Sub-Octave-Tunable Microstrip Notch Filter

Douglas R. Jachowski and Andrew C. Guyette

Microwave Technology Branch, Electronics Science and Technology Division
Naval Research Laboratory, Washington, DC 20375 USA

Abstract — **A frequency-agile narrowband microstrip bandstop filter technology able to maintain near constant absolute bandwidth while tuning over a frequency range of nearly an octave is described. The technology is demonstrated by a reconfigurable notch filter designed to selectively remove unwanted spectral content prior to final amplification in a transmitter's output module. The six-resonator planar microstrip notch filter uses hyperabrupt GaAs varactor diodes to tune the operating frequency over a 92% range, from 480 MHz to 925 MHz. The filter maintains 3MHz-wide stopband attenuation of 34dB to 64dB, absolute 3dB bandwidth of less than 84 MHz, 3dB bandwidth variation of less than 24%, and low stopband reflection over the full tuning range.**

I. Introduction

The growing importance of equipment compatibility and interoperability is making improved control of spectral content a driving force in the evolution of transmitter architectures. One recently proposed wideband transmitter architecture [1] employs a sub-octave-banded power amplifier (PA) approach to help reduce spurious spectral content. To make it easier to control spectral output, the approach allows for the inclusion of tunable bandstop, or "notch", filters in each sub-band signal path between the driver amplifier and PA in order to excise unwanted spectral content prior to final amplification, as shown in Fig. 1. And, to satisfy the most demanding applications, unconventional levels of notch filter performance are required in terms of tuning range, stopband attenuation level, 3 dB bandwidth consistency, power reflection, physical size, and cost.

Recently, compact narrowband absorptive notch filters have been demonstrated that enable selective elimination of spectral content at either fixed or dynamically changing frequencies using inexpensive lossy circuit components [2]-[8]. Leveraging this technology, this paper addresses the need for improved 3 dB bandwidth consistency over even wider tuning ranges. As an example, a "third-order", six-resonator, microstrip absorptive notch filter, composed of a properly phased cascade of three "first-order" stages, is described that exhibits less than 24% variation in 3 dB bandwidth over a 92% frequency-tuning range and a 3-MHz-wide stopband attenuation of greater than 60 dB over most of the tuning range and of greater than 34 dB over the full tuning range.

II. Tunable Absorptive Pair

Conventional bandstop filters reflect stopband signals, and resonator loss limits their stopband attenuation and selectivity. In [3] and [8], a two-resonator "absorptive- pair" bandstop filter was introduced that, to at least some extent, absorbs stopband signals – with resonator loss limiting minimum bandwidth rather than stopband attenuation. One of many possible circuit schematics of an absorptive pair is given in Fig. 2(a), in which frequency-invariant admittance inverters k_{01} couple lossy resonators, with admittances Y_p and Y_m, to opposite ends of admittance Y_s with phase shift ϕ, while inverter k_{11} directly couples the two resonators. The simulated responses of conventional and absorptive-pair notch filters, each with identical resonators, are compared in Fig. 2(b), illustrating the advantage of the absorptive pair.

All resonator tuning mechanisms include a resistance that changes as resonant frequency is tuned, causing a change in resonator loss. Increased resonator loss degrades stopband attenuation and selectivity in conventional notch filters, while absorptive pairs can maintain stopband attenuation by compensating for increases in resonator loss with changes in the offset tuning of the resonator frequencies [3, 8], as shown in Fig. 3 and explained by the absorptive pair's criteria for realizing infinite stopband attenuation at frequency f_o [8]:

$$k_{01} = \sqrt{Y_s \frac{k_{11}^2 + g_m g_p + g_m g_p Q_m Q_p (f_p^2 - f_o^2)(f_o^2 - f_m^2)/f_o^2}{k_{11}\sin(\phi)}}$$

where Q_m and Q_p are the unloaded Q's of Y_m and Y_p and

$$f_o = \sqrt{f_m f_p (Q_m f_m + Q_p f_p)/(Q_m f_p + Q_p f_m)}\,.$$

Still, as in conventional approaches, frequency dependence of resonator couplings and loss can lead to undesirable changes in filter bandwidth over a tuning range. To address this problem, a tunable absorptive pair with reduced bandwidth variation has been developed.

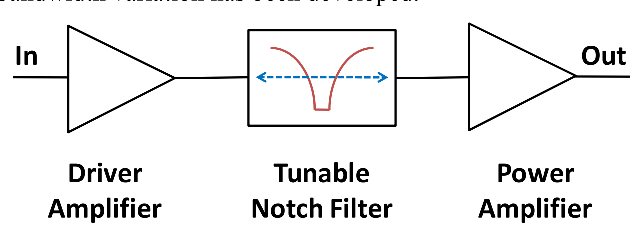

Fig. 1. Schematic of one output-stage signal path in a sub-banded-PA transmitter architecture.

