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Analysis and Design of a New Ring Bandstop Filter Using Lumped Equivalent Circuit

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Abstract—A new ring wideband bandstop filter (BSF) and its exact design method is proposed and investigated in this letter. The BSF is devised by introducing an additional transmission line to a traditional hairpin bandstop filter in parallel, hence giving enhanced selectivity and attenuation performance. A lumped lowpass equivalent circuit is introduced to explain the mechanism of the filter. Rigorous correspondence between the BSF and its equivalent circuit is established by comparing their even- and odd-mode input admittances. This enables the BSF to be synthesized the same way as lumped filters. Both the BSF and the method have been documented by a design example.

1. INTRODUCTION

Compared to waveguide bandstop filters (BSFs), transmission line BSFs are attractive due to the merits of low cost, light weight, small size, and easy integration. The application of these BSFs covers a wide spectrum. As transmission zero (TZ) plays an important role for improvement of attenuation characteristic, many techniques have been explored to acquire TZs as many as possible. The use of shunt stubs has been proven to be a quite successful technique to get narrow to moderate stopband via coupled loading [1, 2] or moderate to wide stopband via direct loading [3, 4]. One shunt stub can normally generate one TZ. Multiple TZs will require multiple stubs or multiple stepped stubs [4, 5], which will increase size and loss inevitably. The technique of cross coupling is then appreciated due to the ability of generating TZs from building multiple transmission routes without increasing filter size. Introducing cross coupling between open-circuited stubs [6, 7] or between unit elements [8–10] are the two most common approaches for BSFs. Meanwhile, the construction of multiple main transmission routes is found to be another effective technique to obtain TZs via signal interference mechanism [11–13]. Combination between the techniques of cross coupling and signal interference may even produce more TZs [14].

The works referred above are mainly confined to structure design to achieve their desired results. Either the concept of filter order or the principle of generation of TZs seems to be ambiguous especially in the case of BSFs based on cross coupling or signal interference techniques. Thus, many researchers have paid their attention to such matters and tried to clarify a signal-interference BSF from the viewpoint of digital filters [15].

In this letter, a fifth order wideband BSF as well as its exact design method is proposed. The BSF is composed of a third order hairpin BSF and a transmission line in parallel. A combination of cross-coupling and signal-interference technique is used to acquire improved attenuation performance. It can be proven that the proposed BSF is rigorously equivalent to a lumped lowpass filter. As a result, the mechanism of the BSF is able to be clarified from the viewpoint of LC circuit. The design of the BSF is directly transformed into the design of its lumped counterpart, which has well-known exact design method.

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2. ANALYSIS AND DESIGN

The transmission line schematic of the proposed BSF and its lumped equivalent circuit are illustrated in Figure 1. Each transmission line section is quarter wavelength at the mid-stopband $f0$. The coupled line (Z_{1e}, Z_{1o}) and inner transmission line (Z_4) constitute a conventional hairpin BSF, which is in parallel with the outer transmission line (Z_2, Z_3). The architecture of the equivalent circuit of Figure 1(b) is originally obtained from the equivalences of an LC π-section for hairpin structure [6], an inductor for a high impedance transmission line and an LC T-section for two cascaded transmission lines [5, 6, 8]. Figure 2 shows the detailed equivalences. It is now obvious that transmission line Z_4 also plays a role of cross coupling L_{12} between source and load while C_{12} represents the cross coupling between open-circuited stubs. The emergence of additional TZs is mainly due to the mechanism of mixed electric and magnetic coupling.

By comparing the even- and odd-mode input admittances of the proposed BSF in Figure 1(a) and its lumped equivalent circuit in Figure 1(b), respectively, rigorous correspondence can be obtained as follows:

$$\begin{cases} Z_{1e} = \left[C_1 - \dfrac{2}{L_{12}} - \dfrac{4\left(1+L_2C_3\right)}{L_2\left(2+L_2C_3\right)^2}\right]^{-1} \\ Z_{1o} = \left[C_1 + 2C_{12} - \dfrac{2C_3}{\left(2+L_2C_3\right)^2}\right]^{-1} \\ Z_2 = L_2 + \dfrac{2}{C_3} \\ Z_3 = \dfrac{4+2L_2C_3}{L_2C_3^2} \\ Z_4 = \left[\dfrac{2}{L_{12}} + \dfrac{4\left(1+L_2C_3\right)}{L_2\left(2+L_2C_3\right)^2}\right]^{-1} \end{cases} \tag{1}$$

