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Compact LTCC source-load coupled SIW filter using mixed coupling

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Abstract: A novel substrate integrated waveguide (SIW) filter with source-load coupling based on low temperature co-fired ceramic (LTCC) technology is proposed. By introducing mixed coupling into input/output SIW in middle layer, the filter not only has good selectivity owing to the controllable transmission zeros, but also has a compact size by the virtue of LTCC structure. Based on the flexible coupling manner in multilayer structure, a demonstration second-order bandpass filter with three transmission zeros has been designed and fabricated. Good agreement between measured and simulated results is observed.

Keywords: LTCC, SIW, filter, mixed coupling, transmission zeros

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

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1 Introduction

Waveguide filters are widely used in various communication systems, owing to their high quality factor and high power capability. However, they are bulky and not suitable for high-density integration, which greatly increases the cost of the entire system. Recently substrate integrated waveguide (SIW) filters which is synthesized in a planar substrate with arrays of metallic via, provides a low-profile, and low-cost solution while maintaining high performance [1]. SIW filters can be fabricated by using the PCB or LTCC processes. Especially, the application of LTCC technology makes the implement of multilayered SIW filters with compact size, light weight and high performance possible, due to its three dimensional integration characteristic, low-tolerance in manufacturing process, and low loss of high-frequency ceramic materials [2, 3].

On the other hand, filters with multiple transmission zeros are required to meet the increasingly stringent demands of modern communication systems in regards to compact size and high selectivity. It is well known that conventional topology structure can produce a maximum of only $N-2$ finite transmission zeros for an Nth-degree network. One approach on filter design can be fulfilled by marshaling the effect of source-load coupling. By adding a direct signal path between the source and the load, N finite transmission zeros can be generated [4]. Although SIW filters with source-load coupled structure have been proposed in [5, 6], their physical sizes are not compact enough because of the single-layer and planar structures.

In this paper, we present a novel SIW source-load coupled filter based on multilayer LTCC technology to meet the need of stringent frequency selectivity and sharp cutoff skirt. By introducing mixed electric and magnetic coupling into input/output (I/O) SIW, the proposed filter with only two resonators has three transmission zeros which can be controlled flexibly through modifying coupling style and adjusting the mixed coupling level. With the assistance of the multilayer LTCC structure and refined mixed coupling manner, the proposed filter has a more compacter size while maintaining high selectivity. A demonstration filter is designed, fabricated and measured to validate the proposed structure.

2 Filter topology and analysis

The coupling scheme of the proposed filter is shown in Fig. 1, where the dark disks represent the resonators in the low-pass prototype and the empty disks symbolize the source and the load. Here, this symmetric topology consists of two resonators coupled to each other. Besides, the source and the load are directly coupled in order to generate up to two transmission zeros.

The coupling matrix M of the prototype in Fig. 1 can be written as

$$[M] = \begin{bmatrix} 0 & M_{S1} & 0 & M_{SL}(\omega) \\ M_{S1} & M_{11} & M_{12} & 0 \\ 0 & M_{12} & M_{22} & M_{2L} \\ M_{SL}(\omega) & 0 & M_{2L} & 0 \end{bmatrix} \tag{1}$$

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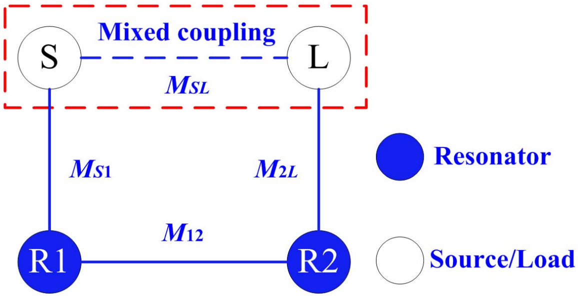

Fig. 1. Coupling scheme of proposed filter.

