Corrugated parallel-coupled line bandpass filters with multispurious suppression

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Abstract: Corrugated coupled stages are devised to design bandpass filters with multispurious suppression. Through two-port analysis, the suppression is found critically dependent on equality of the even and odd mode phase velocities at even harmonics of design frequency f_o. Quarter-wave ($\lambda/4$) corrugated stages are tuned to allocate inherent transmission zeros at both $2f_o$ and $4f_o$, and $6f_o$ for some structures, so that the circuit is free of spurious at these frequencies. Coupled stages with proper coupling lengths are arranged to cancel unwanted peaks at $3f_o$, $6f_o$ and $7f_o$, and tapped input/output scheme is employed to tackle those at $3f_o$ and $5f_o$. Measured data of designed filters show rejection levels better than 30 dB in upper stopband. Three circuits are fabricated and measured to demonstrate the idea.

1 Introduction

Parallel-coupled line filters have been widely employed in the radio frequency (RF) front ends of microwave/wireless communication systems. The circuit is popular since it is reliable, suitable for mass repetition and easy to design. Synthesis formulas have been well documented for the even and odd mode characteristic impedances, and hence linewidth and gap size, of each stage [1]. For microstrip realisation of a quarter-wave ($\lambda/4$) stage, since the coupled lines have unequal modal phase velocities, spurious responses arise at even multiples of the design frequency, or $2mf_o$ with m being a positive integer. The first spurious at $2f_o$ is of the most concern since it degrades the passband symmetry and is responsible for blocking extension of upper rejection band. This problem can be resolved with many effective approaches, including the capacitive compensation [2], the wiggly-line [3], the corrugated structures [4, 5], the stacked configuration [6], the over-coupled stages [7, 8], the suspended substrate [9], the uniform dielectric overlay [10], the periodically non-uniform coupled-line [11], the perturbed ground planes [12, 13].

An ideal bandpass filter has no spurious response in the upper stopband. Even though the spurious at $2f_o$ can be effectively suppressed by the above-mentioned methods, unwanted passbands at $3f_o$, $5f_o$, $7f_o$ and so on also arise because of the distributed nature of the circuit. The stepped-impedance resonators [14, 15] can be used to synthesise bandpass filters with a wide upper stopband. For the multi-layered resonators in [14], a wide aperture in ground plane is etched underneath the high impedance line to lift up the impedance ratio. The first high unwanted $|S_{21}|$ peak occurs at $8.5f_o$. The circuits in [15], on the other hand, have a fully planar structure. In addition to designing resonator geometry to push the fourth resonance to as high frequency as possible, the tapped input/output structures are incorporated to suppress the two leading resonances, so that the upper stopband is extended up to beyond $8f_o$.

Recently, multispurious suppression has been a hot research topic. The wiggly-line in [16] is a significant extension of [3]. For a seventh-order filter, measured data of the leading four spurious passbands show rejection levels exceeding 30 dB. The optimisation of the strip widths, however, may take long simulation time since the circuit has many non-uniform lines which require fine discretisation for accurate characterisation. The undesired responses at $2f_o$ and $3f_o$ can be eliminated either by imposing capacitive terminations [17] or by incorporating concept of the effective even and odd mode characteristic impedances [18] to the coupled stages. In [19], stages of $\lambda/4$, $\lambda/6$, and $\lambda/8$ in electrical lengths are tuned to cancel the spurious at $2f_o$, $3f_o$ and $4f_o$, respectively. In [20], a new class of parallel-coupled line filters with broad stopband response is designed based on synthesis of bandpass prototypes with pre-defined upper stopband characteristics. In [21, 22], spurious peaks are suppressed by choosing the constitutive resonators having identical fundamental frequency but staggered higher order resonances. The dual behaviour resonator filter in [23] achieves the spurious suppression by integrating a low-pass filter in the bandpass filter. In [24], a modified stopband-extended filter is implemented utilising the multiple transmission zeros placed at specified frequencies. In [25], double split-end quarter-wave stepped-impedance resonators are devised to construct a sixth-order filter with a bandwidth of $8.5f_o$ with at least 37.8 dB of attenuation. In [26], the multispurious elimination is achieved with periodic stepped-impedance resonators.

This paper combines the ideas of the corrugated stages [4], overcoupled stages [19] and the tapped input/output scheme [15] to design a parallel-coupled bandpass filter with good rejection in a wide upper stopband. Parallel-coupled filters with properly designed corrugated stages are known to be free of spurious at $2f_o$ [4]. It is a new development in this work that properly tuning the geometric parameters of such a stage can allocate the inherent zeros precisely at both $2f_o$ and $4f_o$ so that the spurious at these frequencies can be eliminated. Some of the stages are validated to have a further transmission zero at $6f_o$. Furthermore, coupling lengths of some stages can be properly adjusted

doi:10.1049/iet-map:20060130

Paper first received 9th June and in revised form 7th December 2006

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to allocate zeros, and hence to cancel the undesired transmission, at $3f_o$ and $6f_o$ or at $7f_o$ so that the upper stopband can be further extended.

