ELectronics EXpress

LETTER

IEICE Electronics Express, Vol.10, No.18, 1–6

Compact tunable bandpass filter with improved stopband rejection and wide tuning range

Baolin Zhao[1a)], **Guanghui Gao**[1], **Xubo Wei**[2], **Peng Gao**[2], **and Yu Shi**[1]

[1] *State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Chengdu 611731, China*

[2] *Research Institute of Electronic Science and Technology, University of Electronic Science and Technology of China, Chengdu 611731, China*

a) *zhaobl99@163.com*

Abstract: A compact tunable bandpass filter (BPF) with wide tuning range and improved stopband rejection based on low-temperature co-fired ceramic (LTCC) technique is presented. The axial coupling structure is employed to achieve a wide tuning range and increase resonator Q. To improve the stopband characteristics, Multiple transmission zeros (TZs) are introduced near the passband. A new tunable BPF with a 100% tuning range from 480 to 960 MHz has been designed and fabricated to verify the proposed method. The measured results are in good agreement with the electromagnetic (EM) simulation. The circuit only occupies $3.5 \times 3.0 \times 1.7\,\mathrm{mm}^3$.

Keywords: tunable BPF, transmission zeros, mixed E/M coupling

Classification: Microwave and millimeter wave devices, circuits, and systems

References

[1] M. A. El-Tanani and G. M. Rebeiz: IEEE Trans. Microw. Theory Tech. **57** [4] (2009) 830.

[2] F. L. Yu, X. Y. Zhang and Y. B. Zhang: Progress In Electromagnetics Research Letters **33** (2012) 131.

[3] M. Sánchez-Renedo, R. Gómez-García, J. I. Alonso and C. Briso-Rodríguez: IEEE Trans. Microw. Theory Tech. **53** [1] (2005) 191.

[4] Q. Xiang, Q. Feng, X. Huang and D. Jia: IEEE Trans. Microw. Theory Tech. **61** [3] (2013) 1124.

[5] M. Sánchez-Renedo: IEEE Microw. Wireless Compon. Lett. **17** [7] (2007) 513.

[6] Q. X. Chu and H. Wang: IEEE Trans. Microw. Theory Tech. **56** [2] (2008) 431.

[7] K. Kageyama, K. Saito, H. Murase, H. Utaki and T. Yamamoto: IEEE Trans. Microw. Theory Tech. **49** [12] (2001) 2421.

DOI: 10.1587/elex.10.20130561
Received July 18, 2013
Accepted August 19, 2013
Publicized September 02, 2013
Copyedited September 25, 2013

1 Introduction

As one of the key components in RF systems, a tunable bandpass filters with compact size, wide stopband rejection, low loss and wide tuning range are increasingly required in modern multifunction receiver and wide-band radar systems to suppress the interference signals and harmonics. It is especially needed in the VHF and UHF frequency band where a crowded radio spectrum requires a high level of isolation of the desired spectrum. In [1, 2, 3, 4], several tunable BPFs with planar microstrip technique have been illustrated to achieve high selectivity and wide tuning range. However the size of filter was too huge for the actual application due to the limitation of coupling microstrip length. In [3], the tunable BPF has achieved a wide tuning range from 470 to 862 MHz, but the circuit was very complex to control the resonator and coupling varactor. In [4], a electrical tunable microstrip bandpass filter with constant bandwidth was achieved by the method of electric coupling coefficient compensation, the filter stopband rejection could be improved by introducing TZs to the circuit. It is desirable to design a filter in which extra TZs can be generated without sacrificing the passband response [5, 6]. The mixed electric/magnetic (E/M) coupling technique has been used in the circuit to improve the filter stopband rejection. In order to improve passband selectivity, the mixed E/M coupling technique can be introduced in the circuit of tunable BPF. In [7], the miniaturized tunable BPFs using LTCC technology was designed. The filter size is $5.6 \times 5.6 \times 3\,\mathrm{mm}^3$. Due to the limitation of coupling method, the filter has less than 15% tuning range. The passband selectivity and stopband rejection also were needed to be improved for the actual application.

In this letter, a miniaturized tunable filter with wide tuning range and enhanced stopband rejection using LTCC technique is presented. Five TZs can be realized in the stopband for enhanced frequency selectivity and stopband characteristics via introducing mixed E/M coupling between the source and load ports. An axial coupling structure is employed to achieve wide tuning range and low loss. Even-odd mode theory is applied to explain the circuits of the proposed tunable filter. To verify the proposed method, a tunable BPF prototype was designed, fabricated and measured.

