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A Novel Tunable LC Bandpass Filter with Constant Bandwidth based on Magnetic Dominant Mixed Coupling

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Abstract—In this paper, a novel tunable LC bandpass filter (BPF) based on LC magnetic-dominant mixed coupling is proposed. The design equations for the coupling coefficient and resonating frequency are given. The magnetic dominant coupling region and electric dominant coupling region are studied. The magnetic-dominant mixed coupling is used to compensate the bandwidth of the tunable filter, so that the tunable filter with constant absolute bandwidth can be obtained. The filter is designed, simulated, and measured, and the measurement matches the simulation very well. The measurement shows that the central frequency tuning range is from 72 MHz to 222 MHz with -3 dB bandwidth of 16.5 ± 3.5 MHz.

1. INTRODUCTION

Tunable RF filters have the characteristics of tunable performance such as center frequency and bandwidth, which can flexibly meet different indicators, realize different frequency selections, and greatly promote the integration of wireless communication equipment miniaturization and control simplification [1, 2]. For achieving a constant bandwidth response during frequency tuning, microstrip tunable filters with varactor diodes have been reported [3–9]. At present, there are mainly two types of bandwidth compensation method. One is based on electric coupling with coupling coefficient compensation [10, 11] and the other based on magnetic-dominant mixed coupling with coupling coefficient compensation [12–14]; however, most of them are implemented with microstrip and working in GHz band. Lumped LC tunable filters with constant bandwidth working from several tens of MHz to hundreds of MHz are very important for short wavelength software defined radio system; however, this type of tunable filter is rarely reported [15].

This paper introduces a tunable LC bandpass filter with a novel magnetic-dominant mixed coupling structure. This novel coupling structure can reduce the value of the lumped coupling inductor compared with the one in [15], which is very important for reducing the size of the component in future integrated circuit realization. The magnetic dominant coupling region and electric dominant coupling region are studied. The magnetic-dominant mixed coupling is used to compensate the coupling coefficient of the tunable filter, and the slope and strength of the coupling coefficient can be predesigned. The second section of the article introduces the mixed coupling structure. The third section describes the filter design and simulation, and the fourth section tests the verification performance. The conclusion is given in Section 5.

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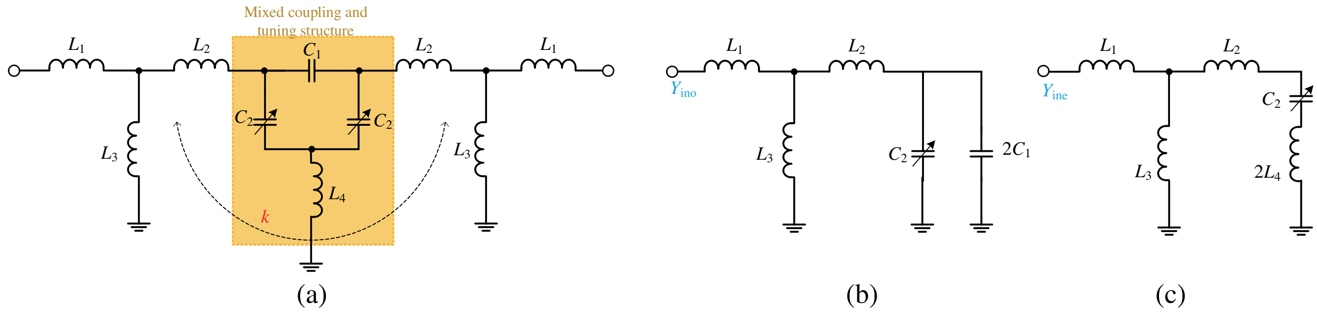

Figure 1. The proposed tunable filter with novel magnetic dominant mixed coupling: (a) the tunable filter circuit, (b) odd mode equivalent circuit, (c) even mode equivalent circuit.

