Frequency Response Control in Frequency-Tunable Bandstop Filters

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***Abstract*—This letter presents a tunable bandstop filter with the capability of controlling the shape of the frequency response. The proposed filter structure can be tuned to have either a Butterworth or a Chebyshev response. The filter can also be tuned to have different center frequencies. Both the frequency response and the center frequency of the filter can be tuned by only adjusting the resonant frequency of each resonator without controlling inter-resonator coupling. Since the proposed filter structure has non-zero inter-resonator coupling, it can find its future application in reconfigurable filters which can be tuned to exhibit either a bandstop or a bandpass response.**

***Index Terms*—Bandstop filter, Butterworth filter, Chebyshev filter, filter synthesis, resonator filter.**

I. Introduction

In many spectral environments, bandstop filters are highly desired to suppress spurious or interfering signals in order to protect sensitive receivers. Many types of tunable bandstop filters, such as an electronically tunable bandstop filter with coupled lines [1], a Barium–Strontium–Titanate (BST) varactor tuned bandstop filter [2], and a tunable bandstop filter integrated with large deflected thermal actuators have been presented [3], along with a piezoelectric actuator tuned bandstop filter [4]. Resonators in these conventional tunable bandstop filter structures are coupled to a uniform transmission line but not to each other. Each resonator is separated along the transmission line by a quarter wavelength. Coupling between the transmission line and the resonators determines the frequency response of the filter. Since these tunable filters do not have inter-resonator coupling, it seems that it is difficult to achieve further reconfigurability such as a bandstop-to-bandpass reconfigurable response.

In this letter, we present a bandstop filter which can be reconfigured to have different frequency responses. The proposed filter structure has coupling between each resonator as well as coupling between each resonator and a transmission line. Each resonator is separated along the transmission line by three quarter wavelength. We can adjust both the center frequency and the frequency response of the filter only by independently tuning the resonant frequency of each resonator. Another advantage of the proposed structure is that we can design non-zero inter-resonator coupling structures with fewer restrictions, possibly enabling further filter reconfigurability in future designs. An experimental filter is fabricated for verifying the proposed bandstop filter structure.

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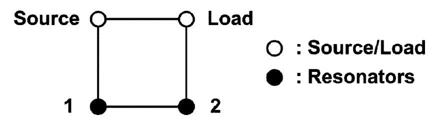

Fig. 1. Coupling routing diagram of a second-order bandstop filter.

II. Theory

A. Conventional Bandstop Filter Design Method

Fig. 1 shows the coupling routing diagram of a conventional second-order bandstop filter and a coupling matrix filter with synchronously tuned resonators is

$$\mathbf{M} = \begin{bmatrix} 0 & M_{S,1} & 0 & M_{S,L} \\ M_{S,1} & 0 & M_{1,2} & 0 \\ 0 & M_{1,2} & 0 & M_{2,L} \\ M_{S,L} & 0 & M_{2,L} & 0 \end{bmatrix} \quad (1)$$

where S and L represent the source and load, respectively, and numbers represent resonators. $M_{S,1}$ and $M_{2,L}$ are external coupling coefficients and $M_{1,2}$ corresponds to the inter-resonator coupling coefficient between resonators 1 and 2. In this letter, we assign a positive sign to $+90^\circ$ insertion phase in the coupling structure. Also, it is assumed that the inter-resonator coupling structure cannot generate a negative coupling coefficient, which is the usual case in practice. $M_{S,L} = -1$ is obvious for a quarter wavelength transmission line between the source and the load, which is the case for conventional bandstop filters. The coupling coefficients for a synchronously-tuned Butterworth bandstop filter are $M_{S,L} = -1$, $M_{S,1} = M_{2,L} = 1.189$, $M_{1,2} = 0$. The normalized coupling coefficients are $M_{S,L} = -1$, $M_{S,1} = M_{2,L} = 1.020$, and $M_{1,2} = 0.2014$ for a synchronously-tuned Chebyshev bandstop filter with 10 dB stopband rejection. Note that the Chebyshev response in this letter is not identical to the standard Chebyshev bandstop filter response [5]. Both filter responses in this letter have an identical 3 dB stopband bandwidth in the normalized frequency domain.

