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A novel compact dual-band bandstop filter with enhanced rejection bands

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ABSTRACT

In this paper, we present the design of a new wide dual-band bandstop filter (DBBSF) using nonuniform transmission lines. The method used to design this filter is to replace conventional uniform transmission lines with nonuniform lines governed by a truncated Fourier series. Based on how impedances are profiled in the proposed DBBSF structure, the fractional bandwidths of the two 10 dB-down rejection bands are widened to 39.72% and 52.63%, respectively, and the physical size has been reduced compared to that of the filter with the uniform transmission lines. The results of the electromagnetic (EM) simulation support the obtained analytical response and show an improved frequency behavior.

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1. INTRODUCTION

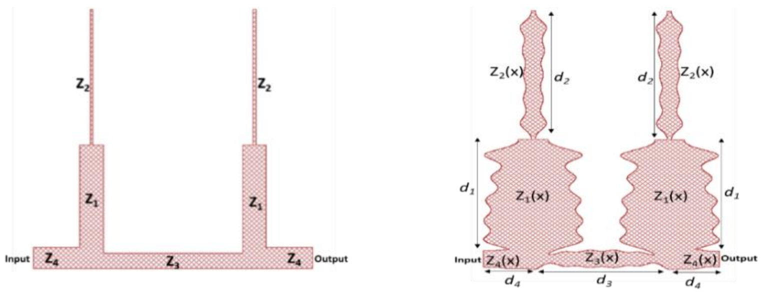
Bandstop filters are critical components in wireless communication systems to suppress unwanted signals or interference at specific frequencies [1]-[3]. They play a vital role in mitigating spurious signals and preventing them from interfering with the desired communication signals. Dual-band bandstop filters (DBBSFs) are a specific type of bandstop filter that have the unique ability to suppress signals at two distinct frequency bands simultaneously. These filters are particularly useful in scenarios where high-power amplifiers and mixers generate unwanted double-sideband spectrum [4]. By using a single DBBSF, it is possible to effectively suppress the unwanted frequencies in both bands, simplifying the filtering process and reducing the size and cost of the overall component.

There are several designs and methodologies that have been proposed to realize a DBBSF [4]-[13]. In Uchida *et al.* [4], a two-step frequency-variable transformation is applied to the low-pass prototype in order to have the dual-band performance. DBBSFs can also be designed by replacing the microstrip lines of conventional bandstop filters with composite right/left-handed metamaterial transmission lines [5]. Feng *et al*. [10], used open/shorted coupled lines for dual-band operation. Chin *et al*. [14], [15] used the stepped-impedance resonators (SIRs) to construct a compact DBBSF [16]. However, none of these circuits could combine a good compact size and wide dual stop bands. In Hammed and Abdulljabar [17], use “stepped impedance loaded resonator” to create a compact “dual-band BSF” utilizing “multilayer technology”; the produced filter circuit area is quite small, although fabrication is a little complex, more expensive to produce than single-layer DBBSFs, and time-consuming. To create a compact multiple bandstop filter, an electrical combination of defected microstrip structure (DMS) and connected dual-mode resonators is used in [18]; however, its frequency response shows narrow rejection bands.

In this work, we present a new compact single-layer dual-band bandstop filter (DBBSF) with wide rejection bands, using nonuniform transmission lines (NUTLs). The method used in this letter to design this DBBSF, is based on replacing conventional uniform transmission lines (UTLs) of the DBBSF in [14] with nouniform transmission lines (NUTLs) governed by a truncated Fourier series. Based on how the impedances are profiled in the proposed filter structure, the FBWs of the two 10 dB-down rejection bands are widened to 39.72% and 52.63% respectively. The obtained theoretical response is supported by full-wave electromagnetic simulations.

2. TRANSMISSION LINE THEORY-BASED ANALYSIS

By replacing the UTLs of the second-order DBBSF shown in Figure 1(a) [14] with optimized NUTLs, the proposed DBBSF is created (Figure 1(b)). This new filter has seven variable-impedance lines that are characterized by the nonuniform impedances $Z_{k=(1,2,3,4)}(x)$ and the lengths $d_{k=(1,2,3,4)}$. The mathematical formulations of these impedances are established following the outline described in the rest of this section.



