Progress In Electromagnetics Research, Vol. 135, 261–269, 2013

A TUNABLE 1.4–2.5 GHz BANDPASS FILTER BASED ON SINGLE MODE

Yanyi Wang*, Feng Wei, He Xu, and Xiaowei Shi

National Laboratory of Science and Technology on Antennas and Microwaves, Xidian University, Xi'an 710071, P. R. China

Abstract—A new type of varactor-tuned microstrip bandpass filter (BPF) based on a single $1/2\lambda$ resonator is investigated. The proposed resonator is composed of a transmission line with both ends short-ended and two varactors inserted symmetrically in the middle section. The variation of coupling coefficient can be controlled by using an inductor. With the proposed structure, it is easy to adjust the external quality factor of the filter and to control the bandwidth. Extra dc-block capacitors for the input and output ports are not necessary because the design of the proposed tunable $1/2\lambda$ resonator makes the varactor act as both a frequency tuning element and a dc-block circuit. The proposed BPF is found to have the advantages of compact size, low insertion loss, large tuning range and good linearity.

1. INTRODUCTION

Electronically reconfigurable or tunable microwave filters [1–6] are attracting more attention for research because of their increasing importance in improving the capability of current and future wireless systems. The tunability of such filters is usually accomplished by using different tunable components such as: RF micro-electromechanical systems (MEMS), p-i-n diodes and varactor diodes. Among various tuning technologies, varactor-tuned BPFs are highly attractive due to their compactness, high tuning speed and low cost.

Most research in tunable filters has been mainly focused on the realization of frequency tuning. However, in practical application, there are some requirements for bandwidth control. A mixed electric and magnetic coupling scheme is introduced to control absolute bandwidth (ABW) in [7]. Recently, filters with both frequency and

Received 17 November 2012, Accepted 14 December 2012, Scheduled 21 December 2012
* Corresponding author: Yanyi Wang (yanyiwang@foxmail.com).

bandwidth tuning capabilities have been reported [8–11]. Chiou and Rebeiz realized a varactor-tuned combline bandpass filter at 1.5–2.2 GHz with the 1-dB bandwidth of 50–170 MHz and insertion loss of 5.1–3.2 dB, respectively [8]. Serrano and Correra developed a tunable dual-mode triangular patch filter at 2.9–3.5 GHz with the 3-dB bandwidth of 4%–12% [10].

In this paper, the investigation aims to reduce the insertion loss and to explore the unique characteristics of the two resonant modes when varactors are introduced in the middle section. This leads to a simple tuning scheme for tuning the passband bandwidth, which is obviously influenced by the coupling inductor. For the experimental filter, the tuning range is 58% from 1.38 to 2.50 GHz whose 3-dB ABW is 116$\pm$11 MHz, and insertion loss of 2.7–3.9 dB (better than 3 dB from 1.8 to 2.5 GHz).

2. THEORY AND DESIGN EQUATIONS

2.1. Electric Field Distribution

Two conventional $1/2\lambda$ resonators with one varactor and two varactors are depicted in Figs. 1(a) and (b). Both types of conventional configurations require a dc-block capacitor for each port when the input/output coupling is directly tapped to the resonators [7], which accumulates extra loss. In this design, center frequency tuning can be achieved by the varactors inserted symmetrically in the middle section, as shown in Fig. 1(c). The microstrip line in the middle is very short and mainly used for the welding of varactors. The electric field distribution of the two types of conventional tunable $1/2\lambda$ resonators are both similar to that of a conventional $1/2\lambda$ resonator with both ends open-circuited as depicted in Fig. 2, whose voltage is minimum in the midpoint, as shown in Fig. 3(a). Hence, both ends must be

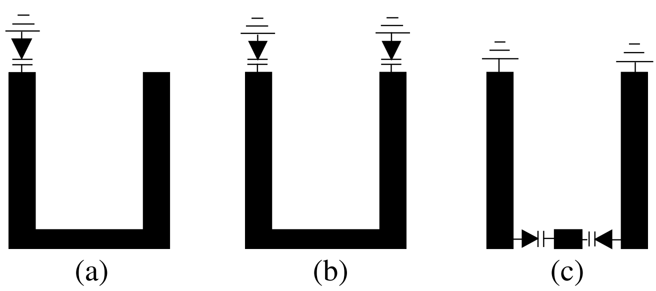


Figure 1. (a) and (b) Two types of conventional tunable $1/2\lambda$ resonator. (c) Proposed tunable $1/2\lambda$ resonator.

short-circuited if a large electric field is desired in the middle section of the resonator. So the proposed tunable $1/2\lambda$ resonator has both ends short-circuited whose electric field is similar to that in Fig. 3(b).

