LTCC Wideband Bandpass Filter Based on Multi-layered Coupling

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Abstract **—** A novel wideband bandpass filter (BPF) based on multi-layered coupling using low temperature co-fired ceramic (LTCC) technology is proposed. Four folded quarter-wavelength layered coupled lines are distributed in 3D space to achieve compact circuit structure. Two transmission zeros near edges of the passband response can be easily realized by the two quarter-wavelength open/short coupled lines. Besides over 15-dB out-of-band rejection, the insertion loss of less than 0.7 dB is realized in the passband. A prototype with 3-dB fractional bandwidth of 25.7% operated at 2.95 GHz is designed and fabricated.

Index Terms **—** Bandpass filter, LTCC, multi-layered coupling, open/short coupled lines, wideband.

I. INTRODUCTION

With the rapid development of wireless communication system, low temperature co-fired ceramic (LTCC) technology has been widely used in many microwave devices, due to its characteristics of low dielectric loss, high frequency, high Q value, multilayer layout and high integration. As vital passive components, more and more researches have been focused on bandpass filters (BPFs) with LTCC technology. At the early stage, LTCC BPFs based on lumped elements are popular and easy- implemented [1]-[3]. In [1], a capacitor connected between the input and output is utilized to create a feedback path to introduce two finite zeros near the passband. A compact BPF using negative coupling structure has been proposed; however, the selectivity of the passband is not so good due to lacking of transmission zeros at the upper stopband [2]. In addition, a wideband BPF with multiple transmission zeros are fabricated by cascading a high- and low-pass filter [3]. In order to improve the flexibility of the implement, semilumped elements are introduced in some LTCC BPFs [4]-[5]. Recently, several LTCC BPFs based on distributed elements were presented [6]-[7]. In [6], a compact LTCC BPF with wide stopband is proposed using discriminating coupling scheme, but the passband is not wide. Moreover, a LTCC wideband BPF based on the dual-mode stepped-impedance resonator was designed and fabricated [7].

In this letter, a novel LTCC wideband BPF based on multi-layered coupling is presented. The filter is completely constructed by distributed elements, which include two quarter-wavelength open/short coupled lines and two quarter-wavelength open coupled lines. The two transmission zeros near the passband can be independently controlled by the coupling value of two quarter-wavelength open/short coupled lines. The compact size can be easily realized by the folded transmission lines and multilayer technology. Due to the symmetry of the circuit, even/odd-mode method can be applied to analyze the characteristic of the filter.

II. DESIGN OF PROPOSED LTCC WIDEBAND BANDPASS FILTER

A. Analysis of planar structure of the filter

As shown in Fig. 1 (a), two quarter-wavelength open coupled lines (Z_{e1}, Z_{o1}, θ) are located between port 1 and 2, and two quarter-wavelength open/short coupled lines (Z_{e2}, Z_{o2}, θ) are shunted connected in the two ports as well as characteristic impedance $Z_0 = 50\ \Omega$. The planar circuit is symmetric along the plane AA′, when the even/odd-mode are excited, a virtual open/short appears along AA′, and the even/odd-mode input admittances Y_{even} and Y_{odd} of the equivalent circuits in Figs. 1 (b) and (c) can be illustrated as:

$$Y_{even} = j\frac{2\tan\theta}{Z_{e1}+Z_{o1}} + j\frac{(Z_{e2}+Z_{o2})\sin 2\theta}{(Z_{e2}+Z_{o2})^2\cos^2\theta-(Z_{e2}-Z_{o2})^2}, \tag{1}$$

$$Y_{odd} = j\frac{(Z_{e1}+Z_{o1})\sin 2\theta}{(Z_{e1}+Z_{o1})^2\cos^2\theta-(Z_{e1}-Z_{o1})^2} + j\frac{(Z_{e2}+Z_{o2})\sin 2\theta}{(Z_{e2}+Z_{o2})^2\cos^2\theta-(Z_{e2}-Z_{o2})^2}. \tag{2}$$

And the S-parameters of the filter can be expressed as:

$$S_{21} = \frac{Y_0(Y_{odd}-Y_{even})}{(Y_0+Y_{even})(Y_0+Y_{odd})}, S_{11} = \frac{Y_0^{\,2}-Y_{even}Y_{odd}}{(Y_0+Y_{even})(Y_0+Y_{odd})}, \tag{3}$$

where $Y_0 = 1/Z_0$, when $S_{21} = 0$, the two transmission zeros of the circuit in Fig. 1 (a) can be obtained as:

$$\theta_{tz1} = \arccos\frac{Z_{e2}-Z_{o2}}{Z_{e2}+Z_{o2}}, \quad \theta_{tz2} = \pi - \theta_{tz1}. \tag{4}$$

