Compact Differential Parallel Coupled Line Band-pass Filter with Open Stub

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Abstract ─ A novel differential narrow-band band-pass filter design method is presented based on the parallel coupled line and the open stub. Based on the transmission line model, the proposed differential band-pass filter is analyzed by using even- and odd-mode analytical method. The central resonant frequency of the proposed differential filter is given. The relations between the filtering performance and the impedance parameters are discussed. A compact differential band-pass filter is designed based on the resonant conditions. The common mode signal is well suppressed. The differential band-pass filter is simulated, fabricated and measured. The measured results and the simulated results are basically consistent.

Index Terms─ Differential band-pass filter, even- and odd-mode analysis, microwave components, open stub, parallel coupled line.

I. INTRODUCTION

Due to its insensitivity to fabrication tolerance and simple synthesis procedures, the parallel coupled line structure is finding wide use in many band-pass filters [1, 2]. The differential filters can suppress the crosstalk, environmental noise, and interference between different elements, so they are widely used in microwave systems. Wang proposed an ultra-wideband differential band-pass filter based on a self-coupled ring resonator. The differential-mode circuit is composed of the meandered fully coupled parallel microstrip lines and short end fully coupled parallel microstrip lines in shunt [3]. Wang proposed a differential broadband filter, which is composed of four quarter-wavelength coupled lines and four quarter-wavelength microstrip lines [4]. By adding the quarter-wavelength microstrip lines, the filtering response has been improved. A differential narrow-band band-pass filter with the input and output capacitive feedings is presented. It is composed of the open end fully coupling parallel microstrip lines and short end fully coupling parallel microstrip lines in shunt [5]. Li presented a differential wide-band band-pass filter composed of a coupled fully wavelength loop [6].

The differential parallel coupled line filters which are the simple structures suffer from spurious responses at the multiples of operating frequency. To eliminate the spurious responses, especially for the second spurious responses, some methods have been proposed. Zhou proposed a novel differential band-pass filter based on the cascaded parallel coupled lines [7]. The spurious response at $2f_0$ moves to higher frequency. Based on the modified coupled feed lines and the coupled line stubs/the coupled line stub loaded resonators, the wideband balanced filters with high selectivity and common mode (CM) suppression are proposed and designed [8].The spurious response at $2f_0$ is suppressed.

In this paper, a differential narrow-band band-pass filter is proposed. The proposed differential band-pass filter is composed of the parallel coupled line and the open stub. Based on odd-even mode analytical method, the differential mode (DM) equivalent circuit is analyzed and discussed. The relations between the filtering response and the filter's parameters are discussed. The harmonic frequencies at the multiples of operating frequency are suppressed. At the same time, the common mode interference is well restrained. Comparing the simulation result with experimental result, it is found that they are basically consistent.

II. DIFFERENTIAL FILTER DESIGN

The schematic of the proposed differential parallel coupled line band-pass filter is shown in Fig. 1 (a). The proposed differential band-pass filter is composed of the parallel coupled line and the open stub. The filter's DM and CM equivalent circuits are derived in Figs. 1 (b) and (e), respectively. The filter's DM equivalent circuit is symmetric, so it can be studied through even- and odd-mode analytical method. Figures 1 (c) and (d) are the even mode half equivalent circuit and the odd mode half equivalent circuit of the filter's DM equivalent circuit.

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The electric lengths of the proposed differential band-pass filter are a_1, a_2 and a_3. The characteristic impedance of the open stub is Z_1. The odd mode impedance and the even mode impedance of the parallel coupled lines are Z_o and Z_e, respectively.

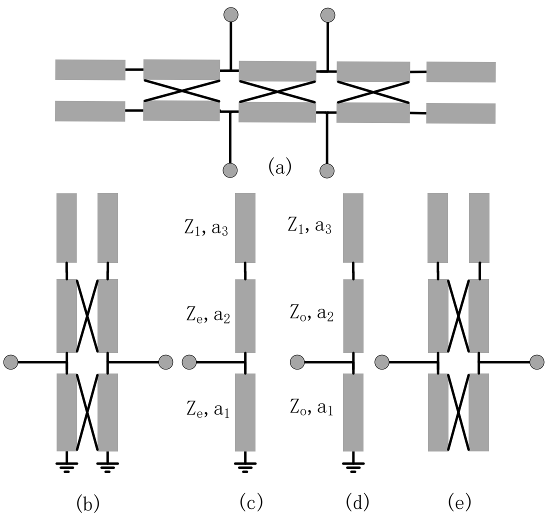

Fig. 1. Proposed differential band-pass filter. (a) Circuit, (b) DM circuit, (c) the even mode half equivalent circuit, (d) the odd mode half equivalent circuit, and (e) CM circuit.

