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A QUASI-ELLIPTIC MICROSTRIP BANDPASS FILTER USING MODIFIED ANTI-PARALLEL COUPLED-LINE

Lingang Wang* **and Long Jin**

Research Institute of Electronic Science and Technology, University of Electronic Science and Technology of China, Chengdu 611731, China

Abstract—A novel band-pass filter (BPF) with lower and upper stopband zeros is proposed. The filter mainly consists of two antisymmetric modified anti-parallel coupled-lines and double pairs of transmission lines. Compared with the traditional anti-parallel coupled-line, the new filter has a better performance at both pass band and stop band. On the basis of even-odd mode method and network theory, the filter has been analyzed in detail. In addition, a simple method to create transmission zeros is investigated, which is beneficial for controlling the stopband zeros. The proposed filter is implemented on RT/Duroid 4350 substrate. Measured results show low insertion loss of less than 1.6 dB in the pass band and good suppressing of more than 22 dB in the lower stop band. Measured results show a good agreement with simulated results.

1. INTRODUCTION

In wireless communication systems, filters with different performances [1–6] play an essential role in selecting or suppressing the signals within assigned spectral limits. Over the past 30 years, the structure of parallel coupled lines has been widely used in band-pass filter (BPF) due to its ease of synthesis method, but, the conventional parallel coupled BPF has the drawback of a large circuit area and spurious responses at twice the passband frequency [7]. In order to improve the performance of filters with coupled lines, anti-parallel coupled-line has been adopted in implementing filters [8–13]. However, some blemishes still present in these filters. For example, in [10], even though it has a compact size, the rejection of lower stop- band is not satisfying. In [11], anti-parallel coupled-line with a termination is used to design

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* Corresponding author: Lingang Wang (wanglingang1025@126.com).

a band-pass filter; it has smaller size and three transmission zeros out of passband, whereas it does not perform excellently at spurious passband (twice the passband frequency). In [12], a microstrip band-stop filter with parallel coupled lines is constructed, but the return loss of upper passband is bad and its size is big.

The paper presents a novel BPF with modified anti-parallel coupled-line (MAPCL). This investigated circuit configuration can be divided into two antisymmetric subnetworks, which is composed of two transmission lines and MAPCL. The BPF has a good performance with one transmission zero (TZ) at the lower stopband and two TZs at the upper stopband. In addition, one of TZs is close to $2f_0$ (f_0 is center frequency of passband), enhancing out-of-band suppression.

2. THEORY OF THE FILTER

2.1. Analysis of Modified Anti-parallel Coupled-line

The schematic of modified anti-parallel coupled-line (MAPCL) is shown in Figure 1. It consists of anti-parallel coupled-line and a termination that has a characteristic impedance of Z_L and electrical length of θ_L at port 3. Although the schematic is asymmetry, even-odd mode analysis can be used for N_C network. The following two equations can be obtained [14]:

$$\begin{pmatrix} v_1 - v_2 \\ i_1 - i_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_o & jZ_o\sin\theta_o \\ jY_o\sin\theta_o & \cos\theta_o \end{pmatrix} \begin{pmatrix} v_4 - v_3 \\ -(i_4 - i_3) \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} v_1 + v_2 \\ i_1 + i_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_e & jZ_e\sin\theta_e \\ jY_e\sin\theta_e & \cos\theta_e \end{pmatrix} \begin{pmatrix} v_3 + v_4 \\ -(i_3 + i_4) \end{pmatrix} \tag{2}$$

where $Z_o = 1/Y_o$, $Z_e = 1/Y_e$ are odd- and even-mode characteristic impedances, respectively, and θ_o and θ_e the corresponding electrical lengths. Its boundary condition at port 3 and port 4 are given

$$v_3 = j(i_3 Z_L \cot\theta_L); \quad i_4 = 0; \tag{3}$$

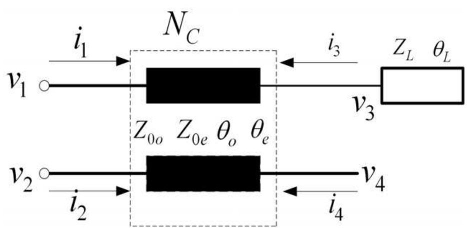


Figure 1. Schematic of modified anti-parallel coupled-line.

