Design Technique for Multilayered Filters Composed of LC Resonators

KE CAO1, YU-JIN ZHOU2

1Jinling Institute of Technology, Nanjing 211169, China (e-mail: caoke@jit.edu.cn)
2Nanjing University of Posts and Telecommunications, Nanjing 210003, China (e-mail: yujin_zhou@qq.com)

Corresponding author: Ke Cao (e-mail: caoke@jit.edu.cn).

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ABSTRACT In multilayer filter design, both the parasitic effects and the lack of fine-tunings may result in the error of component values, which has great influences on performance. In this paper, a design technique for multilayer filter composed of LC resonators is proposed. With this technique, influences of the error of component values may be reduced and the design procedure may be simplified. An elliptic filter composed of four LC resonators is used to demonstrate the proposed technique. Three experimental prototypes with different component values were fabricated for comparisons. Very good agreements between measured responses and designed responses can be observed. The measured parasitic resonances are higher than the third harmonic frequency. These facts show the effectiveness of the proposed technique.

INDEX TERMS Design technique, LC resonators, parasitic effects, bandpass filter, multilayer substrates

I. INTRODUCTION

The rapid development of wireless communications makes the spectrum more and more crowded. To suppress the interfering signals in nearby frequency band or separate uplink and downlink transmission paths, Bandpass Filters (BPFs) are widely used in the RF front-ends of wireless communication systems. The BPFs are required to have high performance, low cost and compact. Therefore, the design of RF filters is a challenging task. For these requirements, the design technique to construct the BPFs on multilayer substrates has been investigated. Both the Low Temperature Co-Fired Ceramic (LTCC) technology and multilayer substrates Printed Circuit Board (PCB) technology are excellent candidates to fabricate RF components in multilayer way.

Both lumped-element filters and distributed-element filters can be fabricated in multilayer way [1-3]. However, the size of the distributed-element filters is relatively large due to the fundamental disadvantage of using quarter-wavelength sections, especially at low frequency band. Therefore, the filters are usually implemented by directly using lumped-element inductors and capacitors at low frequency band [4-6].

In an ideal situation, a multilayered filter may show almost the same frequency responses as the circuit. But the frequency responses of the multilayered filters are always unpredictable due to complicated parasitic effects [7, 8]. In fact, a spiral is not a single inductor in the RF band. Its performance should be characterized by an equivalent circuit with an inductor and several parasitic capacitors [9]. A pair of parallel-plate is not a single capacitor. Its performance should be characterized by an equivalent circuit with several parasitic capacitors and several parasitic inductors [10, 11]. The parasitic effects make it very difficult to design a multilayered component with desired component value and desired frequency responses. Therefore, it is urgent to find a design technique that can reduce the influences of parasitic effects and simplify the design procedures for multilayered filters.

In our research, it is found that the frequency responses of the LC resonator are mainly determined by the product of inductor value and capacitor value, namely the resonance frequency. As long as the product is kept unchanged, slightly changing component values only leads to small changes in frequency responses. According to our data, for every 1% change in the component values, the change in 3dB fractional bandwidth does not exceed 1%. This feature makes the LC resonator very suitable for multilayered filter design. We may regard the accurate resonance frequency as the priority, rather than the perfectly accurate component values. The errors of component value (caused by parasitic effects, stack error, etc.) may be ignored as long as the resonance frequency is accurate. As a result, the design procedures may be simpli-
fied.

In this paper, the proposed design technique for multilayer filter is discussed in detail. A multilayered physical layout for filter is used for demonstration. Several experimental prototypes with different component values were fabricated. The measured results agree very well with the designed results, which show the effectiveness of the proposed technique.

II. PROPOSED DESIGN TECHNIQUE

A. DESIGN OF MULTILAYER LC RESONATOR

Take the LC resonator shown in Fig. 1(a) as an example. The theoretical component values are \( L_0 = 3.3 \text{nH} \) and \( C_0 = 12.0 \text{pF} \). Its resonance frequency \( f_0 \) is 800MHz. Fig. 1(b) shows the corresponding multilayer resonator. It consists of three dielectric layers, each of which is 1mm-thick Rogers 5880 (\( \varepsilon_r = 2.2 \)). The multilayer capacitor and multilayer inductor are named as \( C_{0M} \) and \( L_{0M} \), respectively. Their resonance frequency is noted as \( f_{0M} \).