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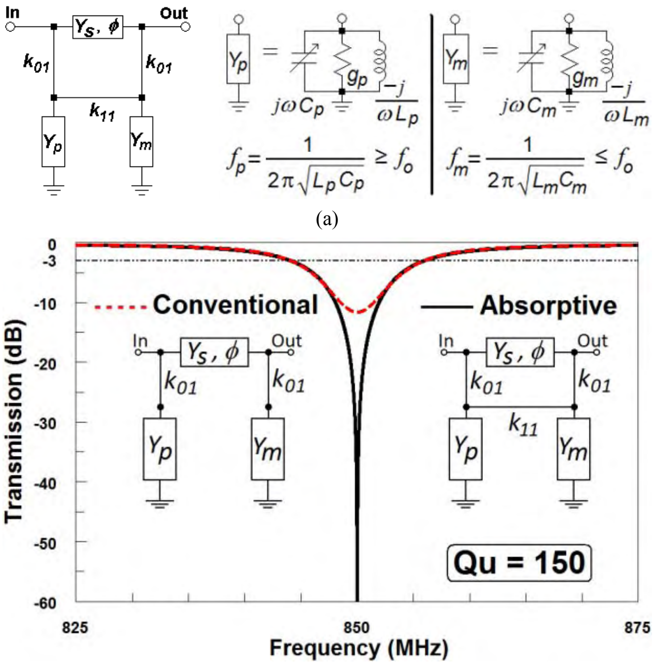


(a)

(b)

Fig. 2. (a) Equivalent circuit of a 2-resonator "absorptive-pair" notch filter and (b) comparison of simulated transmission responses of 2-resonator conventional (dashed red line) and absorptive (solid black line) notch filters, each with a resonator unloaded Q of 150.

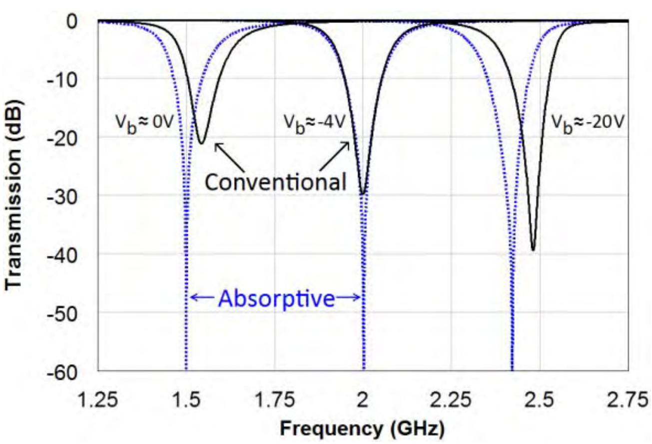
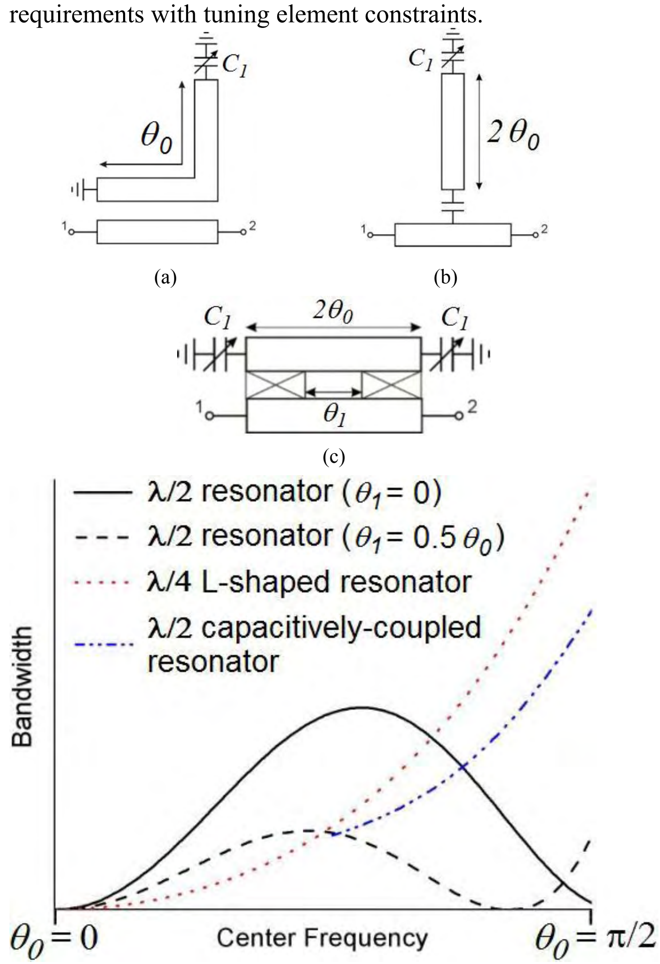


