Hindawi Publishing Corporation
Active and Passive Electronic Components
Volume 2008, Article ID 356049, 6 pages
doi:10.1155/2008/356049

Research Article

Compact Bandstop Filters with Extended Upper Passbands

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Received 12 March 2008; Revised 17 May 2008; Accepted 2 June 2008

Recommended by Yalin Lu

This paper presents new compact bandstop filters (BSFs) with extended upper passbands. In the basic proposed filter configuration, the conventional quarter-wavelength open-stub resonators are replaced with equivalent two-section stepped impedance resonators. Transmission line analysis is used to determine the dimensions of the equivalent stepped impedance sections. The filter structure is analyzed using a full wave electromagnetic (EM) simulator and then realized at 2.3 GHz band. Experiments have also been done to validate the performance of the design concept. Compared with the conventional quarter-wavelength-based bandstop filter, significant extensions of the upper passband beyond 9 GHz and 40% size reduction are achieved. Two other variations of the proposed basic BSF with further size reduction (more than 60%) are implemented and their measured performances are verified.

1. INTRODUCTION

Bandstop filters (BSFs) are key building blocks in modern RF/microwave communication systems. Such filters play the main role of filtering out the unwanted signals and passing the desired signals. In RF/microwave systems, active devices, such as oscillators and mixers, are systematically followed by bandpass/bandstop filters to remove harmonics and other spurious signals. BSFs have found many applications in microwave/millimeter-wave systems where numerous components including diplexers and switches are comprised of BSFs. Moreover, a BSF can be used as a radio-frequency (RF) choke to conduct bias current and to choke off RF transmission over its lower stopbands [1–4].

Microstrip circuits, in general, and specifically filters have the advantages of low-cost, low-weight, and ease of implementation. Conventional microstrip BSF [2–4] is composed of shunt open-circuited resonators that are quarter-wavelength long and with connecting lines that are also quarter-wavelength long. Conventional bandstop filters that consist of transmission lines or uniform distributed elements encounter a severe restriction on the extent of the upper passband imposed by the periodicity of the distributed elements. This causes the stopbands to repeat at odd multiples of the fundamental stopband center frequency. Bandstop filters with quarter-wavelength resonators give a first-upper stopband center frequency located at three times the fundamental stopband. Numerous efforts have been contributed to enhance and control the size, the rejection bandwidth, and the passbands of the microstrip bandstop filters [4–7]. In [8], a modern synthesis technique is employed to design an extended upper passband multi-compound resonator commensurate-line microwave bandstop filter with possible lumped elements. The upper stopband center frequency has been extended to six times the fundamental stopband center frequency by a new design procedure that uses coupled line configuration with the open stubs replaced by loading capacitors. More recently, this ratio has been improved to 18 times the main stopband with realizable element values [9]. In the basic design of [9], resonators made up from commensurate open circuit (OC) and short circuit (SC) stubs coupled by inverters are used. The inverters are, then, converted into proper number of unit elements (UE) which increase the degree of the filter and contributes to the filter response considerably upon optimization. L-type inductively loaded and capacitively loaded parallel coupled line (PCL) resonators are proposed as possible configurations of the new banstop filter design as well. Optimization is executed to

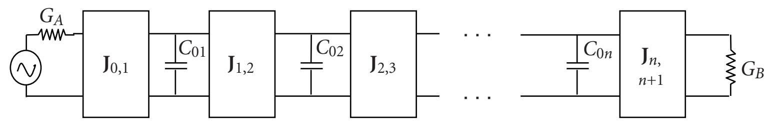

Figure 1: LPF prototype based on shunt capacitors and admittance inverters.

attain the targeted responses of the high-degree filters. The total number of UEs affects the filter total length as well as the required values of the impedances of the PCL resonators. The main limitation for realization of such filter circuits seems to be coming from the implementation of lumped capacitors which should operate up to the targeted upper-edge frequency.

