Tunable, Substrate Integrated, High Q Filter Cascade for High Isolation

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***Abstract* — A combination of tunable bandpass/bandstop filter substrate integrated cavity filters is shown for high spectral isolation. Greater than 90 dB of isolation is shown, which is potentially useful for isolating small signals in the presence of large interferers. Both filters are created using the same substrate integrated evanescent-mode cavity resonators which are placed in series or in shunt by changing the cavity feeds. The resonators are tuned using deformation of a copper membrane induced by a piezo electric actuator. The bandstop filter is able to place deep nulls on the skirt of the bandpass filter function on both the high and low frequency sides. The notch can be tuned from 2.1% to 9.6% away from the center frequency of the bandpass filter. The bandstop filter is also designed with a tunable shape which allows for wider bandwidth isolation on demand.**

***Index Terms* — Cavity resonators, Bandpass filters, Bandstop filters, Tunable filters, Piezoelectric transducers, Cascade circuits**

I. Introduction

As cognitive or spectrally aware radio architectures are advanced, they will become capable of determining the location of interferers in the spectrum that might saturate a receiver. Tunable deep nulls are highly desirable in the receiver front end frequency response of these systems to remove the interferers and eliminate nonlinearities in the receive chain. A non-cognitive radio has to try to have the sharpest filter skirts possible by using as many poles as allowed by the system because the location of the interference is undetermined. Alternatively, it is possible to directly target interferers using a spectrally aware system.

Dynamic, deep nulls in the spectrum, with 70 to 90 dB of isolation, will allow for the possibility of simultaneous transmission and reception even in systems containing high power transmitters. One mechanism capable of providing these levels of isolation is a cascade of series and shunt resonators acting in concert to provide bandpass and bandstop functionality. A typical filter topology for the desired system is shown in Fig. 1. In this paper, we demonstrate the integration of these filters using high-Q tunable evanescent-mode cavities within a commercial high frequency PCB substrate.

The resonators are defined by plated vias in the substrate and are tunable using an air-filled varactor inside each of the resonators. The four resonators are equivalent to each other in structure, but the resonator feeds differ between the bandpass and bandstop cases. In the bandpass case, a series resonator feed is used. A transmission line, in this case a coplanar waveguide, is brought to the edge of the resonator and shorted, ending in a magnetic field coupling slot. This circular slot couples the magnetic field of the coplanar waveguide with the magnetic field of the first mode of the resonator. In the bandstop case, a shunt feed is used. A semi-circular slot is incorporated in the ground plane of a microstrip line. Other than the slot in the ground plane, the microstrip line is a through line. This slot couples the magnetic field of the microstrip mode with the magnetic field of the first mode of the resonator. Effectively, the slot is only a substantial mismatch to the feed line when the resonator is at resonance. Therefore, the shunt-feed bandstop case passes the off resonance spectral content of the signal, while the series-feed bandpass case attenuates the off resonance content of the signal.

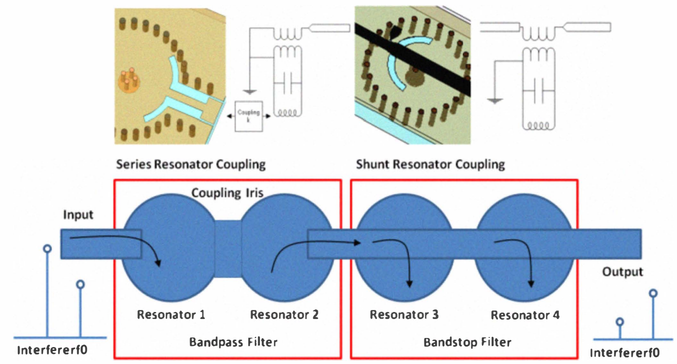

Fig. 1. Schematic and visual representation of applied external coupling mechanisms for bandpass-bandstop filter cascade.