where all characteristic impedance, inductance, and capacitance are in henry and farad, respectively. As an alternative, all parameters of the lowpass filter in Figure 1(b) can also be expressed as

$$\begin{cases} C_1 = \dfrac{1}{Z_{1e}} + \frac{1}{Z_4} \\ L_2 = \dfrac{Z_2^2}{Z_2+Z_3} \\ C_3 = \dfrac{2}{Z_2} + \dfrac{2}{Z_3} \\ L_{12} = 2\left[-\dfrac{Z_3}{Z_2^2} - \dfrac{Z_3}{Z_2\left(Z_2+Z_3\right)} + \dfrac{1}{Z_4}\right]^{-1} \\ C_{12} = \dfrac{1}{2}\left[-\dfrac{1}{Z_{1e}} + \dfrac{Z_{1o}Z_3 + Z_2^2 + Z_2Z_3}{Z_{1o}Z_2\left(Z_2+Z_3\right)} - \dfrac{1}{Z_4}\right]. \end{cases} \tag{2}$$

It is now quite clear from Equation (2) that C_1 comes from Z_{1e} and Z_4; L_2 and C_3 come from Z_2 and Z_3; L_{12} comes from Z_2 to Z_4; and C_{12} comes from all transmission line elements. As for the case of $C_{12} = 1/L_{12} = 0$, the LC network of Figure 1(b) will degenerate to a fifth order all-pole filter. However, this will not change the equivalence between the proposed BSF and its lumped counterpart. The relationship of $Z_{1e} > Z_{1o}$ and $Z_4 > 0$ remains unchanged according to Equation (1). Since L_{12} and C_{12} are terms of bypass routes, the change of these two element values will not lead to the change of filter order. Then it will come to a conclusion that the order of the proposed BSF is five.

Consider a special case when $Z_{1e} = Z_{1o} = Z_1$, which means that cross coupling between the open-circuited stubs vanishes. Then the proposed BSF will degenerate into a typical ring filter shown in Figure 3(a). As the impedance Z_1 of the shunt stubs approaches infinity, a further degenerate ring BSF shown in Figure 3(b) is obtained. It can be found from Equation (2) that the corresponding LC element must not vanish in such two degenerated cases. In other words, both the filters in Figure 3 are also

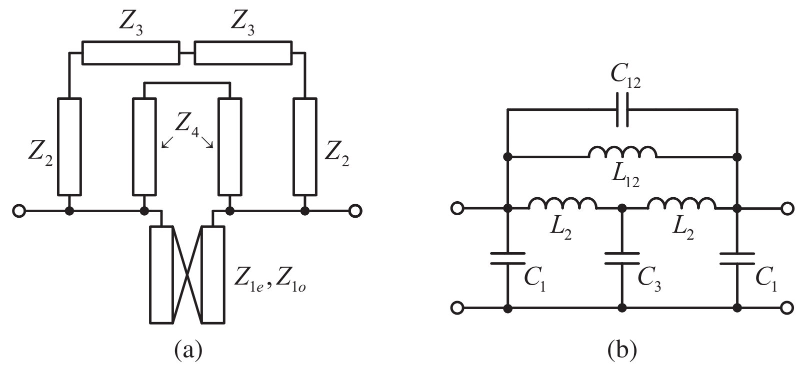


Figure 1. (a) Proposed BSF. (b) Lumped equivalent circuit.

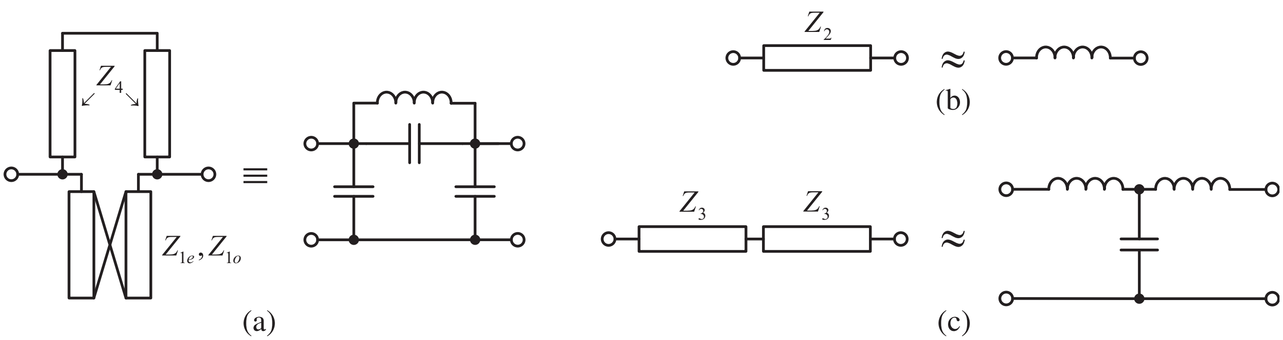


Figure 2. Detailed equivalences between the proposed BSF and its lumped equivalent circuit.

