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LETTER

Compact tunable dual-band bandpass filter with independently tunable passbands and high selectivity

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Abstract This paper presents a compact varactor-tuned dual-band bandpass filter with independently tunable passbands and high selectivity. The filter consists of two varactor-loaded half-wavelength dual mode resonators, each of which features independent tunability of odd- and even-mode resonant frequencies by varying the capacitances of the corresponding loading varactor diodes. Benefiting from this feature, the filter offers two independently controllable passbands. In addition, hook-shape feed lines are utilized to create transmission zeros between the two passbands, which enhances the selectivity of the filter.

Keywords: compact, tunable, dual-band filter, high selectivity
Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

With the increasing demands of multiband communication systems, tunable filters have attracted considerable attention due to their advantages of low cost, compactness and lower complexity [1, 2]. For the past years, much research work has been conducted to design tunable bandpass filters [3, 4, 5, 6, 7, 8, 9, 10, 11]. For instance, a tunable bandpass filter with constant absolute bandwidth and suppressed second harmonic was presented in [6] based on half-wavelength resonators. In [9], a three-pole combline filter was implemented to achieve flexible control of frequency and bandwidth. In order to increase the tuning ranges of passband, the recent few years have seen some research focused on tunable dual-band BPF. In [12, 13, 14, 15], the designed filters offered only one tunable passband, while the other passband was static at a fixed frequency. To overcome this, several tunable dual-band filters with two independently controlled passbands were presented using various resonators [16, 17, 18, 19, 20, 21, 22, 23]. For example, in [18], a tunable dual-band BPF using varactor-loaded stub-loaded resonators was reported. However, each passband required two controlling voltages, which increased the circuit complexity of the filter. In [20], a tunable dual-band filter was realized based on evanescent-mode cavity resonators and offered two controllable passbands with wide tuning ranges. In [22], a tunable dual-band filter with constant absolute bandwidths was developed by exploiting quarter-wavelength resonators. In many applications, tunable dual-band filter with high selectivity is desired. However, the filters referred above do not have good selectivity. In [24], a tunable dual-band filter with high selectivity was reported based on varactor-loaded stub loaded resonators, but the filter required a large number of varactor diodes, which complicated the design process.

In this paper, a novel tunable dual-band filter with compact size, independently controllable passbands, high selectivity and a smaller number of varactors is presented. First, the varactor-loaded resonator of the filter is theoretically analyzed by the odd- and even-mode approach, exhibiting the flexible tunability of odd- and even-mode resonant frequencies. To achieve high selectivity, hook-shape feed lines are employed at the input and output ports. Finally, a varactor-tuned dual-band filter is designed and implemented.

2. Analysis of proposed resonator

The proposed resonator is illustrated in Fig. 1(a). It consists of a meandered half-wavelength transmission line resonator loaded with two variable capacitors (denoted as C_o and C_e), where C_o is placed between two arms of the resonator and C_e is attached at the centre point of the resonator. Since the configuration of the resonator is symmetrical, the odd- and even-mode approach can be utilized to analyse its characteristics. To facilitate the analysis, the transmission line of the resonator with characteristic admittance Y and physical length $2(L_1 + L_2)$ is assumed to be lossless, and the discontinuity is ignored.

Fig. 1(b) shows the odd-mode equivalent circuit of the resonator. The input admittance of the odd-mode can be expressed as

$$Y_{ino} = jY\frac{Y\tan(\beta_o L_1) + 2\omega_o C_o - Y\cot(\beta_o L_2)}{Y + (Y\cot(\beta_o L_2) - 2\omega_o C_o)\tan(\beta_o L_1)} \quad (1)$$

where β_o is the phase constant of the odd-mode resonant angular frequency ω_o. With the resonant condition of $\mathrm{Im}(Y_{ino}) = 0$, the odd-mode resonant frequency f_o can be derived as

