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A Simple Bandpass Filter with Independently Tunable Center Frequency and Bandwidth

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Abstract—A varactor-tuned microstrip bandpass filter (BPF) with independently tunable center frequency and bandwidth is proposed in this paper. The proposed BPF with a simple configuration is composed of a half-wavelength transmission line with both ends short-ended and a T-shaped transmission line. Meanwhile, two varactors are inserted symmetrically in the middle section of the half-wavelength transmission line to adjust the resonant frequency. The T-shaped transmission line is connected to the half-wavelength transmission line by a lumped capacitor. In addition, two inductors loaded symmetrically in the feed line are employed to control the coupling coefficient. It is convenient to adjust the frequency and bandwidth of the filter independently by using only three varactors, which simplifies the circuit structure greatly. The predicted results on S parameters are compared with the measured ones, and a reasonable agreement is achieved.

1. INTRODUCTION

Tunable microstrip bandpass filters (BPFs) are gaining more and more attention in multi-mode microwave communication systems due to their good performance of simple structure, compact size and low cost. Although different design methods of tunable filters were developed in the past few decades [1–3], most prior works concentrated on tuning the resonant frequency of the resonators using semiconductor. A tunable three-pole BPF with bandwidth and transmission zero control was proposed in [4], which has high insert loss and a complicated structure. A tunable combline filter with continuous control of center frequency and bandwidth was presented in [5]. Unfortunately, the proposed filter has a larger size and narrow fractional bandwidth (FBW).

In this paper, a simple microstrip BPF with independently tunable center frequency and bandwidth is proposed. Two varactors inserted symmetrically in the middle section of the half-wavelength transmission are used to tune the center frequency and the varactor inserted in the T-shaped transmission line is employed to achieve the tuning of bandwidth. In order to validate its practicality, a reconfigurable BPF with bandwidth ($BW_{3\,dB}$) tuning range from 7.8%–11.6% (150 to 220 MHz) and frequency ranging from 1.7 to 2.1 GHz is fabricated. Good agreement between the simulated and measured results is observed.

2. THEORY AND DESIGN

2.1. Analysis of Tunable Half-Wavelength Resonator

Two conventional half-wavelength resonators with one varactor and two varactors are shown in Figs. 1(a) and (b), respectively. The equivalent models and field distribution of the two conventional resonators

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are shown in Fig. 2. A short open-circuit stub of lossless microstrip line can be equivalent to a shunt capacitor and that a similar short-circuited stub can be equivalent to a shunt inductor. A varactor can be equivalent to a transmission line. As can be observed, the voltage is minimum in the midpoint with one end open-circuited and is maximum in the midpoint with both ends open-circuited. Therefore, in order to get a strong electric field in the midpoint, both ends should be short-circuited [6].

In this design, the proposed half-wavelength resonator can be achieved by the varactors inserted symmetrically in the middle section, as shown in Fig. 3. Owing to the geometrical symmetry, the odd-even-mode method can be performed by analyzing only half of the circuit. As depicted in Fig. 3, since the voltage at the midpoint is null in odd mode, the influence of the varactors on frequency shifting is very weak. However, the voltage at the midpoint is maximum in even mode. Therefore, the varactors have an obvious influence on the change of center frequency. Thus, the even-mode resonant frequency can be tuned by changing the varactors inserted symmetrically in the middle section.

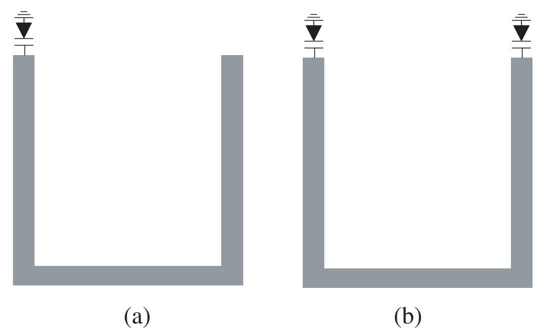

Figure 1. Two types of conventional tunable half-wavelength resonator with (a) one varactor and (b) two varactors.

