Studies on Synthesis Design of Ultra-Wideband Parallel-Coupled Line Bandpass Filters with Chebyshev Responses

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***Abstract* — In this paper, synthesis design of a class of ultra-wideband parallel-coupled line bandpass filters with Chebyshev responses is presented. Through the exact synthesis approach with virtue to closed-form insertion loss function, characteristic impedances of each coupled and connecting line section are explicitly determined. Based on the obtained impedance values, the realizable range of filtering bandwidth is extensively investigated. Moreover, under the restriction in fabrication and material, physical dimensions of the coupled line section are discussed using the modified design formulas. Finally, a five-pole parallel-coupled line bandpass filter with a fractional bandwidth of 90.1% is designed, fabricated and measured to provide an experimental validation on the presented synthesis approach.**

***Index Terms* — Bandpass filters, Chebyshev response, coupled line, ultra-wideband filters.**

I. INTRODUCTION

In the past few decades, parallel-coupled microstrip line has been widely used in the design of microwave bandpass filters [1]-[3]. With the increasing demand of filtering blocks for ultra-wideband (UWB) communication systems, this kind of parallel-coupled line bandpass filters with wide operating passband have recently been developed to cover the preferred UWB masks [4]. Unlike the traditional parallel-coupled line filters using a single resonant mode, these proposed bandpass filters were constructed via enhancement of coupling strength of parallel-coupled line and excitation of first few resonant modes to form an expected wide passband.

Currently, there are two existing ways to design this kind of multimode-resonator-based bandpass filters [4]. The first way is to equally allocate first few resonant frequencies in the desired wide passband. Based on the simple transmission line theory, fundamental properties of the multimode resonator can be characterized and its multiple resonant frequencies can be properly adjusted to match the transmission poles of a Chebyshev passband [5]. So far, a variety of UWB bandpass filters with varied configurations of this resonator has been developed so as to meet various specified requirements, such as sharp roll-off slope, wide upper-stopband rejection and notch-bands in the UWB passband [4]. But, all of these methods are still executed based on the cut-and-try approach relying on commercialized full-wave simulators.

Another way is to perform the exact synthesis approach [6]-[10], aiming to analytically determine the characteristic impedances of each coupled and connecting line section under the specified transfer or insertion loss function. However, as the desired bandwidth is larger, all the element parameters are no longer constant with respect to frequency. Therefore, the realized bandwidth is always smaller than the desired wide bandwidth [7]-[9], due to unexpected fringing effect, open-ended capacitance and discontinuities' effects. To circumvent this issue, one of solutions is to optimize each coupled line using the full-wave simulator [10]. The physical dimensions can be determined at the stage-level after optimization, but it is still time-consuming to achieve accurate impedance values. An alternate solution is to modify the design formulas [9], where the bandwidth decrement can be compensated at the pre-designed synthesis level.

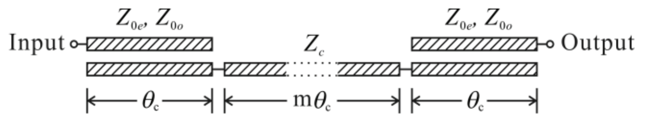

Fig. 1. Ultra-wideband parallel-coupled line filter using single line resonator. (m = 0: three transmission poles; m = 1: four transmission poles; m = 2: five transmission poles.)

In this paper, a class of ultra-wideband parallel-coupled line bandpass filters is synthesized to exactly achieve and exhibit Chebyshev-function responses. By choosing suitable impedances of coupled line and length of connecting line, parallel-coupled bandpass filters with single line resonator can be designed to produce three, four, or five in-band transmission poles. According to the required in-band ripple-level and bandwidth, characteristic impedances of each coupled and connecting lines are explicitly calculated on a basis of synthesis approach. To compensate for bandwidth decrement, the design formulas are further revised with the bandwidth more than 60%. Thus, physical dimensions of the coupled line can be easily obtained from the 2-D ADS-LineCalc [11]. For the limits in material and fabrication, the realizable bandwidths are extensively discussed. Finally, a UWB bandpass filter with five transmission poles is designed and fabricated for experimental verification of the proposed synthesis approach.