Based on the coupling coefficients for Butterworth and Chebyshev filters, we can conclude that bandstop filters which can be tuned to have different frequency responses are required to have tunable coupling structures. In most practical designs, designing a high-performance electrically-tunable inter-resonator coupling structure is more difficult than designing a tunable external coupling structure. Although a tunable inter-resonator coupling structure has been proposed and successfully applied to a tunable bandpass filter [6], loss is generated by tuning elements like varactors in tunable coupling structures. Also, varactor-tuned inter-resonator coupling structures cannot have a large enough tuning range for both small and large coupling coefficients. Therefore, we propose a new type of bandstop filter which does not need a tunable inter-resonator coupling structure for different frequency responses.

B. Proposed Bandstop Filter Design Method

In the proposed design method, we can have an arbitrary non-zero inter-resonator coupling coefficient for Butterworth and Chebyshev bandstop responses with a given constraint. The coupling matrix for the proposed design method is given by

$$\mathbf{M}' = \begin{bmatrix} 0 & M'_{S,1} & 0 & M'_{S,L} \\ M'_{S,1} & M'_{1,1} & M'_{1,2} & 0 \\ 0 & M'_{1,2} & M'_{2,2} & M'_{2,L} \\ M'_{S,L} & 0 & M'_{2,L} & 0 \end{bmatrix} \tag{2}$$

where $M'_{S,L} = 1$, $M'_{1,1} = -M'_{2,2}$, and $M'_{2,L} = M'_{S,1}$. Since $M'_{1,1}$ and $M'_{2,2}$ are non-zero values, each resonator is asynchronously tuned. It is of note that $M'_{S,L} = 1$ in the proposed filter design as opposed to $M_{S,L} = -1$ in the conventional filter design and this allows us to have an arbitrary inter-resonator coupling coefficient for Butterworth and Chebyshev bandstop responses. The filter designed by using (2) shows the same frequency response as the filter designed by using (1) when

$$\begin{aligned} M'_{1,1} &= \pm\sqrt{M'^2_{S,1}(M_{1,2} + M'_{1,2}) + M^2_{1,2} - M'^2_{1,2}} \\ M'_{S,1} &= M_{S,1} \end{aligned} \tag{3}$$

where

$$M'^2_{S,1}(M_{1,2} + M'_{1,2}) + M^2_{1,2} > M'^2_{1,2}. \tag{4}$$

Therefore, the inter-resonator coupling structure can have an arbitrary amount of coupling with a given constraint if the resonant frequency of each resonator can be tuned independently. For example, a Butterworth bandstop filter with $M'_{1,2} = 0.7$ needs to have $M'_{1,1} = -M'_{2,2} = \pm 0.707$ for the prescribed response. According to (4), the maximum $M'_{1,2}$ we can choose is 1.4142 for a Butterworth response. The resonators of frequency-agile bandstop filters need to be tuned in order to have different center frequencies. Therefore, the tuning elements for controlling the resonant frequency of each resonator can be used to control both the center frequency and the frequency response of the filter. We can have arbitrary non-zero inter-resonator coupling coefficients for a Butterworth bandstop filter if each resonator can be tuned independently such that $M_{1,1}$ and $M_{2,2}$ satisfy the relationship given in (3). Similarly, a Chebyshev bandstop filter can also have an arbitrary inter-resonator coupling coefficient. For example, a 10 dB Chebyshev bandstop filter with $M'_{1,2} = 0.7$ requires $M'_{1,1} = -M'_{2,2} = \pm 0.6985$ for the prescribed response.

III. Filter Design and Measurement

In this section, an evanescent-mode cavity bandstop filter is designed to verify the proposed design method. Fig. 2 shows the filter structure. Two evanescent-mode cavity resonators are embedded in 3.175 mm thick Rogers TMM3 substrate ($\epsilon_r = 3$, $\tan\delta = 0.0012$). The side walls of the resonators are established by via-holes, and the resonant frequency of each resonator is controlled by the gap between a post and a conductor layer on the bottom side of the cavity. A 0.38 mm thick commercially available piezoelectric actuator from Piezo Systems is attached to the conductor layer on the bottom side in order to control the gap by deforming the membrane. The actuator is integrated outside of the cavities where electromagnetic fields are stored using conductive silver epoxy. Since the actuators are external to the cavities, this tuning method does not introduce nonlinearities. The microstrip transmission line is fabricated in a 1.27 mm thick Rogers TMM10i substrate ($\epsilon_r = 9.8$, $\tan\delta = 0.002$). External coupling structures are implemented by coupling slots in the conductor layer between the two dielectric substrates. An iris between two resonators forms the inter-resonator coupling structure.

