Active Filters, NICs, NACs, and Knocks

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Discrete Filter Technology

Ceramic Filter

Insertion Loss..................Low 0.3 to 5.0 dB

Power Handling
Capability.....................Medium 1 to 50 watts

Physical size........12mm, 6mm, 4mm, 3mm diam
Freq range (ε=90) < 0.8 < 1.5 < 2.4 < 3 GHz
(ε=36) < 1.2 < 2.2 < 3.6 < 5 GHz
Q (at mid freq) 600 400 300 250

Temperature Stability........Very Good, adjustable
Mechanical Stability.................Very Good
Bandwidth....................1.5 to 10%

Saw, and other acoustic filters

Insertion Loss........3.0 to 20.0 dB

Power Handling
Capability..................Low < 1 w

Physical Size................Very Small
Temperature
Stability......................Good

Mechanical
Stability......................Very Good

Very Narrow Bandwidth........<5%

But, we are going to look at filters that can be integrated.
The Inductor Story - part 1

Seymour Cohn pointed out that:
1. Energy Is Stored In The Volume.
2. Dissipation Occurs On The Surface of Conductors (lossless dielectric)
3. Therefore, $Q \sim \text{Vol/Area}$ is probably a linear function of diameter, $D$

As the size of the inductor increases, its $Q$ goes up. Eventually, the inductor gets so large that it begins to be an efficient radiator, or antenna, unless it is shielded. An inductor in a filter could, therefore, be used as an antenna. Its efficiency would depend on its loss resistance and its radiation resistance.

The $50D \sqrt{f}$ line does a good job of predicting inductor $Q$ for a family of inductors with wildly different winding parameters, but the same core diameter. The wire was close spaced in some cases, overlapped in others, and very widely spaced, larger diameter for the smallest values. Eventually, the parasitic capacitance of the inductor causes its effective $Q$ to roll off at high frequencies. Smaller coil forms simply scale down $Q$ with size.
It is very likely that the Q dependence on inductance seen in published data simply is caused by the fact that larger value inductors were measured at lower frequency. A Q of 4 inductor measured at .5 GHz (X on the graph—50 nH) would be equivalent to a Q of 12 inductor (Xh on the graph—2 nH) measured at 4.5 GHz.
If Only Filters Were Not So Difficult!

Simple Laws Of Physics Determine Filter Performance:

1. Energy Is Stored In The Volume.

2. Dissipation Occurs On The Conductors And In The Dielectric.


4. The Best Active Filters Begin Life As Passive Filters, because:

5. TO A TRANSISTOR, GENERATING $J_{1ma}$ IS THE SAME AS GENERATING $1ma$. A Transistor Does Not Store Energy, It Dissipates It.

6. An approach to the design of active filters for noise or power capability will follow.
Active Inductor Equivalent Circuits

These are the simplest, traditional circuit realizations for active inductors. More complex circuits, suitable for ICs, are discussed later. Delay in the feedback loop rotates the C towards a negative resistance, and makes everything move more quickly with frequency.
More On Active Inductors

- An opamp is not necessary. Every device in the loop adds delay, reduces the useable bandwidth
- Fix the problems that the active devices have
- Multiple devices are cheap
- Darlington and cascode raise impedance, gain
- Use negative feedback to reduce sensitivity
- Delay adds negative resistance, narrows bandwidth

- The “inductor” current is provided by an active device
- Any Q greater than 1 will mean that large “reactive” current will flow through the active device.
- Even a low Q passive inductor is better than an active one
SIMPLE CAUER ACTIVE FILTER

BFP405 @ 2V, 2mA, with 1pF Q tweaks

No tweaks
The same voltage (V) is across the tuned circuit and the load. $P_{\text{diss}} = \frac{V^2}{R_U}$, and $P_{\text{out}} = \frac{V^2}{R_L}$: 

$$\frac{P_{\text{out}}}{P_{\text{diss}}} = \frac{R_U}{R_L}$$  \hspace{1cm} (1)$$

The unloaded Q of the tuned circuit is: 

$$Q_u = \frac{R_u}{X_c}$$  \hspace{1cm} (2)$$

After canceling the circuit loss ($R_u$), the source ($R_s$) and the load ($R_L$) equally load the tuned circuit: 

$$Q_L = \frac{R_s}{2X_c}$$  \hspace{1cm} (3)$$

Therefore, substituting (2) and (3) into (1): 

$$\frac{P_{\text{out}}}{P_{\text{diss}}} = \frac{Q_u}{2Q_L} ,$$

or in dB, 

$$P_{\text{diss}} = P_{\text{out}} + 10 \cdot \log_{10} \left( \frac{2Q_L}{Q_u} \right) = P_{\text{out}} + 10 \cdot \log_{10} \left( \frac{Q_L}{Q_u} \right) + 3 \text{dB}$$  \hspace{1cm} (4)$$

