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Double-folded substrate integrated waveguide band-pass filter with transmission zeros in LTCC

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A miniaturized substrate integrated waveguide (SIW) band-pass filter with two transmission zeros is proposed in low-temperature co-fired ceramic (LTCC) technology. The miniaturization of the filter is achieved by vertically stacking three double-folded SIW resonators. To strengthen the coupling between the feeding structure and the resonators, a new meandered microstrip feeding line is introduced. In addition, to realize better out-of-band rejection performance, two $\lambda_g/4$ short-circuited lines are adopted in the filter design to achieve two transmission zeros outside the passband. To verify the design concept, an X-band LTCC band-pass filter was designed, fabricated, and measured. Both simulation and measurement results indicate that the proposed filter has good frequency response, high selectivity, and a size reduction of about 87% in comparison with conventional planar direct-coupled waveguide filter.

1. Introduction

With the development of microwave and millimeter wave communication systems, microwave filters with high performance, small size are required. Thus, substrate integrated waveguide (SIW) filters are proposed and researched. The SIW, formed by placing two rows of metallic via-holes, either in printed circuit board or in low-temperature co-fired ceramic (LTCC) substrate, retains main properties of the conventional waveguide like high Q and low loss. Moreover, it is easy to be integrated with other planar circuits. Due to all these advantages, SIWs have been applied to a great number of applications [1–5]. However, compared with microstrip filters, SIW filters are large in size, therefore miniaturization is required.

Conventional SIWs are based on rectangular cavities, circular cavities, or elliptic cavities [6–9]. In [7], a fourth-order cross-coupled circular cavity filter is proposed with all circular SIW cavities resonating in the TM_{010} mode, but it is still large in size. Recently, several filters with new type of SIW resonators [10–19], such as half-mode SIW (HMSIW), ridge SIW, and folded SIW, have been proposed to achieve good performance with compact size. Hong proposed the concept of folded-waveguide resonators [10]. It is shown that folded-waveguide resonator, which is formed by folding conventional TE_{101} waveguide along two axes without changing its mode, can achieve circuit size reduction with its footprint about a quarter of that

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of a conventional TE_{101} waveguide. In [14], double-folded SIW is utilized for size reduction and several coupling structures are discussed. Transmission zeros are accomplished by introducing cross coupling between nonadjacent resonators. Besides, by taking the advantages of LTCC technology, cavities are arranged with greater flexibility [18,19]. In this paper, our goal is to design a miniaturized band-pass filter at X-band. Based on LTCC technology, a double-folded SIW filter is proposed with two transmission zeros for high selectivity applications.

2. Design and theory

2.1. Double-folded SIW

The 3-D configuration of the miniaturized three-pole Chebyshev filter is shown in Figure 1 (a), which is fabricated using LTCC substrate with a dielectric constant of 5.9, a thickness of 96 μm per layer, and a loss tangent of 0.0015. The filter is composed of two quarter-wavelength short-circuited microstrip lines and three direct-coupled double-folded SIW (DFSIW) resonators, which are designated as resonators 1–3. The diameters of the vias are chosen to be 0.15 mm. Figure 1(b) shows the coupling and routing scheme of the filter, where each node represents a resonator and the solid lines represent the direct coupling path. $M_{1,2}$ and $M_{2,3}$ are the coupling coefficients between two adjacent resonators and no cross coupling is introduced.

