THE DESIGN OF CMOS GIGAHERTZ-BAND CONTINUOUS-TIME ACTIVE LOWPASS FILTERS WITH Q-ENHANCEMENT CIRCUITS

Yuyu Chang  John Choma, Jr.

Department of Electrical Engineering
University of Southern California
Los Angeles, CA 90089
{yuyuchan, johnc}@usc.edu

Jack Wills

Information Sciences Institute
University of Southern California
Marina del Rey, CA 90292
jackw@isi.edu

ABSTRACT

A tunable second-order lowpass filter architecture capable of operating in the gigahertz frequency range is proposed. Two Q-enhancement techniques are utilized to extend the Q tuning range. Simulation results employing standard 0.5μm CMOS technology have successfully verified that the center frequency tuning and the hybrid Q-tuning approach operate between 1.26GHz and 2.3GHz center frequencies with Q larger than 1000. A tunable lowpass filter with a center frequency at 2.07GHz with a Q equal to 31 is designed to have 44dB input dynamic range and 27.8mW power dissipation.

1. INTRODUCTION

Recently radio frequency circuit implementation in submicron CMOS technology has received intense attention because it would allow integration of other digital signal processing circuits, providing a low cost single-chip solution [1][2]. In telecommunication applications, gigahertz-band filters with high quality factors (Q) are necessary, but are difficult to produce in a standard digital CMOS process.

Considerable research has been conducted for years to develop high performance monolithic filters for high frequency operations. A dominant high speed continuous-time filter implementation, called the OTAC filter [3][4][5], uses an open-loop integrator as a basic building block, exploiting an operational transconductance amplifier whose high impedance output port is terminated with an integrating capacitor. However, attempts to reach higher operating frequencies have met difficulties due to excess phase problems [6]. Such filters with center frequencies ranging from a few kHz up to low hundred MHz have been reported [7]. Another approach is to exploit the high frequency attributes of transistors as filter elements to simulate passive filters [8][9].

This paper describes a second-order filter configuration based on the second approach for implementation of the lowpass functioning capable of operating in the gigahertz frequency range with a quality factor of interest. Emphases are placed on detailed design topologies including the transfer function and Q-enhancement techniques. Noise performance and linearity are also discussed.

2. LOWPASS FILTER CIRCUIT TOPOLOGY

![Figure 1: A basic lowpass filter schematic with a low quality factor.]

The basic lowpass filter is illustrated in Figure 1. It can be proved through small signal analysis that the
frequency response is a simple second-order transfer function with a pair of complex poles, which can be viewed as a lowpass filter. The shortcomings of this simple configuration are that the Q of the filter is quite low (usually less than 2) and strong dependence exists between the frequency and Q tuning. However, both problems can be solved by introducing extra Q-enhancement circuitry. Figure 2 shows a second-order lowpass filter schematic with Q-enhancement circuitry. In this figure, transistors M1 and M2 comprise the input amplifier cascode stage. This configuration offers several advantages that include reducing the Miller Effect at the gate terminal of the transistor M1, increasing the effective isolation between the input stage and the following stage, and improving the stability of the circuit. The core components of the filter are formed by transistors M3, M6, M7, and M8. This negative feedback configuration constrains the gate of the transistor M3 to a very low impedance node.

![Figure 2: The second-order lowpass filter schematic with Q-enhancement circuitry.](image)

Assuming $g_m > g_ds$ for all transistors and ignoring all non-dominant high-order terms, it can be proved that the transfer function of the lowpass filter is approximately equal to

$$A_{v_{LP}}(s) = \frac{V_{out_{LP}}(s)}{v_s(s)} \approx \frac{g_{m1} g_{m3}}{c} \frac{1}{s^2 + s A + B}$$  \hspace{1cm} (1)$$

where

$$A = \frac{g_{m3} \left( g_{m3} c_2 + g_{m7} c_3 \right) - g_{m3} g_{m7} c_4}{g_{m6} c}$$

$$B = \frac{g_{m3} g_{m7}}{c}$$

$$c = c_1 c_2 + c_2 c_3 + c_1 c_3$$

$$c_1 = c_{gs2} + c_{gs2} + c_{gs3} + c_{gs3} + c_{bs7} + c_{ds7} + c_{ds7}$$

$$c_2 = c_{gs7}$$

$$c_3 = c_{gs6} + c_{gs7} + c_{gs7} + c_{ds10} + c_{ds10}$$

$$c_4 = c_{gs3} + c_{gs4} + c_{gs4} + c_{bs6} + c_q$$

$c_1, c_2,$ and $c_3$ represent accumulated parasitic capacitance in the circuit, and $c_4$ represents an extra physical Q-enhancement poly-silicon capacitor $c_q$ in shunt with the parasitic capacitance of other transistors existing at the drain of the transistor M3.

