Tunable Bandstop Filter with a 17-to-1 Upper Passband

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***Abstract*—Tunable bandstop filters with wide upper passbands are important in systems that operate over a wide frequency range in the presence of dynamic interference. This paper shows a tunable bandstop filter with a 17-to-1 ratio between its upper passband cutoff frequency and its lowest notch center frequency. The wide upper passband results from the combination of highly-loaded resonators and a new external coupling structure that is well-matched to the filter's port impedance over a wide frequency range. The filter described in this paper can attenuate a UHF signal while allowing for low-loss transmission or reception of signals at X-band frequencies.**

***Index Terms*—Tunable filters, Passive filters, Tunable resonators, Filters, Microwave filters.**

I. INTRODUCTION

While attempting to capture wide-band signals for analysis, receivers are often compressed by strong interference. These high-power signals are very often in the high MHz to low GHz portion of the spectrum because of the availability of high power transmitters and favorable propagation characteristics in this frequency range. Ideally a receiver would have a tunable bandstop filter that could suppress these interfering signals selectively while maintaining the receiver's ability to look at the rest of the usable spectrum. However, spurious resonator modes and effects of the reactance of coupling structures have made this level of filter performance difficult to achieve since a bandstop filter with an ultra-wide upper passband requires mitigation of both. Examples that focus on spurious resonances can be seen in [1], where a 5-to-1 upper passband was shown, and in [2], which shows a tunable bandstop filter with an 8.9-to-1 upper passband. An example of coupling structure reactance mitigation can be seen in [3].

Highly-loaded coaxial cavity resonators can be designed to have a very wide spurious-free range [4]. However, past bandstop filters using these resonators have upper passbands that are limited to a 7.8-to-1 ratio or less by the reactance of their external coupling structures [5]. The challenge of designing these structures is that energy must be coupled into the shunt resonators appropriately for the desired fractional bandwidth Δ and ratio of the resonator impedance Z_r to the system impedance Z_0 without creating a large impedance mismatch between the coupling structure impedance Z_C and Z_0. These concepts are shown in Fig. 1. This paper presents a new coupling structure for highly-loaded coaxial cavity resonators that is well matched to the system impedance and enables a 17-to-1 upper passband ratio without strongly affecting their tuning range or quality factor, which is a 118% improvement of the state-of-the-art.

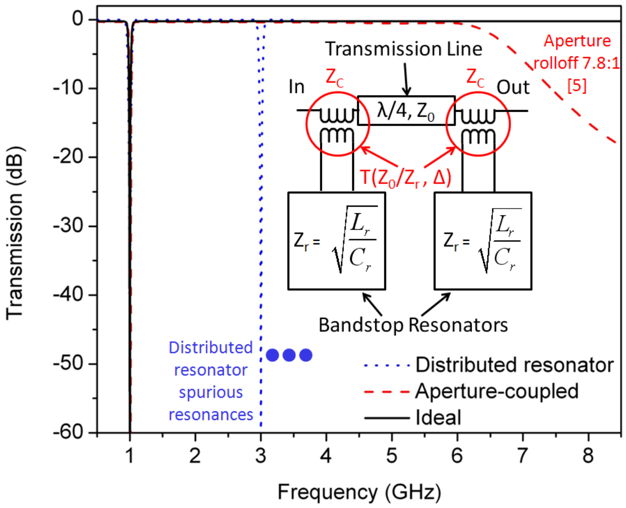

Fig. 1. Bandstop responses and common limiting factors of their upper passbands. Inset shows a schematic of a 2-pole bandstop filter. The coupling structure transformation ratio (T) depends on the ratio of the system impedance (Z_0) to the resonator impedance (Z_r), as well as the desired fractional bandwidth (Δ). With sufficient resonator spurious-free range, the upper passband is limited by the impedance mismatch between the coupling structure impedance (Z_C) and Z_0.

II. WIDE UPPER PASSBAND BANDSTOP FILTER CONCEPT AND DESIGN

Vector plots of the E and H fields of the fundamental mode of a highly-loaded coaxial cavity resonator can be seen in Fig. 2a). The H field distribution is similar to that of the fundamental mode of a coaxial cable. However, the E field is primarily stored in a small gap between the loading post and the upper wall of the cavity. For the fundamental mode, the E field is uniform across the area of the loading post if edge effects are neglected. Storing the E field in this manner allows a coaxial resonator to have a fundamental resonance at a frequency where it is electrically short, producing next higher-order modes that are much higher in frequency than the fundamental mode. An E field vector plot of one of the next higher-order modes can be seen in Fig. 2b).