2 Zeros of a cascade of two coupled-line stages

One purpose of using a relatively high ε_r substrate is to make circuit size smaller. For a traditional parallel-coupled line filter on such a substrate, however, the spurious peaks will be much higher than those on substrates of low ε_r. For example, the $|S_{21}|$ peak at $2f_o$ for a substrate of $\varepsilon_r \simeq 10$ can be close to 0 dB [8, 11, 16]. Since the purpose of this work is to demonstrate the effectiveness of coupled-line corrugation on elimination of unwanted harmonics, the RT/Duroid 6010 microwave laminates with $\varepsilon_r = 10.2$ and thickness = 1.27 mm are adopted.

Fig. 1 shows the layout of a uniform coupled-line stage. Given circuit bandwidth Δ and maximally flat or Chebyshev passband function, 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 conventional synthesis formulas [1].

The zeros of a coupled stage must be accurately allocated at $2mf_o$, m = positive integer, so that entire circuit can be free of spurious at these frequencies. The reason is investigated as follows. The Z-parameters of the coupled stage in Fig. 1 can be derived as [1]

$$Z_{11} = Z_{22} = -j\frac{1}{2}(Z_{oe}\cot\theta_e + Z_{oo}\cot\theta_o) \quad (1)$$

$$Z_{12} = Z_{21} = -j\frac{1}{2}(Z_{oe}\csc\theta_e - Z_{oo}\csc\theta_o) \quad (2)$$

where θ_e and θ_o denote the electrical lengths of the stage for the even and odd modes, respectively. At f_o, $\theta_e \simeq \theta_o \simeq \pi/2$. For simplicity, consider a first-order filter with a cascade of two such stages. The forward transmission can be derived by directly multiplying two identical $ABCD$ matrices converted from the Z-matrix given in (1) and (2)

$$\frac{1}{|S_{21}|^2} = 1 + \left[j\frac{Z_{11}}{Z_{21}^2 Z_o}(Z_{11}Z_{22} - Z_{12}Z_{21} - Z_o^2)\right]^2 \quad (3)$$

where Z_o is the reference port impedance. At frequencies near $2mf_o$, $\theta_e \simeq \theta_o \simeq m\pi$, the cot and csc functions approach infinity so that the magnitude of each Z-parameter is much larger than Z_o. Thus, (3) can be reduced to

$$\frac{1}{|S_{21}|^2} \simeq 1 + \left[j\frac{Z_{oe}Z_{oo}}{Z_o}\frac{Z_{11}}{Z_{21}^2}(\cot\theta_e\cot\theta_o + \csc\theta_e\csc\theta_o)\right]^2 \quad (4)$$

Substituting (1) and (2) into (4) yields

$$\frac{1}{|S_{21}|^2} \simeq 1 + \left[\frac{Z_{oe}Z_{oo}}{Z_o}\frac{\chi\times(1+\cos\theta_e\cos\theta_o)}{(Z_{oe}\sin\theta_o - Z_{oo}\sin\theta_e)^2}\right]^2 \quad (5a)$$

$$\chi = Z_{oe}\sin\theta_o\cos\theta_e + Z_{oo}\sin\theta_e\cos\theta_o \quad (5b)$$

Fig. 1 *Uniform microstrip coupled stage as a two-port network*

The inherent zero of $|S_{21}|$ can be obtained by enforcing

$$Z_{oe}\sin\theta_o - Z_{oo}\sin\theta_e = 0 \quad (6)$$

Obviously, the conditions

$$\theta_e = \theta_o = m\pi \quad (7)$$

are a possible solution to (6). In this case, not only will there be no spurious peaks near $2mf_o$ but also the response will have a notch at $2mf_o$, because the zero of the denominator in (5a) has one order higher than that of the numerator in (5b). When (6) holds but (7) does not, however, $|S_{21}|$ response will present a large peak at the frequency where $\chi = 0$ which is close to the zero frequency given in (6). This point will be further demonstrated in next section.

