Periodic Stepped-Impedance Resonator (PSIR) Bandpass Filters with Multispurious Suppression

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Abstract **— Periodic stepped-impedance resonators (PSIRs) are proposed to design bandpass filters for multi-spurious suppression. Denoted as PSIRN, a PSIR of λ/2 long at design frequency f_o consists of N periods of hi-Z and low-Z sections. A PSIRN coupled section shows transmission zeros at various frequencies. The zeros can be tuned by changing the impedance ratio of the hi-Z and low-Z sections, and can be adopted to suppress the spurious peaks. Responses of the PSIR filters show good rejection in the upper stopband.**

Index Terms **— Microstrip filter, multi-spurious suppression, stepped-impedance resonator (SIR), transmission zeros, upper stopband.**

I. Introduction

With the rapid development of microwave and wireless communications, high selectivity and wide upper stopband are becoming essential requirements for the bandpass filters in the RF front end for overall system performance consideration. Over a few decades, the parallel-coupled line configuration has been one of the most widely used structures for design of planar microstrip bandpass filters [1]. This configuration, however, suffers from the spurious responses at harmonic frequencies. Designed at passband frequency f_o, a practical parallel-coupled circuit has multiple unwanted responses at its harmonics. The even-order harmonics are resulted from that the coupled stages have unequal even- and odd-mode phase constants, and the odd-order spurious responses arise due to the inherent distributed nature of the transmission line network. Specifically, the spurious response at twice the design frequency, $2f_o$, not only seriously degrades the attenuation rate at upper stopband but also destroys symmetry of the passband response [2-9]. This problem becomes more severely when the filters are implemented on substrates with relatively high dielectric constant.

Many researches of parallel-coupled line filter design on spurious suppression and stopband extension have been demonstrated [2-10]. In [2] and [3], the substrate suspension technique and dielectric overlay method are proposed for suppressing the second harmonic ($2f_o$). Based on providing different electric lengths for the even- and odd-modes, corrugated coupled-line microstrip is also an effective way for extending the upper stopband up to $3f_o$ [4]. The inherent transmission zero of a coupled stage can be easily tuned to collocate with the unwanted $|S_{21}|$ peak at $2f_o$ via the over-coupling scheme [5-6]. The wiggly line in [7] is also a successful design for harmonic suppression.

Recently, several strategies have been developed for multi-spurious suppression. In [8], the idea of over-coupling is extended to design over-coupled middle stages so that the spurious peaks at $2f_o$, $3f_o$, and $4f_o$ can be suppressed and the upper stopband can be greatly broadened up to $5f_o$. On the strength of the coupled theory and Bragg effects in waveguides, a nonuniform wiggly-line filter is presented to effectively reject the high-order harmonics [9]. The nonuniform structure, however, requires long simulation time due to fine circuit discretization. In [10], the stepped-impedance resonators (SIRs) have been found advantageous in designing microstrip bandpass filters with a wide upper stopband. One of the key features of an SIR is that its resonant frequencies can be easily tuned by adjusting its structure parameters. Incorporating with tapped-line structure, the SIR filter has good rejection in the stopband up to $8.2f_o$.

In this paper, we propose a new periodic stepped-impedance resonator (PSIR) for building parallel-coupled line bandpass filters with free of spurious response up to more than $5f_o$. The resonator consists of a cascade of periodic hi-Z and low-Z sections. With proper choice of the impedance ratio for each coupled stage, multi-spurious suppression can be achieved. In the following, Section II investigates the resonant characteristics of PSIRs, Section III studies the tuning of the transmission zero of a PSIR coupled stage, Section IV demonstrates the simulated and measured results, and Section V draws the conclusion.

II. The Periodic Stepped-Impedance Resonator (PSIR)

Fig. 1 shows a layout of the proposed PSIR of period N = 1, which is denoted as PSIR1. The following resonance conditions for this circuit can be formulated by the even- and odd-mode analysis [1]:

$$(1 + R^2)\tan 2\theta_1 + R(\tan\theta_2 - \cot\theta_2) = 0 \quad \text{(odd-mode)} \quad (1)$$

$$R^2\tan 2\theta_1 + 2R\tan\theta_2 - \tan^2\theta_2 \tan 2\theta_1 = 0 \quad \text{(even-mode)} \quad (2)$$

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Fig. 1. Layout of a PSIR1.

