Cross-coupled bandpass filter based on circular substrate integrated waveguide resonator

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Abstract: In this paper, circular substrate integrated waveguide (CSIW) filters are presented. Π-shape slots etched along the electric walls of the CSIW on the upper layer are proposed firstly, which enhance the magnetic coupling parameters between two CSIW cavities. Meanwhile, S-shape slots as the electric coupling structure are firstly used on CSIW filters. With both magnetic and electric coupling, the third-order and fourth-order cross-coupled bandpass filters based on circular substrate integrated waveguide resonator (CSIWR) are designed, which possess one transmission zero (TZ) and two transmission zeros, respectively. Measured results of these filters with a high selectivity agree well with simulated ones.

Keywords: circular substrate integrated waveguide (CSIW), Π-shape slots, S-shape slots, cross-coupling

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

References


1 Introduction

In the modern communication systems, it is well known that the substrate integrated waveguide (SIW) technique is an attractiveness for their low-cost, high-Q, and high-density integration of microwave and millimeter-wave components and sub-systems [1, 2]. The conventional SIW cavities are rectangle structure. However, considering the size, Q-factor and design flexibility, circular SIW resonators and their applications to the passive components are presented [3, 4, 5]. In [6], a cross-coupled CSIW filter is presented with a transmission zero (TZ) implemented under the passband, but the filter has low selectivity upper the passband, high insertion loss and the perceptual window is hard to be adjusted. Multilayer CSIW filter [7] achieves high performance, but it is costly with complicated process.

In this letter, circular substrate integrated waveguide (CSIW) resonators are proposed. In order to keep the integrity of the circular SIW resonant mode, Π-shape slots etched along the electric walls of the CSIW on the upper layer are proposed firstly. S-shape negative coupling structure [8] is firstly used to realize cross-coupled filters with the circular SIW cavity. The filters including third-order and fourth-order cross-coupling topologies, are designed with the center frequency 8.8 GHz and 8.6 GHz, respectively. The minimum in-band insertion and in-band return losses of both filters are below 1.3 dB and −20 dB, respectively. The third-order filter possesses a TZ in the lower stopband, and for the fourth-order filter, it can produce asymmetrical frequency response by generating two TZs on both sides of passband. Measured results of these filters agree well with simulated ones.

2 Circular SIW resonator and coupling structure

2.1 Circular SIW resonator

The configurations and electric field distributions of the fundamental mode of a CSIW resonator are shown in Fig. 1, which are equivalent to the traditional circular waveguide. The resonant frequency of mode for circular cavity with metallic vias can be calculated as [9]:

Where \( c \) is velocity of light in the vacuum, \( R \) and \( h \) are the equivalent radius and the height of the circular cavity, \( \mu_r \) and \( \varepsilon_r \) are relative permeability and permittivity of the substrate.

For circular cavity, \( TE_{111} \), \( TE_{011} \) and \( TM_{010} \) modes are used commonly. In this paper, the dominant mode of the circular SIW cavity is \( TM_{010} \) mode. The resonance frequency has nothing to do with the cavity height \( h \). So the resonant frequency of \( TM_{010} \) is derived from formula (1):

\[
f_{TM010} = \frac{0.383c}{R\sqrt{\mu_r \varepsilon_r}}
\]

![Fig. 1. The configurations and electric field distributions of \( TM_{010} \) mode of a circular cavity resonator](image)

### 2.2 Coupling structure

The electric field distributions of the positive coupling structure with \( \Pi \)-shape slots etched on the upper layer are shown in Fig. 2. In this paper, \( g \) and \( W \) are 0.2 mm and 2 mm chosen for all the simulated filters. In general, magnetic coupling is realized by adjusting the width of the post-wall iris. However, in order to keep the integrity of the circular cavity, the width of post-wall cannot be too large. \( \Pi \)-shape slots etched on the upper layer of the CSIW resonator are presented.

![Fig. 2. The electric field distributions of positive coupling structure with \( \Pi \)-shape slots](image)
The Π-shape slots are etched along the electrical wall, which enhances the electric field intensity between the two cavities. It is obvious that the nature and the extent of the slot fields determine the nature and the strength of the coupling. By utilizing the slots, the positive coupling is enhanced dramatically.

Fig. 3 shows the top view and the bottom view of the negative coupling between two circular SIW cavities. Here two reverse S-shape slots are etched on the top and bottom of the cavities. Transmission zero comes from cross-coupling. Effect of $b$ on transmission zero in the fourth-order filter is shown in Fig. 4. It has an impact on TZs and makes TZs controllable. Coupling intensity between two resonant cavities enhances as $b$ elongating, causing both transmission zeros move upward and making them close to the center frequency.

