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High selective bandpass filter with mixed electromagnetic coupling and source–load coupling

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ABSTRACT

High selective bandpass filters with a pair of transmission zeros using right-angled triangular stepped-impedance resonators are proposed and analyzed. The transmission zeros on both sides of passband are attributed to the mixed electromagnetic coupling and capacitive source–load coupling, respectively. The transmission zeros locations from the central frequency can be adjusted by controlling the mixed electromagnetic coupling and source–load coupling. The design is also suitable for dual-band bandpass filter with high frequency selectivity. Single band bandpass filters which center at 2.45 GHz and 3.2 GHz, respectively, and a dual-band bandpass filter which centers at 2.45 GHz and 3.5 GHz have been designed, fabricated and measured, the measurements have demonstrated the prediction. Experimental results show that each passband of the presented filters have a pair of transmission zeros as prediction, which improve the frequency selectivity greatly. The measured filters' passband insertion losses are less than 2.74 dB at central frequencies.

1. Introduction

In modern wireless and mobile communication systems, RF/microwave filters are essential components to reject the unwanted signals and let the required signals pass through. Currently, bandpass filters with high selectivity, low passband insertion loss (IL), wide stopband and compact size have been paid more and more attention for the miniaturization and high performance requirement of communication facilities.

In the past few years, the stepped-impedance resonators (SIRs) [1–3] had been widely applied not only to restrain the spurious responses, but also shorten the resonator size. Required filter central frequency can be obtained conveniently by adjusting the impedance ratio of each SIR section. SIR also can be used to design multi-band filters by controlling and tuning the higher order resonant modes. However, the deficiency of this kind of resonator is that the resonant frequencies are dependent, and transmission zeros are difficult to implement. Triangular SIRs [4,5] are also attractive as the commonly used rectangular SIRs. In [4], spurious responses were successfully suppressed using three isosceles triangular SIRs with direct coupling, [5] used the quad-section meandering SIR with irregular triangular shape for realizing multiple passbands by adjusting impedance ratio.

The filter extra transmission zeros are very important to improve stopband rejection performance which help to reject the possible interferences more effectively. To generate expected transmission zeros, researchers have paid attention to the coupling structures. Conventional coupling structures such as cross-coupling [6] and direct coupling have been widely adopted, but the transmission zero was hard to be controlled theoretically. Source–load coupling [7,8] is also demonstrated to generate a transmission zero. Extra transmission zero also can be generated by separate electric and magnetic coupling (SEMC) [9] or mixed electromagnetic coupling (MEMC) [10,11], and transmission zero location can be controlled by controlling the filter electromagnetic coupling. Commonly, a pair of SEMC or MEMC resonators generate a single transmission zero at either side of the desired passband. Electromagnetic coupling is the essence of physical coupling structures.

In this article, high selective bandpass filters with mixed electromagnetic coupling and capacitive source–load coupling are proposed by using right-angled triangular stepped-impedance resonators (RTSIRs). Transmission zeros on both sides of required passband are realized by mixed electromagnetic coupling and source–load coupling, respectively. The locations of transmission zeros can be adjusted by controlling the coupling magnitude of electric or magnetic coupling. This method can also be used for

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Table 1
Resonant performance variation versus parameters a and d for resonator topology 1, b = 6.36 mm, e = 0.2 mm, g = 4.4 mm, α = 45°.

mm	3 dB bandwidth (GHz)	Center frequency (GHz)	Q_e
a = 10, d = 0.28	0.064	3.08	48.30
a = 12, d = 0.55	0.034	2.45	72.83
a = 14, d = 1.05	0.027	2.29	85.17
a = 16, d = 1.48	0.024	2.04	86.77
a = 18, d = 1.98	0.022	1.96	91.21

high selective dual-band filter design. The proposed bandpass filters have better frequency selectivity compared with [4] and [5], and smaller circuits sizes with dimensions reduction of about 67% compared with [4]

2. Analysis of triangular SIR

A fundamental microstrip stepped-impedance resonator unit is formed by joining together two microstrip transmission lines with different characteristic impedance Z_1 and Z_2 (the corresponding characteristic admittances are Y_1 and Y_2), and the corresponding electric lengths are θ_1 and θ_2, respectively. Here, two kinds of right-angled triangular split ring SIRs with electric-dominant coupling are investigated, as Fig. 1(a) and (b) show Fig. 1(c) is the equivalent circuit of the resonators, while, the odd mode and the even mode equivalent circuits are illustrated in Fig. 1(d) and (e), respectively. Where, C_m is the end coupling capacitance of the split ring SIR. From Fig. 1(d) and (e), the input admittance of the odd mode and the even mode can be expressed respectively as

$$Y_{in}^{o} = j\frac{Z_1\left[\tan(\theta_2)+2Z_2\omega_{od}C_m\right] - Z_2\cot(\theta_1)\left[1-2Z_2\omega_{od}C_m\tan(\theta_2)\right]}{Z_1Z_2\left[1-2Z_2\omega_{od}C_m\tan(\theta_2)\right]} \quad (1)$$

$$Y_{in}^{e} = j\frac{Z_2\tan(\theta_1)+Z_1\tan(\theta_2)}{Z_1Z_2} \quad (2)$$

The resonance occurs when the input admittance is zero for both the even mode and the odd mode, that is

$$Y_{in}^{e} = Y_{in}^{o} = 0 \quad (3)$$

From formulas (1)–(3), the resonant conditions of the even mode and the odd mode can be obtained respectively as

$$Z_2\tan(\theta_1)+Z_1\tan(\theta_2)=0 \quad (4)$$

$$Z_1\left[\tan(\theta_2)+2Z_2\omega_{od}C_m\right] - Z_2\cot(\theta_1)\left[1-2Z_2\omega_{od}C_m\tan(\theta_2)\right] = 0 \quad (5)$$

