Multispurious Harmonic Suppression in Compact Coupled-Line Bandpass Filters by Trapezoidal Corrugations

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***Abstract*—Present paper highlights the design of compact third-order coupled-line Chebyshev bandpass filters centered at 2.5GHz with multispurious harmonics suppression. The conventional filter has been folded symmetrically about the horizontal plane miniaturized to folding and in-line configurations with compactness of more than 50% and 60%. However, degradations of harmonic levels have been occurred for the proposed folding configurations due to additional open-end couplings. Accordingly, trapezoidal corrugations with optimum dimensions and periodicity have been employed in both $\lambda/4$ length coupled end sections and $\lambda/6$ length coupled middle sections to suppress spurious harmonics at $2f_0$, $3f_0$ and $4f_0$. As a result, an extended stopband with suppression level around 35dB upto $4.8f_0$ along with a compactness of 67% has been obtained.**

Keywords— Microstrip bandpass filter; harmonic suppression; fourth harmonics; compactness

I. Introduction

In transceiver system, bandpass filters with improved skirt characteristics, low insertion loss, symmetrical passband response are in great demand for both commercial and satellite applications. Microstrip parallel-coupled line bandpass filters are extensively used to meet up these requirements [1]. However, such filters experience asymmetric passband response, poor upper stopband skirt characteristics and redundant passbands at the multiples of the designed frequency. Traditionally, harmonics are observed due to the difference in the even- and odd-mode phase velocities in the inhomogeneous dielectric medium of microstrip structure. Accordingly, the multispurious characteristics exhibit degradation in image rejection process. Moreover, other than harmonics problem, conventional coupled-line filter requires relatively higher amount of area inappropriate for miniaturized subsystems. In this context, improved passband performance with sharp skirt characteristics in a miniaturized design platform has been addressed as a primary research objective in [2-5]. A compact bandpass filter centered at 1.95GHz has been designed by folding the quarter-wavelength resonators into S-shaped and accordingly compactness of 35% has been achieved [2]. Subsequently, by tuning the locations of transmission zeros, compact tunable wide bandpass filter with high selectivity has been proposed in [3]. Recently, compactness of more than 91% has been obtained in [4] over a conventional coupled-line filter by reactively loading coupled-lines and eliminating the first and last inverters of the filter. Later, parallel-coupled lines have been folded in U-shape in [5] to design a compact ultra-wideband filter centered at 2.5GHz exhibiting more than 55dB rejection levels at the stopband edges. However, limited investigations have been demonstrated on harmonic on the said compactness. Thus, designing of compact bandpass filters with improved stopband performances at multiband becomes a challenging issue. In [6] wiggly-lines have been employed in a seventh-order filter, and rejection levels of 30 dB for the leading four spurious passbands have been recorded. Subsequently, in [7], electrical length of $\lambda/4$, $\lambda/6$, and $\lambda/8$ are optimized discretely to reject the spurious at $2f_0$, $3f_0$ and $4f_0$, respectively with a rejection level better than 30dB. In [8], a wide stopband extended up to $11.4f_0$ with a rejection level better than 27.5 dB has been achieved by employing various dissimilar quarter-wavelength stepped-impedance resonators (SIRs). Subsequently, corrugated coupled stages have been devised to have multispurious suppression better than 30dB, by transmission zero allocation method [9]. Later, the multispurious suppression has been studied in [10] by means of a precise control of the coupling between parallel resonators at unwanted resonant frequencies and more than 25dB of rejection level upto $7f_0$ has been addressed. However, in [6-10] the multispurious suppression has been investigated on conventional parallel-coupled line bandpass filter structure. Recently, in [11] periodic triangular corrugations with optimum dimensions on folded and in-line structures have been studied, exhibiting a second harmonic suppression level of 62dB and 30dB along with 62% and 74% of size reduction.

In present article, the ideas of the overcoupled stages [7] and the corrugated coupled stages [9] have been extended to design miniaturized bandpass filters of [10] with an improved rejection level upto fourth harmonic. The corrugated stages with rectangular corrugations proposed in [9] have been modified with trapezoidal shaped corrugations to minimize the edge diffraction. By optimizing the coupling periods of the corrugations, the inherent transmission zeros have been allocated at the harmonics of the desired center frequency. Two compact third-order filters (folded and in-line) centered

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at 2.5GHz with fractional bandwidth of 20% have been designed. The substrate material used is FR4 epoxy having dielectric constant, ε_r = 4.4, loss tangent, tanδ = 0.016 and thickness, h = 1.6 mm.

