A Dual-band Bandpass Filter with The Second Passband Independently Tunable

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Abstract. This article proposes a dual-band bandpass filter (BPF) based on stub-loaded resonator (SLR) with the second passband independently tunable. Varactors loaded on the end of the central stub are employed to independently tune the second passband. Two shunt quarter-wavelength open stubs and source-load (S-L) coupling are applied to generate transmission zeros (TZs) to enhance the selectivity and improve the out-band rejection. For verification, a tunable dual-band BPF is designed, fabricated and tested, which realizes frequency tuning range (FTR) of the second passband from 2.24 to 2.71 GHz with constant fractional bandwidth (CFBW) of 1.5±0.4%. The simulated and measured results are in good accordance.

1. Introduction

In the wireless communication system, the requirements for the development of multi-band filters [1,2] have increased dramatically. Tunable filters with the characteristics of compactness, lower insertion loss (IL) and high performance that can meet the multi-band feature have aroused great attraction [3,4]. Various tunable filters can be realized by different kinds of reconfigurable devices, such as varactor [5], PIN diode [6] and micro-electromechanical system (MEMS) device [7]. Therefore, some research on tunable dual-band bandpass filter (BPF) has been conducted in recent years [8-11].

In [8], a tunable dual-band BPF with harmonic suppression feature has been proposed. However, the two passbands cannot be independently tuned, and the passband selectivity and out-band rejection are not good. In [9], a three-pole tunable dual-band BPF has been presented. However, the selectivity is poor and its size is large. In [10], a novel switchable dual-/single-band tunable BPF based on a switchable J-inverter has been proposed, but its selectivity and out-band rejection are poor. In [11], a tunable dual-band BPF using lumped-element dual-resonance resonator has been proposed, but its selectivity is poor.

In this article, a tunable dual-band BPF using stub-loaded resonator (SLR) with the second passband independently tunable is presented. The proposed coupling structure (including internal and external coupling) is designed to flexibly control the coupling to obtain the desired bandwidth. Then, two shunt quarter wavelength open stubs and source-load (S-L) coupling are applied to produce transmission zeros (TZs) to improve the selectivity and out-band rejection. Finally, by reasonably adjusting the varactor installed on the end of central stub, the frequency tuning (FT) can be achieved. The simulation is in accordance with the measurement.
2. Filter design and analysis

2.1. Resonant characteristics of the proposed SLR

Figure 1 depicts the presented tunable dual-band BPF, which consists of SLR, feedlines, varactor diodes and bias circuits. Varactor $C_{v1}$ loaded on the end of the central stub is utilized to independently tune the even-mode resonant frequency, and $C_{v2}$ attached to the feedlines is employed to adjust the external coupling. Resistors $R_{bias}$ and capacitances $C_{block}$ (and $C_1$) are acted as dc bias and dc block, respectively.

The equivalent circuit of the varactor loaded SLR is shown in figure 2(a). Due to its symmetrical structure, the even-and odd-mode analysis method is used to analyse its resonant characteristics. Under even-mode excitation, the symmetrical plane $A$-$A'$ can be viewed as virtual open. The equivalent circuit is displayed in figure 2(b). In order to simplify the equation, assuming the input admittance of the central stub loaded with $C_{v1}$ is $Y_{in,1}$, the input admittance under even-mode excitation is written as

$$Y_{in\text{-even}} = Y_{in,1} + jY_{in,1} \tan \beta L_1 \frac{Y_{in,1}}{Y_1}$$

where

$$Y_{in,1} = jY_{in,1} \omega C_{v1} + Y_{in,1} \tan \beta L_2 \frac{Y_{in,1} \omega C_{v1}}{Y_2} \tan \beta L_2$$

The even-mode resonant frequency can be derived from the resonant condition

$$Y_{in\text{-even}} = 0$$

Thus, the value of $C_{v1}$ can be expressed as

$$C_{v1} = -\frac{Y_{in,1}}{\omega_e} (\tan \beta L_1 + \tan \beta L_2) + \frac{Y_{in,1}}{Y_2} C_{v1} \tan \beta L_2$$

Where $\omega_e$ is the even-mode resonant angular frequency.

