A K-BAND SIW FILTER WITH BYPASS COUPLING SUBSTRATE INTEGRATED CIRCULAR CAVITY (SICC) TO IMPROVED STOPBAND PERFORMANCE FOR SATELLITE COMMUNICATION

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Abstract—A novel method of using bypass coupling SICC resonator to generate transmission zeros in filter stopband to improve stopband attenuation is presented. A SIW quasi-elliptic function filter for Satellite Communication application with bypass coupling SICC resonator is designed and fabricated to validate the method. The results show that the method is effective on improving the filter stopband performance.

1. INTRODUCTION

Microwave and millimeter-wave communication systems, especially airborne platforms, communication satellites, earth stations, and wireless base-stations, more and more requires filter with stringent selective, low insertion and potential integration into the circuit. The waveguide filters are widely used because of their high Q value, high power capability and outstanding selective. However, they are bulky, heavy and not suited for integration. Substrate integrated waveguide (SIW) filter provides a low-profile, low-cost, possible integration and low-weight scheme while maintaining high performance, which is satisfied with the needs perfectly, but the discontinuities in the post wall of the SIW cavity resonator are needed to generate the appropriate coupling for a small number of resonators in the filter. These discontinuities lead to poor stopband attenuation with an increasing amount of power carried across the coupling sections. Additionally substrate dissipation causes a loss to the SIW resonator Q value,

more badly with the frequency increasing, the Q descending make the filter selective to deteriorate. Many techniques were developed to improve the stopband performance, the techniques often utilize the conventional step impedance resonator, defected ground structure and the E-plane discontinuities [1–3], which are difficult to realize for SIW filters implemented on a single-layer substrate. Multiple transmission zeros generated by cross-coupling or nonphysical cross-coupling of higher order modes be used to improve the stopband attenuation are published in [4–6]. Nevertheless, the transmission zeros have much more difficult to manage and cannot be far away from the desired passband due to the limitation of the physical structure, and the insertion loss will raise in passband with separate paths for energy flow. Other methods such as using zigzag meandered topology to introduce extra cross-couplings and using optimal angle between the input and output ports of SICC filter to engender transmission zeros in stopband to get a better fitting of the electrical response are presented in [10, 11] too.

In this paper, a novel method to improve filter stopband performance using bypass coupling SICC resonator is presented. The bypass coupling SICC resonator is introduced in SIW filter though an inverter to engender transmission zeros in the filter stopband. The transmission zeros in stopband are to enhance the filter stopband attenuation. The TM_{010} mode is selected as the operating mode in the SICC only when the SICC height h and the radius R meet with $h < 2.1R$ [7], and the SICC resonant frequency can be entirely controlled by radius and height. The inverter parameters in a practical filter are always assumed to be frequency independent. Bringing the bypass coupling of the SICC resonator in the SIW though inverter not effect the SIW filter passband. The transmission zeros can be set up at arbitrary place in stopband by the SICC radius, the height of SICC is fixed by the SIW filter. A k-band SIW filter for Satellite Communication is designed and fabricated to validate the method. The filter has a passband about 2.5 GHz form 17 GHz to 19.5 GHz and excellent stopband attenuation over a frequency range of 23.1–26 GHz better than 45 dB. The results show the technique is useful to improve the filter stopband performance and is simple to implement in design.

2. DESIGN OF THE SIW FILTER WITH BYPASS COUPLING SICC RESONATOR

An inverter prototype with bypass coupling resonators is shown in Fig. 1, it consists of one passband resonator as the L_1, C_1 and two bypass bandstop resonators as the L_2, C_2 and L_3, C_3 respectively.