For simplicity, let $\theta_o = \theta_e = \theta$. By using (1)–(3), Y parameters can be obtained and simplified as follows:

$$Y = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix} = j \begin{pmatrix} ((Y_e + Y_o)\tan\theta)/2 & ((Y_e - Y_o)\tan\theta)/2 \\ ((Y_e - Y_o)\tan\theta)/2 & ((Y_e + Y_o)\tan\theta)/2 - 4\tau \end{pmatrix} \quad (4)$$

where: $\tau = 1/((Z_e + Z_o)\sin 2\theta - 4Z_L \cot\theta_L \cos^2\theta)$.

From (4), it is found that $Y_{11} \neq Y_{22}$ because of the asymmetry, there are two cases to obtain $ABCD$ parameters. When port 1 and 2 serve as the source and load port respectively, we should use (5); For the other case, $ABCD$ parameters should be derived using (6).

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}_C = \begin{pmatrix} \frac{-Y_{22}}{Y_{21}} & \frac{-1}{Y_{21}} \\ \frac{Y_{12}Y_{21} - Y_{11}Y_{22}}{Y_{21}} & \frac{-Y_{11}}{Y_{21}} \end{pmatrix} \quad (5)$$

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}'_C = \begin{pmatrix} \frac{-Y_{11}}{Y_{12}} & \frac{-1}{Y_{12}} \\ \frac{Y_{21}Y_{12} - Y_{22}Y_{11}}{Y_{12}} & \frac{-Y_{22}}{Y_{12}} \end{pmatrix} \quad (6)$$

2.2. Analysis of Proposed Bandpass Filter

After the above analysis, we have $ABCD$ parameters of MAPCL. In the following. The above $ABCD$ parameters will be used to analyze the proposed BPF using MAPCL, as is shown in Figure 2. The filter can be divided into two antisymmetric subnetworks: N_U and N_D. In both subnetworks, two transmission lines that have a characteristic impedance of Z_1 (Z_2 and Z_1 are assumed to be equal) and electrical length of θ_1 (θ_2 and θ_1 are assumed to be equal) are used to connect both sides of the MAPCL. It is worth mentioning that ABCD parameters of N_U and N_D should be calculated using (5)

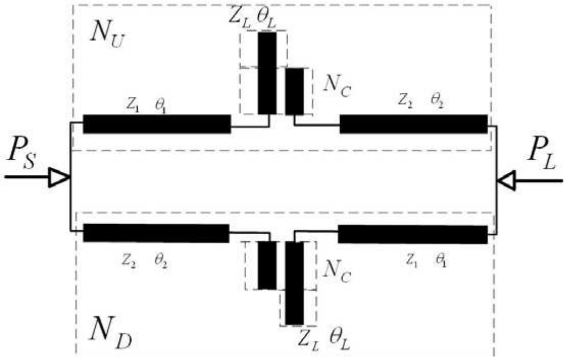


Figure 2. Proposed bandpass filter using MAPCL.

and (6), respectively.

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}_{N_U} = \begin{pmatrix} \cos\theta_1 & jZ_1\sin\theta_1 \\ jY_1\sin\theta & \cos\theta_1 \end{pmatrix} \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{N_C} \begin{pmatrix} \cos\theta_1 & jZ_1\sin\theta_1 \\ jY_1\sin\theta & \cos\theta_1 \end{pmatrix} \quad (7a)$$

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}_{N_D} = \begin{pmatrix} \cos\theta_1 & jZ_1\sin\theta_1 \\ jY_1\sin\theta & \cos\theta_1 \end{pmatrix} \begin{pmatrix} A & B \\ C & D \end{pmatrix}'_{N_C} \begin{pmatrix} \cos\theta_1 & jZ_1\sin\theta_1 \\ jY_1\sin\theta & \cos\theta_1 \end{pmatrix} \quad (7b)$$

In the next step, we can have their own Y parameters that can be derived from their $ABCD$ parameters [15]. Considering that the subnetworks N_U and N_D are connected in parallel, as shown in Figure 2. Y parameters of the combined network can be computed easily:

$$Y_{total} = Y_{N_U} + Y_{N_D} = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix}_{N_U} + \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix}_{N_D} = \begin{pmatrix} Y_{T11} & Y_{T12} \\ Y_{T21} & Y_{T22} \end{pmatrix} \quad (8)$$