where M_{S1} and M_{2L} represent the coupling between source/load and each resonator, M_{12} symbolizes the coupling between resonator 1 and resonator 2, M_{11} and M_{22} of diagonal elements in the coupling matrix express the differences in the resonant frequencies of resonators, and $M_{SL}(\omega)$ denotes the mixed coupling between source and load. It should be noted that, the mixed coupling which is composed of electric and magnetic coupling is introduced to obtain an additional transmission zero. $M_{SL}(\omega)$ can be obtained by using the conventional solution method of a mixed coupling coefficient, as described in [6]

$$M_{SL}(\omega) = [\omega L_m - 1/(\omega C_m)]/\omega_0 L \tag{2}$$

where L_m and C_m denote the coupling capacitance and inductance. The coupling coefficient at center frequency ω_0 is written as

$$k(\omega_0) = L_m(1 - \omega_m^2/\omega_0^2)/L \tag{3}$$

where $\omega_m = (L_m C_m)^{-1/2}$. Moreover, it also has

$$M_{SL}(\omega) = k(\omega_0)\omega_0(\omega^2 - \omega_m^2)\omega/[\omega(\omega_0^2 - \omega_m^2)] \tag{4}$$

Here, it can be obtained that $M_{SL}(\omega) = k(\omega_0)\omega_0/\omega$ for electric coupling and $M_{SL}(\omega) = k(\omega_0)\omega/\omega_0$ for magnetic coupling, respectively.

To achieve above mentioned topology, a multilayer SIW filter is designed and embedded into a LTCC substrate. The 3D overview, geometric configurations and side view of the proposed filter are illustrated in Fig. 2 (a), (b) and (c), respectively. Compared to the conventional structure, the filter is composed of two TE_{101} resonators and I/O SIW, two resonators being below I/O SIW. The coupling manner is realized through an inductive window in the common sidewall between two adjacent cavities, as well as circular or rectangular slots in the common plane between two resonators and I/O SIW. The coupling characteristic and the coupling strength can be flexibly controlled and modified by adjusting the position and the size of circular or rectangular slots and inductive window. Meanwhile, in order to introduce mixed electric and magnetic coupling, an interdigital slot-line (ISL) is placed between input and output SIW at the center of top plane. The values of electric and magnetic coupling of mixed coupling are mainly controlled by the length (I_1) of ISL or width of W_{SL}. Fig. 3 (a) shows the simulated frequency response with different values of I_1. There is only single coupling manner

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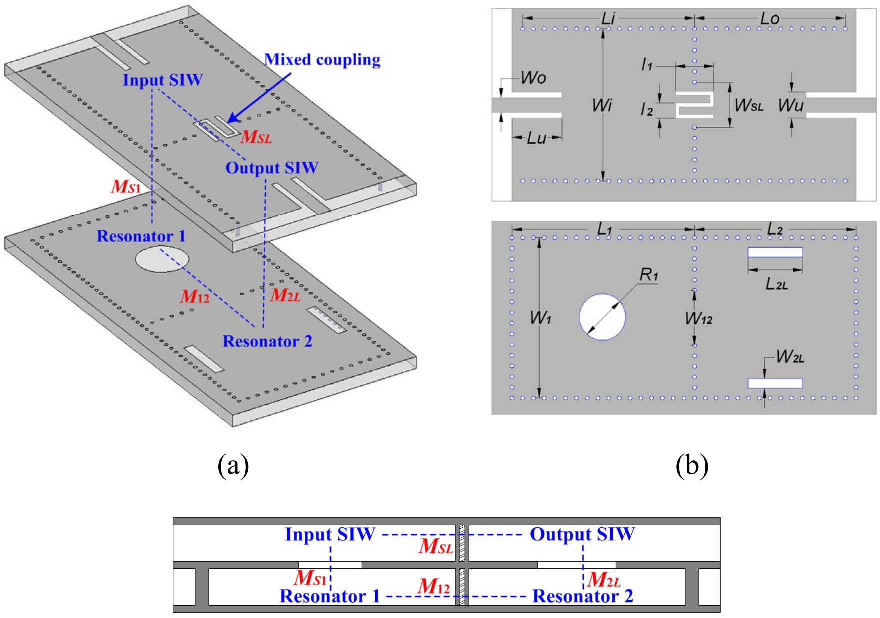