Since the proposed tunable $1/2\lambda$ resonator is symmetrical in structure, the odd-even-mode method can be implemented. For odd-mode excitation, the voltage is null in the midpoint. However, the point loaded with a virtual grounding varactor in the mid-part in odd-mode, as shown in Fig. 4, can not be analyzed in the traditional way as an

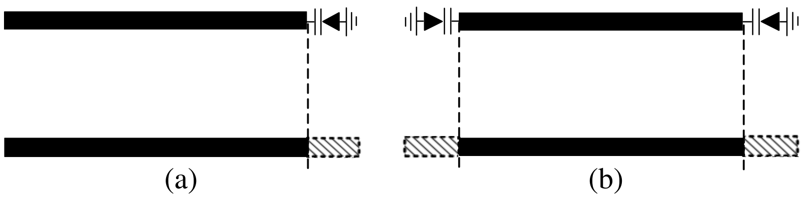


Figure 2. (a) and (b) The equivalent models of the two kinds of tunable $1/2\lambda$ resonator.

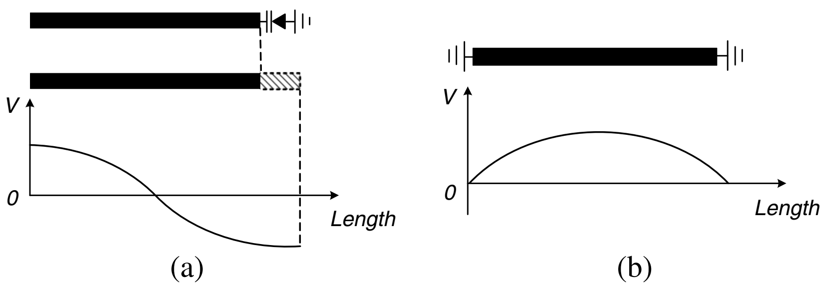


Figure 3. Voltage distribution of two kinds of $1/2\lambda$ resonator. (a) $1/2\lambda$ resonator loaded with a varactor. (b) $1/2\lambda$ resonator with both the ends short-circuited.

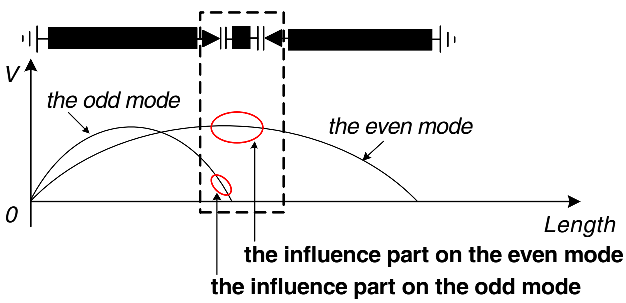


Figure 4. The voltage/electric-field distribution for the dual-mode of the proposed $1/2\lambda$ resonator.

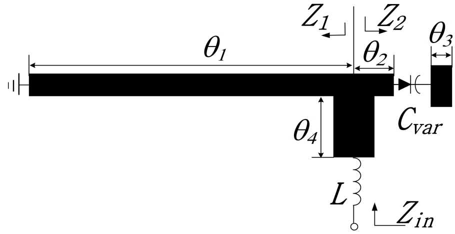


Figure 5. Model of the input impedance for even-mode.

open-circuited transmission line. Referring to Fig. 4, the influence of varactors on frequency shifting in odd-mode is very weak according to the electric field distribution. So the resonant frequency of odd-mode is nearly invariable. As for even-mode excitation, there is no current flow through the symmetrical plane. The influence of varactors is great in the middle section where the electric field is strong, and the varactors have an obvious influence in the change of center frequency. Therefore, only the even-mode is utilized in the proposed BPF.

