High-Q Intrinsically-Switched Quasi-Absorptive Tunable Bandstop Filter With Electrically-Short Resonators

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Abstract — Tunable high-Q intrinsically-switchable quasi-absorptive bandstop filters are presented in the 4 GHz to 6 GHz and 6.3 GHz to 11.4 GHz frequency ranges. Their responses can be reconfigured between all pass and tunable bandstop filter responses by simply tuning the center frequency of their resonators, avoiding insertion loss and control voltages associated with the series switches required in conventional bandstop filter banks that have similar response reconfiguration capability. In contrast to previously shown intrinsically-switchable bandstop filters, the filters shown in this paper require only one tuning element per resonator, have a significantly higher quality factor (650), and use electrically-short resonators. When combined with destructive interference attenuation enhancement techniques, these characteristics enable >60 dB maximum attenuation in the bandstop state and less than 2.0 dB insertion loss in the all pass state.

Index Terms — Filters, microwave filters, passive filters, tunable filters, tunable resonators.

I. Introduction

Switched tunable filter banks can adaptively add or remove filter responses over a wide frequency band in response to a changing operating mode or interference situation. For example, switched bandstop filter banks can exhibit a response with several tunable notches or an all pass response, as shown in Fig. 1a). Such capability is often obtained by switching between two parallel paths in each filter that can be seen in Fig. 1b): one with a bandstop filter and one with an all pass transmission line. This circuit facilitates response adaptation at the cost of increased passband insertion loss and control voltages due to the series switches required.

Alternative filter architectures that achieve response adaptation between all pass and bandstop shapes without series switches exist [1], [2], making the filter configuration shown in Fig. 1c) able to provide the responses in Fig. 1a). However, in the all pass state the passband insertion loss and group delay flatness in the frequency band of the suppressed bandstop response is limited due to the use of constructive interference between resonant and non-resonant paths. Another design technique was presented in [3] that enabled low passband insertion loss and flat group delay in the all pass state through adjustment of both the electric and magnetic external coupling to each resonator. This concept was demonstrated with microstrip resonators and semiconductor varactors that limited the resonator quality factor (Q), and

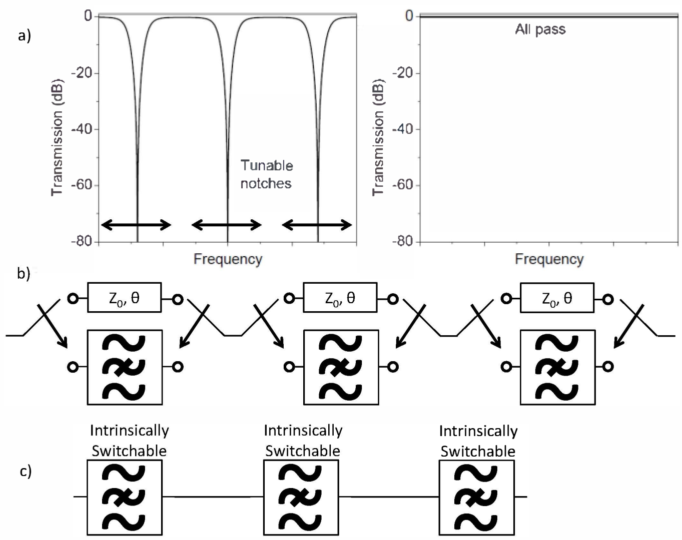

Fig. 1. a) Tunable notch response and all pass response. b) Schematic of switched tunable bandstop filter bank that can implement both responses in a). c) Intrinsically switched tunable filter bank that can implement both responses in a).

therefore the required 3 dB bandwidth for a desired notch depth was wider than would be desired in some applications. In addition, the microstrip resonators had two tuning elements each. This paper presents for the first time filters that use the concept in [3] in a way that is appropriate for electrically-short resonators that do not provide the opportunity for differential tuning and coupling over significant phase lengths. They are implemented with highly-loaded coaxial cavity resonators [4] that have a single tuning element and higher Q, enabling narrower bandwidth, deep notches, and fewer control voltages.

