Novel Corrugated Coupled-Line Stage with Ideal Frequency Response and Its Application to Bandpass Filter Design with Multi-Harmonic Suppression

Jen-Tsai Kuo, U-Hou Lok and Meng-Huan Wu

Department of Communication Engineering, National Chiao Tung University
1001 Tahsueh Rd., Hsinchu 300 TAIWAN

Abstract — **Coupled-line stages are designed with corrugated periods to accurately allocate inherent transmission zeros at three leading even harmonics of design frequency, f_o. The corrugation pattern is finely trimmed so that phase velocities of the two eigenmodes can be simultaneously equalized at these frequencies. By decreasing number of coupled periods in a stage, frequencies of the zeros can be arbitrarily scaled up to a certain extent. In this way, a parallel-coupled line bandpass filter with a cascade of several such stages can be synthesized to be free of spurious harmonics up to at least $10f_o$, with aid of tapped input/output coupling scheme. The measured data of the fabricated bandpass filter show a rejection level of better than 30 dB in the upper stopband up to $18f_o$.**

Index Terms — **Bandpass filter, corrugation, coupled-line stage, spurious suppression, stopband.**

I. INTRODUCTION

Parallel-coupled line bandpasss filters (BPFs) have been widely used in the RF front end of microwave and millimeter-wave communication systems for several decades. It is easy to design, reliable and suitable for mass repetition. The development of design method for such filters has been mature and well documented in open literature and microwave engineering textbooks, e.g. [1]. The circuit response, however, suffers from spurious peak at every harmonic of the passband frequency (f_o) [2-10]. The first spurious at $2f_o$ is of the most concern since it not only degrades the passband symmetry but also greatly deteriorates the circuit performances in the upper stopband. This spurious arises due to that even- and odd-mode phase constants of the stage, β_e and β_o, are unequal. Thus, many effective approaches for equalizing β_e and β_o [2-5] have been proposed to tackle this problem.

Two important points about this issue are worth mentioning. First, such circuits on a substrate with higher permittivity will exhibit more difference in β_e and β_o and make the spurious problem more seriously. The second point is that spurious responses may occur at each harmonic of the passband frequency. Although the methods in [2-5] eliminate the spurious peak at $2f_o$, there are also unwanted passbands at $4f_o$, $6f_o$, etc. This is again caused by the unequal β_e and β_o at these frequencies. It will be demonstrated mathematically later that the success of spurious suppression critically depends on the equality of β_e and β_o at these frequencies. Furthermore, there are also undesired peaks at odd harmonics due to the distributed nature of the coupled stages.

Recently, many convincible approaches have been proposed to suppress multi-order harmonics. The wiggly-line in [6] is a significant extension of [2]. By modulating the linewidths of the coupled-stages following a sinusoidal law with different periods, multiple spurious passbands can be significantly rejected. In [7], the undesired responses at both $2f_o$ and $3f_o$ are eliminated by imposing capacitive terminations to the coupled stages. In [8-9], spurious peaks are suppressed by choosing constitutive resonators having identical fundamental frequency but staggered higher order resonances. In this way, spurious peaks of one resonator can be rejected by stopband of the other. The dual behavior resonator filter in [10] achieves the multi-spurious suppression by integrating a low-pass filter in the design. In [11], the multi-spurious elimination is achieved by periodic stepped-impedance resonators. In [12], coupled-line stages of $\lambda/4$, $\lambda/6$, and $\lambda/8$ are tuned to accurately place transmission zeros at $2f_o$, $3f_o$, and $4f_o$, respectively, so that the spurious at these frequencies can be effectively eliminated. The tapped input/output scheme is also feasible for generation two zeros for tackling undesired peaks [13].

