Tunable Bandstop Filter with Bandwidth Compensation

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Abstract **─** In this paper, a tunable bandstop filter with bandwidth compensation is proposed. The equivalent circuit model of the tunable capacitor network is presented to study the tunable mechanism. The electric coupling factor of the tunable capacitor network increases while the tunable capacitor increases. This mechanism can be used to compensate the bandwidth of the tunable filter. In our work, semiconductor varactor diode loaded microstrip LC resonator is adopted to design a tunable bandstop filter. Each resonator requires only one varactor diode for both central frequency and resonator coupling coefficient control. The *S*-parameters and group delays of the tunable bandstop filter are presented. The measurement shows that the -30 dB absolute bandwidth varies from 371 MHz to 305 MHz, while the central frequency of the stopband varyies from 3.195 GHz to 2.285 GHz.

Index Terms **─** Electric coupling, tunable bandstop filter.

I. INTRODUCTION

Microwave bandstop filter is one of the most important components to filter out the unwanted signals or nearby huge power signals, and avoid frequency aliasing in the intermediate frequency [1-3]. Recently, it is very popular to add tuning ability to conventional microwave components to realize electrically tunable/reconfigurable microwave components, which can well satisfy the requirements of modern multi-band and programmable wireless systems [3]-[16]. Tunable microwave bandstop filters will play a key role in the future radio frequency front-end.

Various tuning techniques have been utilized for tunable filter designs. Magnetic materials, i.e., ferrite were employed to tune the stopband. However, the magnetic bias circuit is complex and the filter size is bulky [7]. Semiconductor varactor diode [9]-[16], liquid metal [5], and micro-electro-mechanical (MEMS) [6], [8] tuned planar resonators are used in compact tunable bandstop filter designs. Recently, tunable filters with constant bandwidth or controllable bandwidth are becoming an attractive topic in this area [10]-[16]. However, few works on tunable bandstop filter with constant bandwidth or controllable bandwidth have been reported in the literature. In [15], a constant bandwidth tunable bandstop filter was designed based on a dual-band circuit with a wide passband and integrated narrow stopband. In [16], a mixed electric and magnetic coupling structure is introduced to obtain tunable bandstop filter with constant absolute bandwidth.

In this paper, a novel approach is proposed to design electrical tunable bandstop filter with bandwidth compensation. A tunable capacitor network with controllable electric coupling coefficient is proposed. Based on the simple electric coupled tunable capacitor network, the bandwidth of the bandstop filter can be compensated. The tunable bandstop filter is designed, fabricated and measured.

II. FILTER DESIGN THEORY

From the microwave filter coupling matrix theory [17], the coupling matrix between the resonators can be written as:

$$M_{i,j}=\frac{k_{i,j}f_0}{ABW}=\frac{k_{i,j}}{FBW}, \tag{1}$$

where, $k_{i,j}$ (i,j=1,2,...) is the coupling coefficient, FBW is the fractional bandwidth, ABW is the absolute bandwidth, f_0 is the center frequency.

Since the frequency response of the filter is determined by the coupling matrix, equation (1) shows that constant ABW tunable filter requires the product of coupling coefficient and center frequency is constant. It means that, the coupling coefficient should increase while the central frequency of the tunable filter decreases.

Figure 1 (a) shows a second order LC resonant network with electric coupling (C_m). The resonant frequency decreases when capacitor C increases. The coupling coefficient k can be expressed as:

$$k=k_e=\frac{C_m}{C}, \tag{2}$$

where, k_e is the electrical coupling coefficient, C is the resonant capacitance, C_m is the electrical coupling

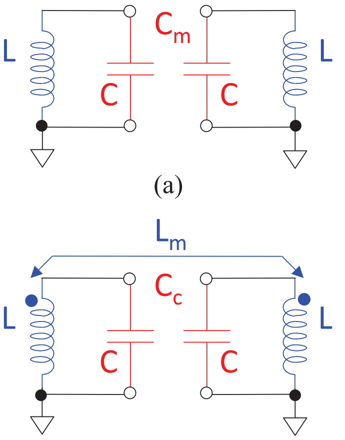
Submitted On: April 9, 2014
Accepted On: May 25, 2015

capacitance. Since the coupling capacitor is too small to be efficiently tuned by semiconductor process in microwave band, it can be seen from equation (2) that the coupling coefficient decreases when the capacitor C increases, therefore the FBW decreases when the resonant frequency of the LC resonator decreases.