Two bandstop resonators are coupled in the circuit though inverter to generate transmission zeros in stopband. The admittance viewed from the input/output is given by

$$B(\omega) = jb_1 \left(\frac{\omega}{\omega_{01}} - \frac{\omega_{01}}{\omega} \right) + \frac{J_1^2}{jb_2 \left(\frac{\omega}{\omega_{02}} - \frac{\omega_{02}}{\omega} \right)} + \frac{J_2^2}{jb_3 \left(\frac{\omega}{\omega_{03}} - \frac{\omega_{03}}{\omega} \right)} \quad (1)$$

where

$$b_i = \omega_{0i} C_i \quad \omega_{01} = 1\sqrt{L_i C_i} \quad i = 1, 2, 3. \quad (2)$$

Two transmission zeros at $\omega_{z1} = \omega_{02}$, $\omega_{z2} = \omega_{03}$ may be produced as described in Equation (1). The inverter parameters J in a practical filter are always assumed to be frequency independent [8]. The bypass resonators are coupled in the filter though the inverter to generate
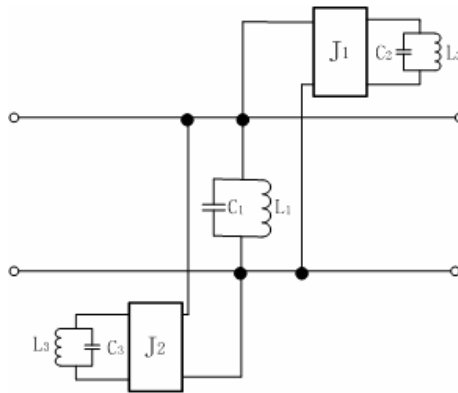

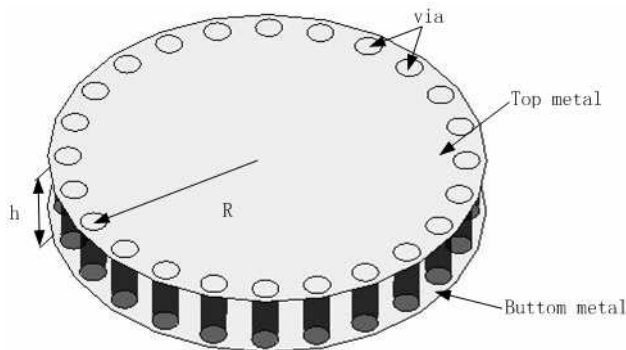**Figure 1.** Prototype of inverter bypass coupling resonator.

Figure 2. Structure of SICC resonator.

the transmission zeros. The transmission zeros position in passband or stopband will be controlled by the bypass resonator's resonant frequency and not be interaction with the filter passband performance. When the bypass resonator is constructed by SICC resonator, the SICC height and radius meet with $h < 2.1R$, the SICC resonant frequency as the transmission zero is completely controlled by the SICC radius and height, and the inverter parameters J will be frequency independent owing to the TM_{010} mode is selected as the operating mode in the SICC only [7].

An SICC is shown in Fig. 2. Dielectric filled structure of the conventional cylindrical waveguide resonators can be readily implemented in substrate by replacing the vertical metallic walls by closely spaced via posts and covering the bottom and top metal layers. The current lines of TM mode waveguide are along the waveguide. Because via-holes are along current lines, TM mode is selected as the operating mode in SICC only. The resonant frequency (unloaded) of SICC can be computed by

$$f_{mnl} = \begin{cases} \frac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\frac{P'_{nm}}{R}\right)^2 + \left(\frac{l\pi}{h}\right)^2} & TE_{mnl} \text{ mode} \\ \frac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\frac{P_{nm}}{R}\right)^2 + \left(\frac{l\pi}{h}\right)^2} & TM_{mnl} \text{ mode} \end{cases} \tag{3}$$

where μ_r and ε_r are relative permeability and permittivity of substrate respectively, c is the speed of light in free space, p'_{mn} and p_{mn} are the nth roots of the mth Bessel function of the first kind and its derivative, and R is the SICC radius, h is the length of the SICC along the z axis [9]. The TM_{010} is the dominant mode in one SICC resonator provided $h < 2.1R$ [7], the resonant frequency of the SICC is determined by the height and radius and the spurious resonant frequency is suppressed by the dominant mode.