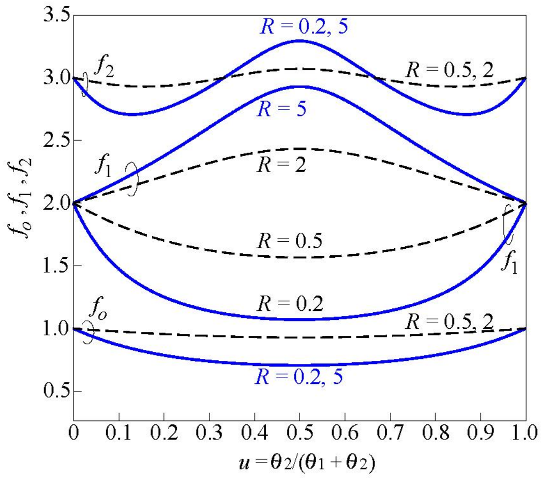


Fig. 2. Normalized resonant frequencies of a PSIR1.

Fig. 3. A PSIR2 coupled stage.

TABLE I
NORMALIZED HIGHER-ORDER RESONANT FREQUENCIES OF PSIR1 ~ PSIR5

	f_1/f_o	f_2/f_o	f_3/f_o	f_4/f_o
PSIR1	2.61 1.69	3.30	4.30	5.30
PSIR2	1.97	2.90	3.35 4.90	5.70
PSIR3	1.97	2.90	3.75	4.62
PSIR4	1.97	2.90	3.75	4.62
PSIR5	1.97	2.90	3.75	4.62

where R is the impedance ratio of the PSIR defined as

$$R = \frac{Z_2}{Z_1} \tag{3}$$

When $R = 1$, $\theta_1 + \theta_2 = \pi/4$ at f_o. It can be seen from (1) and (2) that the resonant frequencies of a PSIR1 can be adjusted by altering the value of R and the lengths of the hi-Z and low-Z segments. A simple root-searching program can be employed to calculate the resonant frequencies. Fig. 2 plots the resonant frequencies f_k against $u = \theta_2/(\theta_1+\theta_2)$ for the fundamental, the first, and the second higher-order modes for R = 0.2, 0.5, 2 and 5. For the odd resonances, the PSIRs with R = 0.2 and 0.5 have the same f_o and f_2 as those with R = 5 and 2, respectively. For the even resonance, however, the natural frequencies for PSIRs with R and $1/R$ have an increasing distance when R deviates farther away from unity.

The resonant frequencies of a PSIRN for $N > 1$ can be obtained in a similar fashion. Table I lists the simulated resonant frequencies of PSIRN, N = 1, 2, …, 5, normalized with respect to f_o = 2.45 GHz, for R = 0.5 and u = 0.5. One can see that the PSIR1 and PSIR2 have distinct f_k/f_o ratios for $k \geq 1$, while the PSIR2 and PSIR3 have different f_k/f_o values for $k \geq 3$. Note that all these three resonators have identical f_o but quite different f_1, f_2, and f_3. This property would be beneficial for designing distributed bandpass filters with a wide upper stopband.

III. COUPLING RESPONSES OF THE PSIRN COUPLED STAGES

A coupled PSIR2 stage is designed as shown in Fig. 3. At f_o, the quarter-wave section consists of two half PSIR2s with impedance ratios R and $1/R$. A general coupled PSIRN stage can be designed in the same way. Suppose the circuits are designed on a substrate with ε_r = 10.2 and thickness h = 1.27 mm. Such a high dielectric substrate is purposely chosen to demonstrate performance of our approach. Fig. 4 plots the coupling characteristics of the PSIR1, PSIR3, and PSIR5 stages with R = 0.5, 0.6, …, 0.9. The simulation data are obtained by the full-wave software package IE3D [11]. Here, the designed frequency f_o = 2.45 GHz, the widths of low-Z and hi-Z segments W_1 = 1.38 mm and W_2 = 0.15 mm, respectively, and gap size S = 0.6 mm.

In Fig. 4(a), two transmission zeros can be observed for each R. The zero between $2f_o$ and $3f_o$ can be tuned in a small range when the R is altered. The second zeros occur near $5f_o$. Fig. 4(b) shows the $|S_{21}|$ responses of the PSIR3 stages. The first zeros locate between $2.8f_o$ and $3.3f_o$, and the second ones between $4.6f_o$ and $6.1f_o$ when R is varied from 0.5 to 0.9. This example demonstrates that the transmission zeros can be tuned by changing the impedance ratio R for PSIR coupled stages. As indicated in Fig. 4(c), the tuning ranges of the leading two zeros of the PSIR5 stages via changes of R are even larger than those of the PSIR3 stages.

It is worth mentioning that all the PSIRN stages, N = 1, 2, …, 5, are commensurate, if the discontinuity effect is ignored. In this study, the relative deviation of the physical lengths of a PSIR1 and a PSIR5 is less than 3%.