The three-pole Chebyshev filter ($n = 3$) with 0.1 dB ripple level is designed based on the specifications of 10% bandwidth centered at 9 GHz. The design parameters of band-pass filters, such as the coupling coefficients and external quality factors, can be obtained from the circuit elements of a low-pass prototype filter. The element values of the low-pass prototype filter are found to be $g_0 = 1$, $g_1 = g_3 = 1.0316$, $g_2 = 1.1474$, and $g_4 = 1$. From [20], the band-pass design parameters can be calculated by

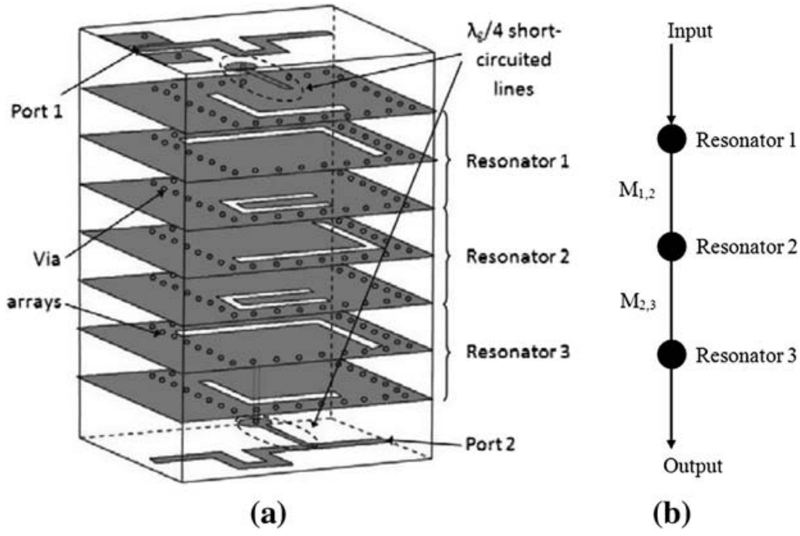

Figure 1. (a) 3-D configuration of the three-pole DFSIW filter. (b) Coupling and routing scheme of the proposed filter.

$$\begin{aligned} Q_{e1} &= \frac{g_0 g_1}{\mathrm{FBW}} \quad Q_{en} = \frac{g_n g_{n+1}}{\mathrm{FBW}} \\ M_{i,i+1} &= \frac{\mathrm{FBW}}{\sqrt{g_i g_{i+1}}} \quad \text{for} \quad i = 1 \quad \text{to} \quad n-1 \end{aligned} \tag{1}$$

The generalized coupling matrix and the input/output external quality factors for our case are found to be

$$\begin{aligned} M &= \begin{bmatrix} 0 & 0.092 & 0 \\ 0.092 & 0 & 0.092 \\ 0 & 0.092 & 0 \end{bmatrix} \\ Q_{e1} &= Q_{e3} = 10.316 \end{aligned} \tag{2}$$

In order to minimize the circuit size, double-folded SIW resonators are used instead of conventional SIWs. Each double-folded SIW resonator consists of four layers of LTCC substrate, two conductor planes laid, respectively, at bottom and top layers and a metal conductor plane with L-shaped slot in between them. Figure 2(a) shows the middle metal plate with an L-shaped slot of the DFSIW resonator. Besides, further minimization of circuit size can also be achieved by vertically stacking adjacent resonators, which are directly coupled by U-shaped slots as shown in Figure 2(b). Each slot is placed in the common plate near the sidewalls of the cavities and in the direction perpendicular to the surface current. It significantly interrupts the surface current flow and introduces strong coupling [21]. The dimensions of the U-shaped slot can be decided based on the coupling coefficients calculated according to (1). The related parameters (unit: mm) are: $S_{w1} = 0.2$, $S_{w2} = 0.2$, $S_{w3} = 1$, $S_{p1} = 2.1$, $S_{p2} = 4.1$, $S_{p3} = 2.2$, $S_{p4} = 1.2$, $S_{l1} = 3.8$, $S_{l2} = 3$, $S_{l3} = 2.4$, $V_x = 4.85$, $V_y = 4.35$, $V_{d1} = 0.621$, $V_{d2} = 0.606$.