The transmission zeroes formed by the distributed resonators in the BSF basic circuit shape the stopband response of the filter [1, 2, 9, 10]. Based on that, new shaped structures of compact bandstop filter sections are presented in this paper. The proposed designs remove the repeated odd-multiple resonance limitation using nonuniform stepped impedance resonators that have shorter electrical lengths. These simple filter-configurations that incorporate no lumped elements have more degrees of freedom for the dimensions of the stepped resonators and accomplish wider upper passbands. These structures feature compact size BSFs and avoid using shorted stubs or via holes as well. The desired operation is accomplished by using stepped impedance shaped sections [11, 12]. Each branch with quarter-wave length ($\lambda/4$) is converted to its equivalent two-section stepped impedance shaped section. The resulted basic filter configuration will have a significant more than 40% area-size reduction. The proposed filter structures have their classical stopbands besides wide extended passband regions. To facilitate the design of the proposed basic filter, closed forms are depicted utilizing transmission line analysis of the stepped impedance sections. The final layout of the basic filter structure is designed based on these formulas, and then analyzed using a full wave electromagnetic (EM) simulator. To verify the design concept, a microstrip bandstop filter element exhibiting extended upper passband operation is realized on FR4 substrate ($\varepsilon_r = 4.6$, thickness (h) = 1.4986 mm) at 2.3 GHz band. The measured results are in a very good agreement with the theoretical results for the rejection and passband operations of the proposed structure. Two other variants of the proposed basic stepped impedance BSF that achieve more than 60% surface size-reduction are simulated and implemented and their measurements ensure their good performances as compared to the covenantal BSF. These filter structures can be used as a stand alone simple bandstop filter or as a section in a higher order multisection filter.

2. ANALYSIS

The conventional microstrip-based bandstop filter can be derived from the lowpass filter (LPF) prototype. The design starts with n-section low pass filter in the form of shunt capacitors and admittance inverters [1, 9, 10] as shown in Figure 1. A suitable frequency transformation [1, 10] converts the shunt capacitors of the LPF prototype circuit to a series resonance circuit at the fundamental frequency that could be implemented by open circuit microstrip stubs as shown in Figure 2. All stubs and transmission line inverters connecting the stubs are with the commensurate length of ($\lambda/4$) at the center frequency (f_0) of the bandstop filter.

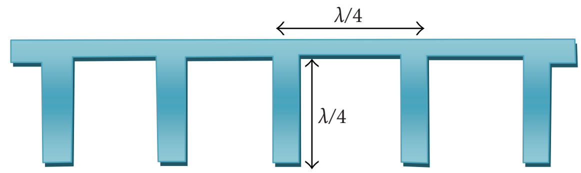

Figure 2: Conventional commensurate microstrip BSF derived from the LPF prototype.

LP prototype to distributed element BSF mapping resulting in circuit made up of OC and SC stubs and ideal inverters could be, effectively, employed as described in [9]. This transformation converts the shunt capacitors into shunt arm series OC and SC stubs. The series combinations of SC and OC stubs form distributed resonators of finite transmission zero (FTZs) which shape the stopband of the filter. The resonators (FTZs) can also be formed by parallel combination of SC and OC stubs in series arms [9]. The use of quarter wavelength open-stub resonators causes the stopband behavior to be repeated at odd multiples of the center frequency of the fundamental response. In particular, the nearest spurious stopband is located at three times the fundamental stopband.

Figure 3 depicts one section of the conventional distributed microstrip BSF [2–4]. In the present work, each quarter wave length ($\lambda/4$) open-stub section of the conventional BSF of is converted to a stepped-impedance shaped transmission line section. The stepped (shaped) transmission line model shown in Figure 2 is consisted of two connected series transmission line sections. The equivalence between the uniform quarter-wavelength long open-stub section and the nonuniform stepped impedance section is investigated using transmission line theory.

Let θ_1 and θ_2 denote the effective electrical lengths of the lines with Z_1 and Z_2 characteristic impedances, respectively. Investigating the input impedance of the stepped impedance section at resonance, the following equation can be derived [8, 11]:

$$K = \frac{Z_2}{Z_1} = \tan\theta_1 \ \tan\theta_2, \quad (1)$$

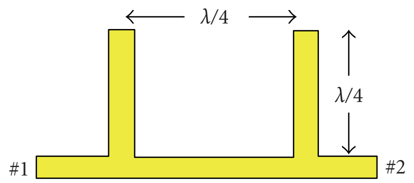

Figure 3: Conventional one-section BSF with two resonators structure.

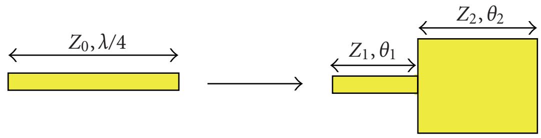

Figure 4: Equivalence of stepped impedance and open circuit quarter-wave sections.

where K equals to Z_2/Z_1. Design curves are drawn in Figure 3 for different values of K. The total electrical length of the resonator is given by

$$\theta_t = \theta_1 + \theta_2. \quad (2)$$

It is noted that for $K = 1$ (uniform resonator), the total electrical length is 90° and the total length of the nonuniform resonator decreases as the impedance ratio K decreases. A quarter-wavelength uniform resonator will resonate at its fundamental frequency and repeats at odd multiples of the fundamental frequency whereas the nonuniform stepped impedance resonator will effectively remove this resonance (odd multiples) repetition.