2. MAGNETIC DOMINANT MIXED COUPLING LC STRUCTURE

The proposed filter is shown in Figure 1(a). In the mixed-coupling and tuning structure, C_1 and L_4 are the electric and magnetic coupling elements, and a tunable capacitor C_2 is used to tune the central frequency with predefined coupling coefficient based on the mixed-coupling. The odd and even mode equivalent circuits are shown in Figures 1(b) and (c). It can be seen from Figure 1(c) that the circuit structure has a value twice the coupling inductor enters the resonant loop in series in the even mode; therefore, this novel coupling structure can reduce the value of the lumped coupling inductor comparing with the one in [15] (which is with half value of the coupling inductor in parallel with the resonator inductor). To analyze the tunable capability of the proposed filter, the odd- and even-mode input admittances are written as follows:

$$Y_{ino} = \frac{1}{j\omega L_1 + \dfrac{1}{\dfrac{1}{j\omega L_3} + \dfrac{1}{j\omega L_2 + 1/j\omega\left(C_2 + 2C_1\right)}}} \tag{1}$$

$$Y_{ine} = \frac{1}{j\omega L_1 + \dfrac{1}{\dfrac{1}{j\omega L_3} + \dfrac{1}{j\omega\left(L_2 + 2L_4\right) + 1/j\omega C_2}}} \tag{2}$$

The odd and even mode resonating frequencies f_{o} and f_{e} can be obtained by making the imaginary part of the input admittances equal to zero:

$$\begin{cases} IM(Y_{ino}) = 0 \\ IM(Y_{ine}) = 0 \end{cases} \tag{3}$$

According to the resonating frequencies f_o and f_e, the center frequency is defined as $f_c = (f_e + f_o)/2$, and the coupling coefficient $|k|$ can be obtained as [16]:

$$|k| = \left|\frac{f_o^2 - f_e^2}{f_o^2 + f_e^2}\right| \tag{4}$$

Figure 2(a) shows that the even and odd mode resonating frequency can be tuned by C_2, and the calculation matches the simulation very well. Figure 2(b) indicates that the mixed coupling is electric dominant coupling when C_2 is with small value, and it is magnetic-dominant coupling when C_2 is with large value. It shows that the magnetic dominant coupling coefficient can be increased with the increase of C_2 to compensate the bandwidth at low frequency band, and C_1 can regulate the coupling region under certain L_4. Figure 2(c) illustrates that the strength and slope of the magnetic-dominant coupling coefficient curve can be controlled by C_1 and L_4. Therefore, the proposed LC filter structure can meet the requirement of tunable filter with constant bandwidth in magnetic dominant coupling region.

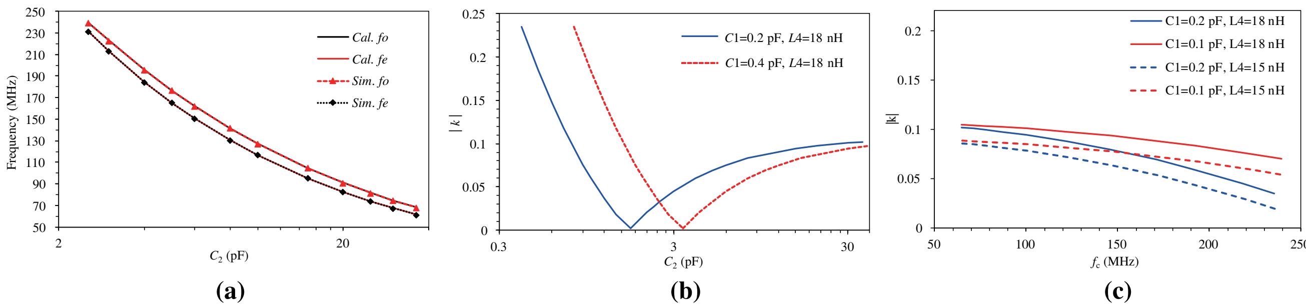

Figure 2. The tunable capability of the proposed structure: (a) central frequency f_c versus C_2, (b) the magnetic dominant coupling region and electric dominant coupling region, (c) the strength and slope of the magnetic-dominant coupling coefficient can be pre-designed. ($L_1 = L_2 = 82\,\text{nH}$, $L_3 = 68\,\text{nH}$, $L_4 = 18\,\text{nH}$, $C_1 = 0.2\,\text{pF}$).