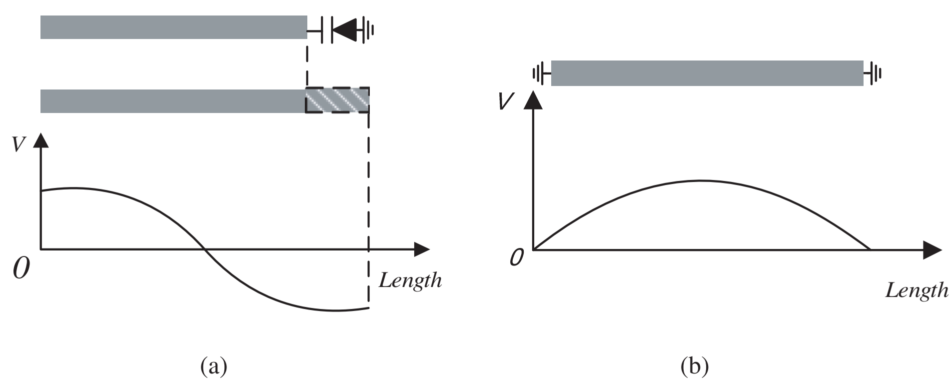

Figure 2. Voltage distribution of two kinds of $1/2\lambda$ resonator loaded with (a) a varactor and (b) both ends short-circuited.

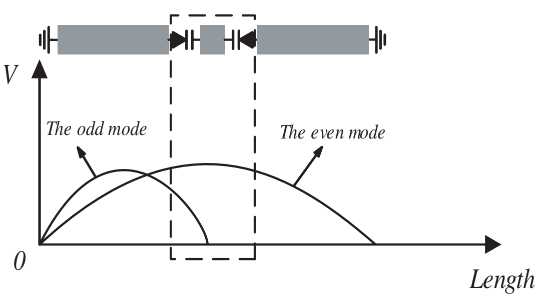

Figure 3. Voltage/electric-field distribution of the proposed resonator.

2.2. Analysis of Tunable Half-Wavelength Loop Resonator

Figure 4(a) gives the configuration of the conventional closed loop resonator. Since the resonator is symmetrical, the odd- and even-mode analysis method can be implemented. The even-mode equivalent circuit and odd-mode one are shown in Figs. 4(b) and (c), respectively. By adjusting the perturbation θ_1, the electrical length of even mode is changed as $0.5\theta + \theta_1$, while the odd mode remains as 0.5θ. The electrical length of odd mode is not affected by θ_1 and the resonant frequency of odd mode remains fixed when θ_1 is changed, as shown in Fig. 5. Therefore, the perturbation θ_1 can affect the bandwidth of the conventional closed loop resonator. In this paper, the perturbation θ_1 is achieved by a series resonator, as shown in Fig. 6(a). The even mode equivalent circuit and the odd mode equivalent circuit are given in Figs. 6(b) and (c), respectively. Since the odd mode is not affected by the perturbation, its resonant frequency remains the same as that of the conventional closed loop resonator. However, due to added LC resonator introduced as a perturbation, the resonant characteristics of the even mode are influenced in such a way that there exist two resonant modes. Finally, the series resonator composed of lumped elements is converted to an equivalent T-shaped resonator, as given in Fig. 6(d). As illustrated in Fig. 7, when the value of L_1 in the T-shaped transmission line increases from 3 to 5 mm, the odd-mode resonant frequency is fixed. Meanwhile, the even-mode frequency is changed.

The geometry of the proposed tunable BPF based on a half-wavelength resonator is shown in Fig. 8. In this design, the LC elements shown in Fig. 6(a) are converted to an equivalent T-shaped transmission line. A varactor inserted in the T-shaped transmission line is employed to tune the bandwidth. Meanwhile, in order to enhance the coupling between the half-wavelength resonator and the T-shaped transmission line, a surface mounted devices (SMD) capacitor is loaded on the gap. Furthermore, in order to match the input/output impedance, two small inductors are loaded symmetrically on the feed line.

