Design of Microstrip Bandpass Filters with Suppression of Spurious Harmonics

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Abstract **J:Coupled corrugated microstrip lines, suspended coupled microstrip lines, over-coupled end stages, and stepped impedance resonators (SIR’s) are used to construct high performance bandpass filters for suppressing the spurious harmonics. The leading two structures are designed to equalize the phase velocities of the eigen-modes in the longitudinal direction, so that filters of medium and wide bandwidths can be implemented with good suppression of spurious harmonics at twice the fundamental frequency. Over-coupled stages are used to compensate the phase difference resulted from the unequal even and odd mode phase velocities. SIR filters are found to have a wide stopband up to more than 4 times the passband frequency. Both simulation and measured results are presented for each structure.**

摘要 – 本文使用波浪狀耦合微帶線、懸空基板耦合微帶線、過度耦合微帶線、以及步階阻抗諧振腔等四種結構，設計高品質微波帶通濾波器，有效壓抑高階寄生響應。在前兩種結構中，設計目標是讓每一級耦合微帶線的特徵模相位速度相同，以壓抑兩倍通帶頻率處的寄生響應；在濾波器的前後端耦合級，加上過度耦合的設計，也能補償濾波器中各耦合級因相位速度不同所引起的相位差；以步階阻抗諧振腔所設計的濾波器，其截止帶可大於通帶頻率的四倍。針對上述四種結構，文中皆有電路製做量測，並附模擬與實驗數據比對。

I. INTRODUCTION

In the RF front-end of a modern communication system, bandpass filters with wide stopband and high selectivity are usually required to enhance the overall circuit performance. In the last thirty years, parallel coupled microstrips have been one of the most commonly used filters due to its planar structure, ease of synthesis method, and low-cost [1,2].

It is known that the parallel coupled microstrip filters suffer from the spurious response at $2f_o$, twice the passband frequency, which may seriously degrade the attenuation level in the stopband, and greatly limit the applicability of the filters. It is resulted from the deviation between the even- and odd-mode phase velocities of each coupled section.

Many works [3-6] has been proposed to tackle this problem. They fall into two categories [4]: providing different lengths for the even and odd modes, and equalizing the modal phase velocities. It is found in [3] that connecting a short uncoupled line section at either end of the coupled section can improve the filter characteristics, if the section lengths are chosen correctly. In [4], an over-coupled resonator is proposed to extend phase length for the odd mode to compensate phase difference. The capacitively compensated structures [5, 6] are also effective in suppressing the spurious passband at $2f_o$. It should be noted that the values of the loading capacitors are subject to the electrical parameters of each coupled section.

The first and second spurious responses of filters designed with stepped impedance resonators (SIR’s) can be pushed far beyond $2f_o$ and $3f_o$, respectively, with a proper choice of impedance ratio [7]. Different stripline SIR’s with specified coupling angles can also be combined to suppress the spurious responses. The design in [8] completely suppresses the $2f_o$ resonance with inductive effect. Its first parasitic response is observed at frequency close to $3f_o$. The coupled wiggly microstrip lines in [9] also show an effective suppression on the spurious passband at $2f_o$. The strip-width perturbation does not require the filter parameters to be recalculated, and the classical design methodology for coupled-line microstrip filters can still be used.

II. FILTERS WITH COUPLED CORRUGATED MICROSTRIPS

One possible way for equalizing the phase velocities of the quasi-TEM eigen-modes of coupled microstrips is to use corrugated lines [10]. The design of coupled corrugated lines is based on the following two propagation characteristics of the eigen-modes of coupled microstrips. First, in a pair of symmetric coupled microstrips, the electromagnetic energy for the odd-mode gathers around the central slot area, while that for the even-mode around the outer edge of the metallic strip. Second, the phase velocity for the odd-mode is faster than that of the even-mode. Thus, to equalize the phase of the odd and even modes in each coupled stage, one can employ coupled corrugated microstrip lines, as shown in Fig.1. Along the corrugated coupled lines, the propagation path for odd-mode is the central corrugated contour, while that for the even mode is close to that of straight coupled microstrips. It means that in the longitudinal direction, both eigen-modes can have identical phase velocities if the corrugation pattern can be properly designed.

In constructing a filter, the corrugation pattern should be trimmed for each coupled stage before the whole circuit is designed. Fig.2 shows the simulation and measured results for a third-order Chebyshev bandpass filter with corrugated coupled microstrip sections [10]. The simulation results for a filter designed with classical method is also plotted for comparison. It indicates that the corrugation pattern has an improvement of 40dB in suppression of the spurious harmonics at $2f_o$. The possible radiation loss caused by the corrugation is also plotted for comparison.