A two-pole, highly-loaded coaxial cavity resonator bandstop filter was designed to be tunable around a frequency of 1 GHz, and a model of the filter can be seen in Fig. 3. Much of the fabrication and operation of the filter is similar to that of previous highly-loaded coaxial cavity resonator filters that use closely-spaced plated vias to define the cavity sidewalls [6], [7]. These resonators have a small gap (5 μm to 30 μm) between the loading post and top conductive wall of the cavity. The resonant frequency is very sensitive to changes in the

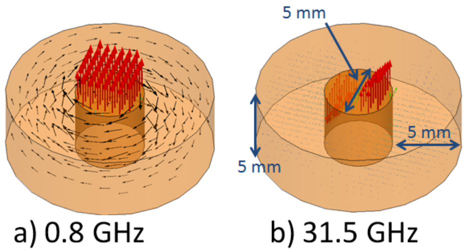

Fig. 2. a) E (red arrows) and H (black arrows) field vector plots of the fundamental mode of a highly-loaded coaxial cavity resonator. b) E field vector plots of a higher-order mode of the same resonator.

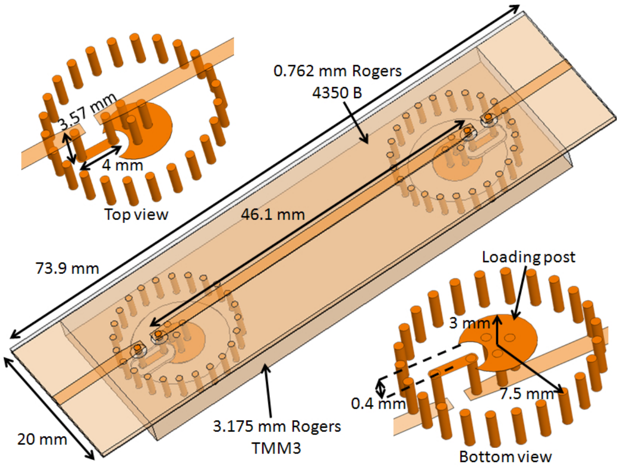

Fig. 3. Fabricated 2-pole filter structure. Top and bottom views of the external coupling structure are shown for clarity.

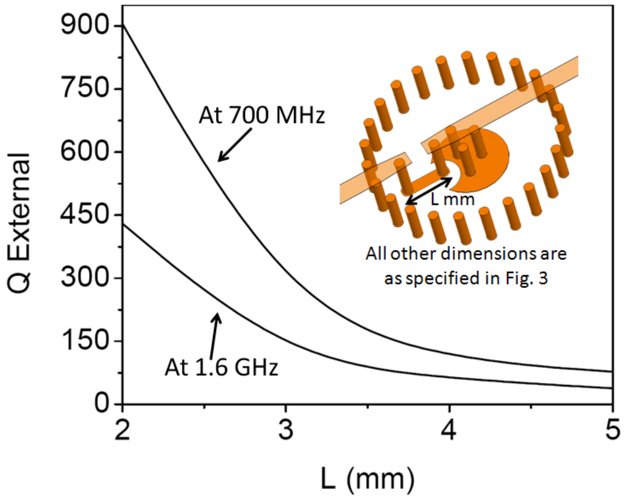

Fig. 4. Simulated external quality factor vs. coupling structure length.

small gap, so it can be tuned over wide frequency ranges with small amounts of mechanical deformation of the top conductive wall of the cavity. This mechanical deformation can be achieved using piezoelectric or MEMS actuators.

In contrast to previous filters that use these resonators, this design incorporates a 'U' shaped external coupling structure that can be seen in Fig. 3. The structure couples the magnetic field of the source-to-load microstrip transmission line to the magnetic field of the cavity resonator and is formed by routing the source-to-load transmission line through the cavity. The structure can be designed to be well-matched up to relatively high frequencies, which produces a wide upper passband. The vertical sections of the coupling structure are made using 0.8 mm diameter plated vias that extend from the source-to-load microstrip line into the cavity resonator. Small apertures are cut into the microstrip line ground plane so that the vias are not shorted to ground. The horizontal part of the structure is a plate of copper offset in height from the loading post. The width of the copper plate, as well as the height offset from the loading post, allow it to be designed to act like a short section of microstrip transmission line that is matched to the system impedance. In the fabricated filter, the width of the horizontal section is 1 mm, the length is 4 mm, and the height offset from the loading post is 0.4 mm. In Rogers TMM3 material, this produces an approximately 50 ohm transmission line with an electrical length of approximately 7.8 degrees at 1 GHz.

The amount of coupling can be designed by adjusting the length of the horizontal part of the structure. The external quality factor (Q external) vs. the length of the horizontal part of the structure (L) can be seen in Fig. 4 for the design shown in Fig. 3. The external quality factors available in this particular design are relatively high, providing the ability to realize only narrowband bandstop filters. The challenge of getting Q external low enough to make wider and deeper bandstop filters is the difference between the system characteristic impedance and the resonator characteristic impedance. A 50 ohm system impedance was used in this design. However, the highly-loaded coaxial cavity resonators used in this design have a simulated characteristic impedance as low as 5.4 ohms, which makes the required transformation ratio for a desired bandwidth filter very high and the challenge of low out-of-band reactance difficult.