This paper enhances the design of corrugated coupled stages in [5] to allocate at least three leading inherent transmission zeros at $2f_o$, $4f_o$ and $6f_o$ accurately. The geometric parameters of such stages on a substrate with $\varepsilon_r = 10.2$ are presented. Then the approach in [12] is employed to design the corrugated stages to create transmission zeros at other harmonics of the design frequency. Finally, the tapped input/output is adopted to generate transmission zeros for suppression of unwanted responses. As a result, a successive spectrum of attenuation poles can be established up to at least ten times the passband frequency. In the following, Sec. II discusses the spurious property of a cascade of two coupled-line stages, Sec. III describes the corrugation and transmission characteristic of a coupled stage, Sec. IV demonstrates simulation and measured results of an experimental BPF, and Sec. V draws the conclusion.

1-4244-0688-9/07/$20.00 ©2007 IEEE

Fig. 1. A uniform microstrip coupled stage as a two-port network.

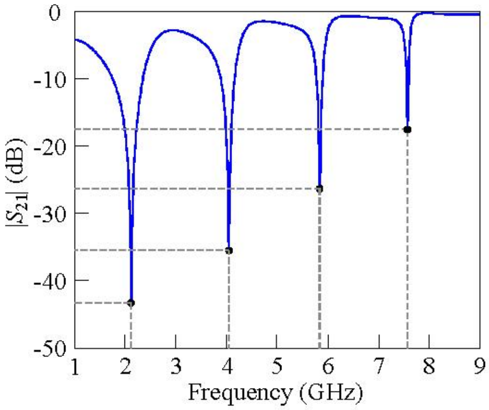


Fig. 2. Frequency response of a typical uniform coupled stage. f_o = 1 GHz, W_u = 0.8 mm, S_u = 0.5 mm.

II. TRANSMISSION ZEROS OF A FIRST-ORDER BPF

For a parallel-coupled line filter on a substrate with higher ε_r, the spurious peak levels will be much higher than those with lower ε_r. For instance, the $|S_{21}|$ peak at $2f_o$ for a substrate of $\varepsilon_r \approx 10$ can be close to 0 dB [3-6]. It is the purpose of this work to demonstrate the effectiveness of coupled-line corrugation on simultaneous elimination of multiple unwanted harmonics, a substrate with $\varepsilon_r = 10.2$ and thickness = 1.27 mm is adopted herein.

Fig. 1 shows the layout of a uniform coupled-line stage. Given fractional bandwidth Δ of a BPF, the linewidth W_u and gap size S_u of each stage can be determined after the even- and odd-mode characteristic impedances, Z_{oe} and Z_{oo}, are calculated by the synthesis formulas [1]. Consider a first-order BPF with a cascade of two such stages. The forward transmission coefficient can be obtained by directly multiplying two identical *ABCD* matrices converted from the *Z*-matrix parameters of the stage. Based on the fact that all *Z*-parameters consist of csc or cot functions so that their magnitudes are much larger than Z_o (the system impedance) near $2nf_o$ (n = integer), we have

$$\frac{1}{|S_{21}|^2} \approx 1 + \left[\frac{Z_{oe} Z_{oo}}{Z_o} \frac{\xi \times (1 + \cos\theta_e \cos\theta_o)}{(Z_{oe} \sin\theta_o - Z_{oo} \sin\theta_e)^2} \right]^2 \tag{1}$$

$$\xi = Z_{oe} \sin\theta_o \cos\theta_e + Z_{oo} \sin\theta_e \cos\theta_o \tag{2}$$

where θ_e and θ_o denote the electric lengths for the even- and odd-modes of a coupled stage, respectively. Note that $\theta_e \approx \theta_o \approx \pi/2$ at f_o.

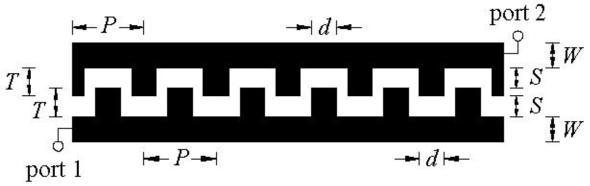


Fig. 3. A corrugated coupled-line stage.