3 Corrugated coupled-line stage

Evolved from Fig. 1, the corrugated coupled stage in Fig. 2 has $S = S_u$, $W = W_u - T/2$ and period P. The variables T and d stand for the length and width of the corrugation 'teeth', respectively. Along the coupled lines in Fig. 1, the odd mode propagates faster than the even mode. Because of the corrugation in Fig. 2, that is, $T \neq 0$, the even and odd modes migrate to the c and π modes, respectively. The c mode travels along the outer conductor edges, whereas the π mode propagates along the rectangular zigzag trace between the strips. Thus, it is possible to make these two modes have identical phase velocities when number of periods or the teeth length T are properly chosen.

Accurately allocating inherent zeros of a $\lambda/4$-stage at both $2f_o$ and $4f_o$ is important for extending the upper stopband. Fig. 3 shows the circuit tuning at $2f_o$ and $4f_o$. The horizontal axis is frequency normalised with respect to $f_o = 2.45$ GHz. Suppose that the uniform coupled stage is defined by the conventional synthesis [1] with $S_u = 0.4$ mm and $W_u = 0.6$ mm. Based on [4], with $S = S_u$ and $W = 0.4$ mm, stage A is tuned at $d = 0.6$ mm and $T = 0.53$ mm to allocate the inherent zero at $2f_o$ precisely, as shown in Fig. 3*a*. If the stage is ideal, it is expected to have further null transmission at $4f_o$, $6f_o$ and so on. Its second zero, however, is at $4.08f_o$, that is, 2% away from $4f_o$. Based on (6), it can be deduced that $\theta_e > \theta_o > 2\pi$, and hence $\beta_e > \beta_o$, provided $Z_{oe} > Z_{oo}$. Here, the subscripts e and o, respectively, stand for c and π modes, and β_e and β_o are their corresponding phase constants. There are degrees of freedom to further tune the stage at $4f_o$. As the first step, the teeth width d is reduced to 0.5 mm. Both zeros shift to frequencies higher than $4f_o$. The teeth length T is then extended to slow down the phase velocity of the π mode, that is, to increase β_o. The solution, that is, stage B, is obtained with the two inherent zeros at $2f_o$ and $4f_o$ with $T = 0.58$ mm, as shown in Fig. 3*a*.

The responses for cascade A (two A-stages) and cascade B (two B-stages) in the vicinity of $4f_o$ are shown in Fig. 3*b*. Both cascades possess the same zeros as in Fig. 3*a*. Cascade

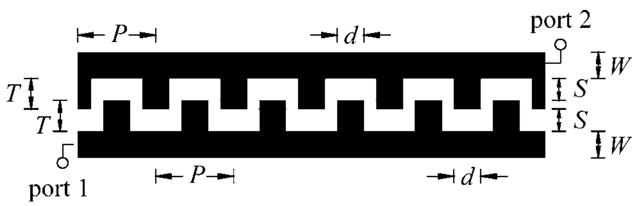

Fig. 2 *Corrugated coupled stage*

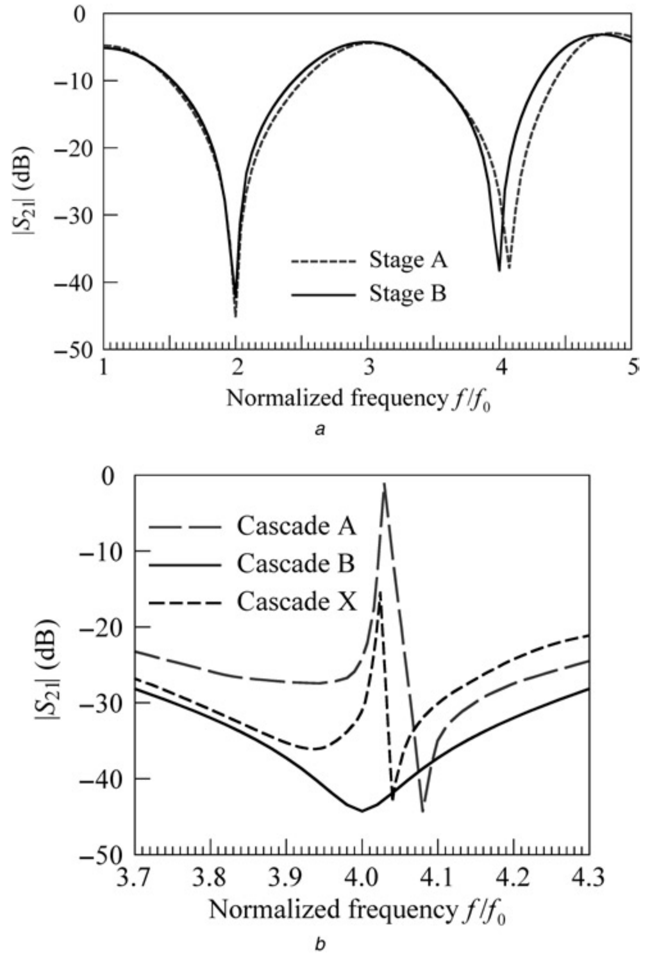

Fig. 3 *Geometry tuning of a corrugated stage*

a $|S_{21}|$ responses for the coupled stages
b $|S_{21}|$ responses of cascades of two identical stages near $4f_o$. $W = 0.4$, $S = 0.4$. Stage A: $d = 0.6$, $T = 0.53$. Stage B: $d = 0.5$, $T = 0.58$. Stage X: $d = 0.5$, $T = 0.57$, all in millimetre

