Design of High Order Cross-Coupled Constant Absolute Bandwidth Frequency-Agile Bandpass Filters

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Abstract ─ Novel high order constant absolute bandwidth (ABW) cross-coupled electrical tunable bandpass filters (BPFs) are proposed. Microstrip cross-coupled tunable resonators are designed and investigated to meet the coupling requirement of the tunable BPF with constant ABW. A thorough theoretical analysis is derived to determine the performance of the proposed filter and verify the initial values of design parameters. To verify the design concept, two prototypes are fabricated and measured. The measurements show that the proposed four-order filter has a -3 dB ABW of 119.5±2.5 MHz with 1.31~1.98 GHz tuning frequency. And the proposed six-order filter has a -3 dB ABW of 102±6 MHz with 1.39~2.07 GHz tuning frequency. High selectivity has been achieved in the proposed filter by TZs (transmission zeros) beside the passband, good agreement between simulated and measured results has been demonstrated.

Index Terms ─ Bandpass filter, filter, four-order, six-order, source-load coupling.

I. INTRODUCTION

In recent years, people pay more and more attention to the research of filter [1-4]. Specifically, constant bandwidth BPF and high order BPF with high selectivity are a longstanding concern for wireless communication systems [5-9]. Up to now, many planar tunable filters have been proposed, but most of them focus on the design of two-order tunable filters [5-8]. Only a few numbers of high order (more than two poles) tunable filters have been reported to meet the high selectivity requirement. For example, in [9-12], the direct coupling topology was applicable to the varactor-loaded $\lambda/2$, $\lambda/4$ or LC resonators resulting in the simple-tunable filters. In [13], a four-order tunable BPF with cross-coupled stepped-impedance resonator (SIR) is designed, however, the passband and TZs are distorted, and the bandwidth is not constant due to the uncontrollable coupling coefficients. In order to introduce the TZs and enhance the selectivity of the tunable response, the cross-coupling or extra cross coupling structures were added to the conventional high order tunable filters [14]–[18]. Many different methods have been introduced and reported to design constant bandwidth BPFs. A magnetic-dominated mixed coupling method is proposed based on quarter wavelength resonator loaded with tunable capacitor at its open termination [5]. Since the coupling structure is magnetic-dominated, the whole hybrid coupling can be pre-designed while the tunable capacitance increasing. This method has been widely used in constant bandwidth tunable filters design [6-10]. Another method is built on electric coupling coefficient control. Constant bandwidth tunable filters based on microstrip LC resonators with electric coupling compensation capacitor network are provided in [9].

The above techniques are able to achieve the high order tunable filters. However, most of them are very complex, because a lot of varactors or pin diodes (more than the resonators) are utilized, and deteriorate the insertion loss. Besides, the selectivity of the reported filters needs to be further improved. Similar to the frequency-fixed filter design, the tunable filter with the fully canonical response is preferable. Only [14] reported a four-order tunable filter with the fully canonical response, but which needs a mass of controllable capacitor and bias to stabilize the passband, and the constant ABW was not achieved. To best of our knowledge, there is hardly any reported four-order or six-order cross-coupled tunable BPF with constant ABW (where there is no need to employ extra varactors to control the coupling between resonators).

This paper focuses on the novel high order cross-coupled tunable filter topology with constant ABW. The basic theories [19-20] are used in designing the proposed filters. This filter has four or six resonators. Cross-coupled tunable resonators and simple tuning method are designed to deal with multiple coupling coefficient curves requirement of tunable BPF with constant ABW.