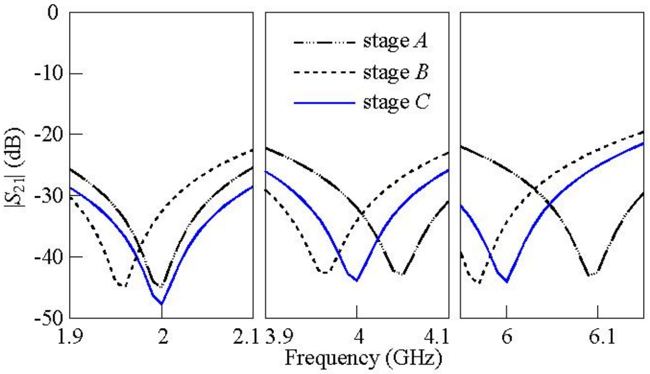


Fig. 4. Corrugation tuning of a coupled stage for obtaining zeros at $2f_o$, $4f_o$ and $6f_o$ (f_o = 1 GHz). Stage *A*: $W = 0.3$, $S = 0.5$, $T = 0.95$, $d = 1.35$; stage *B*: $W = 0.3$, $S = 0.5$, $T = 1.02$, $d = 1.35$; stage *C*: $W = 0.3$, $S = 0.5$, $T = 0.99$, $d = 1.2$, all in mm.

The transmission zeros of $|S_{21}|$ can be obtained by enforcing

$$Z_{oe} \sin\theta_o - Z_{oo} \sin\theta_e = 0 \tag{3}$$

One possible set of solution to (3) is $\theta_e = \theta_o = n\pi$. Not only will there be no spurious peak near $2nf_o$ but also will the response present a dip at $2nf_o$, because the zero of the denominator in (1) has one order higher than that of the numerator. When it is not the case, however, the $|S_{21}|$ response will exhibit a large peak, since when $\theta_o \approx \theta_e \approx n\pi$ but they are unequal at $2nf_o$ ($\theta_e > \theta_o$ for coupled microstrips), ξ in (2) will have a zero, and $|S_{21}|$ may become as high as 0 dB. Thus, it can be concluded that the conditions $\theta_e = \theta_o = n\pi$ are required to avoid the spurious peaks near $2nf_o$.

III. CORRUGATED COUPLED STAGE

Fig. 2 shows frequency response of a typical coupled stage in Fig. 1. Its length is finely tuned to allocate the maximal coupling at f_o = 1 GHz. Due to the dispersion of coupled microstrips, nevertheless, the inherent transmission zeros deviate away from $2nf_o$, n = 1, 2, 3... Also, the effective rejection levels at these zeros are degrading as frequency is increased. Based on the discussion in Sec. II, spurious peaks will occur. This motivates us to develop the corrugated coupled stage shown in Fig. 3. The geometric parameters include $S = S_u$, $W = W_u - T/2$, period P, and length T and width d of the corrugation "teeth." Note that W_u and S_u in Fig. 1 have been defined by the conventional synthesis formulas [1], thus there are three degrees of freedom for tuning the response.

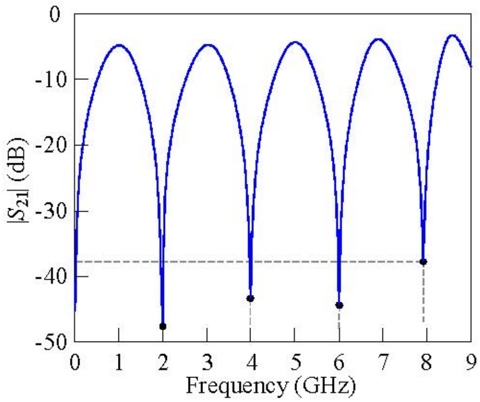


Fig. 5. Frequency response of stage *C* in Fig. 4.

