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Design of Fixed- and Varactor-Tuned Bandstop Filters with Spurious Suppression

Andrew C. Guyette

Microwave Technology Branch, Naval Research Laboratory
Washington, DC, 20375, USA
`andrew.guyette@nrl.navy.mil`

Abstract— **A new spurious suppression method for bandstop filters based on constructive interference is presented. The technique is successfully applied to realize a fixed-tuned filter with an upper passband extending more than 9 times the fundamental bandstop response, as well as a varactor-tuned bandstop filter with an upper passband extending to 8.9 times the fundamental.**

I. INTRODUCTION

Bandstop filters are needed in many RF and microwave systems where they are used primarily to excise foreign interferers and mitigate co-site interference. In the case of wideband systems it essential that this filtering is achieved without sacrificing bandwidth, which requires that the bandstop filters possess wide passbands free of spurious responses. Unlike bandpass filters, where the upper stopband can be readily extended with the use of a lowpass filter, extending the passband of bandstop filters is a much more difficult problem.

The method typically used to extend the passband of a bandstop filter is to shift the higher-order resonances up in frequency with the use of stepped-impedance or lumped-element-loaded resonators. This approach has successfully been used to extend the passband up to 6 times the fundamental frequency [1], but much beyond this the extreme physical dimensions of the resonators becomes a practical limitation. One way to overcome this limitation and allow the upper passband to be extended even further is to suppress the higher-order spurious resonances. It is shown in this paper that spurious suppression can be achieved by effectively cancelling out resonator couplings using a constructive interference technique, which in theory can be used to extend the passband indefinitely. This technique is demonstrated to be applicable to both fixed-tuned and varactor-tuned bandstop filters.

A fixed-tuned microstrip prototype and a varactor-tuned microstrip prototype were designed, built, and tested to demonstrate the concept. The fixed-tuned bandstop filter achieves a stopband rejection of over 50 dB with an upper passband extending to over 9 times the fundamental frequency. The varactor-tuned bandstop filter achieves a 56% center-frequency tuning range with a passband extending 8.9 times the lowest-tuned center frequency.

II. BASIC CONCEPT

Shown in Fig. 1a is a highpass prototype of a conventional 1st-degree bandstop section, comprised of a resonator coupled to a transmission line. The coupling is modelled with an admittance inverter *K*. If this resonator was realized using distributed elements, the higher-order resonant modes would manifest as spurious responses in the upper passband.

Shown in Fig. 1b is the proposed 1st-degree bandstop section, comprised of a resonator coupled to a transmission line twice across an electrical length θ. Coupling the resonator to the transmission line twice effectively forms two signal paths, and depending on the value of θ either destructive or constructive interference can result. Also note that the two couplings *K* may be opposite in sign, depending on the coupling mechanism and topology of the resonator used. Using even/odd-mode analysis the 3-dB bandwidth of this section can be shown to be:

Case 1 (couplings *K* are the same sign):

$$BW = 4K^2 \cos^2 \frac{\theta}{2} \tag{1}$$

Case 2 (couplings *K* have opposite sign):

$$BW = 4K^2 \sin^2 \frac{\theta}{2} \tag{2}$$

Assume for the moment that both couplings K have the same sign, and so the bandwidth is given by (1). Eq. 1 is a maximum when θ is an integer multiple of 360°:

$$\theta = 2\pi n, \quad n = \{0,1,2 \ldots\} \tag{3}$$

Under this condition the phase difference between the two signal paths is 180° and maximum destructive interference occurs, resulting in maximum stopband bandwidth for a given coupling *K*. Eq. 1 is zero (and thus the coupling to the resonator is effectively cancelled) when θ is an odd multiple of 180°:

$$\theta = \pi n, \quad n = \{1,3,5 \ldots\} \tag{4}$$

Under this condition the two paths are in phase and maximum constructive interference occurs. When the couplings *K* are of opposite sign, the bandwidth is given by (2) and condition (3) results in minimum and (4) results in a maximum.

In order to suppress an unwanted spurious resonance the length of the transmission line between the two couplings is chosen such that **constructive** interference occurs at the spurious frequency, while **destructive** interference occurs at the fundamental bandstop frequency.