II. DESIGN OF FOUR-ORDER SOURCE-LOAD BPF

Figure 1 shows the proposed four-order source-load BPF. The resonators are represented by the number 1 to 4. The source or load is represented by S or L, and

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electric or magnetic coupling is represented by E or M, respectively. In order to devise this BPF, the coupling coefficient between the resonators must be obtained based on the prototype of the filter. In this paper, the design index: RL (Return Loss)=20dB, the normalized zero position is ±2 and ±4, and the N+2 coupling matrix is obtained by the method of reference [19]. The calculated normalized coupling coefficients are M_{S1}=1.0217, M_{SL}=0.0115, M_{12}=-0.8664, M_{23}=0.77286, M_{14}=-0.19728. The other coefficients in the matrix are the same as these five coefficients, or 0. When ABW=120MHz, the resonant frequency f_0=1.2~2GHz, then the desired non-normalized coupling coefficient k and Qe can be obtained from the following:

$$k_{ij} = FBW \cdot M_{ij}(i, j = S, 1, 2..L), \tag{1}$$

$$Qe = \frac{1}{FBW \cdot M_{S1}{}^2}, \tag{2}$$

where FBW is fractional bandwidth and FBW=ABW/f_0. When the resonant frequency and ABW are settled to 1.6 GHz and 120MHz, then FBW=7.6%. The non-unitary coupling matrix [k] and non-unitary Qe are calculated by (1) ~ (2):

$$[k] = \begin{bmatrix} 0 & -0.065 & 0 & -0.015 \\ -0.065 & 0 & 0.059 & 0 \\ 0 & 0.059 & 0 & -0.065 \\ -0.015 & 0 & -0.065 & 0 \end{bmatrix}, \tag{3}$$

$$Qe=10.4, \tag{4}$$

$$k_{SL} = k_{LS} = 0.00087. \tag{5}$$

Once the coupling matrix [M] is determined, the filter frequency responses can be computed in terms of scattering parameters:

$$S_{21} = -2j[A]^{-1}_{n+2,1}, \tag{6}$$

$$S_{11} = 1 + 2j[A]^{-1}_{11}. \tag{7}$$

The matrix [A] is given by:

$$[A] = [M] + \Omega[U] - j[R], \tag{8}$$

in which [U] is similar to the (n+2) × (n+2) identity matrix, except that $[U]_{11} = [U]_{n+2,n+2} = 0$, [R] is the (n+2) × (n+2) matrix with all entries zeros, except for $[q]_{11} = [q]_{n+2,n+2} = 1$, and Ω is the frequency variable of lowpass prototype. The lowpass prototype response can be transformed to a bandpass response having a fractional bandwidth FBW at a center frequency f_0 using the well-known frequency transformation:

$$\Omega = \frac{1}{FBW}\left(\frac{f}{f_0} - \frac{f_0}{f}\right). \tag{9}$$

From equations (1) (2), In order to obtain constant ABW filter, the coupling coefficient needs to decrease with the increase of resonant frequency, while the external quality factor needs to increase with the increase of resonant frequency. For the coupling coefficient, the distance between two couplers and the position of the capacitance C_v need to be adjusted. In order to get an extra adjustment degree of freedom, the SIR structure is used in the regulation of k_{23} and k_{14} in this paper. For external quality factors, the length and width of the coupling lines and input capacitance C_{in} can be adjusted to achieve the purpose of constant ABW.

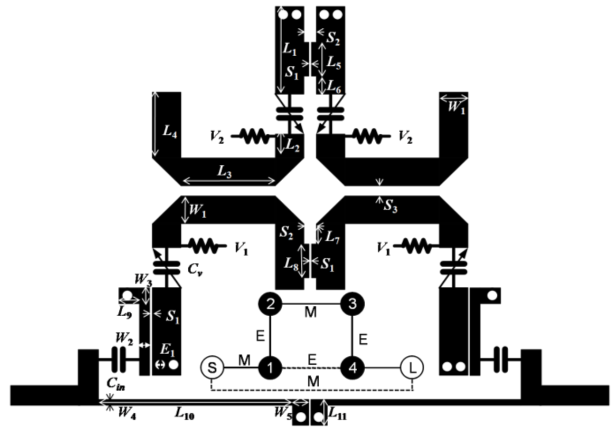

Fig. 1. The proposed four-order source-load BPF.