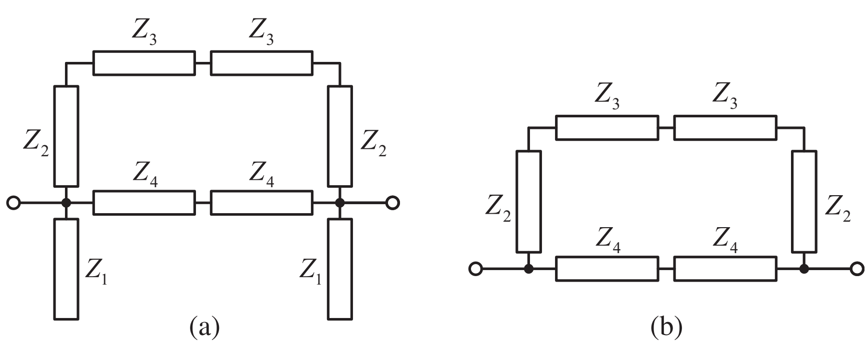


Figure 3. Ring BSFs (a) without cross coupling and (b) without shunt stubs.

equivalent to the lumped lowpass filter of Figure 1(b). They are fifth order BSFs. Equations (1) and (2) enable the design of these BSFs to be handled the same as an LC network, which has much mature design theory and method.

According to Equation (1), C_{12} is only related to Z_{1o}. Thus the relationship between responses of the proposed BSF and capacitance C_{12} is illustrated in Figure 4. When $C_{12} = -0.00324$, no cross coupling occurs between shunt stubs. Stopband only has an attenuation of 6.8 dB, which is a response for the BSF in Figure 3(a). With the increase of C_{12}, cross coupling arises and grows gradually. It is found that stopband attenuation can be enhanced apparently even if no new TZs emerge. A further increase of C_{12} will finally introduce two new TZs around f and give rise to an optimum result of stopband performance.

Another role of the coupled line (Z_{1e}, Z_{1o}) on the performance of the proposed BSF is further illustrated in Figure 5. As can be seen from Equation (2), Z_{1e} and Z_{1o} are only related to C_1 and C_{12}.

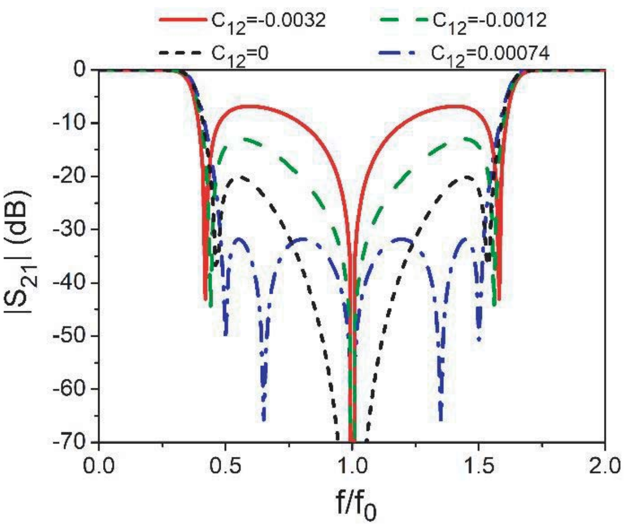


Figure 4. Responses of the proposed BSF with different $C_{12}(C_1 = 1/68.77,\ L_2 = 168.3,\ C_3 = 1/30.4,\ L_{12} = 408)$.