The proposed SIW filter is designed as in Fig. 3. According to the Fig. 1 topology, Fig. 3(a) shows the structure of a fourth-order oversized TE_{101}/TE_{301} SIW filter with bypass coupling SICC resonators. Fig. 3(b) is a contrastive filter with Fig. 3(a), and it has structure the same as that in Fig. 3(a) except without bypass coupling resonators. The design detail of the oversized SIW filter has been presented in [4].

The filter is designed on a single-layer Rogers R04003 substrate (relative permittivity $\varepsilon_r = 3.55$, loss tangent $\sigma = 0.0027$) with a height of 0.508 mm and using linear arrays of metallized via-holes with a diameter of 0.5 mm. The distance between the via-holes is 1 mm. Fig. 4 shows the simulation S parameter comparison result of the SIW filters with and without the bypass coupling using the Ansoft HFSS software. It is seen that two transmission zeros have
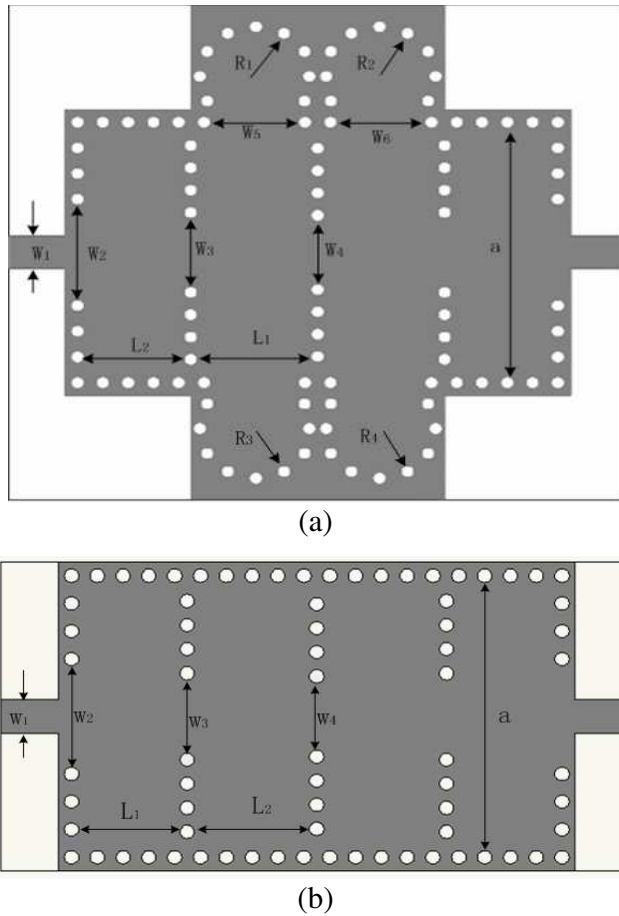
(a)

(b)

Figure 3. The fourth-order SIW filter. (a) With bypass coupling SICC resonators; (b) With not bypass coupling SICC resonator.