(a) (b)

(c)

Fig. 2. Structure of proposed LTCC SIW filter: (a) 3D overview, (b) geometric configuration, and (c) side view.

between the source and load without ISL, and two transmission zeros are located below and above the stopband, respectively. With introducing ISL into I/O SIW, an additional transmission zero can be obtained. As shown in Fig. 3 (a), I_1 mainly controls location of the third transmission zero (TZ3), which will shift toward the passpand when the value of I_1 increases. The transmission zero at the up stopband moves toward lower frequency owing to increasing mixed coupling level. Moreover, other parameters of coupling slots, including length of the rectangular slot (L_{2L}), width of the inductive window (W_{12}), diameter of the circular slot (R_1), etc., can also impact the positions of the transmission zeros. As an illustrative instance in Fig. 3 (b), L_{2L} mainly controls location of the first transmission zero (TZ1), which will move toward lower stopband with the increasing of L_{2L}. Furthermore, the introduction of the dedicated I/O SIW can be used to enhance maximum selectivity below the passband.

It should be noted that the width and length of feeding structure can also affect the frequency responses of the SIW filter. One feeding technique named current probe is adopted for obtaining the transition from SIW to microstrip with a planar structure. Planar I/O structure is suited for integration on microwave circuit application. Fig. 3 (c) shows the in-band return loss of the proposed filter with different width (W_u) of slots in current probe. Besides, slot length (L_u) of current probe has similar impact on the frequency responses. Thus, it should be mentioned that selecting appropriate values of width and length in current probe is availed to achieve good frequency responses of the filter.

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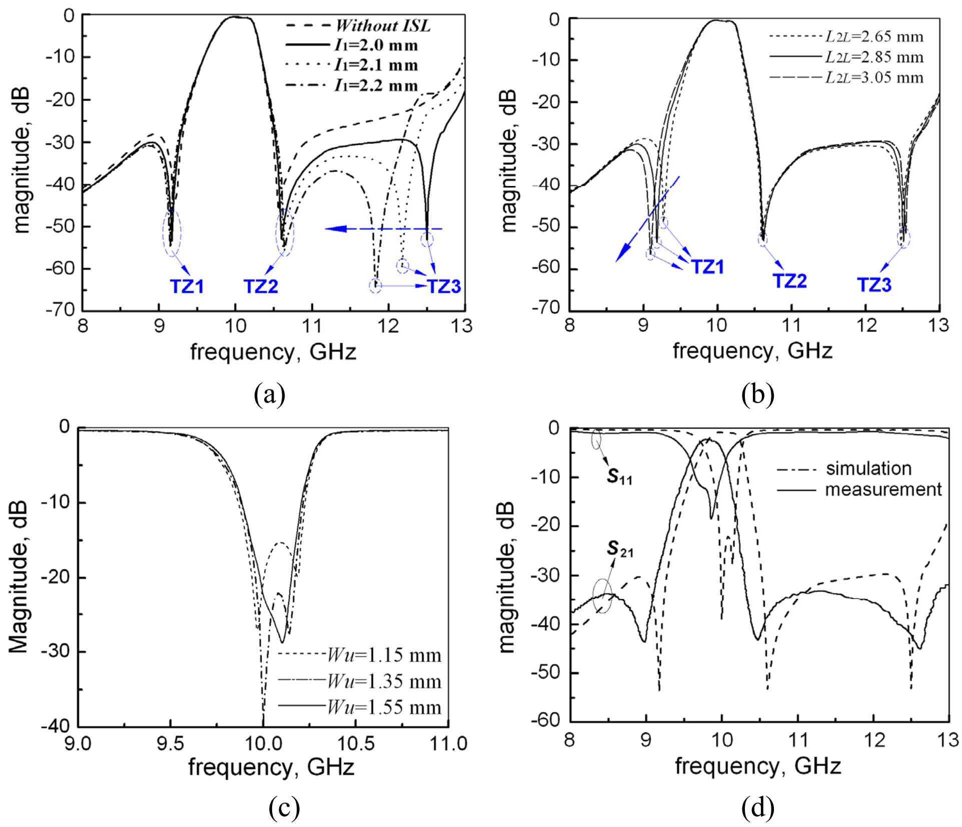

Fig. 3. (a) Simulated response with different values of I_1, (b) simulated response with different values of L_{2L}, (c) simulated response with different values of W_u, and (d) comparison of simulated and measured results.