II. Single-Tuning-Element Intrinsically-Switched Bandstop Resonators

Fig. 2a) shows the schematic of an intrinsically-switchable bandstop resonator [3]. Using ABCD, Y, and S parameter analysis and offset tuning the resonator to normalize the high pass prototype frequency of zero transmission to the origin, the transfer function of this network can be determined as

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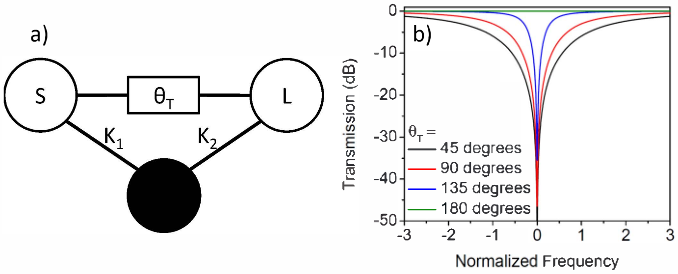

Fig. 2. a) Schematic of intrinsically switchable bandstop resonator [3]. b) Bandstop and all pass responses as θ_T is varied.

$$S_{21} = e^{-j\theta_T} \frac{s}{s + \frac{1}{2}\left(K_1^2 + K_2^2 + 2K_1K_2\cos\theta_T\right)}, \qquad (1)$$

where s is the frequency variable $j\omega$, θ_T is the electrical length of the transmission line in Fig. 2a), and K_1 and K_2 are the coupling values in Fig. 2a) [3]. If θ_T is 180 degrees at the resonator's center frequency and K_1 is equal to K_2, the magnitude of the transfer function becomes one at all frequencies, designating an all pass response. Effectively, the 180 degree phase shift between the K_1 and K_2 coupling points makes K_2 = - K_1. In [3], θ_T was made to be tunable to an equivalent 180 degrees over a wide frequency band through the use of differentially tuned distributed resonators, enabling the resonator to be intrinsically switched at any frequency in the band. This is not possible for electrically-short tunable resonators with a single tuning element and a passive transmission line. However, electrically-short resonators with a single tuning element can be made to exhibit a bandstop response when the resonator is tuned near frequencies where θ_T is away from 180 degrees and an all pass response when the resonator is tuned near frequencies where θ_T is 180 degrees. Therefore, with a wide enough resonator tuning range, resonators with the capability to exhibit bandstop and all pass responses can be made with a single tuning element and no switches. Fig. 2b) shows the behavior of such a resonator as it is tuned across a frequency range that corresponds to a θ_T of 45 to 180 degrees and normalized to the origin. Various bandwidths and an all pass response can be seen.

III. Filter Design and Implementation

Two 2-pole filters were implemented using the intrinsic switching concept described in Section II and tunable substrate-integrated highly-loaded coaxial cavities. The resonators are tuned through electromechanical actuation of a small gap between a loading post and a flexible cavity wall, which changes the loading capacitances. Tuning of one filter was done using piezoelectric actuators [5] over a range of 4 GHz to 6 GHz, and the other filter used MEMS tuners [6] to cover 6.3 GHz to 11.4 GHz. The tuning concepts are more fully explained in [5], [6] and will not be repeated here in order to focus on the design of intrinsic switching capability. The filters were also made to use destructive interference between their source-to-load paths and resonant paths to increase the attenuation of the bandstop responses [3]. With the tunable high Q resonators, intrinsic switching concept, and destructive interference technique used in the design, the design 3 dB fractional bandwidth could be as low as 0.8% while expecting maximum attenuation of >60 dB and an all pass response when the resonators are tuned to a designed frequency.

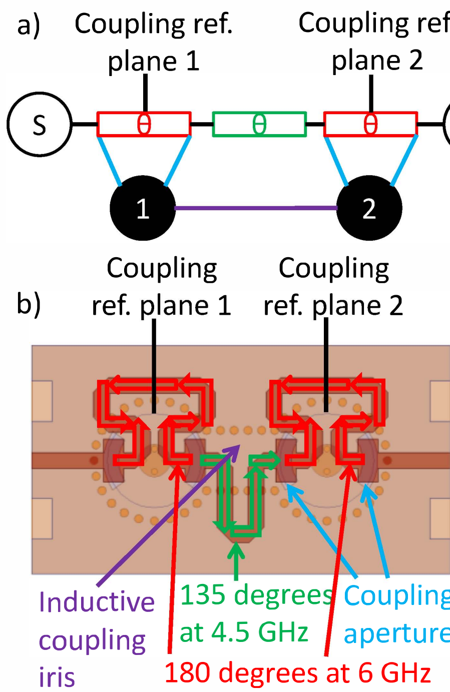

Fig. 3. a) Filter schematic. b) HFSS Simulation model with phase lengths marked.

