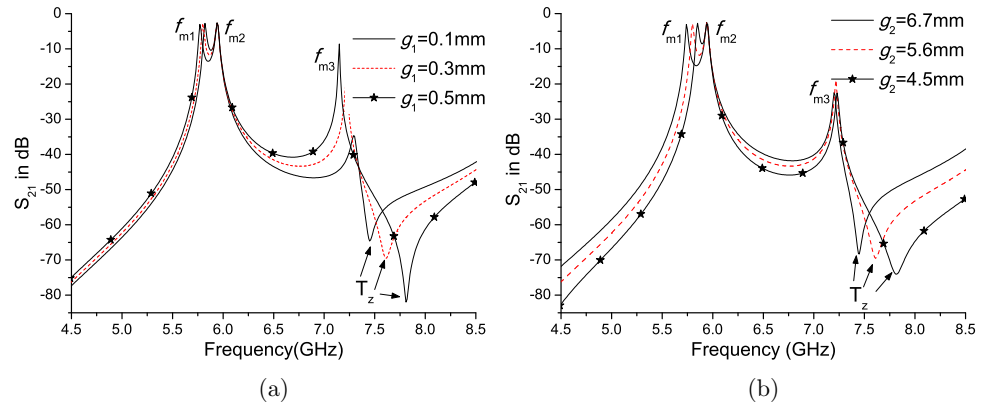**Fig. 5.** Relationship between the external quality factor Q_e and the length l_{p1} and l_{p2}.

(a) (b)

Fig. 6. Resonant frequencies with (a) fixed $l_2 = 16\,\text{mm}$, $g_2 = 5.6\,\text{mm}$, and varied g_1, and (b) fixed $g_1 = 0.3\,\text{mm}$, $l_2 = 16\,\text{mm}$, and varied g_2.

Fig. 6(b) indicates that g_2 mainly affects f_{m1}. The transmission zero T_z moves close to f_{m3} as g_1 decreasing and g_2 increasing. Thus, f_{m1}, f_{m3} and T_z can be adjusted to satisfy the design specification by simply varying the parameters g_1, g_2 and l_2. Finally, the parameters g_1, g_2 and l_2 are optimized as: $g_1 = 0.3\,\text{mm}$, $g_2 = 5.6\,\text{mm}$, $l_2 = 20.9\,\text{mm}$. The simulated S-parameters are compared with the ideal results and shown in Fig. 4. The poor agreement in the upper stopband between the ideal and simulated results is due to the spurious passband generated by the SIW cavity resonator.

3 Experimental verification

To verify the characteristics of the in-line triplet SIW filter outlined in the previous section, a third-order 15 dB return loss filter with 7% FBW at 5.5 GHz is fabricated on the Duroid 5880 substrate and its photograph is shown in Fig. 7. The performance is measured by Agilent network analyzer N5230C. The measured frequency responses are shown in Fig. 8, and agrees well with the simulated results. The

losses and slight shift in the center frequencies are attributed to manufacturing tolerances. The measured 3 dB passband is in the range from 5.28 to 5.6 GHz ($FBW_{5.5GHz} \approx 5.82\%$) and its measured input return loss ($|S_{11}|$ in dB) is less than -10.5 dB. The measured transmission zeros T_z is located at 5.99 GHz resulting in sharp upper skirt, with an attenuation level of more than 45.6 dB. The upper-stopband in experiment is extended up to 7.9 GHz with an insertion loss larger than 20 dB.
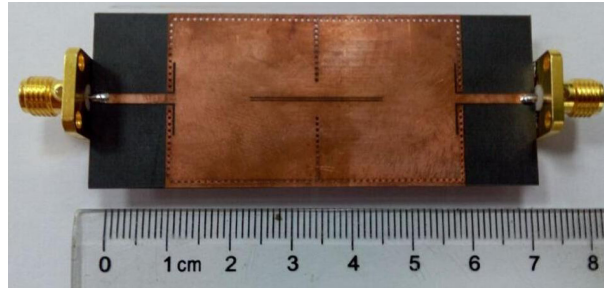

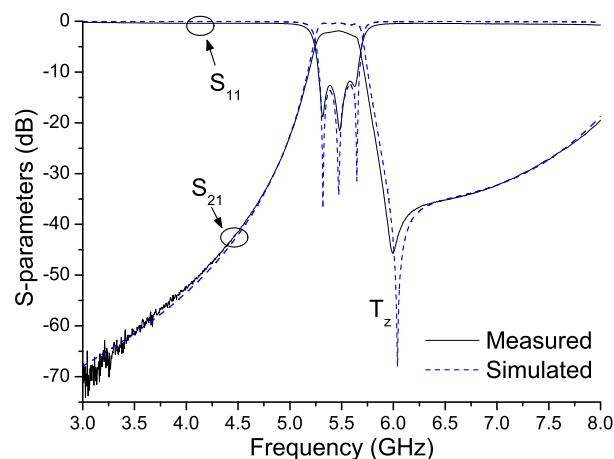**Fig. 7.** Photograph of the fabricated in-line triplet SIW filter.

Fig. 8. Simulated and measured S-parameters of in-line triplet SIW filter.

4 Conclusion

In this paper, a novel compact in-line triplet SIW bandpass filter is proposed by etching GCPW line resonator between two SIW cavity resonators. The resonant frequency generated by the GCPW line is adjusted and works together with the resonant frequencies of two coupled SIW cavity resonators to form a third-pole filter with the same size as traditional second-order SIW filter. A transmission zero in the upper-stopband is created by the cross coupling. Finally, a 15 dB return loss filter prototype with 7% FBW at 5.5 GHz is designed and fabricated, and the measured results demonstrate the validity of the proposed configuration.

Acknowledgments