Similar approach can be applied to three-line microstrip sections for designing wide band filter with suppression of the spurious resonance [11]. Fig.3 shows that the unwanted response at $2f_o$ can be suppressed to a level below –50 dB. It is to be noted that the response symmetry is also greatly improved. The simulation results are obtained by invoking the full-wave simulator IE3D [12].

III. FILTERS ON A SUSPENDED SUBSTRATE

The second way for equalizing the odd and even modes phase velocities of coupled microstrips is to use a suspended substrate [13]. The required height of substrate suspension depends on the structural parameters, including line width, gap size, substrate thickness and substrate ε_r, of the coupled microstrips. In traditional design of a parallel coupled microstrip bandpass filter, however, it consists of a cascade of coupled microstrip sections. The structural parameters of each coupled section are determined by the element values of the lowpass filter prototype, so that line width and gap size, and hence the substrate suspension height required for equalizing the eigen-mode phase velocities, can be different from stage to stage.

Although each coupled stage may require its own substrate suspension height, it is possible to find an optimal suspension height for the substrate to obtain a satisfactory suppression of the spurious resonance at $2f_o$. To facilitate the simulation, the cascade of parallel coupled stages is analyzed by the network approach. A database can be established for the transmission line parameters of each coupled stage, effective dielectric constants and characteristic impedances of the even and odd modes, which must be determined by a full-wave method. In [13], bandpass filters with 10%, 20%, and 25% fractional bandwidths are designed and fabricated on suspended substrate. Fig.4 shows one of them. The simulated and measured results show a good agreement. The spurious response at $2f_o$ is suppressed to a level lower than –40dB. The simulation result for filter without substrate suspension, i.e. $h_1 = 0$, is also provided for comparison.

IV. FILTERS WITH OVER-COUPLED END STAGES

Over-coupled stages can be used to extend the phase length for the odd mode to compensate the difference in the phase velocities. It is found that the passband response can be altered if every coupled stage is over-coupled, since the resonant frequency of each stage could be altered. Thus an optimization process becomes inevitable in obtaining a filter with high performance. In [14], the over-coupled scheme is applied only to the end stages. The traditional synthesis procedure and design method for planar microstrip bandpass filters require no modification at all. Entire filter with over-coupled end stages is first analyzed by network analysis, through the successive multiplication of *ABCD* matrices, followed by a conversion from a two-port *ABCD* matrix to the *S*-parameter matrix. The phase constants and characteristic impedances of the symmetric and the two three-line coupled sections are calculated by a full-wave method. The over-coupled length to the input/output resonator can then be optimized with ease. It is found that the “optimal” length for over-coupling depends on the structure and specification of the filter.

Fig.5 shows the measured and simulated responses of a third-order Chebyshev bandpass filter. Both results agree very well in the passband. The levels of the spurious responses for both measurement and simulation near twice the passband frequency are below –40dB.

V. FILTERS WITH STEPPED IMPEDANCE RESONATORS

For the SIR structure shown in Fig.6, it is convenient to define the impedance ratio of the stepped impedance segments as

$$R = Z_2/Z_1 \tag{1}$$

It can be shown that the resonant frequencies of an SIR can be determined by

$$\tan\theta_1 = R\cot\theta_2 \quad \text{(odd-mode)} \tag{2}$$

$$\cot\theta_1 = -R\cot\theta_2 \quad \text{(even-mode)} \tag{3}$$

Based on (2) and (3), and given R and the lengths of the hi-Z and lo-Z segments, one can calculate the fundamental and every higher order resonant frequency of an SIR. It is to be noted that the fundamental and even-numbered resonances occur in the odd mode, and all the odd-numbered resonances in the even mode.

The resonant frequencies of an SIR depend on the choice of the R value. It has been found [7] that the smaller the R value is, the higher frequency the first higher order mode has. However, the characteristic impedance of a practical microstrip line has both upper and lower limits. The limits depend on substrate thickness, substrate ε_r, the fabrication process, and resolution of layout. In our SIR filters, the RT/duroid 5880 substrate, $\varepsilon_r = 2.2$ and thickness = 0.508 mm, is used for circuit fabrication, and $Z_1 = 105\ \Omega$ is adopted for the hi-Z segment.

Fig.7 shows the circuit layout for a third-order parallel coupled bandpass SIR filter with tapped-line input/output resonators. Such a feeding scheme is purposely chosen to create two extra transmission zeros near the passband, in order to enhance the selectively of the filters. The positions of the zeros can be tuned via the use of a quarter-wave transformer [15].

