

Octave Tunable Lumped-Element Notch Filter

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Abstract — A new lumped-element notch filter architecture with uniform attenuation characteristics over an octave tuning range is described. The approach is demonstrated by a 20 to 55 MHz varactor-tuned two-resonator notch filter with minimum notch attenuation of 40dB, 3dB bandwidths of ~2.5 MHz, tuning times of less than 3 μ s, control voltages below 5V, and passband insertion loss less than 0.2dB from 18 to 60 MHz.

Index Terms — filters, tunable, lumped-element, notch, absorptive, bandstop, frequency-agile.

I. INTRODUCTION

Tunable notch filters are used to protect receivers from narrowband interference and prevent unintended output from transmitters in systems that must cope with changing operational requirements or function in dynamic spectral environments. When space is critical, the filters must use lumped, rather than distributed, components.

Lumped elements have poor unloaded quality factors (Q_u) that usually lead to poor filter performance. And, when filters must tune quickly, semiconductor or ferroelectric tuning devices must be used. But fast tuning devices also have poor Q_u and increasingly degrade filter performance the farther in frequency a filter is tuned. So, conventional semiconductor-tuned lumped-element notch filters are unable to tune over broad frequency ranges while maintaining good performance.

Conventionally designed narrowband lumped-element notch filters can suffer from realization difficulties, and tuning their frequency usually affects their bandwidth. Recently, tunable lumped-element notch filters based on a common microwave notch filter architecture [1] have been described [2] that address these problems. Unfortunately, they require independent control of both coupling and frequency to tune over even a moderate frequency range ($f_{\max}/f_{\min}=1.55:1$) and exhibit limited stopband attenuation and selectivity.

A potentially more promising approach based on a tunable absorptive notch filter architecture [3] has been suggested in [4]. While this approach offers broader tuning ranges, superior stopband attenuation and selectivity, uniform characteristics over the full tuning range, and tuning of frequency alone, some inductors remain difficult to realize. This paper describes a method to address this issue and uses it to realize a lumped-element notch filter that maintains its selectivity and 40dB stopband attenuation over a wide frequency tuning range ($f_{\max}/f_{\min}=2.8:1$) with control voltages of less than 2.6V (to 55 MHz) and transition times on the order of microseconds.

II. TUNABLE LUMPED-ELEMENT ABSORPTIVE NOTCH FILTER

The new lumped-element absorptive-pair notch filter architecture is derived from the circuit in Fig. 1(a), described in [4], in which inductors and varactors are assumed to include significant resistance. Use of inductive admittance inverters keeps tuning of resonator capacitance from affecting coupling to the transmission line so that filter bandwidth is unaffected by frequency tuning. A highpass artificial transmission line is used so that negative shunt inductance of the admittance inverters can be absorbed into the transmission-line shunt inductors. Unfortunately, the large values of the inductors of the resulting Π inductor networks can be difficult to realize.

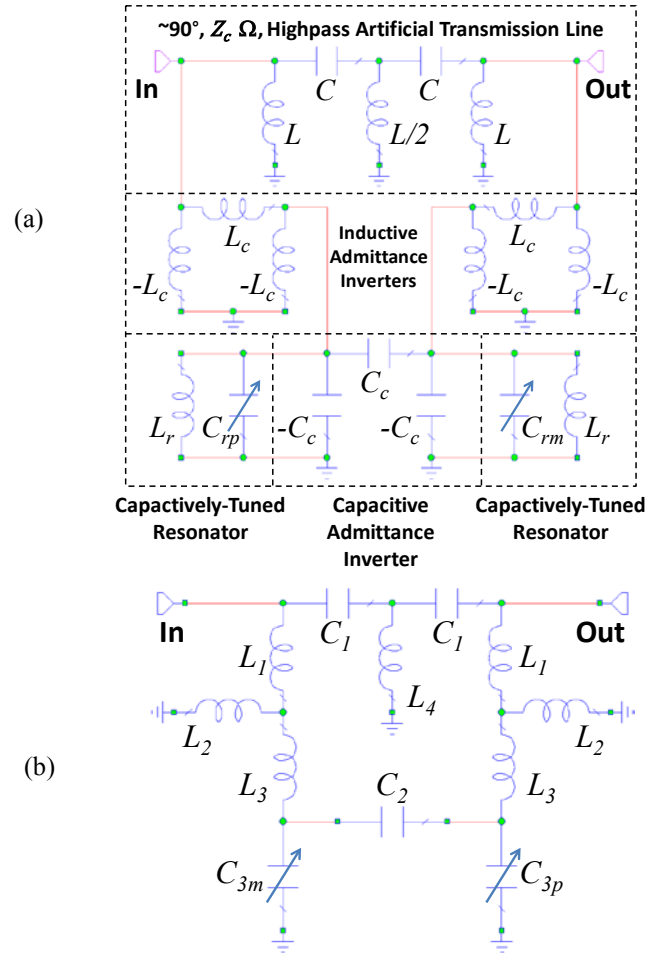


Fig. 1. Schematics of tunable lumped-element absorptive-pair bandstop filters: (a) from [4] and (b) showing the new approach.

