

Design of Compact Electronically-Tuned Bandpass Filter with Sharp Rejection Skirt Using the Trans-Directional Coupled Line

Xiaojian Guo, Shao-Jun Fang, Hongmei Liu*, and Zhongbao Wang

Abstract—A compact frequency-tuned bandpass filter (BPF) with sharp rejection characteristic is presented. It is composed of a trans-directional (TRD) coupled line and two short-circuited stubs. By changing the capacitor values of the coupled line and the electrical lengths of the short-circuited stubs, a frequency-tuned BPF with sharp rejection is obtained. For verification, a prototype tuned from 1.0 GHz to 1.6 GHz (46.2%) is designed and fabricated. The measured results show that the proposed structure exhibits the return loss of more than 17 dB, the insertion loss of 1.4 dB, and the 3-dB fractional bandwidth (BW) of 43.2–50%. Sharp rejections are also obtained, agreeing well with the simulation results.

1. INTRODUCTION

Frequency-tuned bandpass filter (BPF) with low insertion loss and compact structure is highly required in the next generation wireless and mobile communication systems. In recent years, various frequency-tuned BPFs have been designed and proposed using different design methods [1–5]. In [1], a two-path mixed coupling tunable BPF with high selectivity and constant bandwidth (BW) is introduced. In [2], a 4-pole tunable BPF with intrinsic transmission zeros (TZs) tuning is reported, which has a high rejection. However, the structure in [2] is complicated, and the insertion losses [1, 2] are needed to be improved. In [3], a second-order Chebyshev dual-mode tunable BPF with constant passband BW is described, and a frequency tuning range of 19% is achieved. Besides, by using novel multi-mode resonators, the feature of frequency tunability and controllable passband BW can also be realized [4]. However, the insertion loss becomes poor when the frequency decreases. To improve the frequency tuning range, BPF using switchable varactor-tuned resonators is proposed [5]. However, high losses are also exhibited.

In this letter, a compact frequency-tuned BPF with sharp rejections is proposed. It is composed of a trans-directional (TRD) coupled line [6] and two short-circuited stubs. By changing the values of the shunt capacitors and the electrical lengths of the short-circuited stubs, a frequency-tuned BPF with wide tuning range and high-selective filtering responses is established. Low insertion loss and compact size are also exhibited.

2. THEORETICAL ANALYSIS

Figure 1 shows the schematic of the proposed BPF. It consists of a TRD coupled line with the through and coupled ports loaded with the short-circuited stubs. The isolated port of the TRD coupled line is the output port for BPF. The TRD coupled line, which is constructed by capacitor loaded coupled lines, is served as the transversal filtering section. The feature of bandpass can be obtained by the transversal

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* Corresponding author: Hongmei Liu (lhm323@dlmu.edu.cn).

The authors are with the School of Information Science and Technology, Dalian Maritime University, Dalian, Liaoning 116026, China.

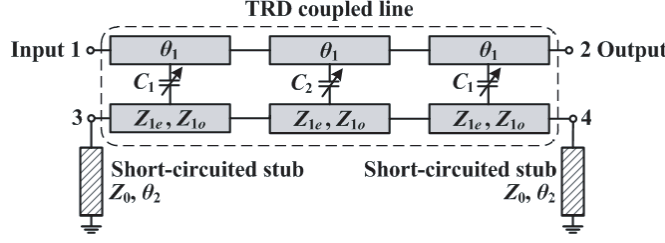


Figure 1. Schematic of the proposed frequency-tuned BPF.

combination of the signal traveling through the two shorted-circuit stubs. The even- and odd-mode characteristic impedances of the coupled lines are represented by Z_{1e} and Z_{1o} . The electrical length of each coupled line is defined as θ_1 at the center frequency of f_1 . Two types of varactors, denoted as C_1 and C_2 , are connected between the middle of each coupled line. The short-circuited stub has an impedance of Z_0 and electrical length of θ_2 , where Z_0 is the port impedance.

