HAIRPIN FILTERS WITH TUNABLE TRANSMISSION ZEROS

Chih-Ming Tsai, Sheng-Yuan Lee, and Chin-Chuan Tsai

National Cheng Kung University, Department of Electrical Engineering
1 University Road, Tainan 70101, TAIWAN

***Abstract* — In the previous work, it was found that filter designed with $0°$ feed structure could have two extra transmission zeros in the stopband. In this paper, a method for tuning the frequencies of these two transmission zeros using impedance transformers is proposed. These zeros can be tuned to reject unwanted signals near the passband, such as image signals. This new approach has been experimentally verified with three second-order Butterworth filters.**

I. INTRODUCTION

Tapped-line feed topology has been widely used in filter design due to its simplicity and space-saving [1, 2]. For the electric coupling structures shown in Fig. 1, which are widely used in four-pole cross-coupled filters as the input and the output sections, it has been shown that there are two types of tapped-line feed topologies [3]. The $180°$ feed structure was generally used. However, the other tapped-line feed topology ($0°$ feed), which can create two extra transmission zeros, was recently introduced. The zeros are close to and on the opposite sides of the passband, so the out-of-band rejection and the selectivity of these circuits can be increased significantly. They are at the frequencies when the feed point on the resonator is virtually shorted. Therefore, these zero frequencies are related to the feed point location. However, the feed point of a resonator cannot be moved without changing the loaded Q of a filter. In other words, the zeros created by this $0°$ feed topology are normally fixed.

In this paper, a method is proposed to tune these transmission zeros. Firstly, the equation for calculating the loaded Q of a tapped-line resonator is derived. A new structure with an impedance transformer inserted between the feed transmission line and the resonator is then proposed. Based on the equation, the impedance transformer could be designed to yield the given loaded Q and zero locations. Finally, several second-order Butterworth filters are designed and fabricated to demonstrate this method.

II. LOADED Q OF A TAPPED-LINE HALF-WAVELENGTH TRANSMISSION-LINE RESONATOR

It has been shown that a filter designed with $0°$ feed structure has two extra transmission zeros, which are useful for high selectivity and high stopband rejection [3]. However, the frequencies of these two zeros are not tunable because the tapped-line feed points must be selected to yield the loaded Q of a filter design. In this section, a method using impedance transformers to modify the feed points, without changing the loaded Q, will be presented.

It is well known that the loaded Q can be found by the expression [4]

$$Q = \frac{\mu}{2G}\frac{\partial B}{\partial \mu} \tag{1}$$

where G and B are the overall conductance and the overall susceptance. For example, the loaded Q at the feed point of the hairpin resonator shown in Fig. 2 can be derived as

$$Q = \frac{\mu}{4Y_L}\frac{Y_0}{f_0}\sec^2 \frac{-}{1}\Bigg|_{\mu=2\circledR f_0} \tag{2}$$

where Y_0 is the characteristic admittance of the transmission line of the resonator, Y_L is the load conductance and f_0 is the resonant frequency of the resonator. This equation assumes no conductor and dielectric losses in the resonator. It can be used for the synthesis of the load Q of all half-wavelength uniform transmission-line resonators with open ends. It also shows that there are only two proper feed points for a given loaded Q, which are symmetric and on the opposite locations about the center of the resonator.

0-7803-6540-2/01/$10.00 (C) 2001 IEEE

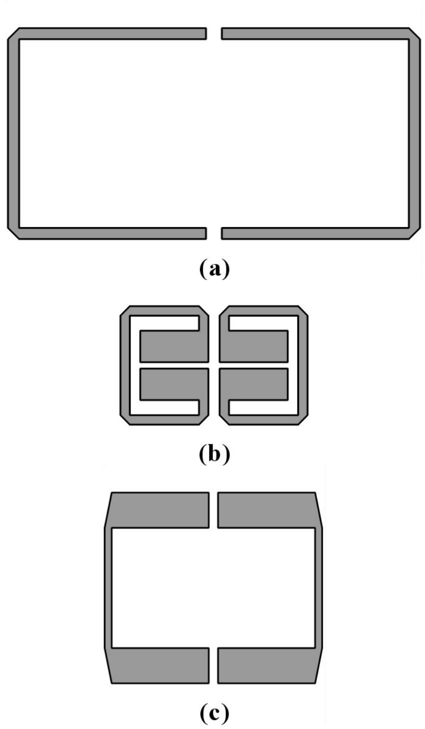


Fig. 1. Electric coupling circuits with (a) hairpin resonators, (b) miniaturized hairpin resonators, and (c) stepped-impedance hairpin resonators.

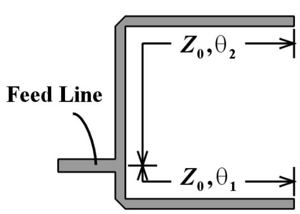


Fig. 2. A tapped-line hairpin resonator.