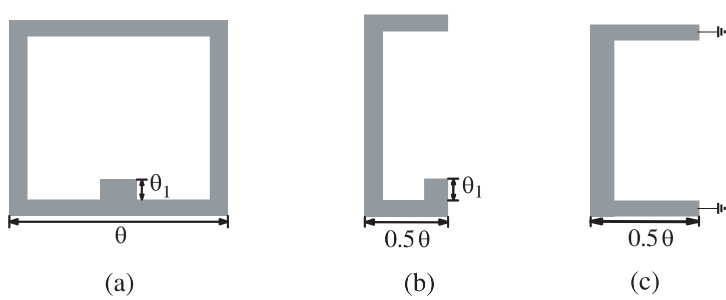

Figure 4. Conventional closed loop resonator, (a) basic configuration, (b) even mode, (c) odd mode.

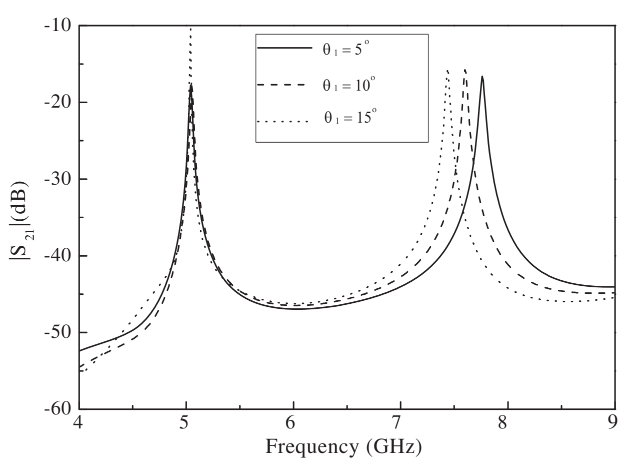

Figure 5. The transmission characteristics of the conventional loop resonator for various length θ_1.

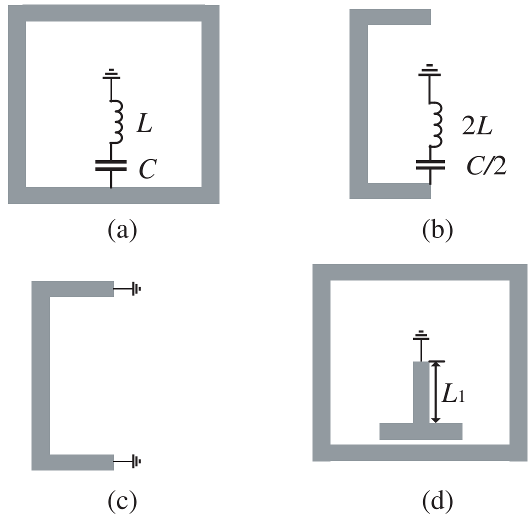

Figure 6. Proposed closed loop resonator: (a) equivalent circuit, (b) even mode equivalent circuit, (c) odd mode equivalent circuit, (d) configuration with T-shaped resonator.

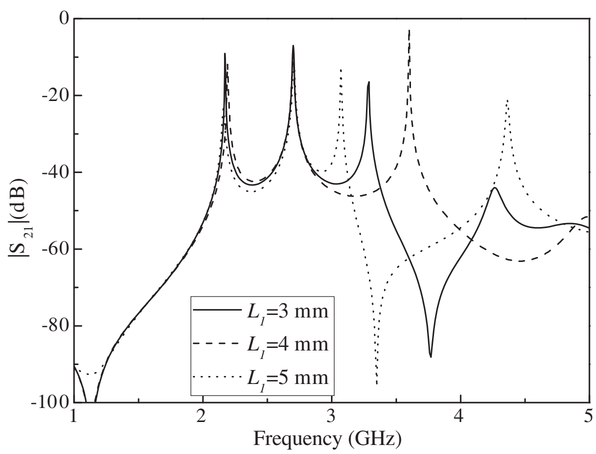

Figure 7. Simulated frequency responses of the proposed closed loop resonator with T-shaped resonator for different L_1.

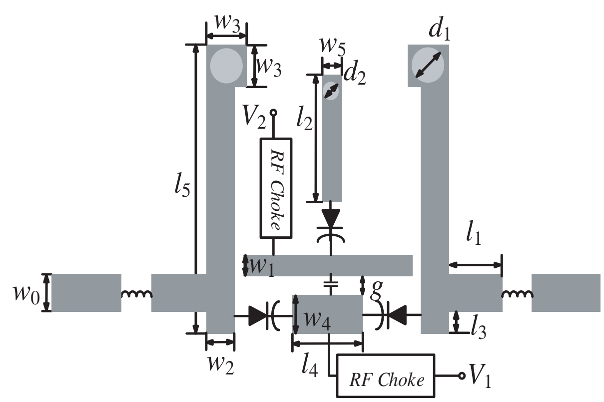

Figure 8. Geometry of the proposed tunable BPF.

