TH2C-5

Stepped Impedance Resonator Bandpass Filters with Tunable Transmission Zeros and Its Application to Wide Stopband Design

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***Abstract* – Bandpass filters with a very wide stopband are designed using parallel coupled stepped impedance resonators (SIR), which have advantageous resonance harmonic characteristics. The singly loaded Q (Q_{si}) of a tapped SIR is derived, so that the relation between Q_{si} and the position of tap point can be established. It is known that a single resonator with tapped input can create an extra zero. It is found that in this paper, with proper tapping at the first and the last SIR's of a bandpass filter, two zeros can be created and tuned independently over a wide frequency range. By exploiting both the advantageous resonance characteristics of SIR and tapped-line input, a bandpass filter with high selectivity and/or wide stopband can be realized. The experimental results show a good agreement with the simulated prediction.**

I. INTRODUCTION

In the RF front-end of a modern communication system, bandpass filters with wide stopband and high selectivity are usually required to enhance the overall circuit performance. In the last thirty years, parallel coupled microstrips have been one of the most commonly used filters due to its planar structure, ease of synthesis method, and low-cost [1]. It is known that the parallel coupled microstrip filters suffer from the spurious response at $2f_o$, twice the passband frequency, which may seriously degrade the attenuation property in the stopband. It is resulted from the deviation between the even- and odd-mode phase velocities of each coupled section. Various methods can be used to compensate this effect, e.g. [2]. However, most of them either add cost to or complicate the original filter.

The first and second spurious responses of filters designed with stepped impedance resonators (SIR) can be pushed far beyond $2f_o$ and $3f_o$, respectively, with a proper choice of impedance ratio [3]. The design in [4] completely suppresses the $2f_o$ resonance with inductive effect. Its first parasitic response is observed at frequency close to $3f_o$.

Filters with tapped-line input can save space as well as cost since the first and the last sections of the filter are eliminated [5]. A further benefit, two extra transmission zeros in the stopband, can be created [6]. This is a very useful feature for practical RF transmitters and receivers in rejecting image frequencies and enhancing the attenuation characteristics in the stopband of the filter. The tapped coupling [7] can also be used to generate a transmission zero at any desired frequency. Note that in [6] the two extra zeros are tuned simultaneously. It is clear from [7] that, without alternating the passband response, we can apply tapped couplings to both the first and the last resonators to have the two extra zeros be independently tuned.

In this paper, we aim at designing a filter with good selectivity or a very wide stopband. To this end, we use SIR's as the building blocks to make the 2nd and 3rd resonances much higher than $2f_o$ and $3f_o$, respectively, and synthesize the filter based on a parallel coupled structure. Then with proper tappings, the two extra zeros can be freely located either on both sides or on either side of the passband. If both the extra zeros are devoted to cancel the second harmonic resonance, the filter may have a very wide stopband up to $4f_o$, which is the frequency of the third harmonic resonance.

The presentation is as follows. Section II formulates the calculation of singly loaded Q (Q_{si}) of a tapped SIR. Section III addresses the tuning of the extra transmission zeros and Section IV presents some simulation and experimental results to demonstrate the idea described above.

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II. THE SIR AND ITS SINGLY LOADED Q

For the tapped SIR shown in Fig.1, the spurious resonance frequencies can be controlled by the impedance ratio

$$R = Z_2/Z_1 \quad (1)$$

It has been shown in [3] that the lower R value, the higher the spurious resonance frequencies. Herein, the line width of Z_1 is chosen to be 0.25 mm, which is close to the lower limit of our fabrication facility, and that of Z_2 is determined by setting $R = 0.4$ on a 50-mil substrate of $\varepsilon_r = 10.2$. The physical length of the resonator is then determined by the phase constant to have $\theta = 45°$ at the center frequency.

It can be shown that the Q_{si} for the tapped SIR in Fig.1 can be derived as

$0 < l < \lambda/8$:

$$Q_{si} = \frac{R_L}{2Z_1}[f^2(p)h(p) + f^2(q)h(q)] \quad (2)$$

$$f(\zeta) = \frac{\sec(\zeta)}{R - \tan(\zeta)}$$

$$h(\zeta) = \frac{R\pi}{2} + \zeta(1 + R^2)$$

where $p = \pi(1 + b_n\delta)/4$, $q = \pi(1 - b_n\delta)/4$, $\delta = 1 - l/L$, and $b_n = 1 + \beta_2/\beta_1$, and

$\frac{\lambda}{8} < l < \frac{\lambda}{4}$:

$$Q_{si} = \frac{R_L}{2Z_2}\left\{m\sec^2(m) + \left[\frac{\sec(x)}{1 + R^2\tan(x)}\right]^2\left[\frac{3\pi R^2}{2} + x(1 + R^4)\right]\right\} \quad (3)$$

where $x = \pi(b_n\delta - b_m)/4$, $m = \pi b_n(1 - \delta)/4$, and $b_m = \beta_2/\beta_1$.