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14. ABSTRACT

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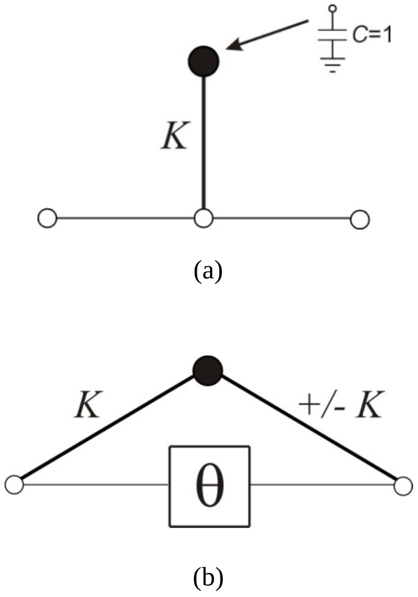


Fig. 1. 1st-degree highpass prototype sections comprised of shunt capacitors and couplings *K*. (a) Conventional. (b) Proposed.

III. A FIXED-TUNED BANDSTOP FILTER WITH 2ND AND 3RD-ORDER SPURIOUS SUPPRESSION

To demonstrate the spurious suppression concept a fixed-tuned bandstop filter consisting only of distributed elements was design, built, and tested. The 2nd and 3rd-order spurious responses of a stepped-impedance resonator are suppressed using constructive interference, which is implemented with both a delay line as well as with distributed coupling.

Fig. 2 illustrates how distributed coupling can be used to implement constructive interference. Fig 2a is an L-shaped combline resonator side coupled to a transmission line, with the coupled and uncoupled lengths given by θ_1 and θ_2, respectively. The fundamental resonance occurs at the frequency at which the sum of θ_1 and θ_2 is equal to 90°. If θ_1 and θ_2 are chosen such that, at a given spurious frequency, θ_1 is an odd multiple of 180° and θ_2 is an odd multiple of 90°, the equivalent circuit shown in Fig 1b is valid [3] (at the spurious frequency). Fig 2b consists of two in-phase signal paths, resulting in constructive interference and so the spurious is effectively cancelled. In other words, spurious suppression is achieved by decoupling a bandstop combline resonator in such a way that at a given spurious frequency it becomes equivalent to a 180° resonator coupled along its entire length.

Shown in Fig. 3 is the layout of the 2nd-degree microstrip filter in *SONNET*. It consists of two 1st-degree bandstop sections in cascade, each of which is comprised of a stepped-impedance combline resonator coupled to a transmission line such that the input impedance looking into the uncoupled length of resonator becomes a short at the 3rd-order spurious frequency. The 2nd-order spurious is suppressed by coupling the resonator to the transmission line twice across an electrical length equal to approximately 360° at the 2nd-order spurious frequency. There exists inductive coupling between the two resonators which is utilized to increase the stopband attenuation by adding destructive interference [2]. This inductive coupling is controlled by adding a small amount of capacitive coupling between the open ends of the resonators.

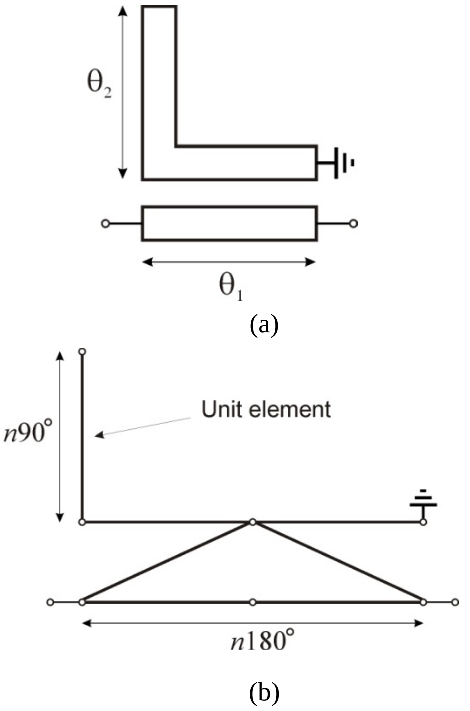


Fig. 2. Constructive interference implemented with distributed coupling. (a) L-shaped side-coupled combline bandstop resonator. (b) Simplified equivalent circuit at a suppressed spurious frequency, consisting of a combline resonator coupled twice across a transmission line. Note the correspondence with Fig. 1b.