According to Fig. 1, the S -parameters (S_{11}^B and S_{21}^B) of the BPF can be expressed as

$$S_{11}^B = \frac{(S_{31}^2 + S_{41}^2)(e^{j(2\theta_2+\pi)} - S_{11}) + 2S_{21}S_{31}S_{41}}{(S_{11} - e^{j(2\theta_2+\pi)})^2 - S_{21}^2} \quad (1a)$$

$$S_{21}^B = \frac{2S_{31}S_{41}(e^{j(2\theta_2+\pi)} - S_{11}) + S_{21}(S_{31}^2 + S_{41}^2)}{(S_{11} - e^{j(2\theta_2+\pi)})^2 - S_{21}^2} \quad (1b)$$

where S_{11} , S_{21} , S_{31} , and S_{41} are the S -parameters of the TRD coupled line.

In order to achieve perfect passband characteristic, S_{11}^B and S_{21}^B should be equal to 0 and $e^{j\theta_0}$ respectively at the tuning center frequency f . Here, θ is the electrical length for f . By substituting $S_{11}^B = 0$ and $S_{21}^B = e^{j\theta_0}$ into Eq. (1), we have

$$S_{11}|_{f_0} = e^{j(2\theta_2+\pi)} - \frac{2S_{31}S_{41}}{e^{j\theta_0}} \quad (2)$$

To obtain perfect stopband feature, the condition of $S_{11}^B = e^{j\theta_z}$ and $S_{21}^B = 0$ should be satisfied at f_z (f_z is the frequency at TZs). Thus, substituting the condition into Eq. (1) derives

$$S_{11}|_{f_z} = e^{j(2\theta_2+\pi)} - \frac{S_{31}^2 + S_{41}^2}{e^{j\theta_z}} \quad (3)$$

From Eqs. (2) and (3), it is found that perfect passband and stopband characteristics can be obtained by selecting suitable S -parameters of the TRD coupled line and θ_2 . According to the analysis of the TRD coupled line [7], the S -parameters of the TRD coupled line can be adjusted by changing the values of C_1 and C_2 when Z_{1e} , Z_{1o} , and θ_1 are fixed. In addition, the initial values of Z_{1e} , Z_{1o} , and θ_1 can be calculated when the initial center frequency f_1 is determined. Therefore, by adjusting C_1 , C_2 , and θ_2 , the condition of Eqs. (2) and (3) can be satisfied, and the frequency tuned BPF can be realized. The design procedure of the proposed BPF is summarized in a flowchart, as shown in Fig. 2.

To realize a varied θ_2 , an equivalent circuit of the short-circuited stub is proposed, as shown in Fig. 3. It consists of two parallel stubs, one of which is a varactor ending in a short circuit, and the other is an inductor connected to a short-circuited transmission line. The short-circuited transmission line has a fixed electrical length of θ_{21} and an impedance of Z_0 . The capacitance of the varactor and the inductance of the inductor are defined as C_3 and L , respectively. The relation between the short-circuited stub and its equivalent circuit is listed below:

$$\theta_2 = \arccot \left(\frac{Z_0}{Z_0 \tan(\theta_{21}) + \omega L} - Z_0 \omega C_3 \right) \quad (4)$$

Equation (4) indicates that the electrical length θ_2 will be adjusted by changing the capacitance of the varactors C_3 when the values of inductor and the parameters of the short-circuited transmission

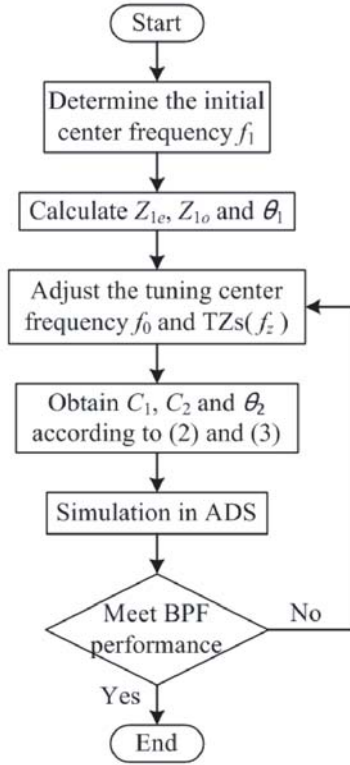


Figure 2. Flowchart of the proposed BPF design procedure.

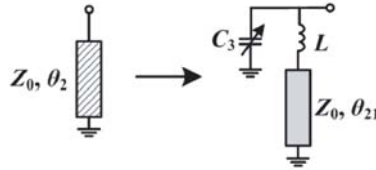


Figure 3. Equivalent circuit of the short-circuited stub.