3. FILTER DESIGN AND SIMULATION

To verify the constant bandwidth tunable capability of the proposed circuit, an $N+2$ coupling matrix shown in Eq. (5) is used to define the filter response [16]. The positive values of the matrix represent magnetic coupling, and the negative values are electrical coupling. The filter topology is shown in Figure 3(a). The white circles noted as numbers 1 and 2 represent two resonators employed in this design. Black circles noted as letters S and L represent source and load. Letter E denotes electric coupling, and letter M represents magnetic coupling. Since the resonators are with magnetic dominant mixed coupling, source to load electric cross-coupling is used to generate two transmission zeros (Tzs) besides the passband. By setting the absolute bandwidth (ABW) to 17 MHz, the tunable S-parameter can be deduced as shown in Figure 3(b), and the requirement of the external quality factor Q_e and coupling coefficient between the two resonators are shown in Figure 3(c) as dash lines by using Eqs. (7) and (6) [17].

$$M = \begin{pmatrix} 0 & 0.6860 & 0 & -0.0222 \\ 0.6860 & 0 & 0.5536 & 0 \\ 0 & 0.5536 & 0 & 0.6860 \\ -0.0222 & 0 & 0.6860 & 0 \end{pmatrix} \tag{5}$$

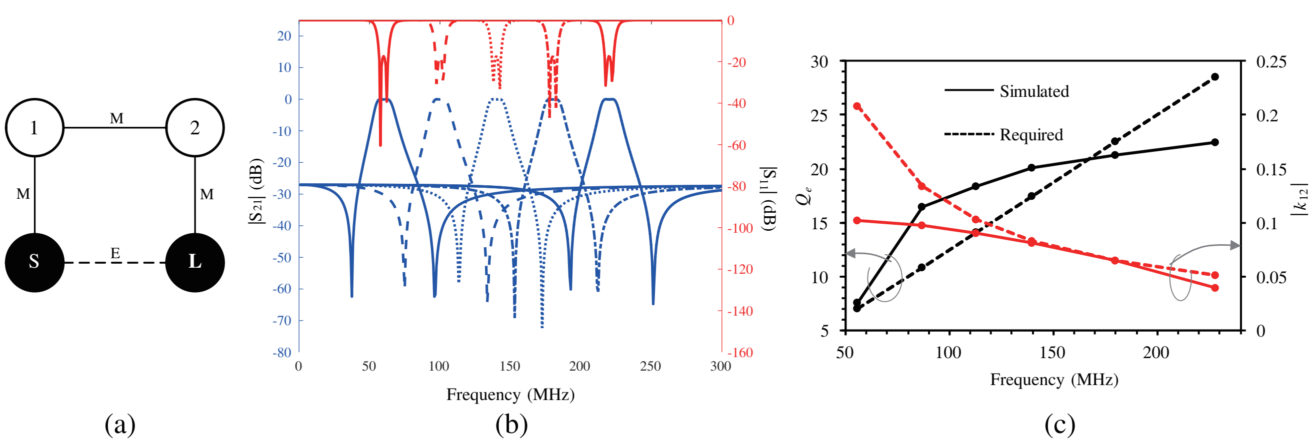

Figure 3. (a) The filter coupling topology, (b) calculated S Parameters, (c) the required (dash lines) and simulated (solid lines) Q_e and coupling coefficient between the two resonators $|k_{12}|$versus the central frequency of the passband.

$$k_{ij} = \frac{M_{ij} \cdot ABW}{f_c}, \quad (i, j \neq S, L) \tag{6}$$

$$Q_e = \frac{f_c}{M_{S1}^2 \cdot ABW} \tag{7}$$

The designed second-order tunable LC BPF based on mixed coupling is shown in Figure 4(a). A capacitor C_3 is used as the electric type source and load coupling to generate the cross-coupling Tzs. The PCB layout is shown in Figure 4(b). The circuit is designed on FR4 ($h = 1$ mm, $\varepsilon_r = 4.6$, $\tan\theta = 0.019$), and the width of the $50\,\Omega$ line is 1.8 mm. The varactor diode SMV1212-004 is applied as tunable capacitors. The varactor diodes are biased by Vc ranging from 0 V to 8 V through a $10\,\text{k}\Omega$ resistor. The inductors and capacitors marked in the layout are from *Coilcraft* and *American Technical Ceramics*, and their touch stone files were used in the simulation. The simulation of the external quality factor Q_e and coupling coefficient between the two resonators are shown in Figure 3(c) as solid lines. The simulated S-parameters, -3 dB bandwidth, and insertion loss are shown in Figure 5.