(a) (b)

Figure 1. Geometry of the DBBSF with SIRs using: (a) UTLs and (b) NUTLs

At first, each NUTL is subdivided into M uniform electrically-short portions with lengths of $\Delta x_{k=(1,2,3,4)} = d_{k=(1,2,3,4)}/M$. Then, at each frequency f_s of the bands $[f_{l1}, f_{h1}]$ and $[f_{l2}, f_{h2}]$ (where f_{l1}, f_{h1}, f_{l2} and f_{h2} are the extremities of the two rejection bands where the filter is designed to operate), the ABCD matrice of the k-th NUTL is determined by multiplying successively the ABCD matrices of its M uniform portions:

$$[AB;CD]_{Z_k(x)} = \prod_{p=1}^{M}[AB;CD]_p \quad (1)$$

While the ABCD matrix of each portion p can be computed by [19]:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}_p = \begin{pmatrix} cos(\Delta\theta_{pk}) & jZ_k(x_p)\, sin(\Delta\theta_{pk}) \\ \frac{j\, sin(\Delta\theta_{pk})}{Z_k(x_p)} & cos(\Delta\theta_{pk}) \end{pmatrix} \quad (2)$$

Where $x_p = (p - \frac{1}{2})\Delta x_k$ represents the center of each portion p, ε_{peff} the effective dielectric constant of each portion p (which is determined using the approximate design formulas of the microstrip line [20]), and $\Delta\theta_{pk}$ the electrical length of the portion p of the k-th line:

$$\Delta\theta_{pk} = \frac{2\pi}{\lambda}\Delta x_k = \frac{2\pi}{c} f_s \sqrt{\varepsilon_{peff}}\Delta x_k \quad (3)$$

In which, c is the speed of the light.

To optimally design the proposed DBBSF, a truncated Fourier series extension for the impedances of the filter lines is used [21]-[26]:

$$Z_{k=(1,2,3,4)}(x) = Z_{0k}\, exp\left[c_0 + \sum_{n=1}^{N}\left(a_n\, cos(\frac{2\pi nx}{d_k}) + b_n\, sin(\frac{2\pi nx}{d_k})\right)\right] \quad (4)$$

Where Z_{0k}, is a predefined reference impedance.

The above-defined impedances $Z_{k=(1,2,3,4)}(x)$ should be constricted by the fabrication tolerances and matching conditions, at the two end terminations of the NUTLs [21]-[27]:

$$Z_{min} \leq Z_k(x) \leq Z_{max} \tag{5}$$

$$Z_k(0) = Z_k(d_k) = Z_{0k} \tag{6}$$

Where Z_{min} and Z_{max} in (5) are the minimum and maximum impedances values, respectively, that bound the nonuniform impedances $Z_{k=(1,2,3,4)}(x)$ in order to guarantee that the manufacturing limits are not exceeded. While the constraint in (6), ensures that both terminations of the NUTLs are equal and matched to Z_{0k}, which is achieved by verifying [21]-[26]:

$$c_0 + \sum_{n=1}^{N} a_n = 0 \tag{7}$$

Next, the ABCD matrix of the nonuniform lines 1 and 2 in cascade, can be determined by:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}_{Ca\_12} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{z_1(x)} \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{z_2(x)} \tag{8}$$

In which, once calculated, the ABCD matrix of the open-circuited stub (composed of the lines 1 and 2 in cascade) is calculated by [19]:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}_{StubO\_12} = \begin{pmatrix} 1 & 0 \\ \frac{1}{Z_{StubO\_12}} & 1 \end{pmatrix} \tag{9}$$

Where $Z_{StubO\_12} = A_{Ca\_12}/C_{Ca\_12}$ is the input impedance of the open-circuited stub. Then, the global ABCD matrix of the proposed filter structure is expressed by:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}_{G} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{z_4(x)} \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{StubO\_12} \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{z_3(x)} \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{StubO\_12} \begin{pmatrix} A & B \\ C & D \end{pmatrix}_{z_4(x)} \tag{10}$$

The resulting global ABCD matrix is used to express the reflection coefficients (S_{11}) and the transmission coefficients (S_{21}) of the proposed DBBSF, at each frequency f_s, which are [19]:

$$S_{11} = \frac{A+B/Z_0-CZ_0-D}{A+B/Z_0+CZ_0+D} \tag{11}$$

$$S_{21} = \frac{2}{A+B/Z_0+CZ_0+D} \tag{12}$$

Where $Z_0 = 50\,\Omega$ is the ports impedance. The error function is set so that the DBBSF has a response that matches the design specifications in the two stop bands:

$$E = \begin{cases} \sqrt{(|S_{11}|-1) + |S_{21}|^2} & \text{for } \mathrm{f}_{l1} \leq f_s \leq f_{h1} \\ \sqrt{|S_{11}|^2 + (|S_{21}|-1)^2} & \text{for } \mathrm{f}_{pl} \leq f_s \leq f_{ph} \\ \sqrt{(|S_{11}|-1) + |S_{21}|^2} & \text{for } \mathrm{f}_{l2} \leq f_s \leq f_{h2} \end{cases} \tag{13}$$

Where f_{pl} and f_{ph} are the passband extremities of the DBBSF.