The simulated k and Qe can be got as [20]:

$$k = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2}, \tag{10}$$

$$Qe = \frac{2\pi f_0 \cdot \tau_{S_{11}}(f_0)}{4}, \tag{11}$$

where the f_1 and f_2 are characteristic frequencies when the input port is very weakly coupled to the coupled resonator structure, τ_{S11} is the group delay.

Consider an I/O structure that only involves the source-load coupling as shown in Fig. 2 (c). The simulated direct source-load coupling k_{SL} can be obtained as [20]:

$$k_{SL} = \frac{-1 - \sqrt{1 - |S_{21}|^2}}{|S_{21}|}, \tag{12}$$

where $0 \leqslant |S_{21}| \leqslant 1$ and $k_{SL} = 0$ for $|S_{21}|$=0.

As shown in Fig. 2, the C_v of the resonator and the length of its coupling line are first selected by the desired adjustable range. Secondly, in the range of adjustable frequency, five coupling coefficients are required to be designed. For the coupling coefficient k_{12}, k_{23}, k_{14}, and Qe, can be varied by the position of the C_v, the coupling distance between the resonators, and the different positions of the SIR. After the initial adjustment of the four parameters, the k_{SL} was adjusted separately. Each coupler is then combined from the initialized BPF.

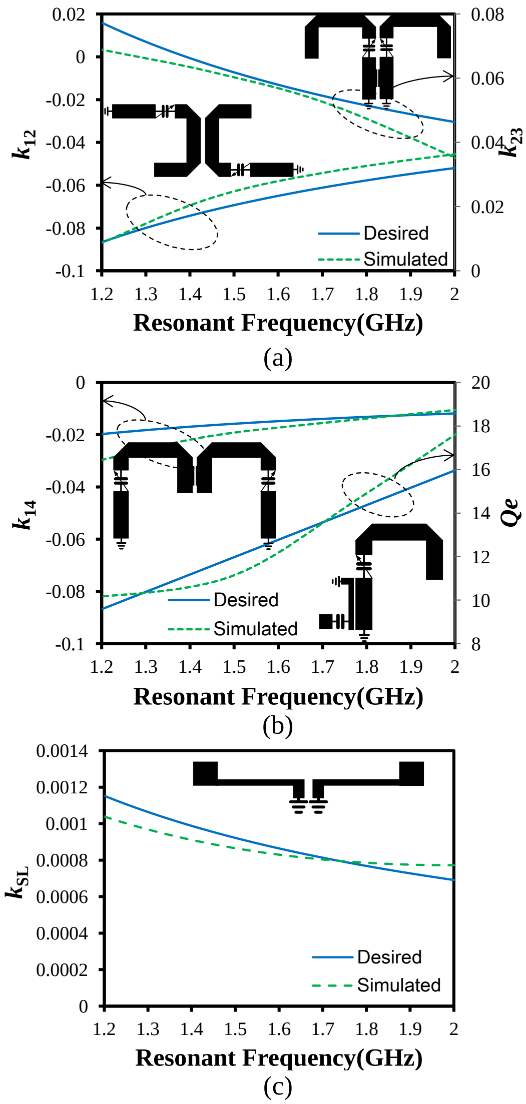

Fig. 2. Desired and simulated result: (a) coupling coefficient k_{12} and k_{23}, (b) coupling coefficient k_{14} and external quality factors Qe, and (c) source-load coupling coefficient k_{SL}.

Based on the tuning, the strength of magnetic-dominated coupling coefficient k_{23}, electric-dominated coupling coefficient k_{12} and k_{14} and source-load coupling coefficient k_{SL} decrease as the resonant frequency increase, and the external quality Qe increase as the resonant frequency increase, then the simulated slope of k_{12}, k_{23}, k_{14}, k_{SL} and Qe can be same with the desired. So these coupling structures can be used to build the cross-coupled tunable BPF with constant ABW.