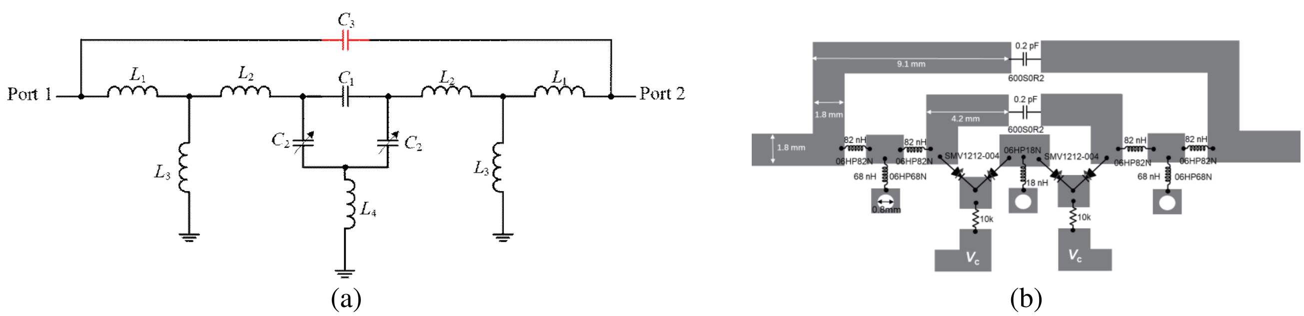

Figure 4. (a) The tunable filter schematic, (b) layout of the filter.

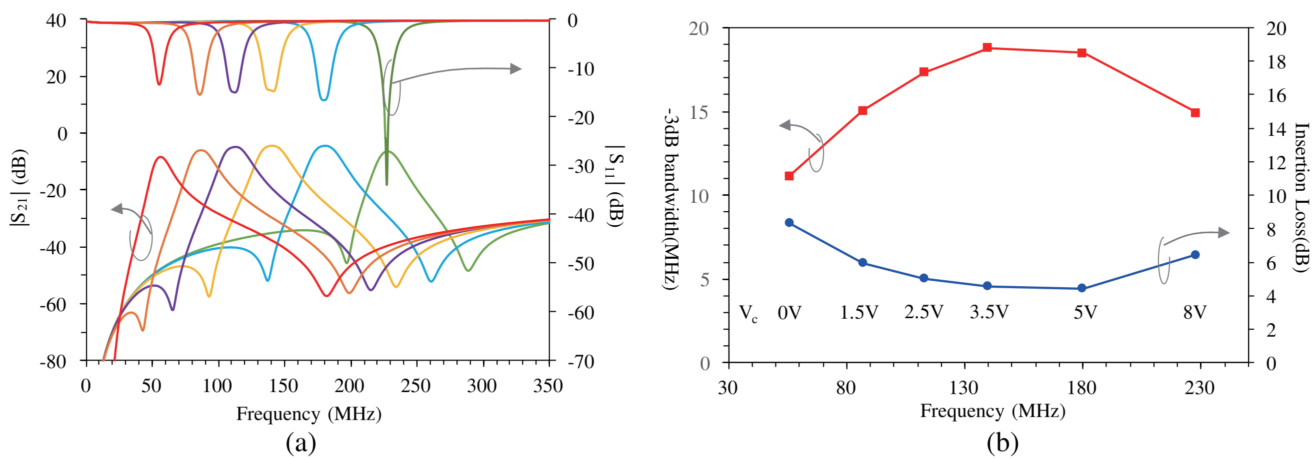

Figure 5. The simulation results: (a) S-Parameters, (b) -3 dB bandwidth and insertion loss.

It can be seen from Figure 5(a) that the filter passband can be tuned in the range of 56 MHz to 228 MHz, and two transmission zeros are generated besides the passband to enhance the out-band rejection. Figure 5(b) indicates that the simulated -3 dB bandwidth is 15 ± 4 MHz, and the insertion loss ranges from 4.4 dB to 8.3 dB.