II. SYNTHESIS DESIGN OF ULTRA-WIDEBAND FILTERS

The ultra-wideband parallel-coupled line bandpass filter prototype circuit with single line resonator is shown in Fig. 1. It consists of two coupled line sections with even- and odd-mode characteristic impedances Z_{0e} and Z_{0o}, connected by a single transmission line section having a relative low impedance Z_c. The electrical length θ_c is defined at low cutoff frequency. By multiplying the individual *ABCD* matrices of each section, the insertion loss function of entire network can be derived from the overall *ABCD* matrix. Similar to the direct synthesis approach in [7], [8], the rational polynomial

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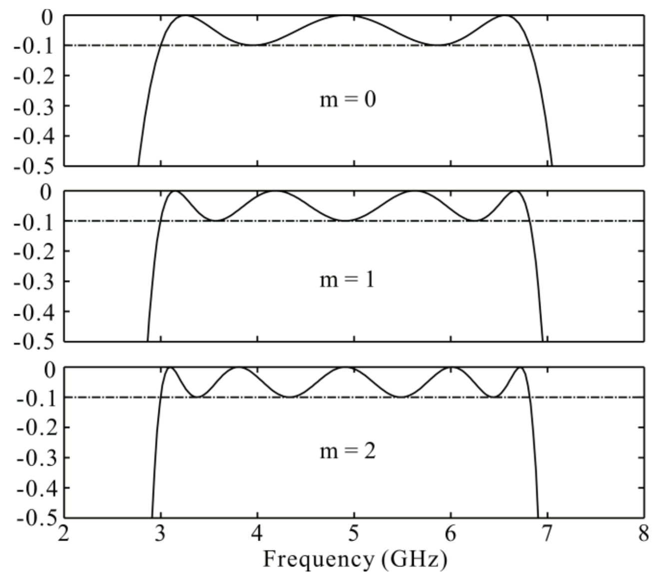


Fig. 2. Frequency responses of ultra-wideband parallel-coupled line filter with a single line resonator. (m = 0: Z_{0e} = 158.9 Ω, Z_{0o} = 30.2 Ω; m = 1: Z_{0e} = 155.6 Ω, Z_{0o} = 43.4 Ω, Z_c = 54.1 Ω; m = 2: Z_{0e} = 153.4 Ω, Z_{0o} = 51.2 Ω, Z_c = 29.6 Ω)

form of the targeted insertion loss function for Chebyshev filter can be derived as follows,

$$\frac{P_0}{P_L} = 1 + \varepsilon^2 \cos^2 (n\phi + q\xi) \tag{1a}$$

and

$$\cos(n\phi + q\xi) = T_n(x)T_q(y) - U_n(x)U_q(y) \tag{1b}$$

$$x = \cos\phi = \frac{\cos\theta}{\cos\theta_c} \tag{1c}$$

$$y = \cos\xi = \frac{\tan\theta_c}{\tan\theta} \tag{1d}$$

where P_0 is the available power from the source, P_L is the power delivered to the load, and ε is the specified equal-ripple constant in the passband, $T_n(x)$ and $U_n(x)$ are the Chebyshev polynomial functions of the first and second kinds of degree n, respectively.

As a result, the characteristic impedances of filter topology in Fig. 1 can be explicitly determined if the specifications are defined. If the electrical length θ_c is given 55° at 3.0 GHz, the frequency responses with 0.1 dB ripple-level can be obtained and they are plotted in Fig. 2. Different from the traditional parallel-coupled line bandpass filter using single resonant mode, two poles are in addition produced if a single line resonator is formed with m = 0. If the other single line section is connected between the coupled line sections, another one or two transmission poles can be achieved and this case is shown in Fig. 2 with m = 1 or m = 2, respectively.

For each individual section of coupled line, the extra large or small impedance values cannot be achieved in reality. So, the realizable bandwidth of a parallel-coupled line bandpass filter is always restricted in practical implementation. Fig. 3