III. DESIGN OF SIX-ORDER BPF

According to the above method and theory of designing four-order filter, the six-order filter is realized to have one pair of TZs on the normalized resonant frequency ±1.2 for high selectivity and maximum in-band return loss of the filter is 20dB. By using the synthesis technique [19], when the resonant frequency is 1.6GHz and the ABW is settled to 120MHz, the main design coupling coefficients are k_{12}=k_{56}=0.062 k_{23}=k_{45}=-0.040, k_{34}=-0.059, k_{25}=0.020 and external coupling factor Qe=13.6.

Figure 3 shows the proposed six-order BPF. Figure 4 is the comparison curve between simulated and desired after the adjustment of coupling coefficient. It can be seen that after a series of adjustments, the coupling coefficient curve has basically met the requirements. By using these initial values and further optimization, the purpose of designing a high-order constant ABW filter can be achieved.

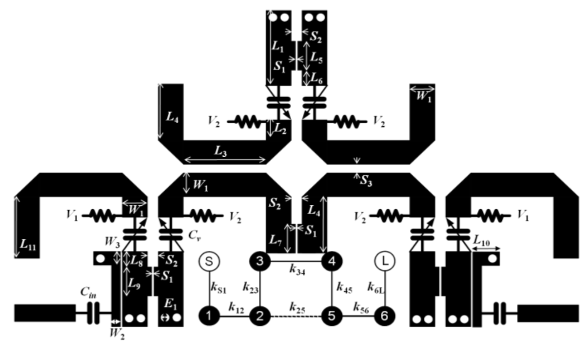

Fig. 3. The cross-coupled topology of the proposed six-order tunable bandpass filter.

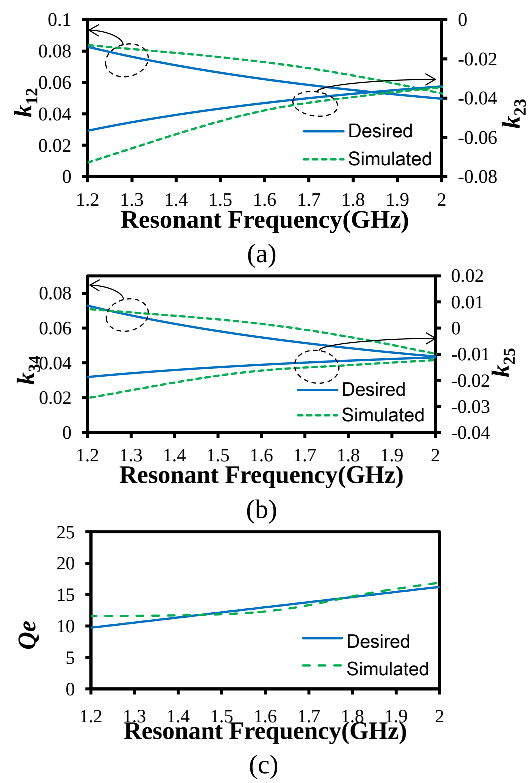

Fig. 4. The desired and simulated: (a) k_{12} and k_{23}; (b) k_{34} and k_{25}; (c) Qe.

IV. FABRICATION AND MEASUREMENT

Through the above analysis, combined with simulation software Sonnet and Agilent Advanced Design System for collaborative simulation, the four-order BPF with optimized geometry parameters (L_1=19.5, L_2=2.8, L_3=16.7, L_4=13.9, L_5=7.6, L_6=2.9, L_7=2, L_8=5.2, L_9=3.1, L_{10}=23.1, L_{11}=5.4, W_1=2.6, W_2=1, W_3=1.3, W_4=0.6, E_1=0.8, S_1=0.1, S_2=1.3, S_3=0.1, Unit: mm, Cin=2.2pF) has been obtained, and the six-order BPF filter with optimized geometry parameters (L_1=18.3, L_2=4, L_3=15.2, L_4=10.5, L_5=10.2, L_6=2.2, L_7=3, L_8=2.2, L_9=10.2, L_{10}=3.9, L_{11}=12, W_1=2.6, W_2=0.8, W_3=1.2, E_1=0.8, S_1=0.1, S_2=1.5, S_3=0.3, unit: mm Cin=2.4pF) has been obtained. The substrate is 0.8mm F4B-2 with a relative dielectric constant of 2.65 and a loss tangent of 0.001. SMV1405 varactors (C_v-0~30V, 0.63~2.67pF) is considered to be tuning elements. Since the input and output resonator are coupled to the feed in network, the designed filter needs to be synchronously tuned, and two different bias voltage V_1 and V_2 are used to tune the passband.