At last, the following S-parameters of the whole filter is calculated using (4)–(8)

$$S_{21} = \frac{-2Y_0\beta\gamma}{(Y_0\gamma+\alpha)^2-\beta^2} \quad (9a)$$

$$S_{11} = \frac{(Y_0\gamma)^2+\beta^2-\alpha^2}{(Y_0\gamma+\alpha)^2-\beta^2} \quad (9b)$$

where

$$\alpha = j\left(2\sin 2\theta_1\left(-Z_1\rho_2^2\tan^2\theta\cdot\psi + Z_1\rho_1^2\tan^2\theta\cdot\psi - 4\rho_1\tan\theta - Y_1\cdot\psi\right)\right) + j\left(8 - 4\rho_1\tan\theta\cdot\psi\right) \quad (10a)$$

$$\gamma = 2Z_1\sin^2\theta_1\left(-\rho_1^2\tan^2\theta\cdot\psi + 4\rho_1\tan\theta\cdot\psi + \rho_2^2\tan^2\theta\cdot\psi\right) - 2\cos^2\theta_1\cdot\psi + Z_1\sin 2\theta_1\left(2\rho_1\tan\theta\cdot\psi - 4\right) \quad (10b)$$

$$\beta = j\left(-4\rho_1\tan\theta\cdot\psi\right) \quad (10c)$$

$$\rho_1 = (Y_e+Y_o)/2;\ \rho_2 = (Y_e-Y_o)/2;\ \psi = (Z_e+Z_o)\sin 2\theta - 4Z_L\cot\theta_L\cos^2\theta$$

The condition of transmission zeros can be analytically solved by $\beta\gamma = 0$, which can be derived from (9a). In the following, we will analyze it in detail.

(1) When $\beta = 0$, the following equation can be obtained easily

$$(Z_e+Z_o)\tan\theta = 2Z_L\cot\theta_L \quad (11)$$

From (11), it can be observed that the transmission zero can be created by MAPCL in Figure 1. In other words, we can get different transmission zero by changing the value of the parameters.

(2) Concerning the complicated expression of γ, we use numerical method to analyze the zeros of $\beta\gamma$. Normalized $(\beta\gamma)$ is plotted versus frequency in Figure 3. A close inspection of Figure 3 shows three zeros appear from DC to 7.8 GHz under three different values of $(Z_o,\ Z_e,\ \theta_L,\ \theta,\ \theta_1)$. That means the bandpass filter has three transmission zeros $(f_{z1},\ f_{z2},\ f_{z3})$ at the stop band.

Figure 4(a) reveals the stopband zero of f_{z1} depends on the length θ_1. It monotonically decreases as θ_1 increases. The same

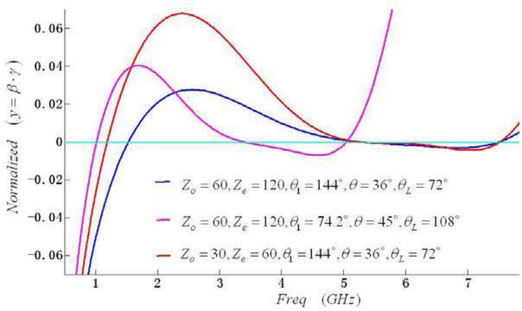


Figure 3. Normalized $(\beta\gamma)$ versus frequency under different values of electrical parameters (center frequency is at 2.7 GHz).