The schematic of the 4 GHz to 6 GHz piezo-tuned filter can be seen in Fig. 3a), and it is composed of two intrinsically-switched bandstop resonators connected by a transmission line. In addition, the two resonators are coupled to one another to provide the secondary path necessary for destructive interference with the source-to-load path at the center frequency of the filter to increase attenuation. Figs. 3b) and 4a) show simulation models of the filter. The filter was designed to be in the intrinsic off state when tuned to 6 GHz and the maximum depth bandstop state when tuned to 4.5 GHz. Therefore, the transmission lines between the two coupling points for each resonator, which are marked by red-outlined arrows in Fig. 3b), are 180 degrees long at 6 GHz. Since each coupling aperture has the same size, K_2 = - K_1 at 6 GHz, and the coupling reference plane is in the middle of the transmission lines that are 180 degrees at 6 GHz. With these coupling reference planes, half of the phase lengths of the transmission lines that are 180 degrees at 6 GHz are included in the source-to-load coupling phase length. These halves are 90 degrees at 6 GHz and 67.5 degrees at 4.5 GHz.

The total source-to-load phase length must be 90+180*n degrees at the bandstop center frequency in order to act as an

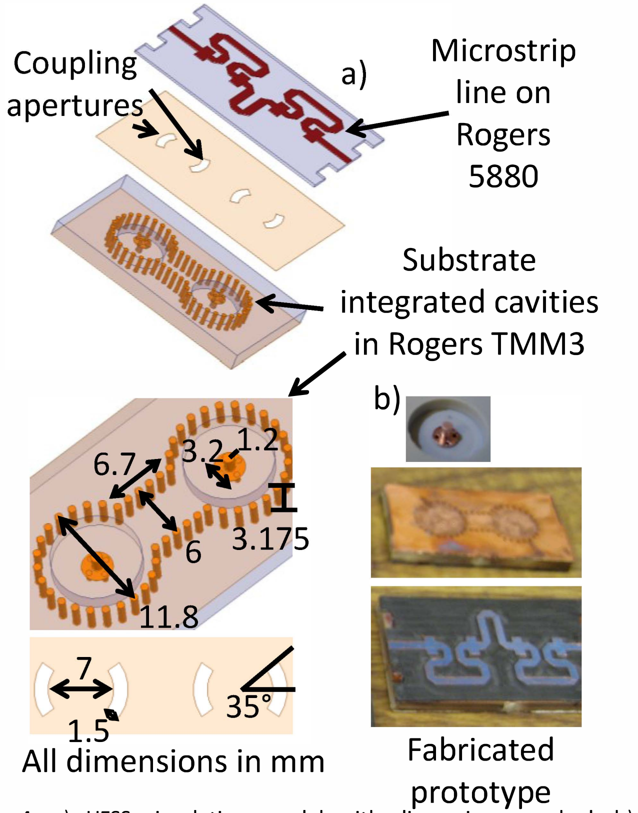

Fig. 4. a) HFSS simulation model with dimensions marked. b) Photographs of filter mid-fabrication.

impedance inverter, n=0, 1, 2… Since the phase added to the source-to-load path from both of the transmission lines used for intrinsically switching the resonators is a total of 135 degrees at 4.5 GHz (two 67.5 degree sections), 270 degrees is the shortest length that satisfies the requirement of the source-to-load impedance inverter. Therefore, an additional line length of 135 degrees at 4.5 GHz was added between the resonators, which is highlighted by green-outlined arrows in Fig. 3b).