The fabricated four-order BPF with source-load is illustrated in Fig. 5. The core area is 80mm×82mm. The fabricated six-order BPF with source-load is illustrated in Fig. 7. The core area is 72mm×107mm. The S-parameters are measured by Agilent E5071C vector network analyzer. Figure 6 and Fig. 8 show the measured S-parameters, which is in good agreement with the simulation. The resonant frequency of four-order BPF can be continuously tuned from 1.31 GHz to 1.98 GHz, and four-TZs are generated beside the passband, leading to a sharp selectivity. The -3dB ABW is in the range of 119.5±2.5MHz. The insertion loss of the passband is 2.7 dB ~ 4.4 dB. The resonant frequency of six-order can be continuously tuned from 1.39 GHz to 2.07 GHz, and TZs are generated beside the passband, leading to a sharp selectivity. The -3 dB ABW is in the range of 102±6MHz. The insertion loss of the passband is 5.2 dB~6.8 dB. The return loss of two filters is better than 10 dB over the entire tuning range.

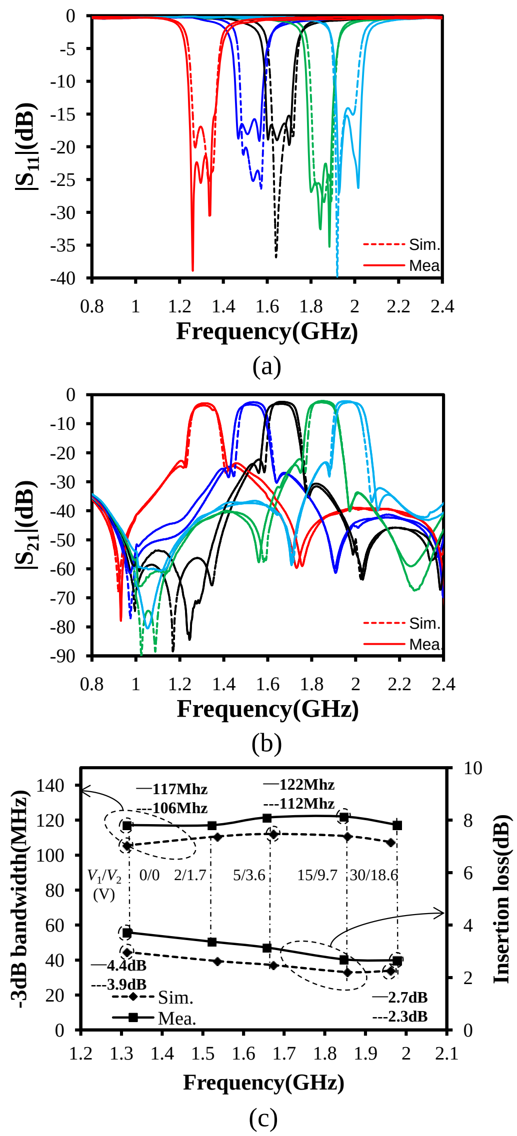

Fig. 6. Comparison between simulated and measured results of proposed four-order source-load BPF: (a) S_{11}, (b) S_{21}, and (c) -3dB bandwidth and insertion loss.