B presents no peak near $4f_o$, as expected. For cascade A, however, there is a -2 dB spurious peak at $4.04f_o$, the midway position between the zero and $4f_o$. For further demonstration, response of a cascade X is also plotted. It consists of two identical $\lambda/4$-stages with zeros at $4.04f_o$. The spurious peak locates at around $4.02f_o$ and its level is reduced to -15 dB. This suggests that for the particular circuit configuration the zero should be no more than 1% deviation from $4f_o$ if a peak level of better than 15 dB is pursued.

The forward transmission of an ideal $\lambda/4$-stage has a zero at $2mf_o$ when the coupling length is a multiple of 180°. Similarly, a coupling length of $\lambda/6$ at f_o will be a multiple of 180° and create a zero at $3mf_o$ [19]. Therefore for generating zeros at both $2mf_o$ and $3mf_o$ using the same corrugated coupled line, six periods are adopted in a stage. Note that the corrugation pattern has been trimmed for $2mf_o$, only trivial tuning is required for recovering from possible offsets, because of microstrip dispersion, when shifting $2f_o$ and $4f_o$ to $3f_o$ and $6f_o$ by using four of the six periods for inter-stage coupling. There is also a need to suppress the spurious at $7f_o$. The stage is then designed to have seven periods and four of them ($4/7 \times \lambda/4$) are used in the coupling length. The transmission zeros are thus allocated at $3.5mf_o$.

Fig. 4 presents the geometric parameters of corrugated stages in Fig. 2 for simultaneously tuning zeros at $2f_o$ and $4f_o$. The results for $S = 0.2$, 0.6 and 1.0 are in Fig. 4*a* and those for $S = 0.4$, 0.8 and 1.2 in Fig. 4*b*. All dimensions are in millimetre. When S is increased or d is decreased, the corresponding T is increased. This is because that for the odd mode propagation with increasing S or decreasing d, the coupling between the two strips decreases and hence the wave travels faster. The 'teeth' length is then increased to compensate or slow down its phase velocity. For the solutions in solid dots, the stage has an extra zero at $6f_o$ within 0.5% accuracy. This property is of course useful for extra elimination of the undesired spurious at $6f_o$, but it exists only for structures with relatively small W and S.

Based on the data in Fig. 4 with simple interpolation, one can have good initial guess for geometric parameters which are not provided in Fig. 4. Note that the simulation circuit consists of only a coupled stage which can be one-fifth or one-sixth of a whole filter. So the simulation time can be only 1/30 of that required by a full circuit, since the CPU time is proportional to square of number of discretisation cells.

4 Experiments

Three circuits are designed and fabricated for demonstration. The first circuit is a third-order Chebyshev filter with $f_o = 2.45$ GHz, 0.1 dB ripple and $\Delta = 8\%$. The circuit layout is in Fig. 5*a* and the simulation and measured

