Tapped wiggly-coupled technique applied to microstrip bandpass filters for multi-octave spurious suppression

Sheng-Fuh Chang, Yng-Huey Jeng and Jia-Liang Chen

A tapped wiggly-coupled technique is applied to parallel-coupled microstrip bandpass filters for multi-octave out-of-band spurious suppression. The coupled edges of tapped microstrip resonators are wiggled to equalise the odd-mode and even-mode phase velocities such that the nearest two spurious harmonics can be eliminated. The simulation and experiment show that both the second and the third spurious level are reduced below 42 dB up to 9 GHz for a 2.45 GHz and 5.7% bandwidth bandpass filter.

Introduction: The microstrip parallel-coupled bandpass filter has been widely used in microwave circuits. However, it suffers from poor out-of-band suppression due to the inherent spurious passbands, particularly the nearest two components at $2f_o$ and $3f_o$, where f_o is the frequency of desired passband frequency. Various methods have been developed for eliminating the second spurious harmonic ($2f_o$). Denis *et al.* [1] replaced one section of parallel-coupled microstrip resonators with multiple sections of shorter resonators. Another effective approach is perturbing the microstrip dimension, such as wiggling the coupled gap [2, 3] or sinusoidally varying the microstrip width [4]. All these methods were shown as effective to suppress the second harmonic $2f_o$ but had no effect on the third harmonic $3f_o$. Therefore, their out-of-band suppression is limited to less than twice the passband central frequency. Furthermore, from the circuit implementation aspect, the acute saw-tooth of the microstrip in [2] and the sinusoidal line-width variation in [4] require stringent fabrication accuracy, which results in fabrication difficulty. To suppress the third spurious harmonic at $3f_o$, one possible way, proposed by [1], was to tap the resonator at a certain length so that a virtual RF short circuit could be formed at $3f_o$. However, this tapping method was unsuitable for widely-used parallel-coupled bandpass filters. In this Letter, the tapped wiggly-coupled technique is presented for parallel-coupled bandpass filters to eliminate both the second and the third spurious harmonics. The advantage of this method is that it provides effective multi-octave spurious suppression without increase of the circuit size and with little fabrication complexity. Both EM simulation and measurement was carried out to confirm the proposed technique.

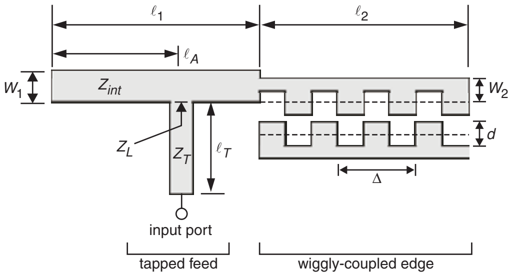

Fig. 1 *Schematic diagram of tapped wiggly-coupled bandpass filter (only half of circuit drawn)*

Circuit design: The classical microstrip parallel-coupled bandpass filter has the drawback of the existence of spurious passband approximately at integral multiples of the passband central frequency. In particular, the first two closest spurious components ($2f_o$ and $3f_o$) dominate the poor out-of-band performance. These two spurious harmonics are generated from different mechanisms. The second harmonic results because the odd-mode wave propagates faster than the even-mode wave in the coupled microstrips. Since the odd-mode field concentrates primarily around the coupling gap and the even-mode field more on the outer edges of the coupled line, one possible way to equalise their phase velocities is to increase the coupled-edge length while keeping the outer-edge length unchanged, as shown in Fig. 1. The rectangular wiggle profile is chosen here for ease of fabrication. The wiggle depth d and pitch Δ can be estimated from the quasi-static analysis, similar to the approach in [2, 5]. Under the quasi-static assumption, the odd-mode wave moves along the wiggled edges so that it travels a longer path to synchronise with the slower even-mode wave moving along the shorter unwiggled edges. Further corrected by the rigorous 2.5 D Sonnet electromagnetic simulation and comparison with the experimental data, the wiggle depth d and the wiggle pitch Δ are empirically formulated as