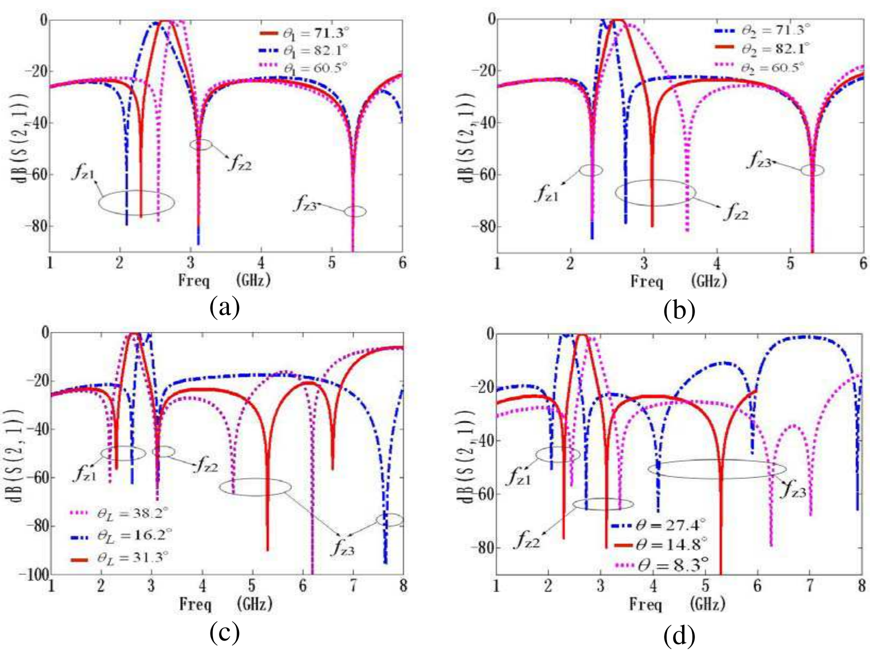


Figure 4. The relation between stopband zeros and different values of θ_1, θ_2, θ_L, θ (electrical lengths refer to center frequency $f = 2.7$ GHz).

performance of f_{z2} can be observed in Figure 4(b). Figure 4(c) shows the performance variation of the three stopband zeros with different values of θ_L. It is of interest to find that f_{z2} is independent of the length θ_L. Figure 4(d) illustrates the length θ simultaneously influences the three stopband zeros. All of them decrease with θ increasing.

In fact, the lowest one (f_{z1}) of three zeros is determined by left segment of N_U and right segment of N_D, which is approximately equivalent to an open-circuit transmission line with quarter-wavelength at (f_{z1}), as is shown in Figure 5(a); and f_{z2} is determined by right segment of N_U and left segment of N_D. The highest one (f_{z3}) is determined by (11), as is discussed in case (1). Using the above equivalent circuits, a filter can be analyzed and designed easier. In the following, we briefly verify the feasibility of the above equivalent circuits by Agilent ADS 2009. Figure 5(c) illustrates dB $|S_{21}|$ of MAPCL with a transmission line is similar to that of a quarter-wave transmission line with terminated open-circuit. Where $\lambda z1$, $\lambda z2$ is the guided wavelength of f_{z1} and f_{z2}, respectively.

In order to match the input and output impedance to 50 ohm respectively, the characteristic impedance of the microstrip should be

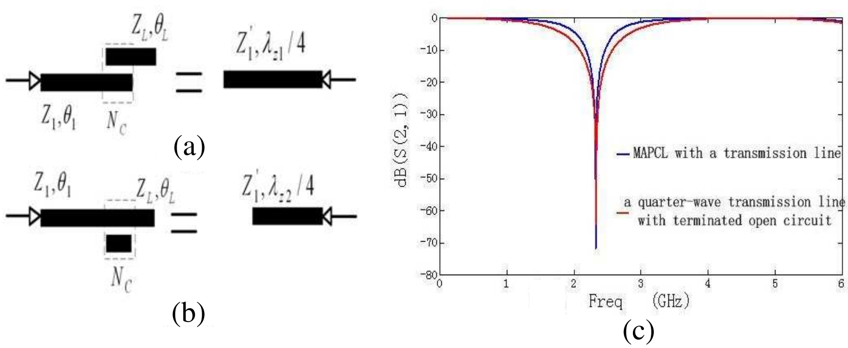


Figure 5. Equivalent circuit model: (a) left segment of N_D, (b) left segment of N_U and (c) comparison between dB $|S_{21}|$ of MAPCL with a transmission line and that of a quarter-wave transmission line with terminated open-circuit.