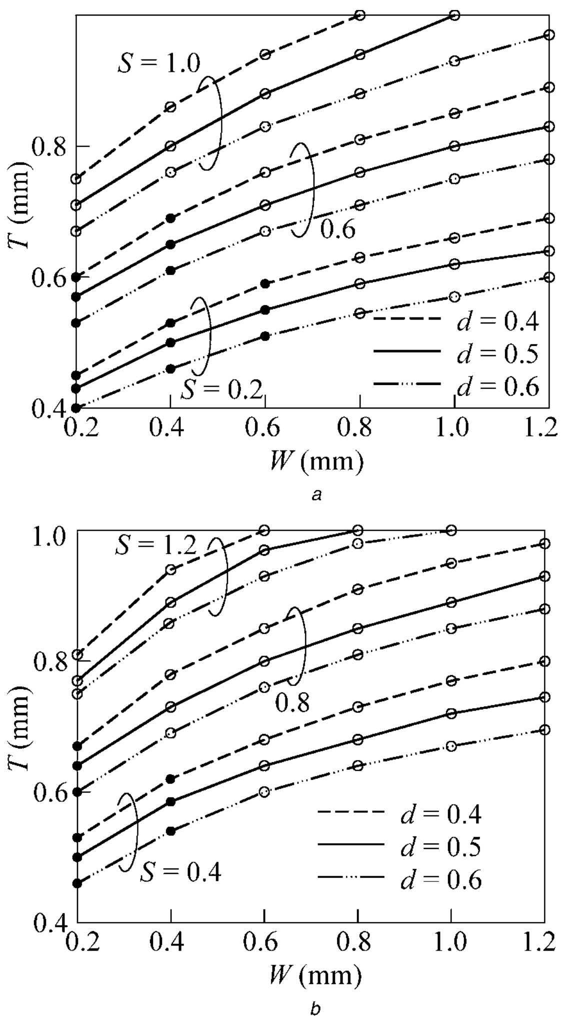

Fig. 4 *Geometric parameters for a corrugated stage with zeros simultaneously tuned at $2f_o$ and $4f_o$*

a $S = 0.2$, 0.6, 1.0
b $S = 0.4$, 0.8, 1.2, all in millimetre. $f_o = 2.45$ GHz, substrate: $\varepsilon_r = 10.2$, thickness = 1.27 mm

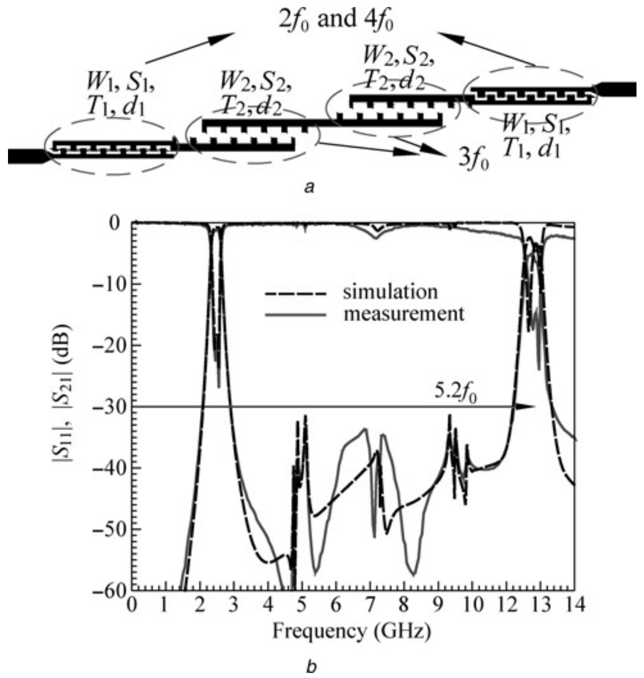

Fig. 5 *Performance of a third-order corrugated bandpass filter*

a Layout
b Simulation and measured results. $W_1 = 0.2$, $S_1 = 0.37$, $T_1 = 0.52$, $d_1 = 0.4$, $W_2 = 0.57$, $S_2 = 1.09$, $T_2 = 0.52$, $d_2 = 0.4$, all in millimetre

responses are in Fig. 5*b*. The two end stages are tuned to suppress the spurious responses at $2f_o$ and $4f_o$, and the two stages in between are tuned at $3f_o$, so that the upper stopband is extended up to $5f_o$. The two middle stages use only $\lambda/6$ for interstage coupling. The circuit is symmetric about its centre, so that only the dimensions of the first and second stages are given in the figure caption. It is interesting to note that near $2f_o$, $3f_o$ and $4f_o$ the glitches show cancellation of the zeros and the spurious by each other. Note also that two end stages are employed to tackle the same spurious. This is because that bandwidth of the unwanted spurious is increasingly wider as its harmonic order is higher.

Fig. 6*a* shows the layout and Fig. 6*b* the performance of a fifth-order corrugated filter with a passband function identical to that of Fig. 5. Tapped input/output is used to create zeros for cancelling the spurious at $5f_o$. The zero frequency can be determined by the open stub whose electrical length is one quarter wavelength at the design frequency. Impedance transformers are inevitable since the tapped points are chosen by the zeros [15]. As shown in Fig. 6*a*, since tapped input/output couplings are employed to provide necessary couplings between the feed lines and the input/output resonators, there are only four parallel-coupled stages in the circuit. The two end coupled stages are designed to tackle the spurious $2f_o$ and $4f_o$ and the other two create transmission zeros at $3f_o$ and $6f_o$. The two end stages also possess zero transmission at $6f_o$ so that it also provides spurious suppression to the circuit at this frequency. The measured and simulation results show that the upper stopband covers a band up to $6.5f_o$ with rejection levels better than 30 dB. Generally, the positions of the two end stages can be interchanged with the other two, provided that the coupling coefficients follow the synthesis formulas. The outer stages of a bandpass filter, however,