A. Improved Filter Architecture

To enable use of lower resistance, lower value inductors, the Π inductor networks of Fig. 1(a) are transformed to T networks by equating transfer matrices. Fig. 1(b) shows the new tunable lumped-element notch filter circuit that results.

B. Design Procedure

With help from the equations and procedure from [4], it is a relatively straightforward task to determine suitable values for the elements of the circuit of Fig. 1(b).

The design procedure begins by determining element values for the circuit of Fig. 1(a). Using equation (2) from [4], the transmission line's phase variation, $d\phi$, from 90° over a specified frequency range, f_{\min} to f_{\max} , is found by solving

$$\frac{f_{\max}}{f_{\min}} = \frac{\sin((1+d\phi/90)\pi/8)}{\sin((1-d\phi/90)\pi/8)}. \quad (1)$$

Using (2) and (6) from [4], the artificial transmission line's highpass cutoff frequency, f_c , and "design" frequency, f_o , are

$$f_c = f_{\min} \sin((1 + d\phi/90)\pi/8) \quad (2)$$

$$f_o = f_c / \sin(\pi/8). \quad (3)$$

For a specified transmission-line impedance, Z_c , and using (5) and (6) from [4], the L and C of Fig. 1(a) are

$$L = Z_c \sqrt{1 - \sin^2(\pi/8)} / (2\pi f_o \sin(\pi/8)) \text{ [H]} \quad (4)$$

$$C = 1 / (4\pi f_o Z_c \sin(\pi/8) \sqrt{1 - \sin^2(\pi/8)}) \text{ [F]}. \quad (5)$$

Designing inverter inductance L_c , inverter capacitance C_c , and resonator inductance L_r of Fig. 1(a) is a less exact process due to the inherently ambiguous properties of the tunable components C_{rp} and C_{rm} . First, a model for the tuning elements must be chosen. A reasonable model for reversed-biased varactor diodes is a constant capacitance, C_p , in parallel with a series-RLC circuit in which series inductance, L_s , is constant and series resistance, R_v and capacitance, C_v , are functions of an applied bias voltage, v . While even diodes from the same lot can exhibit appreciable differences, sufficiently accurate varactor models can be determined empirically by extracting their element values from measured data, such as done in [4].

Once a circuit model of the tuning elements has been determined and substituted for components C_{rp} and C_{rm} in Fig. 1(a), the values for L_c , C_c , and L_r – as well as for the two bias voltages, v_p and v_m , of the two tuning elements – are found by iteratively optimizing this modified circuit at low- and high-frequency tuned states ($< f_{\min}$ and $> f_{\max}$), as well as at a central-frequency tuned state, f_{mid} . Each of these three states is defined by a different pair of bias voltages: (v_{p1}, v_{m1}) , (v_{p2}, v_{m2}) , and (v_{p3}, v_{m3}) , where $(v_{p1} \approx v_{m1}) \geq v_{\min}$ is enforced for the low frequency state and $v_{m3} < (v_{p3} \leq v_{\max})$ is enforced for the high frequency state. The lowest and highest permitted bias voltages, v_{\min} and v_{\max} , are chosen to maximize the filter power handling within constraints imposed by the available

bias supply and by breakdown-voltage and capacitance-versus-voltage characteristics of the tuning device, and typically remain flexible throughout the design process. The optimization should account for the Q_u of the inductors, and should continue until a notch attenuation of about 50dB is achieved for each of the three tuned states. L_c , C_c , and L_r are the same for all tuned states. As a final refinement, separately optimized lowpass-filter bias circuits with high selectivity and cut-off frequency are included as part of the tuning element circuits and the notch filter optimization process is repeated.