For practical realization of microstrip lines, the characteristic impedances should be bounded in the region ($25\,\Omega \leq Z \leq 150\,\Omega$). Consequently, the corresponding practical impedance ratio must be in the range ($0.17 \leq K \leq 4$).

Utilizing (1), the first spurious frequency (f_{s1}) of the stepped impedance resonator can be deduced since the equality will be repeated at each spurious frequency. The ratio of the first spurious response to the center frequency (f_{s1}/f_0) depends on the values of the impedance ratio K as well as the stepped-sections electrical lengths. Figure 6 illustrates the control of the first spurious frequency by the impedance ratio K for varying θ_1 value while Figure 7 compares the frequency responses of the conventional and the modified (stepped resonator based, $K = 0.25$ and $\theta_1 = 25^\circ$) BSFs. It is manifested from these figures that the smaller the impedance ratio K, the wider is the upper passband region for compact BSFs. As inferred from these figures, reentrant responses in a realizable single-section stepped impedance resonator can be delayed up to eight times the center frequency.

Investigating Figure 5 for the relation of θ_1 and θ_2 for different values of K, the symmetry of θ_1 and θ_2 values around the line $\theta_1 = \theta_2$ can be noticed. This permits the advantage of interchanging θ_1 and θ_2 values without changing the impedances Z_1 and Z_2, that is, keeping K unchanged. This advantage gives another degree of freedom in selecting

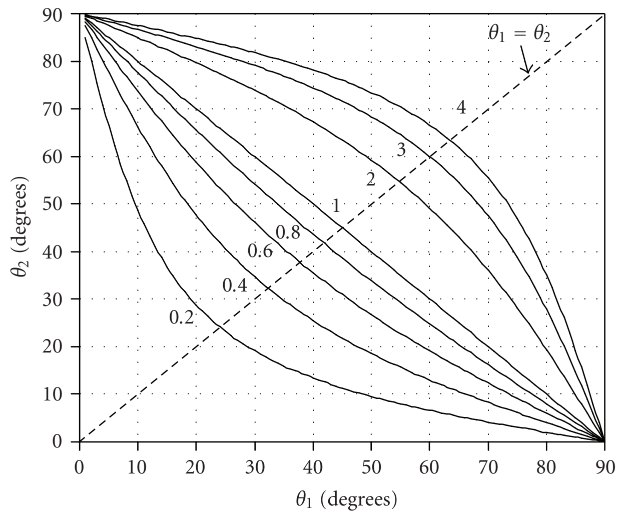

Figure 5: θ_1 versus θ_2 for different values of K.

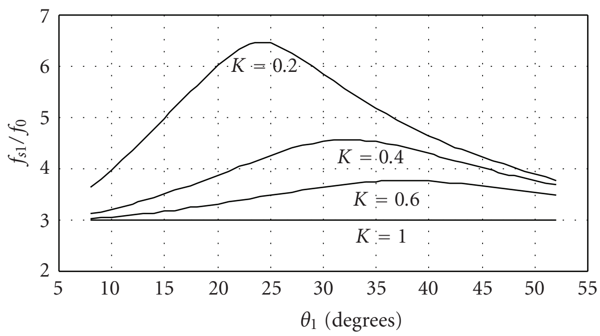

Figure 6: Variation of the first spurious frequency with the impedance ratio K.

the proper line lengths according to the geometry constrains. In the next section, design and implementations of the stepped impedance BSF in different configurations utilizing the above analysis along with numerical optimization to compensate for edge and proximity effects are carried out. For compact design, the following parameters are chosen, $Z_1 = 120\,\Omega$, $Z_2 = 30\,\Omega$ and hence $K = 0.25$.

3. DESIGN, SIMULATION, AND EXPERIMENTAL RESULTS

A compact BSF is designed for the 2.3 GHz band. Based on the previously outlined design procedures with $Z_0 = 50\,\Omega$, the filter parameters will be $Z_1 = 120\,\Omega$, $Z_2 = 30\,\Omega$, $\theta_1 = 18^\circ$, and $\theta_2 = 36^\circ$. The designed BSF is simulated using a full wave EM software package and then realized on FR4 substrate ($\varepsilon_r = 4.6$, $h = 1.4986$ mm). Figure 8 shows the layout of the designed BSF. Further optimization to yield the desired performance has been carried out. The wider lower impedance transmission line sections are brought inside the filter inner space to save space, and then further optimization for the dimensions of all filter sections are

