A Folded Coupled-Line Structure and its Application to Filter and Diplexer Design

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***Abstract* — In this paper, a folded coupled-line structure which can create a transmission zero is studied. A rough estimate for the frequency of this transmission zero is also given. A compact second-order filter with the folded coupled-line structures and a skew-symmetric (zero-degree) feed structure is designed. The improved shape factor and out-of-band response of this new filter are compared with those of a conventional second-order filter. Finally, this new filter topology is applied to the design of a diplexer.**

I. Introduction

A second-order planar filter is suitable for low-loss narrow-band applications, because the required circuit elements are few in number. However, there are some problems in such type of filters. For example, the steepness of the skirts near the passband is not very large because of the low-order frequency response. Besides, the out-of-band rejection degrades significantly due to the directly coupling structure. In order to solve these problems, a skew-symmetric (zero-degree) feed structure was proposed to create two transmission zeros near the passband, and hence to improve the shape factor and the rejection of unwanted signals [1]. Nevertheless, the stopband rejection at the higher frequencies far away from the transmission zero is still not deep enough.

In this paper, a folded coupled-line structure, which can create a transmission zero away from the passband is proposed to improve the out-of-band response. In order to estimate the frequency of this transmission zero, the impedance matrix of this coupling structure is derived from the impedance matrices of the microstrip coupled-line structures with some assumptions. A rough estimate, which relates the frequency to the length of the folded coupled-line structure, is then given. A filter with the proposed coupled-line structures is designed to demonstrate the theoretical analysis. The stopband response of this new filter is also compared with that of a conventional filter. Moreover, the skew-symmetric feed structure is applied to the filter to create a wide high-rejection stopband. Finally, two diplexers based on the proposed filter topology are designed to demonstrate the other applications.

II. A Folded Coupled-Line Structure

Figure 1(a) shows the proposed folded coupled-line structure in this paper. Signals are fed into this structure at the terminal 1a and 4b on the microstrip line 1 and 4, respectively. The microstrip line 1 is connected with the microstrip line 3 via a short line section and the other end of the line 3 is open. A similar circuit layout is applied to line 2 and 4. In order to analyze the existence of the transmission zero, the impedance matrix between the port 1a and 4b is derived by using the technique proposed by Swanson [2]. Based on that method, multiple coupled microstrip line circuits can be quickly analyzed with the four-port impedance matrices of two coupled microstrip lines, as shown in Figure 1(b). The impedance parameters of this four-port circuit are [3]:

$$Z_i = Z_{11} = Z_{22} = Z_{33} = Z_{44} = -j0.5[Z_{0e}\cot\theta_e + Z_{0o}\cot\theta_o], \quad (1)$$

$$Z_n = Z_{12} = Z_{21} = Z_{34} = Z_{43} = -j0.5[Z_{0e}\cot\theta_e - Z_{0o}\cot\theta_o], \quad (2)$$

$$Z_f = Z_{13} = Z_{31} = Z_{24} = Z_{42} = -j0.5[Z_{0e}\csc\theta_e - Z_{0o}\csc\theta_o], \quad (3)$$

$$Z_t = Z_{14} = Z_{41} = Z_{23} = Z_{32} = -j0.5[Z_{0e}\csc\theta_e + Z_{0o}\csc\theta_o]. \quad (4)$$

Additionally, several assumptions have been made to simplify the analysis of this folded coupled-line structure. The widths and the lengths of all microstrip lines are selected to be the same. The spaces between adjacent lines are also set to be equal. The lengths of the short connecting lines in this structure are assumed to be negligible. Moreover, the couplings between non-adjacent lines are also neglected.