For both noise figure and power handling, EQN. (4) gives the degradation of performance due to the tuned circuit not being truly lossless, but actively loss cancelled.

$$NF_{\text{dB}} = NF(\text{active device, in circuit}) + 10 \cdot \log_{10} \left( \frac{Q_L}{Q_u} \right) + 3 \text{dB}$$  \hspace{1cm} (5)$$
Bisecting the circuit makes it clear by inspection that the gate tap does not have to be equal to the drain tap point. The optimum source impedance for noise figure is not likely to be the optimum load impedance for power output. In general, the gate-source will want to be tapped up, that is, at a higher impedance point than the drain-source. Not only does this improve the noise figure, it also raises the available gain, allowing more negative feedback. This improves the intermodulation distortion.
This illustrates the point that the gate-to-gate source impedance can be advantageously raised to improve both noise figure and intercept.
Narrow Band MMIC Filters
No Degeneration, Gain Set By Second Gate

Setting the transconductance, and hence the negative resistance by starving the lower FET as in this example will not result in a process tolerant, or high dynamic range filter. Adjustable negative feedback would be better. (FET as a variable resistor, or use a varactor)
In the upper figure, the monolithically defined, nearly identical negative resistances track one another. The master oscillator is a tuned circuit operating outside the band of the filter, or it could be the local oscillator. Controlling the amplitude of the oscillation sets the negative resistance. The slave filter is loaded by the input and output, and thus is stable, but the negative resistance will raise the effective unloaded resonator Q to infinity.

In the lower figure, as the series coupling varactors change the bandwidth, the shunt varactors re-center the frequency of the filter.
We can see that differential circuits are very closely related to their single-ended cousins. The Hartley and Colpitts oscillators are functionally equivalent, just with a change in the feedback method.

Also, there is no special way to generate a negative $Z$, any amplifier loop that results in the current flowing in the opposite direction from the element that is assumed to be connected across those terminals does the job. Over a narrow band, an inductor appears to be a negative capacitor. We are trying to make a negative capacitor that operates over a significantly wider bandwidth than a lowly inductor.
# NIC FILTER PERFORMANCE (Antique)

<table>
<thead>
<tr>
<th></th>
<th>Bandwidth and Center Frequency (MHz)</th>
<th>Noise Figure (dB)</th>
<th>Power Output 1-dB Compression (dBm)</th>
<th>Third-Order Intercept (dBm)</th>
<th>Total Variation in gain, 25°C to 60°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial NIC (1970)*</td>
<td>0.6 and 50</td>
<td>17</td>
<td>-20</td>
<td>-11</td>
<td>5.2</td>
</tr>
<tr>
<td>2nd Integrated FET-NIC</td>
<td>0.6 and 50</td>
<td>6 - 7</td>
<td>+12</td>
<td>+23</td>
<td>0.9</td>
</tr>
<tr>
<td>High-Power NUNIC Filter</td>
<td>2.7 and 230</td>
<td>&gt;21</td>
<td>+29</td>
<td>+35</td>
<td>0.8</td>
</tr>
</tbody>
</table>

*≈ 50 Ω impedance, based on standard NIC theory, no attention to noise, power, sensitivity, etc.
Conveniently, the FET chosen had an optimum noise source impedance close to the optimum load for power output of the PNP transistor, and could share the same port, directly across the tuned circuit.
Given Their Limitations, Are Active Filters Useful?

- Active inductors make good low power loads for broadband amplifiers.
- Yes, for small signal, low power, tolerant applications
- In notch filters, they can de-tune themselves - watch out
- Negative resistance can be stabilized with excess gain.
Making Active Filters Work

For - r filters... Use the master-slave approach to tame the unstable characteristics of negative resistance filters

1. Beware of N.F. And power handling in-band;
   Design for N.F., *Design for power*

2. Band pass filters power handling probably ok out of band,
   but noise figure is poor in-band.

3. Approximate rules for bandpass designs:
   \[ IP3 = IP3_{dev} - 10 \times \log(2 \times q_i/q_o) + 10 \times \log(1 + g_m \times r_s) \]
   \[ NF_{db} = 10 \times \log(2 \times q_i/q_o) + NF_{dev fb} \text{ and } NF_{dev fb} \text{ at its minimum is: } 10 \times \log(f_{min}) \]
   Where \( F_{min} = 1/(2q_i) \) and \( q_i \equiv (f_t/f) \times (1/g_m \times r_s) \)