Design of bandstop filters utilising circuit prototypes

W.M. Fathelbab and M.B. Steer

Abstract: A systematic circuit-oriented approach to the design of bandstop filters with pre-defined upper passband characteristics is presented. An experimental filter is built with a fundamental stop-band centred at 1.085 GHz and a first spurious stopband centred at 5.4 GHz.

1 Introduction

Conventionally-designed bandstop filters typically have a first spurious stopband at a frequency only three times that of the fundamental stopband centre frequency, f_o [1, 2]. A solution to this problem was recently proposed by Levy *et al.* [3] who introduced bandstop filter structures with extended upper passbands. Design of the filters in [3] begins with conventional bandstop networks and improvement of their upper passband performance is subsequently done by circuit optimisation.

It is the purpose of this paper to redesign the filter structures presented in [3] based on a systematic circuit-oriented approach. The method presented provides insight into the physical operation of these filters and requires minimal circuit optimisation.

2 Circuit-oriented design

Fig. 1*a* depicts a lumped element lowpass prototype that realises finite-frequency transmission zeros due to the series parallel LC branches. This prototype is then transformed to that of Fig. 1*b* (with impedance inverters) using the conventional bandstop transformation for a certain stop-band bandwidth. From Fig. 1*b* the impedance function of any of the lumped bandstop resonators can be expressed in terms of the Laplace variable, s as

$$Z_i(s) = \frac{(L_iC_i)s^2 + 1}{(C_i)s} \qquad i = 1, 2, 3\ldots \tag{1}$$

The transmission zeros of the fundamental stopband are found from (1) as follows

$$\omega_{oi} = \pm\frac{1}{\sqrt{L_iC_i}} \qquad i = 1, 2, 3\ldots \tag{2}$$

Each lumped bandstop resonator can be exactly transformed into a shunt section comprising series short- and open-circuited stubs of characteristic impedances Z_{SCi} and Z_{OCi}, respectively. This leads to the distributed bandstop prototype shown in Fig. 2. In this case, the impedance function of any of the distributed bandstop resonators can be expressed in terms of the Richards' variable, S as

$$Z_i'(S) = \frac{(Z_{SCi})S^2 + Z_{OCi}}{S} \qquad i = 1, 2, 3\ldots \tag{3}$$

Consequently, the set of resonant frequencies of (1) may now be rederived using (3) to give

$$\omega_{oi} = \pm\left(\frac{2\omega_r}{\pi}\right)\tan^{-1}\left(\frac{\sqrt{Z_{SCi}Z_{OCi}}}{Z_{SCi}}\right) \qquad i = 1, 2, 3\ldots \tag{4}$$

In (3) and (4), S is equal to $j\tan((\pi/2)(\omega/\omega_r))$ where ω_r is the angular frequency at which the stubs of the prototype are one quarter-wavelength long. Thus, to transform a lumped element bandstop resonator into its distributed counterpart equations (1) and (3) and that their differentials must be equal at each respective resonant frequency, ω_{oi} for a selected commensurate frequency, ω_r. This leads to the following design expressions

$$Z_{SCi} = \frac{\begin{pmatrix} (-\pi\omega_{oi}^3L_iC_i + \pi\omega_{oi})S^2 \\ -j(2\omega_r\omega_{oi}^2L_iC_i + 2\omega_r)S \\ +\pi\omega_{oi}^3L_iC_i - \pi\omega_{oi} \end{pmatrix}}{j2\pi\omega_{oi}^2C_i(S^2-1)S} \qquad i = 1, 2, 3\ldots \tag{5}$$

$$Z_{OCi} = \frac{S\begin{pmatrix} (-\pi\omega_{oi}^3L_iC_i + \pi\omega_{oi})S^2 \\ +j(2\omega_r\omega_{oi}^2L_iC_i + 2\omega_r)S \\ +\pi\omega_{oi}^3L_iC_i - \pi\omega_{oi} \end{pmatrix}}{j2\pi\omega_{oi}^2C_i(S^2-1)} \qquad i = 1, 2, 3\ldots \tag{6}$$