Fig. 4a) shows a layer-by-layer view of the structure and dimensions of the cavities and coupling apertures. The source-to-load coupling was implemented with a 50 ohm microstrip line that was fabricated on 0.504-mm thick Rogers 5880 material (ε_r = 2.20, tan(δ) = 0.0009 at 10 GHz) using a PCB milling machine. The winding of the transmission line was done to make the device smaller, and any change in effective phase length due to cross coupling was corrected in ANSYS HFSS simulation. A copper layer contains apertures that implement K_1 and K_2 from Fig. 2, coupling the microstrip line to the substrate-integrated cavity resonators. The resonators were fabricated in 3.175-mm thick Rogers TMM3 material (ε_r = 3.27, tan(δ) = 0.002 at 10 GHz). 0.8-mm diameter plated vias were used to define the features of the cavities. 0.38-mm thick, 12.7-mm diameter piezoelectric actuators from Piezo Systems, Inc. were used to tune the resonators. Fig. 4b) shows photographs of an open resonator and its loading post mid-fabrication and both sides of the filter before addition of

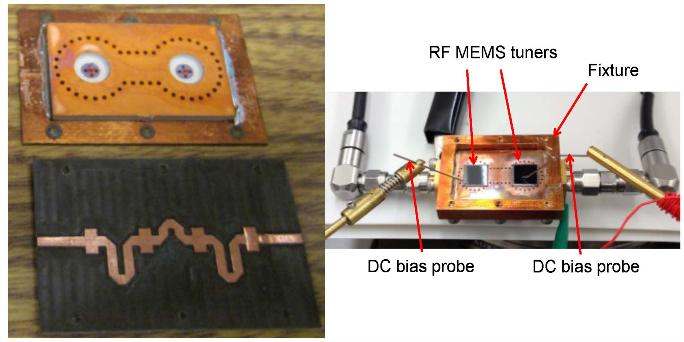

Fig. 5. a) Images of the MEMS-tuned 6 GHz to 12 GHz bandstop filter before addition of MEMS, connectors, and fixture. b) Measurement setup.

connectors and piezoelectric actuators. The piezoelectric actuators were placed on the top surface shown in the middle photograph in Fig. 4b) to deflect the flexible cavity wall toward and away from the loading posts.

Fig. 5a) shows photographs of the MEMS-tuned intrinsically-switchable filter that covers 6.3 GHz to 11.4 GHz before the addition of MEMS tuners, connectors, and measurement fixture. Note that the concepts of intrinsic switching and quasi-absorptiveness were implemented in this filter in the same manner as they were in in the piezo-tuned filter that covers 4 GHz to 6 GHz. The filter was designed to be in the intrinsic off state when tuned to 12 GHz and the maximum depth bandstop state when tuned to 9 GHz. Shorter microstrip lines result from the higher operating frequencies. Fig. 5 b) shows the completed MEMS-tuned filter during measurement.

IV. Measured Results

Fig. 6 shows superimposed measured results of the intrinsically-switchable substrate-integrated piezo-tuned filter. The resonators tune from 4 GHz to 6.3 GHz, and >60 dB attenuation is achieved over the 4.25 GHz to 5.0 GHz tuning range with a maximum of 68 dB attenuation. At 4.5 GHz, the measured 3 dB fractional bandwidth was 0.78%, and the measured 10 dB fractional bandwidth was 0.39%. Below 4.25 GHz, the proper phase relationship for destructive interference between the source-to-load path and the resonant path is no longer upheld, and attenuation quickly decreases. Above 5 GHz, the intrinsic switching effect reduces the external coupling, also decreasing attenuation. As the resonators are tuned to near 6 GHz, the external coupling is cancelled and an all pass response results. The all pass response is shown with a thicker line in Fig. 6. Therefore, this filter can provide a deep, narrow notch over almost a GHz band and provide an all pass response if tuned higher in frequency. Fig. 7 shows measured vs. simulated responses at 4.65 GHz. The quality factor was extracted from a single resonator and is 650 at 4.5 GHz.

Fig. 8 shows superimposed measured results of the intrinsically-switchable substrate-integrated MEMS-tuned

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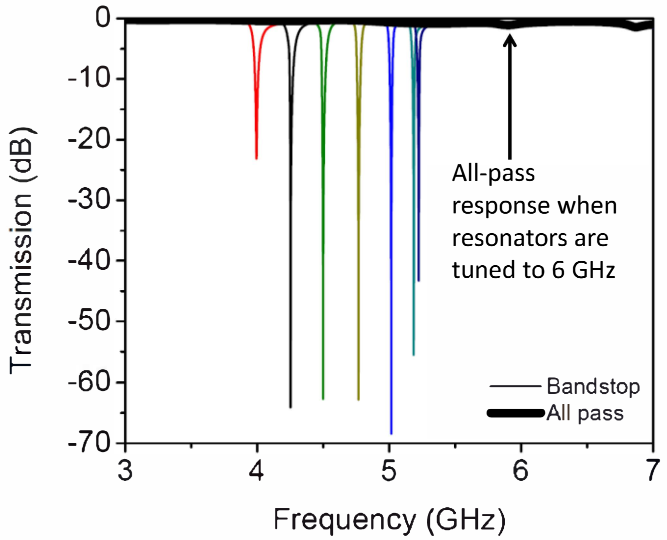

Fig. 6. Measured results showing >60 dB attenuation and intrinsic all pass state.