A. Filter design equation

For simplicity, it is assumed that the even mode propagation is equal to the odd mode propagation ($\theta_e = \theta_o = \theta_0$). It is also assumed that the electric lengths are $a_1 = \theta$, $a_2 = 2\theta$, $a_3 = 2\theta$. The form of the even mode half equivalent circuit is the same as the odd mode half equivalent circuit, so the even mode input impedance expression is the same as the odd mode input impedance expression. The even (or odd) mode input impedance can be calculated by the formula (1). By enforcing $Z_{ine(o)} = \infty$, the solutions of $\tan\theta$ for the corresponding resonant frequencies can be obtained by using formula (2). The corresponding resonant frequencies include the central resonant frequency (θ_0), the even mode resonant frequency (θ_e) and the odd mode resonant frequency (θ_o). In order to realize the miniaturization of the filter, the smaller solution of *tanθ* can be calculated by using formula (3):

$$Z_{ine(o)} = \frac{jZ_e \tan\theta[Z_1 \tan^4\theta - (4Z_e + 2Z_1)\tan^2\theta + Z_1]}{(2Z_e + 3Z_1)\tan^4\theta - (6Z_e + 4Z_1)\tan^2\theta + Z_1}, \quad (1)$$

$$(2Z_e + 3Z_1)\tan^4\theta - (6Z_e + 4Z_1)\tan^2\theta + Z_1 = 0, \quad (2)$$

$$\tan\theta = \sqrt{\frac{3Z_e + 2Z_1 - \sqrt{9Z_e^2 + 10Z_eZ_1 + Z_1^2}}{2Z_e + 3Z_1}}. \quad (3)$$

Based on the impedance characteristics of the microstrip line, it is assumed that the range of the normalized Z_1 is from 1.6 to 1.8. It is also assumed that the range of θ is from 13.5° to 22.5°. Figure 2 shows the variation of the normalized $Z_{e(o)}$ against different normalized Z_1 and θ_0. When Z_1 is fixed, $Z_{e(o)}$ will decrease with the increase of θ. When θ is fixed, $Z_{e(o)}$ will increase with the increase of Z_1. Since Z_e is more than Z_o, $\theta_e < \theta_0 < \theta_o$ is obtained. If θ_e, θ_0 and θ_o are chosen, the impedance parameters can be obtained in Fig. 2. It is possible to realize the proposed band-pass filter based on the angle parameters and the impedance parameters.

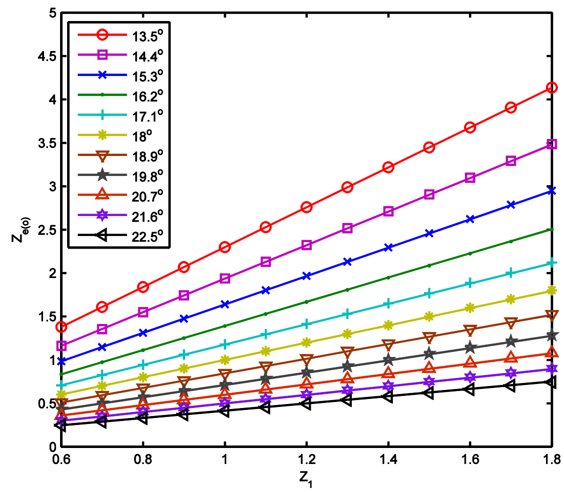

Fig. 2. Variation of the normalized Z_e (or Z_o) against different normalized Z_1 and θ.