2 Filter analysis and design

Fig. 1 shows the circuit schematic of proposed tunable BPF. The proposed filter was symmetric with respect to the I/O ports. The resonator consists

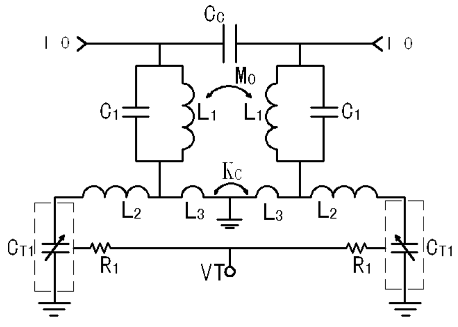

Fig. 1. Proposed tunable filter configuration

DOI: 10.1587/elex.10.20130561
Received July 18, 2013
Accepted August 19, 2013
Publicized September 02, 2013
Copyedited September 25, 2013

IEICE Electronics Express, Vol.10, No.18, 1–6

of inductor L_2 and back to back varactor diodes C_{T1} which was designed for improved filter linearity characteristics. The taped inductor L_2 has been used to realize axial coupling structure and improve frequency selectivity. The inductor L_1 has been used to improve the matching features and stopband rejection. Three transmission zeros near the passband of proposed filter can be realized by the capacitor C_c, the magnetic coupling M_0 between matched inductors L_1 and the axial magnetic coupling K_c between the taped inductors (L_2+L_3). The capacitor C_1 parallel with L_1 can introduce two TZs in the circuit to improve wideband stopband response. The resistor R_1 is used as a RF choke to provide the Bias voltage to varactor C_{T1}. Based on the double tuned circuit analysis, the conditions of wide-band tuning and resonance can be deduced as

$$\eta = K_C Q_P = 1 \tag{1}$$

$$Q_p = \sqrt{(L_2 + L_3)/C_{T1}}/R, \quad K_C = L_M/(L_2 + L_3) \tag{2}$$

$$f_0 = 1/2\pi\sqrt{(L_2 + L_3)C_{T1}} \tag{3}$$

Where η is the coupling factor of the filter, the filter acquires the condition of critical coupling when η is equal to 1. If the η is kept constant, the critical coupling coefficient K_c is inversely proportional to the parallel quality Q factor. From the equation (1) and (2), the condition of wide-band tuning range can be realized by choosing the good proportion between C_{T1} and K_C. The resonant frequency can be gained by the equation (3).

Considering the structure's symmetry, an odd- and even-mode analysis is adopted. By evaluating the even- and odd-mode input admittances, the transmission characteristic of the proposed filter could be calculated by (4)–(7). The magnetic coupling K_C is equivalent to inductor L_4 in formula (7). When $Y_{even}=Y_{odd}$, five transmission zeros can be achieved near the passband of proposed filter, as shown in Fig. 2. The TZ_1, TZ_2, and TZ_3 are used to improve the frequency selectivity. The TZ_4, TZ_5 are employed to widen the stopband of proposed filter.

$$S_{21} = \frac{Y_0(Y_{odd} - Y_{even})}{(Y_0 + Y_{even})(Y_0 + Y_{odd})} \tag{4}$$

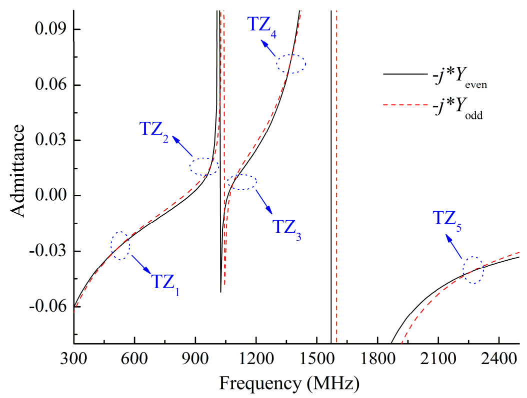

Fig. 2. The even- and odd-mode input admittances of proposed filter

DOI: 10.1587/elex.10.20130561
Received July 18, 2013
Accepted August 19, 2013
Publicized September 02, 2013
Copyedited September 25, 2013