been produced in the stopband at $25.1\,\text{GHz}$ and $27\,\text{GHz}$ by the two dimensions bypass coupling SICC resonator with $R_1 = R_3 = 1.5\,\text{mm}$, $R_2 = R_4 = 2\,\text{mm}$. Three transmission zeros have been generated at $21.3\,\text{GHz}$, $25.1\,\text{GHz}$ and $26.9\,\text{GHz}$ by the three dimensions bypass coupling SICC resonator with $R_1 = R_3 = 1.5\,\text{mm}$, $R_2 = 2\,\text{mm}$, $R_4 = 3\,\text{mm}$. The SIW filter passband has a litter change but the stopband attenuation augmented with the additional bypass SICC. The stopband attenuation is elevated with the rising number of the same dimensions resonators as depicted in Fig. 4 at $25.1\,\text{GHz}$. One SICC with $R = 2\,\text{mm}$ is $55\,\text{dB}$, and two SICCs with similar radius is
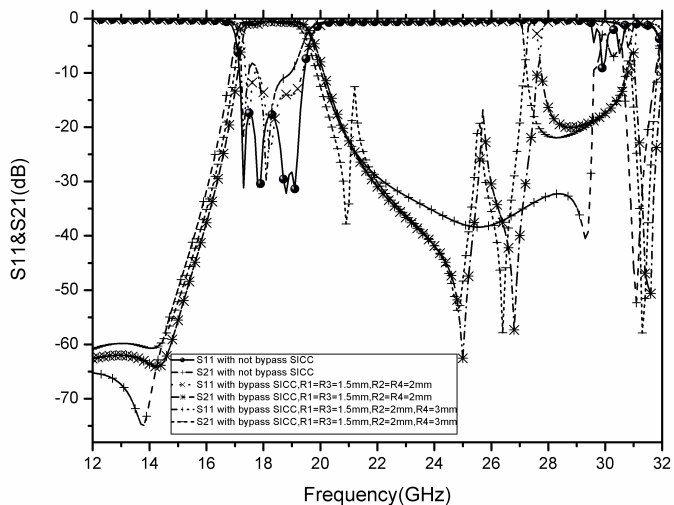
Figure 4. Simulation comparison of the SIW filter with different bypass coupling SICC resonator.
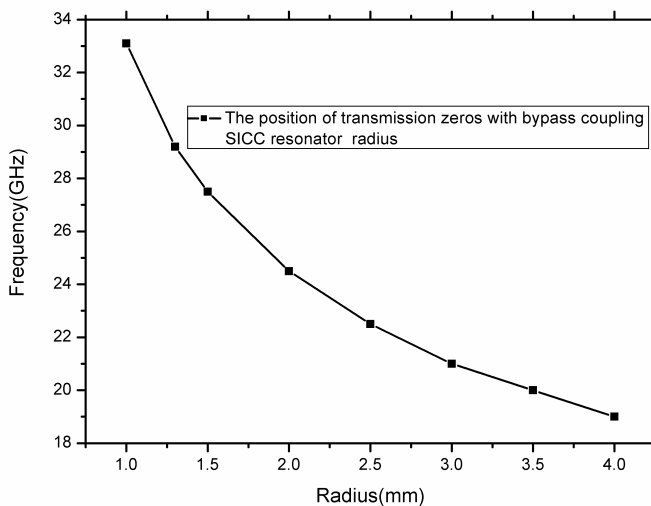

Figure 5. The position of transmission zeros vs. bypass coupling SICC resonator radius.

65 dB. Equation (1) illuminates the phenomenon. If $\omega_{02} = \omega_{03}$, the admittance will be doubled or more at the frequency ω_{03}. Fig. 4 shows that the stopband bandwidth becomes narrow because of introducing transmission zeros. The trade-off of the stopband bandwidth and stopband attenuation should comply with the rule: if the designed high selective filter stopband bandwidth requirement is less than the stopband bandwidth without additional transmission zeros, the stopband bandwidth is not main design parameter; if the requirement is close to or overstep the stopband bandwidth without the additional transmission zeros, some transmission zeros should be located near or overstep the upper stopband bandwidth to stretch bandwidth, and the performance between the zeros should be improved by optimizing technology. In accordance with Equation (2), using Ansoft HFSS, the position of transmission zeros with the bypass coupling SICC resonator radius can be as shown in Fig. 5. The transmission zeros can be chosen from Fig. 5 and positioned in the filter artificially based on the design needs. The comparison results show that the method using the bypass coupling SICC resonator to produce transmission zeros in stopband is valid to enhance the filter stopband performance and will not change passband characteristics.

3. VALIDATION AND EXPERIMENTAL RESULTS

In order to validate the method, a SIW quasi-elliptic function filter with bypass coupling SICC resonator is designed and fabricated. The filter for satellite communication terminal needs a central frequency at 18.3 GHz, 3 dB passband about 2.5 GHz, and a stopband selective better -45 dB at 12–16 GHz and 23–26 GHz. The final optimum results of the filter dimensions present in Table 1 by the ansoft HFSS, metallized via-hole diameter is 0.5 mm, and the space between via-holes is 1 mm. The filter was fabricated on a single-layer Rogers R04003 substrate with a height of 0.508 mm by standard printed circuit board (PCB) processes. Fig. 6 shows the photograph of the filter.