Fig. 3. Comparison of the simulated response of a tuned conventional notch filter (solid black line) with the measured characteristics of a tuned absorptive-pair notch filter (dotted blue line), each with the same resonators and varactor-diode tuning elements, measured at three different pairs of independent varactor bias voltages: about 0V, -4V, and -20V.

A. Tunable Filters with Reduced Bandwidth Variation

Narrowband bandstop filters are typically realized using resonator-to-transmission-line couplings uniformly distributed over less than a quarter wavelength (λ/4) of the resonator [9, 10], such as shown in Figs. 4(a) and 4(b). Such filters generally exhibit a -3dB bandwidth that increases with tuned resonant frequency, as shown by the dotted red and dot-dashed blue lines in Fig. 4(d). In order to realize a constant-bandwidth response in a fashion analogous to the tunable combline bandpass filters of [11], a bandstop filter structure with a bandwidth minimum located at a frequency above the tuning range is required.

One such structure is a half-wavelength (λ/2) resonator edge-coupled to a through line as in Fig. 4(c). If the resonator is uniformly coupled (θ_1 = 0), the structure has an allpass response (bandstop response with zero bandwidth) when the tuning capacitances C_1 are zero. As the capacitances C_1 are increased, the resonator's resonant frequency decreases while the bandwidth increases, reaching a maximum at a certain frequency (Fig. 4(d), solid black line). Designing the bandstop filter's tuning range around this frequency of maximum bandwidth gives a response with reduced bandwidth variation, similar to that of the tunable bandpass filter of [11]. Decoupling the resonator at its center (θ_1 > 0) decreases inductive coupling, which decreases the frequency of maximum bandwidth (Fig. 4(d), dashed black line), providing more design flexibility when trying to simultaneously satisfy operating frequency, tuning range, and bandwidth variation requirements with tuning element constraints.



(a) (b)

(c)

(d)

Fig. 4. Diagrams of bandstop filters with capacitively-tuned (a) edge-coupled L-shaped λ/4, (b) capacitively-coupled λ/2, and (c) edge-coupled λ/2 resonators, and (d) a plot of the simulated bandwidth versus tuned center frequency for each filter. $2\theta_0$ is the electrical length of the λ/2 resonators at the tuned center frequency and θ_1 is the centered portion of the edge-coupled resonator decoupled from the through line.

B. Modified Tunable Absorptive Pair

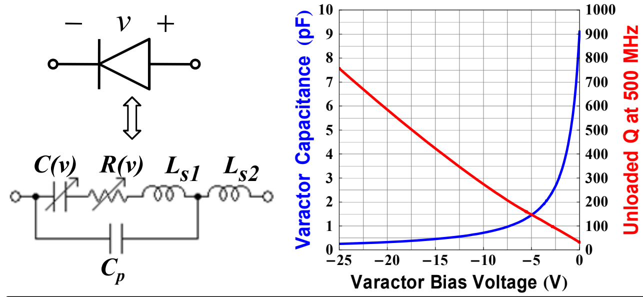
To minimize bandwidth variation across the filter's tuning range, the absorptive-pair architecture was modified to incorporate the tunable capacitively-loaded half-wavelength resonators introduced in the previous section. To verify the capabilities of the modified absorptive-pair, a first-order, two-resonator filter was designed using iterative analysis and optimization. The design process began by characterizing microstrip loss on a Rogers' RO3210 substrate (25-mil thick, 10.2 dielectric constant, 0.003 dielectric loss tangent, 0.017 mm copper, 0.878 ratio of effective copper resistivity relative to gold) by matching measurements of a conventional half-wavelength-resonator notch filter to simulations of a corresponding microstrip layout in a commercial planar electromagnetic (EM) field simulator by adjusting conductor resistivity. Also, a series-resistor-inductor-capacitor model of the varactor, as shown in Fig. 5, was extracted from two-port s-parameter measurements of a 50Ω microstrip line with a shunt-connected reverse-biased varactor diode to ground. Then, a microstrip layout – conceptually representative of, but topologically different than, Fig. 1 (with resonators coupled to each other across the through transmission line) – was iteratively-optimized at three tuned operating-frequency states: 525, 747.5, and 970 MHz. Experience with [8] indicated that the design should constrain the resonators' resonant frequencies to be equal at the target lowest-tuned frequency and constrain one of the two bias voltages to be the highest acceptable voltage at the target highest-tuned frequency.