$$d = \frac{\Delta}{2}\left(\frac{C_{fow}}{C_{fo}} - 1\right)\exp\left(2.18\frac{C_{fe}}{C_{fo}}\right) \qquad (1)$$

where C_{fow} is the odd-mode unit-length capacitance of the wiggled microstrip and C_{fo} and C_{fe} denote the odd-mode and even-mode unit-length capacitances of the unwiggled microstrip, respectively. To have insight of the wiggled-edge effect, we simulate a pair of 90° parallel-coupled microstrip resonators at 2.45 GHz, as shown in Fig. 2 (where $\Delta = 0.8$ mm, $d = 0.48$ mm and $\ell_c = 16.8$ mm). This indicates that for the unwiggled case, the passband is up-shifted close to 4.5 GHz and the spectrum response around this frequency becomes asymmetric. This implies the passband ripple will increase and the second harmonic spurious will be present if unwiggled microstrip resonators are used to realise Chebyshev or Butterworth prototype filters. In contrast, for the wiggled case, the passband occurs at the desired frequency f_o of 2.45 GHz and it presents a transmission zero at $2f_o$ such that the second spurious can be eliminated when the wiggled coupled resonators are employed to realise the prototype filter.

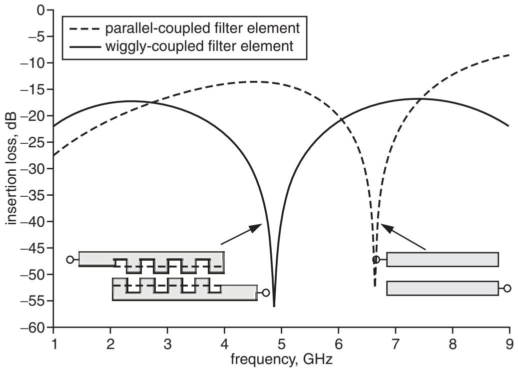

Fig. 2 *Simulated frequency response of wiggly- and unwiggly-coupled microstrip resonators*

Another drawback of a parallel-coupled microstrip bandpass filter is the inherent spurious harmonic at $3f_o$, which results from the periodical feature of the parallel-coupled microstrip used to realise the J-inverter (see [6]). This can be solved with the input/output tapping method, as shown in Fig. 1, which was originally proposed to solve the tight coupling problem [7] but here it is used to eliminate the third harmonic. The original passband response is unchanged if a quarter-wavelength microstrip Z_T is added at the proper tapped position as below

$$\ell_A = \frac{\lambda_3}{4},\quad \ell_T = \frac{\lambda_0}{4},\quad Z_T = \sqrt{Z_o, Z_L},\ \text{and}$$
$$Z_L = Z_{int}\frac{2}{\pi}Q_s\cos^2\left(\frac{\pi}{2}\frac{\ell_A}{\ell_1}\right) \qquad (2)$$

where λ_0 is the wavelength at the passband central frequency f_o, λ_3 is the wavelength at $3f_o$, Z_L denotes the impedance at the tapped position, Z_{int} denotes the first resonator impedance, and $Q_s = g_0 g_1 f_o / BW_{3dB}$ (g_0 and g_1 are prototype element values, BW_{3dB} is the 3 dB bandwidth).

A 5.7% bandwidth, 2.45 GHz third-order Chebyshev filter is designed using (1) to obtain the wiggled depth d and using (2) to obtain the input/output tapped position. The calculated circuit is then simulated by a full-wave electromagnetic simulator, Sonnet, to include the layout discontinuity and the mutual coupling between the wiggled teeth. The final circuit parameters are $Z_L = 267\ \Omega$, $Z_{int} = 34\ \Omega$, $Z_T = 115\ \Omega$, $\ell_A = 5.65$ mm, $\ell_T = 21.1$ mm, $\ell_1 = 17.8$ mm, $W_1 = 1.8$ mm, $\ell_2 = 16.8$ mm, $W_2 = 1.04$ mm, $d = 0.48$ mm, $\Delta = 0.8$ mm. The substrate parameters are dielectric constant $\varepsilon_r = 3.8$, substrate thickness $h = 0.457$ mm and loss tangent = 0.0025. The circuit layout and photograph are shown in Fig. 3.