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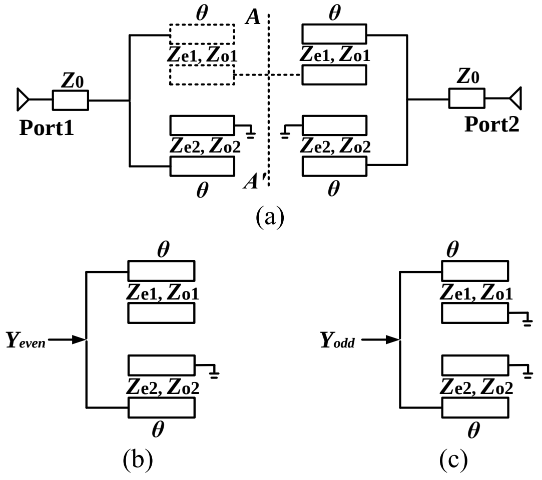
Consequently, the locations of the transmission zeros are only determined by the coupling coefficient k_2 ($k_2 = (Z_{e2}-Z_{o2})/(Z_{e2}+Z_{o2})$).

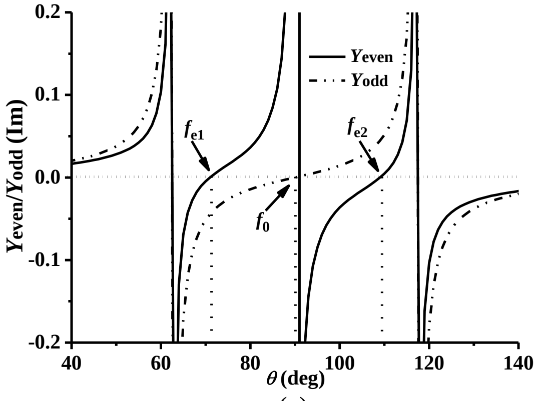
Figure 2 (a) shows the even/odd-mode input admittances versus θ, and Fig. 2 (b) shows $|S_{21}|$ versus the normalized frequency f/f_0. The bandwidth of the bandpass filter is mainly determined by the two even-modes (f_{e1},f_{e2}). As shown in Fig. 2 (c), the in-band return loss improves as k_1 ($k_1 = (Z_{e1}-Z_{o1})/(Z_{e1}+Z_{o1})$) increases, but the out-of-band rejection level improves as k_1 decreases. Moreover, the 3-dB bandwidth and locations of transmission zeros have no changes as k_1 varies. It should be pointed that k_2 can be seen as independent parameters for adjusting the locations of two transmission zeros (f_{tz1},f_{tz2}) as shown in Fig. 2 (d). When k_2 increases, the 3-dB bandwidth increases and f_{tz1}, f_{tz2} move far away from each other. The above transmission characteristic reduces the design complexity of the filter effectively.



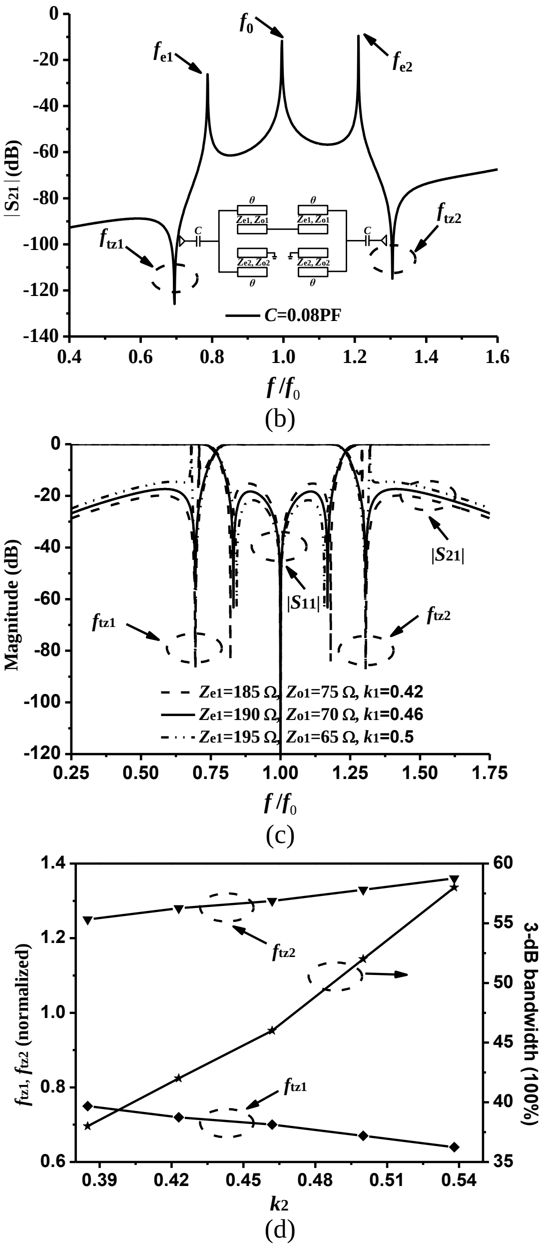
(a)

(b) (c)

Fig. 1. The planar circuit diagram of proposed wideband BPF. (a) Ideal circuit of the filter, (b) even-mode equivalent circuit, and (c) odd-mode equivalent circuit.