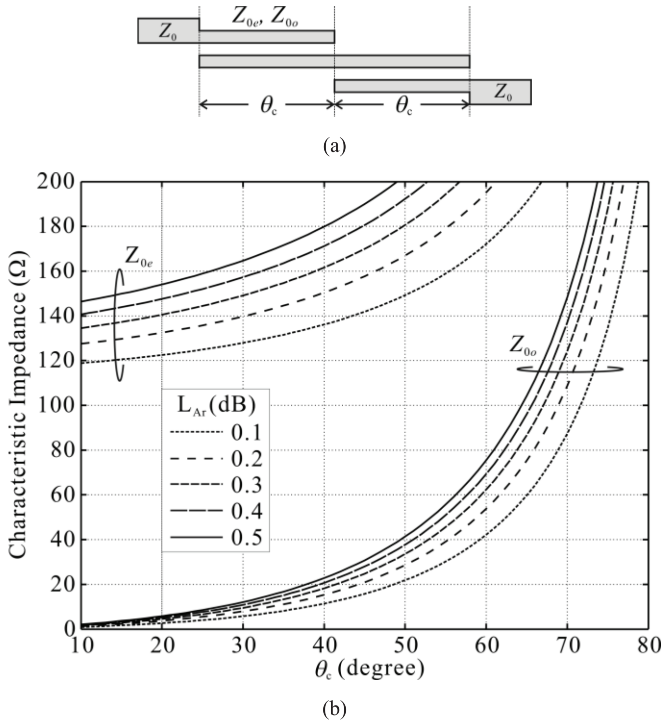
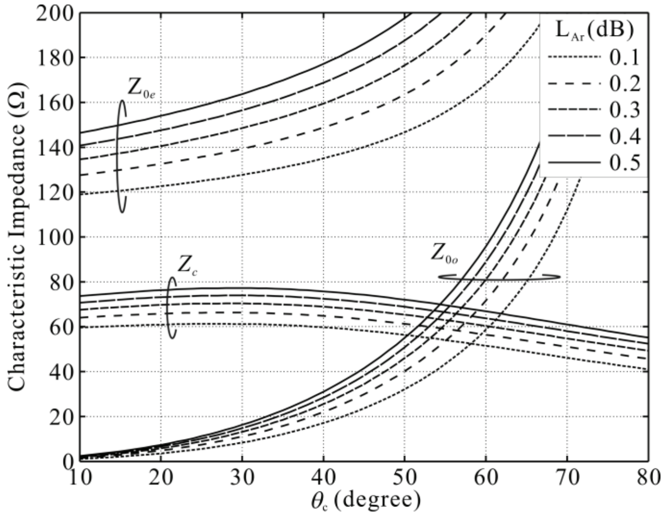


Fig. 3. (a) Schematic of the ultra-wideband parallel-coupled line filter without connecting line (m = 0). (b) Required even- and odd-mode characteristic impedances of coupled lines versus electrical length θ_c.

shows the schematic of the filter without connecting line and its required even- and odd-mode characteristic impedances for varied electrical length θ_c. Here, the fractional bandwidth of such a passband can be given by Δ=2-4θ_c/π. It means that the smaller θ_c, the larger fraction bandwidth. As θ_c increases from 10° to 80°, both even- and odd-mode characteristic impedances are increased steadily at the beginning and then go up at an exponential rate. Generally speaking, the odd-mode impedance less than 30 Ω requires the coupling gap of coupled line to be extremely small, while its even-mode one higher than 180 Ω needs to have a very narrow strip width. On the other hand, the odd-mode impedance higher than 80 Ω requires a relative wide slot. But, it unfortunately limits the even-mode impedance values. According to the calculated impedance values, the realizable range of θ_c with 0.1 dB ripple-level is 55° ~ 62°, where the corresponding fractional bandwidth Δ is 62.2% ~ 77.8%. When the desired ripple-level increases from 0.1 to 0.5 dB, the bandwidth Δ could be larger, but the dynamic range becomes smaller and smaller.

To realize a wide passband with good in-band behavior, more transmission poles need to be produced by increasing the number of resonators as a traditional approach. The work in [4] exhibits that the additional transmission poles can also be brought out by exciting and employing the first few resonant modes of a single stepped-impedance resonator. The relevant responses are illustrated in Fig. 2. For the two cases with m = 1 and m = 2 in Fig. 1, the calculated characteristic impedances are shown in Fig. 4. As predicted, the realizable range of θ_c with 0.1 dB ripple-level and m = 1 is enlarged to