4. FABRICATION AND MEASUREMENT

The fabricated filter is shown in Figure 6, whose size is 35 mm × 20 mm. The measured S-parameters results are shown in Figure 7(a). It shows that the central frequency can be tuned from 72 MHz to

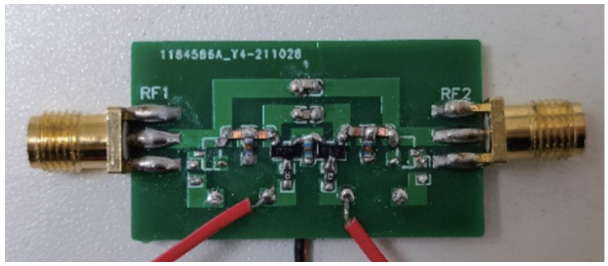

Figure 6. The photograph of fabricated tunable bandpass filter.

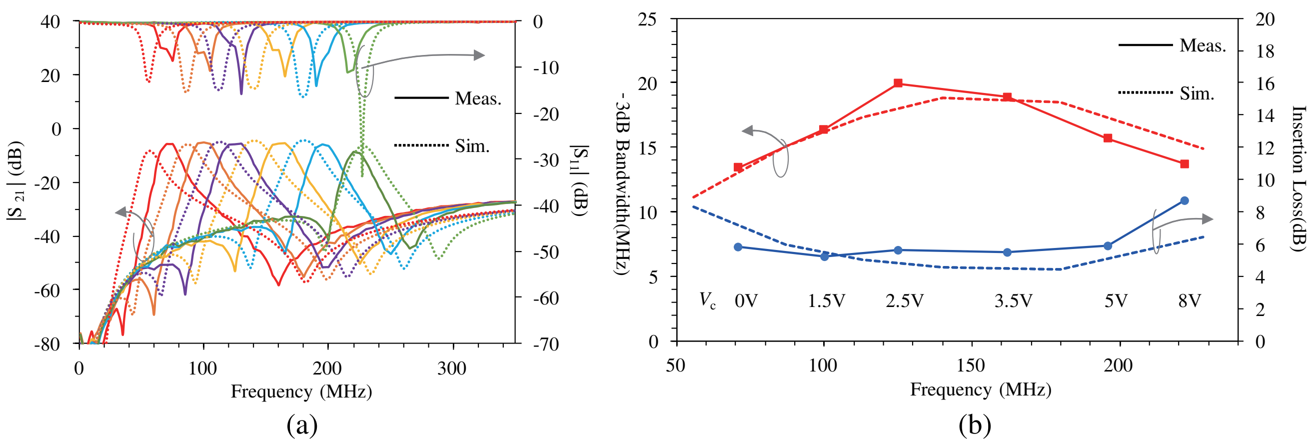

Figure 7. (a) Measured and S-Parameters, (b) measured -3 dB bandwidth and insertion loss.

222 MHz, and two transmission zeros are generated besides the passband. The -3 dB bandwidth and insertion loss results are shown in Figure 7(b). The results show that the -3 dB bandwidth is in the range of 13 MHz to 20 MHz, and the insertion loss ranges from 5.2 dB to 8.7 dB. Compared with the previous works, the bandwidth variation of this work is improved in VHF band, as shown in Table 1.

Table 1. Comparison with precious works.

Reference	**Frequency tuning range**	**Bandwidth**	**Insertion loss**	**Tuning element**	**Filter Order**
[15]	0.07–0.27 GHz	37.5 ± 17.5 MHz	2.2–2.9 dB	Varactor	2
[18]	0.43–0.72 GHz	75 ± 4 MHz	1.34–2.92 dB	Varactor	2
[19]	0.89–1.13 GHz	46.8 ± 3.4 MHz	3.2–4.3 dB	Varactor	4
This work	0.072–0.222 GHz	16.5 ± 3.5 MHz	5.2–8.7 dB	Varactor	2

5. CONCLUSION

In this paper, a novel mixed coupling tunable LC bandpass filter with constant bandwidth is proposed. The magnetic-dominant mixed coupling is used to design the tunable filter with constant absolute bandwidth. Measurement results show that the central frequency tuning range of fabricated filter is from 72 MHz to 222 MHz with -3 dB bandwidth of 16.5 ± 3.5 MHz. The insertion loss ranges from 5.2 dB to 8.7 dB.

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