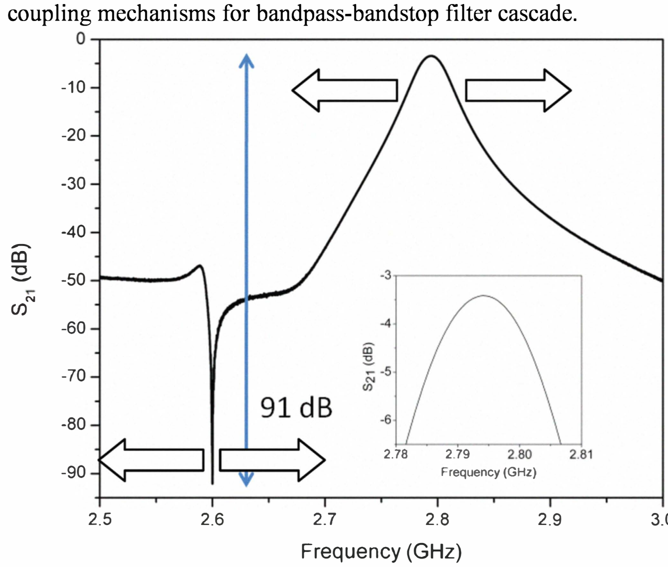

Fig. 2. Measured results of > 90dB isolation with the combination of tunable bandpass and bandstop filters.

The concept is shown in Fig. 2, which is a plot of measured results from cascading a tunable two pole bandpass filter with a tunable two pole bandstop filter to achieve greater than 90 dB of isolation between two frequency bands of interest.

Previous work in tunable bandstop filters has produced integrated planar designs [1] and larger 3-D structure designs [2]. Some previous planar designs are widely tunable, over an octave [3]. Alternative bandstop filters technologies include Yttrium Iron Garnet (YIG) filters [4]. However, these structures are difficult to integrate and do not have the level of reconfigurability presented herein. The proposed bandstop filter combines the ease of integration and electronic tuning capability of previous planar designs with high Q values.

II. Variable Bandwidth Bandstop Filter Design

The proposed bandstop filter design and equivalent lumped element circuit are shown in Fig. 3. The shunt cavity resonators are coupled together through a varactor loaded transmission line, which we will label the inter-resonator transmission line to separate it from the inter-filter transmission line that is between the bandpass and bandstop filters. The high Q dielectric resonators are designed in 3.175 mm thick Rogers TMM3 substrate and defined by vias. The resonators are loaded with a capacitive post, reducing the physical size of the cavity for a desired resonant frequency. The resonators' capacitive posts are covered with a 1 μm layer of Parylene-N from Specialty Coating Systems to prevent shorting of the capacitor plates. Then a copper membrane is laminated onto the substrate to close the cavity and form the top plate of the capacitor inside of the resonator. A 0.38 mm thick commercially available piezoelectric actuator from Piezo Systems is attached to the copper membrane to allow for electronically controllable deformation of the membrane. This deformation changes the capacitance and thus the center frequency of the resonator. This approach maintains relatively high values of Q while providing a wide tuning range [5]. High resonator Q values in bandstop filters allow for deeper notches for a given bandwidth and less insertion loss in the pass band. The Q value for the resonators presented in this work is 757 at 2.85 GHz.

The geometry of the slots in the ground plane for external coupling into the resonators was chosen to be semi-circular to align the magnetic field pattern of the first mode of the resonator while minimizing the perturbation to the microstrip line. The size of the slots was chosen to achieve the transformer ratio that results in the desired bandwidth for a given post size that maximizes the resonator Q [6]. Ansoft HFSS and Agilent ADS software was used to find the optimal slot size, setting the transformer ratio such that the external Q is:

$$Q_{ext} = \frac{R}{\omega_0 L} = \frac{Z_0}{\omega_0 L T^2} = \frac{50}{\omega_0 (1.182x10^{-9})(0.205^2)} = \frac{1.0x10^{12}}{\omega_0} \quad (1)$$

where T is the transformer ratio created by the slot in the ground plane.

The inter-resonator transmission line was fabricated using 0.787 mm thick Rogers Duroid 5880 material and laminated to the resonators. The length of the inter-resonator transmission line was chosen to be a quarter wavelength impedance transformer at the upper end of the tunable range. Therefore, the impedance transformer is a quarter wavelength or less over the tunable frequency range. As shown in [7], the resonators load the through line and the rate of change of their reactance is greater on the high frequency side of the notch than the low frequency side, producing asymmetry in the response. Shortening the transformer from its nominal quarter wavelength is a common way to mitigate this asymmetry.

