High-Q Tunable Bandstop Filters with Adaptable Bandwidth and Pole Allocation

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Abstract — **Tunable bandstop filters are demonstrated with wide tuning ranges, tunable bandwidth, and a variable number of dynamically allocated poles. The number of poles can be dynamically applied at different frequencies to maximize isolation for a given interference scenario. These filters are made with evanescent-mode cavities which use a new loading post geometry that results in greater external coupling for a given physical coupling aperture size. This geometry concentrates the magnetic field within the cavity structure near the coupling aperture, allowing for a smaller coupling aperture and reducing perturbation to the feeding transmission line. The design allows for wider bandwidth bandstop filter responses compared to previously reported geometries. Relatively low external *Q* values are achieved with minimal perturbation to the passband response. A relatively high *Q* (450 @ 3 GHz) allows for deep notches and good selectivity.**

Index Terms — **Cavity resonators, filters, microwave filters, piezoelectric actuators, tunable circuits and devices.**

I. INTRODUCTION

Radio systems in crowded, dynamic spectral environments will increasingly rely on tunable spectral isolation, especially as the spectrum is opened for cognitive radio operation [1]. In many systems, multiple bandstop filters will be used to filter out several of the most problematic interfering signals. Ideally, these filters would be able to re-task each of their individual resonators to create different filtering shapes across the spectrum. In addition, multiple notch filters could be created when needed, or the responses could be combined in order to create maximum spectral isolation over a single band. Fig. 1 shows three states of this concept using a system of four bandstop resonators. In Fig. 1, this system of resonators is able to provide four 1-pole bandstop responses, two 2-pole bandstop responses, or one 4-pole bandstop response.

Several tunable bandstop filters have been created recently. It has been shown that very wide frequency tuning ranges can be achieved [2]. Bandstop filters have been shown with extended, resonance free passband responses [3], and others have MEMS tuning mechanisms [4]. A recent paper has shown a tunable level of attenuation [5]. However, none of the filters show *Q* higher than 150 and some have limited bandwidths. [5] shows wider bandwidths and uses absorptive resonators that reduce the dependence on high *Q* for a good filter shape. However, the absorptive resonators limit the total tuning range of the filter because of the complicated relationships which need to be satisfied in order to provide a good notch shape.

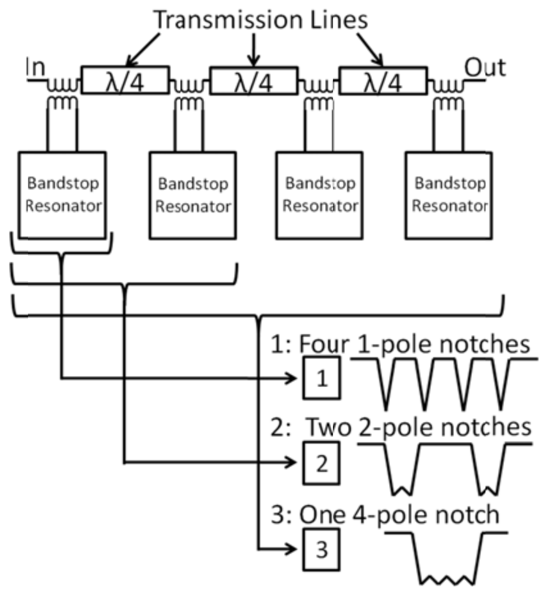

Fig. 1. Tunable four pole bandstop filter whose poles can tune independently to create four 1-pole notches, two 2-pole notches, or one 4-pole notch.

A critical issue in creating wide bandwidth, high-*Q* filters is coupling into the resonators without excessively perturbing the feedline. Strong coupling into bandstop resonators can perturb the feedline and degrade the out-of-band response of the bandstop filter. In Fig. 1, the coupling mechanisms are depicted as transformers between sections of transmission lines which are ideally $\lambda/4$ in length. Traditionally, eliminating the perturbation to the feedline means reducing the external coupling which reduces the bandwidth and maximum attenuation of the filters. Preferably, one could find a mechanism to adjust the coupling by altering the dimensions of the resonator without impacting the transmission line.