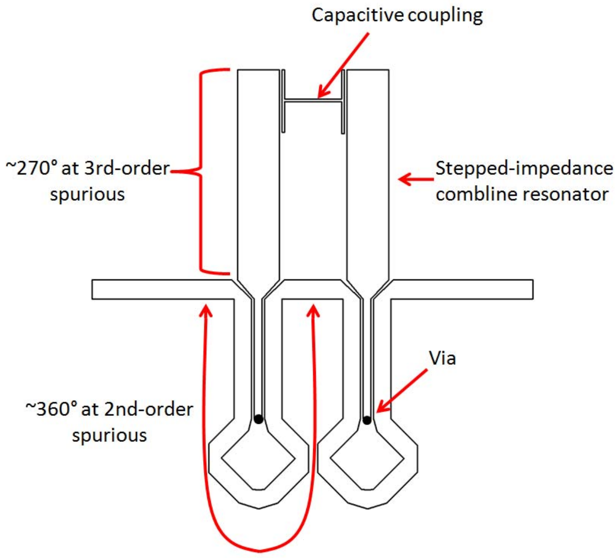
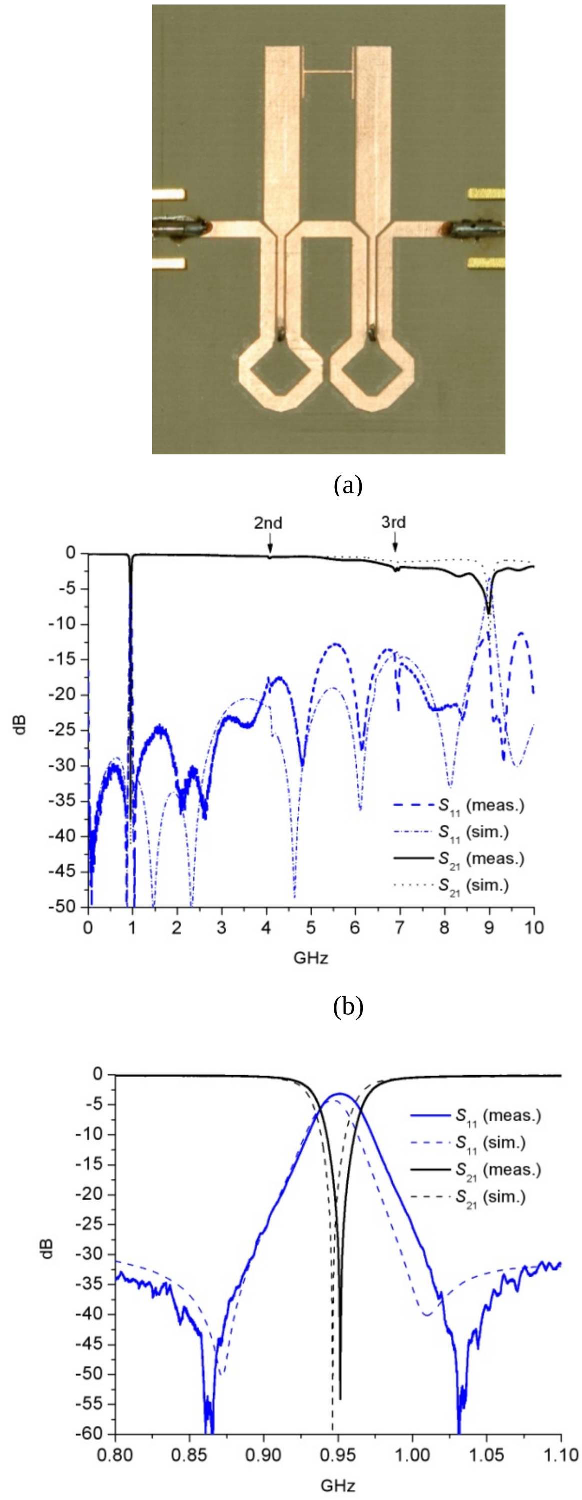


Fig. 3. Layout of the fixed-tuned bandstop microstrip prototype in *SONNET*. The 2nd- and 3rd-order spurious responses are suppressed with constructive interference.