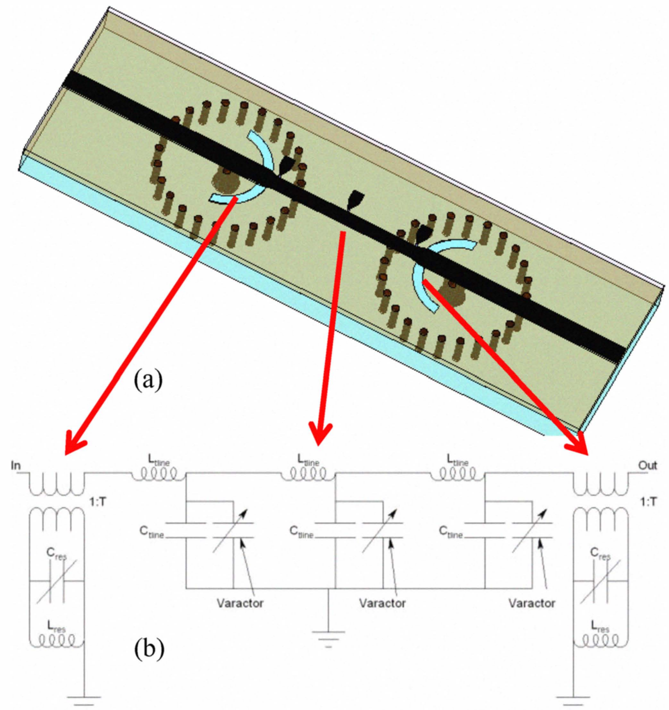

Fig. 3. (a) 3-D layout of proposed bandstop filter (b) Equivalent circuit with lumped element transmission line approximation.

The impedance of the inter-resonator transmission line impedance transformer was increased to a value of 66 ohms. This was done to reduce the nominal capacitance of the line because it is capacitively loaded with three varactors in order to tune the bandwidth of the filter. When transforming the first resonator of a low pass filter prototype to a parallel bandstop configuration, the bandwidth can be specified in terms of the inductance as [8]:

$$\Delta = \frac{\omega_0 L}{g_1 Z_0} \quad (2)$$

Where g_1 is the filter coefficient for a low pass filter prototype and Δ is the fractional bandwidth of the filter. A similar expression can be derived in terms of the capacitance of the resonator that shows the same inverse relationship to system characteristic impedance.

As seen in Fig. 3, these varactors can be thought of as an additional shunt capacitor in the lumped element equivalent of the inter-resonator transmission line. As the varactor capacitance is increased, the capacitance of the inter-resonator transmission line increases, decreasing its characteristic impedance and thus increasing the fractional bandwidth of the filter. The

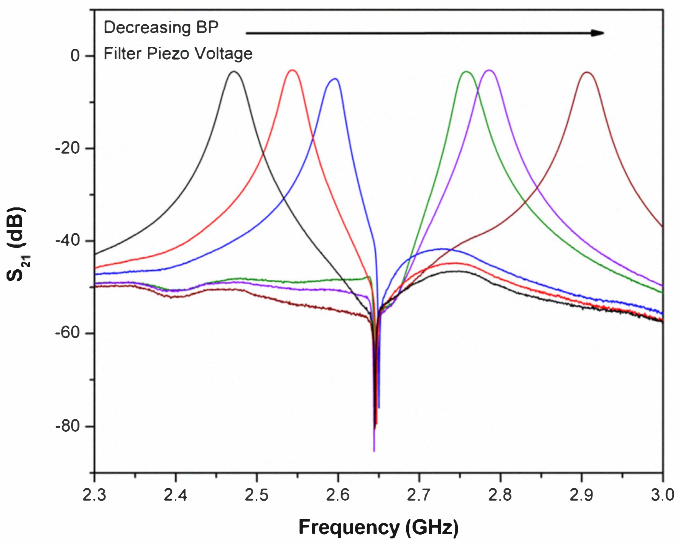

Fig. 4. Bandpass filter being tuned around a bandstop filter, useful in a situation with a constant interferer.