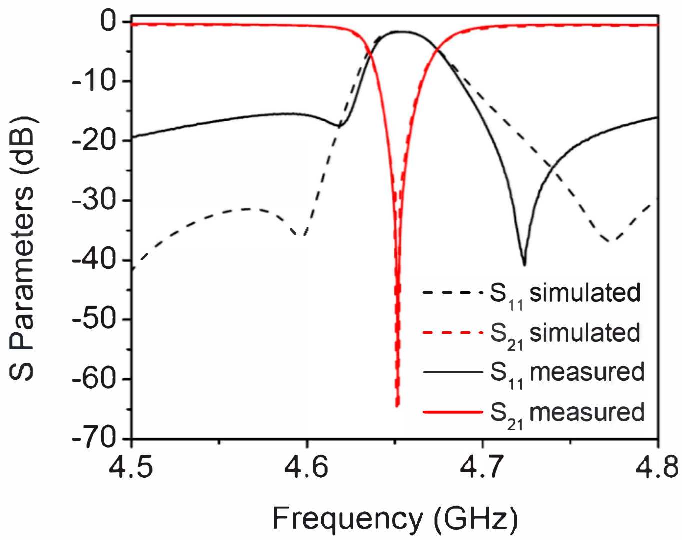

Fig. 7. Measured vs. HFSS simulated results at 4.65 GHz.

filter. The resonators tune from 6.3 to 11.4 GHz, and 74 dB attenuation is achieved near 9 GHz. At 9 GHz, the measured 3 dB fractional bandwidth was 3.41%, and the measured 10 dB fractional bandwidth was 2.03%. Attenuation decreases away from 9 GHz as the phase relationship between the source-to-load path and the resonant path deviates from what is needed for destructive interference below 9 GHz and the intrinsic-switching effect reduces external coupling above 9 GHz. This filter was unable to tune to its intrinsic off frequency of 12 GHz, but Fig. 8 shows that the bandstop response approaches the intrinsic off state as it tunes to 11.4 GHz. The quality factor was extracted to be 497 at 9 GHz.

V. Conclusion

Electrically-short tunable bandstop resonators with single tuning elements can be made intrinsically-switchable through

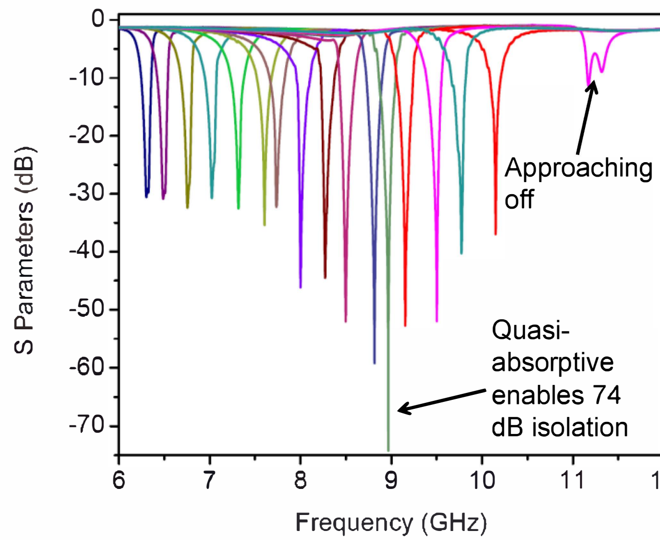

Fig. 8. Measured results of the MEMS-tuned filter.

careful design of tuning ranges, external coupling, and source-to-load phase lengths. This technique, destructive interference bandstop filter theory, and the wide tuning range and high Q of highly-loaded coaxial cavity resonators enable intrinsically-switchable bandstop filters with narrow bandwidth and high attenuation. Such filters are expected to be useful in systems that operate over a wide bandwidth while intermittently experiencing high power, narrow bandwidth interference.

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