(a)



(b)

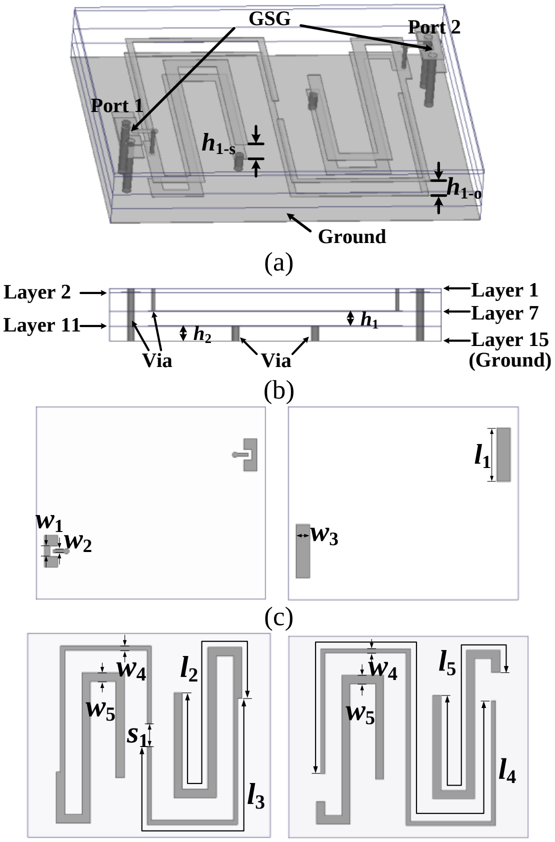
(c)

(d)

Fig. 2. Simulated frequency responses of Fig. 1. (a) Even/odd-mode resonant frequencies versus θ, (b) analysis of resonator frequencies under weak coupling, $Z_{e1} = Z_{e2} = 190\ \Omega$, $Z_{o1} = Z_{o2} = 70\ \Omega$, (c) $|S_{21}|$&$|S_{11}|$ of Fig. 1 (a) versus k_1, $Z_{e2} = 190\ \Omega$, $Z_{o2} = 70\ \Omega$, and (d) f_{tz1}, f_{tz2} and 3-dB bandwidth versus k_2, $Z_{e1} = 90\ \Omega$, $Z_{o1} = 70\ \Omega$.

B. Constructions of LTCC 3D model of the filter

In order to obtain the compact size of the filter, the planar circuit can be converted into the LTCC 3D structure. As shown in Fig. 3 (a), the proposed filter is fabricated on a 14-layer LTCC substrate with the dielectric constant of 5.9 and loss tangent of 0.002. And the dielectric thickness of each layer is 0.1 mm. As we can see, the planar edge-coupled structures have been improved to multi-layered coupled structures. In addition, the folded coupled lines can decrease its size efficiently. Figure 3 (b) shows the filter is composed of five metal layers. On the layer 1 are the G-S-G ports, and the rectangular metal sheets on the layer 2 linked between the ground and ports can be used to match the port impedance. The coupled quarter-wavelength resonators are on the layer 7 and 11, so the coupling gap (h_1) between coupled lines is 0.4 mm. It should be pointed that, the coupling gap of open/short coupled lines is $h_{1\text{-s}}$, and the coupling gap of open coupled lines is $h_{1\text{-o}}$. The ground plane is on the layer 15, and h_2 is also 0.4 mm. All the interconnection and grounding are realized by via-holes. The layout of each layer is shown in Figs. 3 (c)-(e), the parameters are determined as follows: w_1 = 0.37 mm, w_2 = 0.13 mm, w_3 = 0.5 mm, w_4 = 0.15 mm, w_5 = 0.3 mm, l_1 = 2 mm, l_2 = 12.3 mm, l_3 = 10.4 mm, l_4 = 21 mm, l_5 = 11.3 mm, l_6 = 7.2 mm, l_7 = 8.55 mm, s_1 = 0.8 mm. When $h_{1\text{-s}}$ increases, the two transmission zeros move towards each other and the bandwidth of the filter decreases as shown in Fig. 4 (a). As we know, the coupling coefficient k_2 decreases as $h_{1\text{-s}}$ increases, so the simulated results in Fig. 4 (a) are corresponding to the Equation (4). By contrast, Fig. 4 (b) shows the locations of the transmission zeros and bandwidth nearly have no changes when $h_{1\text{-o}}$ varies.