B. Performance of the proposed differential filter

In order to study the DM filtering response of the proposed differential band-pass filter, the following three conditions are analyzed and discussed. The proposed differential band-pass filter against different Z_1 is analyzed when $\theta_0 = 18^o$, $\theta_e = 17.1^o$ and $\theta_o = 18.9^o$ are fixed. Table 1 gives three groups of the proposed differential band-pass filter's normalized impedance parameters when $\theta_0 = 18^o$, $\theta_e = 17.1^o$ and $\theta_o = 18.9^o$ are assumed. Based on the parameters in Table 1, the DM S-parameters of the proposed differential band-pass filter can be calculated by using formula (4) and (5) [9]:

$$S_{11dd} = S_{22dd} = \frac{Z_{ine}Z_{ino} - 1}{(Z_{ine} + 1)(Z_{ino} + 1)}, \quad (4)$$

$$S_{21dd} = S_{12dd} = \frac{Z_{ine} - Z_{ino}}{(Z_{ine} + 1)(Z_{ino} + 1)}. \quad (5)$$

The calculated DM S-parameters of the proposed differential band-pass filter with different Z_1 are shown in Fig. 3. With the decrease of Z_1, the DM filtering response has been improved in the pass-band. The DM performance will become worse in the pass-band when Z_1 decreases to a certain value.

Table 1: The differential band-pass filters' normalized impedance parameters ($\theta_0 = 18^o$, $\theta_e = 17.1^o$, $\theta_o = 18.9^o$)

	Z_1	Z_e	Z_o
Filter 1	1.1	1.30	0.93
Filter 2	1.3	1.53	1.10
Filter 3	1.5	1.77	1.27

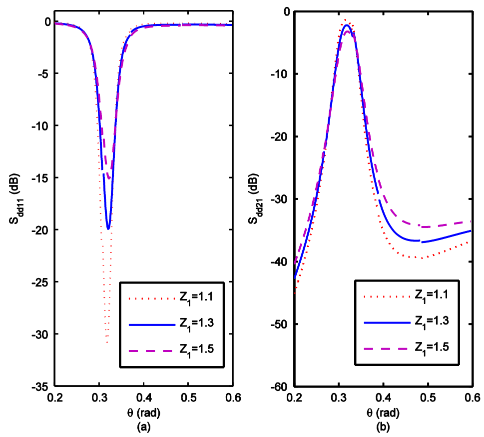

Fig. 3. Variation of (a) S_{dd11} and (b) S_{dd21} against different Z_1.

At the same time, the proposed differential band-pass filter against different $\theta_e - \theta_o$ is analyzed when Z_1 and θ_0 are fixed. Table 2 gives the angle parameters and the normalized impedance parameters of the proposed differential band-pass filter. Figure 4 shows the calculated DM S-parameters of the proposed differential band-pass filter with different $\theta_o - \theta_e$, 0.9°, 1.8° and 3.6°, respectively. When Z_1 and θ_0 are fixed, the DM performance of the proposed differential band-pass filter is improved with the increase of $\theta_o - \theta_e$. Similarly, the DM performance will be worse when $\theta_o - \theta_e$ increases to a certain value. When Z_1 and θ_0 are fixed, the location of the transmission zero remains the same.

When $(\theta_e - \theta_o)/\theta_0$ (fractional bandwidth) and Z_1 are fixed, the DM performance of the proposed differential band-pass filter against different θ_0 is discussed. Table 3 gives the angle parameters and the normalized impedance parameters. Figure 5 shows the calculated DM S-parameters of the proposed differential band-pass filter against different θ_0 . The calculated DM S-parameters of the proposed differential band-pass filter with different θ_0 are shown in Fig. 5. The DM performance of the proposed differential band-pass filter is improved with the increase of θ_0 . As before, the DM performance of the proposed differential band-pass filter becomes worse when θ_0 reaches to a certain value. The location of the transmission zero moves to low frequency with the increase of θ_0 .