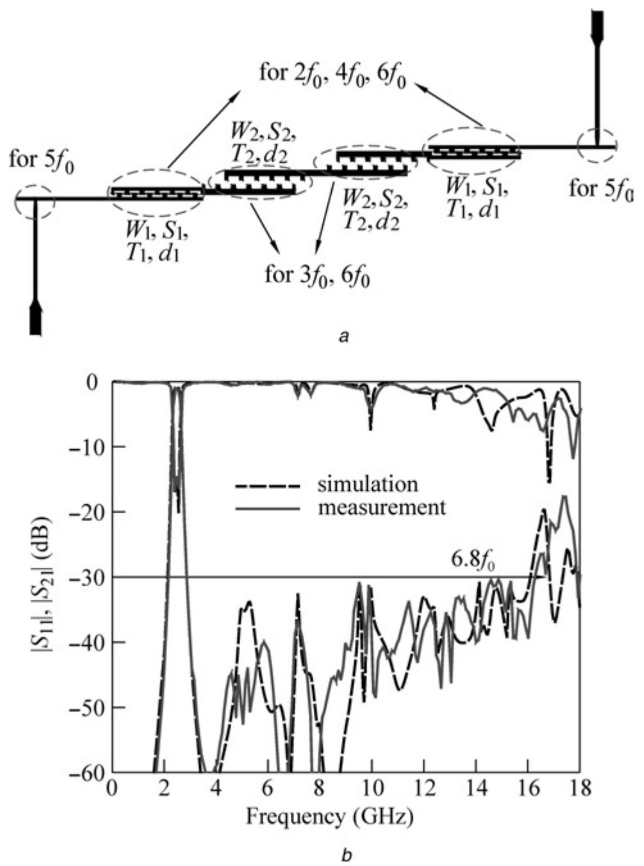

Fig. 6 *Performance of a fifth-order corrugated bandpass filter*

a Layout
b Simulation and measured results. $W_1 = 0.28$, $S_1 = 0.39$, $T_1 = 0.48$, $d_1 = 0.5$, $W_2 = 0.61$, $S_2 = 1.15$, $T_2 = 0.54$, $d_2 = 0.4$

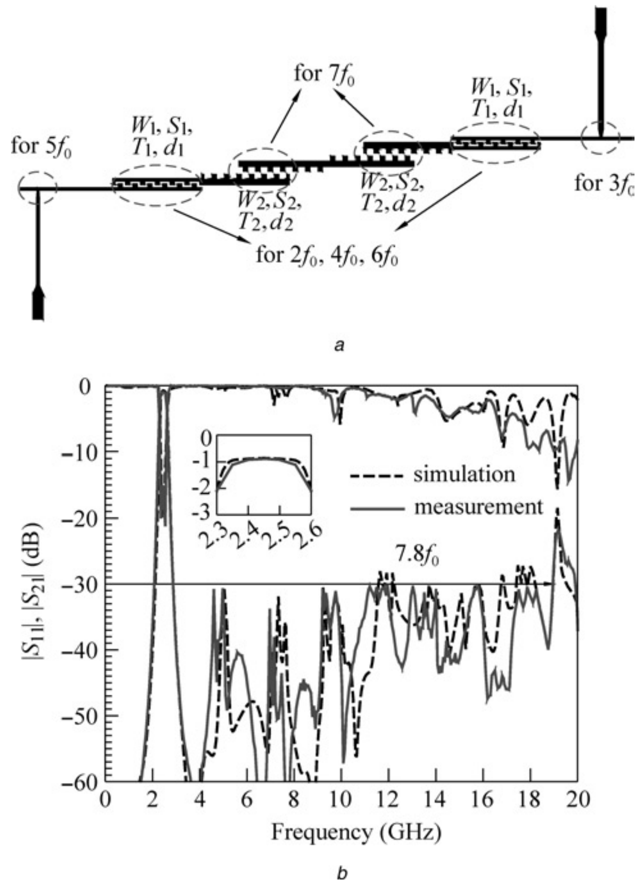

Fig. 7 *Performance of the second fifth-order corrugated bandpass filter*

a Layout
b Simulation and measured results. $W_1 = 0.282$, $S_1 = 0.37$, $T_1 = 0.46$, $d_1 = 0.48$, $W_2 = 0.62$, $S_2 = 1.02$, $T_2 = 0.56$, $d_2 = 0.5$

usually need more couplings than the middle ones. Thus $\lambda/4$-stage will be preferred to $\lambda/6$-stages as outer stages.