With the above assumptions and the condition $I_{2b} = I_{3a} = 0$, the impedance parameters between the port 1a and 4b can then be derived as

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$$Z_{1a,1a} = Z_{4b,4b} = Z_i + \frac{2Z_t Z_n Z_f - 2Z_i Z_n^2 - 2Z_i Z_t^2}{4Z_i^2 - Z_f^2}, \quad (5)$$

and

$$Z_{1a,4b} = Z_{4b,1a} = \frac{4Z_i Z_t Z_n - Z_t^2 Z_f - Z_n^2 Z_f}{4Z_i^2 - Z_f^2}. \quad (6)$$

The equations of the impedance parameters herein are still too complex to analyze. But, if the approximation of $\theta_e = \theta_o = \theta$ is made, an approximate equation for the transmission zero condition can then be derived by applying $Z_{1a,4b} = 0$:

$$(Z_{0e} + Z_{0o})^2 \cot^2\theta = \frac{1}{4}(Z_{0e} + Z_{0o})^2 \csc^2\theta + \frac{1}{4}(Z_{0e} - Z_{0o})^2 \cot^2\theta. \quad (7)$$

Usually, a coupled-line structure has the property of $(Z_{0e} + Z_{0o})^2 >> (Z_{0e} - Z_{0o})^2$. Therefore, Equation (7) can be reduced as

$$\cos\theta \approx \frac{1}{2}. \quad (8)$$

From Equation (8), it is clear that the frequency of the transmission zero is dominated by the line length θ of the folded coupled-line structure and is at the frequency when $\theta \approx 60°$. In practice since the lengths of the short connecting lines are not zero, and θ_e and θ_o are not equal in a microstrip coupled-line structure, the above result is just an approximate solution. Therefore, a rough estimate for the position of the created transmission zero is at the frequency when the electrical length of the folded coupled-line structure is about $2\theta/3 \approx 40°$.

III. Filter Design Examples

Three second-order filters using conventional coupled-line structures, the folded coupled-line structures, and the folded coupled-line structures with a skew-symmetric feed structure were designed to verify the previous discussions. These filters were designed on Rogers RO3003 substrates with a relative dielectric constant of 3.00, a loss tangent of 0.0013, and a thickness of 0.508 mm. The circuits are denoted as Filter A, B, and C respectively. All filters are designed for the center frequency at 1.5 GHz and the bandwidth of 40 MHz. The circuit layouts are shown in Figure 2(a) – (c). Filter A has the largest circuit size of 43.1 mm by 15.1 mm. The sizes of Filter B and C are both 20.1 mm by 18.8 mm, which are 60 % of the size of Filter A. Moreover, the folded coupled-line structures used in Filter B and C are the same and have the lengths of about 6.9 mm. Therefore, according to the discussion in the previous section, a transmission zero near 3.12 GHz should be found in the responses of Filter B and C.

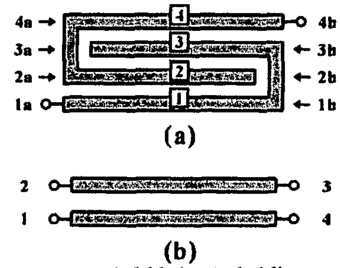

Figure 1. (a) A proposed folded coupled-line structure. (b) A microstrip coupled-line structure.

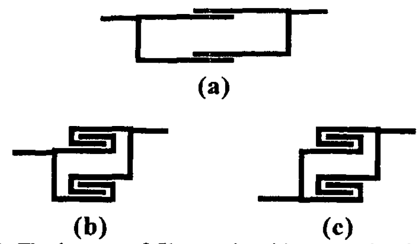

Figure 2. The layouts of filters using (a) conventional coupled-line structures, (b) the folded coupled-line structures, and (c) the folded coupled-line structures with a skew-symmetric feed structure.

The responses of these filters are given in Figure 3(a) and (b). Figure 3(a) depicts the passband responses of the three filters. The insertion losses are about 1 dB and the return losses are greater than 15 dB for all filters. It also shows that the steepness of the skirts near the passbands of Filter A and B are almost the same, because the frequency of the extra transmission zero in Filter B is far away from the passband. Filter C has the smallest shape factor, because a skew-symmetric feed structure is used and hence two more transmission zeros are created on the opposite sides of the passband. The comparison of stopband responses is depicted in Figure 3(b). It is clear that Filter A has the worst signal rejection, which is less than 20 dB in the stopband higher than the center frequency. This is because the signals at the input resonator are directly coupled to the output resonator and hence the out-of-band coupling is still strong. In the stopband response of Filter B, a zero is found at 2.46 GHz, which consists with the previous discussions and improves the out-of-band rejection significantly. The stopband rejection can be enhanced even more if a skew-symmetric feed structure is applied. The response of Filter C shows that two more zeros are created at 1.3 GHz and 1.8 GHz. With the zero at 1.8 GHz and another one created by the folded coupled-line structure at 2.46 GHz, this filter has more than 35-dB rejection from 1.75 GHz to 2.6 GHz.