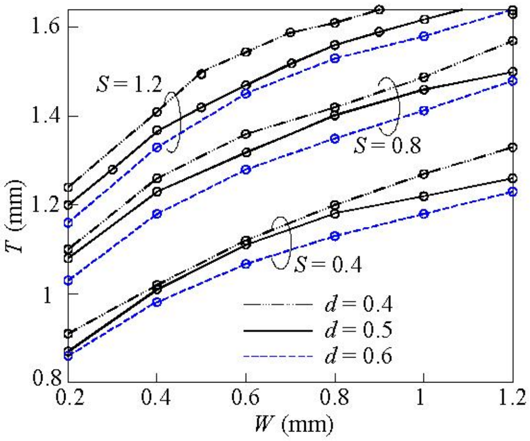


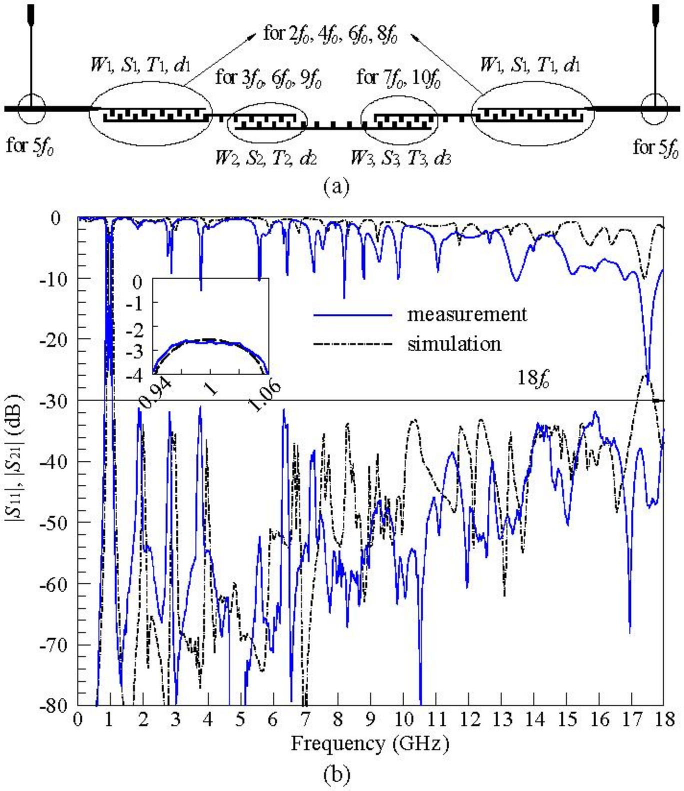
Fig. 6. Corrugation parameters of coupled stages for $|S_{21}|$ responses with transmission zeros at $2f_o$, $4f_o$, and $6f_o$.

The corrugation tuning starts with W_u = 0.8 mm and S_u = 0.5 mm as used in Fig. 2. Based on [5], stage *A* with d = 1.35 mm and T = 0.95 mm is obtained to allocate the first inherent zero at $2f_o$ precisely. Its second and third zeros, however, are at $4.05f_o$ and $6.1f_o$. They are more than 1% away from the target frequencies, as shown in Fig. 4. According to our experience, the spurious will be lower than 25 dB if the deviation is less than 0.5%. It can be deduced that $\theta_e > \theta_o > 2\pi$, and hence $\beta_e > \beta_o$, provided $Z_{oe} > Z_{oo}$ at $4f_o$. Here, the subscripts *e* and *o* respectively stand for the *c* and π modes, and β_e and β_o are their respective phase constants. First, the teeth length *T* is extended to 1.02 mm (stage *B*) to increase β_o. The three zeros shift to frequencies with about the same distances to their respective target positions. Then *d* is decreased to 1.2 mm, along with finely tuned T = 0.99 mm, and finally stage *C* is obtained with the three inherent zeros at $2f_o$, $4f_o$ and $6f_o$.