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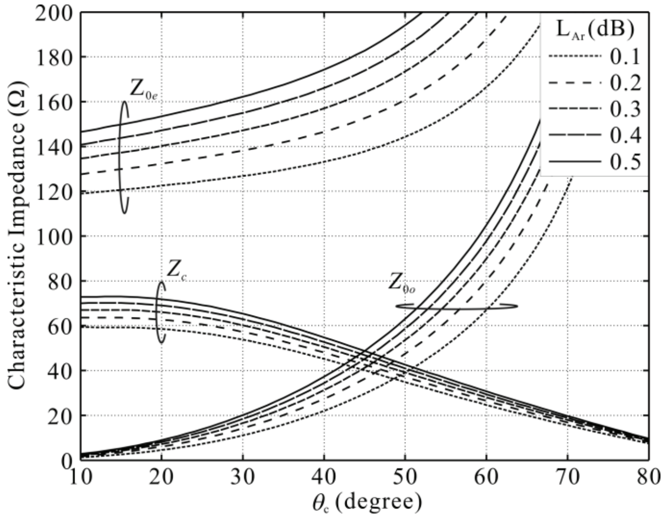

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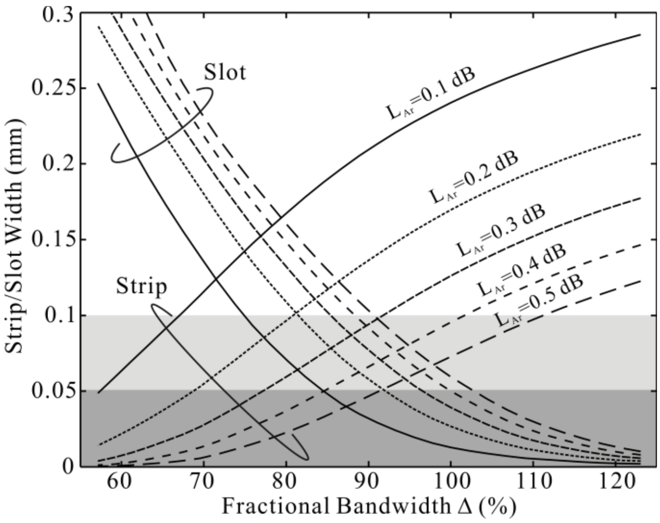
Fig. 4. (a) Required characteristic impedances for the filter with connecting line (m = 1). (b) Required characteristic impedances for the filter with connecting line (m = 2).



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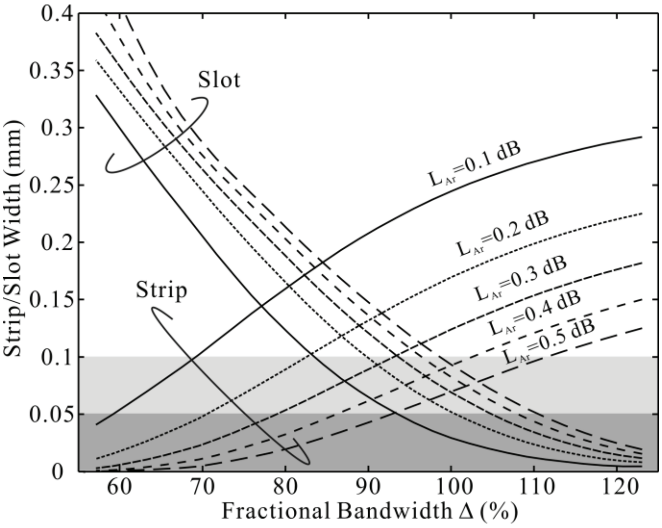


(b)

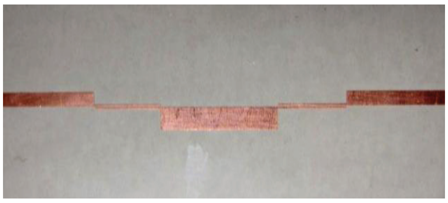
Fig. 5. Physical dimensions of coupled line section for specified substrate. (a) With m = 1. (b) With m = 2.

49° ~ 63°, where the corresponding Δ is 60.0% ~ 91.1%. For the case with m = 2, this range is enlarged to 45.2° ~ 63.1°, which implies 59.8% ~ 99.6% fractional bandwidth with 0.1 dB ripple-level. At the same time, characteristic impedances of connecting line are also shown in Fig. 4, where all of them are realizable within the above discussed bandwidth range. In particular, for the filter with 0.5 dB ripple-level and m = 2, the realizable fractional bandwidth could be 103.3% ~ 119.3% (θ_c = 36.3~ 43.5°), which can cover the whole UWB passband with the fractional bandwidth of 109.5% [4].