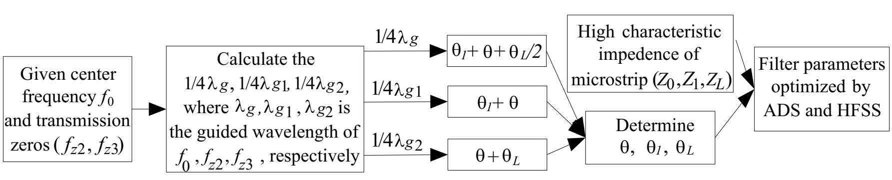


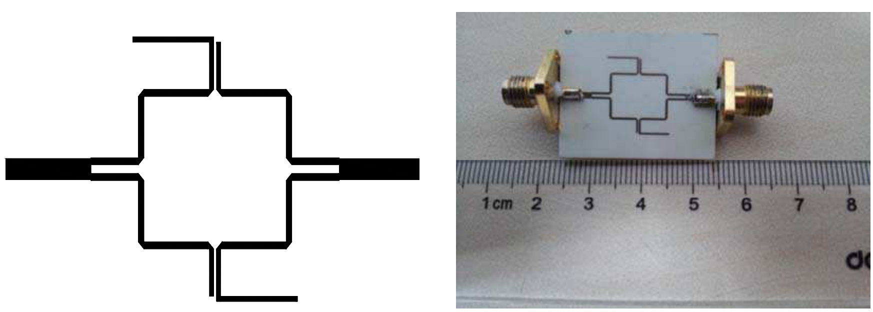
Figure 6. Design procedure of the proposed filter.

set as high impedance due to the parallel subnetwork. At last, the procedure to choose the dimension of the filter is presented in Figure 6.

3. FABRICATION AND MEASUREMENT

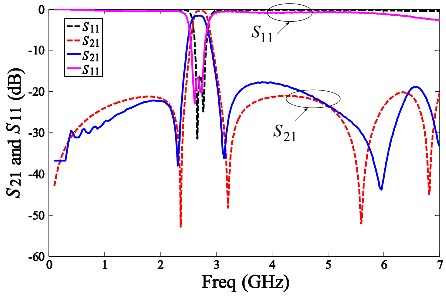
To validate the proposed design, a bandpass filter with $f_0 = 2.7\,\text{GHz}$ is fabricated on a 0.508 mm-thick RT/Duroid 4350 substrate. The layout of filter is shown in Figure 7(a), in order to make the filter compact, the layout of filter is somewhat different form the structure in Figure 2. Furthermore, the coupling effect of the parallel lines in the feed lines is negligible due to the small coupling coefficient. The parallel lines in both feed lines are only the part of the length θ_1 and θ_2 respectively. They do not act as coupled-line. Figure 7(b) shows the photograph of the proposed filter. The dimensions of the filter are determined using the procedure in Figure 6. After optimization by Agilent ADS 2009 and Ansoft HFSS, $Z_1 = Z_2 = 85.3$, $\theta_1 = \theta_2 = 68.1$, $Z_L = 90$, $\theta_L = 29.8$, $Z_e = 123.2$, $Z_o = 64.7$, $\theta_e = \theta_o = 14.0$.

Figure 8 depicts the simulated results and the measured results. It is shown that the lower stop-band transmission zero is at 2.3 GHz and the upper stop-band transmission zeros occur at 3.1 GHz and 5.9 GHz respectively. The measured result shows that the rejection of lower stop-band is larger than 22 dB, and that of upper stop-band from 3.05 GHz to 7 GHz is larger than 18 dB. The insertion loss of the pass-band ranging from 2.64–2.74 GHz is smaller than 1.6 dB and the return loss is better than 16 dB. The size of the filter is $0.27\lambda_g \times 0.24\lambda_g$ (λ_g is the guided wavelength at the center frequency of 2.7 GHz). A higher insertion loss on measurements is mainly attributed to the substrate, two SMA connecters, radiation and dielectric loss. The shift of the frequency might be due to the unexpected fabrication error.



(a) (b)

Figure 7. (a) Layout of the filter. (b) Photograph of the filter.



(---:simulated results —: measured results)

Figure 8. The simulated results and the measured results of the propose filter.

4. CONCLUSION

A novel bandpass filter with three transmission zeros in wide stopband has been introduced. The filter has a very simple structure, which is composed of two antisymmetric modified anti-parallel coupled-lines and double pairs of transmission lines. The analysis of the proposed BPF and stopband zeros have been discussed in the paper. At last, the filter is validated on RT/Duroid 4350 substrate, and measured results are in good agreement with simulated results.

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