The simulation and measurement results are shown in Fig. 7. It

Table 1. Dimensions of the filter structure (unit: mm).

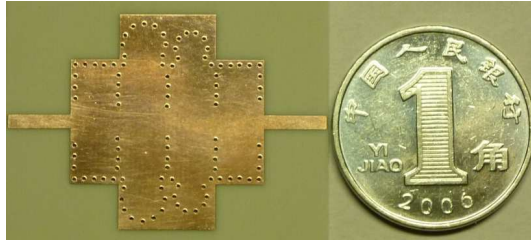| W_1	W_2	W_3	W_4	W_5	R_3	a
1.28	3.87	2.76	2.45	3.12	2.12	10.5
W_6	L_1	L_2	R_1	R_2	R_4	
2.81	4.52	4.03	2.12	1.45	1.45	

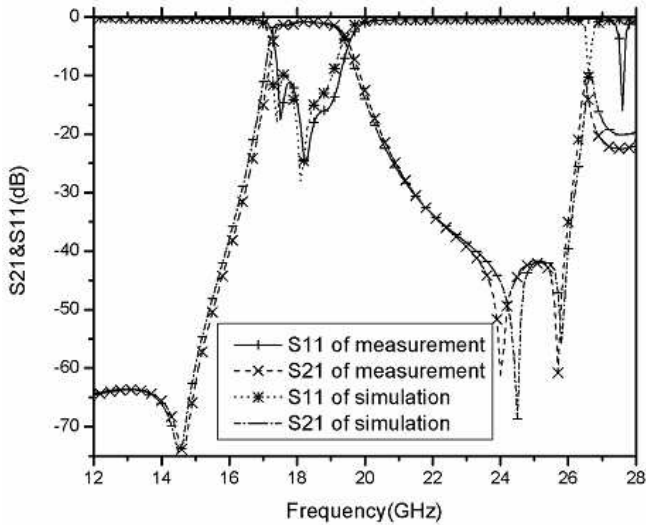**Figure 6.** Photograph of the fabricated filter.

Figure 7. Simulation and measurement results of the proposed filter.

is observed that the transmission zeros in the stopband are produced by the bypass coupling SICC resonator and are slightly lower than simulation due to the fabrication accuracy. The filter 3 dB passband is about 2.5 GHz (from 17 GHz to 19.5 GHz). The insertion loss is -1.6 dB at 17.5 GHz and -1.2 dB at 19 GHz, including the insertion loss of two SMA connectors. Removing the connector losses about -0.6 dB, the complete filter (including the input/output microstrip) has an insertion loss level of -1 dB in passband, and the measured passband (17.3–19.3 GHz) ripple is lower than 0.4 dB. This filter has a characteristic of a small return loss lower than -13 dB in the passband and an excellent selectivity performance in the stopband. The stopband attenuation over a frequency range of 23.1–26 GHz is better than 45 dB because the two transmission zeros are settled there.

So the method of engendering transmission zeros in stopband though bypass coupling SICC resonator is validated to improve the stopband performance, and it can be employed in other filter design easily.

4. CONCLUSION

A novel method using bypass coupling SICC resonator to introduce transmission zero in SIW filter stopband is proposed, and the design approach of generating the transmission zeros in stopband to improve stopband attenuation is presented. A SIW quasi-elliptic function filter for Satellite Communication application with bypass coupling SICC resonator is designed and fabricated to validate the method. The measured results are in good agreement with the design data. The filter has a 3 dB passband about 2.5 GHz from 17 GHz to 19.5 GHz and excellent stopband attenuation over a frequency range of 23.1–6 GHz better than 45 dB. The SICC resonant frequency can be entirely controlled by radius and height owing to the TM_{010} mode selected as only the operating mode where the SICC' height h and radius R meet $h < 2.1R$. Because the operating mode is unique in SICC, to place transmission zeros in the desired place is flexible by using the inverter bypass coupling. The technique is effective on improving the filter stopband performance and is simple to implement in the other filters.

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