By definition, the center frequency of the bandpass filter $\omega_o$ is given by

$$\omega_o = \sqrt{\frac{g_{m3} g_{m7}}{c}}$$  \hspace{1cm} (2)$$

and the quality factor of the filter is therefore equal to

$$Q = \frac{g_{m6} \sqrt{c} g_{m3} g_{m7}}{g_{m6} \left( g_{m3} c_2 + g_{m7} c_3 \right) - g_{m3} g_{m7} c_4}$$  \hspace{1cm} (3)$$

Eq.2 reveals that the center frequency is determined by the transconductance of the transistors M3, M7, and $c$, the parasitic capacitive effect exhibited in the circuit. Here the transconductance of the transistor M7 is chosen as a prime candidate to be tuned by varying Vbias3 while Vbias1 and the input DC bias voltage of transistor M1 remain constant. An observation that can be made from Eq.3 is that the Q can be independently tuned by varying the capacitance $c_4$ without altering the center frequency $\omega_o$. Simulation shows that by properly sizing all transistors to achieve center frequencies at 1GHz and 2.2GHz with Q over 500 requires an extra capacitor $c_q$ equal to 0.9pF and 0.2pF, respectively.

Further insight can be gained by considering the other high frequency parasitic poles and zeros implicitly presented in the circuit, but not shown in Eq.1 due to analytical complexities. However, assuming the core feedback loop is broken, increasing the values of the capacitor $c_q$ and Vbias2 generate more phase shift at the output unity-gain frequency since the parasitic poles and/or zeros tend to move to lower frequencies, thereby decreasing the phase margin of the open-loop.
circuits and boosting the quality factor of the close-loop circuit [10].

Consequently, the Q-enhancement techniques result from two approaches: physically adding a capacitor $c_q$ and electrically tuning $V_{bias2}$. Figure 3 shows that without adding $c_q$, the center frequency response of the second-order lowpass filter has a center frequency located at 2.48GHz and a Q equal to 2.4. In this paper, we compromise both approaches by choosing a capacitor value $c_q$ equal to 0.35pF with the tuning of $V_{bias2}$ together to reach a wide Q tuning range in highly spread center frequencies. By varying $V_{bias2}$ and $V_{bias3}$, the Q larger than 1000 with center frequency tunings between 1.26GHz and 2.3GHz are achieved with the addition of capacitor $c_q=0.35pF$. Figure 4 exhibits the Q variations from 10 to 1256 at the center frequency at 2.07GHz while all bias voltages remain except that only $V_{bias2}$ is tuned from 2.8V to 3.46V. The measured deviation of the center frequency in Figure 4 is 25MHz. If the low Q characteristic is required, then the value of $c_q$ must be reduced. Q equal to 1.2 can be obtained in the frequencies of interest.

3. NOISE ANALYSIS

Noise performance is another essential consideration that governs the filter design in communication applications. It determines the smallest input signal that the filter can effectively process. The input-referred thermal noise can be expressed as

$$
\frac{V_{in,LP}^2}{10} = 4kT R_s + \frac{8}{3}kT \left( \frac{1}{g_{m1}} + \frac{g_{m2}^2}{g_{m1}^2 g_{m3}} + \frac{g_{m7} g_{m8}}{g_{m1} g_{m3}} + \frac{g_{m7}}{g_{m1} g_{m3}} + \frac{g_{m6}}{g_{m1}} \right)
$$

(4)

In the above equation, $R_s$ represents the output impedance of the preceding stage, where a smaller of $R_s$ leads to better noise performance. In some cases, $R_s$ is fixed at 50Ω. We also note that the input-referred thermal noise can be minimized by properly adjusting the transconductance of the transistors: increasing $g_{m1}$; decreasing $g_{m7}$, $g_{m8}$, and $g_{m9}$. In addition, $g_{m3}$ must be simultaneously increased to maintain the same center frequency $\omega_0$ for fair comparisons, as indicated in Eq.2. The transistor $M1$ of the input stage plays a critical role in the input-referred noise representation, and a large transistor size W/L is required. For the same bias current, a better strategy of minimizing the transconductance is to increase the gate-to-source voltages of transistors M7, M8, and M9 without using large transistor sizes, and thus reduce the capacitive loading.

The linearity of a broad band filter can be tested by applying a single-tone signal so that the dominant harmonic terms fall into the passband of the filter without significantly attenuated by the frequency response of the filter.

A lowpass filter with a center frequency at 2.07GHz and Q equal to 31 is designed employing 0.5μm CMOS BSIM3 model to illustrate the feasibility of this filter configuration. The Q tuning range with a capac-
Table 1: The performance metrics of the lowpass filter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor Cq</td>
<td>0.35pF</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>2.07GHz</td>
</tr>
<tr>
<td>Q</td>
<td>31</td>
</tr>
<tr>
<td>Q-tuning Range</td>
<td>10 - 1256</td>
</tr>
<tr>
<td>Maximum Input Swing for 1% THD</td>
<td>18.4mV_{rms}</td>
</tr>
<tr>
<td>Total Passband Noise (Voltage referred to input)</td>
<td>0.123mV_{rms}</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>44dB</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>27.8mW</td>
</tr>
</tbody>
</table>

5. REFERENCES


4. CONCLUSION

CMOS low-Q and high-Q tunable second-order filter topologies for lowpass filtering have been analyzed, designed and simulated. The high-Q filter with a center frequency close to transistor fT is achieved by considering the distributed high frequency parasitic capacitance and characteristics of transistors as filter elements. Other parasitic poles and zeros along with lower principal complex poles largely contribute to the quality factor in the gigahertz filter design.

In the future, the temperature sensitivity of the center frequency and Q will be further investigated and analyzed.

Acknowledgments

This project is sponsored by DARPA (Contract No. N62346-96-C-8607). The authors would like to thank Jeff LaCoss for his support.