Fig. 7*a* shows the layout and Fig. 7*b* the performance of the second fifth-order filter. The two end parallel-coupled stages tackle the spurious $2f_o$, $4f_o$ and $6f_o$. The two middle stages have seven periods, and four of them are used to establish interstage couplings. Note that the second transmission zero of the coupled seven-period stages at $7f_o$ is utilised for the spurious suppression, instead of its first zero at $3.5f_o$. This stage is essentially important for further extending the upper stopband. The tapped input/output structures are then designed to cancel the spurious at $3f_o$ and $5f_o$. The measured results show that the upper stopband is extended up to $7.8f_o$ with rejection levels better than 30 dB. The possible passband degradation can be an important issue when corrugated structures are used in circuit design. The zoomed inset in Fig. 7 shows the detailed passband response. The inband insertion loss is only 1 dB. This is very close to that of a design with only uniform coupled stages. The effect of corrugation on filter performance will become significant at higher frequencies, say, beyond 10 GHz [27].

5 Conclusion

Microstrip bandpass filters are designed to have multispurious suppression up to more than $5f_o$, $6f_o$ or $7f_o$ with corrugated coupled stages by allocating transmission zeros at harmonics of the passband. The design is purposely demonstrated on a substrate of relatively high dielectric constant. Based on the analysis of a first-order bandpass filter, the tuning of each zero relies on a sufficiently small deviation (1% or less) of the even and odd mode phase velocities at the harmonics for successful spurious suppression. For precisely allocating the inherent transmission zeros at both $2f_o$ and $4f_o$, geometric parameters of corrugated coupled stages are presented. The structure is very flexible since 2/3 and 4/7 of a $\lambda/4$-stage used for interstage coupling can effectively eliminate the unwanted peaks at $3f_o$ and $7f_o$, respectively. The tapped input/output configuration is also incorporated to eliminate the undesired responses at $3f_o$ or $5f_o$.

Based on the proposed approach, bandpass filters of higher orders can be designed to have an even wider rejection bandwidth since more coupled stages can be configured. Bandpass filters of no more than fifth-order with an upper rejection band covering over $10f_o$, however, can be a tough task if a high rejection level is required.

6 Acknowledgment

This work was supported in part by the National Science Council, Taiwan, under Grants NSC 94-2213-E-009-073 and 94-2752-E-009-003-PAE.