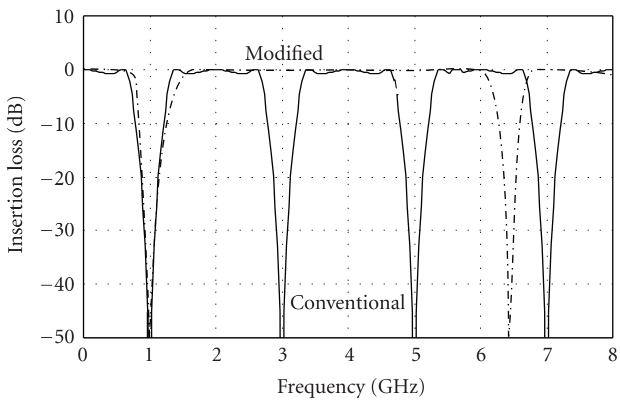

FIGURE 7: The first spurious frequency of conventional and modified BSFs.

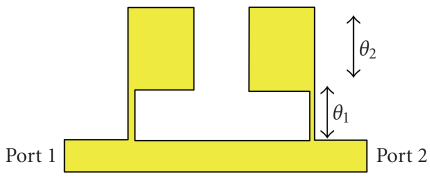

FIGURE 8: The proposed bandstop filter with stepped resonator structure.

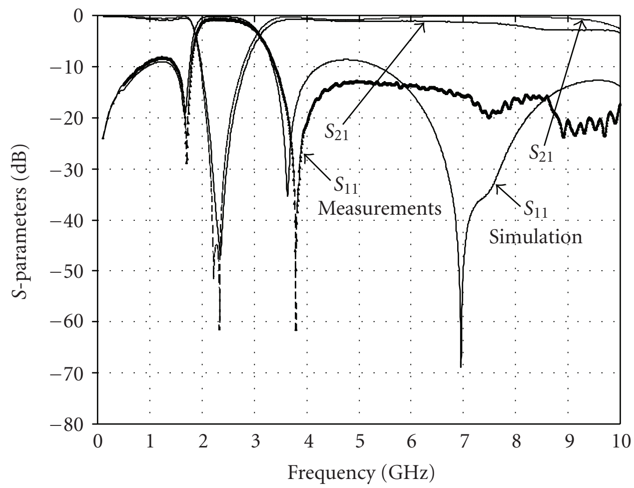

FIGURE 9: Simulation and measurement results of the proposed stepped impedance bandstop filter.

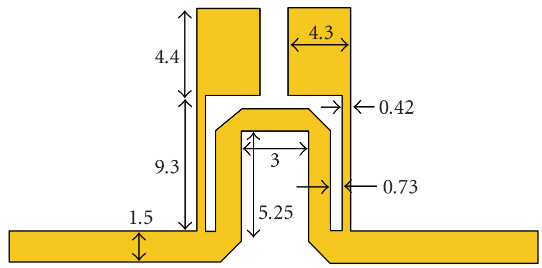

FIGURE 10: The shaped stepped impedance bandstop filter with dimensions in mm.

carried out numerically. The inverter section impedance is tuned to improve the return loss of the upper passband. The fabricated bandstop filter resulted in a more than 40% size reduction as compared to the conventional all-quarter-wave length-based filter.

The measurement results of the realized BSF filter are compared with the simulation results in Figure 9. From Figure 9, it is evident that the measurement results are in a very good agreement with the simulated results. In the rejection band, the measured coupling S_{21} maintains a very low value around −46 dB with the reflection coefficient S_{11} in its maximum value around 1 dB. In the passband, the coupling S_{21} is within (−2 dB) over a wide extended passband up to 9 GHz. Actually, the slight loss-increase at the higher frequencies is obviously attributed to the lesser quality FR4 substrate at frequencies higher than 2 GHz. The simulation results show almost a perfect insertion loss over the entire extended upper passband. The reflection coefficient S_{11} maintains a value less than −13 dB in the extended passband. The proposed compact BSF does not have the repeated stopbands at odd multiples of the operating frequency and, hence, demonstrates a well-extended passband region up to 9 GHz with enhanced performance in terms of the insertion loss and the return loss values.

The second BSF configuration is similar to the first one but with the series 90° line shaped and bended and with the section lengths θ_1 and θ_2 interchanged to have a better space utilization efficiency. More optimization is applied to compensate for edge discontinuity and proximity coupling effects of the structure. This configuration shown in Figure 10 is implemented on Duroid substrate ($\varepsilon_r = 2.33$, substrate thickness $(h) = 0.508$ mm, loss tangent $(\tan\delta) = 0.004$). Figure 11 demonstrates the good performance of this shaped configuration as presented by the simulation and measurement S-parameters of the BSF structure. S_{11} and S_{21} maintain quite good values in the stopband and in the passband.