The traditional method to control the coupling coefficient is based on mixed coupling (L_m, C_m), as shown in Fig. 1 (b). Due to the cancellation of magnetic and electric coupling, the coupling coefficient can be written as [18]:

$$k \approx k_m - k_e = \frac{L_m}{L} - \frac{C_m}{C}, \tag{3}$$

where, k_m is the magnetic coupling coefficient, L is the resonant inductance, L_m is the mutual inductance. The resonant frequency decreases when capacitor C increases, and the coupling coefficient increases. Therefore the FBW increases when the resonant frequency decreases. The bandwidth can be compensated. However, this method cannot be used in the filter topologies with pure electric coupling.



(a)

(b)

Fig. 1. Second order coupling network: (a) electrical coupling, (b) mixed coupling.

Figure 2 shows the proposed tunable capacitor network with controllable electrical coupling coefficient. The traditional capacitor network of C and C_m is replaced by the novel capacitor network of C_T, C_f and C_c. By using the symmetry of the circuit model in Fig. 2, the odd- and even-mode capacitor C_{odd} and C_{even} can be written as:

$$C_{odd} = \frac{C_T\ C_f + 2C_c}{C_T + C_f + 2C_c}, \tag{4}$$

$$C_{even} = \frac{C_T C_f}{C_T + C_f}. \tag{5}$$

Based on equation (4) and (5), the electric coupling factor k_e of the tunable capacitor network can be written as [18]:

$$k_e = \frac{C_{odd} - C_{even}}{C_{odd} + C_{even}} = \frac{C_c}{C_f + C_c + \dfrac{C_f^2 + 2C_f C_c}{C_T}}. \tag{6}$$

By studying (6), it shows that k_e increases when C_T increases, and the slope of k_e to C_T can be controlled by C_c and C_f. Let C_T to be the tunable capacitor, it can be seen from equations (4) and (5) that the tunable ratio of C_{odd} and C_{even} is limited mainly by C_f. While C_f increases, the tunable ratio increases. Benefiting from the resonant frequency splitting effect, the bandwidth can be controlled by the coupling coefficient. Thus, this mechanism can be applied to compensate the bandwidth of the tunable filter.

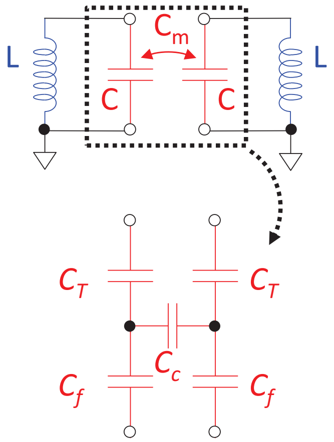


Fig. 2. Tunable capacitor network with controllable electrical coupling coefficient.

III. DESIGN AND MEASUREMENT

Figure 3 shows the layout of the proposed bandstop filter based on novel tunable capacitor network with controllable electric coupling coefficient. The filter is designed on 0.8 mm F4B-2 substrate (ε_r=2.65, $tan\theta$=0.001). Skyworks SMV1405 is chosen as the varactor diode, the anode and cathode terminals of the varactor diodes are connected between the capacitor and inductor of the LC resonators, respectively. Three 100 kΩ resistors are chosen as the biasing RF choke, as shown in Fig. 3. A lumped element equivalent circuit model for the tunable capacitor network of the LC resonators is depicted in Fig. 3. In this model, the microstrip patch of the LC resonators is modeled as the capacitor C_f. C_c indicates the electric coupling effect between the two resonators, and C_T is the varactor diodes.

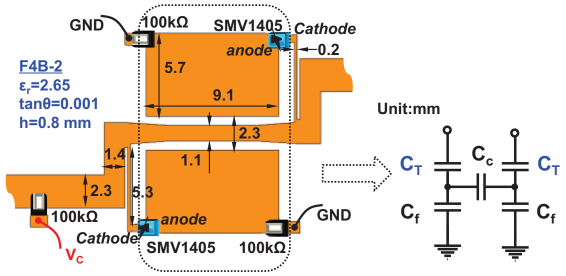
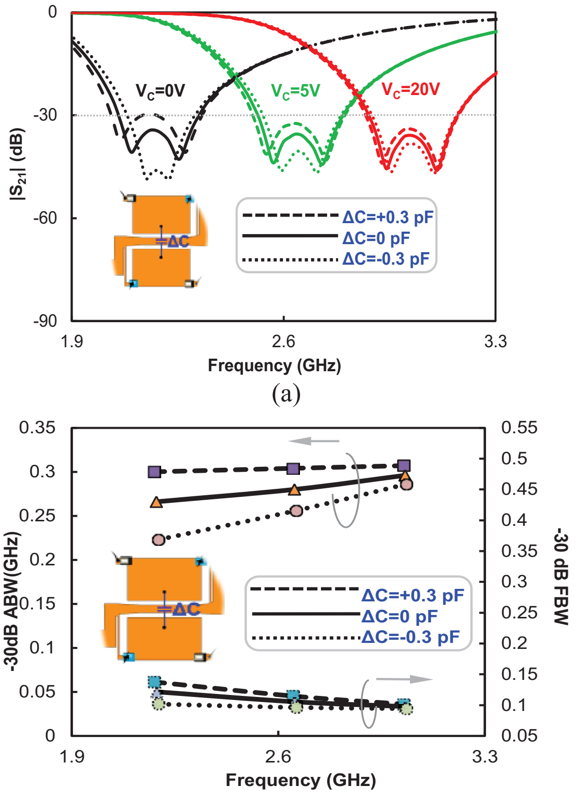


