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COMPACT BANDPASS FILTER WITH MIXED ELECTRIC AND MAGNETIC (EM) COUPLING

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Abstract—A compact wide-band bandpass filter (BPF) with high frequency selectivity using stepped impedance resonators (SIRs) is presented in this paper. The proposed BPF consists of four SIRs, which share a common grounded via-hole. To improve the frequency selectivity, multiple transmission zeros (TZs) are employed in the stopband by mixed electric/magnetic (EM) coupling. The novel filter with 32.2% fractional bandwidth (FBW) has been designed and fabricated to verify the validity of the proposed method. Measured results are in good agreement with the electromagnetic simulation. The measured results show three finite transmission zeros in the stopband, located at 2.47 GHz, 5.26 GHz, 9.39 GHz, respectively. The circuit size of proposed BPF only occupies $3.10 \times 13.30\,\mathrm{mm}^2$.

1. INTRODUCTION

Microstrip bandpass filters with low insertion loss, compact size and high selectivity play more and more important roles in mobile communication systems and radio frequency (RF) front/end of the wireless communication systems [1–4]. Transmission zeros are usually employed to improve the rejection of the BPFs without increasing circuit size and insert loss. There are mainly three methods to achieve TZs, such as cross-coupling, source-load coupling, and mixed electric/magnetic coupling.

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The non-adjacent coupling technique of generating TZs is found effective in many practical applications [5–16]. The methods include cross-coupling and source-load coupling to generate transmission zeros by providing multipath effect. Cross-coupling filters are attractive since they exhibit high selective responses by the non-adjacent resonators. Among these cross-coupled filters, the cascade trisection (CT) and cascade quadruplet (CQ) [7, 8] are two of the most commonly used coupling schemes. A lot of studies on source-load coupling have been reported, and various kinds of resonators have been presented [11–16]. Recently, the mixed electric/magnetic (EM) coupling technique is also found able to introduce transmission zeros in lots of practical applications [17–21]. The mechanism of producing transmission zeros in cascaded structures through separated and mixed EM coupling was analyzed in detail [18, 19].

In this paper, a compact wide-band BPF using SIRs is presented. To improve the frequency selectivity and stopband characteristics, mixed EM coupling is introduced in the conventional box-section filter [22] to achieve transmission zeros near the passband. The location of transmission zeros can be controlled by adjusting the mixed EM coupling strength. A bandpass filter prototype has been designed, fabricated and measured to verify the validity of the proposed method.

2. DESIGN OF BANDPASS FILTER WITH MULTIPLE TRANSMISSION ZEROS

In this paper, a compact wide-band BPF with multiple transmission zeros is presented. Figure 1(a) shows the layout of proposed bandpass filter. The proposed BPF consists of four SIRs, where all the SIRs shared a common grounded via-hole and the input/output ports are asymmetry. In the proposed filter, mixed EM coupling is introduced between the resonators R1 and R2 as well as R3 and R4. The low impedance lines of the SIRs provide the electric couplings, while the grounded via-hole offers the magnetic couplings. Figure 1(b) shows the corresponding coupling and routing scheme.

The mixed EM coupling is introduced to employ transmission zeros and the mixed coupling strength can be defined as Eq. (1), where the K_E and K_M are defined as the electric coupling and magnetic coupling, respectively. Owing to the canceling effect of the mixed coupling, a finite transmission zero can be obtained in the stopband. In [18, 19], when electric coupling is dominate, $f_{even} > f_{odd}$, the transmission zero can be achieved on the lower stopband. While the magnetic coupling is dominate, $f_{even} < f_{odd}$, the transmission zero can be introduced on the upper stopband. In [23], the odd- and even-

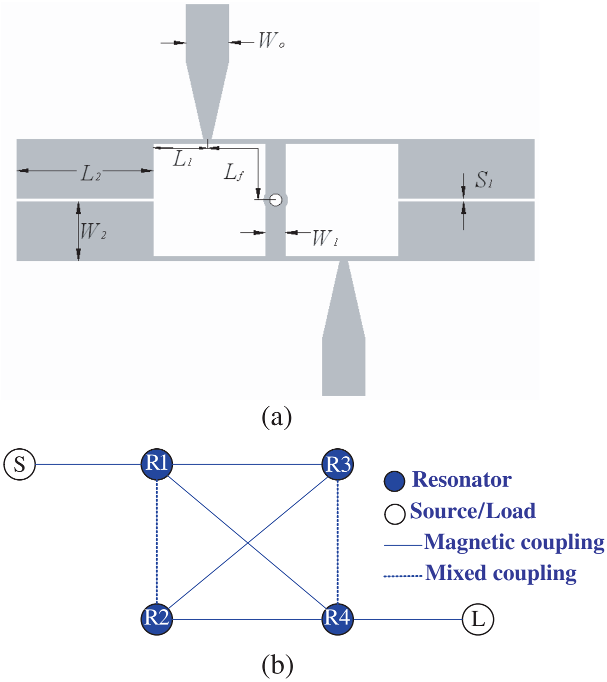

Figure 1. (a) Layout of proposed BPF. (b) Corresponding coupling and routing scheme.

mode analyses of the resonance frequencies have been presented. The impacts of controlling the strength of electric and magnetic coupling have also been analyzed.

$$M_{mixed} = \frac{f_{odd} - f_{even}}{f_{odd} + f_{even}} = K_M - K_E \tag{1}$$

To enhance the skirt selectivity, three transmission zeros are introduced in the stopband by introducing mixed EM coupling and the harmonic effects of the distributed transmission lines.