II. Design Methodology

For a third-order filter, element values of the Chebyshev low-pass filter with pass-band ripple of 0.01dB are computed as $g_0 = g_4 = 1.0000$, $g_1 = g_3 = 1.0315$, $g_2 = 1.1474$[1]. Table I provides the design parameters of conventional parallel coupled lines. One of the disadvantages of this conventional parallel coupled line is the large layout dimension of 1004.11mm^2 as shown in Fig. 1(a). Accordingly, the size of the conventional filter has been reduced by the symmetric folded structure as shown in Fig. 1(b), in which an open-end length correction of 0.264mm. is incorporated due to fringing fields[1]. Accordingly, a size reduction of 46.37% has been achieved due to folding mechanism. Optimization of offset-gap length provides a design tradeoff between the passband performance and harmonic suppression. Subsequently, due to the gap of 0.528mm. with respect to the symmetry plane, an additional capacitive coupling has been introduced between the in-line resonators. The folded structure has been further miniaturized by using the in-line structure as shown in Fig. 1(c). As a result, a size reduction of 64.2% compared to conventional filter and 33.24% compared to folded filter has been achieved in in-line filter. However, compared to the folded structure, three distinct offset gaps (length of 0.528mm.) are created and hence the controlling of open-end coupling becomes critical design parameters. Fig. 2 compares the simulated S-parameters plots of conventional, folded and in-line filters. From Fig. 2 it has been observed that the upper stopband rejection level improves to 43dB and the insertion loss at the second harmonic is increased (18dB) in both folded and in-line filters due to additional open-end offset gap couplings.

TABLE I. Microstrip Line design Parameters Specifications

j	$J_{j,j+1}/Y_0$	$(Z_{0e})_{j,j+1}$ (ohms)	$(Z_{0o})_{j,j+1}$ (ohms)	$w_{j,j+1}$ (mm.)	$s_{j,j+1}$ (mm.)	$l_{j,j+1}$ (mm.)
0	0.499	87.470	37.500	0.940	0.30	16.897
1	0.201	62.077	41.967	1.543	0.82	16.666
2	0.201	62.077	41.967	1.543	0.82	16.666
3	0.499	87.470	37.500	0.940	0.30	16.897

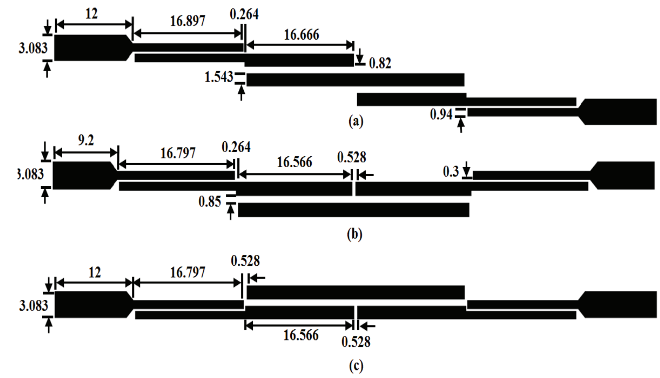

Fig. 1. Layout of third-order parallel-coupled bandpass filters. (a) conventional, (b) folded, and (c) in-line filter. All dimensions are in mm.

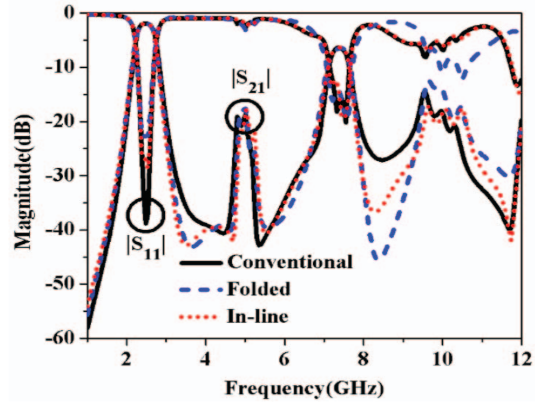

Fig. 2. S-parameters of conventional, folded and in-line bandpass filters.