![FIGURE 1. (a) LC resonator circuit. (b) Multilayer LC resonator layout.](image)

Because of parasitic effects, it is very difficult to make \( C_{0M} \) and \( L_{0M} \) equal to \( C_0 \) and \( L_0 \), respectively. But we can easily make \( C_{0M} \times L_{0M} = C_0 \times L_0 \) by keeping \( f_{0M} = f_0 \). The inaccurate components will cause the performance of multilayer resonator to deviate from that of circuit. But designing inaccurate components is much easier than designing accurate ones because less simulations are required. As a result, the design procedure may be simplified.

The key to this design technique is the trade-off between the accuracy of components and their influence on performance. To discuss it, scaling factor \( \alpha \) is used. It represents the accuracy of components and we have

\[
C_{0M} = \alpha C_0
\]

\[
L_{0M} = L_0 / \alpha
\]

In this case, the product of \( C_{0M} \times L_{0M} \) is a constant. \( \alpha = 1 \) means that the multilayer component values are perfectly accurate. \( \alpha = 0.9 \), for example, means that the multilayer component values are changed by about \( \pm10\% \).

Ignoring parasitic effects, the \( S_{21} \) of multilayer resonator is given by

\[
S_{21M} = \frac{2j\omega L_{0M}}{2j\omega L_{0M} + Z_0(1 - \omega^2 L_{0M} C_{0M})} = \frac{2j\omega L_0}{2j\omega L_0 + \alpha Z_0(1 - \omega^2 L_0 C_0)}
\]

where \( Z_0 \) is the characteristic impedance.

According to (3), near the resonance frequency \( f_0 \), \( S_{21M} \) approaches one because \( Z_0(1 - \omega^2 L_0 C_0) \) approaches zero. In this case, the change of \( \alpha \) has a very small influence on \( S_{21M} \).

The farther away from the resonance frequency, the greater the effect of the change of \( \alpha \) on \( S_{21M} \).

Fig. 2 shows the EM simulation results of the multilayer LC resonator when \( \alpha \) takes different values. Equations form [12] are used to calculate the component values. The Zero around 1.7GHz is introduced by the self-resonance of multilayer capacitor [4]. Table I shows the detailed data of EM simulations. To evaluate the influences of different \( \alpha \) on performance, 3dB and 10dB fractional bandwidth are used.

![FIGURE 2. EM simulation results of multilayer LC resonator when \( \alpha \) takes different values.](image)

| \( \alpha \) | Insertion loss (dB) | 3dB fractional bandwidth | 10dB fractional bandwidth |
|---|---|---|---|
| 0.8 | 0.12 | 66% | 138% |
| 0.95 | 0.13 | 58% | 125% |
| 1 | 0.14 | 50% | 122% |
| 1.05 | 0.15 | 50% | 122% |
| 1.2 | 0.18 | 44% | 102% |

According to these results, it can be seen that:

1) Although the quality factors of capacitor and inductor are different, the change of \( \alpha \) has very small influences on insertion loss. When \( \alpha \) changes from 1.2 to 0.8, the insertion loss changes from 0.18dB to 0.12dB. This small change may be ignored in some design.

2) The greater the change of \( \alpha \), the greater the impact on bandwidth. In these examples, for every 1% change in \( \alpha \), the change in 3dB and 10dB fractional bandwidth does not exceed 1%. For example, when \( \alpha \) decreases from 1.2 to 0.8, the 3dB fractional bandwidth increases from 44% to 66% and the 10dB fractional bandwidth increases from 102% to 138%.

Therefore, we may regard the accurate resonance frequency as the priority in multilayer LC resonator design, rather than the perfectly accurate component values. Errors of
component value within a certain range (like ±5%), weather due to lack of fine-tunings or due to parasitic effects, can be ignored. Large component value errors (like ±20%) may result in some changes in performance away from the passband. But they may be improved with fine-tunings.

B. MULTILAYER FILTER DESIGN TECHNIQUE

According to the analysis in the previous section, a design technique for multilayer filter composed of LC resonators is proposed, as shown in Fig. 3.

![Flowchart of proposed filter design technique](image)

The design starts with a fine-tuned multilayer LC resonator, which will be called the initial resonator hereinafter. It is the foundation of the following design. Its performance should match that of resonator circuit as much as possible, especially the resonance frequency.

