A 420\(\mu\)W 100GHz-GBW CMOS Programmable-Gain Amplifier Leveraging the Cross-Coupled Pair Regeneration

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Outline

- Introduction
- Circuit description
- Measurement
- Conclusions
Programmable Gain Amplifier (PGA)

- Key building block in signal processing for ultrasound, wireless, disk drives, etc;
- Required to provide fixed output swing from a wide range input signal level;
- Main design challenges:
  - Accurate dB-linear gain control;
  - Very high GBW (20MHz BW with 60dB gain leads to 20GHz GBW).
Multi-stage PGAs

- Multi-stage amplifiers commonly exploited for high GBW at low power;
- Limited gain variation in each stage simplifies dB-linear gain control;
- Penalty of gain compression, particularly at low gain:

\[ OP_{1dB_N} \approx A_v^{N-1} \frac{\sqrt{A_v^2 - 1}}{\sqrt{A_v^{2N} - 1}} \]

\[ OP_{1dB_1} \]

- 10dB gain
- 60dB gain

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PGA Leveraging Regeneration

- Regeneration enables linear-in-dB gain control and ultra-wide GBW in a single stage;
- Negative resistor realized with two cross-coupled pairs;
- Amplification divided in 4 steps within a clock period $T_{\text{CK}}$. 
1: Reset

- Output capacitors short-circuited;
- Common mode set to $V_{dd}/2$ for higher output swing.
2: Sampling

- Differential input pre-amplified and sampled.

\[ A_{v,smp} = \frac{g_{m,in}}{C_{a,b}} T_{smp} \]
3: Regeneration

- XCPs on shunt $C_{a,b}$ with negative resistance ($-1/g_{m,xc}$);
- Output rises exponentially with a positive time constant ($g_{m,xc}/C_{a,b}$):

\[
V_{out}(t) = V_{smp} e^{\frac{g_{m,xc}}{C_{a,b}} t}
\]
4: Hold

- All switches are turned off;
- Final value of $V_{out}$ stored on output capacitors.

$$A_v = \frac{g_{m,in}}{C_{a,b}} T_{smp} e^{\frac{g_{m,xc}}{C_{a,b}} T_{reg}}$$
Gain Bandwidth Product

\[ BW = \frac{1}{2T_{CK}} \]

\[ A_{v,reg} = e \frac{g_{m,xc}}{C_{a,b}} \alpha T_{CK} \]

\[ A_{v,reg}(dB) \cdot BW = 4.3\alpha \frac{g_{m,xc}}{C_{a,b}} \]

- Bandwidth trades linearly with **gain in dB** yielding extraordinary GBW improvement;

- **Ex.:**

  Design parameters
  
  \[
  f_{CK} = 100 \text{ MHz} \\
  g_{m,xc} = 2.5 \text{ mS} \\
  C_{a,b} = 2 \text{ pF} \\
  \alpha = 0.5
  \]

  Regenerative Amplifier
  
  \[
  BW = 50 \text{ MHz} \\
  GBW_{reg} = 25.9 \text{ GHz}
  \]

  Transconductance Amplifier
  
  \[
  GBW_{std} = 199 \text{ MHz}
  \]
Equivalent Input Noise

\[ \nu^2_{n,in} \approx \frac{4kT\gamma}{g_{m,in} T_{smp}} + \frac{2kT\gamma C_{a,b}}{g_{m,in}^2 T_{smp}^2} \]

- Cross-coupled pairs contribution independent of \( g_{m,xc} \);
- Moderate gain in the sampling phase sufficient to make it negligible.