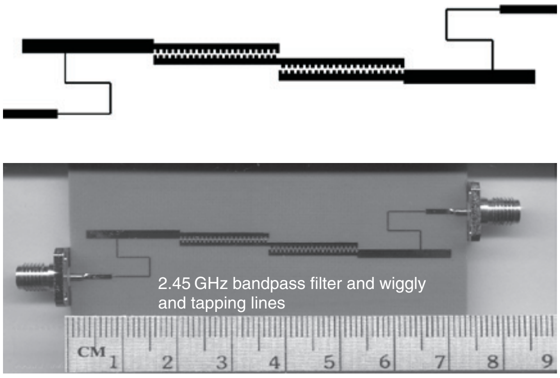

Fig. 3 *Layout and photograph of tapped wiggly-coupled bandpass filter*

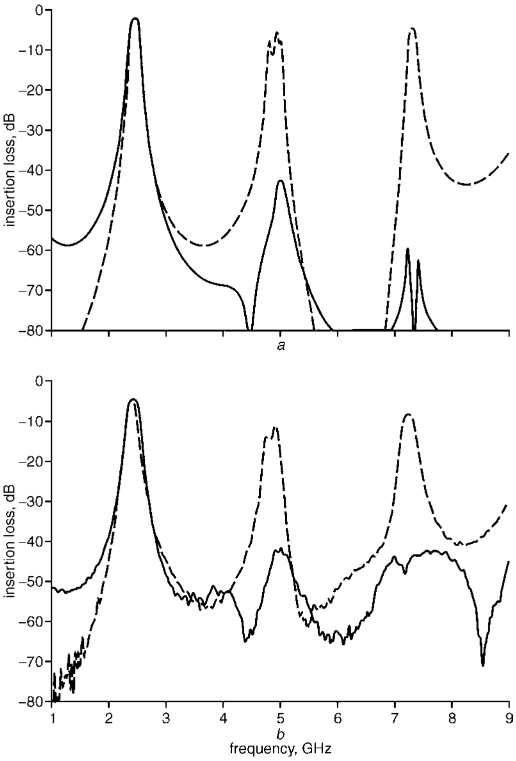

Fig. 4 *Simulated and measured performance of conventional and tapped wiggly-coupled bandpass filter*

a Simulated *b* Measured
– – – conventional —— proposed

Simulation and measurement results: The simulation and measurement results of the proposed filter are shown in Fig. 4, where the results of the unwiggled filter are included for comparison. For the unwiggled filter, the desired passband at 2.45 GHz is obtained but the undesired spurious harmonics appear at 4.95 and 7.4 GHz. These spurious harmonics are effectively eliminated by the tapped wiggly-edge design. The measured spurious harmonic level is suppressed below −42 dB from 3 to 9 GHz with passband insertion loss less than 3.2 dB. This demonstrates that better than 42 dB out-of-band suppression is achieved up to the quadruple of desired passband central frequency.

Conclusions: A tapped wiggly-coupled filter is proposed to have narrow passband with strong suppression of the second and third spurious harmonics. The wiggly-coupled line equates the odd-mode and even-mode phase velocities such that the second spurious harmonic is eliminated. Together with the third harmonic suppression effect by the input/output tapped feed, the designed filter exhibits the feature of strong out-of-band suppression over three octaves range. Both simulation and measurement demonstrated that stronger than 42 dB spurious rejection is achieved from 3 to 9 GHz, while keeping desired passband loss less than 3.2 dB at 2.45 GHz.

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Sheng-Fuh Chang, Yng-Huey Jeng and Jia-Liang Chen (*Department of Electrical Engineering, Center for Telecommunication Research, National Chung Cheng University, 160 San-Hsin Va., Ming-Hsiung, Chiayi, 621, Taiwan, Republic of China*)

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