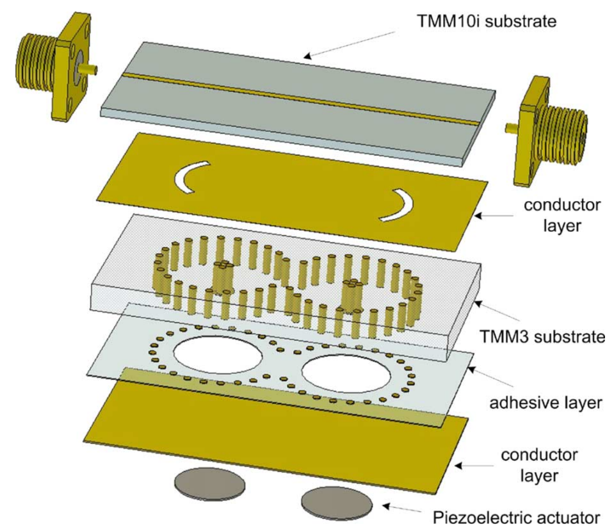

Fig. 2. Proposed bandstop filter with two substrated-integrated evanescent-mode cavity resonators.

For implementation of positive $M'_{S,L}$, the length of transmission line between the two coupling slots is $3\lambda_g/4$. The size of the coupling slots is determined by $M'_{S,1}$, $M'_{2,L}$, the bandwidth, and the center frequency. The width of iris can be chosen arbitrarily since $M'_{1,2}$ can be arbitrary as long as (4) is satisfied. In this letter, the width of iris is 5.5 mm. The diameter of each via-hole is 0.8 mm and that of the post at the center of the cavity is 2.8 mm. The radius of the cavity is defined by the distance between the center of the cavity and the center of one of the via-holes which form the side wall of the cavity and is designed to be 7.5 mm.

Fig. 3 shows the measured frequency response of the bandstop filter with a Butterworth response. Although the transmission line is three quarter-wavelength long at one frequency, the center frequency of the filter can be adjusted as long as the line length approximates three quarter wavelength. It is of note that the filter can have a Butterworth response, although it has non-zero inter-resonator coupling. The filter can also be tuned to have a Chebyshev response, and Fig. 4 shows the measured frequency response of a Chebyshev bandstop filter with 10 dB stopband rejection. It is shown that the filter can be reconfigured to have different frequency responses and also be tuned to have different center frequencies. Measured results agree well with synthesized ones in the stopband and its vicinity. Return loss discrepancy in the passband is mainly due to the dispersive characteristic of the transmission line which