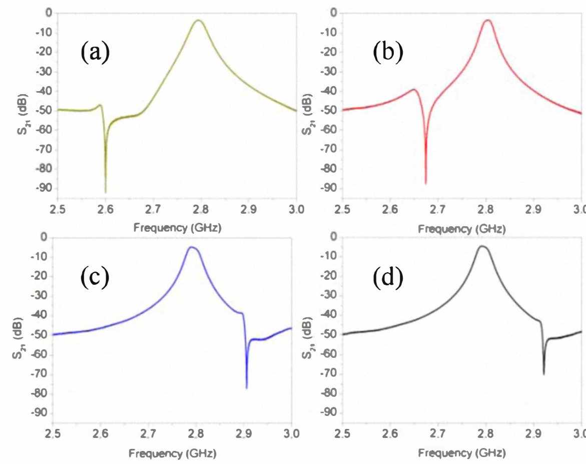

Fig. 5. Bandstop filter being tuned around a bandpass filter, useful in a situation with a hopping interferer. BS filter piezo voltage is decreased from (a) to (d).

response of the filter away from the notch frequency degrades with increasing loading because of worsening return loss, so the value of 66 ohms was chosen as a tradeoff between the out of band reflection and the bandwidth adjustability. A Microsemi MV20001-150A varactor with low absolute capacitance and high capacitance tuning range (0.15 pF-0.5 pF) was used.

III. Bandpass/Bandstop Cascade

When a bandstop filter is placed in cascade with a bandpass filter and the two filters are tuned to different frequencies, the bandpass out of band response presents an impedance to the bandstop input port that is different from the characteristic impedance of the system at the operating frequency of the bandstop filter. Therefore, the inter-filter transmission line affects the bandstop filter frequency response, and the response is far from a superposition of the individual filter S-parameter responses. Specifically, the length of the inter-filter transmission line changes the depth of the null produced in the frequency response. For high isolation, the phase of the output reflection coefficient of the bandpass filter and that of the input reflection coefficient of the bandstop filter should be examined and corrected for at the center frequency of the bandstop filter (assuming the bandpass filter precedes the bandstop filter in the system).

The inter-filter transmission line results in modified phase of the output reflection coefficient of the bandpass filter, and it was found that the null depth achieves a maximum, which is the best case, when the phase difference between the modified reflection coefficient of the bandpass filter at the bandstop filter center frequency and input reflection coefficient of the bandstop filter is 180 degrees. The minimum null depth was found when the phase difference was 90 degrees.

A low loss phase shifter could be used to ensure the optimal phase between the filters. However, one of the aims of the present work is to show that significant performance benefits can be realized without varying the phase of the connection. Accordingly, all measurements shown are taken with the same physical length connecting the bandpass and bandstop filters.

Because of the effect of out-of-band bandpass port impedance on the subsequent notch filter, the filter cascade isolation performance is best when the bandpass and bandstop filters are tuned in close proximity to each other. This is a favorable effect as the cascade's performance is most important when the two filters are tuned near one another. When an interferer is spectrally far from the pass band of the bandpass filter, the bandpass filter will provide high levels of isolation by itself. When an interferer is near the pass band of the bandpass filter, the cascade effect produces high levels of isolation that would otherwise be difficult to achieve for a static bandpass filter.

IV. Measured Results

Measured results showing the bandpass filter being tuned about a stationary bandstop filter are shown in Fig. 4. This would represent the case where the receive band is searching for a signal in the presence of a fixed interferer. Measured results showing the bandstop filter being tuned about a fixed bandpass filter are shown in Fig. 5, representing the case when an interferer is hopping through the spectrum around a fixed receive band. These plots show that isolation of 70-90 dB is possible between two spectrally close frequencies of interest over the 2.3 to 3.0 GHz band. Fig. 6 compares the cascaded result to the response of a simple two pole bandpass filter, showing the deep notch in the spectrum comes at the expense of 0.7 dB extra insertion loss in the pass band. The total pass band insertion loss of the four resonator chain increases to -3.4 dB. Fig. 7(a) shows that the bandpass and bandstop filters can be tuned within 55 MHz of one another around 2.63 GHz (2.1%). In Fig. 7(a), the bandpass filter is tuned to 2.595 GHz and the bandstop filter is tuned to 2.650 GHz. The bandpass filter insertion loss increases from -3.4 dB to -4.9 dB at this 2.1% spacing and degrades further at lower spacings. Using