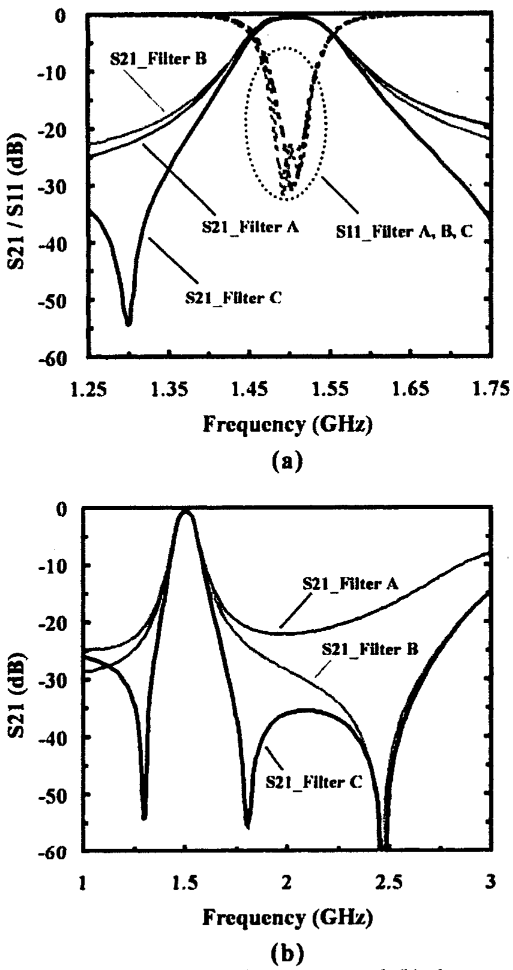

Figure 3. (a) The passband responses and (b) the out-of-band responses of Filter A, B, and C.

IV. Diplexer Design

The diplexer designed in this section is based on the circuit topology of Filter C in section III, because the two zeros created by a skew-symmetric feed structure are on the opposite sides of the passband and hence are useful for diplexer applications. The two passbands of the desired diplexer are centered at 1.5 GHz and 1.7 GHz. The bandwidths for both bands are 40 MHz. The passband response of Filter C in the previous section is suitable for the low channel specifications. Another filter with the similar circuit structure is designed at 1.7 GHz for the high channel. Each filter is then designed to be open at the center frequency of the other, by tuning the length of their input feed lines. The diplexer, denoted as Diplexer A, is then formed by connecting these two filters at the input ports and is shown in Figure 4(a). Figure 4(b) depicts the response of the designed diplexer. The insertion losses are about 1 dB and the return losses are greater than 15 dB for both bands. These responses meet the requirements. However, the rejection of high band signal at the low channel is less than 40 dB because the created zeros and the high channel are not close enough.

From the previous work [4], it had been proposed that the frequencies of the transmission zeros created by a skew-symmetric feed structure could be tuned by using impedance transformers. Based on the method, another diplexer denoted as Diplexer B was designed to improve the channel rejections. Nonsynchronous impedance transformers [5] were used to replace parts of the feed lines. For each filter, one of the transmission zeros is tuned to be closer to the other channel's passband, without increasing the circuit size. The circuit layout of Diplexer B is shown in Figure 5(a). It is clear that the size of Diplexer B is almost equal to the one of Diplexer A. The passband responses of the two channels are depicted in Figure 5(b). The insertion loss and the return loss of each channel are nearly the same with the ones of Diplexer A. The rejection of the other channel's signal is increased to be more than 45 dB because one of the zeros of each channel filter has been tuned to be at the center frequency of the other channel. Additionally, in Figure 5(c), it shows that the zeros created by the folded coupled-line structures of the channel filters are very helpful for signal rejections at the frequencies away from the passbands.