Figure 2 shows the impacts of the gap S_1 and feed location L_f on the frequency responses. The TZ_1 and TZ_3 are employed owing to the canceling effects of the mixed coupling between R1 and R2 as well as R3 and R4, and TZ_3 is also affected by input/output feed location. The TZ_2 is introduced owing to the harmonic effects of the distributed transmission lines. Figure 2(a) shows the impact of the electric coupling strength on the locations of three transmission zeros. The TZ_1 and TZ_3 are far away from operation frequency as the strength of electric coupling increases, while TZ_1 shifts close to the

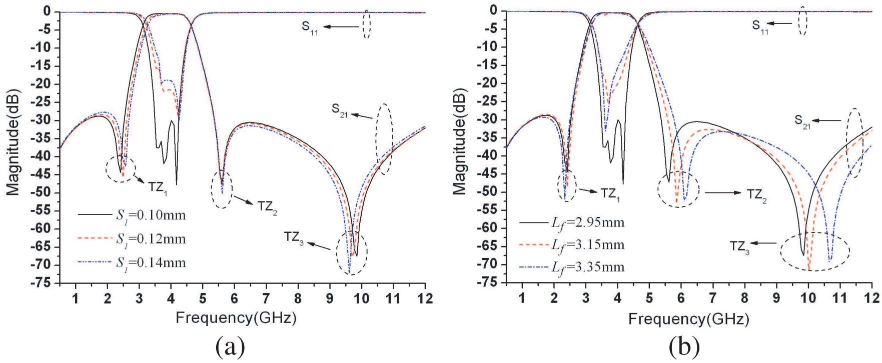

Figure 2. The impact of (a) the gap S_1 (b) feed location L_f on the frequency responses.

operating frequency gradually, which improves the skirt selectivity of the proposed BPF. As the TZ_1 moving wide passband is achieved. And the TZ_2 is not moved. Figure 2(b) shows the impact of feed location of input/output. The TZ_2 and TZ_3 will shift to near the passband as decreasing L_f for high skirt selectivity, but the bandwidth does not change.

3. FILTER FABRICATION AND MEASURED RESULTS

The BPF was optimized by electromagnetic simulation using Ansoft HFSS and fabricated on Rogers RO4350 substrate with a relative dielectric constant of 3.66, a thickness of 0.508 mm and a loss tangent 0.002. The geometrical dimensions are decided as: $W_0 = 1.10$ mm, $W_1 = 0.30$ mm, $W_2 = 1.50$ mm, $W_3 = 0.10$ mm, $L_1 = 1.40$ mm, $L_2 = 3.50$ mm, $L_f = 2.95$ mm, $S_1 = 0.10$ mm, $R = 0.155$ mm. The total area of the proposed BPF circuit is $3.10 \times 13.30\,\mathrm{mm}^2$, which corresponds to a size of $0.067\lambda_g \times 0.290\lambda_g$, where the λ_g is the guided wavelength at the centre frequency of the passband.

Figure 3 shows a photograph of the proposed BPF in this letter. An Agilent E8363B network analyzer was used to measure the proposed BPF. Simulated and measured results of the proposed filter are compared in Figure 4 with good agreement. The measured results show that the center frequency at 3.85 GHz and 32.2% fractional bandwidth (FBW) is achieved. The insertion loss is less than 0.85 dB in the passband. In addition, the frequency selectivity was enhanced by introducing three transmission zeros near the passband located at 2.37 GHz with 47.92 dB rejection, 5.16 GHz with 32.77 dB rejection,

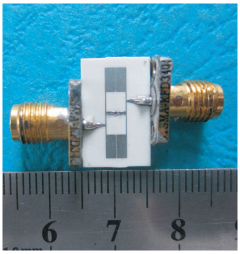

Figure 3. Photograph of the proposed BPF.

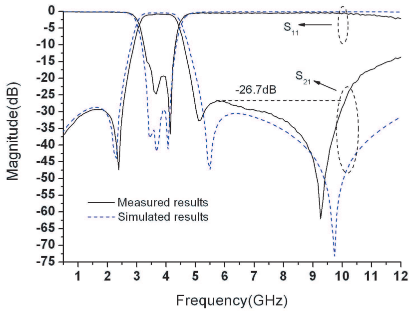

Figure 4. The simulated and measured frequency responses.

Table 1. Compare with other proposed bandpass filter.

Ref.	Center Frequency (GHz)	3 dB FBW (%)	Transmission zeros location (GHz)
[7]	5.5	10.9	4.4, 7.0
[11]	2.4	6.9	1.9, 2.15, 2.6, 3.19
[21]	2.45	3.9	2.01, 2.2, 2.62, 3.95
This work	**3.85**	**32.2**	**2.47, 5.26, 9.39**
Ref.	Return loss (dB)	Insertion loss (dB)	Circuit size $\lambda_g \times \lambda_g$
[7]	$\geqslant 10$	$\leqslant 1.5$	0.30×0.28
[11]	$\geqslant 19$	$\leqslant 2.0$	0.14×0.40
[21]	$\geqslant 12.6$	$\leqslant 2.5$	0.32×0.29
This work	$\geqslant$ **19.4**	$\leqslant$ **0.85**	$\mathbf{0.067 \times 0.29}$

9.29 GHz with 72.94 dB rejection, respectively. And the return loss is better than 19.4 dB in-band. Table 1 summarizes the comparison of the proposed filter with other reported bandpass filters.

4. CONCLUSIONS

A compact wide-band BPF with multiple transmission zeros is presented in this paper. Three transmission zeros are introduced to improve the passband selectivity, which had been verified by simulation and measurement. The new BPF exhibits favorable selectivity and wide upper stopband performance and occupies a size of only $0.067\lambda_g \times 0.290\lambda_g$.

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