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A Miniaturized Bandpass Filter with Low Passband Insertion Loss and High Harmonic Suppression in Ultra-wide Stopband*

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Abstract — This paper presents a novel 2.4GHz Chebyshev bandpass filter that exhibits low insertion loss in the passband and high harmonic suppression in ultra-wide stopband. Asymmetric compact microstrip resonant cells combined with a shunt open-circuited microstrip line are employed as admittance inverters instead of the traditional quarter-wavelength lines to suppress the second, third and fourth harmonics in the upper bands. Folded lines are used to realize the half-wavelength shunt open-circuited stubs to achieve a size reduction and performance improvement. By introducing a new optimization strategy, the filter can be efficiently optimized by separately optimizing the resonant cells and folded lines. Measured results show very good performance with a low insertion loss of 0.69dB and return loss of 30.5dB at the center frequency with 0.01dB equal-ripple bandwidth of 5%. The ultra-wide stopband is from 3.37GHz to 9.88GHz, where harmonics up to the fourth order are highly suppressed.

Key words — Miniaturized filter, Low insertion loss, High harmonic suppression, Asymmetric compact microstrip resonant cell, Folded line, Optimization design.

I. Introduction

Microwave bandpass filters of high performance are essential components in modern wireless communication systems. In addition to the cost, reliability and size, their electrical performances, such as out-of-band rejection and in-band transmission loss, must also be considered. However, many planar bandpass filters implemented using half-wavelength or quarter-wavelength resonators inherently have harmonic spurious frequencies at the multiples of their center frequencies. This is undesirable for sensitive receivers because a wider upper stopband is necessary to reject out-of-band signals coming into the channel. Several approaches to suppressing spurious harmonics were proposed[1−10]. However, almost all of these techniques do not provide low insertion loss, wide stopband, and compact size simultaneously. In Refs.[1, 2], the concept of equalizing the phase velocities of eignemodes was proposed to suppress the unwanted spurious passbands. However, these parallel coupled-line filters have the drawback of a large circuit size and require a long tuning process to achieve multi-harmonic suppression. In Ref.[3], Defected ground structures (DGS) and spur-lines were employed to suppress harmonics and the filter exhibits low insertion loss and wide rejection band. But one common disadvantage for filters having a pattern etched in the ground plane is that the whole structure must be suspended far from the ground conductor and are not convenient to be integrated with other components. Furthermore, the size of the filter in Ref.[3] is also not very compact. Other filters employing cross-coupled resonators, discriminating coupling, Stepped-impedance resonator (SIR) and other techniques, which have wide stopband, usually exhibit high insertion loss in their passbands[4−10].

In this paper, a novel miniaturized bandpass filter with low passband insertion loss and high harmonic suppression in ultra-wide stopband is proposed. Asymmetric compact microstrip resonant cells combined with a shunt open-circuited microstrip line at the center of the cell are used to suppress the out-of-band harmonics. Furthermore, non-uniform folded lines are proposed to replace the conventional shunt open-circuited stubs for further size reduction. The proposed filter exhibits low insertion loss in the passband, high rejection in the wide stopband, and a very compact size.

The proposed filter, consisting of three asymmetric compact microstrip resonant cells and four non-uniform folded lines, has many critical parameters for optimization. It is therefore very time-consuming to optimize its performance both in the passband and in the stopband by performing the full-wave simulation of the entire filter. To speed up the design process and quickly obtain optimized performance, a new optimization strategy is presented in this paper. First, the input impedance Z_{in} of the folded line is represented with a piecewise function. Then asymmetric compact microstrip resonant cells and folded lines are treated as separated components in the circuit diagram of the filter. A very efficient optimization is then performed for the filter's circuit diagram. After achieving the optimized Z_{in} meeting the specifications of the

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filter, we can finally adjust the parameters of the folded line to fit this impedance's frequency response. The proposed filter achieves excellent performance with a compact size.

II. Description of the Filter Configuration

In our previous work[11], a symmetrical Chebyshev bandpass filter was implemented and its circuit diagram is shown in Fig.1. Z_A, Z_B and Z_{OC} are characteristic impedances of the transmission line sections in Fig.1 and are expressed as follows

$$Z_A = \frac{1}{Y_0 J_{01}} \tag{1}$$

$$Z_B = \frac{1}{Y_0^2 J_{01}^2}\sqrt{\frac{g_0}{g_3}} \tag{2}$$

$$Z_{OC} = \frac{\pi FBW}{2g_1 Y_0 J_{01}^2} \tag{3}$$

where g_0, g_1, g_2, g_3 are the normalized element values in the low-pass prototype, FBW and ω_0 are fractional bandwidth and the center angular frequency. Y_0 is the port admittance. J_{01} is the admittance inverter, and the choice of its value may have certain freedom according to the fabrication tolerance.