(a)

(b)

(c)

Fig. 4. Microstrip fixed-tuned bandstop filter with extended passband. (a) Fabricated circuit. (b) Broadband response. (c) Detail of narrowband bandstop response.

Shown in Fig. 4a is the fabricated circuit (30-mil *Rogers Duroid 3003*, milled with an *LPKF Protomat S62*). Shown in Fig. 4b and Fig. 4c are the wide- and narrow-band measured results, respectively. The fundamental bandstop response has a bandwidth of 38.9 MHz, a center frequency 951.5 MHz, and 54 dB of stopband attenuation. The spurious responses occurring at 4.05 GHz and 6.91 GHz are successfully suppressed leaving small (<0.5 dB) insertion loss dips occurring at those frequencies. The first unsuppressed response occurs at 8.94 GHz, resulting in a passband extending to more than 9 times the fundamental bandstop center frequency. The only post-fabrication tuning done was to adjust the capacitive coupling between the resonators to improve the notch depth. No tuning was required for spurious cancellation.

IV. A VARACTOR-TUNED BANDSTOP FILTER WITH 2ND-ORDER SPURIOUS SUPPRESSION

The constructive interference concept can also be used to suppress spurious responses in varactor-tuned bandstop filters. The idea is to utilize capacitive loading to shift the unwanted higher-order resonances down in frequency to coincide with the bandwidth nulls provided by constructive interference. Fig. 5 illustrates the basic concept. The higher-order resonances are increasingly shifted into the bandwidths nulls as frequency increases due to the increasing reactance of the lumped capacitance. In theory this results in the suppression of an infinite number of spurious responses. In practice this is limited by the parasitics of a real capacitor.

Shown in Fig. 6 is the layout of the 2nd-degree microstrip varactor-tuned filter in *SONNET*. Similar to the fixed-tuned filter it consists of two 1st-degree bandstop sections in cascade. Each bandstop section is comprised of a varactor-loaded combline resonator coupled twice to a transmission line across an electrical length equal to approximately 1080° (3x360°) at the frequency of the 2nd-order spurious response at 4.5 GHz. This length was chosen as it also creates a bandwidth null at 1.5 GHz which is right above the tuning range, allowing for a more constant absolute bandwidth vs. center frequency. As in the fixed-tuned filter, a small amount of coupling between the resonators is utilized to improve the stopband rejection.

Shown in Fig. 7a is the fabricated circuit (30-mil *Rogers Duroid 3003*, milled with an *LPKF Protomat S62*). The varactors are unpackaged *Microsemi MV21010* abrupt junction (C_j=2.05-4.45 pF) wire bonded to minimize parasitics. Shown in Fig. 7b are the measured results for three tuning voltages. The center frequency tunes from 838.3 MHz to 1308.6 MHz (56%) while the 3-dB bandwidth varies from 62.6 MHz at the highest-tuned center frequency to 99.1 MHz at the lowest (+/- 22%). The stopband rejection varies from 10 dB to 22 dB. The passband extends to 7.47 GHz, which is 5.7 times the fundamental at highest-tuned frequency and 8.9 times the fundamental at lowest-tuned frequency.

V. CONCLUSIONS

A new method of extending the upper passband of bandstop filters by suppressing spurious responses has been presented. The basic concept behind the approach is constructive interference, and it has been applied to realize a microstrip fixed-tuned purely-distributed 2nd-degree bandstop filter with a passband extending more than 9 times the fundamental response. It is also been shown that by using lumped elements it is theoretically possible to eliminate all spurious, and a microstrip varactor-tuned 2nd-degree bandstop filter with a passband extending to 8.9 times the fundamental response demonstrates the concept.