2.2. Analysis of External Quality Factor

Figure 5 is the input and output network of the proposed filter. Once Z_{in} is found, external quality factor Q_e is then determined as

$$Q_e = \frac{\chi}{Z_0} = \frac{\omega_0}{2Z_0} \frac{\partial \mathrm{Im}\left[Z_{in}\right]}{\partial \omega}\bigg|_{\omega=\omega_0} \tag{1}$$

where χ is the reactance-slope parameter of the resonator. The input/output impedance for even-mode can be deduced as

$$Z_1 = jZ_{01} \tan\theta_1 \tag{2}$$

$$Z_2 = Z_{01} \frac{\left(\frac{1}{j\omega C} - jZ_{02}\cot\theta_3\right) + jZ_{01}\tan\theta_2}{Z_{01} + \left(\frac{1}{\omega C} + Z_{02}\cot\theta_3\right)\tan\theta_2} \tag{3}$$

$$Z' = \frac{Z_1 Z_2}{Z_1 + Z_2} \tag{4}$$

$$Z_{in} = j\omega L + Z_0 \frac{Z' + jZ_0\tan\theta_4}{Z_0 + jZ'\tan\theta_4} \tag{5}$$

Although Q_e is defined for a singly loaded resonator, if the resonator is symmetrical, one could add another symmetrical load or port to form a two-port network, define a doubly loaded external quality factor Q'_e as

$$Q'_e = \frac{Q_e}{2} = \frac{\omega_0}{\Delta\omega_{3\,\mathrm{dB}}} \tag{6}$$

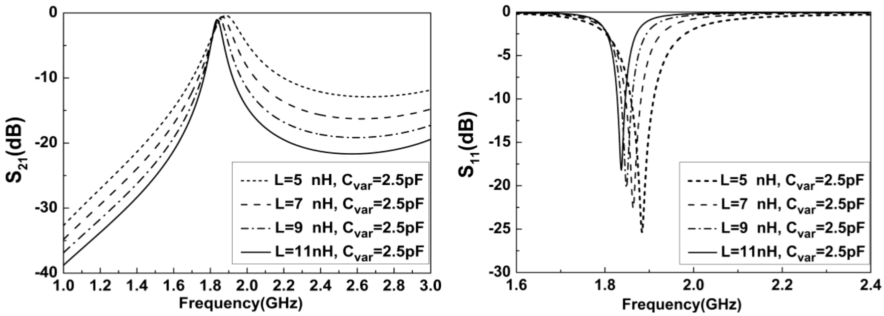
The singly loaded external quality factor Q_e is simply twice of Q'_e. From Equations (1) and (5), it can be concluded that Q_{em} increases as the inductance L increases, i.e., Q_{em} can be adjusted by the inductance L. When the Q_{em} factor decreases, at a fixed resonant frequency the ABW will increase indicated by Equation (6). Then the insertion loss will decrease [12] because of the increase of BW indicated by Equation (7):

$$\mathrm{IL}\,(\mathrm{dB}) = 4.343 \sum_{i=1}^{n} \frac{\omega_0 \Omega_c}{\mathrm{BW} Q_{ui}} g_i \ \mathrm{dB} \tag{7}$$

where g_i $(i = 1 \sim n)$ is the value of low-pass prototype, and Q_{ui} represent the unloaded quality factors of the resonator corresponding to g_i.

Illustrated in Fig. 6, the value of the varactor is set as 2.5 pF and when the value of the inductor decreases from 11 to 5 nH, the following results can be concluded: 1) the center frequency keeps almost constant; 2) the bandwidth of the passband increases as a result of the decrease of Q_{em}; 3) the insertion loss decreases. So the simulation with the help of Agilent-ADS verifies the accuracy of the analysis discussed above.

The structure of the propose BPF is shown in Fig. 7: 1) The input/output impedance matching is realised by a small inductance which has less loss compared with a capacitor. 2) Two varactors not only act as frequency tuning elements, but a dc-choke for both input and output ports. Thus, this circuit doesn't need to introduce dc-choke



(a) (b)

Figure 6. The bandwidth versus the value of the inductor based on the topology in Fig. 7 when the value of the varactor is fixed. (a) S_{21}, (b) S_{11}. ($W_0 = 2.2$ mm, $W_1 = 1.5$ mm, $W_2 = 2$ mm, $W = 2.5$ mm, $R = 0.8$ mm, $L_1 = 11.0$ mm, $L_2 = 3.8$ mm, $L_3 = 2.0$ mm and $L_4 = 5.2$ mm.)