3. IMPLEMENTATION AND RESULTS

In order to verify the accuracy of the above design, a tunable BPF is fabricated and measured. The substrate is RT/Duroid 5880 with the thickness of 0.8 mm and dielectric constant of 2.65. All the dimensions of the proposed filter are selected as follows: $w_0 = 2.2\,\text{mm}$, $w_1 = 1\,\text{mm}$, $w_2 = 1.5\,\text{mm}$, $w_3 = 2.5\,\text{mm}$, $w_4 = 2\,\text{mm}$, $w_5 = 1\,\text{mm}$, $l_1 = 5.2\,\text{mm}$, $l_2 = 5\,\text{mm}$, $l_3 = 2\,\text{mm}$, $l_4 = 3.8\,\text{mm}$, $l_5 = 11\,\text{mm}$, $g = 0.8\,\text{mm}$, $d_1 = 1.6\,\text{mm}$, $d_2 = 0.9\,\text{mm}$. Two SMV1413-079LF surface mounted varactors from Skyworks Corporation are used in the prototype circuit. The capacitance of the varactors can be tuned from 2.67 to 0.63 pF by varying the bias voltage from 0 to 32 V. The coupling inductor is 6.8 nH (0603) and the coupling capacitor is 2.2 pF (0603) in this fabricated filter. In addition, a resistor (0603, 20 KΩ) from muRata is connected with the inductors to limit the current.

The measurement of S parameters was accomplished by an Agilent vector network analyzer N5230A. Fig. 9 presents the simulated and the measured results of the fabricated filter. It is shown that the proposed BPF can be tuned from 1.7–2.1 GHz. The insert loss of the filter varies from 2.2 dB to 3 dB and the return loss is better than 20 dB over the passband. Moreover, the bandwidth can be tuned from 7.8%–11.6% (150–220 MHz). The deviations of the measurements from the simulations are mainly due to the fabrication tolerance as well as the SMA connectors. The fabricated compact tunable BPF is shown in Fig. 10. The overall size is about 24 mm ×12 mm ($0.22\lambda_g \times 0.11\lambda_g$, where λ_g is the guided wavelength at 1.9 GHz). A comparison of the performance of the proposed tunable filter with some recently reported works is shown in Table 1, which further depicts that the proposed tunable filter outperforms the others as it has a better performance and a smaller size.

Table 1. Comparison with some recently reported tunable filters.

	Frequency (GHz)	Tuning Rate	$BW_{3\,dB}$ (%)	Insert loss (dB)	Number of Varactors	Size ($\lambda_g \times \lambda_g$)
[4]	1.5–2.2	37.8%	7–14	3.0–6.5	9	0.23 × 0.31
[7]	1.55–2.1	30.1%	2.2–8	4.5–6.0	10	0.23 × 0.33
[8]	1.9–2.3	18%	27.1–28	2.8–3.2	6	0.43 × 0.38
[9]	1.24–1.50	21%	5.4–6.2	3.9–4.3	6	0.17 × 0.18
Our work	1.7–2.1	21%	7.8–11.6	2.2–3.0	3	0.22 × 0.11