Similarly, under odd-mode excitation, the central plane can be regarded as virtual short, as indicated in figure 2(c). The input admittance when applying odd-mode excitation is deduced as

$$Y_{in\text{-odd}} = -jY_{in,1} \cot \beta L_1$$

The odd-mode resonant frequency can be derived by

$$Y_{in\text{-odd}} = 0$$

Then, the two resonant frequencies (denoted as $f_1$ and $f_2$) of SLR are applied to form the two passbands. As seen from the equation (4), the even-mode resonant frequency can be independently tuned by reasonably adjusting the varactor $C_{v1}$.
2.2. Design of the coupling structure

In the design process of the filter, the coupling structure is of significance (including internal and external coupling structure, corresponding to internal coupling coefficient $M_{ij}$ and external quality factor $Q_e$), which is a basic and initial step.

Based on frequency specifications ($f_1$ and $f_2$ are 1.87 and 2.72GHz), the 3 dB fractional bandwidths (FBWs) are set as 2.7% and 1.5%, respectively. Then, the $M_{ij}$ and $Q_e$ of the two passbands can be obtained

$$M_{i1}^I = 0.018 \quad Q_e^I = 31.34$$
$$M_{i2}^I = 0.01 \quad Q_e^I = 58.14$$

(7)

The $M_{ij}$ and $Q_e$ of the two passbands can be extracted with the help of EM simulator and calculated by

$$M = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2}$$

(8)

$$Q_e = \frac{\omega_0 \tau_{\text{g}}(\omega_0)}{4}$$

(9)

Where $f_2$ ($f_1$) denotes the higher (lower) resonant frequency, $\tau_{\text{g}}$ ($\omega_0$) represents the group delay at the resonant angular frequency $\omega_0$.

It is important to control the coupling structure to obtain the specified $M_{ij}$ ($M_{i1}^I$ and $M_{i2}^I$). Figure 3(a) illustrates the coupling coefficients as a function of the gap $S$ and finger number $n$. It can be seen that $M_{i1}^I$ and $M_{i2}^I$ both decrease with the increase of $S$, and $M_{i2}^I$ declines faster. While both have not reached the specified value. The interdigital structure composed of a certain number of short fingers between resonators is utilized to enhance the coupling to meet the desired value. As can be seen from the inserted figure in figure 3(a), $M_{i2}^I$ and $M_{i2}^I$ increase with fingers $n$ when the gap $S$ is fixed as 2.5 mm. Besides, it can be viewed from figure 3(b) that the central stub is folded to independently control the $M_{i2}^I$ to meet the design requirement.

Apart from that, the external coupling can be obtained by the proposed feeding structure. Figure 3(c) and (d) plot $Q_e$ as functions of different parameters $S_3$ and $S_4$ at different values of $S_2$ and $S_5$. In
order to realize the wanted $Q_e$ in the frequency tuning process, $Cv_2$ is adopted. $Q_e^I$ and $Q_e^{II}$ can be finely adjusted by reasonably changing these gaps and $Cv_2$.

In order to enhance the passband selectivity and improve the out-band rejection, S-L coupling and two shunt quarter-wavelength open stubs employed at the input/output (I/O) ports are introduced to generate TZs.

![Figure 3](image)

Figure 3. (a) $M$ as a function of gap width $S$ and fingers number $n$. (b) $M$ vs $S_6$. $Q_e^I$ and $Q_e^{II}$ vs (c) $S_3$ under different values of $S_2$. (d) $S_4$ under different values of $S_5$.

3. Fabrication and measurement

For demonstration, the proposed tunable dual-band BPF is designed and fabricated on the Rogers 5880 with the relative dielectric constant of 2.2 and a thickness of 0.787 mm. The photograph is shown in figure 4, and its total size is 20 mm×32.6 mm (0.168 g×0.274 g, where $g$ denotes the guided wavelength at the first passband).