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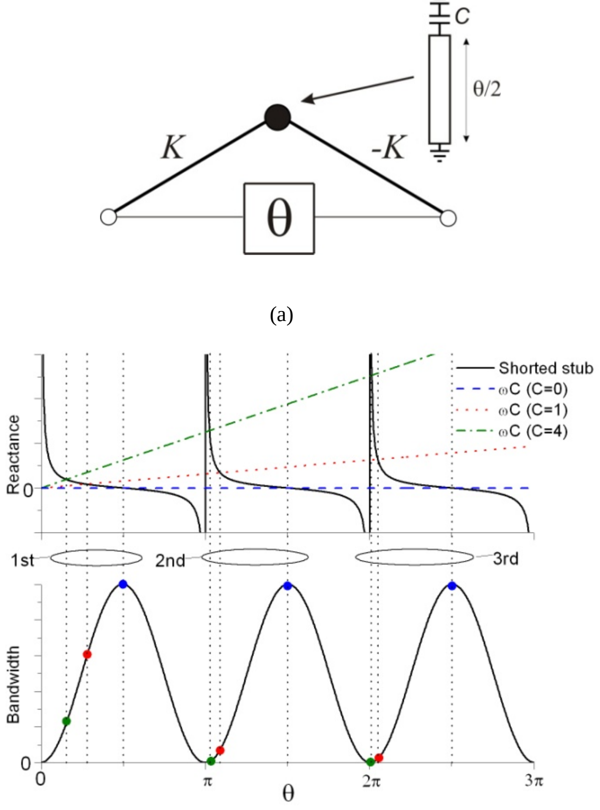


(a)

(b)

Fig. 5. Concept of using capacitive loading to shift the spurious resonances of a combline resonator to coincide with the bandwidth nulls obtained constructive interference. (a) Circuit topology. (b) Plot showing how resonances shift for various values of capacitance.

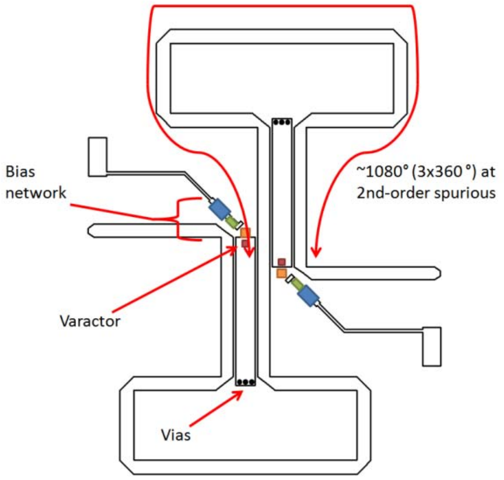
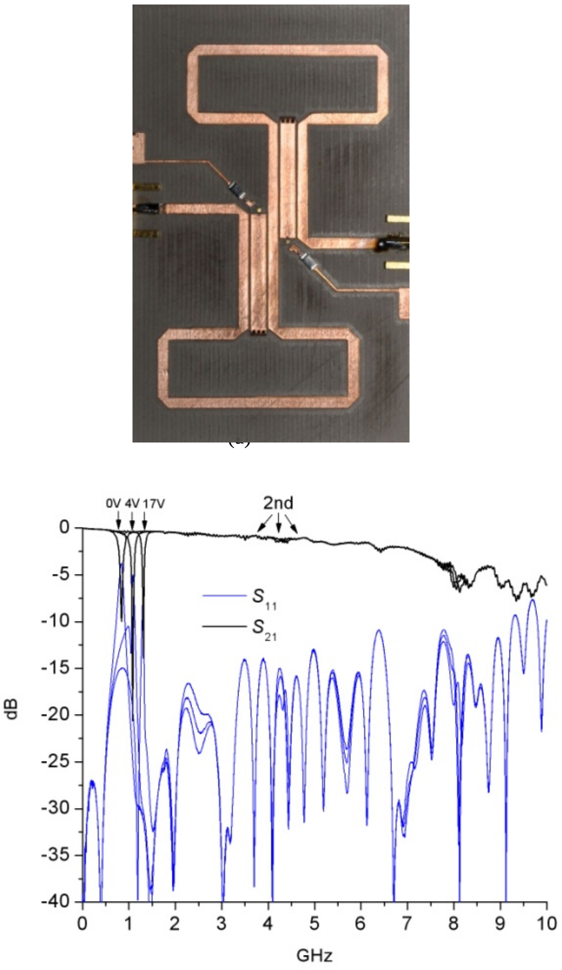


Fig. 6. Layout of the varactor-tuned bandstop microstrip prototype in *SONNET*. The 2nd-order spurious response is suppressed with constructive interference.



(b)

Fig. 7. Microstrip varactor-tuned bandstop filter with extended stopband. (a) Fabricated circuit. (b) Broadband response for three varactor tuning voltages.