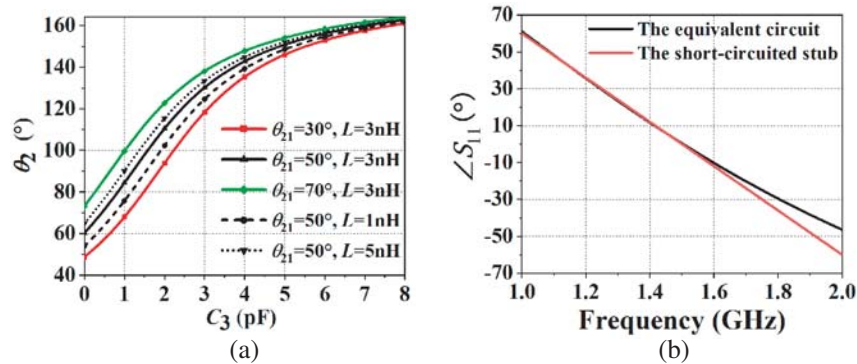


Figure 4. Performance of the short-circuited stub. (a) Curves of θ_2 versus C_3 with different values of θ_{21} and L . (b) $\angle S_{11}$ of the short-circuited stub and the equivalent circuit at 1.5 GHz.

line are fixed. Fig. 4(a) shows the curves of θ_2 versus C_3 with different values of θ_{21} and L . To achieve wide frequency tuning range, the values of θ_{21} and L are chosen as 50° and 3 nH , respectively. And the range of θ_2 is $60\text{--}163^\circ$ when C_3 is varied from 0 pF to 8 pF , corresponding to a frequency tuning range of

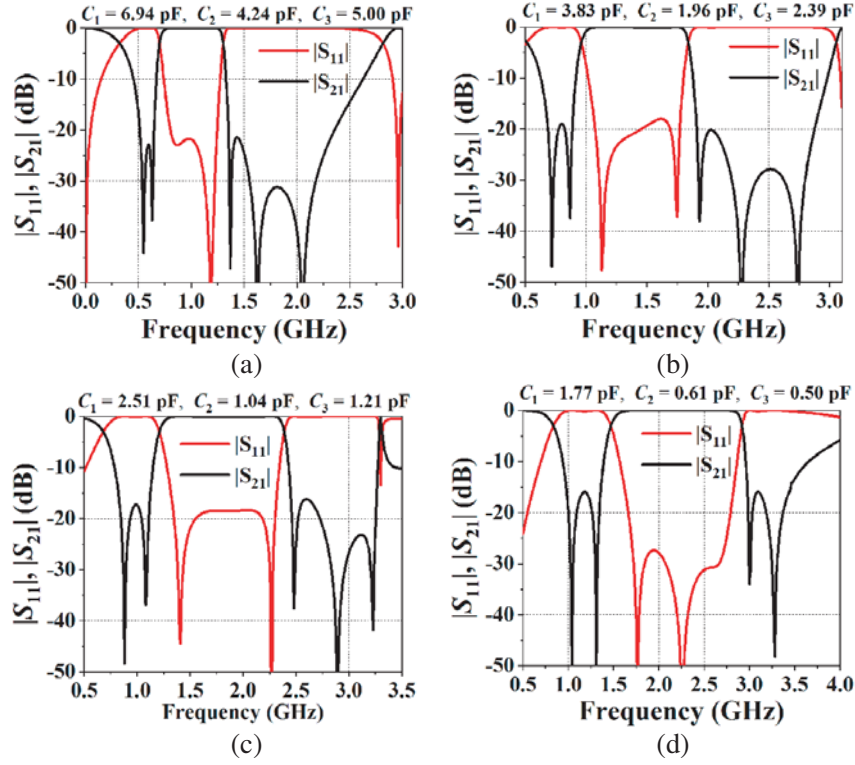


Figure 5. Optimized S -parameters of the proposed BPF at four different frequencies. (a) 1.0 GHz, (b) 1.4 GHz, (c) 1.8 GHz, (d) 2.2 GHz.

