Quasi-Elliptic Wideband Bandstop Filter Using Stepped-Impedance Coupled Line

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***Abstract*—A cross-coupled wideband bandstop filter (BSF) with a 5th-order quasi-elliptic response is proposed and investigated in this letter. The BSF is composed of stepped-impedance coupled line connected by an open-circuited shunt stub. An enhanced selectivity and stopband rejection can be achieved as a result of two new transmission zeros, generated from the stepped-impedance coupled line. Based on the derived rigorous correspondence between the BSF and its lumped prototype, design of the proposed BSF can be handled as the same to the lumped network. A BSF example is given with measured stopband attenuation of 34.4 dB over a fractional bandwidth of 113.4%.**

***Index Terms*—Bandstop filter (BSF), cross coupling, quasi-elliptic, wideband.**

I. Introduction

BANDSTOP filters (BSFs) with properties of wide stopband, high attenuation, steep skirt and compact size are desired in many communication systems. To meet these requirements, introduction of transmission zeros (TZs) is crucial. One efficient approach is to introduce electric [1], [2] or magnetic [3]–[5] coupling between two nonadjacent transmission lines. The resulting filters can typically provide two new TZs in the stopband, leading to the 3rd-order elliptic/quasi-elliptic response and apparent improvement of the stopband performance. Higher order magnetic-coupled BSFs are also available in [6], but no more TZs are generated. As an alternative approach, TZs can be achieved from signal interference between two main transmission paths [7], [8]. A 5th-order quasi-elliptic BSF is proposed in [9] based on a cross-coupled ring. In addition, the load of shunt stubs at the input and output ports is another effective approach to improve the stopband performance [10]. However, all these published works lack detailed analyses and discussion on the exact design of these filters to achieve synthesized performance.

In this letter, a 5th-order quasi-elliptic wideband BSF with stepped-impedance coupled line is proposed to further enhance the selectivity and stopband rejection level. It is achieved by introducing two additional TZs using the coupled-line structure. Rigorous correspondence relationship between the BSF and its lumped prototype is firstly established, which enables the BSF to be designed the same way as the lumped network. A BSF example is finally designed and fabricated. The measured stopband attenuation is 34.4 dB over a fractional bandwidth of 113.4% and agrees well with the theoretical and simulated results.

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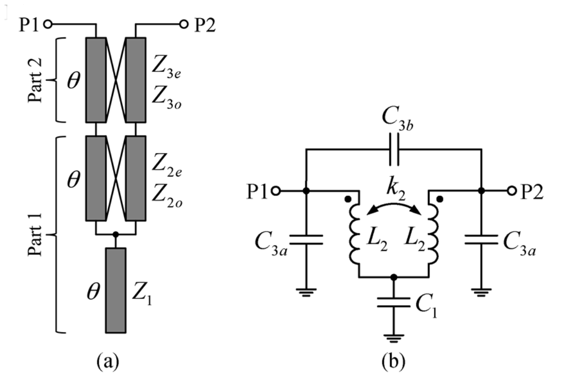

Fig. 1. (a) Proposed BSF. (b) Lumped prototype.

II. Design and Analysis

The proposed BSF shown in Fig. 1(a) is constructed by introducing an additional section of coupled line (Part 2) to the 3rd-order BSF (Part 1) of [3]. The even-/odd-mode characteristic impedance Z_{3e}/Z_{3o} is different from Z_{2e}/Z_{2o}. Therefore, the structure is a kind of stepped-impedance coupled line. All transmission lines are of commensurate electrical length θ, which is a quarter-wavelength at the stopband center frequency f_0. The lumped lowpass prototype circuit of the BSF is shown in Fig. 1(b). The capacitances C_{3a} and C_{3b} correspond to the additionally introduced coupled line of Fig. 1(a), while the mutual inductive coupling corresponds to the original coupled line of Z_{2e}/Z_{2o}. As a result, the additionally introduced capacitances together with the original circuit give rise to a 5th-order quasi-elliptic response.