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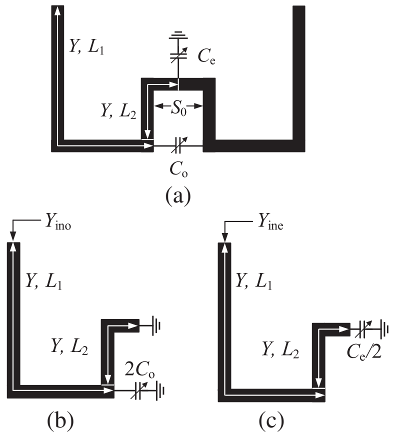

Fig. 1. (a) Schematic of the proposed resonator. (b) Odd-mode equivalent circuit. (c) Even-mode equivalent circuit

$$Y\tan\left(\frac{2\pi f_o L_1\sqrt{\varepsilon_r}}{c}\right) + 4\pi f_o C_o = Y\cot\left(\frac{2\pi f_o L_2\sqrt{\varepsilon_r}}{c}\right) \quad (2)$$

where ε_r is the relative dielectric permittivity of the substrate, and c denotes the speed of light in the free space. From Eq. (2), it can be observed that the odd-mode resonant frequency depends on the variable capacitor C_o.

For the even-mode equivalent circuit, as shown in Fig. 1(c), the even-mode input admittance is given as

$$Y_{\text{ine}} = jY\frac{\omega C_e + 2Y\tan(\beta_e(L_1 + L_2))}{2Y - \omega C_e\tan(\beta_e(L_1 + L_2))} \quad (3)$$

where β_e is the phase constant of the even-mode resonant angular frequency ω_e. With the resonant condition of $\text{Im}(Y_{\text{ine}}) = 0$, the even-mode frequency f_e can be obtained as

$$2\pi f_e C_e + 2Y\tan\left(\frac{2\pi f_e(L_1 + L_2)\sqrt{\varepsilon_r}}{c}\right) = 0 \quad (4)$$

From Eq. (4), it can be noted that the even-mode resonant frequency depends on the variable capacitor C_e. Accordingly, from Eq. (2) and (4), we can conclude that the odd- and even-mode resonant frequencies can be controlled independently by varying the capacitances of the C_o and C_e, respectively. To verify this, the simulated S_{21} of the resonator varying with the capacitances of C_o and C_e under weak coupling are shown in Fig. 2, which shows independent tunability of the odd- and even-mode resonant frequencies of the resonator. In our design, the fundamental odd- and even-mode resonant frequencies are utilized to form the lower and higher passbands, respectively.

3. Filter design and implementation

Fig. 3(a) shows the configuration of the tunable second-order dual-band filter based on the proposed resonator. The filter consists of two coupled varactor-loaded resonators that arranged in pseudo-interdigital architecture [25] for compactness. To obtain high selectivity, a pair of hook-shape feed lines are introduced at the input and output ports to create transmission zeros (TZs). The lower and higher passbands of the filter can be controlled independently by adjusting the voltages V_1 and V_2, respectively.

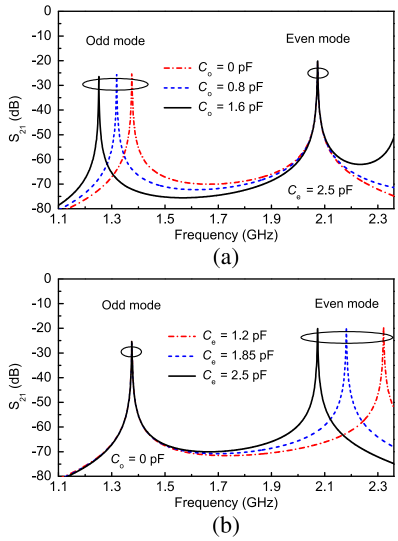

Fig. 2. Simulated S_{21} of the resonator with different loaded variable capacitances under weak coupling ($L_1 = 33.55$ mm, $L_2 = 9.25$ mm and $S_0 = 2.5$ mm). (a) Varying C_o, when $C_e = 2.5$ pF. (b) Varying C_e, when $C_o = 0$ pF.