The entire structure in Fig. 3 was made using a commercial PCB milling machine and standard copper plating processes. While the structure in Fig. 3 is physically long, it could be significantly shortened by meandering the transmission line between the two resonators. It can also be seen in Fig. 3 that the source-to-load transmission line substrate, which is 0.762 mm thick Rogers 4350B material (ϵ_r=3.66, tan(δ)=0.0037 @ 10 GHz), extends beyond the cavity substrate, which is 3.175 mm thick Rogers TMM3 material (ϵ_r=3.27, tan(δ)=0.002 @ 10 GHz). This was done for better grounding of the SMA end-launch connectors and would not be part of an integrated design.

III. MEASURED RESULTS

The response of the fabricated bandstop filter was measured using an Agilent Technologies N5230C PNA, and the final structure was simulated using Ansoft HFSS. Measured vs. simulated S_{11} and S_{21} responses can be seen in Fig. 5a). Fig. 5a) shows a measured 654 MHz, 15 dB attenuation, 1.2% 3 dB fractional bandwidth bandstop filter with a passband

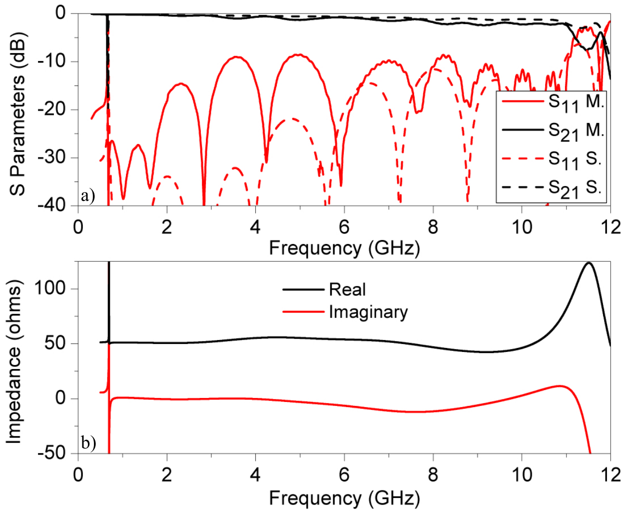

Fig. 5. a) Wideband simulated vs. measured results of the fabricated filter showing a 17-to-1 upper passband. S. = simulated, M. = measured. b) Simulated input impedance of coupling structure and resonator.

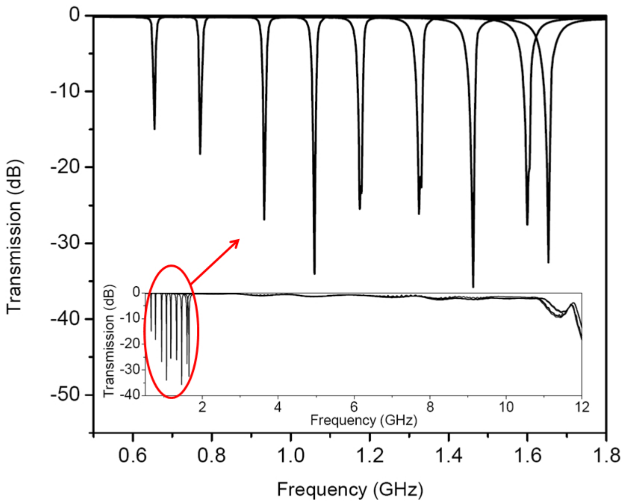

Fig. 6. Narrowband measured results of the fabricated filter showing the available tuning range. Inset shows wideband tuning measurement.

that extends to the 3 dB insertion loss point at 11.1 GHz, corresponding to a 17-to-1 ratio between the upper passband cutoff frequency and the notch center frequency. Note that the coupling structure reactance is what causes the passband to degrade, and the next higher-order mode of the filter is significantly higher in frequency than the 3 dB rolloff point of the passband. The full-wave simulations in Fig. 5b) show that the input impedance of the coupling structure and resonator is approximately 50 ohms until the cutoff frequency.

Agreement can be seen between measured and simulated results. However, the measured results have worse return loss than the simulated results and slight discrepancies with the simulated results in reflection zero location. This can be explained by inaccuracies in fabrication of the height of the coupling structure relative to the cavity loading post, mismatch at the coaxial-to-microstrip transition between SMA connectors and the filter, and the extra length and loss due to the connectors.

Fig. 6 shows that the response is tunable through mechanical deformation of the flexible membrane above the loading post, similar to past highly-loaded coaxial cavity resonator filters [8]. The filter is tunable from 0.654 to 1.65 GHz while providing 15 dB to 35 dB of attenuation. The 3 dB fractional bandwidth varies from 1.2% to 3.2% across the tuning range. This tuning range makes the filter relevant for attenuating signals from television stations, cellular telephone towers, and LightSquared LTE systems.

IV. CONCLUSION

A tunable bandstop filter with a 17-to-1 ratio between its upper passband roll-off frequency and its notch center frequency was shown in this paper. To the authors' knowledge, this is the largest ratio measured to date. Future work will involve extending the passband even further and increasing the amount of external coupling so that wider bandwidth bandstop filters can be implemented.

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