V. Conclusions

A folded coupled-line structure, which can create a transmission zero away from the passband, has been studied. With some circuit simplifications, a rough estimate of the frequency of the created zero has been made. A filter with the proposed coupled-line structures has been designed and compared with a conventional filter. Another filter with a wide high-rejection stopband has also been designed by using the proposed coupling structures and a skew-symmetric feed structure. Finally, two diplexers have been designed to demonstrate the other application of the research

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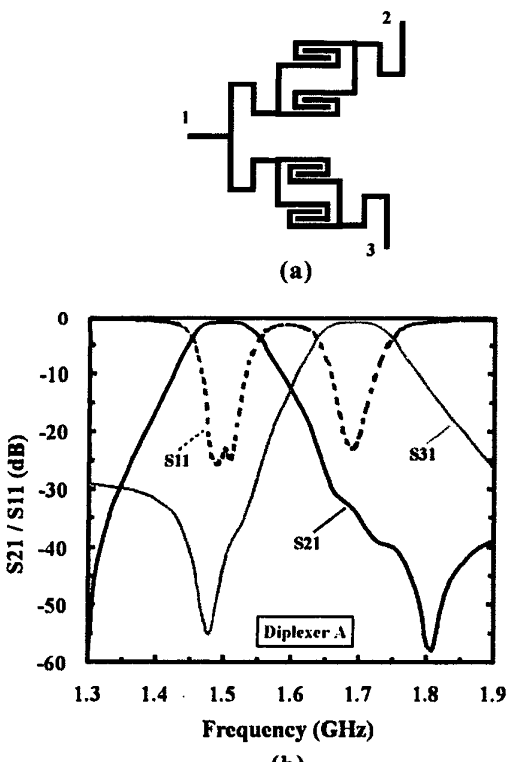

Figure 4. (a) The layout and (b) the response of Diplexer A.

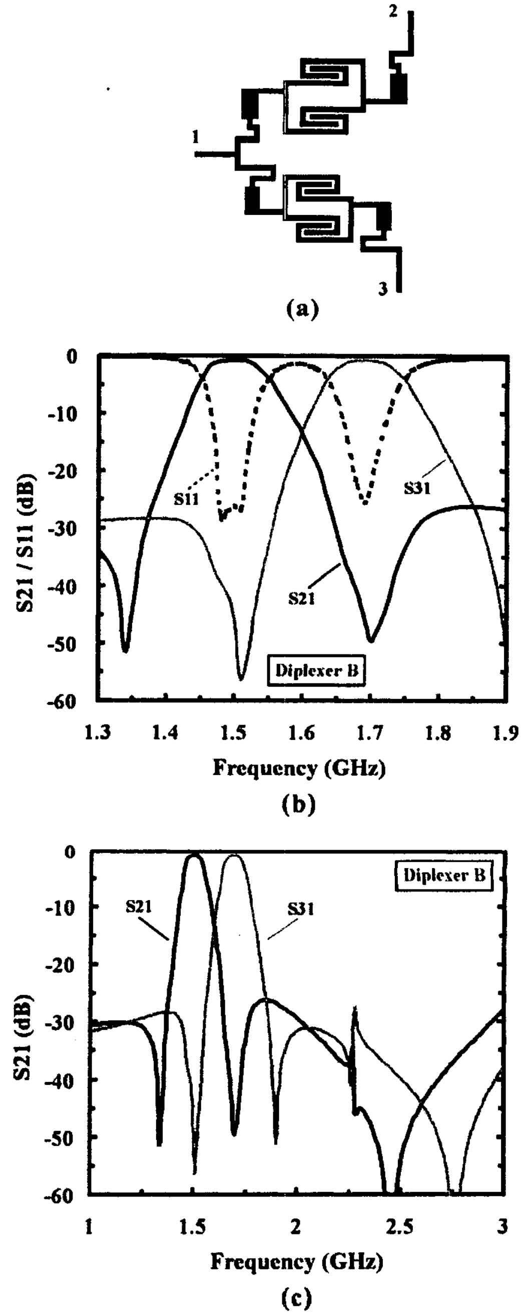

Figure 5. (a) The layout, (b) the passband response, and (c) the out-of-band response of Diplexer B.