IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 17, NO. 1, JANUARY 2007

A Two-Stage SIR Bandpass Filter With an Ultra-Wide Upper Rejection Band

Ching-Luh Hsu and Jen-Tsai Kuo, *Senior Member, IEEE*

***Abstract*—Two-stage stepped-impedance resonator (SIR) filters are designed to have a wide upper stopband. Two transmission zeros are also created near the passband to form a quasi-elliptic response. For a 20-dB rejection level, with properly designed SIR geometry and tapped-line structure, the leading three spurious resonances of the SIR are suppressed by transmission zeros and respective unmatched singly loaded Q (Q_{si}) values. Measured results illustrate that stopbands up to 8.4 and 5.3 times the design frequency can be achieved for rejection levels of 20 and 30 dB, respectively.**

***Index Terms*—Microstrip filter, rejection, stepped-impedance resonator (SIR), tapped-line, upper stopband.**

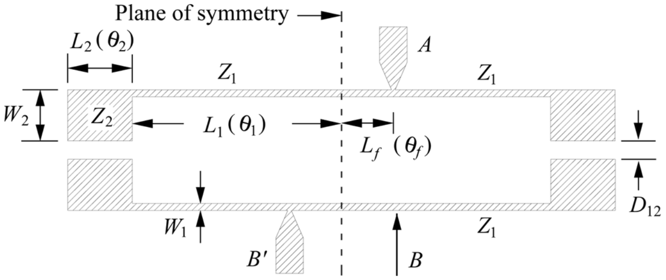

Fig. 1. Layout of the two-stage SIR BPF with tapped input/output.

I. INTRODUCTION

PARALLEL-COUPLED microstrip bandpass filters (BPFs) are known to have spurious responses which greatly deteriorate circuit performance in the upper rejection band. Recently, many techniques [1]–[4] have been proposed to effectively suppress the second harmonic. As a result, the width of the upper stopband can be doubled. The odd-order harmonics, however, still arise due to the distributive nature of transmission line networks. Recently, the "wiggly-line" sections [5] are designed for multispurious suppression. In addition, the idea of overcoupling [2] is extended in [6] to construct BPFs with an upper stopband up to five times the passband frequency.

Stepped-impedance resonators (SIRs) [7]–[11] are suitable to design microstrip BPFs with good stopband performance. It is because that the nth resonance of an SIR can be tuned to a frequency much higher than n times the fundamental frequency (nf_1) by adjusting the circuit geometry. For example, the multilayer structure in [8] is designed to implement BPFs with a wide stopband. The filters in [9]–[11] also demonstrate a broad rejection band.

In this letter, two second-order SIR BPFs are designed to have wide upper stopbands with 20- or 30-dB rejection levels. For the 20-dB design, the SIR geometry and tapped input/output structure can be designed to simultaneously suppress the second, the third, and the fourth resonances. If only the second resonance of the SIR is concerned, a 30-dB rejection level can be achieved. Both circuits feature simplicity and compactness since neither extra transformer nor design with different SIRs is required. Experiments are conducted to demonstrate the design.

II. FILTER DESIGN

Fig. 1 shows layout of the two-stage BPF. The circuit design involves three parts: The SIR geometry, the distance D_{12}, and the tap position, L_f or θ_f. The resonant conditions of the SIRs are given as [8], [10]

$$R\tan\theta_1 = \cot\theta_2 \tag{1}$$
$$R\cot\theta_1 = -\cot\theta_2 \tag{2}$$

where $R = Z_1/Z_2$ is called the impedance ratio. The gap space D_{12} is determined by the coefficient C specified by

$$C = \frac{\Delta}{\sqrt{g_1 g_2}} \tag{3}$$

where Δ is the fractional bandwidth and g_1 and g_2 are the element values of the low-pass prototype. The singly loaded Q (Q_{si}) of a tapped resonator is defined as

$$Q_{si} = R_L \left.\frac{\omega_0}{2}\frac{\partial B}{\partial \omega}\right|_{\omega_o} \tag{4}$$

where R_L is the impedance seen by the resonator looking toward the source or load, ω_o is the operation frequency, and B is the input susceptance of the SIR seen at the tap point. The derived Q_{si} formula can be referred to [10]. The tap point is determined by matching Q_{si} with the external Q (Q_{ext})

$$Q_{\text{ext}} = \frac{g_0 g_1}{\Delta}. \tag{5}$$

The excitation of the circuit can be performed by symmetric $(A-B)$ or skew-symmetric $(A-B')$ feeds, since the Q_{si} values are the same at points B and B'. The latter will be used since it creates two extra transmission zeros near the passband [12].