In this work, a tunable 4-pole post-loaded cavity resonator bandstop filter is shown which can implement the capabilities shown in Fig. 1 and adjust its attenuation and bandwidth in response to the spectrum. This filter uses an in-cavity method for reducing the perturbation of the filter's passband response for a given amount of coupling, enabling large coupling values while retaining an unloaded *Q* which was measured as high as 450.

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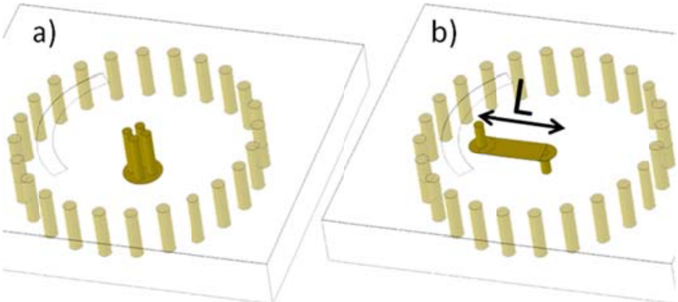

Fig. 2. a) Conventional resonator structure, b) proposed resonator structure.

II. Resonator Structure For Reduced Out-Of-Band Perturbation or Increased Coupling

Evanescent-mode cavity resonators have been extensively employed in widely frequency tunable filters [6]. Fig. 2a) shows an example of a conventional substrate-integrated evanescent-mode cavity resonator with a straight loading post, but the technique discussed in this section could be applied to any type of post-loaded cavity. The side wall of the resonator is established by via-holes, and the resonant frequency of the resonator is controlled by the gap between the post and the conductor layer on the bottom side of the cavity. An actuator is usually attached to this conductor layer to adjust the resonant frequency. In tunable bandstop filter structures, a microstrip transmission line is usually attached to the top side of the resonator, and a coupling aperture in the conductor layer on the top side of the cavity provides coupling into the resonator. The geometry of this coupling aperture determines the amount of coupling with a given microstrip line. Only a small amount of coupling can be gained by increasing the size of the coupling aperture before it adds too much inductance to the ground plane of the microstrip line, degrading the out-of-band return loss of the filter to unacceptable levels.

The proposed structure in Fig. 2b) is able to provide a given amount of coupling with a smaller coupling aperture than the conventional evanescent-mode cavity bandstop resonator. The loading post in the resonator is "bent" in order to redirect the current path inside the resonator closer to the sidewall of the cavity. The magnetic field is therefore asymmetric within the cavity and condensed in a region where a coupling aperture is placed. The external Q can be increased by simply increasing the length of the bent portion of the post (labeled 'L' in Fig. 2b)), and therefore the coupling can be made larger for a given aperture size. This allows bandstop filters with less out-of-band response perturbation or bandstop filters with wider bandwidths than would be possible with the standard post configuration shown in Fig. 2a). The other half of the bent post remains centered in the cavity in order to facilitate integration of electromechanical actuators for wide tuning ranges.