$$S_{11} = \frac{Y_0^2 - Y_{odd}Y_{even}}{(Y_0 + Y_{odd})(Y_0 + Y_{even})} \tag{5}$$

$$Y_{even} = \frac{1}{\dfrac{j\omega(L_1 + M_0)}{1 - \omega^2 C_1(L_1 + M_0)} + \dfrac{(1 - \omega^2 L_2 C_{T1})(j\omega L_3 + j\omega L_4)}{1 - \omega^2 L_2 C_{T1} - \omega^2 L_3 C_{T1} - \omega^2 L_4 C_{T1}}} \tag{6}$$

$$Y_{odd} = j\omega \cdot 2C_C + \frac{1}{\dfrac{j\omega L_3(1 - \omega^2 L_2 C_{T1})}{-\omega^2 L_3 C_{T1} + 1 - \omega^2 L_2 C_{T1}} + \dfrac{j\omega(L_1 - M_0)}{1 - \omega^2 C_1(L_1 - M_0)}} \tag{7}$$

3 Filter simulation and measurement

The tunable BPF was designed for a 100% tuning range from 480 MHz to 960 MHz. The following values were chosen to minimize the passband insertion loss: the center frequency f_0 680 MHz, coupling inductor L_2=16 nH, 3 dB relative bandwidth 8%, so we could calculate the initial parameters L_1, (L_2+L_3), C_{T1} and K_C by equation (1)–(3). The ratio between L2 and L3 is 3:1. The odd- and even-mode analysis was adopted to analyse the TZs. When Y_{even}=Y_{odd}, the parameters M_0, C_C and C_1 could be calculate by (4)–(7). Based on the method discussed above, the initial parameters could be obtained. The simulation/optimization using ADS has been done to get exact design parameters. The parameters of the filter were determined as follows: L_1=6 nH, L_2=16 nH, the tap ratio is 1 to 4, C_{T1}=(1.86∼6.95) pF, $R_1 \geqq 10$ K, C_1=2.4 pF, C_C=0.06 pF, M_0=0.002, K_c=0.056. Fig. 3. shows the 3-D structure and the physical dimension of filter. The tunable BPF is optimized by the electromagnetic (EM) simulation using Ansoft HFSS 10 and embedded into a LTCC substrate, the dielectric constant and loss tangent of which are 5.9 and 0.002, respectively. The FX

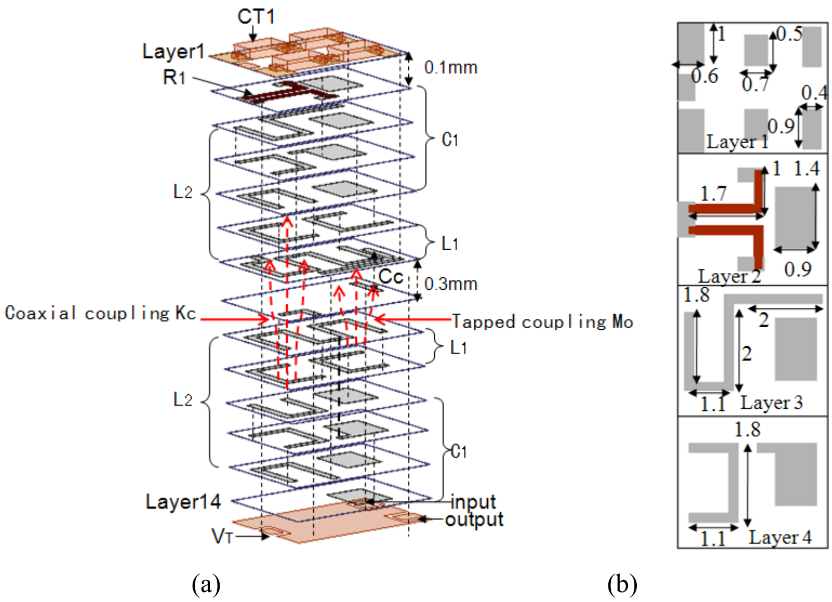

Fig. 3. LTCC structure of presented tunable BPF, and dimensions of patterns on layer1 to layer 4 (unit: mm) (a) LTCC structure b) Dimensions

DOI: 10.1587/elex.10.20130561
Received July 18, 2013
Accepted August 19, 2013
Publicized September 02, 2013
Copyedited September 25, 2013

87-102 thick film resistor pastes have been used in the filter, the resistivity was 1 KΩ/Sq. Fig. 4. shows the EM simulated response of the tunable BPF. While keeping low loss, the circuit of filter realizes a continuous tuning of pass-band with three TZs between 480 MHz and 960 MHz.