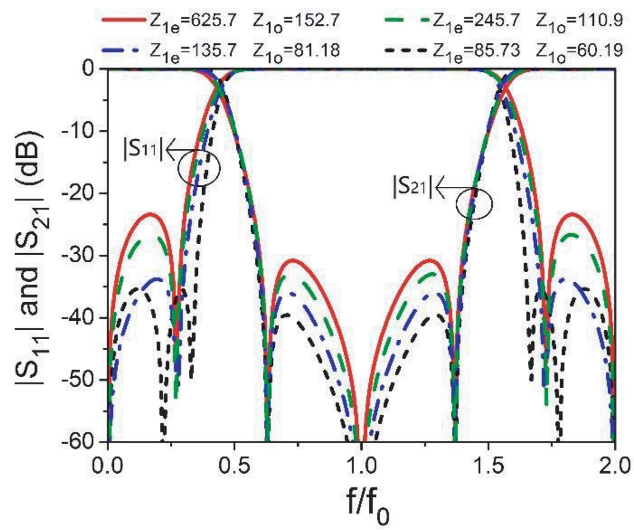


Figure 5. Responses of the proposed BSF with constant value of $(1/Z_{1e} - 1/Z_{1o})(Z_2 = 159.7,\ Z_3 = 78.8,\ Z_4 = 138.7)$.

If some specific values of Z_{1e} and Z_{1o} are chosen to keep the value of $(1/Z_{1e} - 1/Z_{1o})$ to be constant, it can be found that performance of the proposed BSF will be decided only by Z_{1e} without changing the location of TZs. A decrease of Z_{1e} can help to bring not only an enhanced stopband rejection level but also a steep passband skirt due to the smaller space between cutoff frequencies of passband and stopband.

Although the proposed BSF has been proven to be handled like the LC filters, the feasible impedance suffers great limitation due to implementation techniques. As far as attenuation and selectivity are concerned, elliptic responses generally have optimum results as well as the most stringent fabrication requirement. Then generalized Chebyshev or Quasi-elliptic approximation may be a popular alternative. It should be noted that the proposed BSF can also be approximated to all-pole responses. A comparison among these approximations is shown in Figure 6. The corresponding element values are listed in Table 1.

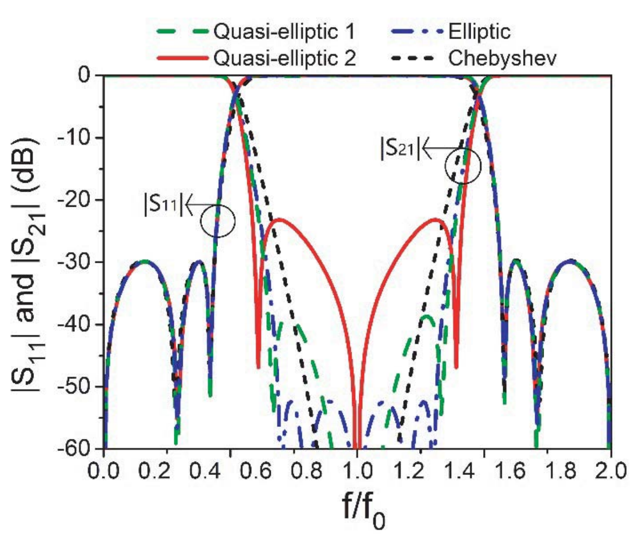


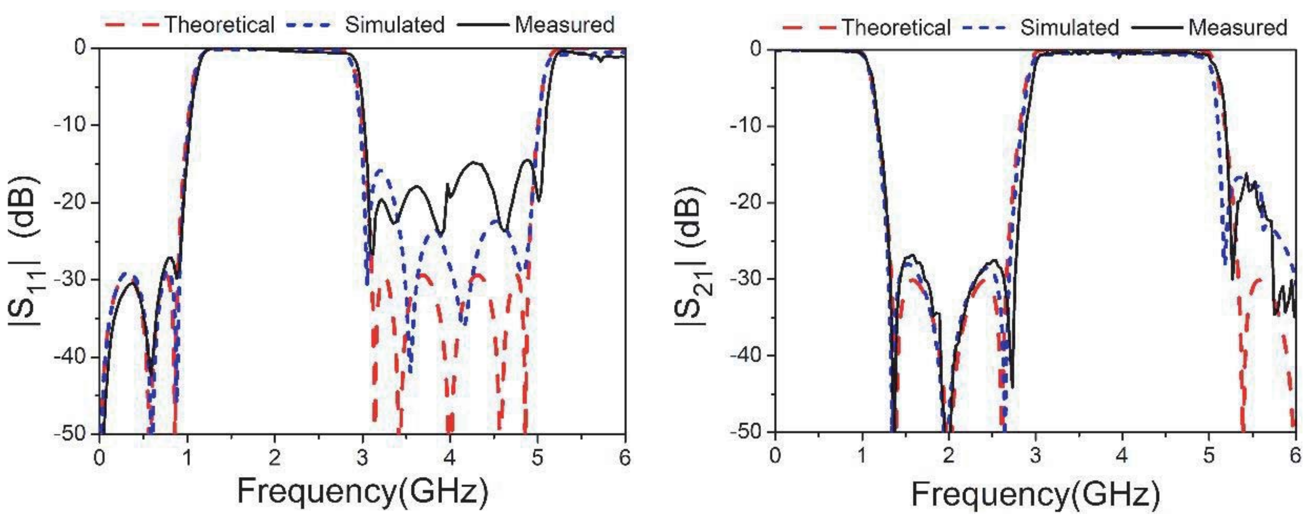
Figure 6. Responses of different approximation.