The final optimized dimensions are set as follows: $l_1=1.2$ mm, $l_2=1$ mm, $l_3=0.8$ mm, $l_4=26.2$ mm, $l_5=14.18$ mm, $l_6=1.6$ mm, $l_7=0.5$ mm, $l_8=3.2$ mm, $l_9=6.5$ mm, $l_{10}=4.35$ mm, $l_{11}=2.8$ mm, $l_{12}=2.3$ mm, $l_{13}=9.6$ mm, $l_{14}=3.65$ mm, $l_{15}=3.7$ mm, $l_{16}=23.7$ mm, $l_{17}=20.1$ mm, $l_{18}=1.8$ mm, $w_1=0.4$ mm, $w_2=1.5$ mm, $w_3=0.2$ mm, $w_4=0.1$ mm, $w_5=0.2$ mm, $w_6=0.2$ mm, $w_7=0.45$ mm, $w_8=0.3$ mm, $w_9=0.2$ mm, $w_{10}=1$ mm, $s_1=3.1$ mm, $s_2=0.94$ mm, $s_3=0.6$ mm, $C_1=4$ pF (0402), $C_{block}=100$ pF (0402), $R_{bias}=10$ kΩ (0402). The Silicon varactor MA46H120 is adopted for $Cv_1$ and $Cv_2$.

The simulation and test are conducted by ANSYS HFSS and Agilent N5244A, respectively. Figure 5 illustrates the simulated and measured results. The frequency tuning range (FTR) of the second passband is achieved from 2.24 GHz to 2.71 GHz with the first passband fixed at 1.85GHz, accordingly the constant FBW (CFBW) of 1.5±0.4% is obtained. The measured return loss (RL) and IL is higher than 11.5 and 4.2 dB, respectively. Five TZs indicates the proposed tunable dual-band BPF has high selectivity and good out-band rejection. Table 1 shows the filtering performance parameters of five tunable states. Table 2 gives performance comparisons with the reported works, exhibiting high selectivity, good out-band rejection and compact size.
Figure 4. The photograph of the fabricated tunable BPF.

Figure 5. The simulated and measured results of the proposed tunable BPF. (a) $S_{21}$. (b) $S_{11}$.

Table 1. Performance parameters of five states

| State | $f_2$ (GHz) | FBW (%) | $V_1$ (V) | $V_2$ (V) |
|-------|-------------|---------|-----------|-----------|
| 1     | 2.24        | 1.06    | 2.7       | 1.6       |
| 2     | 2.34        | 1.28    | 3.8       | 2.4       |
| 3     | 2.45        | 1.41    | 4.9       | 3.5       |
| 4     | 2.59        | 1.44    | 9.1       | 4.8       |
| 5     | 2.71        | 1.45    | 29.2      | 8.7       |

Table 2. Performance comparisons with reported works

| Ref. | Dual-band | Lower band | Higher band | TZs | Circuit size $(\varepsilon \times g)$ |
|------|-----------|------------|-------------|-----|--------------------------------------|
| 4    | no        | 1.5-1.9    | -           | >10 | -                                    |
| 9    | yes       | 1.15-1.72  | >7.6        | >11 | >10                                  |
| 10   | yes       | 0.69-0.9   | >3.1        | >15 | >3.9                                 |
| This work | yes    | 1.85       | >3.5        | >11.27 | 2.24-2.71 | >4.2 | >11.5 | 5 | 0.168>0.274 |

4. Conclusion

In this paper, a dual-band BPF based on SLR with the second passband independently tunable is designed, analysed and tested. Appropriately adjusting the coupling structure and $C_{v2}$, the desired $M_\beta$ and $Q_e$ can be obtained in the tuning process. The second passband can be independently tuned by reasonably adjusting $C_{v1}$. The measured results indicate the presented BPF possesses advantages of high selectivity, good out-band rejection, and compact size.
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