Fig. 5 plots the frequency response of the corrugated stage (stage *C*) up to 9 GHz. The transmission characteristics of the stage are close to that of a TEM (dispersionless) stage. Fig. 6 plots the corrugation parameters of coupled stages for simultaneously allocating zeros at $2f_o$, $4f_o$ and $6f_o$ when S = 0.4, 0.8 and 1.2 and d = 0.4, 0.5 and 0.6, all in mm. When *S* is increased or *d* is decreased, the required *T* is increased. This is because that increasing *S* or decreasing *d* will decrease the coupling between the two conductors and hence the odd-mode wave can travel faster. The "teeth" length is then increased to compensate or slow down its phase velocity [5].

IV. APPLICATION TO BPF DESIGN AND EXPERIMENT

A fifth-order BPF in Fig. 7(a) is synthesized and fabricated for demonstration of multi-spurious suppression using the developed corrugated stages. It has f_o = 1 GHz, Δ = 8% and a 0.1-dB ripple. There are four coupled stages in the circuit in addition to the tapped input/ouput stages designed to place zeros at $5f_o$. An impedance transformer is required for compensating the altered external *Q* value due to the change of the tap point [13]. The two end stages are tuned to suppress the spurious at $2f_o$, $4f_o$, $6f_o$ and $8f_o$. The second stage uses only a coupling length of $\lambda/6$ to eliminate the spurious at $3f_o$, $6f_o$ and $9f_o$ [12]. The third stage has seven corrugation periods, and four of them are used for interstage coupling. Its leading three transmission zeros are then at $3.5f_o$, $7f_o$ and $10f_o$, since its coupling length is $(4/7)\times(\lambda/4) = \lambda/7$. The gap sizes of the $\lambda/6$- and $\lambda/7$-stages have to be decreased for providing necessary coupling levels specified by the synthesis procedure [12].



(a)

(b)

Fig. 7. Layout and performances of the fabricated fifth-order corrugated BPF. (a) Circuit layout. (b) Simulation and measured results. Geometric parameters: W_1 = 0.26, S_1 = 0.79, T_1 = 1.12, d_1 = 1.4, W_2 = 0.33, S_2 = 1.03, T_2 = 1.13, d_2 = 1.4, W_3 = 0.33, S_3 = 1.05, T_3 = 1.09, d_3 = 1.4, all in mm.

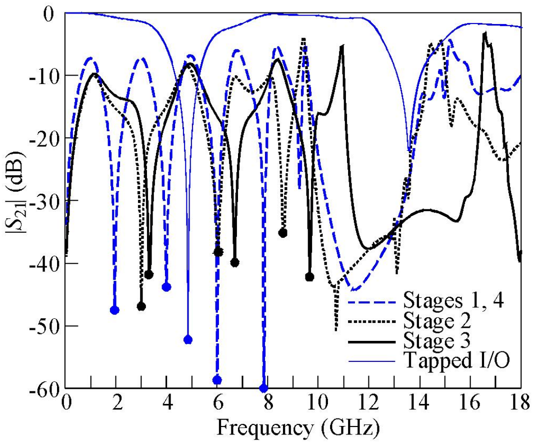


Fig. 8. Frequency responses of the coupled stages in Fig. 7(a).

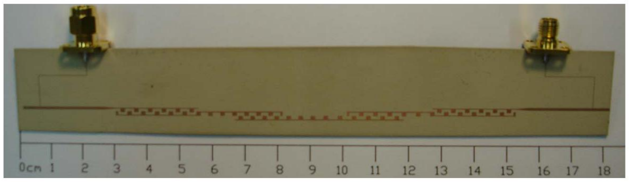


Fig. 9. Photo of the fabricated circuit.