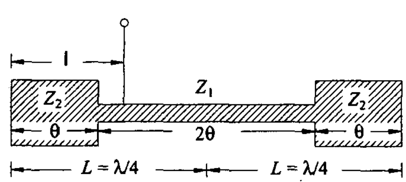

Fig.1 Structure of the tapped SIR.

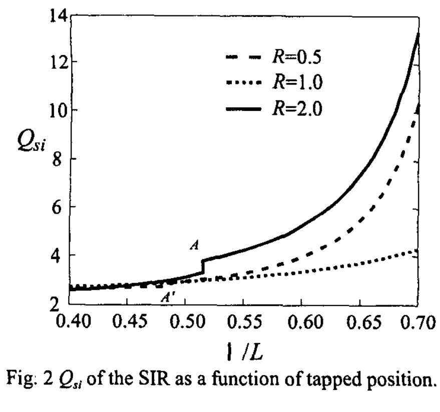

Fig. 2 Q_{si} of the SIR as a function of tapped position.

Fig. 2 plots the values of Q_{si} for three different impedance ratios with respect to the tap position. The case for $R = 1$ stands for a uniform line resonator. When $R \neq 1$, each Q_{si} curve has a discontinuity due to the impedance steps existing in the resonator.

III. THE EXTRA TRANSMISSION ZEROS

In Fig.1, assume that the right half of the tapped SIR is coupled with the next SIR. Based on [7], the frequency of the extra zero introduced by the tapped coupling can then be determined by treating the cascaded nonuniform line section to the left of the tap point as an open stub, so that the input impedance at tap point is virtually short-circuited. The frequency of the zero can then be tuned via sliding the tap point on the SIR. It is to be noted that the singly loaded Q (or Q_{si}) of the SIR has been determined by the design specification. Thus an arbitrarily located tap point corresponds to a fixed source or load impedance, looking from the tap point toward the generator or load [3]. If it is not identical to the impedance of the generator or load, a quarter-wave transformer can be employed to establish the impedance matching.

Fig.3 shows the frequency of the zero normalized to the center frequency f_o versus the position of the tap point. It can be seen that the f_z/f_o can be tuned over a wide range from around 0.7 to greater than 5.

IV. SIMULATION AND MEASUREMENT

Parallel coupled SIR, as in Fig.4, is used to synthesize bandpass filter with fractional bandwidth no less than 10%. Fig. 5 plots the simulation responses of a Chebyshev filter of order three, center frequency f_o = 2GHz, fractional bandwidth Δ = 20%, and impedance ratio R = 1. By sliding the tap point along one of the outmost SIR, the frequency of the transmission zero varies correspondingly. From f_{z1} to f_{z2}, and from f_{z2} to f_{z3}, the tap point is moved outward the filter with a distance of 0.022λ. It is interesting to note that the response below the upper passband edge, including the position of the zero in the lower stopband, does not change significantly for this particular case study.

Three Chebyshev filters are fabricated and measured to further demonstrate the idea described above. The specifications of these filters are summarized in Table I. The full-wave electromagnetic simulator IE3D [10] is used to validate our design before the circuits are fabricated.

Filters A and B have identical passband specifications. In filter A, the two extra zeros are chosen to locate on both sides of the passband, while in filter B, the zeros are tuned to coincide on the upper stopband to have a wider rejection bandwidth. Figs. 6 and 7 plot the simulation and measured results for these two cases. The prediction of the frequencies of the zeros shows a very good agreement with the experiments.

Fig. 8 plots the simulated $|S_{21}|$ responses for filter B, which is of order five, without any tuning of the extra zeros. It means that the tap point is determined by the Q_{si} value, which is fixed by the filter specification, and there is no need to use any quarter-wave transformer. The second and third harmonic resonances can be observed at $2.75f_o$ and $4f_o$, respectively, and their peak values are close to that of the passband at $f_o = 2.35$ GHz. Now, we locate the two extra zeros at 6.34 GHz and 6.85 GHz to cancel the second harmonic resonance. The results are shown in Fig. 9. The second harmonic resonance is successfully suppressed to a level lower than –40 dB. As a result, the entire response has a very wide stopband.

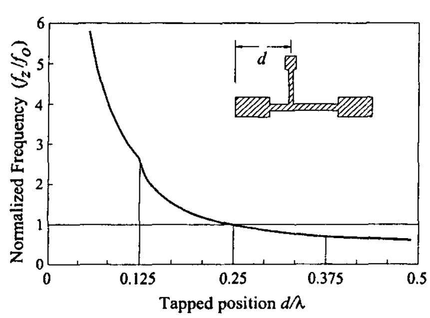

Fig.3 Normalized frequency of transmission zero versus tap position.