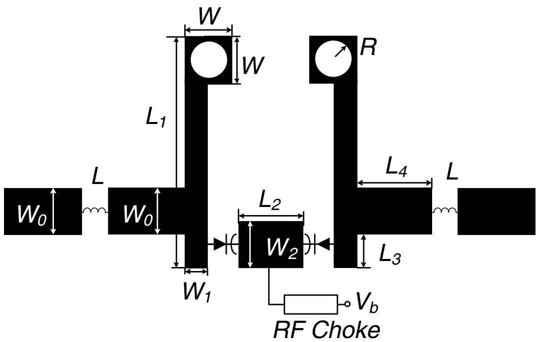


Figure 7. Topology of the fabrication model of the filter.

capacitors. 3) A first-order filter is adopted. In every aspect discussed above, it can reduce the insertion loss of the tunable filter.

3. IMPLEMENTATION AND RESULTS

The structure of the experimental BPF is shown in Fig. 7. The substrate is Teflon with the thickness of 0.8 mm and the dielectric constant of 2.65. SMV1405-079LF surface mount varactor diodes from Skyworks Corporation are used in the prototype circuit. To get a better Q value, two parallel SMV1405-079s are used at the position of the varactor. The capacitance of the varactor diode can be tuned from 2.67 to 0.66 pF by varying the bias voltage from 0 to 30 V. The equivalent electric length is adjusted by the capacitance of the varactors. The external coupling inductor is selected as 6.8 nH from Coilcraft. All the dimensions of the symmetrical structure are selected as follows: $W_0 = 2.2\,\text{mm}$, $W_1 = 1.5\,\text{mm}$, $W_2 = 2\,\text{mm}$, $W = 2.5\,\text{mm}$ $R = 0.8\,\text{mm}$, $L_1 = 11.0\,\text{mm}$, $L_2 = 3.8\,\text{mm}$, $L_3 = 2.0\,\text{mm}$ and $L_4 = 5.2\,\text{mm}$.

The fabricated compact tunable BPF is shown in Fig. 8. It was measured with a vector network analyzer (Agilent N5230A). The measured and simulated responses are plotted in Fig. 9. Good agreement between simulation and measurement is obtained. As indicated in Table 1, the 3-dB ABW keeps nearly constant when the frequency varies from 2.023 to 2.5 GHz. The filter can be tuned from 1.387 to 2.5 GHz, and among the tuning range, the insertion loss of the fabricated filter varies from 3.9 to 2.5 dB. This is mainly due to the low Q value of the silicon varactor diodes, lump elements and low unload quality factor of microstrip resonator. Only one RF-block circuit is needed in the midpoint of the structure for the applied controlling voltage.

Figure 10 shows that the frequency and bias voltage have almost

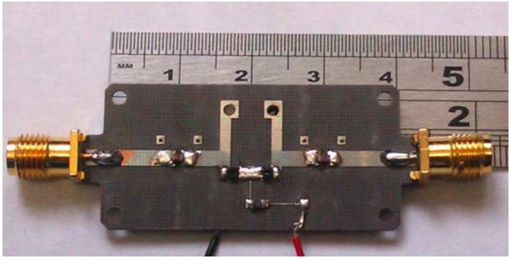
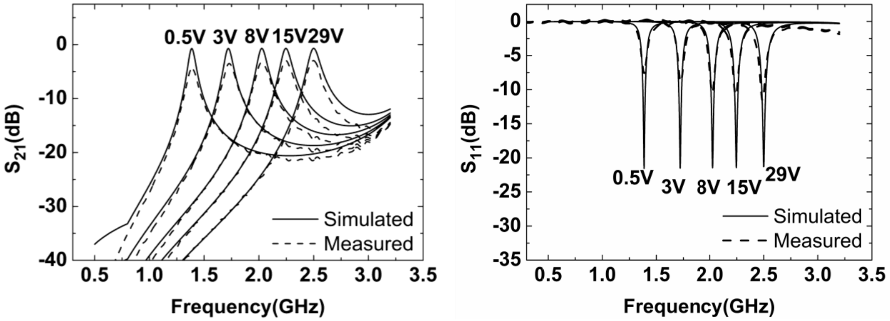


Figure 8. Photograph of the fabricated tunable filter.



(a) (b)

Figure 9. Simulated and measured results with different reverse voltages. (a) S_{21}, (b) S_{11}.

Table 1. Filter specifications.