Examination of (3) shows that the function approaches infinity at multiples of ω_r so that the first upper passband is centred at ω_r. With the knowledge of (4), it is seen that (3) also goes to zero at the following set of frequency points

$$k\cdot 2\omega_r - \omega_{oi} \quad \text{and} \quad k\cdot 2\omega_r + \omega_{oi} \qquad k = 1, 2, 3\ldots \tag{7}$$

The response of a bandstop filter with distributed resonators satisfying (3) is shown in Fig. 3. The interesting feature is that the location of the first pair of spurious stopbands is a function of the commensurate frequency, ω_r, and thus by specifying ω_r as large as possible, it is feasible to have a wide spurious-free upper passband.

doi:10.1049/iet-map:20060147

Paper first received 29th June and in revised form 19th November 2006

W.M. Fathelbab is with the Department of Electrical and Computer Engineering, South Dakota School of Mines and Technology, Rapid City, SD 57701-3995, USA

M.B. Steer is with the Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27695-7911, USA

E-mail: wfathelbab@ieee.org

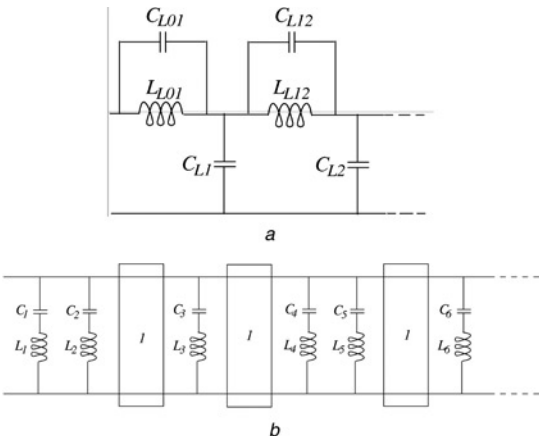

Fig. 1 *Lumped element prototypes*

a Initial lowpass prototype
b Corresponding bandstop prototype with impedance inverters

For example, doubling the commensurate frequency (i.e. moving from ω_r to $2\omega_r$) leads to a response where the spurious responses are shifted leaving behind a broad upper passband region. This vital property of distributed bandstop filters was not highlighted in [3].

The next step is the realisation of the impedance inverters of the prototype. In an analogous fashion to the design approach of [2], each inverter in the distributed prototype of Fig. 2 must be approximated by a physical transmission line that is resonant at the fundamental stopband centre frequency. This is a relatively broadband approximation to an inverter valid for filters with fundamental stopband bandwidths of up to 40%. The proceeding step degrades the return loss (RL) level of the passband and the level of degradation is directly proportional to the width of the fundamental stopband. To elaborate on this point, two filters were synthesised for the same centre and commensurate frequencies, but for different fundamental stopband bandwidths. The RL level in the passband was originally 20 dB. Upon approximation of the inverters by transmission lines, the

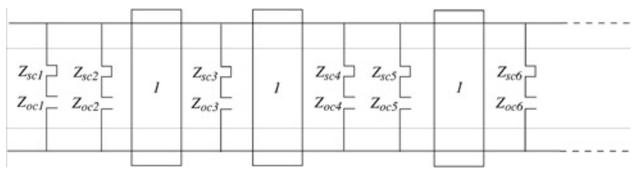

Fig. 2 *Distributed bandstop prototype with impedance inverters*

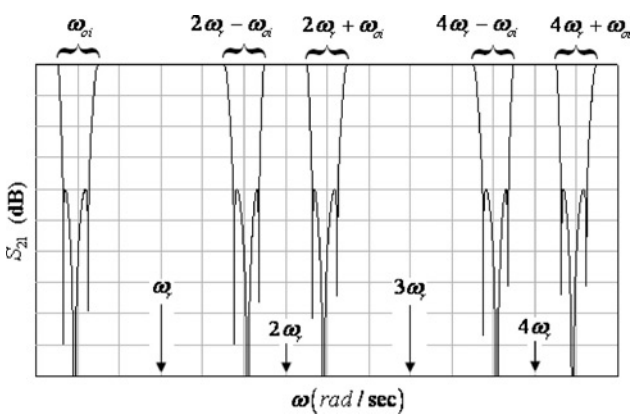

Fig. 3 *Frequency response of a distributed bandstop filter for a commensurate frequency ω_r*

values of the characteristic impedances of the transmission lines were adjusted slightly to restore the RL level back to an acceptable level. The plots illustrated in Fig. 4 show that the optimised RL level was better than 15 dB in the narrowband case but only better than 7 dB in the wideband case. Possible adjustment of the rest of the element values in the networks would eventually lead to better overall performance as is common practice in filter design based on prototype synthesis.