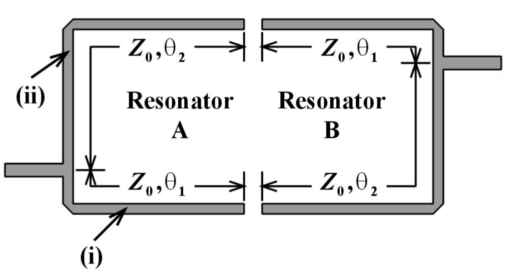


Fig. 3. An electric coupling circuit with 0° feed structure.

Moreover, a possible way of moving the feed point of a resonator with a given loaded Q is suggested by the equation (2). That is, the value of θ_1 can be changed if the load conductance at the feed point is changed. The load conductance Y_L at the feed point is usually the system conductance Y_S $(=1/50 \text{ mhos})$, but it can be modified if an impedance transformer is used. Therefore, the feed point of a resonator can be shifted, without changing the filter design.

The feed point can also be changed by modifying the value of Y_0. However, this method is not suggested because the line width of the transmission-line resonator will be modified. Then the coupling structures of the designed filter may need to be retuned. This could be a time-consuming work in higher-order filter designs, especially when cross-coupling is used.

III. Tunable-zero Design In Filters With 0° Feed Structure

It has been shown that a filter designed with 0° feed structure can have two extra transmission zeros at the frequencies when the feed points are virtually shorted. That is, the transmission line length from one open end of the resonator to the feed point is a quarter wavelength. For example, the electric coupling structure with 0° feed in Fig. 3 has the zeros at the frequencies when the transmission line section (i) or (ii) is a quarter wavelength. In section II, it has been presented that impedance transformers could be used for moving the feed points without changing the loaded Q. Therefore, the frequencies of the two transmission zeros could be tuned. If quarter-wavelength transmission-line transformers are used, the design can be based on the equation (2). Firstly, if a zero is desired to be at the frequency of f_1 or f_2, which is lower or higher than the resonant frequency of the resonator, the value of θ_1 is calculated by the equation

$$\theta_1 = 180° - 90° \times (f_0 / f_1) \tag{3}$$

or

$$\theta_1 = 90° \times (f_0 / f_2)\,. \tag{4}$$

Then, the characteristic impedance of impedance transformers can be calculated by

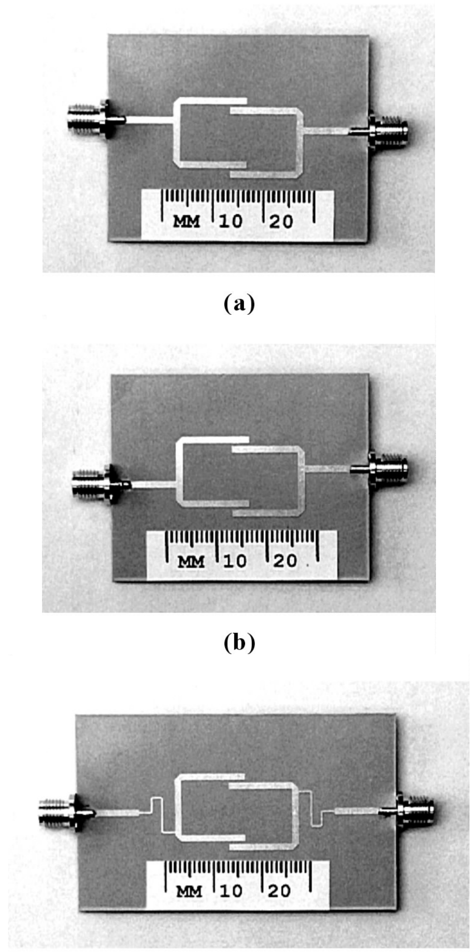
$$Z_T = \sqrt{\frac{2Q}{\pi Y_S Y_0 \sec^2 \theta_1}} \tag{5}$$

where Q is the loaded Q of the designed filter, Y_S is the system conductance, and Y_0 is the characteristic admittance of the transmission line of the resonator.

If the conductance Y_L is increased by adding a low impedance quarter-wavelength transmission-line impedance transformer, the value of $\bar{\ }_1$ must be increased to keep the desired load Q unchanged. Therefore, the two extra zeros are moved closer to the resonant frequency of the resonator. On the other hand, the frequencies of the two zeros could be moved away from the resonant frequency if the load conductance Y_L is decreased by using a high impedance quarter-wavelength transmission-line impedance transformer. The tunability of the transmission zeros by using this method is limited by the realization of the impedance transformers. For example, the line width could be too narrow to be fabricated when a high impedance quarter-wavelength transmission-line impedance transformer is needed. Or, the impedance transformer line width might be too wide when the zeros are moved very close to the resonant frequency of the resonator. Under this circumstance, the discontinuities at the feed points could disturb the response of the filter. Fortunately, these problems could be overcome by replacing one-section transmission-line impedance transformers with multi-section transmission-line impedance transformers.