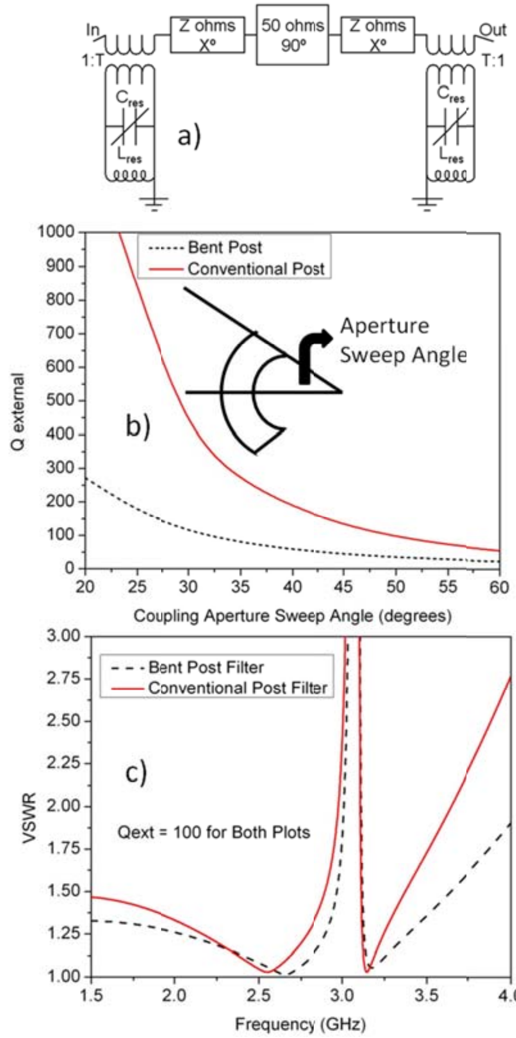

Fig. 3. a) Equivalent circuit model of coupling apertures and filter. b) Q external variation vs. aperture sweep angle for both loading post geometries. c) VSWR for both post geometries.

The effect of the size of the coupling aperture on the filter transmission line can be understood with the model in Fig. 3a). The coupling aperture adds inductance to the ground plane because it re-routes the current of the microstrip line mode. This increases the effective characteristic impedance of the line near the coupling aperture with a dependence on its size. The higher impedance cross section of the line near the coupling apertures can be modeled as an electrically short transmission line, which can be equivalently represented by a series inductance of impedance $Z\beta\ell$, where Z, β, and ℓ are the characteristic impedance, propagation constant, and physical length of the transmission line that represents the coupling aperture.

The full-wave simulated comparison of the coupling into the two resonators in Fig. 2 vs. coupling aperture sweep angle is shown in Fig. 3b). The proposed structure provides notably more coupling for a given coupling aperture sweep angle. At a sweep angle of 25 degrees, the Q external for the bent post resonator is five times smaller than the Q external for the

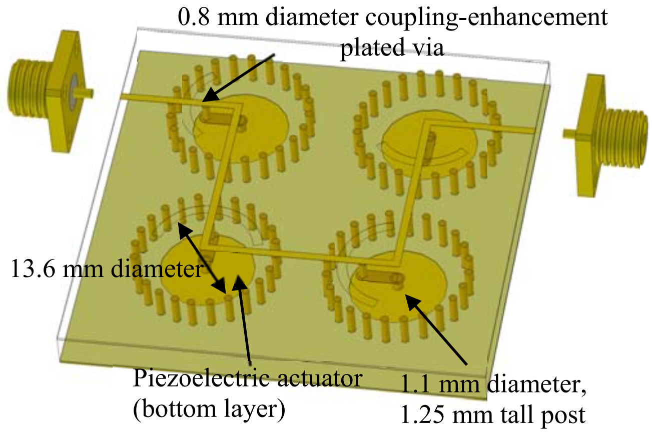

Fig. 4. Model of fabricated filter using the proposed resonator.

conventional post resonator. Similar resonators with both post types were fabricated with a 40 degree coupling aperture sweep angle. The measured Q external of the bent post resonator was 55.5, and the measured Q external of the straight post resonator was 172.8. These results are within 4.6% and 6.7% of the values in Fig. 3 b). Fig. 3 c) shows the full-wave simulated VSWR for 2-pole filters using both resonator types with a coupling aperture sweep angle set to provide an external Q of 100 in both cases (31.5^{o} bent, 49^{o} conventional). The VSWR of the proposed structure is lower than the VSWR of the conventional structure by up to 45% in the 1.5 to 4 GHz band. These results correspond to an equivalent series inductance of 1.18 nH for the bent post design versus 1.65 nH for the straight post design in the model of Fig. 3a).