Manuscript received July 19, 2006. This work was supported in part by the MoE ATU Program and by the National Science Council, Taiwan, R.O.C., under Grants NSC 94-2221-E-009-037-MY2 and NSC 95-2752-E-009-003-PAE.

C.-L. Hsu is with the Department of Communication Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, R.O.C. and also with the Department of Electronics Engineering, Ta Hwa Institute of Technology, Hsinchu 303, Taiwan, R.O.C.

J.-T. Kuo is with the Department of Communication Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, R.O.C. (e-mail: jtkuo@cc.nctu.edu.tw).

Digital Object Identifier 10.1109/LMWC.2006.887248

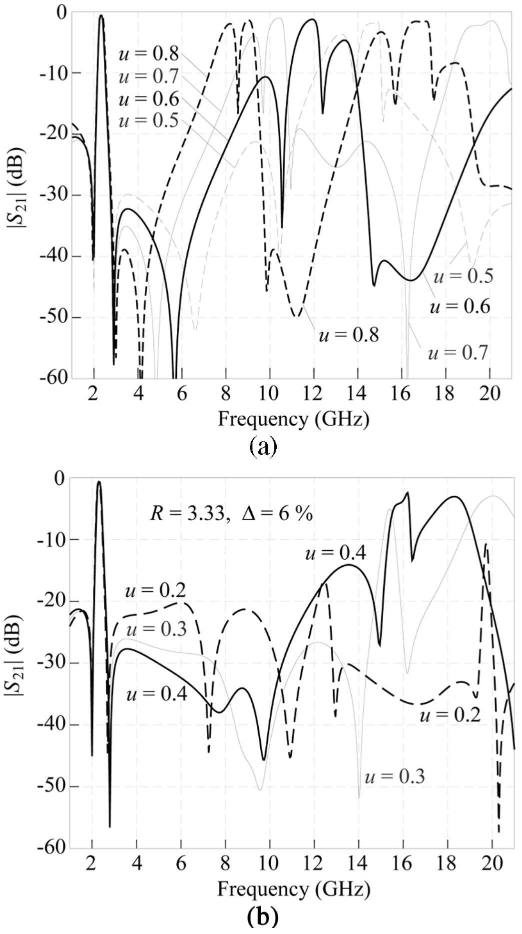

Fig. 2. Simulated responses of two-stage bandpass filters. $f_1 = 2.45$ GHz, $R = 3.33$, $\Delta = 6\%$. (a) $u = 0.5$, 0.6, 07, and 0.8. (b) $u = 0.2$, 0.3, and 0.4.

III. OPTIMIZATION OF PARAMETERS

Based on (1) and (2), resonant spectrum of an SIR can be predicted [10]. It can be validated that for all impedance ratio R the ratio of the first higher resonant frequency (f_2) to f_1 has an extreme value if the length ratio $u = \theta_2/(\theta_1+\theta_2)$ is 0.67. Thus, it is intuitive to choose $u = 0.67$ for design of a broad upper stopband. For a substrate of $\varepsilon_r = 2.2$ and thickness = 0.508 mm, $R = 3.33$, $Z_1 = 100\ \Omega$, $f_1 = 2.45$ GHz, bandwidth $\Delta = 6\%$, Fig. 2(a) plots simulated $|S_{21}|$ responses for $u = 0.8$, 0.7, 0.6, and 0.5. With properly designed tapped structures, all the cases have nearly identical passbands, but possess distinct rejection characteristics in the upper stopband. One can see that $u = 0.6$ has the farthest first unwanted peak away from the passband. However, the levels of these peaks decrease as u decreases. For 30- and 20-dB attenuation levels, the rejection bands extend to $3.3f_1$ (8 GHz) and $4.5f_1$ (11 GHz), respectively, if $u = 0.5$ is used. Both bands are wider than those of the circuit with $u = 0.6$.

To see if a better rejection bandwidth exists, we further investigate the results with $u = 0.4$, 0.3, and 0.2 in Fig. 2(b). The upper edges for the 20-dB rejection level using $u = 0.2$ and 0.4 are 12.1 GHz and 11.9 GHz, respectively. It can be validated that these two frequencies are due to the fourth resonances of the SIR which can be obtained by (2). The reason why the second and third resonances show low $|S_{21}|$ levels is that at these resonances each circuit has improper Q_{si} (or the input/output coupling C) values so that maximal power transfer does not occur. Note that the Q_{si} value depends much on the tap position L_f which has been fixed by the passband function. For $u = 0.3$, the rejection bandwidth of the 20-dB level can be improved to 14.5 GHz. It suggests that a better rejection bandwidth exist for $0.2 \leq u \leq 0.4$.

