Rigorous design method for distributed-element bandpass filter with reflectionless response at two ports

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This letter reports an accurate and rigorous design method for a distributed-element reflectionless bandpass filter capable of producing a reflectionless response at two ports simultaneously. The design method relies on novel transmission-line reflectionless filter prototypes. This work presents a stub-based reflectionless filter prototype and its design formulas in terms of a target transmission response. It also provides a stub-less coupled-line reflectionless filter prototype equivalent to the stub-based prototype in case where stubs are not feasible. A second-order bandpass filter has been designed and fabricated to verify the design method. Reasonable agreement between the measured performance and the simulated one has been obtained, confirming that the proposed design is valid.

Introduction: Conventional microwave filters perform filtering function in the stopbands by reflection. That is, they block the transmission of signals in the stopbands by reflecting the signals back to the source. It is well known that these reflected signals can have detrimental effects to the systems where mixers, power amplifiers or other active components are employed, consequently degrading the overall performance of the system. Thus, measures should be taken to circumvent the problems caused by the unwanted reflection. For example, filters are required to be accompanied by isolators, circulators, or attenuations pads at the expense of volume, cost, and system performance.

In the recent decade, many approaches for designing filters with reflectionless features have been reported. In [1–4], lumped-element realizations of reflectionless filters are presented. Filters with lumped elements have the merit of easy fabrication, but their application is limited to low-frequency systems as lumped-element components do not operate at high frequencies. Attempts have been made to realize reflectionless filters using distributed elements [5–11]. A complementary bandpass/bandstop duplexer-based design for attaining the reflectionless property is described in [5]. In [6] and [7], a lossy matching section was introduced at the input port to eliminate the signal reflection. While the concepts presented in [5–7] have an input-reflectionless property, two-ports-matched design approaches which have no reflections at both ports also have been explored. The works in [8–11] describe symmetric reflectionless filter design methods, but each has drawbacks that one cannot have arbitrary transmission responses [8], one has to rely on time-consuming parametric studies to obtain design parameters [9], [10] or the application is limited to bandstop responses [11].

This letter examines a design methodology for two-port reflectionless bandpass filters and its realization using distributed elements. More specifically, we present a design method which offers two main benefits over the previously reported ones. First, it presents a two-port reflectionless distributed-element bandpass filter which can have predefined frequency responses of any arbitrary order. Second, its design parameters can be obtained in an equation-based manner which does not require parametric studies. For verification of the proposed design method, a second-order reflectionless inverse-Chebyshev bandpass filter is fabricated and measured.

Filter design: Figure 1(a) shows the circuit schematic of a stub-based reflectionless bandpass filter prototype capable of having a predefined $i$th-order canonical transmission response. It is worth noting that the transmission response is determined by the stub impedance and the resistor values which are given by

$$Z_i = \frac{4Z_0g_i}{\pi\Delta}(k = 1, 2, \ldots, i)$$

$$R_{i+1} = Z_0g_{i+1}$$

where $\Delta$ is the fractional bandwidth and $g_i$ are the normalized low-pass response parameters for canonical responses such as Butterworth response. Examples of the normalized parameters ($g_i$-parameters) can be found in [4]. Using (1) and the $g_i$-parameters, the required impedance values of transmission line stubs can be calculated. However, as it will be demonstrated in the following section, the circuit in Figure 1(a) cannot be considered complete because the stubs may have very large characteristic impedance values, which are in most cases impossible to realize.

For solving this problem, this work proposes a design method that avoids such difficulties and enables realization of reflectionless bandpass filters using distributed elements. More specifically, this work exploits the fact that the physically unimplementable stub can be transformed into a pair of coupled lines with practical characteristic impedance values. From the circuit schematic in Figure 1(a), it can be found that the quarter-wavelength lines ($Z_0$) and the shunt stubs ($Z_k, k = 1, 2, \ldots, i$) appear repeatedly in the circuit structure, and the number of repetition depends on the order of the filter. The repeated structures which are in the dotted boxes can be replaced with a pair of coupled lines using the circuit equivalence [12] as shown in Figure 1(b), and the corresponding formulas are given by

$$Z_{c_{i+k}, j} = Z_0\left(1 + \sqrt{\frac{Z_0}{Z_0 + Z_j}}\right)$$

$$Z_{c_{i+k}, j} = Z_0\left(1 - \sqrt{\frac{Z_0}{Z_0 + Z_j}}\right)$$

where $Z_0$ and $Z_j$ are the impedance of the transmission line and the $j$th shunt stub, respectively.

Figure 2 illustrates the frequency responses of the two prototypes shown in Figure 1 when the center frequency is 2 GHz and fractional bandwidth is 0.1. The corresponding $g_i$-parameters for the inverse-Chebyshev responses with 15-dB ripple level in the stopband are $g_1 = 1.0737, g_2 = 1.5359$ and $g_1 = 1.4321$, respectively. It can be observed from Figure 2(a) that the two sets of responses are not distinguishable from each other. Therefore, it can be concluded that the two prototypes can generate a predefined transmission response.