Vol. (V)	Freq. (GHz)	Insertion Loss (dB)	Return Loss (dB)	3-dB ABW (MHz)
0.5	1.38	3.9	−8.0	105
3	1.72	3.1	−9.5	115
5	1.88	2.9	−10.0	117
8	2.02	2.8	−11.4	124
10	2.10	2.6	−11.0	121
15	2.24	2.5	−11.5	120
29	2.50	2.5	−12.2	127

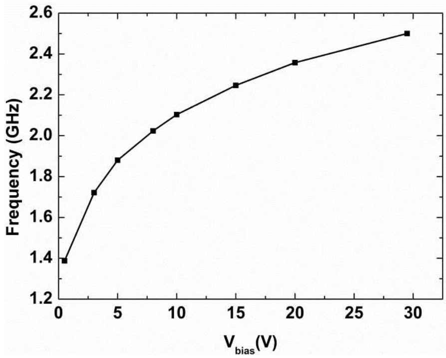


Figure 10. Center frequency versus the bias voltage.

linear relationship when the bias voltage varies from 5 to 30 V. However, when the bias voltage varies from 0.1 to 5 V, the relationship of them is not linear. That is maybe result of the performance of the varactor. According to the datasheet of SMV1405, when the bias voltage varies from 0.1 to 5 V, the value of the capacitance and bias voltage are not linear relationship. That phenomenon is reasonable.

4. CONCLUSION

A varactor-tuned microstrip BPF based on a novel $1/2\lambda$ resonator has been proposed and designed. A study of the bandwidth tuning is done with the external coupling section, and the bandwidth is mainly influenced by the value of the coupling inductor. This topology is easy to implement, can be used for the demand of Wi-Fi and WLAN, and will adapt to many other applications due to its design flexibility.

ACKNOWLEDGMENT

This work was supported by the Fundamental Research Funds for the Central Universities (K50511020013).

REFERENCES

1. Chen, J.-X., J. Shi, Z.-H. Bao, and Q. Xue, "Tunable and switchable bandpass filters using slot-line resonators," *Progress In Electromagnetics Research*, Vol. 111, 25–41, 2011.
2. Lee, W.-S., H.-L. Lee, K.-S. Oh, and J.-W. Yu, "Switchable distance-based impedance matching networks for a tunable HF

system," *Progress In Electromagnetics Research*, Vol. 128, 19–34, 2012.

3. Michalski, J. J., "Inverse modeling in application for sequential filter tuning," *Progress In Electromagnetics Research*, Vol. 115, 113–129, 2011.
4. Feng, T., Y. Li, H. Jiang, W. Li, F. Yang, X. Dong, and H. Chen, "Tunable single-negative metamaterials based on microstrip transmission line with varactor diodes loading," *Progress In Electromagnetics Research*, Vol. 120, 35–50, 2011.
5. Costa, F. and A. Monorchio, "Design of subwavelength tunable and steerable fabry-perot/leaky wave antennas," *Progress In Electromagnetics Research*, Vol. 111, 467–481, 2011.
6. Wu, C.-J., Y.-C. Hsieh, and H.-T. Hsu, "Tunable photonic band gap in a doped semiconductor photonic crystal in near infrared region," *Progress In Electromagnetics Research*, Vol. 114, 271–283, 2011.
7. Zhang, H.-L., X. Y. Zhang, and B.-J. Hu, "Tunable bandpass filters with constant absolute bandwidth," *Antennas Propagation and EM Theory (ISAPE)*, 1200–1203, 2010.
8. Chiou, Y.-C. and G. M. Rebeiz, "A tunable three-pole 1.5–2.2 GHz bandpass filter with bandwidth and transmission zero control," *IEEE Trans. on Microw. Theory and Tech.*, Vol. 59, No. 11, 2872–2878, Nov. 2011.
9. Sanchez-Renedo, M., R. Gomez-Garcia, J. I. Alonso, and C. Briso-Rodriguez, "Tunable combline filter with continuous control of center frequency and bandwidth," *IEEE Trans. on Microw. Theory and Tech.*, Vol. 53, No. 1, 191–199, Jan. 2005.
10. Serrano, A. L. C., F. S. Correra, T.-P. Vuong, and P. Ferrari, "Synthesis methodology applied to a tunable patch filter with independent frequency and bandwidth control," *IEEE Trans. on Microw. Theory and Tech.*, Vol. 60, No. 3, 484–493, Mar. 2012.
11. Wang, Y.-Y., F. Wei, B. Liu, H. Xu, and X.-W. Shi, "A tunable bandpass filter with constant absolute bandwidth based on one ring resonator," *Journal of Electromagnetic Waves and Applications*, Vol. 26, Nos. 11–12, 1587–1593, Jul. 2012.
12. Hong, J.-S. and M. J. Lancaster, *Microstrip Filters for RF/Microwaves Applications*, Wiley, New York, 2001.