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

Ji Ding\(^{(a)}\), Tao Zhang\(^{(2)}\), and Jianfeng Li\(^{1}\)

1 College of Computer and Information, Hohai University, Nanjing, 211100, China
2 College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, 211106, China

\(^{(a)}\) dingji@hhu.edu.cn

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

References

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 integration 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

\[
f_0 = \frac{c_0}{2\sqrt{\varepsilon_r}} \sqrt{\frac{1}{w_2} + \frac{1}{l_2}},
\]

\[
w_{\text{eff}} = w - \frac{d^2}{0.95s}, \quad l_{\text{eff}} = l - \frac{d^2}{0.95s},
\]

where \( d \) and \( s \) are the diameter of metallic via and the space between adjacent vias, respectively. \( c \) is the velocity of light and \( \varepsilon_r \) is the relative dielectric constant. \( w_{\text{eff}} \) and \( l_{\text{eff}} \) 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]: \( w_1 = 1.588 \text{ mm}, w_2 = 12.5 \text{ mm}, w_3 = 0.15 \text{ mm}, l_1 = 22.8 \text{ mm}, d = 0.6 \text{ mm}, s = 1 \text{ mm} \).

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.

![Graph](image)

**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: $g_1 = 0.3$ mm, $w_3 = 0.15$ mm, $l_{p1} = 1$ mm, $l_{p2} = 1$ mm, $w_p = 0.3$ mm)

![Diagram](image)

**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.

\[
M = \begin{bmatrix}
0 & 0.9469 & 0 & 0 & 0 \\
0.9469 & 0.0707 & 0.8371 & -0.3123 & 0 \\
0 & 0.8371 & -0.3399 & -0.8371 & 0 \\
0 & -0.3123 & -0.8371 & 0.0707 & -0.9469 \\
0 & 0 & 0 & -0.9469 & 0
\end{bmatrix}
\]

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.

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. 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: $g_1 = 0.3$ mm, $g_2 = 5.6$ mm, $l_2 = 20.9$ 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.

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

This paper is supported by “Postdoctoral Science Foundation of China” (Grant No. 2015M571654); “National Natural Science Foundation of China” (Grant No. 61272543).