The third configuration investigated and implemented at 2 GHz is that of Figure 12. This configuration has a straight (unshaped) series line but with a shorter length. The length of the series branch is kept around 52° in this structure to get more than 30% additional surface reduction on the BSF design. The effect of this shorter series line in the BSF performance is inconsequential. The slower (smoother and wider) fall of the S_{21} after the transmission zero is the only noticeable effect of this modification as shown in Figure 13. This effect is compensated by the perfect transmission behavior represented by the S_{21} values in the passband region of the BSF.

The three presented structures can be classified as medium stop-bandwidth filters in their basic section-forms. A better performance in terms of deeper rejection and a wider rejection bandwidth can be achieved by cascading more identical stepped impedance sections in the filter

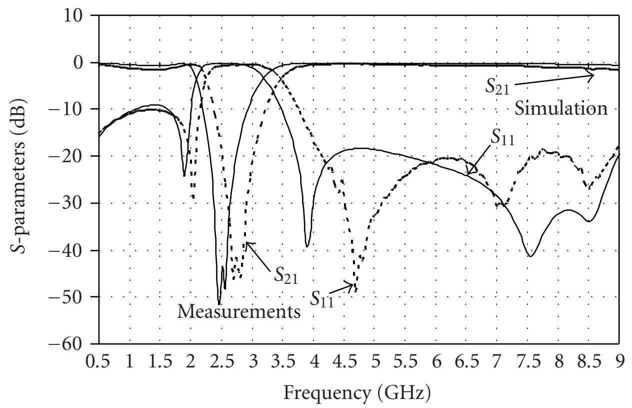

Figure 11: Simulation and measurement results of the shaped stepped impedance bandstop filter.

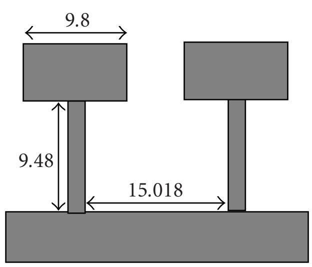

Figure 12: The shortened stepped impedance bandstop filter with dimensions in mm.

structure but at the expense of increasing circuit size and complexity. Numerical optimization incorporating the stubs as well as the unit-elements in multisection filters is successfully used to obtain the required design insertion loss and rejection bandwidth [8–10].

4. CONCLUSIONS

This paper presents analysis and design of new compact bandstop filters with wide extended upper passband regions. The basic design configuration uses stepped impedance section transformation of the quarter wavelength open-stub resonator sections of the filter with no short circuit stubs, lumped elements, or via holes. Practical and simple design procedures are depicted. The design of a basic compact bandstop filter with extended upper passband is examined using a full wave EM software simulator and then realized on FR4 substrate. The measurements of the realized basic filter structure are in a very good agreement with the simulated results and demonstrate the quality of the presented design. Two other variations of this basic stepped impedance BSF design that accomplish more than 60% size-reduction are implemented and measured as well. Simulation and measurements of these reduced size BSFs prove their good performance as compared to the covenantal BSF. The proposed designs can serve as standalone simple

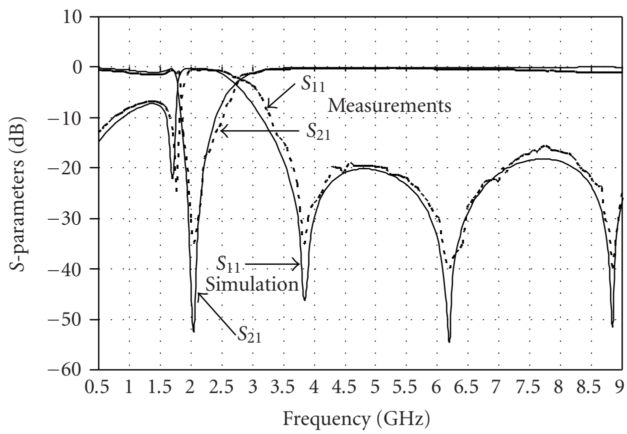

Figure 13: Simulation and measurement results of the shortened stepped impedance bandstop filter.

BSFs or as filter sections that can be cascaded in multisection optimized bandstop filter configurations.

ACKNOWLEDGMENT

This research is supported by the Research Center in the College of Engineering at King Saud University under Grant 38/429.

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