Fig. 3. Schematic diagram of the proposed tunable bandstop filter.

Figures 4 (a) and (b) show the simulated $|S_{21}|$, -30 dB *ABW* and *FBW* of the tunable filter. The passive structure of the filter is simulated by electromagnetic (EM) simulator *SONNET*. Then, the EM simulated touchstone file (S*n*P file) of the passive filter loaded with tunable elements, i.e., SMV1405, 100 kΩ resistor, and an additional ideal electric coupling capacitor Δ*C* as shown in the inset of Fig. 4 (a) and (b), is simulated in *Agilent Advanced Design System* (ADS).



(a)

(b)

Fig. 4. Simulated results when the reverse voltage of the varactor diode varies from 0 V to 20 V, and an additional coupling capacitor Δ*C* between the resonators varies from -0.3 pF to 0.3 pF: (a) $|S_{21}|$, (b) -30 dB *ABW* and *FBW*.

It shows that, the *FBW* of the tunable filter increases while the working frequency decreases. The slope of *FBW* to the central frequency can be controlled by the electric coupling capacitor. Therefore, the bandwidth of the tunable filter can be compensated.

The tunable bandstop filter is fabricated and measured for the validation of the proposed method. The layout shown in Fig. 3 is fabricated on 0.8 mm F4B-2 substrate (ε_r=2.65, *tanθ*=0.001). The core area is 15 mm × 14 mm. Skyworks SMV1405 is chosen as the varactor diode, and the varactor diodes are biased through 100 kΩ resistor RF choke, as shown in Fig. 5. The measurement is done by *Agilent* E5071C vector network analyzer. The measured results are shown in Fig. 6.

Figure 6 (a) shows the *S*-parameters of the tunable bandstop filter; the stopband of the filter can be tuned very well. Since the filter is a lumped-element microstrip filter, it exhibits small physical size and broad spurious-free frequency bands. While the reverse bias voltage V_C of the varactor diodes is 0 V, 5 V, and 20 V, the $|S_{21}|$ and group delay are shown in Figs. 6 (b), (c), and (d), respectively. The measured group delays of the passbands are less than 1 ns and the rejection of the stopband is better than 30 dB. Figure 6 (e) summarizes the measured -30 dB *ABW* and *FBW* versus the central frequency of the stopband. The *FBW* varies from 11.14% to 13.35%, and the ABW varies from 371 MHz to 305 MHz, while the center frequency of the filter varies from 3.195 GHz to 2.285 GHz.