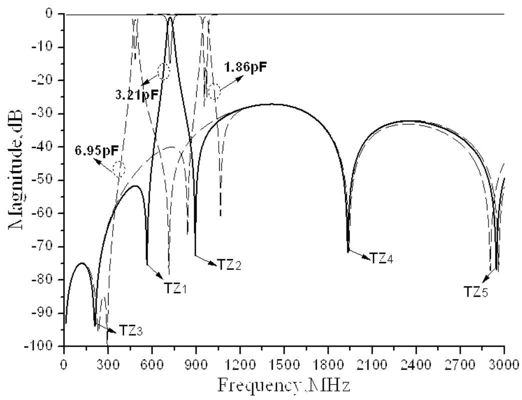

Fig. 4. The EM simulated S-parameter for the physical layout

To validate the proposed topology, a tunable BPF was designed and embedded into a LTCC substrate. The filter was composed of fourteen conductor layers inserted in the LTCC substrate. The varactors (Toshiba, 1SV214) were mounted on the top surface to control pass-band frequency with dc voltage. Fig. 5 shows a photograph of proposed tunable BPF and measurement results. The proposed filter was measured using an Agilent 8503E network analyser. Measured results show that the filter has approximately 100% tuning range of frequency with a controlling voltage 2.15V–17.41 V, the insertion loss (2.75∼2.1) dB (resonator Q of 68–121), return loss <14.5 dB, a 3 dB relative bandwidth (8∼9)%. In addition, the proposed tunable BPF has five TZs on stopband. The tunable BPF shows an 30 dB stopband rejection on both sides of the passband at $f_0 \pm 20\%$. By virtue of 3D structure and folded strip lines, the overall size of the filter is only $3.5 \times 3.0 \times 1.7\,\mathrm{mm}^3$. Good co-relationships are confirmed between the measured data and simulation results. The comparison with related work is summarized in Table I.

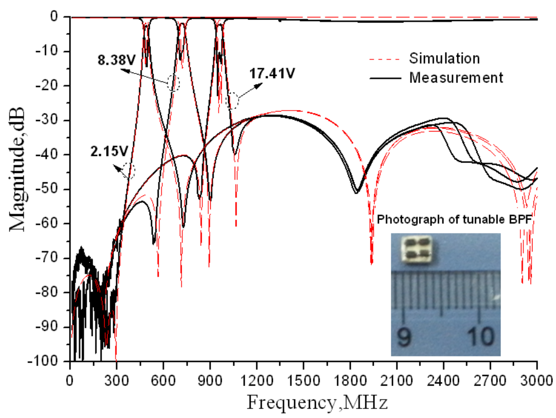

Fig. 5. Simulation and measurement results of the proposed tunable BPF

DOI: 10.1587/elex.10.20130561
Received July 18, 2013
Accepted August 19, 2013
Publicized September 02, 2013
Copyedited September 25, 2013

IEICE Electronics Express, Vol.10, No.18, 1–6

Table I. Comparison With Related Tunable Filters

Design	Tuning range (GHz)	Related Bandwidth (%)	Insertion loss (dB)	TZs	Physical dimension (mm^3)	filter order
El-Tanani. [1]	1.32-1.89	4.9±0. 5	2.9-1.25	2	8*15*0.625	2
Sánchez-Renedo. [5]	0.75-0.9	7.3-8.8	3.5-5.0	5	20*45*0.635	5
K. Kageyama. [7]	0.41-0.47	15	1.4-1.6	2	5.6*5.6*3.0	3
This work	0.48-0.96	8-9	2.75-2.1	5	3.5*3.0*1.7	2

4 Conclusions

A miniaturized tunable filter with super-wide tuning range and improved stopband characteristics using LTCC technique was presented. By making good use of the axial coupled helical inductors, the filter shows strong tunability and low loss. Three transmission zeros were introduced in the stopband to improve the passband selectivity by using mixed coupling technique. Based on LTCC technology and multilayer structure, the tunable BPF has a very compact size and is suitable for many compact wireless systems.

DOI: 10.1587/elex.10.20130561
Received July 18, 2013
Accepted August 19, 2013
Publicized September 02, 2013
Copyedited September 25, 2013