Fig.8 plots the simulated results for an SIR filter with $\Delta = 6\%$ and $R = 0.2$. The specification of the filter is given in [15]. The $|S_{21}|$ response for a uniform impedance resonator filter is also plotted for comparison. The first spurious response for the SIR filter is pushed to $4.4f_o$. It is interesting to note that the shadow region in the plot demonstrates the improvement of stopband rejection of the SIR filter. Fig.9 shows the measured responses for the experimental filter. The measurements agree with the simulation results quite well.

VI. CONCLUSION

Coupled corrugated microstrip lines, suspended substrate, over-coupled stages, and stepped impedance resonators (SIR's) are used to design microstrip bandpass filter for suppressing the spurious responses. The presented simulation and measured results for the four structures show a good agreement. Not only a 40dB suppression of the unwanted response for each method is obtained, but also the passband symmetry is greatly improved.

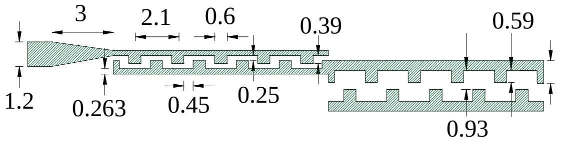

Fig.1 Circuit layout for a third-order Chebyshev bandpass filter with coupled corrugated microstrips. Only half of the circuit is drawn here. Detailed specification and structural parameters see [10].

ACKNOWLEDGEMENT

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REFERENCES

[1] D. M. Pozar, *Microwave Engineering*, John Wiley & Sons, New York, 1998, 2nd Ed.

[2] C.-Y. Chang and T. Itoh, "A modified parallel-coupled filter structure that improves the upper stopband rejection and response symmetry," *IEEE Trans. Microwave Theory Tech.*, vol. 39 no.2, pp. 310-314, Feb. 1991.

[3] B. Easter and K. A. Merza, "Parallel-coupled-line filters for inverted-microstrip and suspended-substrate MIC's," in the 11th *European Microwave Conf. Digest*, pp. 164-167, 1981.

[4] A. Riddle, "High performance parallel coupled microstrip filters", *IEEE MTT-S Symp. Digest*, pp. 427-430, 1988.

[5] S. L. March, "Phase velocity compensation in parallel-coupled microstrip", *IEEE MTT-S Symp. Digest*, pp. 410-412, 1982.

[6] I. J. Bahl, "Capacitively compensated high performance parallel coupled microstrip filters", *IEEE MTT-S Symp. Digest*, pp. 679-682, 1989.

[7] M. Makimoto and S. Yamashita, *Microwave Resonators and Filters for Wireless Communication - Theory and Design*, Springer, Berlin, 2001, pp. 79-83.

[8] Lei Zhu and Ke Wu, "Accurate circuit model of interdigital capacitor and its application to design of new quasi-lumped miniaturized filters with suppression of harmonic resonance," *IEEE Transactions on Microwave Theory and Techniques*, vol.48, no.3, pp. 347 – 356, March 2000.

[9] 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.

[10] Jen-Tsai Kuo, Wei-Hsiu Hsu and Wei-Ting Huang, "Parallel coupled microstrip filters with suppression of harmonic response," To appear in the *IEEE Microwave and Wireless Components Letters*, Oct. 2002.

[11] Jen-Tsai Kuo and Wei-Cheng Lee, "Suppression of spurious responses in three-line microstrip wideband bandpass filters," Submitted to *Electronics Letters*.

[12] Zeland Software Inc., *IE3D simulator*, Jan. 1997.

[13] Jen-Tsai Kuo and Meshon Jiang, "Suppression of spurious resonance for microstrip bandpass filters via substrate suspension," To be presented in the 2002 *Asia-Pacific Microwave Conference*, Kyoto, Japan, Nov. 19-22, 2002.

[14] Jen-Tsai Kuo, Sin-Ping Chen, and Meshon Jiang, “Microstrip bandpass filter with overcoupled end stages for suppressing the second harmonic resonance,” Submitted to the 2003 *Progress in Electromagnetics Researches Symposium* (*PIERS*), Jan. 7-10, Singapore.

[15] Jen-Tsai Kuo and Eric Shih, "Stepped impedance resonator bandpass filters with tunable transmission zeros and its application to wide stopband design," in 2002 *IEEE MTT-S Symp. Digest*, pp. 1613-1616, Seattle, Washington, USA, June 2-6, 2002.