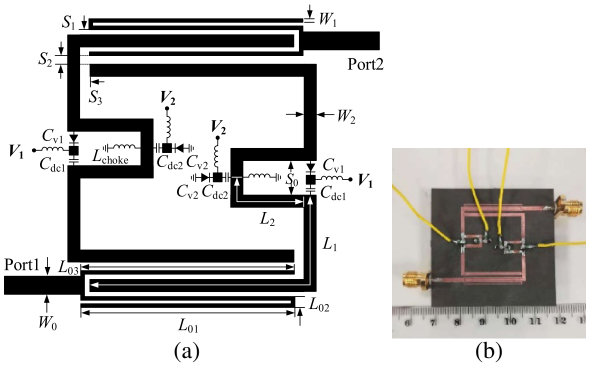

Fig. 3. (a) Configuration of the filter ($W_0 = 1.55$, $W_1 = 0.25$, $W_2 = 1.2$, $L_1 = 33.55$, $L_2 = 9.25$, $L_{01} = 22.23$, $L_{02} = 0.95$, $L_{03} = 22.1$, $S_0 = 2.5$, $S_1 = 0.17$, $S_2 = 0.7$, and $S_3 = 0.2$. unit: mm). (b) Photograph of the fabricated filter.

For demonstration, a tunable dual-band filter was implemented on a 0.508 mm RT/Duriod 5880 substrate with relative constant permittivity of $\varepsilon_r = 2.2$. The filter was designed with the following specifications.

- The lower/higher passband: 1.25–1.36/2.05–2.25 GHz;
- 3-dB fractional bandwidth (FBW) of lower/higher passband: 6.3–7.8%/4.4–5.8%;
- Number of poles: two;
- Type: Chebyshev frequency response.

The initial filter can be designed from its fixed frequency response centering at the upper-frequency edges of the given tuning ranges [18], i.e., $f_1 = 1.36$ GHz, $f_2 = 2.25$ GHz, $\text{FBW}_1 = 7.8\%$, and $\text{FBW}_2 = 5.8\%$, where the subscripts 1 and 2 denote the lower and higher passbands, respectively. The return losses of these two passbands are specified with 15 dB and 10 dB. According to the design theory of filter [26], the desired coupling coefficients and external quality factors are obtained as $K_1 = 0.047$, $K_2 = 0.028$, $Q_{e1} = 25.14$, and $Q_{e2} = 50.38$, respectively. For convenience, the width of the resonator is determined as 1.2 mm. The coupling coefficients of the two passbands can be controlled by adjusting the coupling gap S_3. Whereas the external quality factors can be adjusted by changing the coupling gap S_1, S_2 and the length of feed line L_{03}. The required response can be gained through proper adjustment. To tune the two passbands, four varactor diodes are employed in the filter. The varactors C_{v1} and C_{v2} (shown in Fig. 3(a)) are realized by commercial silicon varactor diodes from Skyworks [27] SMV2019-079LF (0.3–2.22 pF, 20–0 V bias) and SMV1405-079LF (0.63–2.67 pF, 30–0 V bias), respectively. The dc-blocking capacitor C_{dc1} is 3 pF and C_{dc2} is 2.5 pF from Murata Corporation [28]. The RF choke L_{choke} is realized by a 100 nH Murata inductor. The simulation was done by combining the EM simulation software HFSS and ADS. Fig. 3(a) shows the critical dimensions of the filter, and a photograph of the device is shown in Fig. 3(b).