III. Filter Design

A 4-pole evanescent-mode cavity filter with the bent post structure was fabricated to show wide bandwidth and shape reconfiguration capability. A model of the fabricated filter with important dimensions specified can be seen in Fig. 4. The structure utilizes two layers of PCB material. The top layer contains the signal conductor of the filter's transmission line on one side, and bare dielectric on the other. This layer was fabricated on 0.254 mm thick Rogers Duroid 5880 material (ε_r = 2.2, tan(δ) = 0.0009) and laminated to the second layer. The second layer contains the cavity resonators and coupling apertures. This layer was fabricated in 3.175 mm thick Rogers TMM3 material (ε_r = 3.27, tan(δ) = 0.002). The coupling apertures were cut into the top conductor layer of the cavities. The coupling apertures are 1 mm wide and have sweep angles of 30 and 55 degrees to account for the different normalized low-pass prototype coupling values which are needed for this specific 4-pole filter. According to full-wave simulation of individual resonators, these sweep angles correspond to external Q values of 115 and 29, respectively. This layer of copper also serves as the ground plane for the transmission line on the 5880 layer. The cavity walls are defined by 0.8 mm diameter vias, and the cavity diameter from the center of one via to the center of the opposing via is 13.6 mm. A flexible copper membrane was laminated to the bottom layer of the cavities, and T216-A4NO-273X piezoelectric actuators from Piezo Systems, Inc. were attached to the membrane external to the cavities to allow electronic tuning of the gaps between the membrane and the loading posts, enabling frequency tuning of the resonators. The bottom half of the loading posts, which are centered in the cavity and responsible for the variable capacitances, are 1.25 mm tall and have diameters of 1.1 mm. In this case the diameters of the posts are equal. However, the diameters of the posts can be designed to be different, enabling different tuning ranges for each resonator. The distance from the centers of the bottom half of the loading posts and the centers of the coupling-enhancement vias is 3.5 mm. The coupling-enhancement vias have a diameter of 0.8 mm.

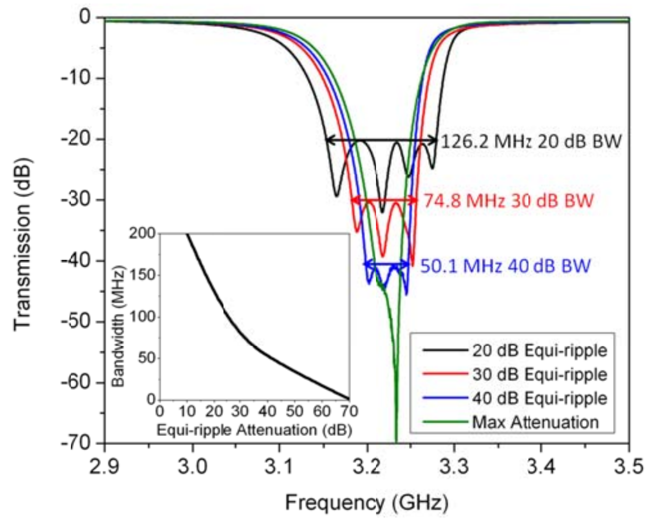

Fig. 5. Four measurements of the tunable filter in Fig. 4 showing BW control. Inset – Plot of bandwidth vs. equi-ripple attenuation.

IV. Measured Results

Measured results of the four pole filter described in section III. can be seen in Figs. 5-8. Fig. 5 shows bandwidth and attenuation reconfiguration capability. The filter was able to be continuously tuned between a 126.2 MHz (3.9% fractional bandwidth (FBW)) 20 dB equi-ripple response and a 50.1 MHz (1.6% FBW) 40 dB equi-ripple response through electronic tuning of the resonant frequencies of the individual resonators, similar to the method introduced in [7]. It was also capable of a Butterworth-like filter shape with over 70 dB of attenuation. Fig. 6 shows the four pole filter tuning from 2.4 to 3.6 GHz with 20, 30, and 40 dB equi-ripple responses. The low passband loss varies from 0.24 dB to 0.53 dB in the 2 to 4 GHz frequency range due to the small perturbations caused by the relatively small coupling apertures utilized.