0.83–2.25 GHz. Fig. 4(b) shows $\angle S_{11}$ of the short-circuited stub and the equivalent circuit at 1.5 GHz. It is observed that a good match can be achieved between the short-circuited stub and its equivalent circuit.

According to the above analysis and design flowchart, optimizations are done using the parameters of C_1 , C_2 , and C_3 as degrees of freedom. Fig. 5 shows the simulated results at four different frequencies. The corresponding values of C_1 , C_2 , and C_3 are also provided. It is observed that a continuously frequency tuning range of 75% (1.0–2.2 GHz) is obtained under the criterion of return loss > 17 dB. It also exhibits a 3 dB fractional bandwidth (FBW) of 60.4–66% and a stopband suppression of more than 15 dB, as well as a sharp rejection.

3. EXPERIMENTAL RESULTS

In this section, a frequency-tuned BPF with a center frequency of 1.5 GHz is fabricated using an F4B substrate ($\epsilon_r = 3$, $\tan \delta = 0.003$, $h = 1.5$ mm). Fig. 6 shows the layout and photograph of the fabricated prototype. The overall size is 49 mm $\times$ 31 mm ($0.17\lambda_g \times 0.12\lambda_g$). The bias-voltage network consists of current limiting resistances R_{bias} and bypass capacitors C_{bias} which are used for establishing proper biasing conditions of the varactors. According to the capacitances of the varactors C_1 , C_2 , and C_3

Table 1. Dimensions of the prototype.

w_1 (mm)	s_1 (mm)	l_1 (mm)	w_2 (mm)
0.85	1.2	10.62	3.34
l_2 (mm)	C_{bias} (μ F)	R_{bias} (k Ω)	C_{block} (nF)
17.94	1.0	10	47

displayed in Fig. 5, the SMV1265 [8] is utilized for C_1 , and the SMV2020 [9] is utilized for C_2 and C_3 from Sky-works Solutions, Inc. The capacitances of the varactors C_1 , C_2 , and C_3 are controlled by V_1 , V_2 , and V_3 . C_{block} is the dc blocking capacitor to isolate dc voltages. Detailed parameters of the proposed BPF are listed in Table 1.

By using the Agilent N5230A network analyzer, the measured S -parameters are obtained, as shown in Fig. 7. The corresponding values of V_1 , V_2 , and V_3 are also given. It is observed that the prototype can be tuned from 1.0 GHz to 1.6 GHz (46.2%) continuously. Compared to the simulated results, the tuning range is deteriorated, which is mainly due to the capacitance limitation of the varactors in practice. During the tuning, the insertion losses are in the range of 0.9–1.4 dB, and the return losses are more than 17 dB at each tuning center frequency. The 3 dB FBWs are varied from 43.2% to 50% when

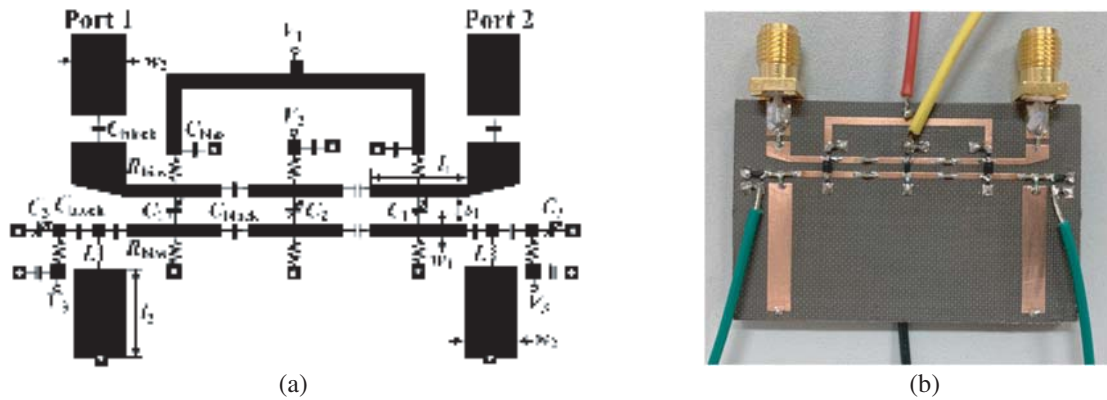


Figure 6. The fabricated prototype. (a) Layout. (b) Photograph.