Table 2: The differential band-pass filters' angle parameters and normalized impedance parameters ($Z_1 = 1.3$, $\theta_0 = 18^o$)

	θ_e (deg)	θ_o (deg)	Z_e	Z_o
Filter 4	17.55	18.45	1.41	1.20
Filter 2	17.1	18.9	1.53	1.10
Filter 5	16.2	19.8	1.81	0.93

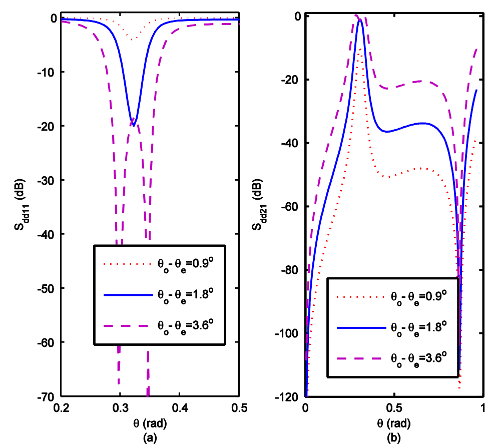

Fig. 4. Variation of (a) S_{dd11} and (b) S_{dd21} against different $\theta_e - \theta_o$.

When $(\theta_e - \theta_o)/\theta_0$ (fractional bandwidth) and Z_1 are fixed, the DM performance of the proposed differential band-pass filter against different θ_0 is discussed. Table 3 gives the angle parameters and the normalized impedance parameters. Figure 5 shows the calculated DM S-parameters of the proposed differential band-pass filter against different θ_0 . The calculated DM S-parameters of the proposed differential band-pass filter with different θ_0 are shown in Fig. 5. The DM performance of the proposed differential band-pass filter is improved with the increase of θ_0 . As before, the DM performance of the proposed differential band-pass filter becomes worse when θ_0 reaches to a certain value. The location of the transmission zero moves to low frequency with the increase of θ_0 .

Table 3: The differential band-pass filters' normalized impedance parameters and angle parameters ($Z_1 = 1.3$, $(\theta_e - \theta_o)/\theta_0 = 0.1$)

	θ_0 (deg)	θ_e (deg)	θ_o (deg)	Z_e	Z_o
Filter 6	16	15.2	16.8	2.17	1.62
Filter 2	18	17.1	18.9	1.53	1.10
Filter 7	20	19	21	1.08	0.74

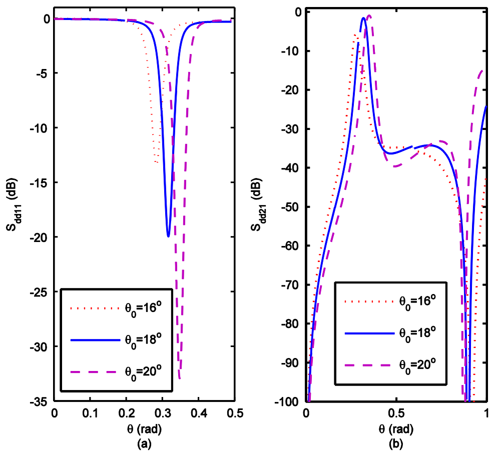

Fig. 5. Variation of (a) S_{dd11} and (b) S_{dd21} against different θ_0 .

III. SIMULATION AND MEASUREMENT

To verify the design theory, a differential band-pass filter is designed based on the angle parameters and the normalized impedance parameters of Filter 2 in Table 1. Figure 6 (a) shows the proposed differential band-pass filter's configuration. The open stubs are bent for filter's size reduction. The substrate with a relative dielectric constant of 2.2, thickness of 0.508 mm and loss tangent of 0.0009 is used. Based on the parameters in Table 1, the initial physical sizes of the proposed differential band-pass filters are obtained by ADS LineCalc tool. Considering the bends and open ends, the final physical sizes of Filter 2 are a=t=1 mm, b=10 mm, c=2 mm, d=8 mm, g=0.4 mm, w=1.55 mm. A differential band-pass filter is fabricated based on Rogers RT/duroid 5880 (tm) and shown in Fig. 6 (b).

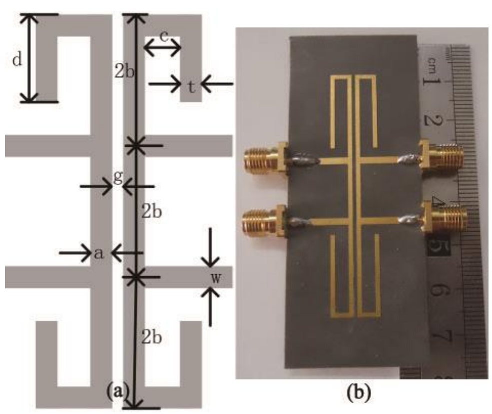

Fig. 6. (a) Configuration and (b) photograph of the proposed differential band-pass filter.