3 Synthesis and implementation of a bandstop filter

The network with the performance of Fig. 4*a* will be derived. Fig. 5*a* shows the synthesised lumped element bandstop prototype. The centre frequency, f_o of the fundamental stopband is 1 GHz and the band-edge frequencies are 962.5 MHz and 1037.5 MHz (i.e. 7.5% bandwidth). The RL level in the passband is 20 dB. The fundamental stopband attenuation level is 40 dB spanning from 977.5 MHz to 1022 MHz. Transformation of this prototype into its distributed form using (5) and (6) for a commensurate frequency, f_r of 3 GHz leads to Fig. 5*b*. Now according to (7), the first pair of upper stopbands will theoretically be centred at frequencies of 5 and 7 GHz. Subsequently, all the inverters in the circuit were approximated by transmission lines that are resonant at f_o. Fine-adjustment of the characteristic impedance of the first transmission line (from the left-hand side of the network) was performed. The value changed from 1 Ω to 1.032 Ω and no other element needed adjustment. Since f_r was selected as $3f_o$ the physical transmission lines were split into three sections as shown in Fig. 5*c*. Consequently, in order to overcome realisation difficulties, the sub-sections inside the dashed boxes were transformed into parallel coupled lines (PCLs) using the

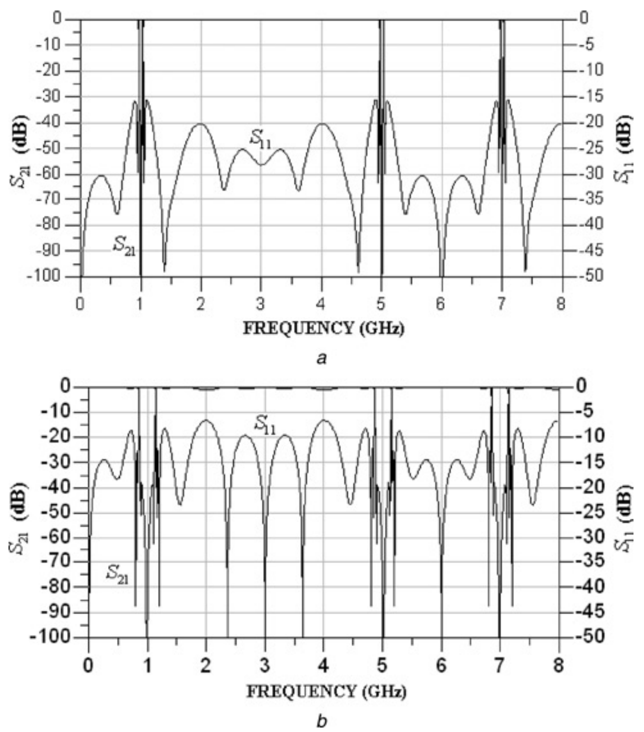

Fig. 4 *Simulated performances of bandstop filters after approximating the inverters in the prototypes by physical transmission lines. The fundamental stopband is centred at 1 GHz and the commensurate frequency is 3 GHz*