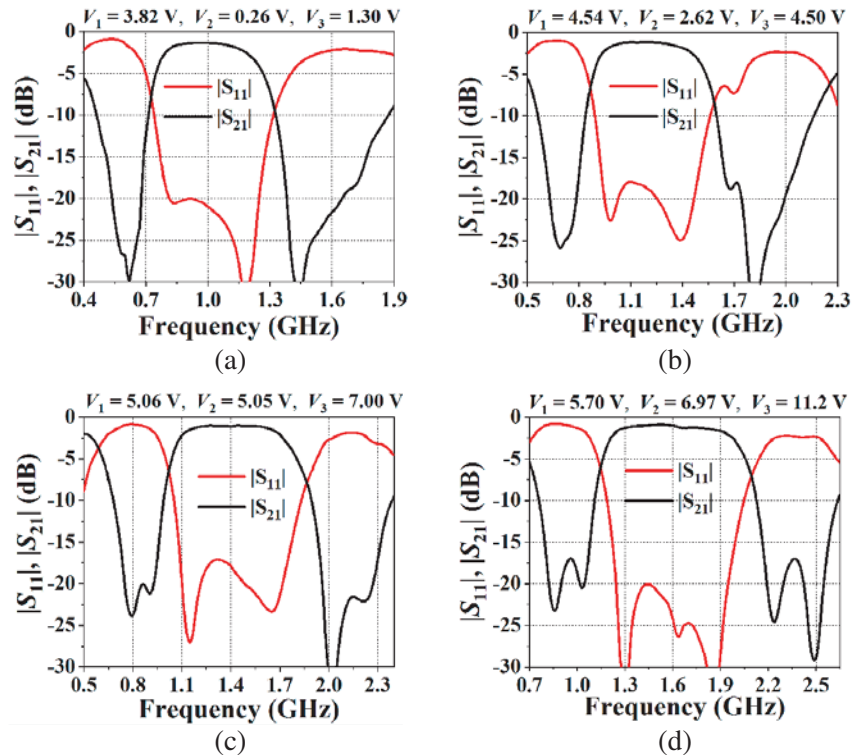


Figure 7. Measured S -parameters of the proposed BPF at four different frequencies. (a) 1.0 GHz, (b) 1.4 GHz, (c) 1.8 GHz, (d) 2.2 GHz.

Table 2. Comparison of this design with previously tuned BPF.

Ref.	Tuning range (%)	Insertion loss (dB)	Return loss (dB)	FBW range (%)	$\frac{BW_{10dB}}{BW_{3dB}}$	Size (λ_g^2)
[1]	54	1.68 ~ 2.9	> 13	7.4 ~ 13	1.6 ~ 1.7	0.020
[2]	50.7	2.2 ~ 4.5	> 10	4 ~ 5.5	N/A	0.022
[3]	19	2.84 ~ 2.9	> 15	4.5 ~ 5.1	N/A	0.077
[4]	62.1	2.4 ~ 5.8	> 15	4.8 ~ 10.7	N/A	0.009
[5]	110.2	3.2 ~ 4.4	> 15	5.2 ~ 15.6	N/A	0.027
This work	46.2	0.9 ~ 1.4	> 17	43.2 ~ 50	1.3 ~ 1.4	0.020

the frequency increases. The main reason for the narrower 3-dB FBWs compared with the simulated results is the nonlinearity of the varactor capacitance corresponding to the frequency. When using BW_{10dB}/BW_{3dB} to quantify the sharp rejection, the measured values are in the range of 1.28–1.44.

Table 2 summarizes the comparisons between this design and previously frequency-tuned BPFs. In items of insertion loss, return loss, and size, the proposed BPF shows the best performance. Moreover, the feature of sharp rejection is also exhibited, which is not considered in [2–5]. Compared with [1], the proposed design shows lower insertion loss, better return loss, and sharper rejection.

4. CONCLUSION

This letter presents a compact frequency-tuned planar BPF with the feature of sharp rejection. Design methods are given. For demonstration, an experimental prototype was designed. The measured results show that the proposed BPF can be tuned from 1.0 GHz to 1.6 GHz (46.2%) with low insertion loss and sharp rejection. After comparison, it is demonstrated that the proposed BPF shows better performances and can be a candidate for microwave applications.

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