DM and CM S-parameters are simulated by HFSS 14.0 and measured by Agilent Technologies' 5230 A vector network analyzer, which are shown in Fig. 7. The measured results of Filter 2 in Fig. 7 show that the differential mode filtering performance is good. 3 dB bandwidth is 0.25 GHz which is from 1.04 GHz to 1.29 GHz. There are five transmission zeros, which are located at 0, 1.72 GHz, 3.45 GHz, 4.35 GHz and 6.25 GHz. A wide stop-band and good selectivity are obtained through the transmission zeros. The common mode suppression is good out of band. The simulated and measured results show a good agreement and validate the proposed theory. The tiny difference between the simulated results and the test results is due to the unexpected tolerance of fabrication, the substrate dielectric loss, and SMA connectors. The frequency differences between the calculated results and the measured results are derived from the effect of the open ends and the bends. The central frequency of the differential band-pass filter can be adjusted by the electric length θ. 3 dB bandwidth can be adjusted through the gap width g.

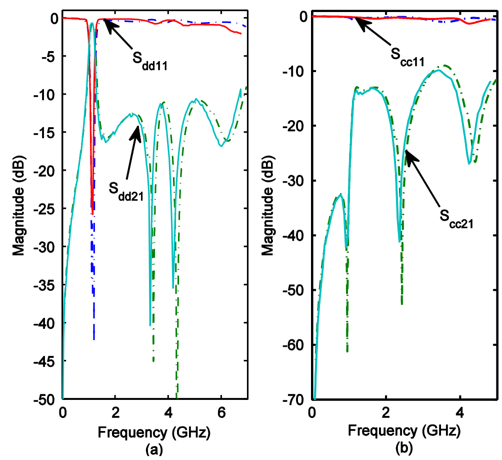

Fig. 7. Simulated and measured results of Filter 2: (a) DM response and (b) CM response (the solid line is the measured results, and the dotted line is the simulated results).

Table 4 shows the comparisons with the proposed differential parallel coupled line band-pass filter. As can be seen in Table 4, the size of the filter in Ref. [3] is small, but the harmonic suppression needs to be improved. In Ref. [4] and Ref. [5], the sizes of the filters are larger and the harmonic suppression also needs to be improved. The harmonic suppression of the filter in Ref. [7] is better, but the size of the filter is larger. In this paper, the proposed differential parallel coupled line filter has both good harmonic suppression and small size, which can realize the miniaturized wide-stop-band differential band-pass filter design. In addition, the structure of the proposed differential parallel coupled line band-pass filter is simple, so it is convenient for theoretical calculation and filter design.

Table 4: Comparisons with the proposed differential parallel coupled line band-pass filter

	The First Spurious Response (GHz)	Transmission Zeros	Out-band Rejection (dB)	Size (λ_g^2)
[3]	$2.5f_0$	2	>10	0.0300
[4]	$2.3f_0$	2	>10	0.4998
Filter 1 in [5]	$2.1f_0$	3	>18	0.1681
[7]	$> 2.7f_0$	5	>20	0.2000
This work	$> 6f_0$	5	>11	0.0139

IV. CONCLUSION

A differential band-pass filter based on the parallel coupled lines and the open stubs is proposed. The transmission line model of the differential band-pass filter is given. The design equations are obtained through even and odd analytical method. The relations between the parameters of the proposed differential filter and the filtering response are analyzed and discussed. The differential band-pass filter is designed, simulated, fabricated and measured. Comparing the simulation result with experimental result, it was found that they were basically consistent, which verifies the design theory. The proposed differential band-pass filter exhibits good DM performance and good CM suppression. Both the structure and the design process of the proposed differential filter are simple, so it can be widely used in microwave circuits.

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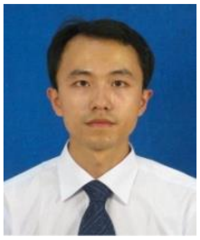

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