IV. FILTER DESIGN, SIMULATION, AND MEASUREMENT

The filter synthesis procedure is similar to that listed in [10]. Fig. 5(a) shows the circuit layout of a third-order filter having

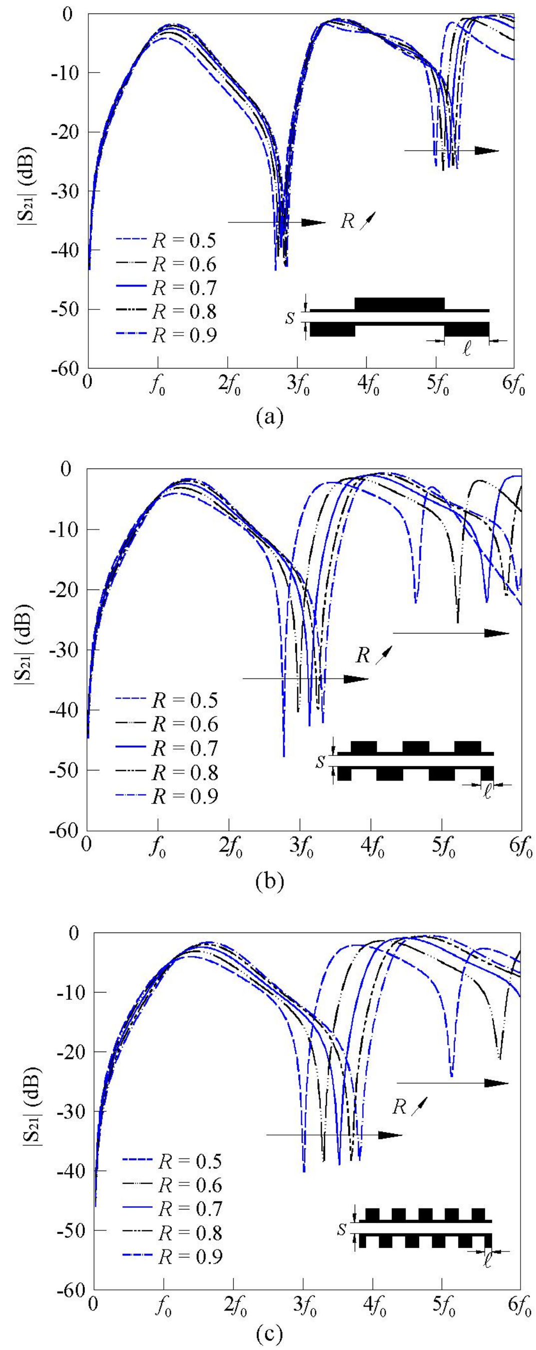


Fig. 4. Simulated coupling responses of PSIR coupled stages with S = 0.6 mm. (a) PSIR1 stage with ℓ = 2.52 mm. (b) PSIR3 stage with ℓ = 0.72 mm. (c) PSIR5 stage with ℓ = 0.37 mm.

two PSIR1 and two PSIR2 stages. Note that one of the end resonators is a PSIR1 and the other is a PSIR2. The middle resonator is a hybrid resonator combing PSIR1 and PSIR2. The circuit is designed on the RT/Duroid 6010 substrate to have f_o = 2.45 GHz, fractional bandwidth Δ = 8% and Chebyshev passband ripple 0.1 dB. Fig. 5(b) compares the simulation and measured results. Good agreement can be observed. The upper stopband having a rejection level better than 30 dB is achieved up to $3f_o$. In the passband, the $|S_{21}|$ insertion loss is -1.5 dB.

In order to further suppress the spurious near $3f_o$ shown in Fig. 5(b), the end PSIR2 stage in Fig. 5(a) is replaced by a PSIR3 stage. The impedance ratios for the PSIR2 and PSIR3 stages are changed to R = 0.4 for tuning the first inherent transmission zero. Fig. 6(a) plots the simulated and measured results. It can be observed that for a rejection better than 30 dB, the upper stopband reaches $5f_o$. Note that the inband insertion loss is only -1.5 dB and return loss is better than -15 dB. The photograph of the circuit is shown in Fig. 6(b).

Fig. 7(a) plots the responses of a fifth-order Chebyshev filter. In the six coupled sections, the first and the second stages are PSIR1 stages, and the third through the sixth sections are designed with the PSIR2 through PSIR5 stages, respectively. The measured $|S_{21}|$ and $|S_{11}|$ curves have good agreement with the simulation counterparts. In the passband, the best insertion loss is -2 dB and the best return loss is better than -30 dB. For a rejection level of 30 dB, the measured responses show an upper stopband up to $5.3f_o$. The photograph of the circuit is shown in Fig. 7(b).