III. Harmonic Suppression By Corrugations

A. Study of Unit PCML Cell

Fig. 3(a) shows the layout of a unit parallel-coupled microstrip line (PCML) structure with length of $\lambda/4$, where λ is the guided wavelength. For the given filter specifications the values of width(w), line(l) and gap(s) can be determined by calculating the even- and odd-mode characteristic impedances Z_{0e} and Z_{0o} [1]. In [11], the concept of phase velocity compensation has been obtained between even- and odd-mode by relocating the transmission zeros subject to periodic corrugations in a folded coupled-line filter. Accordingly, second harmonic rejection level of 62dB and compactness of more than 62% have been achieved with five periodic triangular corrugations. However, the effects of corrugations on higher order harmonics are not studied in [11]. In general, the rectangular corrugation [9] exhibits abrupt transition at the corners for the surface current and hence, the edges at the corners have been tilted to obtain trapezoidal shape. Accordingly, the surface current path becomes smooth at the corners of the corrugations. Fig. 3(b) shows the layout of unit PCML cell with six periodic trapezoidal corrugations in the coupled edges as an initial study. It may be further noted that when $a = b$, the trapezoidal corrugation becomes a rectangular corrugation. For simplicity of the design, the value of base width, w_B and height, h_T have been fixed to $w/2$, where w is the width of the coupled-line. By varying the value of a with b equals to w, the area of the trapezoidal corrugations has been varied, which effectively change the degree of coupling between the corrugated lines. Accordingly, the phase velocity of odd-mode has been compensated with that of the even-mode almost unaltered [11].

Traditionally, an ideal quarter-wavelength PCML cell has inherent transmission zeros at $2mf_0$ for the electrical coupling length of the coupled-lines of 180^o [1]. Similarly, the line with length of $\lambda/6$ at f_0 has an electrical length multiple of 180^o that exhibits zeros at 3mf_0 [7]. Hence, for generating zeros at eve-order harmonics such as $2f_0$, $4f_0$, $6f_0$, $8f_0$ simultaneously with the same corrugated coupled-line structure, six periods of the corrugations have been chosen as shown in Fig. 3(b). However, the odd-order harmonics are unaffected according to the distributed characteristics of quarter-wavelength line.

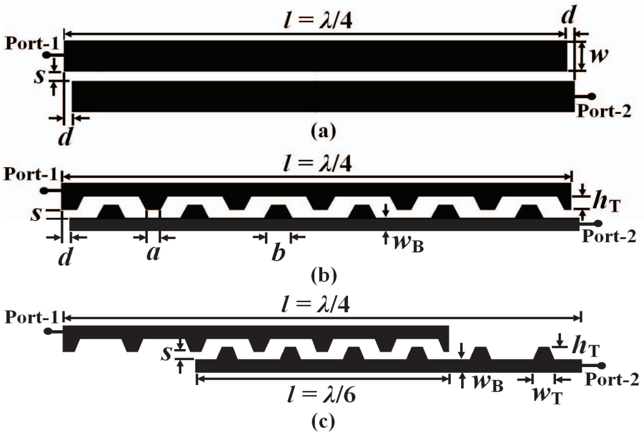

Fig. 3. Layout of unit PCML cell. (a) no corrugations (b) trapezoidal corrugations with coupling periods of 6 for $2f_0$ and $4f_0$ transmission zeros and (c) coupling periods of 4/6 for $3f_0$ transmission zero placement.

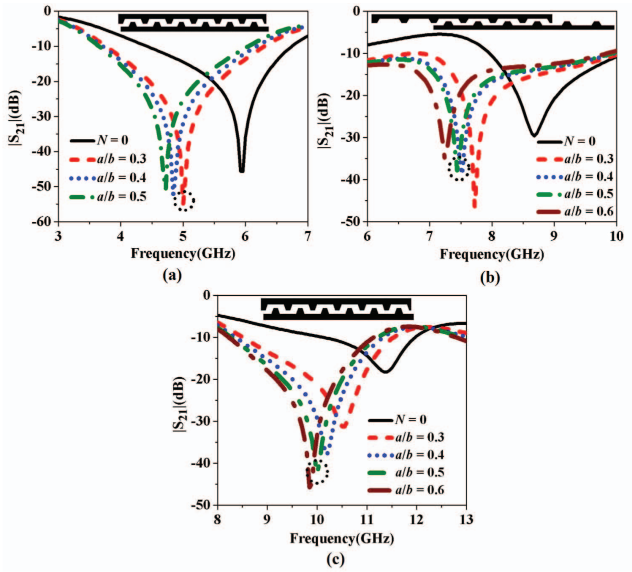

Fig. 4. Placement of transmission zeros by varying the values of a/b. (a) second, (b) third and (c) fourth transmission zero. Here, l = 16.833, $w = w_T = b$ = 0.94mm., s = 0.3mm., d = 0.264mm., $h_T = w_B = w/2$ = 0.47mm., N = 6.