In terms of the element values of the circuit of Fig. 1(a), the element values of the circuit of Fig. 1(b) are given by

$$L_1 = L_c L (L_c - L_r) / (L_c^2 - L_r L) \quad (6)$$

$$L_2 = L_c L_r L / (L_c^2 - L_r L) \quad (7)$$

$$L_3 = L_c L_r (L_c - L) / (L_c^2 - L_r L) \quad (8)$$

and $L_4 = L/2$, $C_1 = C$, $C_2 = C_c$. Negative capacitances $-C_c$ are ignored since their effect is accounted for through optimization of the pairs of tuning-element bias voltages.

C. Experimental Tunable Lumped-Element Notch Filter

A tunable lumped-element notch filter as in Fig. 1(b) was designed using the procedure above. For comparison with [4], an initial tuning range of 26 to 50.375 MHz was chosen and four paralleled stacked pairs of MA4ST2600CK-1146T silicon hyperabrupt varactor diodes, as described in Fig. 4 of [4], were used as tuning elements. Design parameters and resulting element values are listed in Table I, while Table II lists the components used to manufacture the filter. Inductor values were reduced by factors of 3.2 and 3.9 relative to those in [4]. The 2"x2"x0.9" filter, on a Rogers RO4003 substrate (0.060" thick, $\epsilon_r=3.38$, $\tan\delta=0.0021$), is shown in Fig. 2, and simulated and measured performance are shown in Figs. 3-5. Bias voltages range from 1V at 26 MHz to 2.3V at 52 MHz and intermodulation levels are below -22 dBc for two -15 dBm tones – one centered in a notch at 39 MHz and one swept.

Table I. Tunable Notch Filter Parameters and Element Values

	Parameters	Figs. 1a & 3a Values	Fig. 1b Values
specified	$f_{\min}: f_{\max} = 26:50.375 \text{ MHz}$	$L = 585.275 \text{ nH}$	$L_1 = 499.349 \text{ nH}$
	$f_{\text{mid}} \approx 39 \text{ MHz}$	$C = 137.138 \text{ pF}$	$L_2 = 235.693 \text{ nH}$
	$Z_1 = 50 \Omega$	$L_c = 920 \text{ nH}$	$L_3 = 134.883 \text{ nH}$
	$v_{\min}, v_{\max} \approx 0.5\text{V}, 5\text{V}$	$C_c = 1 \text{ pF}$	$L_4 = 292.638 \text{ nH}$
	inductor $Q_u=100 @ 50\text{MHz}$	$L_r = 295 \text{ nH}$	$C_1 = 137.138 \text{ pF}$
found	$d\phi = 34.083^\circ$	$(v_{p1}, v_{m1}) = (0.819, 0.819)$	$C_2 = 1 \text{ pF}$
	$f_c = 12.562 \text{ MHz}$	$(v_{p2}, v_{m2}) = (1.687, 1.649)$	
	$f_o = 32.825 \text{ MHz}$	$(v_{p3}, v_{m3}) = (2.230, 2.230)$	

Table II. Tunable Notch Filter Components (see Figs. 1b & 2)

ID	Value	Part Number
L_1	500 nH $\pm 2\%$	Coilcraft 2929SQ-501GEB (Air Core, Square)
L_2	202 - 250 nH	Coilcraft 144-08J12SL (Tunable, Shielded)
L_3	132 - 165 nH	Coilcraft 144-05J12SL (Tunable, Shielded)
L_4	300 nH $\pm 2\%$	Coilcraft 2222SQ-301GEB (Air Core, Square)
C_1	2 x (68 pF $\pm 2\%$)	ATC 700B680GT 500
C_2	1 $\pm 0.1 \text{ pF}$	ATC 700B1R0BT 500

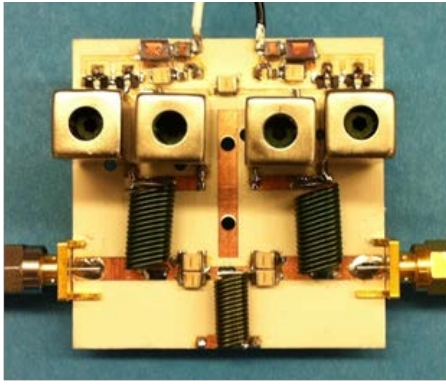


Fig. 2. Photograph of the tunable lumped-element notch filter.