Once the circuit model's 3-MHz-wide stopband attenuation was greater than 60 dB at each of the three operating frequencies and its 3-dB bandwidth was approximately equal at the lowest and highest tuned frequencies for some set of bias voltage pairs, a lumped-element lowpass varactor-bias network (with a 3-dB band edge above 150 MHz and less than 13 ns near-band group delay), resistively terminated at its input and reactively (i.e., varactor) terminated at its output, was added and the EM-modeled microstrip layout was re-optimized, resulting in the two-resonator layout of Fig. 6(a). The isolation level of the reactive bias network was designed to be similar to the filter's stopband attenuation (about 60 dB).

III. Sub-Octave-Tunable Third-Order Notch Filter

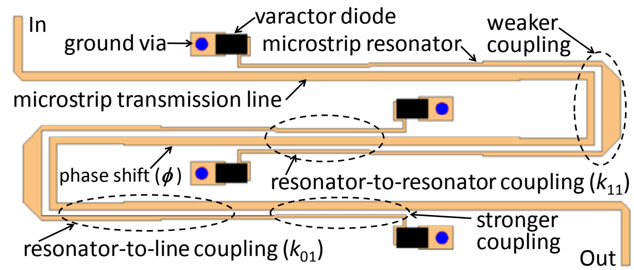
Three first-order notch filter stages of the preceding section were connected in cascade by two 50.7 Ω microstrip lines, each about 35.25° long at 747.5 MHz, resulting in the integrated third-order, six-resonator notch filter shown in Fig. 6(b). Dividing walls were needed between stages to prevent parasitic inter-stage coupling from ruining filter performance.

Superimposed plots of the predicted and measured characteristics of the filter are shown in Figs. 7 and 8. While the filter maintains 3 MHz stopbands of greater than 60 dB attenuation over the majority of its tuning range, the operating frequency range of the filter is shifted about 45 MHz below the designed range and the stopband attenuation degrades at the lower and upper ends of the tuning range. Imprecise

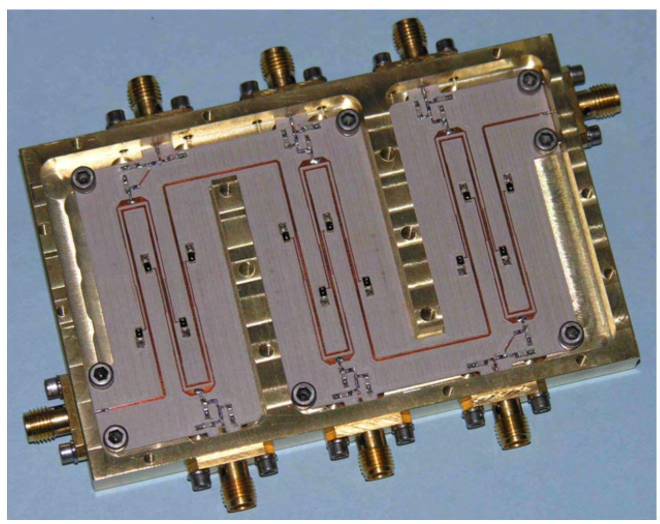


$$C(v) = \frac{9.1}{(1-v/1.5)^{1.25}}\,[pF] \qquad R(v) = \begin{cases} 1.6903 + 0.2289/v, & v > 5.511V \\ 1.0958 - 0.0892\,v, & 5.511V \ge v \ge 2.788V \\ 1.1672 - 0.0636\,v, & 2.788V > v \end{cases} [\Omega]$$

Fig. 5. Model of the reverse-biased Metelics MGV-125-26-0805 GaAs hyperabrupt varactor diode, with L_{s1}=0.4nH, L_{s2}=0.86nH, and C_p=0.07pF).



(a)



(b)

Fig. 6. (a) Annotated layout of a single-stage tunable absorptive notch filter and (b) photo of a corresponding three-stage filter in a 101.6 x 63.5 x 8.9 mm brass enclosure with SMA connectors.

milling of microstrip resonators that have some 0.2 mm line widths and 0.3 mm coupling gaps is believed to have contributed to these deficiencies. Better results could be expected using photolithographic manufacturing. Still, using six independently tunable varactor bias voltages ranging from 1V to 20V, 34dB stopband bandwidths all tune to greater than 3 MHz and the resulting absolute 3-dB bandwidths are all less than 84 MHz and vary less than 24% over a 480-925 MHz, 92.7% tuning range. The passband insertion loss ranges from 0.8 dB at 480 MHz to 1.2 dB at 925 MHz, the minimum passband return loss is greater than 14 dB over the entire tuning range, and the filter is free of spurious responses over more than a 133% frequency range.