2.2. Feeding structure

Figure 3 shows a novel coplanar waveguide (CPW) to SIW I/O feeding structure. To increase the coupling strength, L-shaped slot is utilized and placed at the return path of the surface current. Besides, the open stub of the feeding line placed beyond the center of the L-shaped slot is set to be a quarter wavelength. Thus, it is noticed that the value of external quality fac-

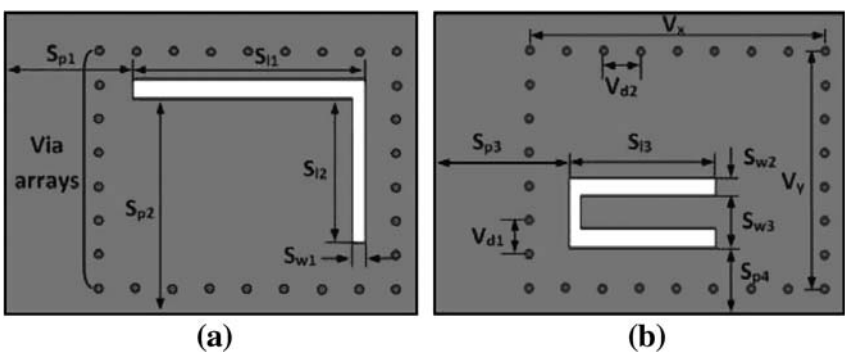

Figure 2. Design parameters of the DFSIW resonators. (a) The middle metal plate with an L-shaped slot of resonators 1, 2, and 3. (b) The bottom metal plate with a U-shaped slot of resonators 1 and 2.

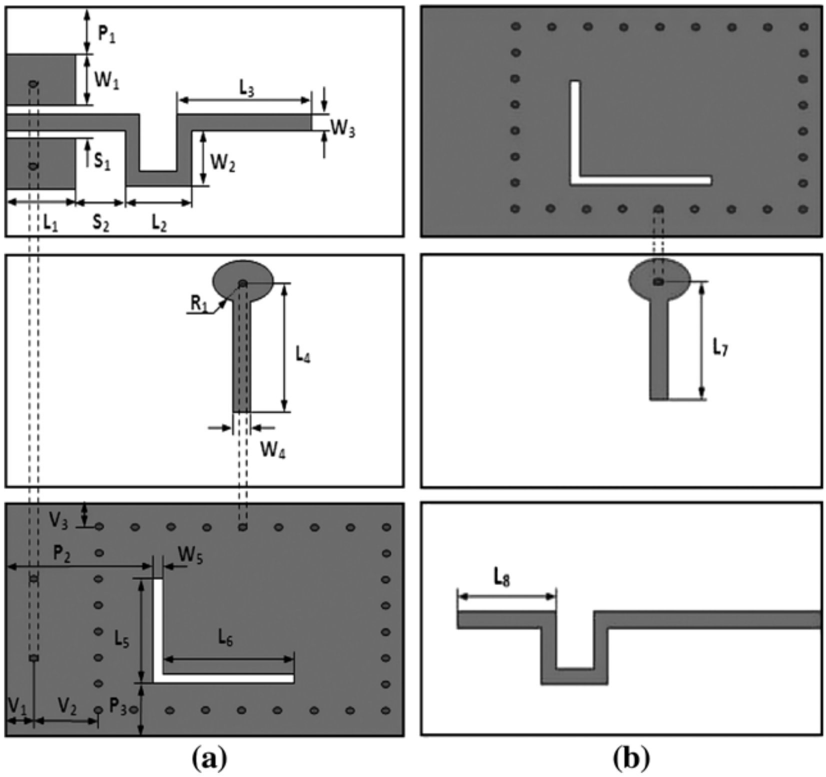

Figure 3. The novel feeding structure. (a) The input structure. (b) The output structure.

Table 1. Dimensions of the feeding structure (Unit: micrometers).