**Ex.:**

\[
\begin{align*}
T_{smp} &= 2.5 \, \text{ns} \\
g_{m,in} &= 3.5 \, \text{mS}
\end{align*}
\]

\[
\begin{align*}
A_{v,smp} &= 12.8 \, \text{dB} \\
\nu_{n,in}^2 &= (54.3 \, \mu V_{rms})^2
\end{align*}
\]
Timing Generation

- Cascaded generators to ensure non-overlapping phases;
- $T_{reg}$ changed linearly controlling $I_0$ with a simple DAC;
- Jitter causes SNR limitation:

$$SNR_{smp} = 20 \log \left( \frac{T_{smp}}{\sigma_{smp}} \right)$$

$$SNR_{reg} = 20 \log \left( \frac{C_{a,b}}{g_{m,xc} \sigma_{reg}} \right)$$
Measurement

- 180nm CMOS (BCD STMicroelectronics)
- Power Consumption = 420 μW
- Total Area = 0.03 mm²
Scope Screenshots

\[ f_{\text{ck}} = 10 \text{ MHz} \quad f_{\text{in}} = 1 \text{ MHz} \]

\[ f_{\text{ck}} = 100 \text{ MHz} \quad f_{\text{in}} = 10 \text{ MHz} \]
Accurate linear-in-dB gain control from 15 to 66 dB;
Max. gain error < 0.6 dB;
Flat in-band gain, 50MHz maximum bandwidth, 100GHz GBW.
Linearity Measurement

- $\text{OP}_{1\text{dB}} = -2 \text{ dBV} @ 45\text{dB} \text{ gain};$
- THD < -40dB from 10dB back off down;
- $\text{OIP}_3 = 4.3 \text{ dBV} \text{ calculated from IM3 test}.$
### Summary of the Performance

<table>
<thead>
<tr>
<th></th>
<th>JSSC-13</th>
<th>TCAS-14</th>
<th>JSSC-15</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology</strong></td>
<td>65nm</td>
<td>150nm</td>
<td>180nm</td>
<td>180nm</td>
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<tr>
<td><strong>Active Area [mm²]</strong></td>
<td>0.01</td>
<td>0.05</td>
<td>0.07</td>
<td>0.03</td>
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<tr>
<td><strong>Gain Range [dB]</strong></td>
<td>-13 / 63</td>
<td>-5.5 / 28</td>
<td>3.6 / 59.6</td>
<td>15 / 66</td>
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<tr>
<td><strong>dB-linear Gain Range [dB]</strong></td>
<td>50</td>
<td>34</td>
<td>56</td>
<td>51</td>
</tr>
<tr>
<td><strong>OP₁dB [dBm]</strong></td>
<td>-</td>
<td>5.6</td>
<td>-3</td>
<td>8</td>
</tr>
<tr>
<td><strong>OIP3 [dBm]</strong></td>
<td>11.5</td>
<td>13 / 17.3</td>
<td>8</td>
<td>14.3</td>
</tr>
<tr>
<td><strong>Input Noise [nV/(Hz)⁰.⁵]</strong></td>
<td>3.5</td>
<td>11.14</td>
<td>10.6</td>
<td>10.7</td>
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<tr>
<td><strong>Bandwidth [MHz]</strong></td>
<td>14.8</td>
<td>60</td>
<td>63.5</td>
<td>50</td>
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<tr>
<td><strong>GBW [GHz]</strong></td>
<td>21</td>
<td>1.5</td>
<td>60.6</td>
<td>100</td>
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<td><strong>N of stages</strong></td>
<td>3</td>
<td>1</td>
<td>15</td>
<td>1</td>
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<td><strong>Power [mW]</strong></td>
<td>2.16</td>
<td>7.56</td>
<td>1.12</td>
<td>0.42</td>
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</tbody>
</table>

- Highest OP₁dB, state-of-the-art linearity and noise performance;
- Record GBW with the lowest power consumption.
Conclusions

- A sampled-time PGA leveraging the cross-coupled pair regeneration has been presented;

- Regeneration naturally leads to dB-linear gain control and outperforms the linear GBW trade-off in a single stage;

- Measurements demonstrate a record 100GHz GBW, the highest $O_{P1dB}$ with state-of-the-art noise performance and lowest power consumption.