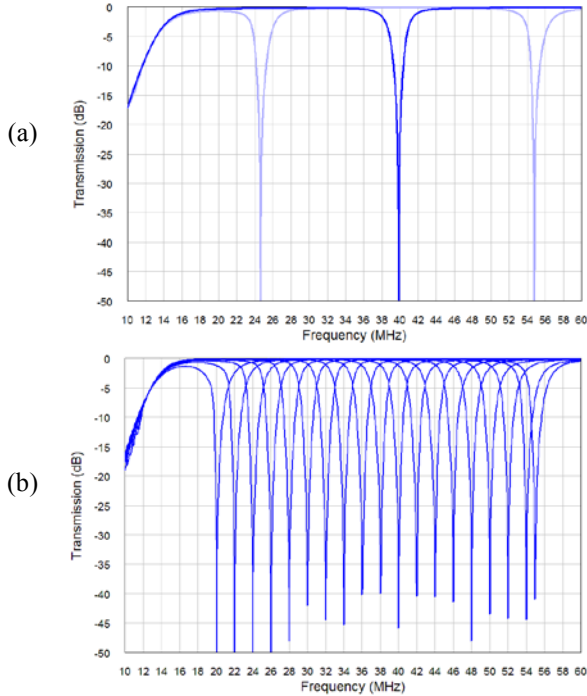


Fig. 3. (a) Simulations of the filter of Fig. 1 tuned to 3 different frequencies and (b) superimposed measurements of the filter of Fig. 2 tuned to 19 different frequencies from 20 to 55 MHz. A 5V bias tunes the notch out of band, leaving a <0.2 dB 18-to-60 MHz passband.

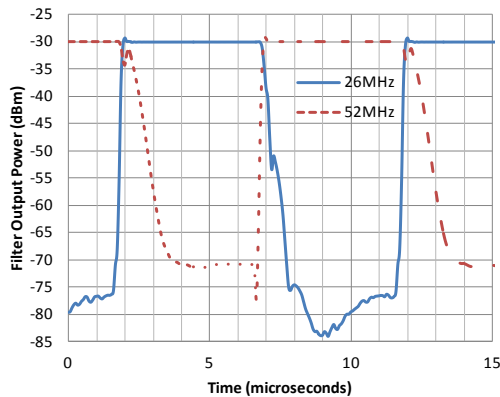


Fig. 4. (a) Measurements of filter output when alternately tuned to 26 and 52 MHz at a 100KHz rate with a -30 dBm CW input signal at 26 MHz and 52 MHz. 40 dB attenuation rise/fall times are 0.7/1.2 μ s for the 26 MHz case and 0.6/2.2 μ s for the 52 MHz case.

III. CONCLUSION

The design of a two-resonator lumped-element absorptive notch filter with tunable frequency has been described and its performance has been demonstrated. The first of its kind, it exhibits exceptional degrees of stopband attenuation and frequency tunability and selectivity. It maintains relatively constant absolute 3dB bandwidth and stopband attenuation in excess of 40dB over more than an octave tuning range with tuning voltages ranging from 1 to 2.3V. The circuit can be cascaded [2-4] to create higher-order filters with greater stopband bandwidth and/or attenuation, as well as tunable bandwidth. Filters of this type are amenable to integration and are expected to find use in protecting receivers from interference and preventing spurious output from transmitters.

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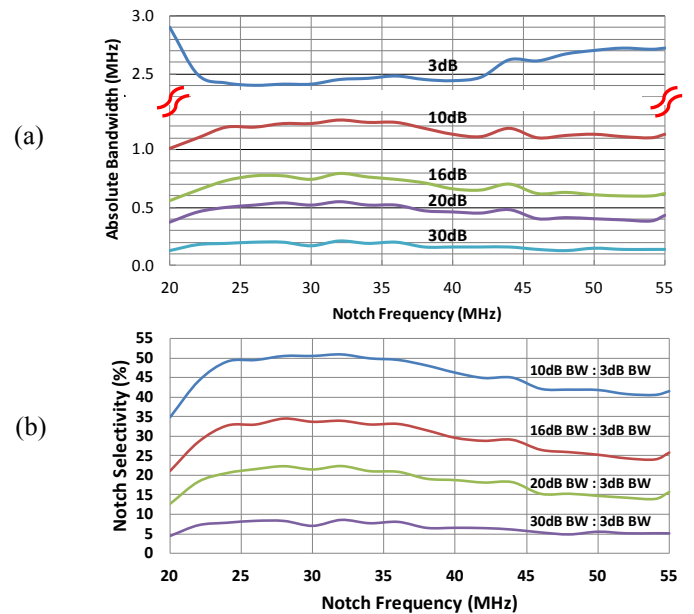


Fig. 5. Measurements of (a) various attenuation bandwidths and (b) filter selectivities for ratios of different attenuation bandwidths (BW). The 16dB:3dB selectivity compares favorably with that in [2].