The second step is to calculate the sizes of other multilayer components with the sizes of initial resonator and theoretical components values. For capacitors, the capacitance is proportional to the area. For inductors, we may imprecisely assume that the inductance is proportional to the length of inductor. In this way, the rough initial sizes of other components can be calculated.

The third step is to build or update the multilayer filter with the calculated sizes.

The fourth step is to tune the sizes of inductors so that the resonance frequency of each resonator is equal to the designed value.

In this way, the multilayer filter is built. Because the component sizes of initial resonator is not accurate, the performance of filter may not agree well with the desired performance. Therefore, the initial resonator may be tuned by changing α and then step 1 to 4 should be repeated.

III. MULTILAYER FILTER DESIGN WITH PROPOSED TECHNIQUE

A. FILTER CIRCUIT AND MULTILAYER LAYOUT

![Flowchart of proposed multilayer filter layout](image)

To demonstrate the proposed technique, a third-order elliptic filter centered at 810MHz with 260MHz 3dB-bandwidth is used. As shown in Fig. 4 (a), the filter is composed of four resonators, which are noted as r1 to r4, respectively.

The theoretical components values can be obtained using the equations in [13], which are: $C_1=C_4=12.0\text{pF}$, $C_2=6.08\text{pF}$, $C_3=3.23\text{pF}$, $L_1=L_4=3.30\text{nH}$, $L_2=12.3\text{nH}$, $L_3=6.51\text{nH}$.

The $S_{21}$ of this filter is:

$$S_{21} = \frac{2Z_0(1-\omega^2L_2C_2)(1-\omega^2L_3C_3)}{2Z_0T(1-\omega^2L_2C_2)(1-\omega^2L_3C_3) + I} \quad (4)$$

where

$$I = j\omega T^2(L_2 + L_3) - j\omega^3T^2L_2L_3(C_2 + C_3) \quad (5)$$

$$T = Z_0\left(j\omega C_1 + \frac{1}{j\omega L_1}\right) + 1 \quad (6)$$

According to (4)-(6), resonator r2 and r3 introduce a Zero, respectively. The Zeros can be separately tuned by tuning corresponding resonance frequency. r1 and r4 influences the out-of-band suppression. The larger the $L_1$ is, the worse the out-of-band suppression is.

To make this circuit more suitable for multilayer design, circuit transformation was performed. Fig. 4 (b) shows the transformed circuit. Resonators r1 and r4 are each replaced with two sub-resonators connected in parallel. Component value of sub-resonators have also been adjusted so the performance before and after the transformation remains unchanged. The adjusted component values are $C_1' = C_2' = 6.00pF$ and $L_1' = L_4' = 6.60nH$.

Fig. 5 shows the proposed multilayer filter layout. Resonator r1 and r2 are designed as a block (Block 1) while r3 and r4 are designed as another block (Block 2). Ports are designed as 50Ω striplines [14].

In Block 1, sub-resonators of r1 are placed on the top and bottom of the layout, respectively. A via hole with large
B. FILTER DESIGN WITH PROPOSED TECHNIQUE

According to the flowchart shown in Fig. 3, the first step is to design the initial resonator. In this example, we choose r1 as the initial resonator, because its capacitor is much larger than other capacitors. According to the design in Section II, the area of 6.0pF MIM capacitor is 168mm² and the length of 3.30nH meandered inductor is about 10mm (via hole is ignored for simplification, hereinafter).

With the known data and theoretical component values, areas of C₂ and C₃ are calculated as 85mm² and 45mm², respectively. The lengths of L₁', L₂, and L₃ are calculated as 20mm, 37mm, and 19.7mm, respectively.

Fig. 6(a) shows the EM simulation results of initial filter layout with calculated sizes. The passband, two zeros, and frequency shift can be easily observed from the figure.

Then all inductors are increased to get desired resonance frequencies. The tuned lengths of L₁', L₂, and L₃ are 22.3mm, 57mm, and 22.8mm, respectively. The new frequency response, as shown in Fig. 6 (b), agrees with circuit response except for the out-of-band suppression.

To improve the out-of-band suppression, more tunings are performed. α of initial resonator (and all other resonators) is increased by about 10%. Fig. 6 (c) shows the final responses, which agree well with circuit responses. The final area of C₁', C₂, and C₃ are about 184mm², 93.2mm², and 49.5mm², respectively.

FIGURE 5. Proposed multilayer filter layout. (a) 3D view. (b) Section view.