As the filter is based on Dual-behavior resonators (DBRs)[12,13] and it is a direct coupled-resonator filter, it has higher Q factor and shows lower insertion loss than other kinds of filters. This filter exhibits good performance in the passband and has two transmission zeros close to the passband for sharp skirts[11]. However, like other filters implemented with $\lambda_g/2$ resonators, the filter has inherent harmonics. Furthermore, the filter exhibits a large size, which is not suitable for compact system requirements. Based on the filter configuration in Fig.1, we propose a compact design with low insertion loss in the passband as well as high out-of-band rejection over a very wide frequency band. The proposed 2.4GHz Chebyshev bandpass filter with 0.01dB equal-ripple bandwidth of 5% is shown in Fig.2.

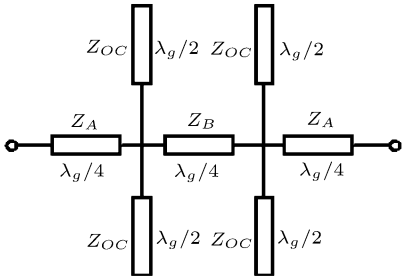

Fig. 1. Configuration of the symmetrical Chebyshev bandpass filter

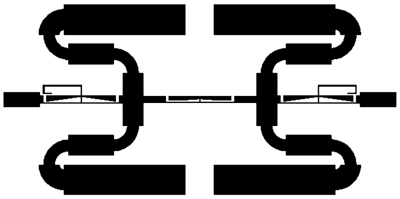

Fig. 2. Configuration of the proposed compact filter of high performance

III. Design of the Proposed Filter

1. Asymmetric compact microstrip resonant cell

To prevent the out-of-band signals from coming into sensitive receivers, an asymmetric compact microstrip resonant cell (cell I) with an open shunt microstrip line at the center of the cell, is employed as the $\lambda_g/4$ admittance inverter. It has characteristic impedance of Z_A. Fig.3 illustrates the top view of this structure. It is known that the asymmetric compact microstrip resonant cell is more compact in size than the symmetric one[14]. However, a conventional asymmetric compact microstrip resonant cell cannot suppress both the second and third harmonics. Therefore, an open-circuited microstrip stub at the center of the cell is proposed and it contributes to another stopband to suppress the second spurious harmonic, as shown in Fig.3. This additional shunt open-circuited stub can be regarded as a $\lambda_g/4$ resonator.

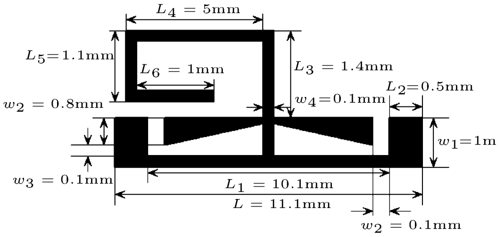

Fig. 3. Layout of the proposed asymmetric compact microstrip resonant cell I

Parametric analysis and optimization using full-wave simulators are both conducted to design the novel asymmetric compact microstrip resonant cell. By adjusting the length of the compact resonant cell L_1 and the length of the shunt open-circuited stub ($L_3+L_4+L_5+L_6$) simultaneously, two different stopbands can be obtained. The parameters L_1, W_2, W_3, W_4 and the total length of ($L_3+L_4+L_5+L_6$) are the major variables affecting the locations of three transmission zeros and the transmission pole. The general design principles of these parameters can be obtained after a series of parameter sweeping and are used to guide the design. The final dimensions of the structure are given in Fig.3 and simulated S-parameters of the structure are illustrated in Fig.4. It can be seen that the rejections at the three transmission zeros, 5GHz, 6.58GHz and 7.35GHz, are 39.9dB, 23.3dB, and 21.5dB, respectively. The proposed structure has a wide stopband up to the third harmonic and has low insertion loss of less than 0.1dB at the center frequency 2.4GHz.

