Highly compact quad-band bandpass filter with flexibly controllable passbands

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This letter reports a highly compact microstrip quad-band bandpass filter based on two folded λ/4 stepped impedance resonators and three folded dual-mode short stub-loaded resonators. The two stepped impedance resonators not only form the first passband but also serve as the feed structure and provide the source-load coupling path for the three higher passbands created by the short stub-loaded resonators. Thus, a compact size can be obtained, and three pairs of transmission zeros (Tzs) are generated near the three higher passbands, which improve the filter selectivity. In addition, the resonators R1 and R2 are connected to a common metallic hole to further save the filter footprint.

The operation principle of the dual-mode SSLR is depicted in Figure 2. Figure 2b,c gives its odd- and even-mode equivalent circuits, respectively. Here, f1 is the characteristic admittance of the half-wavelength resonator with a length of L1, and f2 is the characteristic admittance of the short stub with a length of L2. Assuming f2 = 2f1, the fundamental odd- and even-mode resonant frequencies of the SSLR can be expressed by

$$f_{\text{odd}} = \frac{c}{2L_1\sqrt{\varepsilon_r}}$$

and

$$f_{\text{even}} = \frac{c}{2(L_1 + L_2)\sqrt{\varepsilon_r}}$$

where c is the speed of light in free space and \(\varepsilon_r\) represents the effective permittivity of substrate. Inspecting (1) and (2), the odd-mode frequency fodd is determined by L1, and the even-mode frequency feven can be controlled by L2, independently. Moreover, feven is lower than fodd. Thus, the short stub length L2 can be utilized to adjust the lower passband edge of the BPF created by the SSLR, as will be demonstrated in Figure 4 later.

The QBBPF was implemented on a Rogers 5880 substrate with a relative dielectric permittivity of 2.2 and a thickness of 0.508 mm. The centre frequencies and 3-dB fractional bandwidths (FBWs) of the four passbands were set as follows: f61 = 1.1 GHz, FBW1 = 14.6%, f62 = 2.05 GHz, FBW2 = 5.1%, f63 = 3 GHz, FBW3 = 3.1%, f64 = 3.55 GHz, and FBW4 = 4.2%. For the first passband, its design procedure follows the conventional coupled resonator filter theory [8]. Its external coupling is determined by the tap position L1, while its inter-resonator coupling is determined by the coupling gap g1, as well as the coupling length L2. Regarding to the other three bands, their external couplings can be adjusted by the coupling gaps g2, g3, and g4. Their bandwidths can be conveniently controlled by the short stub lengths L11, L14, and L15, respectively.

It is worth mentioning that due to the special layout arrangement, the QBBPF can enable all passbands to be controlled independently. The simulations of the filter were performed by Ansys EM simulator HFSS. Figures 3 and 4 show that the centre frequency and bandwidth of each passband can be controlled independently. The tuning of each of the three higher bands has negligible impact on the other bands. However, the tuning of the first passband affects the bandwidth and TZs of the higher bands slightly as seen in Figures 3a and 4a. This is expected because the external couplings and source-load couplings for the three higher passbands are provided via the resonators R1 and R2 (forming the lowest band). The geometric dimensions of the filter shown in Figure 1 are L1 = 4.88, L2 = 3.96, L3 = 12.83, L4 = 4.12, L5 = 12.37, L6 = 2.92, L7 = 11.5, L8 = 3.06, L9 = 11.42, L10 = 2.11, L11 = 0.71, L12 = 13.44, L13 = 5.76, L14 = 0.94, L15 = 0.68, L16 = 10.9, L17 = 7.14, L18 = 2.85.
are 0.68/1.85/2.72/1.97 dB, respectively. The measured return losses are 1.1/2.05/2.99/3.52 GHz with 3-dB FBWs of 14.6/4.9/2.8/4%.

The measurements were performed using Agilent E8363B network analyser. The photograph of the fabricated filter is shown in the inset of Figure 5. The measured S-parameters are given in Table 1 in comparison with the simulated ones. Good agreements are obtained between them, while the slight discrepancy may be due to the fabrication tolerance. The measured centre frequencies of the four passbands are 1.1/2.05/2.99/3.52 GHz.

Simulated and measured S-parameters of the QBBPF

Table 1. Comparison with previously reported QBBPFs

| Ref. | f1/f2/f3/f4 (GHz) | IL (dB) | FBW(%) | TZs Size (λg × λg) |
|------|------------------|---------|---------|---------------------|
| [1]  | 2.4/3.5/5.2/6.8  | 0.5/1.3| 6.4/4.9/3.8/2.8 | 5 0.3 × 0.3          |
| [2]  | 1.88/2.55/3.55/5.15 | 1.53/1.64/1.79/2.55 | 4.4/3.8/3.4/3.2 | 8 0.25 × 0.30        |
| [3]  | 1.9/2.8/3.5/4.3 | 2.3/3.6/3.5/3.4 | 5.3/3.4/3.5 | 3 0.22 × 0.153       |
| [4]  | 1.8/3.5/5.8/6.8  | N/A     | 22/17/10/3 | 3 0.18 × 0.15        |
| [5]  | 1.46/2.6/2.5/5.25 | 1.5/1.9/1.7/2 | 8.6/4.5/5.2 | 4 0.14 × 0.12        |
| [6]  | 2.4/3.5/5.5/6.8 | 1.8/1.5/1.7/2.1 | 6.8/6.7/6.1 | 7 0.23 × 0.23        |
| This work | 1.12/0.6/1.85/2.99 | 3.52/3.52/2.92/2.94 | 6 0.07 × 0.14 |

N/A, non-available.

seen that the proposed filter features high selectivity and the smallest normalized circuit size.

Conclusion: A microstrip QBBPF with highly compact size, high selectivity, and flexibly controllable passbands has been presented in this letter. The normalized circuit size of the filter is only 0.07λg × 0.14λg, which is among the smallest ever demonstrated in QBBPFs. The experimental results have verified the design. The presented filter demonstrated a competitive compact multi-band filter technique.

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