Symbol	Value	Symbol	Value
W_1	1.2	L_7	2.825
W_2	1.35	L_8	1.9
W_3	0.4	P_1	1.15
W_4	0.3	P_2	2.5
W_5	0.2	P_3	1.2
L_1	1.2	S_1	0.2
L_2	1.4	S_2	0.7
L_3	2.3	V_1	0.575
L_4	3.125	V_2	0.925
L_5	2.5	$V3$	0.575
L_6	2.2	R_1	0.5

tor Q_e is mainly controlled by the dimensions of L-shaped slot, L_5, L_6, and W_5. Since Q_e has been calculated according to (1), the values of L_5, L_6, and W_5 can be obtained accordingly through simulations. After the final optimization, the detailed parameter values of the feeding structure are listed in Table 1. Usually, in consideration of the symmetry of the structure, open-end straight line is taken to feed the resonator. In this paper, novel meandered open-ended lines are utilized as input and output to increase the length of coupling path. The

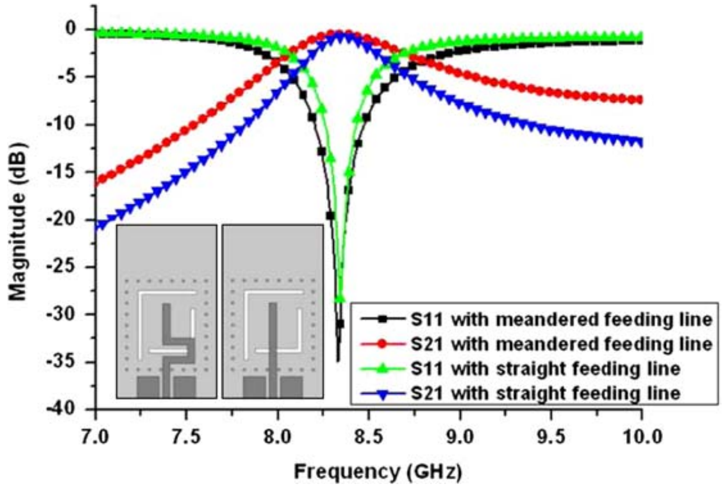

Figure 4. Simulated *S*-parameters with proposed feeding line compared with straight line.

energy is magnetically coupled from the microstrip line into the resonators by means of L-shaped slot etched on the top metal surface of the cavity. To compare the two different feeding lines, they are utilized to feed the same DFSIW resonator and different *S*-parameters are obtained as shown in Figure 4. The 3 dB bandwidth is 9.6% for the filter with meandered feeding line, while it is 5.6% with straight feeding line. Results turn out that better coupling can be achieved with the proposed feeding line.

In addition, a quarter-wavelength short-circuited line with circular patch is coupled to the feeding line at a vertical distance of 0.096 mm. In this way, transmission zero on either high or low side of the pass-band can be implemented in a simple manner, without increasing the circuit size of the filter. So as to achieve better out-of-band rejection performance, two transmission zeros are generated at 10 GHz ($\lambda_g = 12.35$ mm) and 11 GHz ($\lambda_g = 11.22$ mm) by adjusting the length L_4 and L_7 to their respective quarter wavelength.

As the feeding lines for the filter are located at different layers, a bottom-to-top transition composed of thru-hole and vertical feeding probe surrounded with ground vias is utilized to satisfy the condition of on-wafer measurement [14]. Figure 5 presents the entire configuration of the proposed band-pass filter, which consists of a direct-coupled DFSIW section and a transition connected to tapered CPW feeding line. The diameters of the thru-hole and vertical

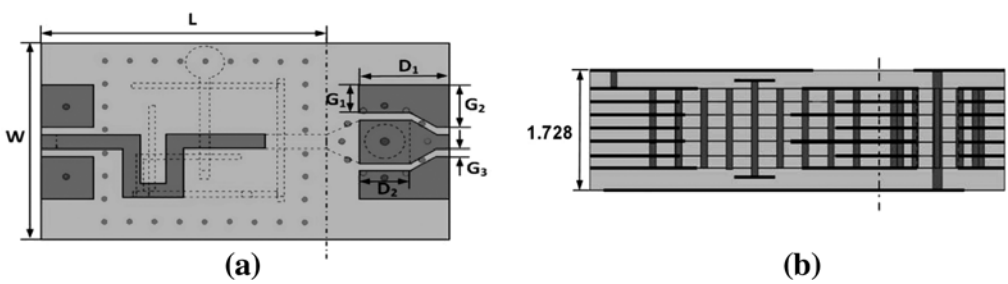

Figure 5. Configuration of the proposed band-pass filter (Units: mm). (a) Top view. (b) Cross-sectional view.