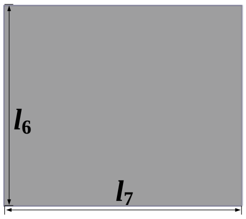


(a)

(b)

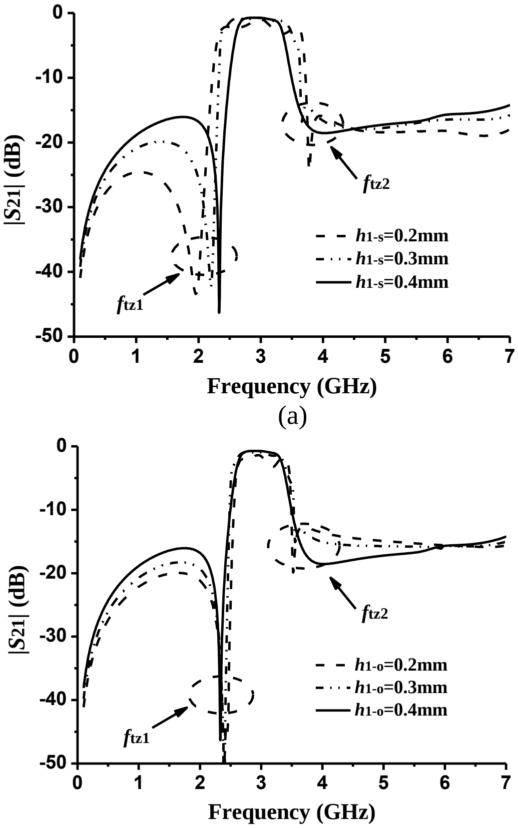
(c)

(d)



(e)

Fig. 3. Proposed LTCC wideband BPF configuration. (a) 3D structure, (b) side view, (c) layer 1 and layer 2, (d) layer 7 and layer 11, and (e) layer 15.



(a)

(b)

Fig. 4. Simulated frequency responses $|S_{21}|$ of the LTCC wideband BPF. (a) Versus $h_{1\text{-s}}$, $h_{1\text{-o}}$ = 0.4 mm, h_2 = 0.4 mm, and (b) versus $h_{1\text{-o}}$, $h_{1\text{-s}}$ = 0.4 mm, h_2 = 0.4 mm.

III. EXPERIMENT AND RESULTS

The measured and simulated results of the LTCC wideband BPF are illustrated in Fig. 5, which show good agreement. The measured centre frequency of the filter is 2.95 GHz with the 3-dB fractional bandwidth of 25.7%. The in-band return loss is greater than 20 dB, and the minimum insertion loss is only 0.7 dB. Over 15-dB out-of-band suppression can be realized by the two transmission zeros near the passband which are located at 2.32 and 3.88 GHz. In addition, the upper stopband rejection is achieved from 3.52 to 7 GHz ($2.37f_0$). The photograph of the filter is also shown in Fig. 5, and its overall size is only 8.55mm×7.2mm×1.4mm.

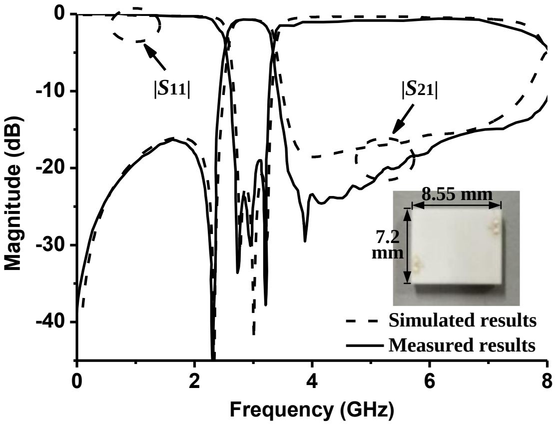


Fig. 5. Photograph, measured, simulated results of the LTCC wideband BPF.

IV. CONCLUSIONS

A novel LTCC wideband BPF based on multi-layered coupling is presented in this letter. The coupling amount of the quarter-wavelength resonators can be easily adjusted by the vertical spacing of the coupled lines. In addition, the two transmission zeros near the passband can be independently controlled by the quarter-wavelength open/short coupled lines, which reduces the complexity of the design obviously. Moreover, the advantages of compact size, good passband selectivity and wide out-of-band suppression of the proposed filter make it competitive for many wireless communication systems.

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