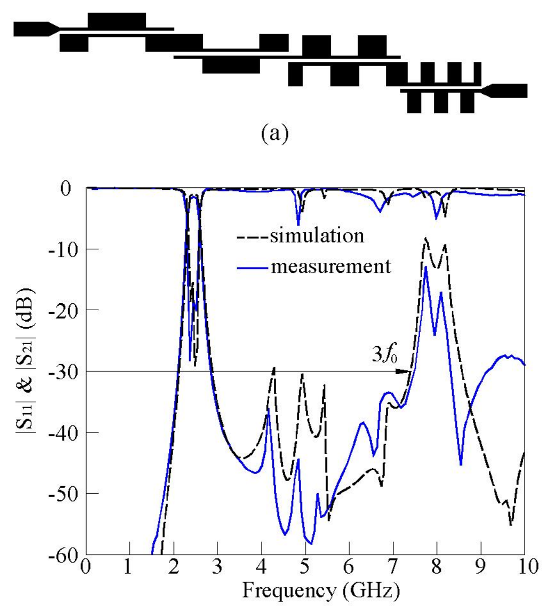
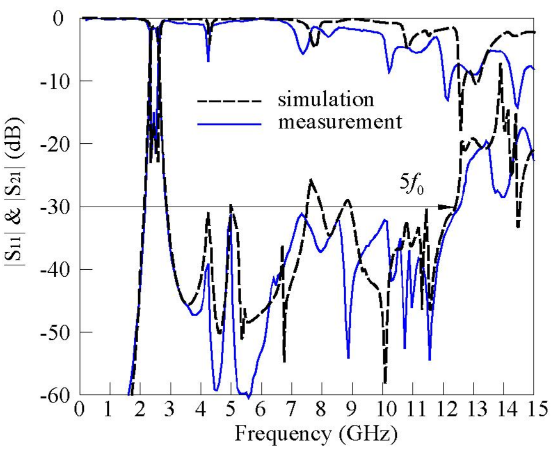


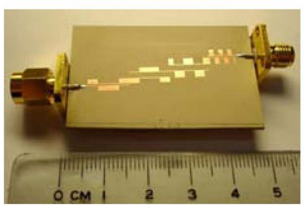
Fig. 5. Layout and performance of a third-order PSIR filter. (a) Circuit layout. (b) Simulated and measured results. Dimensions: S_1 = 0.35 mm, S_2 = 1.5 mm, S_3 = 1.4 mm, S_4 = 0.3 mm. R = 0.5 for all PSIR coupled stages.

V. Conclusion

Periodic stepped-impedance resonators (PSIR) are proposed to design parallel-coupled bandpass filters with multispurious suppression. Most of the higher-order resonant frequencies of the PISR1, PSIR2, and PSIR3 are different from one another. The coupling responses various PSIR coupled stages are studied. The inherent transmission zeros of the coupled stages are tunable via changes of the impedance ratio of the hi-Z and low-Z segments of a PSIR. Measured results show that suppression of unwanted responses achieves at a level better than 30 dB up to $5f_o$ for third- and fifth-order filters.

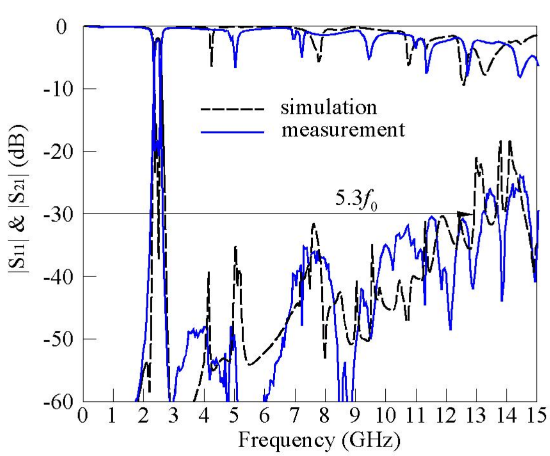


(a)

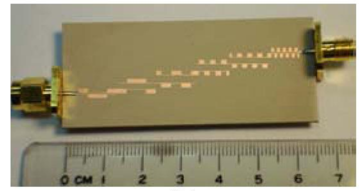


(b)

Fig. 6. (a) Simulated and measured results of the second third-order PSIR filter. (b) Photograph of the circuit. Dimensions: S_1 = S_4 = 0.3 mm, S_2 = 1.4 mm, S_3 = 1.5 mm. R = 0.4 or 0.5. The hi-Z segment has Z_o = 90 Ω.



(a)



(b)

Fig. 7. (a) Simulated and measured results of a fifth-order PSIR filter. (b) Photograph of the circuit. Dimensions: S_1 = S_6 = 0.3 mm, S_2 = 1.5 mm, S_3 = 2.1 mm, S_4 = 1.8 mm, S_5 = 1.6 mm. R = 0.5. The hi-Z segment has Z_o = 100 Ω.

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