3. EXPERIMENTAL RESULTS

A BSF example having the passband ripple of 0.005 dB, the minimum stopband attenuation of 30.1 dB, and a stopband fractional bandwidth of 66.2% at a center frequency of 2 GHz is designed and fabricated. Normalized element values of its lumped lowpass equivalent circuit can be obtained using traditional

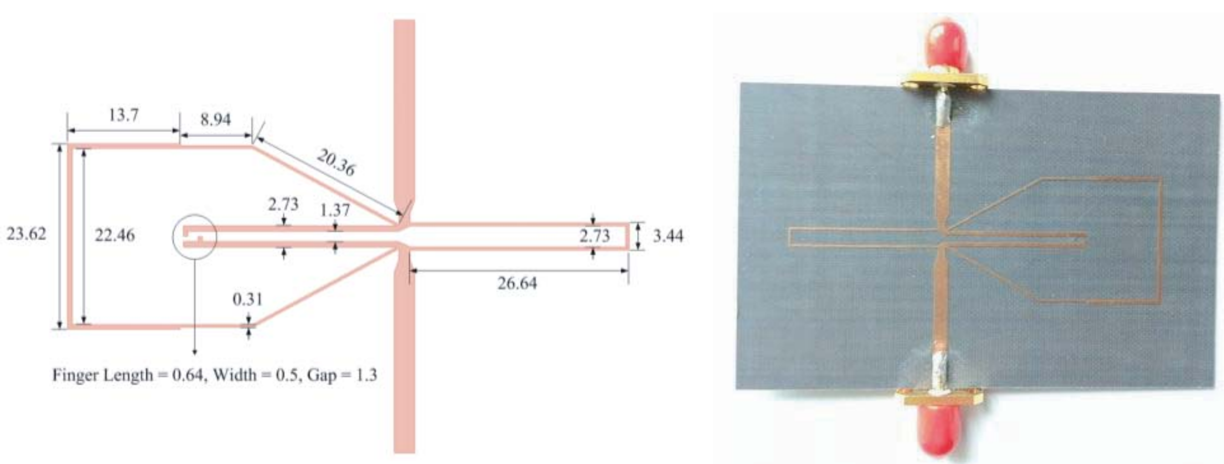
Table 1. Element values of the proposed BSF for responses in Figure 6.

Elements Responses	Z_{1e}	Z_{1o}	Z_2	Z_3	Z_4
Quasi-elliptic 1	181.6	71.58	161.2	122.8	89.72
Quasi-elliptic 2	143.3	75.58	161.2	122.8	93.72
Elliptic	190.1	7.88	161.2	122.8	89.4
Chebyshev	129.4	75.48	131.6	95.42	114.9



(a) (b)

Figure 7. Theoretical, simulated and measured results of (a) S_{11} and (b) S_{21}.



(a) (b)

Figure 8. (a) Layout and (b) photograph of the example filter.

synthesis theory. The scaled elements here are obtained directly from an optimization approach as $C_1 = 0.01689$, $L_2 = 68.64$, $C_3 = 0.03894$, $L_{12} = -937.1$, and $C_{12} = 0.007879$. The element values of the BSF are $Z_{1e} = 108.5\,\Omega$, $Z_{1o} = 85.16\,\Omega$, $Z_2 = 120\,\Omega$, $Z_3 = 89.8\,\Omega$, and $Z_4 = 130.4\,\Omega$. A microstrip substrate with the dielectric constant of 2.65, the thickness of 1 mm, and the loss tangent of 0.003 is used.