TABLE I
THE SPECIFICATIONS AND FREQUENCIES OF THE ZEROS OF THE THREE FABRICATED CHEBYSHEV FILTERS

Filter	f_o GHz	N	Δ	Ripple	Simulation (f_{z1}, f_{z2}) GHz	Measured (f_{z1}, f_{z2}) GHz
A	2.35	2	10%	0.1 dB	(3.45,3.45)	(3.58,3.58)
B	2.35	2	10%	0.1 dB	(1.89,3.45)	(1.87,3.35)
C	2.35	5	20%	0.1 dB	(6.34,6.85)	(6.37,6.67)

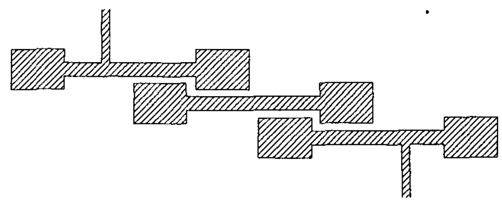

Fig. 4 Planar view of parallel coupled SIR filter.

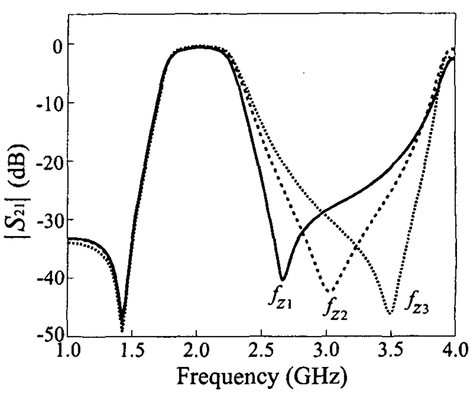

Fig.5 Tuning the frequency of zero by sliding the tap point along the first or the last SIR of a planar Chebyshev filter.

V. CONCLUSION

SIR's are used as building blocks for constructing bandpass filter to have second and third resonance harmonics much higher than $2f_o$ and $3f_o$. The singly loaded Q for a tapped SIR (stepped impedance resonator) is derived. It is shown that both the input and output tapping can be tuned independently, to control the two extra zeros in the stopband to improve the attenuation characteristics and selectivity of the bandpass filters. For all the case studies shown here, the measured results agree well with the simulation.

ACKNOWLEDGEMENT

This work was supported in part by the National Science Council, TAIWAN, under Grants NSC 90-2213-E-009-062, and in part by the joint program of the Ministry of Education and the National Science Council under the Contract: 89–E–F–A06–2–4.

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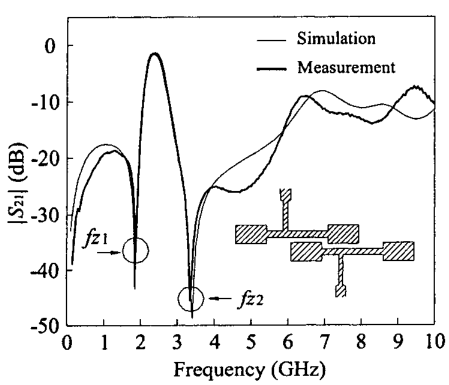

Fig. 6 Simulated and measured $|S_{21}|$ response for filter A.

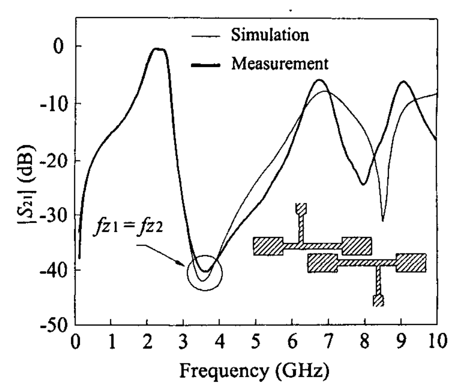

Fig. 7 Simulated and measured $|S_{21}|$ responses for filter B.

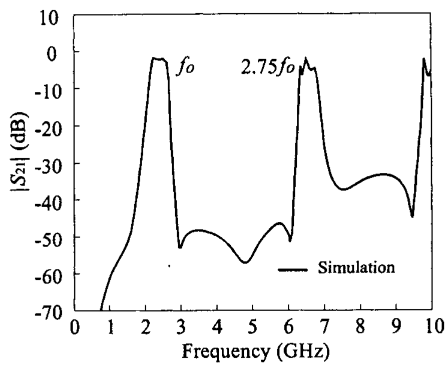

Fig. 8 Simulated $|S_{21}|$ response for filter C. Tap points are determined by the Q_{si} of the filter.

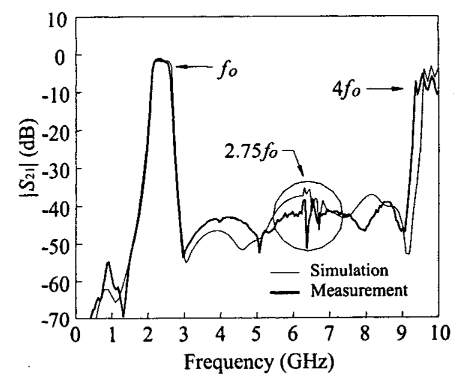

Fig. 9 Simulated and measured $|S_{21}|$ responses for filter C. Tap points are purposely chosen to generate zeros close to $2.75f_o$ to cancel the spurious resonance.