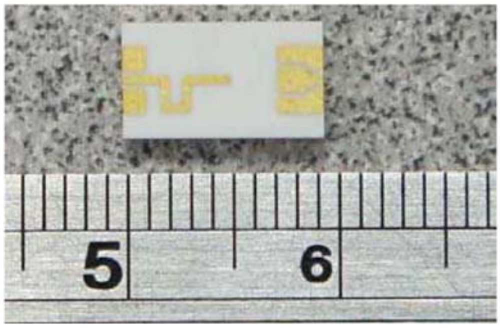

Figure 6. The photo of the band-pass filter.

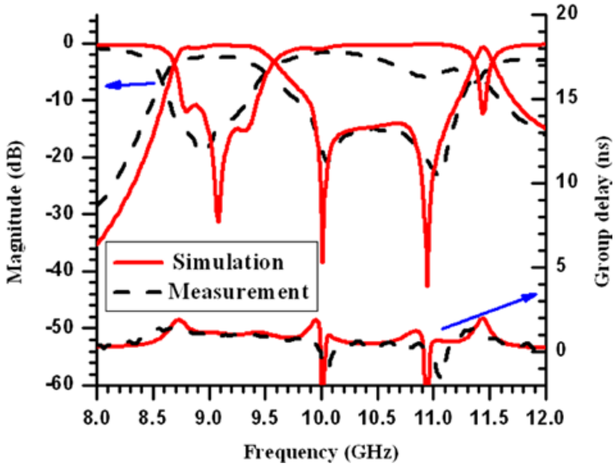

Figure 7. Simulated and measured results of the proposed filter with vertical transition.

probe in transition are chosen to be 1 mm and 0.2 mm, respectively. The parameters of the CPW (unit: mm) are: $D_1 = 2.1$, $D_2 = 1.2$, $G_1 = 0.8$, $G_2 = 1.2$, and $G_3 = 0.2$.

3. Simulation and measurement results

Figure 6 shows a photo of the proposed filter. The simulated and measured results are shown in Figure 7. As can be seen, the two results show good agreement, except for a frequency shift of approximately 0.2 GHz. This discrepancy may be attributed to the LTCC shrinkage. The measured insertion loss is approximately 2.3 dB and the 3 dB bandwidth is approximately 11.1% with a center frequency of 9 GHz. The group delay is relatively flat over the whole passband. Two transmission zeros are generated at 10 and 11 GHz, thus a better than 15 dB suppression degree can be achieved at the side of higher band. The circuit size of this filter without vertical transition is $W \times L = 5.5 \times 6.8\,\text{mm}^2$ i.e. $0.280 \times 0.346\lambda_g^2$, where λ_g is the guided wavelength on the substrate at the center frequency. It is only 12.9% the size of a conventional planar direct-coupled three-pole waveguide filter.

4. Conclusion

A miniaturized double-folded SIW band-pass filter is proposed in LTCC technology. Three double-folded SIW resonators are vertically stacked to reduce the size of the filter. Meandered microstrip feeding line is utilized to strengthen the coupling between the feeding structure and the resonators, and two $\lambda_g/4$ short-circuited lines are adopted to introduce two transmission zeros to increase the selectivity of the filter. Results indicate that the proposed filter has the properties of compact size, good passband performance, and high selectivity. With all the good performance, the proposed LTCC band-pass filter can be widely used in microwave and millimeter wave communication systems.

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