Since the circuit is symmetrical, the even-/odd-mode analysis is performed. To establish rigorous correspondence between the BSF and its lumped prototype circuit, their even- and odd-mode input admittances should be equal to each other in the S-plane based on the Richards' transformation

$$S = j\Omega = j\tan\frac{\pi f}{2f_0} \tag{1}$$

where S, Ω and f are the Richards', lumped and distributed element frequency variables, respectively.

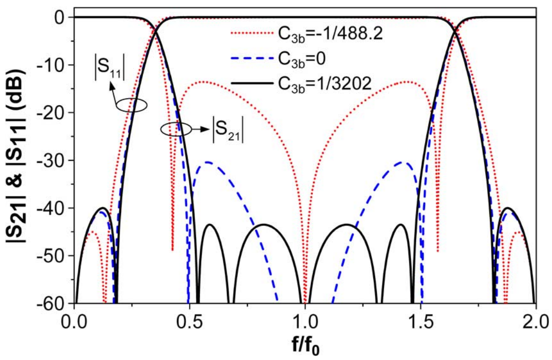

Fig. 2. Responses with different C_{3b} ($C_1 = 1/21.17$, $L_2 = 130.1$, $k_2 = 0.1684$, $C_{3a} = 1/54.43$).

The even- and odd-mode input admittances of the proposed BSF are

$$\begin{cases} Y_{Aine} = \frac{S^3 Z_{2e}^2 + S[Z_{2e}Z_{3e} + 2Z_1(Z_{2e}+Z_{3e})]}{S^2 Z_{3e}[2Z_1 Z_{3e} + Z_{2e}(Z_{2e}+Z_{3e})] + 2Z_1 Z_{2e} Z_{3e}} \\ Y_{Aino} = \frac{S^2 Z_{2o} + Z_{3o}}{S Z_{3o}(Z_{2o}+Z_{3o})}. \end{cases} \quad (2)$$

The even- and odd-mode input admittances of the lumped prototype are

$$\begin{cases} Y_{Bine} = SC_{3a} + \frac{SC_1}{S^2(1+k_2)L_2C_1+2} \\ Y_{Bino} = S(C_{3a}+2C_{3b}) + \frac{1}{S(1-k_2)L_2}. \end{cases} \quad (3)$$

Comparing (2) and (3), the correspondence relationship is derived to be

$$\begin{cases} Z_1 = \frac{2C_1 + C_{3a}(2+L_{2e}C_1)^2}{L_{2e}^2 C_1^3 C_{3a}} \\ Z_{2e} = C_1 C_{3a} L_{2e} Z_1 Z_{3e} \qquad Z_{2o} = (C_{3a}+2C_{3b}) L_{2o} Z_{3o} \\ Z_{3e} = \frac{2+L_{2e}C_1}{C_1 + C_{3a}(2+L_{2e}C_1)} \qquad Z_{3o} = \frac{L_{2o}}{1+L_{2o}(C_{3a}+2C_{3b})} \end{cases} \quad (4)$$

with $L_{2e} = (1+k_2)L_2$ and $L_{2o} = (1-k_2)L_2$. Then the BSF can be handled exactly the same way as the lumped prototype in the S-plane. As a special case when $C_{3a} = C_{3b} = 0$, (4) will degenerate into the formulas applicable to the 3rd-order elliptic BSF in [3]. Note that even if $C_{3b} = k_2 = 0$, we still have $Z_{2e} > Z_{2o}$ and $Z_{3e} > Z_{3o}$ from (4). In other words, cross couplings still exist in the stepped-impedance structure. Then the formulas will applicable to BSFs of all-pole responses. Therefore, the proposed BSF provides one optimum design among the 5th-order BSFs composed of shunt stubs and unit elements [11].