Where, ω_{od} is the resonant angular frequency of the odd mode, $\theta = \left(\omega\sqrt{\varepsilon_{re}}/c\right) l$. Here, l is the physical length, c is the velocity of light in free space, ε_{re} is the effective permittivity. Resonant angular frequencies of the even and the odd modes of the triangular SIR can be obtained by solving (4) and (5) using Matlab. It is proved that the calculated results from (4) and (5) approach to the simulated results. Filter center frequency can be approximately obtained as $f_0 = (1/4\pi)(\omega_{od}+\omega_{ev})$, ω_{ev} is the resonant angular frequency of the even mode.

Calculated resonant performance variations versus physical parameters for the triangular SIR topology 1 and topology 2 are listed in Tables 1–3. For topology 1, it is seen from Table 1 and Table 2 that center frequency and 3 dB bandwidth decrease when circuit size and parameter d increase, while, the external quality factor keeps increasing, and Q_e is more than 48. It also can be seen that when total circuit size keeps unchanged, center frequency and Q_e increase with parameters g and d, but the 3 dB bandwidth has less variation. The center frequency shift is because of the SIR impedance ratio variation, so the filter operation frequency can be easily adjusted and controlled by the impedance ratio. For topology 2, it shows from Table 3 that when circuit size fixes, increasing

Table 2
Resonant performance variation versus parameters g and d for resonator topology 1, a = 12 mm, f = 5.9 mm, e = 0.2 mm, α = 45°.

mm	3 dB bandwidth (GHz)	Center frequency (GHz)	Q_e
g = 2.9, d = 0.30	0.04	2.09	51.05
g = 3.4, d = 0.30	0.037	2.08	55.19
g = 3.9, d = 0.45	0.031	2.25	71.62
g = 4.4, d = 0.55	0.034	2.45	72.83
g = 4.9, d = 1.02	0.031	2.80	89.44

Table 3
Resonant performance variation versus parameter h for resonator topology 2, a = 10 mm, l = 4.8 mm, g = 2.9 mm, p = 0.4 mm, e = 0.4 mm, d = 0.5 mm, α = 45°.

h (mm)	3 dB bandwidth (GHz)	Center frequency (GHz)	Q_e
2.0	0.039	2.80	71.82
2.4	0.035	2.74	79.45
2.8	0.038	2.68	71.14
3.2	0.031	2.61	83.09
3.6	0.036	2.56	70.78

parameter h introduces longer physical length and stronger inner coupling, which brings smaller center frequency. The coupling also has slight effect on fractional bandwidth. Both topology 1 and topology 2 have adequate external quality factor.

In this article, all of the calculations, designs and fabrications are carried out by ceramic substrate with relative permittivity of 10.2 and thickness of 1.27 mm. Feed lines are microstrip lines with characteristic impedance of 50ohm. Simulations have been carried out with Ansoft Ensemble.

3. Bandpass filter with mixed EM coupling and source–load coupling

3.1. Single band bandpass filter

In order to generate a pair of transmission zeros, a new bandpass filter with mixed electromagnetic coupling and source–load coupling using right-angled triangular SIR is presented, as Fig. 2(a) shows, and Fig. 2(b) illustrates the coupling structure. Since a split ring resonator is essentially a quarter-wavelength resonator, the electric field is strong at the open ends of the resonator, while, the magnetic field is strong around its middle, so a pair of coupling SIR is mixed EM coupling structure. Where, the four resonators are capacitive coupling 2-section RTSIRs with identical dimensions. For operating at 3.2 GHz with fractional bandwidth (FBW) of 8.7%, the filter dimensions are set as a = 10 mm, b = 4.24 mm, d = 0.7 mm, t = 0.2 mm, e = 0.4 mm, f = 4.8 mm, g = 2.8 mm. Filter equivalent circuit is illustrated in Fig. 3(a), and Fig. 3(b) is the transformed equivalent circuit where electric and magnetic coupling are substituted by impedance transformer. Where, C_s is the coupling capacitance between feed line and triangular SIR, C_{SL} is the coupling capacitance between feed lines, C_1 is the ground capacitance of the split ring end, C_g is the gap capacitance of the split ring SIR. Here, C_{SL} = 0.085 pF, C_g = 0.050 pF, C_1 = 0.021 pF. L_0 and C_0 are the inductance and capacitance for the triangular SIR itself. L_m is the coupling inductance, and C_m is the coupling capacitance. $\omega_0 = (L_0C_0)^{-1/2}$ denotes the natural resonant frequency, $\omega_m = (L_mC_m)^{-1/2}$ denotes the transmission zero that is generated by mixed EM coupling.

The odd mode and the even mode equivalent circuits can be obtained by using an electric wall and a magnetic wall on T–T', respectively. From Fig. 3(b), we have

$$L_{odd} = L_0 - L_m, \quad L_{even} = L_0 + L_m \quad (6a)$$