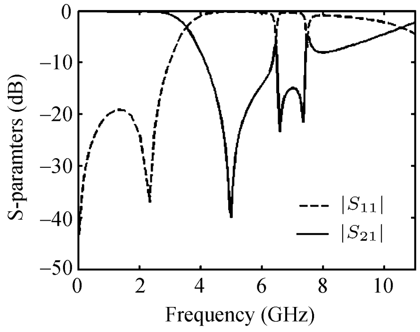

Fig. 4. S-parameters of asymmetric compact microstrip resonant cell I

Meanwhile, the $\lambda_g/4$ microstrip line, which has a characteristic impedance of Z_B, can also be replaced by another asymmetric compact microstrip resonant cell II, shown in Fig.5, for higher-order harmonic suppression and further size reduction. By employing the three asymmetric compact microstrip resonant cells, the longitudinal dimension of the filter is reduced by 21%, compared with the conventional filter prototype in Fig. 1 and the filter exhibits an ultra wide stopband up to the fourth harmonic.

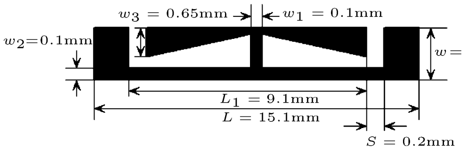

Fig. 5. Configuration of asymmetric compact microstrip resonant cell II

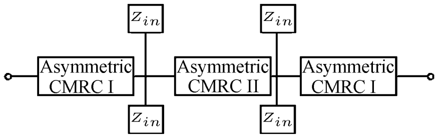

Fig. 6. The block diagram of the proposed filter, where CMRC refers to compact microstrip resonant cell

2. Folded lines

In the optimization processIn the previous section, the longitudinal size of the Chebyshev bandpass filter is greatly reduced by employing asymmetric compact microstrip resonant cells. In this section, we can further reduce its transverse size by replacing the conventional shunt open-circuited stubs with folded lines. In order to achieve good performance both in the passband and in the upper stopband, non-uniform folded lines are proposed. After this replacement, the filter needs to be optimized. However, the optimization of the entire structure using full-wave simulators is very time consuming because it has many variables. In our design strategy, we only optimize the parameters of the folded line by using the impedance loaded method, which is similar to the modular approach for the design of microstrip array antennas[15,16]. According to Eqs.(1) to (3), the design parameters Z_A, Z_B of the admittance inverters are only determined by the normalized elements of the low-pass prototype. Whereas, the characteristic impedance, Z_{OC}, of the shunt open-circuited stub is dependent upon the bandwidth FBW, which is further related to the Q factor of the filter. It is shown that the shunt folded line in the optimization is critical. As there is no strong coupling between the asymmetric compact microstrip resonant cells and the folded lines in the filter, if the three asymmetric compact microstrip resonant cells are fixed as designed in section A, the only thing left is to optimize the folded lines.

The proposed filter can be represented as the block diagram shown in Fig.6. che blok diagramructure ing CMRC. n the filter optimization is very important. In the block diagram, asymmetric compact microstrip resonant cell I and II are designed in the previous subsection. Their S-parameters are extracted from full-wave electromagnetic (EM) simulations. They are used as separated components in the block diagram. The shunt open-circuited folded line is regarded as a component having an input impedance of Z_{in}, which is basically a load to the filter. We consider an equivalent transmission line as the surrogate of the shunt folded line. Then the input impedance Z_{in} of the shunt folded line at the load can be obtained by

$$Z_{in} = Z_0 \frac{Z_l + jZ_0\tan\theta}{Z_0 + jZ_l\tan\theta} \tag{4}$$

$$\theta = k^* f + b \tag{5}$$

where Z_l is the loaded impedance. For an open-circuited stub of an ideal lossless transmission line, the load impedance is assumed to be infinite. However, for a practical design, Z_l has a large value, but finite. Z_0 is the equivalent characteristic impedance and θ is the equivalent electric length of the folded line, which is determined by constants, k and b. f is the operating frequency. The equivalent electric length of the folded line is half a wavelength at the center frequency.

If the folded line is uniform, Eqs.(4) and (5) can represent Z_{in} very well. And the only thing is to determine the practical length of the folded line and the placement of its bends to achieve a good size reduction. However, the uniform folded line will degrade the in-band transmission losses and size reduction is not enough. Based on the above consideration, the folded line proposed in this paper is non-uniform, and Eqs.(4) and (5) should be modified as follows

$$Z_{in} = \begin{cases} Z_0 \dfrac{Z_{l1} + jZ_0\tan(k_1 f + b_1)}{Z_0 + jZ_{l1}\tan(k_1 f + b_1)}, & f \le f_d \\ Z_0 \dfrac{Z_{l2} + jZ_0\tan(k_2 f + b_2)}{Z_0 + jZ_{l2}\tan(k_2 f + b_2)}, & f > f_d \end{cases} \tag{6}$$

where f_d is the starting point of the stopband. We use the subscript 1 or 2 on the related parameters to distinguish the frequencies that are lower or higher than f_d, respectively.