Accordingly, by coupling four periods of six corrugations (4/6 x $\lambda/4 = \lambda/6$) the transmission zero has been placed at $3f_0$ as shown in Fig. 3(c). Fig. 4(a)-(c) highlight the placement of second, third and fourth harmonic transmission zeros by varying the a/b values of the trapezoidal corrugations in a unit PCML cell. It has been observed that the values of a/b for exact placement of second, third and fourth harmonic transmission zeros (5GHz, 7.5GHz and 10GHz) are 0.3, 0.4 and 0.5 respectively.

B. *Study of Third-Order Folded and In-line PCMLBF*

The unit cell study of periodic corrugations on second harmonic suppression [11] has been extended further in the third-order folded and in-line bandpass filters for multispurious harmonic suppression by employing the concept of offset coupling at the middle sections as described in previous section.

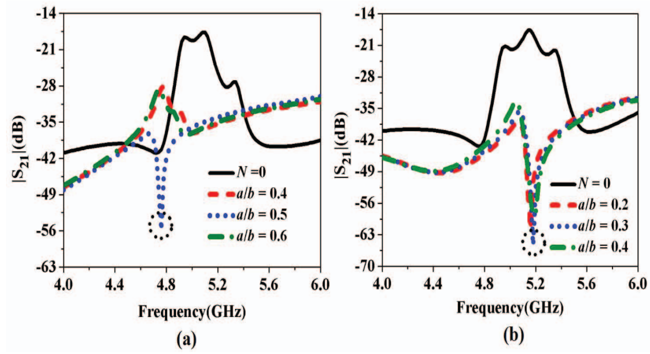

Fig. 5. Parametric study for optimum dimensions of corruagtions. (a) folded and (b) in-line filter.

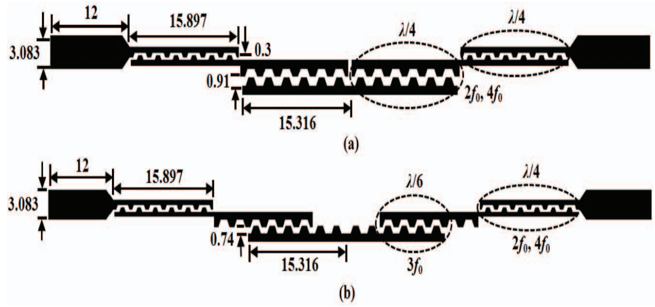

Fig. 6. Layout of third-order folded filter with corrugations. (a) Filter 1 and (b) Filter 2.

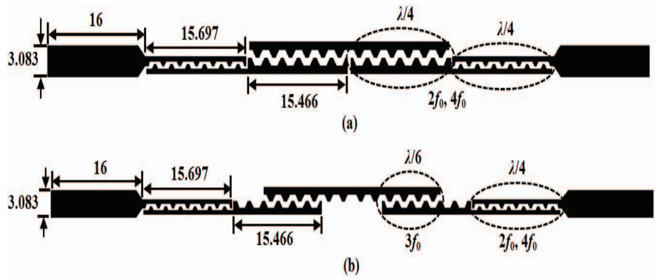

Fig. 7. Layout of third-order in-line filter with corrugations. (a) Filter 3 and (b) Filter 4.

Firstly, the maximum suppression of the second harmonic (5GHz) by corrugations has been studied by varying the value of a/b with the assumptions that $w_B = h_T = w/2$, $b = w$ and N = 6 as highlighted in Fig. 5. It has been observed that maximum second harmonic suppression level of 56dB has been obtained for a/b = 0.5 in folded filter and 65dB for a/b = 0.3 in in-line filter. Fig. 6(a) shows the layout of corrugated folded filter (Filter 1) exhibiting $2f_0$ and $4f_0$ suppression and Fig. 6(b) shows the layout of Filter 2 with offset coupling at the middle stages to suppress the $3f_0$. Similarly, Fig. 7(a)-(b) show the layouts of in-line filters, Filter 3 and Filter 4 to suppress $2f_0$, $4f_0$ and $3f_0$ respectively based on the same principle. The two end sections of the filters are optimized to suppress the spurious responses at $2f_0$ and $4f_0$, and the offset length of middle sections with inter-stage coupling length of $\lambda/6$ are tuned at $3f_0$, such that the upper stopband has been extended up to $5f_0$. Fig. 8(a) - (b) show the photographs of fabricated filters.