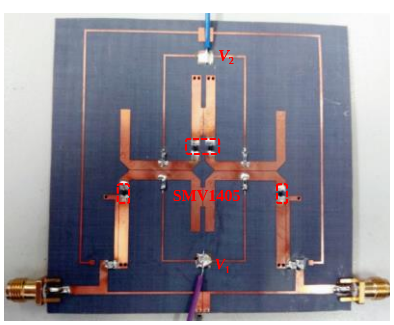

Fig. 5. Photograph of fabricated filter.

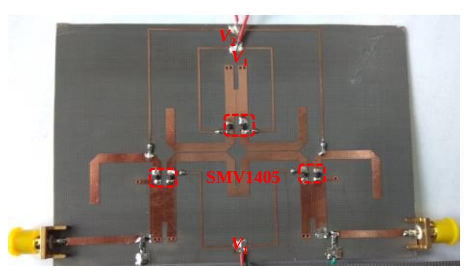

Fig. 7. Photograph of fabricated filter.

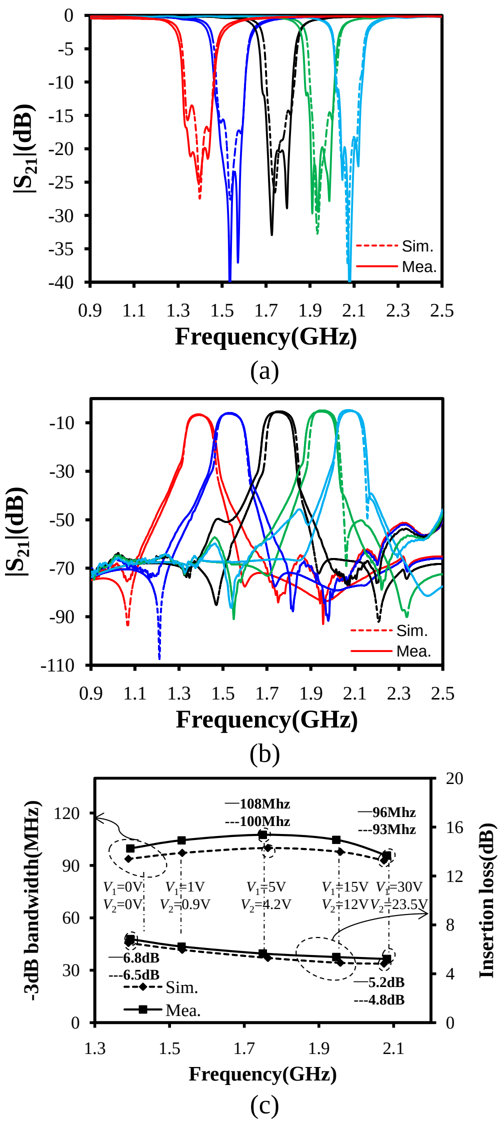

Fig. 8. Comparison between simulated and measured results of proposed six-order BPF: (a) S_{11}, (b) S_{21}, and (c) -3dB bandwidth and insertion loss.

It can be seen from the above measurements that the out-of-band suppression of the six-order filter is better than that of the four-order filter, but the insertion loss of the six-order filter is larger than that of the four-order filter, which also leads to the decrease of the overall bandwidth. How to reduce the insertion loss of high order tunable filters is also an important consideration. The two filters in this paper meet the design requirements.

V. CONCLUSION

The electric-dominated coupling structure and magnetic-dominated coupling structure is proposed, and two novel high order cross-coupled tunable BPF with constant ABW and four-TZs has been designed. The proposed coupling tuning method makes it easier to design high order BPF. Good agreement between simulated and measured responses of the filter is demonstrated. The proposed BPF with high selectivity will find its applications in RF front-end systems.

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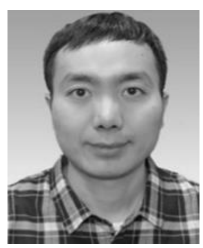

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