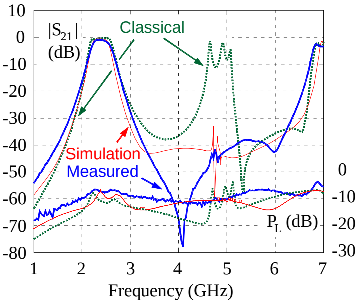

Fig.2 Simulation and measured results for a Chebyshev filter with coupled corrugated microstrips. The dimensions of the corrugation see Fig.1.

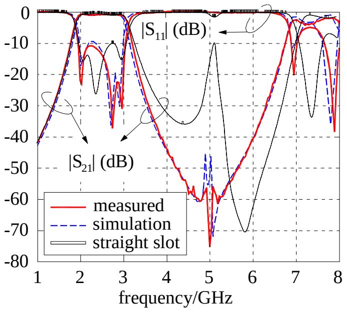

Fig.3 Simulation and measured results for a third-order Chebyshev filter with fractional bandwidth Δ = 50%. Note that simulation result for classical design shows that |S_{21}| has a peak of –10 dB at 2f_o.

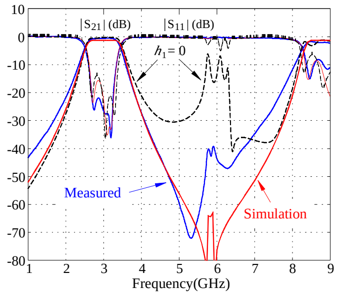

Fig.4 Simulation and measured results for a third-order Chebyshev filter with fractional bandwidth Δ = 25% on a suspended substrate. Detailed structural parameters see [13].

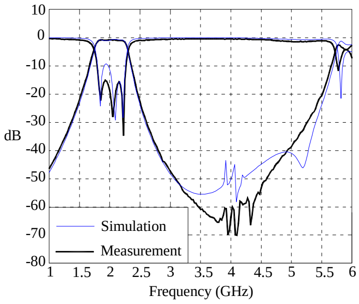

Fig.5 Simulation and measured results for a third-order Chebyshev filter with over-coupled end stages. Detailed structural parameters see [14].

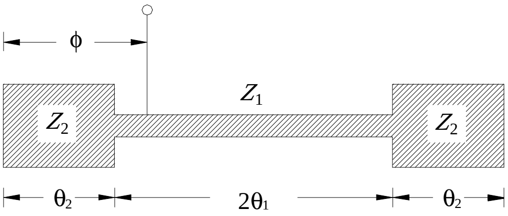

Fig.6 Structure of a stepped impedance resonator (SIR).

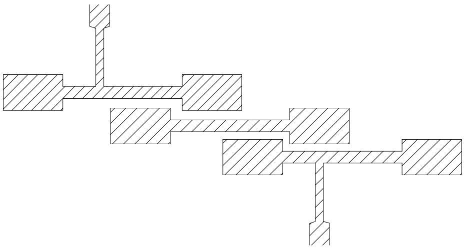

Fig.7 Layout for a third-order microstrip SIR filter with tapped coupling at the input and output resonators.

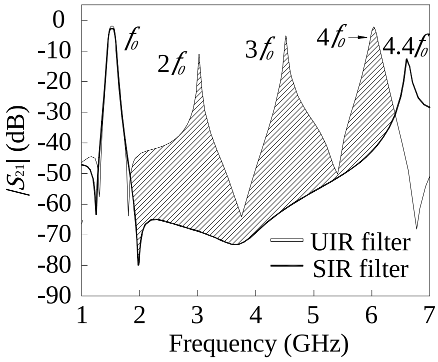

Fig.8 Simulation results for a third-order Chebyshev SIR filter with fractional bandwidth Δ = 6%. Detailed structural parameters see [15]. UIR means uniform impedance resonator.

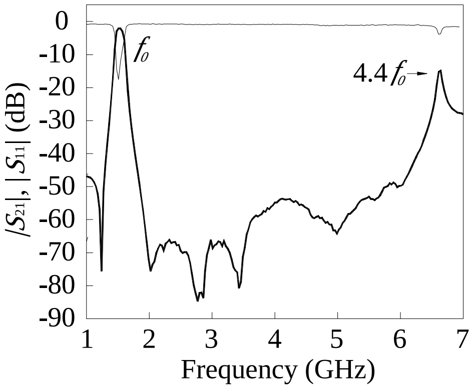

Fig.9 Measured results for a third-order Chebyshev SIR filter in Fig.8.