Using Eq.(6), different values of k and b can be determined for given requirements. When $k_1 = 72.22$, $k_2 = 77$, $b_1 = b_2 = 0$, $Z_{l1} = 1000000$ and $Z_{l2} = 200$, the optimized frequency response of the filter is obtained and shown in Fig.7. It shows a very good performance over a wide frequency range. Meanwhile, once the filter frequency response is optimized, the real and imaginary parts of Z_{in} can be obtained and shown in Fig.8.

The next step is to find an appropriate folded line structure to realize the same frequency response of Z_{in}. After studying

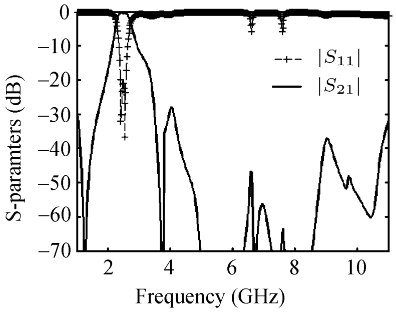

Fig. 7. Optimized S-parameters of the filter using the block diagram in Fig.6

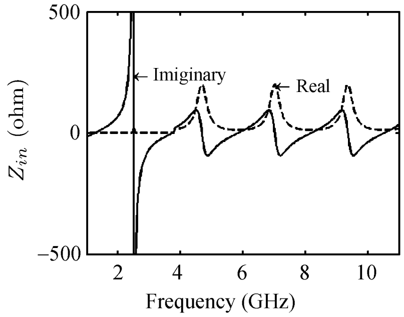

Fig. 8. The real and imaginary parts of Z_{in} of the folded line

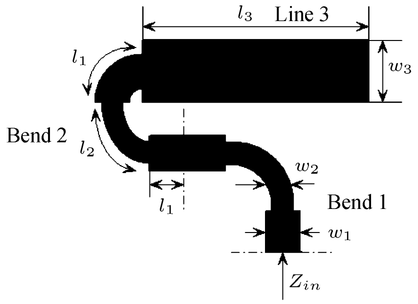

Fig. 9. Configuration of the folded line used in the filter

several structures, we find that the structure in Fig.9 is a good candidate. It is divided into three sections. They are bend 1, bend 2 and line 3. Bend 1 and bend 2 are the same non-uniform bends with different widths. The reference planes of the two bends are indicated by the dash and dot lines. The characteristic impedance of the conventional shunt open-circuited stub in the filter prototype is $Z_{OC} = 39.37\Omega$ with a width of $w = 2.72$mm. When designing the folded line, we can fix w_1 to the value $w_1 = w = 2.72$mm, then the only physical parameter of the bend to be determined is w_2. And if the width w_3 of line 3 is wider than the fixed value $w = 2.72$mm, the physical length of the folded line can be further reduced, similar to a stepped-impedance resonator. Therefore, w_3 can be another parameter to be optimized. The optimization criteria we apply are to have Z_{in} approaching the result obtained by Eq.(6) and to occupy a small footprint as possible. It should be pointed out that the structure must have no strong coupling among its own bends, lines, and with other parts of the filter. It is also known that increasing the number of variables provides more freedom that may result in further improvement in the filter performance. The final parameters of the proposed folded line in Fig.9 are $l_1 = 3$mm, $l_3 = 16.2$mm, $w_1 = 2.72$mm, $w_2 = 1.5$mm, $w_3 = 4$mm, and the bends are all of 90 degrees. Fig.10 presents the frequency response of Z_{in} obtained using Eq.(6) and ADS simulation. They are in good agreement for the resonant frequencies, but exhibit some differences at the amplitude peaks, which do not affect the frequency response of the entire filter. Simulated results of the proposed filter in Fig.2 by ADS and the circuit diagram in Fig.6 by circuit simulator are both presented in Fig.11. They are also in good agreement over a wide frequency range. It is clear that our folded line is a very good replacement of the original open-circuit stub and the proposed impedance optimization strategy is very effective. In Fig.11, there is a slight hump at 3.2GHz, which is caused by asymmetric compact microstrip resonant cell I. It is found that this hump could be suppressed by adjusting the parameters of cell I, while this may degrade the overall performance of the filter at the same time. Since the slight hump is quite minor and does not pose application difficulty, we do not attempt to eliminate it when optimizing the filter's overall performance.