The typical effect of C_{3b} on the filtering response is illustrated in Fig. 2. When $C_{3b} = -1/488.2$, the additionally introduced coupled line will degenerate to a pair of unit elements ($Z_{3e} = Z_{3o}$). The resulting BSF only has a stopband attenuation of 13.6 dB with three TZs offered by the original 3rd-order BSF. With the increase of C_{3b}, cross coupling between the two unit elements is established and increased. Then two new TZs arise at the mid-stopband when $C_{3b} = 0$ and will move toward the lower and upper band edges, if C_{3b} is further increased. Finally, an equal ripple stopband with apparently enhanced rejection level can be achieved.

On the other hand, C_{3a} provides contribution to the rejection and selectivity of the proposed BSF. As shown in Fig. 3, the stopband rejection level is effectively enhanced with the increase of C_{3a}. In contrast with C_{3b} which can bring additional TZs into the stopband without affecting the number of transmission poles of passbands, C_{3a} can bring additional transmission poles into the passbands but has no impact on the locations of TZs. The introduction of either transmission poles or zeros can effectively improve the selectivity.

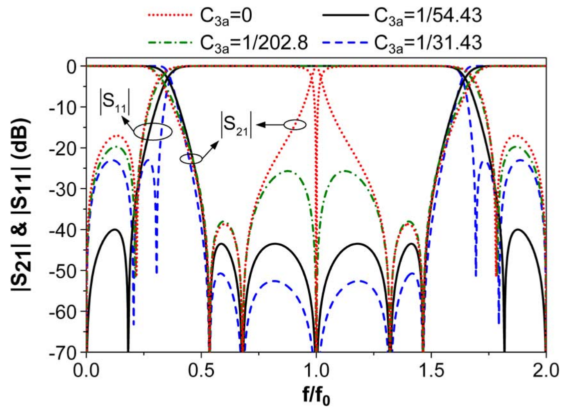

Fig. 3. Responses with different C_{3a} ($C_1 = 1/21.17$, $L_2 = 130.1$, $k_2 = 0.1684$, $C_{3b} = 1/3202$).

The parameters of the proposed BSF can be obtained directly from the published tables of lumped lowpass prototype filters by transforming the prototype of Fig. 1(b) into the standard circuit structure of a 5th-order elliptic response. As for the quasi-elliptic response in Fig. 3, the standard approximation procedure will be required to determine the element values of the lumped prototype. The proposed BSF can also be developed with higher order like those in [6] and [10].

III. Experimental Results

For the passband ripple of 0.011 dB and the minimum stopband attenuation of 37.1 dB, the normalized elements of lowpass prototype are first optimized and then scaled to the lumped elements in Fig. 1(b) for a BSF example with a stopband fractional bandwidth (FBW_S) of 111.2% [12]. The lumped elements are $C_1 = 0.0737$, $L_2 = 162.8$, $k_2 = 0.1192$, $C_{3a} = 0.0084$, and $C_{3b} = 0.0002$. According to (4), the characteristic impedances of the BSF are obtained as: $Z_1 = 19.22\ \Omega$, $Z_{2e} = 164.6\ \Omega$, $Z_{2o} = 79.79\ \Omega$, $Z_{3e} = 75.86\ \Omega$ and $Z_{3o} = 63.59\ \Omega$. It is designed and fabricated on a microstrip substrate with the relative dielectric constant of 2.65, the loss tangent of 0.003 and the thickness of 0.73 mm. The center frequency is 1.5 GHz. A commercial tool LineCalc from Agilent ADS is used to calculate the initial dimensions. As the microstrip circuit is not an ideal TEM structure, the electrical length of odd mode is always less than that of the even mode. Thus, the method of capacitance loading to the coupled line [13] is adopted here to compensate for the difference of electrical length. With the full-wave simulator ANSYS HFSS, the optimized filter parameters are obtained and illustrated in Fig. 4(a). The filter photograph is shown in Fig. 4(b).

