A Quadrature Bandpass $\Delta\Sigma$ ADC for a Multi-Standard TV Tuner

R. Schreier

High-Speed Converters Group
Analog Devices, Wilmington, MA

University of Toronto
Cider Seminar
Oct. 19 2006
TV Tuner System

- Dual-conversion super-heterodyne receiver with an ADC at second IF
- ADC input is current-mode I&Q at 44 MHz
  - BW = 8.5 MHz
  - $f_s = 264$ MHz
A Quadrature $\Delta \Sigma$ ADC Is:

[Jantzi 1997]

- A $\Delta \Sigma$ ADC with quadrature everything
  - NTF and STF are complex
Worry List

1. DAC linearity and noise at high $f_s$  
   $\Rightarrow$ Current-mode DAC, mismatch-shaping

2. Resonator Accuracy: $f_0$ and Q  
   $\Rightarrow$ Coming soon!

3. Path Matching  
   $\Rightarrow$ Large devices, symmetric/merged layout
Ideal NTF– Poles and Zeros

4th-order NTF:

OSR = $f_s/f_B = 31$

3 in-band zeros @ $f_s/6$

image zero @ $-f_s/6$
NTF Magnitude

4b quantization $\Rightarrow$ SQNR~100 dB
Loop Filter Schematic

Analog Inputs: IA, IB, IC, ID

3.3-V circuitry  1.8-V circuitry

Summation circuit which produces flash inputs YB and YD is similar
Why DAC3?

- DAC3 allows any LF/NTF to be realized
  Even though DAC1 has 1 clock cycle of delay
  DAC3 supplies the missing point
DAC2 provides a low-attenuation feedback path for signals in the vicinity of \(-f_0\). Thereby resolving a near singularity in the coefficient calculation procedure.
Resonator Structure

- Tuned by adding positive feedback to make an oscillator and adjusting C until the desired resonance is achieved
  - Amplifier drives both R and C ⇒ trouble?

\[ f_0 = \frac{1}{2\pi RC} \]
Amplifier Gain and Phase

- Finite gain degrades Q
- Phase lag enhances Q
- Analysis shows $\phi = 45^\circ$ yields high Q, regardless of amplifier gain

$$\phi = \arg(\mu)$$

$$\delta = -\mu(1 + j)\omega_0$$

$$\mu = \frac{1}{A}$$
An Amplifier with $\phi = 45^\circ \, @ \, f_0$: 

![Amplifier Diagram]
**Resulting High-Q Resonator**

- Amplifier load yields $\phi = 45^\circ$ @ $f_0$
- Finite $g_m$ shifts the pole frequency, but does not degrade $Q$!
Finite $g_m$ Bandwidth & Non-Zero Switch Resistance

- Switch resistance degrades $Q$
- Finite $g_m$ bandwidth enhances $Q$

$$g_m = \frac{g_{m0}}{1 + s/\omega_p}$$

- Cancellation occurs if $R_{sw} = \frac{2\omega_0}{g_{m0}\omega_p}$
1st Resonator’s Amplifier

- 2-stage amplifier with feedforward stage and all-NMOS signal path
Gain-Scaling

• 12-dB gain range implemented by scaling DAC1’s LSB over a 4:1 range

• At the minimum LSB setting, DAC1’s noise is 6 dB lower than at the maximum LSB setting

• Changes in DAC gain are counteracted by inverse change in Reson1 gain
  Keeps gain of DAC1-Reson1 independent of LSB setting

• The gain-scaling burden is on the front end
  No other circuits need to be adjusted
Gain-Scaling Arrangement

- Gain of DAC1+Reson1 kept constant
Results: STF & NTF

Theoretical NTF (scaled)

Theoretical STF

Measured STF

Measured Zero-Input PSD

STF (dB) & PSD (dBFS/NBW)

Frequency (MHz)

NBW = 12 kHz

-155 dBFS/Hz
Wideband STF

- Input Frequency (MHz)
- |STF| (dB)
  - Passband
  - Alias bands
STF in +1 Alias Band

Output Frequency (MHz)

|STF| (dB)

Min. Alias Attenuation = 65 dB

Desired notch locations
Noise vs. Full-Scale Setting

![Graph showing noise vs. full-scale setting. The x-axis represents the full-scale setting, and the y-axis represents in-band noise (dBmA). The graph includes a linear trend line labeled 'Full-Scale' and another trend line labeled 'Noise'.]
SNR vs. Input Level

- Peak SNR = 76 dB
- Total DR = 90 dB
- Inst. DR = 85 dB

Full-scale = 1.5 mA_p
Full-scale = 0.4 mA_p

Total DR = 90 dB

Input Level (dBmA)

SNR (dB)
Two-Tone Spectrum

-6.5 dBFS tones

IMD = -70 dB
⇒ IIP3 = +32 dBmA

NBW = 12 kHz
# Performance Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>8.5</td>
<td>MHz</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>44</td>
<td>MHz</td>
</tr>
<tr>
<td>Clock Frequency</td>
<td>264</td>
<td>MHz</td>
</tr>
<tr>
<td>Inst. Dynamic Range</td>
<td>85</td>
<td>dB</td>
</tr>
<tr>
<td>Full-Scale Range</td>
<td>12</td>
<td>dB</td>
</tr>
<tr>
<td>Total Dynamic Range</td>
<td>90</td>
<td>dB</td>
</tr>
<tr>
<td>Area in 0.18um CMOS</td>
<td>2.5</td>
<td>mm²</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>375</td>
<td>mW</td>
</tr>
</tbody>
</table>
Performance Comparison

BW (Hz)

DR (dB)

Schreier 2002

Esfahani 2003

Philips 2003

Salo 2002

Ying 2004

Yaghini 2005

THIS WORK

Bandpass

Quadrature

Bandpass
Conclusions

A feedforward implementation of a Quadrature Bandpass $\Delta\Sigma$ ADC needs an extra DAC
An input attenuator is a good idea too.

High Q resonance can be achieved by
1. Using a simple $g_m$ instead of a true op amp
2. Balancing finite $g_m$ bandwidth and non-zero switch resistance

Measured $Q > 40$

Gain-scaling extends DR