![Negative coupling structure](image)

**Fig. 3.** Negative coupling structure

![Effect of $b$ on transmission zero in fourth-order filter](image)

**Fig. 4.** Effect of $b$ on transmission zero in fourth-order filter

### 3 Filter design

#### 3.1 Third-order filter

The structure and the coupling topology of the proposed third-order filter are shown in Fig. 5. The RT/duroid 6006, with $\varepsilon_r = 6.15$, $\tan \delta = 0.0019$ and thickness $h = 0.635$ mm, is chosen for all simulations in this paper. With the negative cross-coupling between resonators 1 and 3, a transmission zero is implemented on the lower of the bandpass. The I/O feed lines are 50 $\Omega$ microstrip lines, and the coplanar waveguides (CPW) (L-shape slots represented by $L_1$ and $\theta$) are located in the CSIW cavity to accomplish the conversion from quasi-TEM mode to TM mode. The filter is specified to work at 8.8 GHz. The coupling matrix of the filter is calculated as follows [10]:

$$
\begin{align*}
    S_{11} & = \frac{(1 + \Gamma_1) (1 + \Gamma_3)}{(1 - \Gamma_1) (1 - \Gamma_3)} \\
    S_{21} & = \frac{\Gamma_1 (1 + \Gamma_3) - \Gamma_3 (1 + \Gamma_1)}{(1 - \Gamma_1) (1 - \Gamma_3)} \\
    S_{22} & = \frac{(1 + \Gamma_1) (1 + \Gamma_3)}{(1 - \Gamma_1) (1 - \Gamma_3)} - S_{21}^2
\end{align*}
$$
\[
M = \begin{bmatrix}
0 & 0.8921 & -0.5082 \\
0.8921 & 0.5769 & 0.8921 \\
-0.5012 & 0.8921 & 0
\end{bmatrix}
\] (3)

The final optimized dimensions are as follows: \( h = 0.635 \text{ mm}, \ d = 0.5 \text{ mm}, \ R_1 = 5 \text{ mm}, \ W_0 = 0.95 \text{ mm}, \ L_1 = 1 \text{ mm}, \ L_2 = 1.5 \text{ mm}, \ b = 1.8 \text{ mm}, \ c = 0.7 \text{ mm}, \ W = 2 \text{ mm}, \ \theta = 25^\circ, \ \theta_1 = 9^\circ, \ \theta_2 = 8^\circ, \ \theta_3 = 30^\circ. \)

![Image of the fabricated CSIW third-order filter](image)

Fig. 5. Geometric configuration and coupling topology of the third-order CSIW filter

A photograph of the fabricated CSIW third-order filter is presented in Fig. 6(a). The measured results compared with the simulated ones are shown in Fig. 6(b). The measured results are in good agreement with the simulated ones. The center frequency \( f_0 \) is located at 8.8 GHz, and the fractional bandwidth is 5.7%. The measured return loss \( S_{11} \) is below \(-20\) dB, while the measured minimum insertion loss \( S_{21} \) is less than 1.25 dB. A TZ is possessed in the lower of the passband with attenuation of \(-50\) dB, which highly improves the selectivity of the lower passband, but it has low selectivity of the upper passband.

### 3.2 Fourth-order filter

Owing to improving the selectivity of the upper passband of the filter, another structure and the coupling topology of the proposed fourth-order filter are shown in Fig. 7. With the negative cross-coupling between resonators 1 and 4, two transmission zeros are implemented on both sides of the bandpass. The filter is specified to work at 8.6 GHz. The coupling matrix of the filter is calculated as follows [10]:

\[
M = \begin{bmatrix}
0 & 0.8869 & 0 & -0.1042 \\
0.8869 & 0 & 0.7404 & 0 \\
0 & 0.7404 & 0 & 0.888 \\
-0.1042 & 0 & 0.888 & 0
\end{bmatrix}
\] (4)

The final optimized dimensions are as follows: \( h = 0.635 \text{ mm}, \ d = 0.5 \text{ mm}, \ R_1 = 5 \text{ mm}, \ W_0 = 0.95 \text{ mm}, \ L_1 = 1 \text{ mm}, \ L_2 = 1.5 \text{ mm}, \ b = 1.5 \text{ mm}, \ c = 0.7 \text{ mm}, \ W = 2 \text{ mm}, \ \theta = 31^\circ, \ \theta_1 = 10^\circ, \ \theta_2 = 30^\circ, \ \theta_3 = 16^\circ. \)
A photograph of the fabricated CSIW fourth-order filter is presented in Fig. 8(a). The measured results compared with the simulated ones are shown in Fig. 8(b). The center frequency $f_0$ is about 8.6 GHz and the fractional bandwidth is about 7%. The measured in-band return loss $S_{11}$ is below $-20$ dB, and the minimum
insertion loss $S_{21}$ is less than 1.2 dB. Two TZs are implemented at frequencies of 8.1 GHz and 9.25 GHz with attenuation of below $-40$ dB, respectively. The measured results agree well with the simulated ones.

4 Conclusion

In this paper, two types of cross-coupling bandpass filters based on circular resonator (CSIWR) are presented. Π-shape slots as magnetic coupling and S-shape slots as electric coupling are used on CSIW cavities to realize cross-coupled filters firstly. The third-order filter possesses a transmission zero (TZ) in the lower stopband and for the fourth-order filter, it can produce asymmetrical frequency response by generating two transmission zeros (TZ) on both sides of passband. The proposed filters have very good selectivity, low insertion, and compact-size geometry.

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