Fig. 7 shows the filter exhibiting dynamic pole allocation capability. A 30 dB 4-pole response, two narrower 30 dB 2-pole responses, and four narrower 12-19 dB 1-pole responses

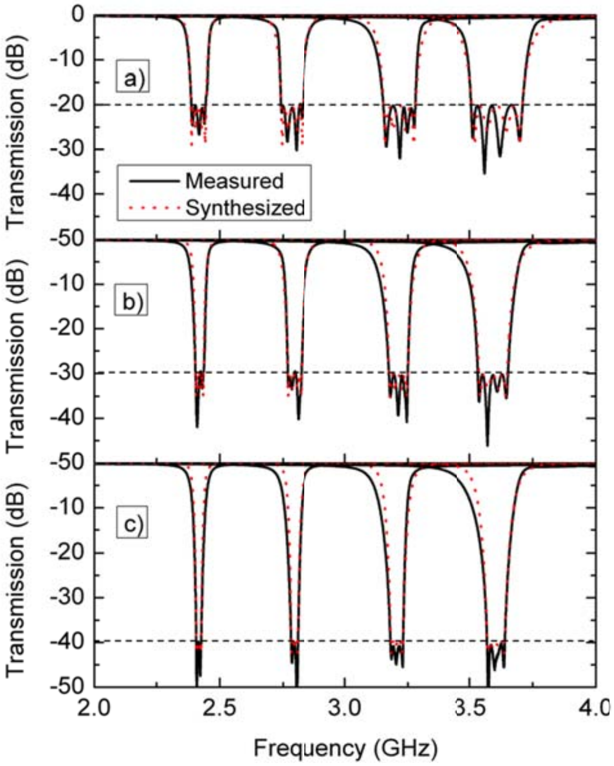

Fig. 6. Four measured and synthesized (with Q of 450) results of the filter in Fig. 4. a) 20 dB attenuation. b) 30 dB attenuation. c) 40 dB attenuation.

are shown. Each resonator can be designed to have a different starting frequency without applied actuator voltage and can therefore cover different frequency tuning ranges. The total coverage of all resonators in this design is from 1.6 to 5.8 GHz. The range where all of the individual resonators overlap is 2.3 to 3.9 GHz. Therefore, a 4 pole filter can be formed from 2.3 to 3.9 GHz, while a 2-pole filter can be placed anywhere from 1.8 to 5.0 GHz, and a 1-pole filter can be placed anywhere from 1.6 to 5.8 GHz. Using this strategy, designers can trade total frequency coverage of a single pole filter for increased frequency coverage of 2-pole and 4-pole responses.

V. Conclusion

High *Q* tunable bandstop filters with variable bandwidth and dynamic pole allocation were designed. A novel post geometry for post-loaded cavity resonators was shown and applied to these tunable bandstop filters. This post geometry increased coupling into the resonators while reducing perturbation of the out-of-band response of the bandstop filter. Bandstop filters were simulated and measured to demonstrate the benefits of the new design and the concepts of tunable attenuation, tunable bandwidth, and dynamic pole allocation. These concepts are expected to be useful in the dynamic spectral environments of the future.

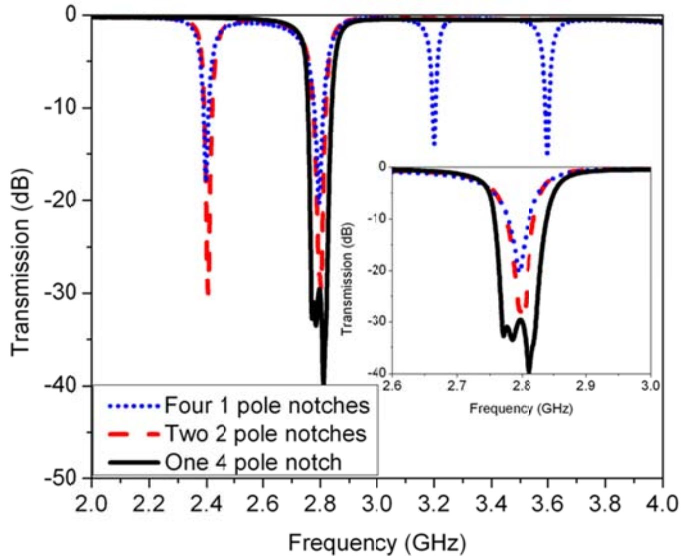

Fig. 7. Measurements showing adaptability for varying spectrums.

VI. Acknowledgement

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