It has been claimed in the previous section that the presented design method can have a predefined frequency response of any order. To demonstrate this, higher-order inverse-Chebyshev filters with 15-dB ripple level and fractional bandwidth of 0.1 have been designed, and their frequency responses are illustrated in Figure 2(b). The corresponding $g_i$-parameters are summarized in Table 1. Overall, it can be observed that the proposed circuits in Figure 1 can produce the theoretically defined filtering responses. The small discrepancy between the transmission responses in Figure 2 and the target ripple level is mainly due to the dispersion characteristics of the transmission lines and the fact that the transmission lines have either 90° or 270° phase shift only at the center frequency. Our analysis indicates that one can observe better agreement between the measured performance and the simulated response. Examples of the normalized parameters ($g_i$-parameters) can be found in [4]. Using (1) and the $g_i$-parameters, the required impedance values of transmission line stubs can be calculated. However, as it will be demonstrated in the following section, the circuit in Figure 1(a) cannot be considered complete because the stubs may have very large characteristic impedance values, which are in most cases impossible to realize.
Table 1. g-parameters for different orders of inverse-Chebyshev responses

| Order  | 3rd order | 4th order | 5th order |
|--------|-----------|-----------|-----------|
| g₁     | 0.8120    |           |           |
| g₂     | 0.8376    | 0.8941    | 0.8941    |
| g₃     | 0.7368    | 0.7689    | 0.7689    |
| g₄     | 0.4852    | 0.5377    | 0.5377    |
| g₅     | 0.7368    | 1.1966    | 1.1966    |
| g₆     | 1         | 1.4320    | 1.4320    |

where \( k \) is an even number and the g-parameters including \( g′_k \) can be easily derived from the ones for elliptic responses. For example, the g-parameters for the third-order elliptic-response filter with 1 dB passband ripple and 15 dB stopband ripple are \( g₁ = 1.6150 \), \( g₂ = 2.2857 \), \( g₃ = 0.7027 \), \( g₄ = 1.6150 \) and \( g₅ = 1 \). Figure 3 depicts the frequency responses of the third-order elliptic response mentioned above. Although implementing an elliptic response requires modifying the even-numbered stubs, a prototype composed of coupled-line sections can be obtained by using the fact the a stub accompanied by a transmission line is equivalent to a pair of coupled lines [12].

As discussed before, the two prototypes in Figure 1 are equivalent to each other. However, in some cases, the stub-based filter prototype finds difficulties in fabrication due to extremely high or low stub impedances whereas the coupled-line based reflectionless filter prototype have realizable line impedances, which will be discussed with the filter design example in the following section.

**Design, fabrication, and measurement:** In order to verify the design method for the distributed-element reflectionless bandpass filter, we have fabricated and measured a second-order reflectionless bandpass filter whose center frequency is 2 GHz and fractional bandwidth is 0.1. The filter is designed to have a second-order 15-dB reflectionless inverse-Chebyshev response. By virtue of the two prototypes in Figure 1, two reflectionless bandpass filter structures, one with transmission stubs and the other with coupled lines can be obtained, and Table 2 provides the calculated impedance values for the stubs and coupled lines. It can be seen that stubs have unrealistic high impedance values whereas the coupled lines have realizable values.
**Table 2. Calculated impedance values of circuit schematics in Figure 1**

| g-parameters | Stub impedance of circuit in Figure 1(a) | Coupled-line impedance of circuit in Figure 1(b) |
|--------------|----------------------------------------|-----------------------------------------------|
| $g_1 = 1.0737$ | $Z_1 = 683 \Omega$ | $Z_{11\text{-}e} = 63.05 \Omega$ |
| $g_2 = 1.5359$ | $Z_2 = 977 \Omega$ | $Z_{12\text{-}o} = 61.03 \Omega$ |
|               | $Z_{12\text{-}o} = 38.97 \Omega$ |                                               |

![Figure 4. Layout of the second-order reflectionless bandpass filter with detailed physical dimensions.](image)

The microstrip line filter design uses on a Rogers 5880 substrate ($\varepsilon_r = 2.2, \tan\delta = 0.00099$) with the thickness of 0.79 mm. The layout and the dimensions for the circuit is given in Figure 4 where the impedance of quarter-wavelength lines $Z_0$ is set to 50 $\Omega$. The filter has been realized through etching, drilling and plating. The photograph of the fabricated filter is shown in Figure 5 with the measured and the simulated frequency responses. The measured minimum insertion loss of 0.95 dB and the excellent reflection characteristics smaller than -10 dB have been achieved in the frequency range of interest.

**Conclusion:** This letter presented a design method of arbitrary-order bandpass filters with reflectionless properties at two ports. The proposed design method enables straightforward implementation of reflectionless bandpass filters using printed circuit technologies. The two distributed-element reflectionless bandpass filter prototypes were demonstrated with design formulas in terms of a target transmission response. Hence, a filter having a different set of specifications such as the filter order, the center frequency, the bandwidth, and the ripple in the stopband can also be designed without any difficulty by virtue of the design formulas given in terms of them. The design concept has been validated by fabricating and measuring the performance of the second-order filter, and the measured results are in good agreement with what is expected from the simulated results. Although the presented work provides a straightforward design method of a two-port reflectionless distributed-element bandpass filter, there is an improvement that still can be made. Future work will include exploring a circuit topology of which the reflection characteristics at both ports are completely identical.

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