7 References

1 Pozar, D.M.: 'Microwave engineering' (Wiley, New York, 1998, 2nd edn.)
2 Bahl, I.J.: 'Capacitively compensated high performance parallel-coupled microstrip filters', *IEEE MTT-S Int. Microw. Symp.*, Long Beach, California, USA, June 1989, pp. 679–682
3 Lopetegi, T., Laso, M.A.G., Hernández, J., Bacaicoa, M., Benito, D., Garde, M.J., Sorolla, M., and Guglielmi, M.: 'New microstrip'wiggly-Line' filters with spurious passband suppression', *IEEE Trans. Microw. Theory Tech.*, 2001, **49**, (9), pp. 1593–1598
4 Kuo, J.T., Hsu, W.H., and Huang, W.-T.: 'Parallel coupled microstrip filters with suppression of harmonic response', *IEEE Microw. Wirel. Compon. Lett.*, 2002, **12**, (10), pp. 383–385
5 Fraresso, J., and Saavedra, C.E.: 'Narrowband bandpass filter exhibiting harmonic suppression', *Electron. Lett.*, 2003, **39**, (16), pp. 1189–1190
6 Tang, C.-W., and Liang, H.-H.: 'Parallel-coupled stacked SIRs bandpass filters with open-loop resonators for suppression of spurious responses', *IEEE Microw. Wirel. Compon. Lett.*, 2005, **15**, (11), pp. 802–805
7 Riddle, A.: 'High performance parallel coupled microstrip filters', *IEEE MTT-S Int. Microw. Symp.*, Baltimore, Maryland, USA, June 1998, pp. 427–430
8 Kuo, J.T., Chen, S.P., and Jiang, M.: 'Parallel-coupled microstrip filters with over-coupled end stages for suppression of spurious responses', *IEEE Microw. Wirel. Compon. Lett.*, 2003, **13**, (10), pp. 440–442
9 Kuo, J.T., Jiang, M., and Chang, H.J.: 'Design of parallel-coupled microstrip filters with suppression of spurious resonances using substrate suspension', *IEEE Trans. Microw. Theory Tech.*, 2004, **52**, (1), pp. 83–89
10 Kuo, J.T., and Jiang, M.: 'Enhanced microstrip filter design with a uniform dielectric overlay for suppressing the second harmonic response', *IEEE Microw. Wire. Compon. Lett.*, 2004, **14**, (9), pp. 419–421
11 Sun, S., and Zhu, L.: 'Periodically nonuniform coupled microstrip-line filters with harmonic suppression using transmission zero reallocation', *IEEE Trans. Microw. Theory Tech.*, 2005, **53**, (5), pp. 1817–1822
12 Velázquez-Ahumada, M.D.C., Martel, J., and Medina, F.: 'Parallel coupled microstrip filters with ground plane aperture for spurious band suppression', *IEEE Trans. Microw. Theory Tech.*, 2004, **52**, (3), pp. 1082–1086
13 Velázquez-Ahumada, M.D.C., Martel, J., and Medina, F.: 'Parallel coupled microstrip filters with floating ground-plane conductor for spurious-band suppression', *IEEE Trans. Microw. Theory Tech.*, 2005, **53**, (5), pp. 1823–1828
14 Quendo, C., Rius, E., Person, C., and Ney, M.: 'Integration of optimized low-pass filters in a bandpass filter for out-of-band improvement', *IEEE Trans. Microw. Theory Tech.*, 2001, **49**, pp. 2376–2383
15 Kuo, J.T., and Shih, E.: 'Microstrip stepped impedance resonator bandpass filter with an extended optimal rejection bandwidth', *IEEE Trans. Microw. Theory Tech.*, 2003, **51**, pp. 1554–1559
16 Lopetegi, T., Laso, M.A.G., Falcone, F., Martin, F., Bonache, J., Garcia, L., Perez-Cuevas Sorolla, M., and Guglielmi, M.: 'Microstrip "wiggly-line" bandpass filters with multispurious rejection', *IEEE Microw. Wirel. Compon. Lett.*, 2004, **14**, (11), pp. 531–533
17 Cheong, P., Fok, S.W., and Tam, K.W.: 'Miniaturized parallel coupled-line bandpass filter with spurious-response suppression', *IEEE Trans. Microw. Theory Tech.*, 2005, **53**, (5) pp. 1810–1816
18 Lee, H.-M., and Tsai, C.-M.: 'Improved coupled-microstrip filter design using effective even-mode and odd-mode characteristic impedances', *IEEE Trans. Microw. Theory Tech.*, 2005, **53**, (9), pp. 2812–2818
19 Jiang, M., Wu, M.H., and Kuo, J.T.: 'Parallel-coupled microstrip filters with over-coupled stages for multispurious suppression', *IEEE MTT-S Int. Microw. Symp.*, Long Beach, California, USA, June 2005, pp. 687–690
20 Fathelbab, W.M., and Steer, M.B.: 'Parallel-coupled line filters with enhanced stopband performances', *IEEE Trans. Microw. Theory Tech.*, 2005, **53**, (12), pp. 3774–3781
21 Chen, C.F., Huang, T.Y., and Wu, R.B.: 'Design of microstrip bandpass filters with multiorder spurious-mode suppression', *IEEE Trans. Microw. Theory Tech.*, 2005, **53**, (12), pp. 3788–3793
22 Lin, S.C., Deng, P.H., Lin, Y.S., Wang, C.H., and Chen, C.H.: 'Wide-stopband microstrip bandpass filters using dissimilar quarter-wavelength stepped-impedance resonators', *IEEE Trans. Microw. Theory Tech.*, 2006, **54**, (3), pp. 1011–1018
23 Manchec, A., Quendo, C., Rius, E., Person, C., and Favennec, J.F.: 'Synthesis of dual behavior resonator (DBR) filters with integrated low-pass structures for spurious responses suppression', *IEEE Microw. Wirel. Compon. Lett.*, 2006, **16**, (1), pp. 4–6
24 Lin, S.-C., Lin, Y.-S., and Chen, C.-H.: 'Extended-stopband bandpass filter using both half- and quarter-wavelength resonators', *IEEE Microw. Wirel. Compon. Lett.*, 2006, **16**, (1), pp. 43–45
25 U-yen, K., Wollack, E.J., Doiron, T.A., Papapolymerou, J., and Laskar, J.: 'A planar bandpass filter design with wide stopband using double split-end stepped-impedance resonators', *IEEE Trans. Microw. Theory Tech.*, 2006, **54**, (3), pp. 1237–1244
26 Chiou, Y.C., Wu, M.H., and Kuo, J.T.: 'Periodic stepped-impedance resonator (PSIR) bandpass filters with multispurious suppression'. *IEEE MTT-S Int. Microw. Symp.*, San Francisco, USA, June 2006, pp. 349–352
27 Kuo, J.T., Lok, U-H., and Wu, M.H.: 'Novel corrugated coupled-line stage with ideal frequency response and its application to bandpass filter design with multi-harmonic suppression', To be presented in the *IEEE MTT-S Int. Microw. Symp.*, Honolulu, Hawaii, USA, June, 2007