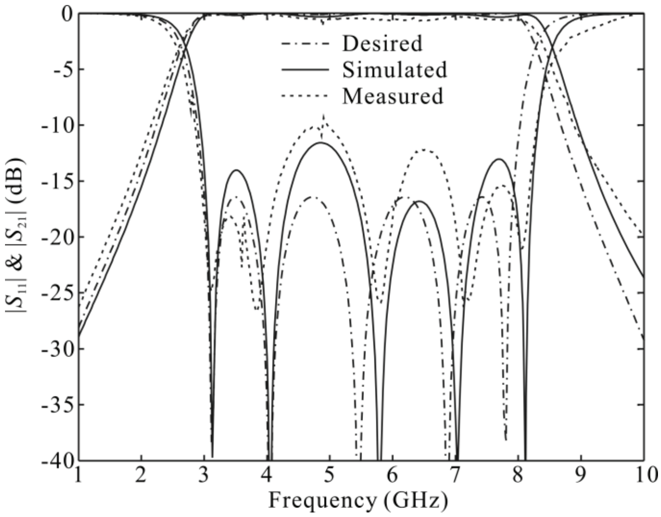
On the other hand, a longer connecting line can result in a wider realizable passband [8]. But, the required characteristic impedance for the center part of connecting line becomes smaller and thus increases the width of metal strip with larger radiation loss. Another way in bandwidth enhancement is to enlarge the realizable impedance range of the coupled line section. In this case, other transmission line structures could be employed in this filter design, such as coplanar-waveguide, suspended stripline, interdigital coupled line, and broadside coupled line [4]. To accurately predict electrical performance of the filters under study, the characteristic impedances derived from ideal transmission line theory can be utilized to determine the initial dimensions for final optimization design of these parallel-coupled line filters.

III. Realization, Implementation and Verification

In this section, the above-discussed parallel-coupled line bandpass filters are designed on the RT/duroid 6010 substrate with the thickness of 1.27 *mm* and dielectric constant of 10.8. As discussed in Section I, the synthesized bandwidth seems to be always smaller than the desired one because of the unexpected frequency dispersion and parasitic effects. To



(a)



(b)

Fig. 6. (a) Photograph of fabricated five-pole bandpass filter using single line resonator (m = 2). (b) Desired, simulated and measured frequency responses of fabricated filter.

compensate this bandwidth decrement, electrical length θ_c in (1) can be simply replaced by,

$$\theta_m = \theta_c\left(1 - \frac{\Delta}{10}\right) \qquad (2)$$

Based on the calculated characteristic impedances in Fig. 4, physical dimensions of coupled line and connecting line can be easily obtained from the 2-D ADS-LineCalc software [11].

Fig. 5 shows the obtained strip/slot widths of the required coupled lines using the revised formulas (1) and (2). As the desired ripple-level is decreased, the required strip width increases, thus leading to narrow its corresponding slot width. If the fabrication procedure restricts a minimum strip/slot width of 0.1 *mm*, the realizable bandwidth can achieve 67.1% ~ 74.9% for the filters with m = 1 and ripple-level = 0.1 dB, while 69.2% ~ 83.5% for the filters with m = 2 and ripple-level = 0.1 dB. If the fabrication restriction is improved to a minimum width of 0.05 *mm*, these realizable bandwidths could be significantly enlarged, as shown in shadow areas of Fig. 5. As an example, a five-pole filter with m = 2, ripple-level = 0.1 dB, and Δ = 90.1% is designed and fabricated. The photograph and frequency responses of the fabricated filter are shown in Fig. 6. The measured results show a good agreement with those obtained from simulation, and the measured bandwidth decrement is only about 2.5%, while the simulated one is within 2.1%.

VI. Conclusion

A class of ultra-wideband parallel-coupled line bandpass filters using single line resonator is analyzed and designed in this paper. Based on the exact synthesis procedure, the characteristic impedances of each coupled and single line sections are analytically determined under the given specifications. The realizable fractional bandwidth for this kind of filters is comprehensively investigated. Under the modified design formulas, all the physical dimensions are calculated in a straightforward way. A design example with a fractional bandwidth of 90.1% is given and its relevant filter is fabricated for experimental verification of the presented synthesis approach.

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