The theoretical, simulated and measured results of the experimental filter are compared in Fig. 5 where good agreement can be observed. The minimum stopband attenuations are 37.1, 36.8, and 34.4 dB, corresponding to FBW_S of 1.112, 1.122, and 1.134 at the center frequencies of 1.5, 1.488, and 1.483 GHz, respectively. The small difference is mainly due to the non-ideal

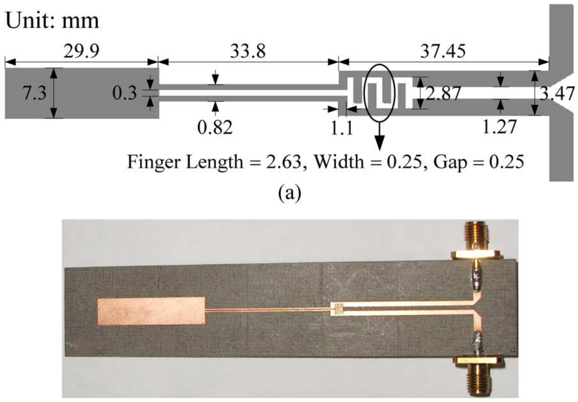

Fig. 4. Layout and photograph of an experimental filter.

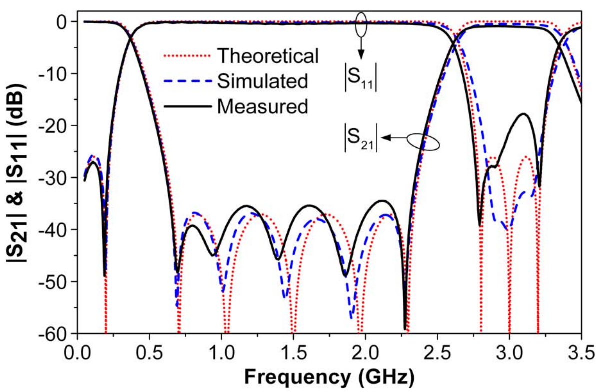

Fig. 5. Theoretical, simulated and measured results of the experimental filter.

TABLE I
COMPARISON WITH MANY WIDE-BAND BSFS

Ref.	f_0 (GHz)	Order	No. of zeros	FBW_S (%)	Attenuation (dB)	Size $(\lambda_0^2)^*$
[2] Fig. 4	2.39	-	2	87	20	0.033
[3]	6	3	3	97	21	0.033
[6]	4	≥5	3	47	23	0.181
[7]	2	-	4	100	20	0.109
[9]	1.5	5	5	60	29	0.016
[10]	1	7	5	140	20	0.056
This work	**1.5**	**5**	**5**	**113.4**	**34.4**	**0.040**

$^*\lambda_0$ is the guided wavelength at mid-stopband.

even-/odd-mode velocity of the coupled microstrip lines. The measured insertion loss is within 0.15 dB up to 0.214 GHz in the lower passband and is less than 1.53 dB from 2.725 to 3.245 GHz in the upper passband. The filter example has a compact size of $0.738 \times 0.054\lambda_0^2$, where λ_0 is the guided wavelength of a 50 Ω line at the mid-stopband. Table I compares the performance of the BSF example with many previous designs. The proposed BSF shows large FBW_S and high stopband attenuation simultaneously, which is superior to the other BSFs.

IV. CONCLUSION

A 5th-order quasi-elliptic wideband BSF with enhanced selectivity and stopband rejection has been proposed by using the stepped-impedance coupled line. The additionally introduced section of coupled line together with the original magnetic coupling gives rise to two new TZs that significantly improve the filtering performance. The BSF is investigated based on a lumped lowpass prototype. Rigorous correspondence relationship between the BSF and the prototype is derived. The parameters of the BSF can be determined either from the published tables of lumped lowpass prototype filters or by performing the classical approximation procedure of lumped circuit. The design has been verified by a BSF example with a measured minimum stopband attenuation of 34.4 dB over a fractional bandwidth of 113.4%.

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