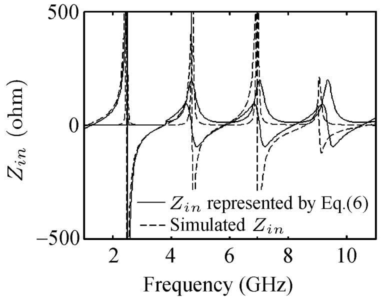

Fig. 10. The frequency response of Z_{in} represented by Eq.(6) and EM simulated results

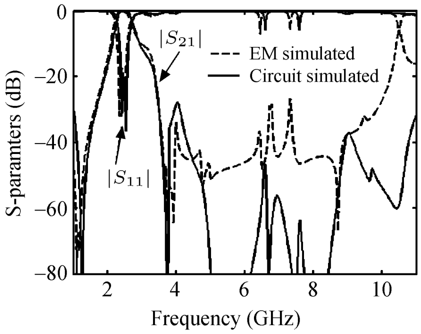

Fig. 11. Circuit simulated and EM simulated results of the proposed filter

Finally, it should be mentioned that the optimization strategy proposed in this paper is very efficient, compared to the full-wave optimization of the entire filter. It is observed that the conventional optimization of the entire filter using full-wave simulation is almost impossible because the CPU time for one simulation is 20h50m25s on a computer with Intel (R) Core (TM) 2 Duo CPU E7400@2.8GHz and 2.00GB memory. However, for our proposed strategy, it only needs 28m43s for one iteration of adjusting the folded line geometries.

IV. Measured Results

The proposed filter has been fabricated by using Rogers 4003 substrate with $\varepsilon_r = 3.55$, $\tan\delta = 0.0027$, and a thickness of 0.813mm, as shown in Fig.12. Our design reduces the total size of the filter prototype in Ref.[11] by 79.3%. Measured and EM simulated S-parameters of the filter are shown in Fig.13 and they are in good agreement. It is shown that the filter exhibits a low insertion loss of 0.69dB and return loss of 30.5dB at the center frequency, with two transmission zeroes at 1.19GHz and 3.78GHz, respectively. In the lower band, the rejection better than 20dB is shown from 0.78GHz to 1.86GHz. Furthermore, an ultra-wide stopband from 3.37GHz to 9.88GHz (20dB) is obtained. The rejection level from 3.5GHz to 8.8GHz is better than 30dB, and the highest rejection is better than 70dB. The second, third and fourth spurious harmonics are effectively suppressed. However, like many other filters designed to achieve wide stopband$^{[17-20]}$, both simulated and measured results of the proposed filter show that there are two spikes at 6.44 and 7.39GHz with 4.95dB and 4.82dB in the S_{11} curve. These two spikes are caused by the radiation loss of asymmetric compact resonant cell I. However, as can be seen in Fig.13, the two spikes do not affect the high rejection (still better than 30dB) at these two frequency points. To validate this, we also measure the performance of the filter when it is enclosed in a metallic box and no change in the wide-band rejection is observed.

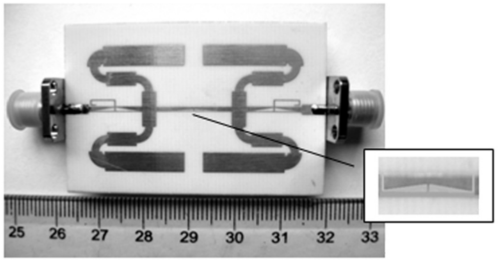

Fig. 12. Photo of our fabricated filter

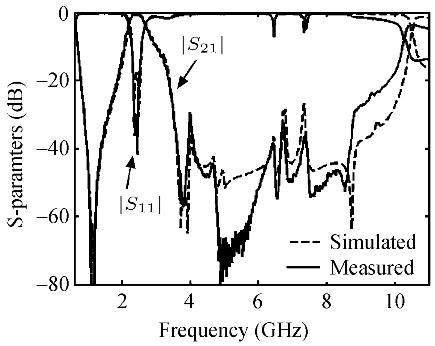

Fig. 13. Measured and simulated results of the fabricated filter

V. Conclusion

This paper has described a miniaturized Chebyshev bandpass filter with good passband performance and an ultra-wide upper stopband. The asymmetric compact microstrip resonant cell combined with an open shunt microstrip stub at the center of the cell has been proposed. Its effectiveness of suppressing higher-order harmonics makes it suitable for applications where the out-of-band specification is critical. Furthermore, the novel non-uniform folded line structures further reduce the filter size and retain good performance both in the passband and stopband. The proposed optimization strategy including the impedance loaded method is very effective to achieve the design goal. This method can also be introduced in other filter designs consisting of stubs or separated parts with no strong coupling.

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