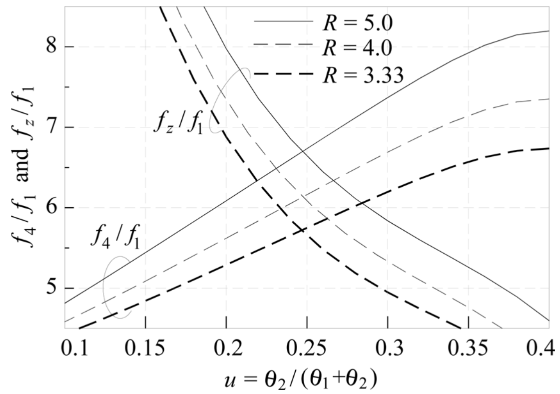

Fig. 3. Finding solutions for locating a transmission zero at the fourth resonance.

The two-stage SIR BPFs with $u = 0.21, 0.22, \ldots, 0.39$ are simulated. It is found that the fourth resonance can be suppressed using $u = 0.25$. The rejection is due to a zero created by two transmission paths of the signal from the input to the output [12]

$$Z_{2o} \cot\theta_{2o} = Z_{2e} \cot\theta_{2e} \tag{6}$$

where Z_{2e} and Z_{2o} are the even- and odd-mode characteristic impedances and θ_{2e} and θ_{2o} are the electric lengths, respectively, of the coupled low-Z sections. Using u as a variable, Fig. 3 plots the curves for allocating the zero at the frequency of the fourth resonance for $R = 3.3$, 4, and 5. The intersection points indicate that all u solutions are close to 0.25.

IV. EXPERIMENT AND MEASUREMENT

The circuit simulation is done by the full-wave software package IE3D [13]. The experiment BPF is designed at $f_1 = 2.45$ GHz with $\Delta = 6\%$. The parameters at f_1 are $Z_1 = 104\ \Omega$, $Z_2 = 31\ \Omega$ $(R = 3.35)$, $\theta_1 = 46.5^\circ$, $\theta_2 = 15.3^\circ$ $(u \approx 0.25)$, and $\theta_f = 11.6^\circ$. Fig. 4(a) plots the simulated and measured results. In the passband, the measured return loss is better than 156 dB and the insertion loss is only 1 dB. The simulation data have a peak slightly higher than the 20-dB level at 19.2 GHz $(7.83f_1)$, which is the fifth resonance of the SIR. The upper stopband of the measured response extends up to 20.8 GHz $(8.49f_1)$. Fig. 4(b) is photograph of the circuit.

Both the SIR BPFs in [10] and [11] have a 30-dB rejection band up to $8.2f_1$. The former, however, has an order of five and requires two extra quarter-wave transformers. The latter is a four-pole quasi-elliptic circuit and its in-band insertion loss is 2.5 dB. We also try to explore the upper edge of the 30-dB rejection for the circuit under investigation. The design procedure is similar to the previous filter and $R = 6.26$ and $u = 0.48$

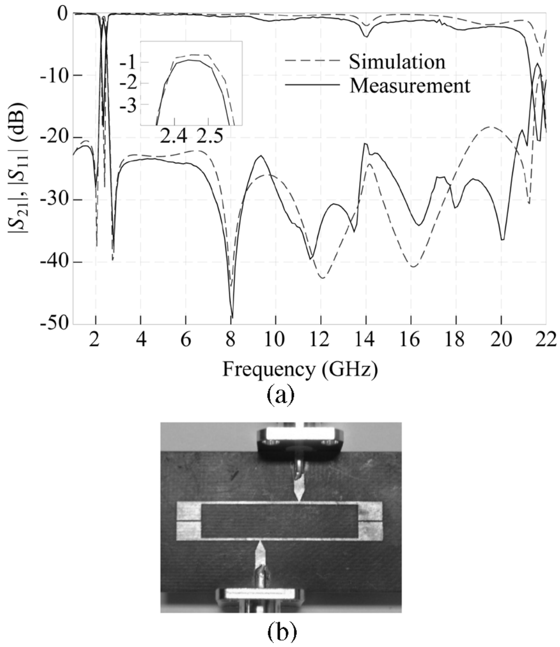

Fig. 4. (a) Simulation and measured responses for the circuit with a 20-dB rejection bandwidth. (b) Photograph of the circuit. $D_{12} = 0.18$, $L_1 = 11.8$, $L_2 = 3.64$, $L_f = 2.93$, $W_1 = 0.4$, $W_2 = 2.9$, all in mm.