a Fundamental stopband bandwith is 7.5%
b Fundamental stopband bandwidth is 40%

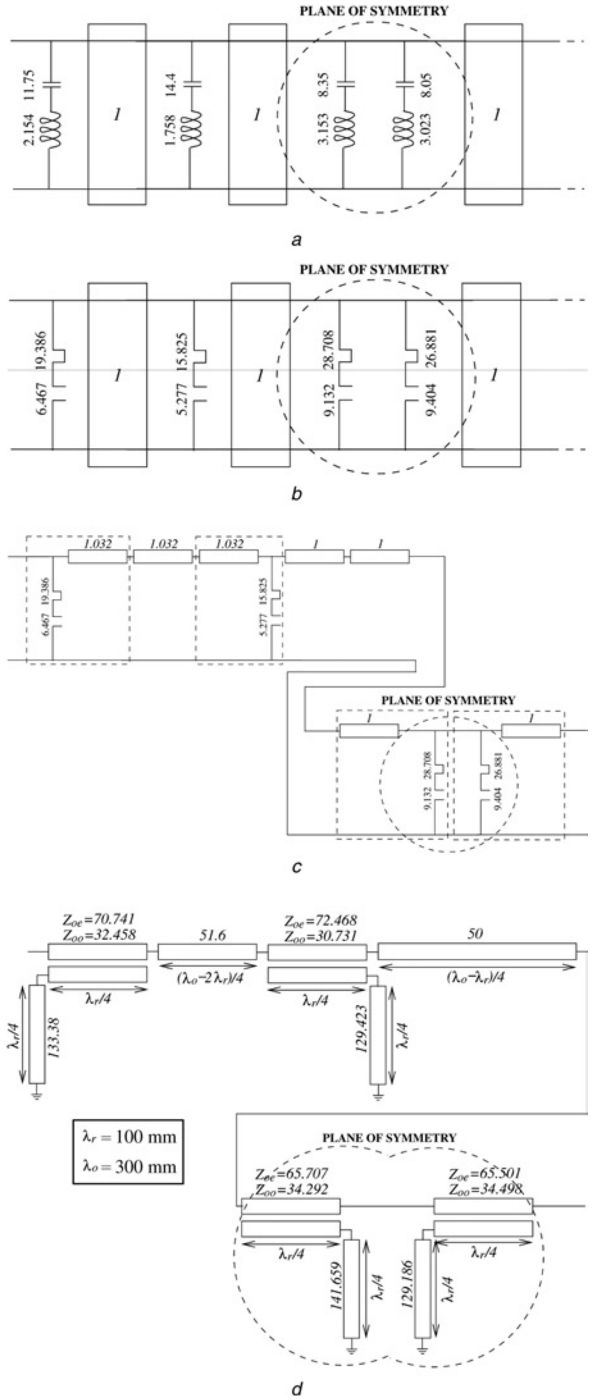

Fig. 5 *Bandstop filter design*

a Synthesised lumped bandstop prototype in 1 Ω system (inductors in nH and capacitors in pF)
b Transformation to distributed prototype (all impedances are in Ω)
c After approximating the inverters by transmission lines
d Electrical filter layout in 50 Ω system

well-known circuit equivalences presented in [1, 3, 4]. The resulting electrical layout of the filter is illustrated in Fig. 5*d*, with small sections of transmission lines separating the PCLs.

A physical layout was then created using ADS [5] for construction on an FR4 printed circuit board (PCB) with a substrate thickness of 62 mil (1.57 mm), relative dielectric constant of 4.7 and loss tangent of 0.016. It is observed from Fig. 5*d* that there is an open-circuited stub with a characteristic impedance of 141.659 Ω. This impedance level is actually the highest that is realisable by the PCB manufacturer corresponding to a 6 mil wide line. This implies that for the 7.5% fundamental stopband, the selected commensurate frequency of 3 GHz can be regarded as the optimum leading to the broadest spurious-free upper passband realisable on this PCB.

The measured response of the filter is shown in Fig. 6. It is observed from Fig. 6*a* that the centre frequency of the filter has shifted up by 8.5%. This can be easily compensated for by slightly increasing the lengths of the bandstop resonators. However, by examining the wide-band performance depicted in Fig. 6*b*, it is clear that the first upper stopband is centred at 5.4 GHz complying with theoretical expectations. It is also observed that the second spurious stopband (that was supposed to be centred at 7 GHz) has disappeared. This is primarily attributed to the parasitic losses in the filter as seen from the plot of Fig. 6*c*.