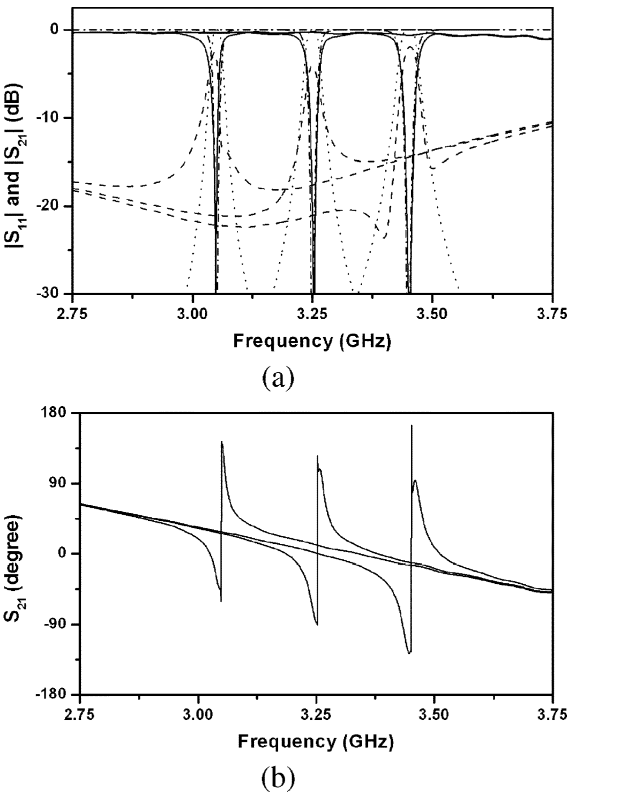

Fig. 3. Measured frequency response of the fabricated bandstop filter. The filter is tuned to exhibit Butterworth bandstop responses at three different center frequencies: (a) $|S_{11}|$ measurement (— —), $|S_{21}|$ measurement (——), $|S_{11}|$ synthesis (· · ·), $|S_{21}|$ synthesis (— · —), (b) S_{21} (degree) measurement.

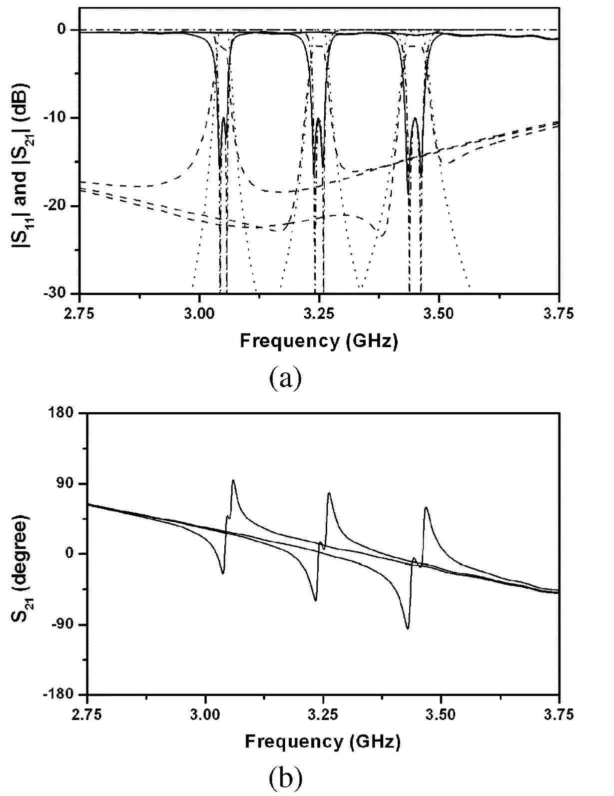

Fig. 4. Measured frequency response of the fabricated bandstop filter. The filter is tuned to exhibit Chebyshev bandstop responses with 10 dB stopband rejection at three different center frequencies: (a) $|S_{11}|$ measurement (— —), $|S_{21}|$ measurement (——), $|S_{11}|$ synthesis (· · ·), $|S_{21}|$ synthesis (— · —), (b) S_{21} (degree) measurement.

is typical to bandstop filters with a transmission line. In this tuning process, the dc voltage for the piezoelectric actuators has been controlled manually. For reducing susceptibility to mechanical shock and vibration, the control circuit presented in [7] can be employed. The filter can be switched between filter states on the order of seconds due to a the use of manual tuning process. Switching time can be reduced by using the above-mentioned control circuit. The power handling capacity is usually limited by the gap between the cavity post and tuning membrane. With the smallest gap (5 μm), a slight degradation of the filter was observed starting at an input power of 200 mW. Controlling the bandwidth can be easily achieved by tuning external coupling, but it is not in the scope of this letter.

The proposed filter structure does not need to have a tunable inter-resonator coupling structure for different frequency responses, and this allows us to reduce the number of dc bias circuits compared to the conventional filter structure. It can also have an arbitrary non-zero inter-resonator coupling coefficient, and this enables further reconfigurability for multiple frequency responses in future designs. For example, it can be reconfigured to exhibit a bandpass response in a more convenient fashion compared to a conventional Butterworth or Chebyshev bandstop filter which requires a zero or small inter-resonator coupling coefficient.

IV. Conclusion

In this letter, we proposed a frequency-agile bandstop filter with tunable frequency responses. The bandstop filter can have arbitrary inter-resonator coupling with a given constraint and the tuning elements for controlling the resonant frequency of each resonator can adjust both the center frequency and the frequency response simultaneously. Since the filter structure has non-zero inter-resonator coupling, it can be applied to design of reconfigurable filters with multiple frequency response shapes. The design method can find its application to higher-order filters with a cascaded structure.

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