IV. FILTER DESIGN EXAMPLES

Three second-order Butterworth hairpin filters using 180° feed structure, 0° feed structure, and 0° feed structure with a quarter-wavelength transmission-line impedance transformer were designed to verify the previous method. The filters are noted as filter A, B and C respectively. Each filter was designed for the center frequency at 2.45 GHz and 3 % bandwidth. The loaded Q and the coupling coefficient K_{12} of each filter were found to be 47.1 and 0.021 [5]. By using the equation (2), the $\bar{\ }_1$ of filter A and B was 79.5º. For filter C, one of the zeros was designed to be at 1.98 GHz. From the equation (3) and (5), the $\bar{\ }_1$ of filter C and the characteristic impedance of the impedance transformers were calculated as 68.6º and $100\,\Omega$.



(a) **(b)** **(c)**

Fig. 4. Photographs of the filters with (a) the $180°$ feed structure, (b) the $0°$ feed structure, and (c) the $0°$ feed structure with quarter-wavelength transmission-line impedance transformers.

These filters were fabricated on the Rogers RO3003 substrate with a relative dielectric constant of 3.00, a loss tangent of 0.0013, and a thickness of 20 mils. In order to increase the coupling coefficient, coupled-lines structures are used. Fig. 4(a), 4(b) and 4(c) are the photographs of filter A, B and C. The measured data is given in Fig. 5. It shows that the passband responses of these three filters are identical. It is also clear that filter B, with 0° feed structure, has two extra transmission zeros. One is at 2.18 GHz and the other is at 2.83 GHz, which are the frequencies when the feed points are virtually grounded.

TABLE I

SUMMARY OF EXPERIMENT RESULTS

Filter	Feed Topology	Feed Point ($^{-}_{1}$)	Zero Frequencies (original design)	Zero Frequencies (experimental results)
A	$180°$ feed	79.5º	None	None
B	$0°$ feed	79.5º	2.19 GHz and 2.77 GHz	2.18 GHz and 2.83 GHz
C	$0°$ feed with $a_0/4$ $100-\Omega$ transmission-line impedance transformers	68.6º	1.98 GHz and 3.21 GHz	1.99 GHz and 3.16 GHz

The zeros are close to the passband and make the out-of-band rejection much better than filter A (designed by using the $180°$ feed structure). For filter C, quarter-wavelength $100-\Omega$ transmission-line impedance transformers are used for decreasing the conductance at the feed points and move the zero frequencies away from the center frequency. The transmission zero frequencies of filter C are successfully tuned to 1.99 GHz and 3.16 GHz as shown in Fig. 5. The theoretical and experimental results are all summarized in TABLE I and the errors are smaller than 2 %.

V. CONCLUSIONS

A method for tuning the transmission zeros of $0°$ feed structures by using impedance transformers are proposed. With this circuit topology, the transmission zeros can be adjusted to reject unwanted signals near the passband. Three second-order Butterworth hairpin filters with different feed structures have been designed to demonstrate the feasibility of this method. The experimental results agree fairly well with the theoretical predictions. The method is very easy and attractive in designing filters with high selectivity, high out-of-band rejection, or high image suppression. Moreover, it is also compatible with many traditional transmission-line filter designs and has no significant side effects.

REFERENCES

[1] E. G. Cristal, "Tapped-line coupled transmission lines with applications to interdigital and combline filters," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-23, pp. 1007-1012, Dec. 1975.

[2] J. S. Wang, "Microstrip tapped-line filter design," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-27, pp. 44-50, Jan. 1979.

[3] S.-Y. Lee and C.-M. Tsai, "New cross-coupled filter design using improved hairpin resonators," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-48, Dec. 2000.

[4] C. G. Montgomery, R. H. Dicke and E. M. Purcell, *Principles of Microwave Circuits*, Chapter 7, McGraw-Hill Book Co., Inc., 1948.

[5] A. B. Williams and F. J. Taylor, *Electronic Filter Design Handbook*, Chapter 5, McGraw-Hill Co., Inc., 3rd Ed., 1995.

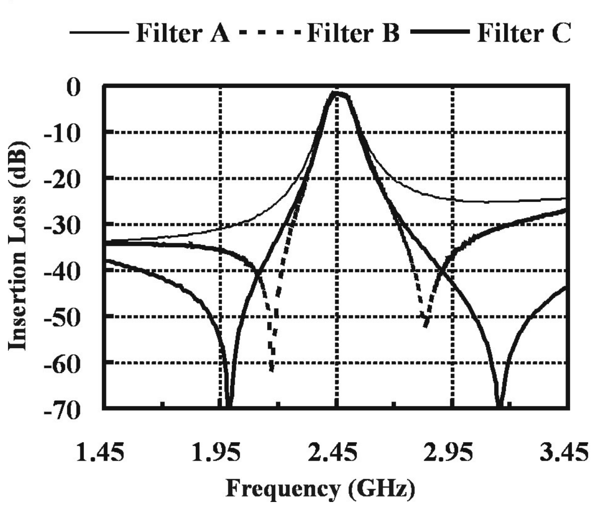


Fig. 5. Experiment results.