IV. Conclusion

A first-order, two-resonator microstrip absorptive notch filter with quasi-constant-bandwidth over a tuning range of nearly an octave was introduced. Three first-order sub-circuits were used to make a third-order, six-resonator filter, which exhibits useful levels of frequency selectivity and stopband bandwidth and attenuation, and demonstrates near octave tunability while maintaining relatively constant bandwidths. Filters of this type are expected to find use in wideband transmitters that must be interoperable with, or compatible with, nearby equipment.

Acknowledgement

Thanks to Marc St. John of MITRE Corp. for suggesting this effort, Gary Shuler of NAVSEA for supporting this effort, and Rogers Corp. for the substrate.

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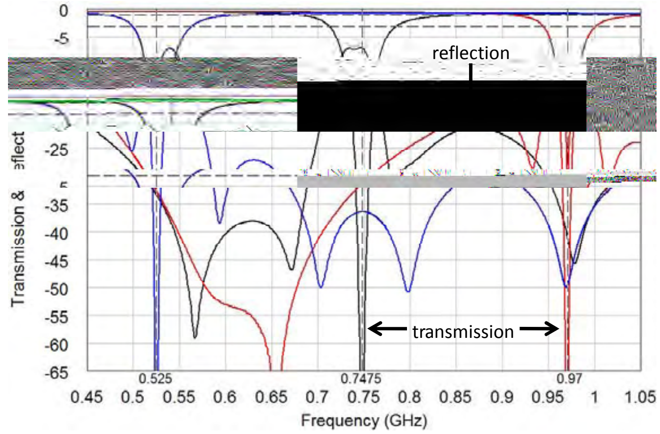
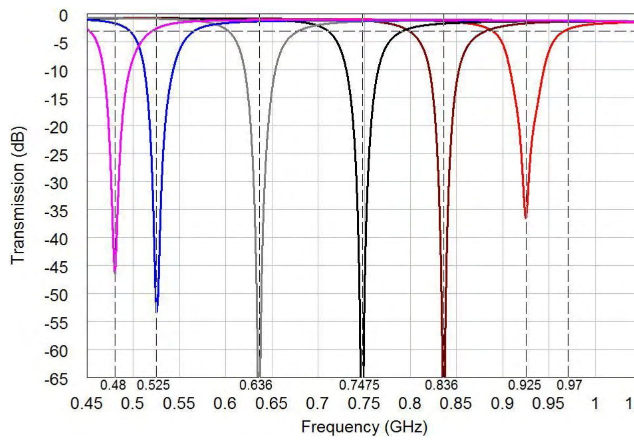
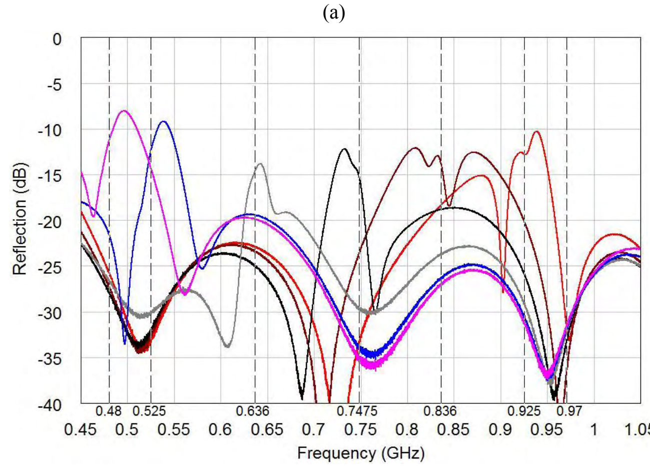


Fig. 7. Superimposed plots of the tunable notch filter's predicted performance when tuned by six independent varactor bias voltages to 525 MHz (blue), 747.5 MHz (black), and 970 MHz (red).



(a)



(b)

Fig. 8. Superimposed plots of the tunable notch filter's measured (a) transmission and (b) reflection characteristics when tuned by six independent varactor bias voltages to 480 MHz (purple), 525 MHz (blue), 636 MHz (gray), 747.5 MHz (black), 836 MHz (brown), and 925 MHz (red).