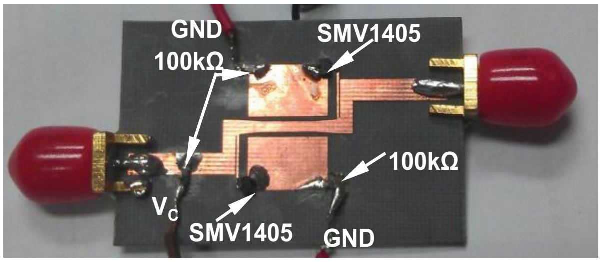
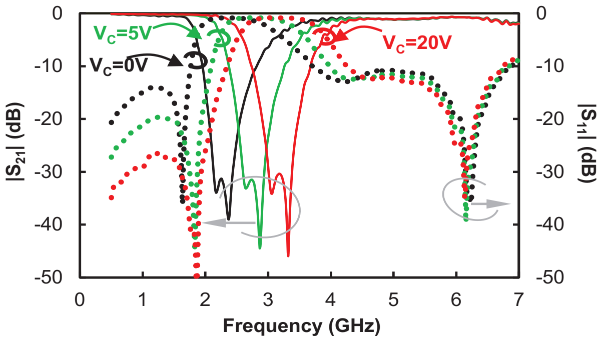
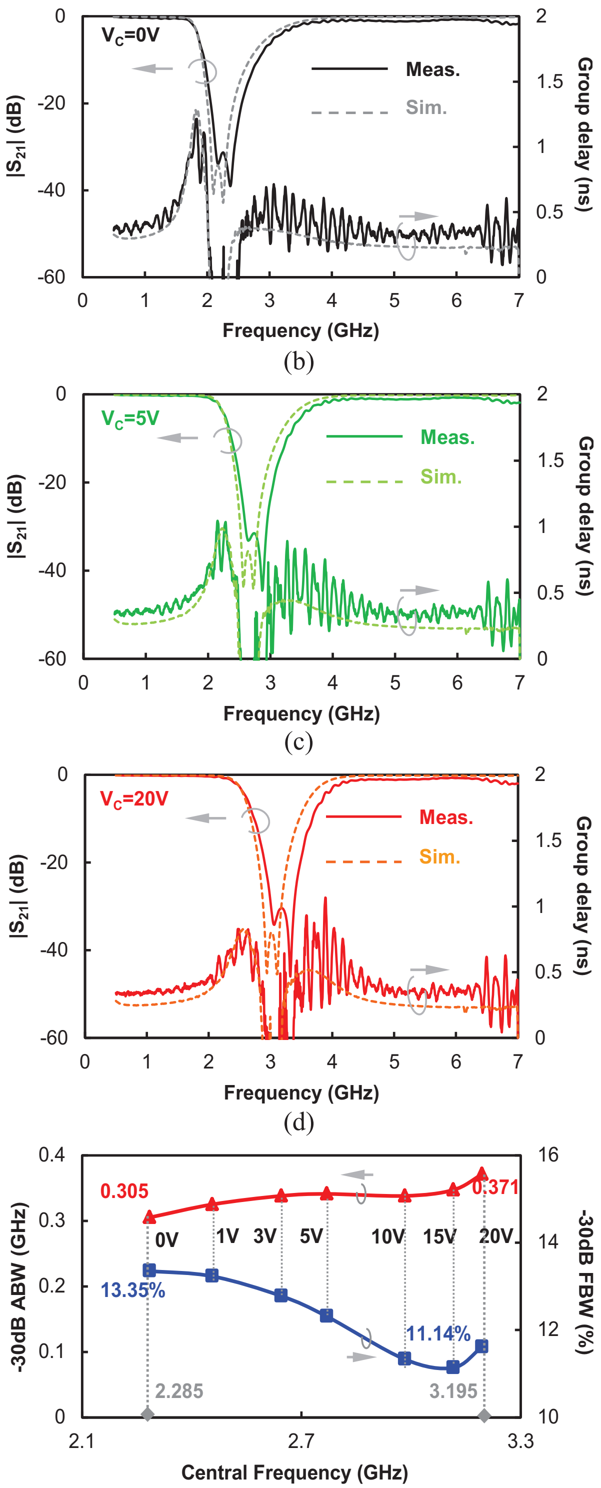


Fig. 5. The photograph of the fabricated tunable bandstop filter.



(a)



(b)

(c)

(d)

(e)

Fig. 6. The simulated and measured characteristics of the tunable filter: (a) the S-parameters of the tunable bandstop filter, (b) the $|S_{21}|$ and group delay when control voltage V_C=0 V, (c) the $|S_{21}|$ and group delay when V_C=5 V, (d) the $|S_{21}|$ and group delay when V_C=20 V, and (e) the measured -30 dB *ABW* and *FBW*.

Therefore, the proposed bandwidth compensation method has been validated. Comparing with [15] and [16], only electric coupling is used to compensate the bandwidth in this method, and the lumped tunable capacitor network is simple and easy to design.

IV. CONCLUSION

This paper has presented a tunable capacitor network to tune bandstop filter. The electric coupling factor of the tunable capacitor network increases when the tunable capacitor increases. This mechanism can be used to compensate the bandwidth of the tunable bandstop filter since the bandwidth can be controlled by the coupling factor through the resonant frequency splitting effect. Microstrip LC resonator loaded with Skyworks SMV1405 semiconductor varactor diode has been adopted to implement the tunable bandpass filters. It shows that the -30 dB fractional bandwidth varies from 11.14% to 13.35%, and the -30 dB absolute bandwidth varies from 371 MHz to 305 MHz, while the center frequency of the stopband varies from 3.195 GHz to 2.285 GHz. The tunable method presented in this paper is simple to implement and is a good candidate for the radio systems requiring flexible channel control.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (NSFC) under Grant 61401375, 61271090, the Fundamental Research Funds for the Central Universities under Grant 2682014RC24, 2682015CX065, the Sichuan Province Science and Technology Support Program 2015GZ0103, and the Cultivation Project of Sichuan Province Science and Technology Innovation Seedling Project 2014-047.

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