4 Conclusion

A step-by-step technique for the design of distributed bandstop filters with fundamental stopbands of up to 40% has

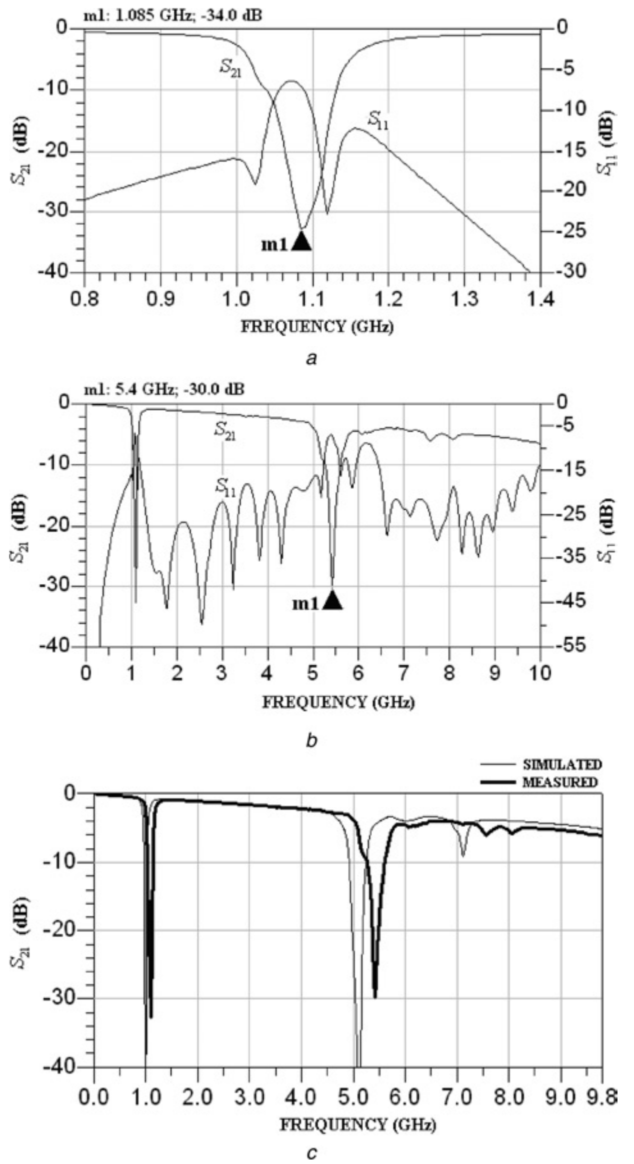

Fig. 6 *Measured performance of the constructed bandstop filter*

a In-band frequency response
b Wide-band frequency response
c Comparison between measured and simulated wide-band performances

been presented. Selection of the commensurate frequency of the distributed bandstop resonators of the filter determines the location of its first pair of upper spurious stopbands. The bigger the commensurate frequency is, the smaller the overall size of the resulting filter and the broader its upper passband. The approach utilises classical circuit synthesis as a starting point leading to filter structures that may require some optimisation. A practical filter was implemented whose performance closely matches the simulations.

5 Acknowledgment

This work was supported by the the National Science Foundation through the EPSCoR grant EPS-0554609 and the U.S. Army Research Office as a Multi-disciplinary University Research Initiative on Multifunctional Adaptive Radio Radar and Sensors (MARRS) under grant number DAAD19-01-1-0496.

6 References

1 Malherbe, J.A.G.: 'Microwave transmission line filters' (Artech House, 1979), pp. 71–108
2 Hunter, I.: 'Theory and design of microwave filters' (IEE Press, 2001), pp. 118–125
3 Levy, R., Snyder, R.V., and Shin, S.: 'Bandstop filters with extended upper passbands', *IEEE Trans. Microwave Theory Tech.*, 2006, **54**, (6), pp. 2503–2515
4 Bell, H.C.: 'L-Resonator bandstop filters', *IEEE Trans. Microwave Theory Tech.*, 1996, **44**, (12), pp. 2669–2672
5 Advanced Design System (ADS), Agilent Technologies, Version 2003A