3 Filter validation and fabrication

To demonstrate the application of above-mentioned structure, a second-order SIW filter is designed to have a central frequency of 10 GHz, a 3 dB fractional bandwidth of 4.5%, and three transmission zeros which are located at 9.2, 10.6 and 12.5 GHz, respectively.

Every SIW unit is built on a five-layer substrate. The SIW cavity size is initially determined by the corresponding resonance frequency of the fundamental TE_{101} mode from

$$f_{res} = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{\left(\frac{\pi}{L_{eff}}\right)^2 + \left(\frac{\pi}{W_{eff}}\right)^2} \tag{5}$$

where f_{res} is the resonant frequency, c is the velocity of light in the vacuum, ε_r is the relative dielectric constant, L_{eff} and W_{eff} are the effective length and width of the resonant cavity given by

$$L_{eff} = l - \frac{d^2}{0.95p} \quad W_{eff} = w - \frac{d^2}{0.95p} \tag{6}$$

where l and w are the length and width of resonant cavity, respectively; d and p are the diameter of metallic via and the space between adjacent vias, respectively.

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Furthermore, the complete filter parameters are fine tuned by slight alterations of each cavity resonator and each coupling in turn until the filter response is optimized to achieve the desired response by using commercial full wave EM simulation software HFSS. The final geometric parameters of the proposed filter are decided as: $L_1 = 9.55$ mm, $L_2 = 8.42$ mm, $L_i = 8.9$ mm, $L_o = 7.9$ mm, $L_u = 2.6$ mm, $L_{2L} = 2.85$ mm, $I_1 = 2.0$ mm, $I_2 = 0.8$ mm, $W_O = 0.75$ mm, $W_1 = 8.36$ mm, $W_i = 7.95$ mm, $W_u = 1.35$ mm, $W_{SL} = 2.35$ mm, $W_{12} = 2.86$ mm, $W_{2L} = 0.5$ mm, $R_1 = 2.55$ mm. The proposed filter is fabricated on an ten-layer substrate using LTCC material Ferro-A6 with relative dielectric constant of $\varepsilon_r = 5.9$, loss tangent of 0.0015 and a single layer thickness of 0.096 mm.

By virtue of the 3D structure and flexible coupling manner, the overall size of the fabricated filter is only $20 \times 10 \times 0.97\,\text{mm}^3$. An Agilent E8363B vector network analyzer is used for measurement. Fig. 3 (d) shows the simulated and measured results. The filter exhibits a central frequency of 9.9 GHz with a bandwidth of about 3.4%, minimum passband insertion loss of 2.29 dB, and in-band return loss greater than 13 dB. Three transmission zeros are located at 9.02, 10.48 and 12.65 GHz, respectively. The measured results are in good agreement with the simulated ones except a small frequency shift and a little discrepancy in the in-band insertion loss. This is mainly caused by manufacturing tolerance of LTCC process and difference between the actual and nominal values of the relative dielectric constant. In addition, the radiation loss of slot lines, conductor loss, dielectric loss of the LTCC substrate, and the influence of the transition between a pair of SMA connectors and microstrip will also result in the discrepancy in the simulated and measured insertion losses.

4 Conclusion

A novel second-order SIW source-load coupled filter with three transmission zeros using LTCC technology is presented. By introducing mixed coupling into source and load, the filter has high and flexible selectivity owing to the tunable transmission zeros. Moreover, a compact size is obtained by profit from multilayer LTCC structure. The measured results coincide with the simulated ones very well. It is expected that the proposed filters will find applications in high-performance and high-integration microwave circuit and system.

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