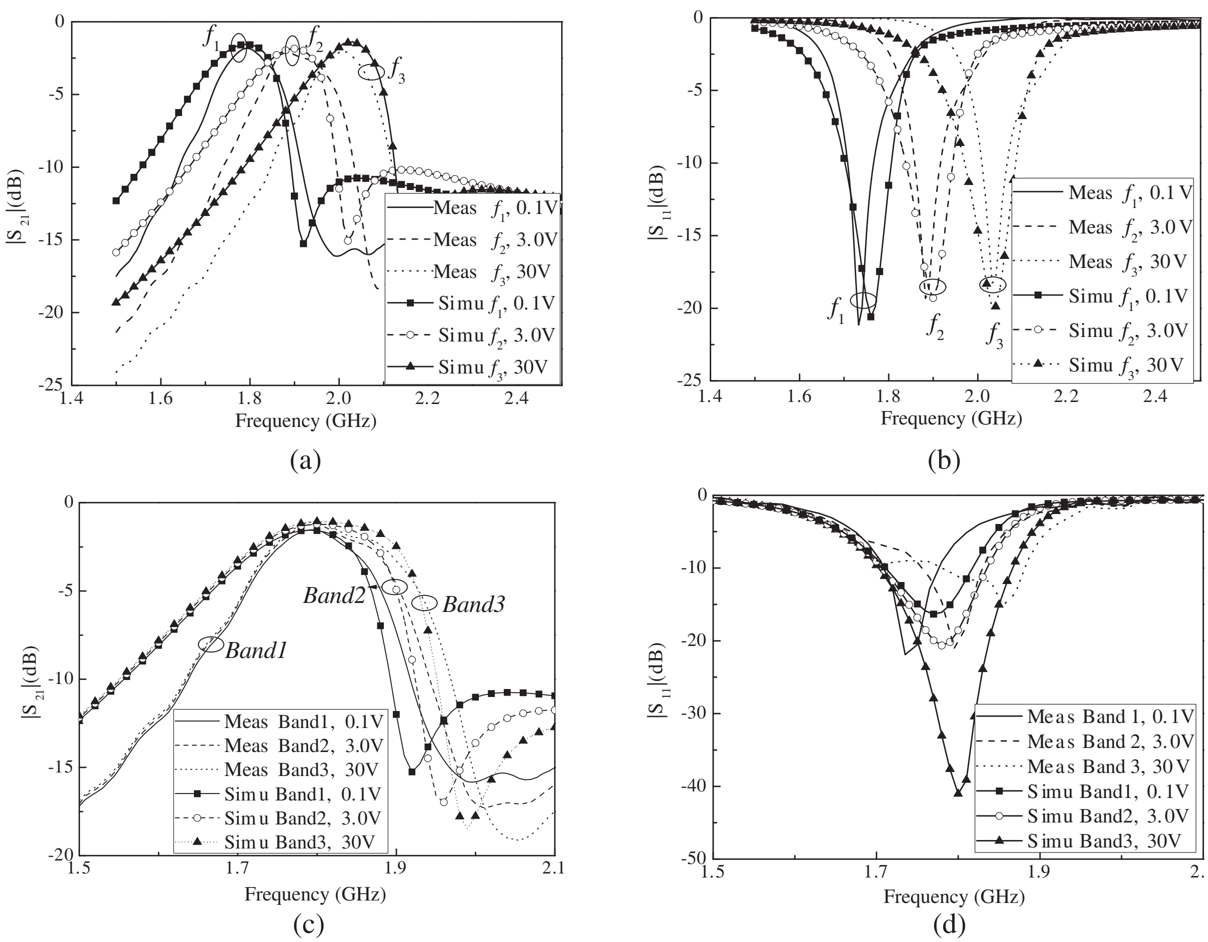

Figure 9. Simulated and measured results with different reverse voltages. (a) & (b) $|S_{21}|$ and $|S_{11}|$ with different center frequencies, (c) and (d) $|S_{21}|$ and $|S_{11}|$ with different bandwidth at 1.8 GHz.

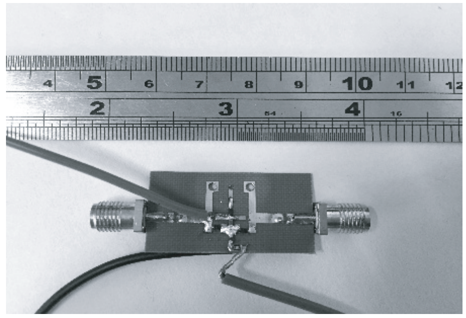

Figure 10. Photograph of the fabricated tunable filter.

4. CONCLUSION

A varactor-tuned microstrip BPF with independently tunable center frequency and bandwidth is proposed in this paper. The center frequency tuning is realized by the varactors inserted symmetrically in the middle section, and the bandwidth tuning is achieved by the varactor inserted in the T-shaped transmission line. It is noticed that only three varactors are employed to achieve the proposed reconfiguration BPF. Good agreement between the simulated and measurement results demonstrates the validity of the design.

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