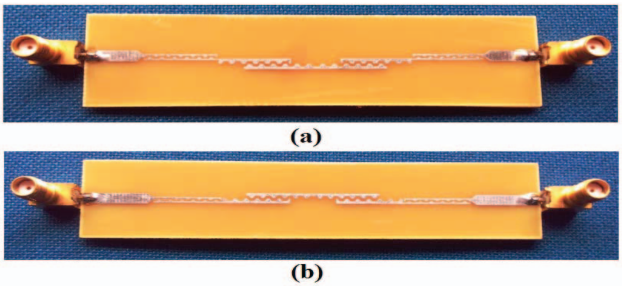

Fig. 8. Fabricated prototypes of proposed filters. (a) Filter 2 and (b) Filter 4.

IV. Results and Discussions

Fig. 9 illustrates the S-parameters plots for the optimized third-order folded filter with corrugations. It has been observed that the Filter 1 exhibits suppression level of 55dB and 31dB at $2f_0$ and $4f_0$ in simulation. However, third harmonic level remains unaffected. Moreover, rejection level at the upper stopband edge frequency has been improved to 47dB with sharp skirt characteristics. Subsequently, Filter 2 exhibits the measured rejection levels of 38dB, 33dB and 36dB at $2f_0$, $3f_0$ and $4f_0$ respectively. Accordingly, an extended stopband upto $4.6f_0$ with rejection level below 33dB has been obtained in measurement. Fig. 10 illustrates the S-parameters plots for the third-order in-line filters with corrugations. Rejection levels of 50dB and 33dB have been observed at $2f_0$ and $4f_0$ for Filter 3 having no suppression at $3f_0$.

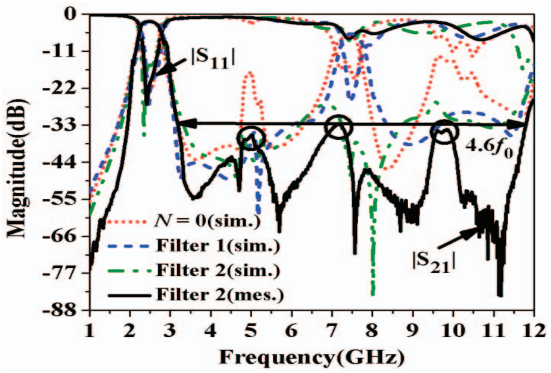

Fig. 9. Comparison of simulated vs. measurement of S-parameters for third-order folded bandpass filters with corrugations.

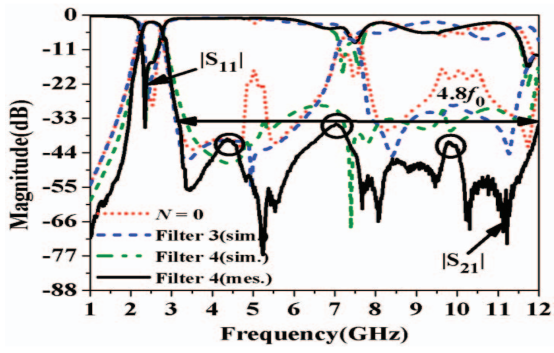

Fig. 10. Comparison of simulated S-parameters for third-order in-line bandpass filters with corrugations.

Accordingly, Filter 4 provides the rejection levels of 39dB, 35dB and 42dB at $2f_0$, $3f_0$ and $4f_0$ respectively in measurement. Moreover, an extended stopband upto $4.8f_0$ with rejection level below 35dB has been obtained. For all the designed filters the return loss in the desired passband is better than 20dB and insertion loss is less than 2.6dB. The compactness of 51.4%, 47.4%, 69.5% and 67.5% have been achieved for Filter 1, Filter 2, Filter 3 and Filter 4 respectively compared to the third-order conventional coupled-line filter.

V. Conclusion

Present article proposes the design of a folded and in-line parallel coupled-line band pass filters and investigates the effects of periodic trapezoidal corrugations for performing the multispurious harmonics suppression. By adjusting the corrugations in the offset coupling length of the middle sections of the filters, harmonics have been suppressed with rejection level lower than 33dB for folded filter upto $4.6f_0$ and around 35dB for in-line filter upto $4.8f_0$. Compared to folded filters the in-line filters give better harmonic suppression performance along with more compactness.

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