After calculating the above error vector, the optimum values of the coefficient c_0, a_n, and b_n in (4) will be acquired by minimizing the following objective function:

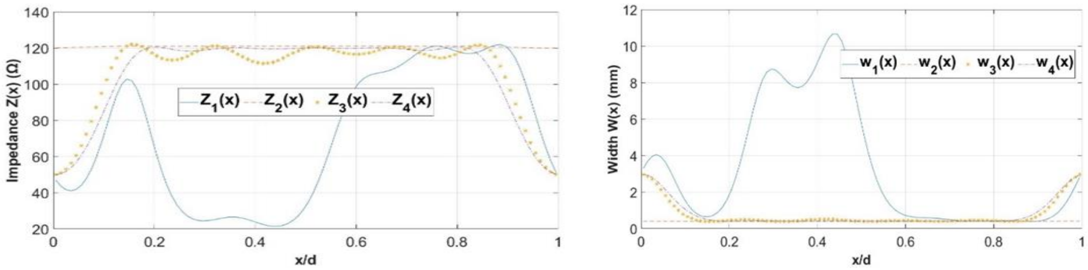
$$Objective = \frac{1}{F_f}\sqrt{\sum_{i=0}^{F_f} E(f_{min} + i\Delta f)} \tag{14}$$

Where $F_f = (f_{h2} - f_{l1})/(\Delta f + 1)$ is the number of frequency points and Δf is the frequency step.

3. RESULTS OF THE THEORETICAL MODEL

In a dual-band bandstop filter is designed, using NUTLs, on a FR-4 substrate with ε_r = 4.3 and a thickness of 1.524 mm. This filter is aimed to provide stop-band performances at the frequencies f_1 = 1.5 GHz and f_2 = 3.15 GHz. In order to reduce the size of the filter structure, the lengths of the nonuniform lines take the values d_1 = 16.54 mm, d_2 = 18.34 mm, d_3 = 14.04 mm, and d_4 = 6.9 mm. The reference impedances required in (4) are fixed as: Z_{01} = 49.05 Ω, Z_{02} = 120 Ω, and Z_{03} = Z_{04} = 50 Ω; while the minimum and maximum impedance values that restrict the varying-impedances $Z_{k=(1,2,3,4)}(x)$ are chosen as 20 Ω and 121 Ω, respectively. To achieve an efficient and fast optimization process at the same time, the numbers of the uniform portions M and the terms of the truncated Fourier series N in (4) are chosen to take the values 25 and 5, respectively.

Figure 2(a) presents the obtained impedance profiles of the DBBSF, after optimizing the coefficient c_0, a_n, and b_n in (4). We notice that all the nonuniform impedance profiles are bounded by the previously defined impedances interval (20 Ω, 121 Ω), and all the optimized lines have $Z_k(0) = Z_k(d_k) = Z_{0k}$. Figure 2(b) contains the widths of the optimized nonuniform lines, they are calculated using the microstrip transmission line theory [20].



(a) (b)

Figure 2. Impedances and widths variations as a function of normalize: (a) impedances and (b) widths

Figure 3 shows the resulting analytical S-parameters of the filter as a function of frequency. We note that the analytical model of the proposed filter has excellent rejection levels on the two frequencies 1.49 GHz and 3.3 GHz ($S_{21} < -129$ dB at 1.49 GHz; $S_{21} < -161$ dB at 3.3 GHz). Since the analytical model has been built based on the transmission line theory, these results need to be verified with an EM simulation.