The measurement of the filter was done by using the Agilent E8363B vector network analyzer. Fig. 4 and Fig. 5 illustrate the simulated and measured results of independently tunable passband center frequencies. The lower passband can be tuned from 1.25 to 1.36 GHz with FBW varying from 6.4 to 7.5% and insertion losses variation from 4.3–1.46 dB. The higher passband can be tuned from 2.1 to 2.31 GHz with FBW varying from 4.7 to 6% and insertion losses variation from 4.85–3.1 dB. Within the above tuning processes, the return losses of the two passbands are both better than 15 dB. Note that the insertion losses of the higher passband are larger than that of the lower passband, it may be attributed to larger losses of the mounted lumped components at high frequencies as well as narrower fractional bandwidth [29]. The deviations between the simulated and measured results may be attributed to the manufacture tolerance and parasitic effect of varactor diodes. Noteworthy is that five TZs are distributed around the two passbands, which significantly enhances the selectivity of the filter. Among them, TZ_1, TZ_4 and TZ_5 are generated owing to the pseudo-interdigital architecture of the filter [25]. TZ_2 is generated because the hook-shape stubs can be equivalent to the quarter-wavelength lines, and TZ_3 is created by the coupling between the hook-shape lines and the resonators [30]. A performance comparison between this filter and some tunable dual-band filters is summarized in Table I.

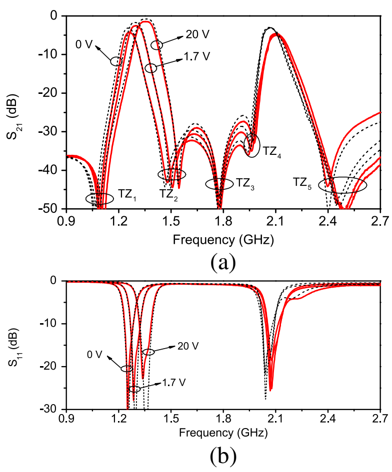

Fig. 4. Simulated and measured S-parameters of tunable lower passband with fixed higher passband (solid line: measured, dotted line: simulated, $V_1 = 0$–20 V, $V_2 = 0.4$ V). (a) S_{21}. (b) S_{11}.

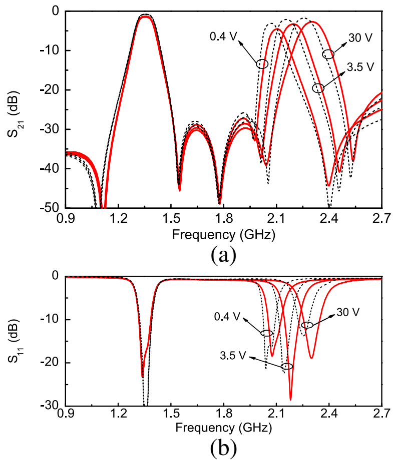

Fig. 5. Simulated and measured S-parameters of tunable higher passband with fixed lower passband (solid line: measured, dotted line: simulated, $V_2 = 0.4$–30 V, $V_1 = 20$ V). (a) S_{21}. (b) S_{11}.

Table I. Comparison with some tunable dual-band filters

Ref.	Frequency Tunable (GHz)	Insertion Loss (dB)	Number of TZs	Number of Tuning Elements	Types of Bias Circuits	Size × Size ($\lambda_g \times \lambda_g$)
[18]	1.48–1.8 2.4–2.88	1.99–4.4 1.6–4.2	2	6	4	0.18 × 0.17
[22]	0.98–1.22 1.63–1.95	2.1–3.0 2.8–4.0	3	4	2	0.21 × 0.17
[24]	0.8–1.02 2.02–2.48	1.12–2.93 1.45–4.89	6	8	2	0.33 × 0.16
This work	1.25–1.36 2.1–2.31	1.46–4.3 3.1–4.85	5	4	2	0.17 × 0.19

λ_g: the guide wavelength on the substrate at the lowest center frequency of the lower passband.

4. Conclusion

A compact varactor-tuned dual-band filter based on varactor-loaded dual-mode resonators has been presented. The filter offers two independently controllable passbands with high selectivity and a smaller number of tuning elements. Benefiting from these advantages. The presented filter has the potential to be applied in modern and future communication systems.

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