FIGURE 6. EM simulation results. (a) Initial filter. (b) Initial filter with tuned inductors. (c) Final results.
TABLE 2. Comparison with related researches.

| Ref. | $f_0$ (GHz) | 3dB B.W. (MHz) | I. L. (dB) | Out-of-band Suppression (dB) | Size ($10^{-3} \lambda_0^3$) |
|------|-------------|----------------|----------|---------------------------|---------------------------|
| [4]  | 0.06        | 15             | 1.95     | 15                        | 0.00064                   |
| Filter I in [5] | 1.55 | 170             | 2.2      | 15                        | 0.6/                       |
| Filter II in [5] | 1.55 | 102             | 4.92     | 19                        | 1.44                      |
| [6]  | 1.57        | 79             | 2.7      | 25                        | 1.5/                      |
| [16] | 2.44        | 340            | 1.7      | 22                        | 4.69/                     |
| [17] | 2.5         | 375            | 1.0      | 13                        | 5.64                      |
| Circuit | 0.8 | 261             |          | 26                        | -                         |
| Prototype I Measured | 0.835 | 263 | 0.73 | 23 | 26 |

respectively. The final length of $L_1$, $L_2$, and $L_3$ are about 19.7mm, 53mm, 20.3mm, respectively.

IV. EXPERIMENT VERIFICATION

PCB technology was used to fabricate the experimental prototype. Some minor modifications have been made because of fabrication requirements. All layers are manually stacked and fixed. The core size of experimental prototype (Prototype I) is about $0.11 \times 0.15 \times 0.016 \lambda_0^3$, or $2.6 \times 10^{-4} \lambda_0^3$. The overall size of Prototype I include the areas for fixing and microstrip-stripline transitions [14], is about $0.24 \times 0.28 \times 0.016 \lambda_0^3$.

The prototype is measured with an Agilent 8720ET Vector Network Analyzer. The measurement results are shown in Fig. 7(a). Besides the slight frequency shift, the measurement results agree very well with EM simulation results. The measured central frequency and 3dB bandwidth are 839MHz and 262MHz, respectively. Those of EM simulation results are 811MHz and 265MHz. Table II compares the prototype I with some related works.

TABLE 3. Comparison of experimental prototypes.

| Prototype | $f_0$ (MHz) | 3dB fractional bandwidth | I. L. (dB) | Out-of-band Suppression (dB) |
|------------|-------------|--------------------------|----------|---------------------------|
| I ($\alpha = 1$) | 839 | 31.2% | 0.63 | 23.8 |
| II ($\alpha = 0.8$) | 835 | 30.0% | 0.69 | 23.9 |
| III ($\alpha = 1.2$) | 845 | 32.8% | 0.64 | 23.3 |

results, even $\alpha$ of r3 is changed by about 20%, the insertion loss only changes by less than 0.05dB and the 3dB fractional bandwidth changes by less than 1.6%. These results show the effectiveness of proposed technique.

V. CONCLUSION

Design technique for multilayered filters composed of LC resonators is proposed, which is intended to simplify the design procedure for this kind of filters. An elliptic filter is taken as the example to demonstrate the proposed technique. A multilayered filter is designed and several experimental prototypes were measured. The measurement results agree well with the designed results. These facts show the effectiveness of the proposed design technique.

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FIGURE 7. EM simulation results and measurement results of prototype I.

Besides prototype I, two more prototypes (Prototype II and III) were fabricated to verify the proposed technique. Fig. 8(a) and Table III shows the measurement results of prototypes. Fig. 8(b) shows the photographs of all prototypes.

Compared to Prototype I, $\alpha$ of r3 in Prototype II is decreased by about 20% while $\alpha$ of r3 in Prototype III is increased by about 20%. According to the measurement

FIGURE 8. Experimental prototypes. (a) Measurement results. (b) Photographs.
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KE CAO was born in Jinan, Shandong Province, China, in 1987. He received the Ph.D. degree in engineering from Nanjing University of Posts and Telecommunications (NUPT), Nanjing, China, in 2017. He is currently with the Jinling Institute of Technology, Nanjing, China. His current research interests include RF/microwave devices, such as antennas and filters.

YU-JIN ZHOU was born in Nanjing, Jiangsu Province, China, in 1988. He received the M.S. and M.E. degree in engineering from Nanjing University of Posts and Telecommunications (NUPT), Nanjing, China, in 2011 and 2014, respectively. His now with Nanjing Electronic Devices Institute. His current research interests include RF/microwave devices.