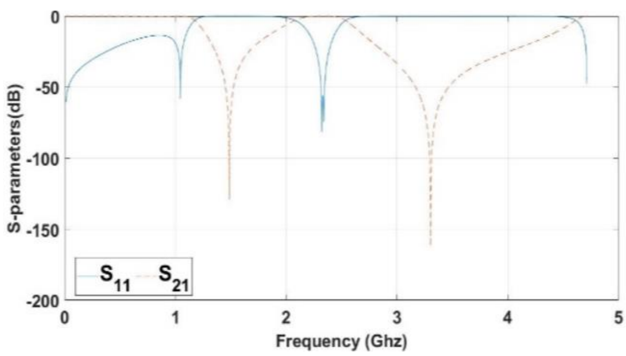


Figure 3. Analytical response of the proposed DBBSF

4. ELECTROMAGNETIC SIMULATION

The final geometry of the proposed DBBSF, based on the optimized widths shown in Figure 2(b), is illustrated in Figure 4 with a three-dimensional view. Figure 5 presents the results of the EM simulation of the proposed DBBSF as a function of frequency (GHz), we note that the two 10 dB stop bands ([1.23 GHz – 1.84 GHz] / [2.52 GHz – 4.32 GHz]) have higher rejection levels (greater than 38 dB) at 1.46 GHz and 3.16 GHz, respectively.

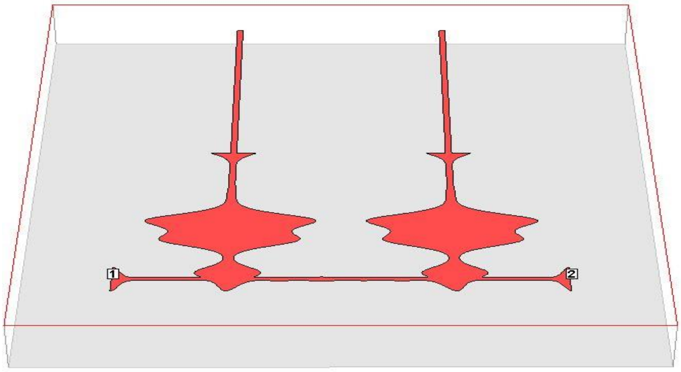


Figure 4. Three-dimensional view of the proposed DBBSF

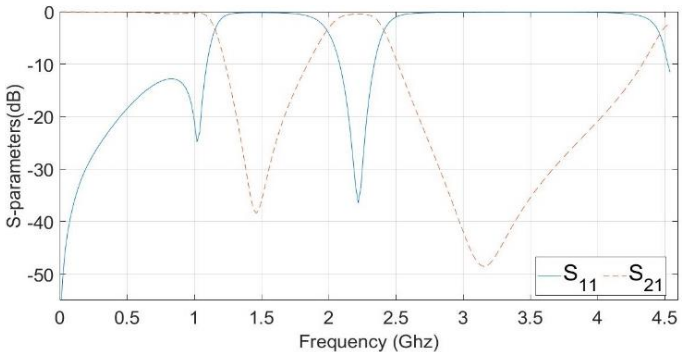


Figure 5. EM simulation results of the proposed DBBSF

Table 1 illustrates the performances of some reported dual-band bandstop filters [10], [14], [15]. The FBWs of the two 10 dB-down rejection bands are widened to 39.72% and 52.63%, respectively. In addition, the physical size of the structure of the new filter is only 27.85×36.57 mm^2, corresponding to a size reduction of 1.35% and 15.1% compared to [14] and [15], respectively. We can see that the proposed filter offers a very good trade-off between the electrical characteristics and the physical size compared to other reported efforts.

Table 1. Comparison between the performances of some DBBSF

Ref.	Central frequency (GHz)	Fractional bandwidth (FBW) of the 10-dB stop-bands (%)	Size (mm2)
[14]	1.57/3.16	35.83/17	28×36.87 †
[15]	1.495/3.11	33.91/16.30	33.38×35.94
[10]	1.5/2.4	16.86/10.82	39.7×18.26 §
This work	1.46/3.16	39.72/52.63	27.85×36.57

Where: †: the size of the filter in [14] is calculated without folding the SIRs stubs, §: the feedlines are not included in the calculation of the size of this filter [10].

5. CONCLUSION

In this paper, we have explored the use of nonuniform transmission lines in the design of a compact dual-band bandstop filter (DBBSF). The principle consisted in replacing the conventional transmission lines, used in the DBBSFs with stepped-impedance resonators (SIRs), by nonuniform lines. The straightforward methodology used allows complete control of the center frequencies and the bandwidths of the designed DBBSFs; this is possible by integrating the suitable design specifications in the algorithm of the optimization during the transmission line theory-based analysis. The impedance variation using the truncated Fourier series leads to a controllable nonuniform width profile; thus, the proposed filter frequency behavior is improved (FBWs of the two 10 dB-down rejection bands are widened to 39.72 % and 52.63 %, respectively) and its size has been reduced.

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