Fig. 7(b) plots the simulation and measured responses of the synthesized circuit. The measured in-band insertion loss is 2.6 dB, and the return loss is 15 dB. The experiment results show that the upper stopband covers the full measured band up to $18f_o$ with rejection levels of better than 30 dB. To investigate why the BPF has such good rejections beyond $10f_o$, Fig. 8 plots the $|S_{21}|$ responses of all the stages in Fig. 7(a). When $f < 10f_o$, totally eleven transmission zeros can be observed. Besides, there are stopbands from 9 GHz to 14 GHz created by stages 1, 2 and 4, and a band with high rejections covering from 11 GHz to 16 GHz by stage 3. These are the essential electromagnetic property of the periodic corrugated stages. Corrugated BPFs designed with such a bandgap property will be reported in other fashion. Fig. 9 shows the photo of the fabricated circuit.

V. CONCLUSION

Coupled-line stages with finely trimmed corrugation are shown to have a nearly ideal frequency response, which has transmission zeros at $2f_o$, $4f_o$ and $6f_o$ precisely. Position accuracy of the zeros is shown critical for preventing the BPF from spurious peaks. The BPF design is very flexible since 2/3 of such a $\lambda/4$-stage can be used to allocate the inherent zeros at $3f_o$, $6f_o$ and $9f_o$, and 4/7 of this $\lambda/4$-stage can eliminate the unwanted passbands at $7f_o$ and $10f_o$, even on a substrate of a relatively high ε_r. The measured $|S_{21}|$ response of the fabricated circuit validates these ideas. The approach is suitable for BPFs designed at relatively low frequencies since the periodic corrugation may cause serious radiation at high frequencies.

ACKNOWLEDGEMENT

This work was supported by the MoE ATU program and by the National Science Council, Taiwan, under Grants NSC 95-2221-E-009-037-MY2 and NSC 95-2752-E-009-003-PAE.

REFERENCES

[1] D. M. Pozar, Microwave Engineering, 3rd ed. New York: Wiley, 2005.

[2] T. Lopetegi, M. A. G. Laso, J. Hernández, M. Bacaicoa, D. Benito, M. J. Garde, M. Sorolla and M. Guglielmi, "New microstrip "wiggly-Line" filters with spurious passband suppression," *IEEE Trans. Microwave Theory Tech.*, vol. 49, no. 9, pp.1593 - 1598, Sept. 2001.

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

[4] S. Sun and L. Zhu, "Periodically nonuniform coupled microstrip-line filters with harmonic suppression using transmission zero reallocation," *IEEE Trans. Microwave Theory Tech.*, vol. 53, no.5, pp. 1817-1822, May 2005.

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

[6] 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 Microwave Wireless Compon. Lett.*, vol. 14, no. 11, pp.531–533, Nov. 2004.

[7] P. Cheong, S.-W. Fok and K.-W. Tam, "Miniaturized parallel coupled-line bandpass filter with spurious-response suppression," *IEEE Trans. Microwave Theory Tech.*, vol. 53, no.5, pp. 1810-1816, May 2005.

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

[9] S.-C. Lin, P.-H. Deng, Y.-S. Lin, C.-H. Wang and C. H. Chen, "Wide-stopband microstrip bandpass filters using dissimilar quarter-wavelength stepped-impedance resonators," *IEEE Trans. Microwave Theory Tech.*, vol. 54, no.3, pp. 1011-1018, Mar. 2006.

[10] A. Manchec, C. Quendo, E. Rius, C. Person and J.-F. Favennec, "Synthesis of dual behavior resonator (DBR) filters with integrated low-pass structures for spurious responses suppression," *IEEE Microwave Wireless Compon. Lett.*, vol. 16, no. 1, pp.4–6, Jan. 2006.

[11] Y.-C. Chiou, M.-H. Wu and J.-T. Kuo, "Periodic stepped-impedance resonator (PSIR) bandpass filters with multispurious suppression," *2006 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 349-352, June 2006.

[12] M. Jiang, M.-H. Wu and J.-T. Kuo, "Parallel-coupled microstrip filters with over-coupled stages for multispurious suppression" *2005 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 687-690, June 2005.

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