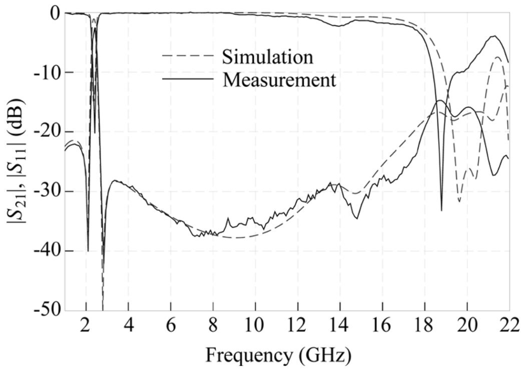

Fig. 5. Simulation and measured responses for the circuit with a wide 30-dB rejection bandwidth. $D_{12} = 0.2$, $L_1 = 5.2$, $L_2 = 4.4$, $L_f = 1.6$, $W_1 = 0.15$, $W_2 = 4.4$, all in mm.

are obtained. Fig. 5 shows the results of the experiment circuit. The measured data show that the stopband extends up to $5.3f_1$, which is close to the third resonance of the SIR.

V. CONCLUSION

Two-stage SIR BPFs are designed to have a quasi-elliptic function response and a wide upper stopband. The circuits have a compact size, a simple design, and low insertion loss. The measured results show that 20- and 30-dB rejection bandwidths of 8.4 and 5.3 times the passband frequency can be achieved. In the 20-dB design, the second and third unwanted resonances of the SIR have low $|S_{21}|$ levels and the fourth one is suppressed by a zero. To enhance the rejection to a 30-dB level, SIR with larger impedance ratio is employed and the upper stopband of the filter is found blocked by the third resonance of the SIR.

If the circuit is designed with higher order, the stopband may be not as wide as the 20-dB case, since the second or the third resonance of the SIR will arise. It is because the g_k values in (3) and (5) are changed, since the circuit order is increased, and the new Q_{si} value may allow more power transfer and result in significant spurious peaks.

REFERENCES

[1] J.-T. Kuo, W.-H. Hsu, and W.-T. Huang, "Parallel-coupled microstrip filters with suppression of harmonic response," *IEEE Microw. Wireless Compon. Lett.*, vol. 12, no. 10, pp. 383–385, Oct. 2002.

[2] J.-T. Kuo, S.-P. Chen, and M. Jiang, "Parallel-coupled microstrip filters with over-coupled end stages for suppression of spurious responses," *IEEE Microw. Wireless Compon. Lett.*, vol. 13, no. 10, pp. 440–442, Oct. 2003.

[3] S. Sun and L. Zhu, "Periodically non-uniform coupled microstrip-line filters with harmonics suppression using transmission zero reallocation," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 5, pp. 1817–1822, May 2005.

[4] M. C. Velazquez, J. Martel, and F. Medina, "Parallel coupled microstrip filter with floating ground-plane conductor for spurious-band suppression," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 5, pp. 1823–1828, May 2005.

[5] T. Lopetegi, M. A. G. Laso, F. Falcone, F. Martin, J. Bonache, J. Garcia, L. Perez-Cuevas, M. Sorolla, and M. Guglielmi, "Microstrip "wiggly-line" bandpass filters with multispurious rejection," *IEEE Microw. Wireless Compon. Lett.*, vol. 14, no. 11, pp. 531–533, Nov. 2004.

[6] M. Jiang, M.-H. Wu, and J.-T. Kuo, "Parallel-coupled microstrip filters with over-coupled stages for multi-spurious suppression," in *IEEE MTT-S Int. Dig.*, Long Beach, CA, Jun. 12–17, 2005, pp. 687–690.

[7] M. Makimoto and S. Yamashita, "Bandpass filters using parallel-coupled stripline stepped-impedance resonators," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-28, no. 12, pp. 1413–1417, Dec. 1980.

[8] C. Quendo, E. Rius, C. Person, and M. Ney, "Integration of optimized lowpass filters in a bandpass filter for out-of-band improvement," *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 12, pp. 2376–2383, Dec. 2001.

[9] W. M. Fathelbab and M. B. Steer, "Parallel-coupled line filters with enhanced stopband performances," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 12, pp. 3774–3781, Dec. 2005.

[10] J.-T. Kuo and E. Shih, "Microstrip stepped-impedance resonator bandpass filter with and extended optimal rejection bandwidth," *IEEE Trans. Microw. Theory Tech.*, vol. 51, no. 5, pp. 1554–1559, May 2003.

[11] C.-F. Chen, T.-Y. Huang, and R.-B. Wu, "Design of microstrip bandpass filters with multi-order spurious-mode suppression," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 12, pp. 3788–3793, Dec. 2005.

[12] C.-M. Tsai, S.-Y. Lee, and H.-M. Lee, "Transmission-line filters with capacitively loaded coupled lines," *IEEE Trans. Microw. Theory Tech.*, vol. 51, no. 5, pp. 1517–1524, May 2003.

[13] Zeland Software Inc., IE3D Simulator Jan. 1997.