The theoretical, simulated, and measured results are compared in Figure 7 where good agreement on the whole can be observed. Deviations primarily come from parameter errors of substrate and fabrication errors during chemical etch. Figure 8 depicts the layout and a photograph of the BSF where interdigital capacitor in layout is used to compensate the difference of even- and odd-mode electrical length of the coupled microstrip line

4. CONCLUSION

This letter presents a wideband BSF using both cross coupling and signal interference techniques, from which steep passband skirt and enhanced stopband attenuation are able to be achieved. A lumped lowpass filter is introduced to clarify the order and mechanism of the BSF. Rigorous correspondence between the BSF and lumped lowpass filter is established. Consequently, design of the BSF is transferred to the synthesis of its lumped counterpart which has much developed design theory. Many fifth order approximations, such as elliptic function, generalized Chebyshev, Chebyshev, are found to be applicable to the proposed BSF. An example BSF has been designed for verification.

REFERENCES

1. Levy, R., R. V. Snyder, and S. Shin, "Bandstop filters with extended upper passbands," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 54, No. 6, 2503–2515, Jun. 2006.
2. Liu, G. and Y. Wu, "Novel in-line microstrip coupled-line band-stop filter with sharp skirt selectivity," *Progress In Electromagnetics Research*, Vol. 137, 585–597, 2013.
3. Yeo, K. S. K. and P. Vijaykumar, "Quasi-elliptic microstrip bandstop filter using tap coupled open-loop resonators," *Progress In Electromagnetics Research C*, Vol. 35, 1–11, 2013.
4. Malherbe, J. A., "Pseudo-elliptic bandstop filter with 1 : 2 : 3 harmonic ratio stubs," *Electronics Letters*, Vol. 49, No. 2, 130–131, 2013.
5. Chen, F. C., R. S. Li, J. M. Qiu, and Q. X. Chu, "Sharp-rejection wideband bandstop filter using stepped impedance resonators," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, Vol. 7, No. 3, 444–449, Mar. 2017.
6. Wenzel, R. J., "Small elliptic-function low-pass filters and other applications of microwave C sections," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 18, No. 12, 1150–1158, Dec. 1970.
7. Luo, S., L. Zhu, and S. Sun, "Stopband-expanded low-pass filters using microstrip coupled-line hairpin units," *IEEE Microwave and Wireless Components Letters*, Vol. 18, No. 8, 506–508, Aug. 2008.
8. Ma, K. and K. S. Yeo, "New ultra-wide stopband low-pass filter using transformed radial stubs," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 59, No. 3, 604–611, Mar. 2011.
9. Shaman, H. and J. S. Hong, "Wideband bandstop filter with cross-coupling," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 55, No. 8, 1780–1785, Aug. 2007.
10. Liang, L. M., Y. A. Liu, J. C. Li, S. L. Li, C. P. Yu, Y. L. Wu, and M. Su, "A novel wide-stopband bandstop filter with sharp-rejection characteristic and analytical theory," *Progress In Electromagnetics Research C*, Vol. 40, 143–158, 2013.
11. Her, M.-L., Q.-M. Lin, K.-Y. Lin, Y.-D. Wu, and Y.-L. Wang, "Dual-mode and three-transmission-zeros bandstop filters with closed-loop ring resonators," *Microwave and Optical Technology Theory Letters*, Vol. 44, No. 2, 114–118, Jan. 2005.
12. Mandal, M. K. and P. Mondal, "Design of sharp-rejection, compact, wideband bandstop filters," *IET Microwave Antennas & Propagation*, Vol. 2, No. 4, 389–393, 2008.

13. Sánchez-Soriano, M. Á., G. Torregrosa-Penalva, and E. Bronchalo, "Compact wideband bandstop filter with four transmission zeros," *IEEE Microwave and Wireless Components Letters*, Vol. 20, No. 6, 313–315, Jun. 2010.
14. Cui, D., Y. Liu, Y. Wu, S. Li, and C. Yu, "A compact bandstop filter based on two meandered parallel-coupled lines," *Progress in Electromagnetics Research*, Vol. 121, 271–279, 2011.
15. Muñoz-Ferreras, J.-M. and R. Gómez-García, "A digital interpretation of frequency-periodic signal-interference microwave passive filters," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 62, No. 11, 2633–2640, Nov. 2014.