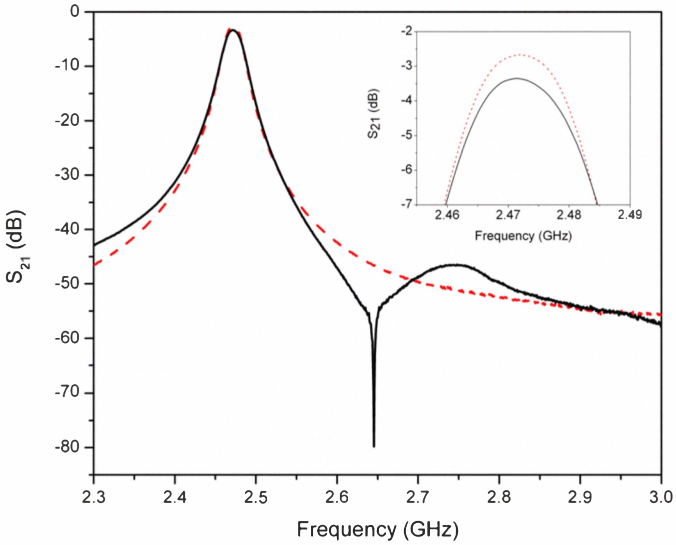

Fig. 6. Comparison of bandpass filter response (red dotted line) with response of cascaded bandpass and bandstop filters (solid black line).

the varactors on the inter-resonator transmission line, the bandstop filter's -20 dB bandwidth was tunable with a width of 24.5 MHz to 41.0 MHz centered at 2.625 GHz using a varactor voltage range of 0 V to 5 V. A system of this configuration also presents many other useful possibilities. For example, while the filter cascade is designed to allow a two pole notch response on the skirt of a bandpass filter, the poles of the bandstop filter can be tuned to different frequencies to create notches at varying positions in the spectrum. Fig. 7(b) shows measured results of a tunable two pole bandpass filter cascaded with a tunable two pole bandstop filter where the two poles of the bandstop filter have been tuned to create dual notches about the bandpass filter pass band, resulting in a quasi-elliptic filter response for the entire circuit.

V. Conclusion

A filter cascade is demonstrated in the 2.3 GHz to 3.0 GHz range using high Q, tunable, substrate integrated bandpass and bandstop filters with bandwidths on the order of 25 MHz. The cascade was capable of producing up to 90 dB of isolation between two independent frequency bands of interest over the range of operation. It is shown that the bandpass and bandstop filters can be brought within 55 MHz of one another at 2.63 GHz (2.1% spacing) before they start to greatly affect each others' responses. The bandpass and bandstop filters were able to be separated by 250 MHz at 2.63 GHz (9.6% spacing) before the phase of the inter-filter transmission line greatly affected the filters' responses. Finally, bandwidth adjustability of the bandstop filter was presented to illustrate additional flexibility when blocking interfering signals. Filter cascades of this type allow sensitive receivers to operate in the presence of spectrally close high power signals. The ability to do this is vital to optimize the capabilities of communication systems in spectrally dense environments. Systems having high power

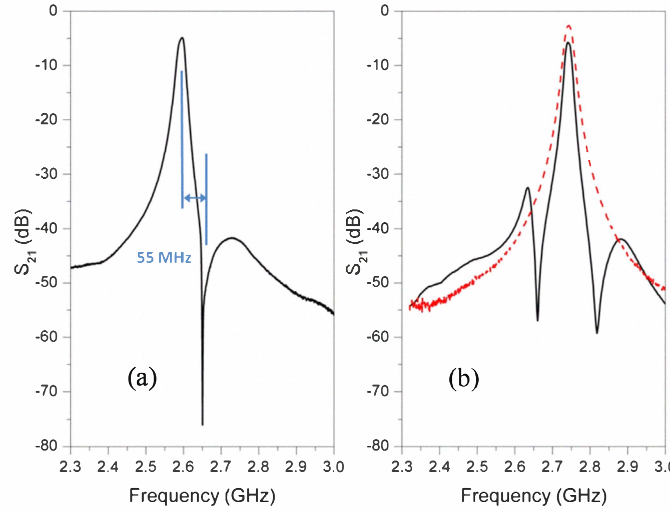

Fig. 7. (a) Bandstop filter tuned within 55MHz of bandpass filter with minimal effect on bandpass filter insertion loss (b) Comparison of bandpass filter response (dashed red line) to response when bandstop poles are tuned to different frequencies about the bandpass response (solid black line).

transmitters and sensitive receivers will now be able to operate both concurrently instead of being constrained to use time division multiplexing, increasing system capability.

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