Super class AB RFC OTA using nonlinear current mirrors


An alternative approach to the design of super class AB recycling folded cascode operational transconductance amplifiers (OTAs) is proposed. Instead of using local common-mode feedback for boosting dynamic currents, simple current mirrors with input transistors entering triode region for large currents are employed. Measurement results from a 0.5 μm CMOS test chip validate the proposal.

Introduction: Super Class AB Operational Transconductance Amplifiers (OTAs) are a very attractive solution when power efficiency is required. They feature both very low quiescent current consumption and very high dynamic current boosting, with output currents ideally proportional to \( V_{dd} \) (with \( V_{dd} \) the differential input voltage). This is achieved by the use of single-stage topologies where dynamic current boosting is carried out both at the adaptive biasing and active load of the differential pair [1]. Recently super class AB operation has been applied to the Recycling Folded Cascode (RFC) OTA [2], [3]. However, reported super class AB RFC OTAs require additional local common-mode feedback (LCMFB) loops at the active load of the differential pair, either using passive [2] or active [3] matched resistors.

In this Letter we propose an alternative implementation of a super class AB RFC OTA which does not modify the active load. Dynamic current boosting at the active load is achieved just varying the bias point of such load. This approach was formerly applied by the authors to the current mirror OTA in [4] and it is thus extended here to the RFC OTA.

Circuit Description: The conventional Folded Cascode (FC) OTA and RFC OTA [5] are shown in Fig. 1a and 1b, respectively. Transistors in the differential pair and NMOS current sources have been split in Fig. 1a to simplify comparison with Fig. 1b. The gain-bandwidth product (GBW) and slew rate (SR) of the FC OTA are

\[
\text{GBW}_{\text{FC}} = \frac{2 g_m}{2 \pi C_c} \quad (1)
\]

\[
\text{SR}_{\text{FC}} = \frac{2 \pi}{g_m} \quad (2)
\]

where \( g_m \) is the transconductance of transistor M. The RFC OTA improves GBW by a factor \( 1+K \) and SR by a factor \( K \), where \( K \) is the current gain of the NMOS current mirrors in the RFC OTA that replace the NMOS current sources of the FC OTA. However, in practice \( K \) is not higher than 4 to prevent too much phase margin (PM) degradation [5], so the improvement is limited. Moreover, SR is still proportional to \( I_B \) and power efficiency is limited since factor \( K \) scales both static and dynamic currents. These issues are overcome by the super class AB RFC OTAs in [2], [3], but they require not only an adaptive bias current source but also rearranging transistors M3B-M4B and including two extra local feedback loops that employ two matched resistors. A simpler way is required. They feature both very low quiescent current consumption and very high dynamic current boosting at the active load is achieved just varying the bias point of such load. This approach was formerly applied by the authors to the current mirror OTA in [4] and it is thus extended here to the RFC OTA.

An approximate analytical expression for the output current \( I_{out} \) when \( V_{dd} > 0 \) can be obtained using the simple square-law MOS model for strong inversion and saturation regions and the expression for ohmic region and low \( V_{os} \) given by \( I_B = \beta (V_{GS} - V_{TH}) \). The resulting current in M3A is

\[
\frac{I_{3A}}{I_B} = \frac{\beta_{4A}}{2} \left( \frac{I_B}{\beta_B V_{DS3B}} \right)^2 \quad (3)
\]

where \( \beta = \mu C_{ox}(W/L) \) and \( V_{DS3B} = V_{TH} - \sqrt{2 \beta B V_{DS} - V_{TH}} \). Expressing \( I_{out} \) as a function of \( V_{out} \), current \( I_{out} \) becomes

\[
\frac{I_{out}}{I_B} = \frac{\beta_{4A}}{2} \left( \frac{I_B}{\beta_B V_{DS3B}} \right)^2 \quad (4)
\]

For a large positive differential input step of \( A \) Volts current in M1A and M4A is very low and M2A enters deep triode region, so \( I_{out} \approx I_{3A} \) and

\[
\text{SR}_A \approx \frac{\beta_{4A}}{2C} \left( \frac{I_B}{\beta_B V_{DS3B}} \right) \quad (5)
\]

Analogously, if \( V_{dd} < 0 \):

\[
\frac{I_{out}}{I_B} = \frac{\beta_{4A}}{2} \left( \frac{I_B}{\beta_B V_{DS3B}} \right)^2 \quad (6)
\]

and for a large negative differential input step of \( -A \) Volts, \( I_{out} \approx I_{4A} \) and

\[
\text{SR}_A \approx \frac{\beta_{4A}}{2C} \left( \frac{I_B}{\beta_B V_{DS3B}} \right) \quad (7)
\]

In practice SR is lower due to second-order effects not considered in the analysis and since transistors operating in saturation may leave this region for large inputs. Note however that a large SR compatible with low static power is achieved as SR is not proportional to \( I_B \).

A simple and robust way to generate \( V_{BUS} \) is shown in Fig. 1c. Choosing \( I_{out} \) and the W/L of M11 correctly, \( V_{BUS} \) can be set slightly above \( V_{os} \) regardless of process, temperature or supply voltage variations as \( V_{BUS} \) is set by the \( V_{out} \) of a scaled replica of M3B-M4B.

The adaptive bias current source employed also improves GBW, as the full differential input signal is applied to each input transistor [1].
Measurement Results: The three OTAs of Fig. 1 were included on a 0.5 μm CMOS chip prototype. Transistors M1A, M1B, M1C, M2A, M2B, M2C have an aspect ratio (in μm/μm) of 190/0.6, that of M3A, M3B, M3C, M4A, M4B, M4C is 60/0.6, M5A, M5B have 180/0.6, that of M6, M7 is 120/0.6, that of M8, M9, M10 is 200/0.6 and that of M11 is 15/0.6. Fig. 2 shows a microphotograph of the OTAs in Fig. 1. Supply voltage was set to ±1 V, $I_{s} = I_{b} = 10 \mu A$, $V_{CC} = -0.5 V$ and $V_{CV} = 0.3 V$.

The measured transient response in voltage follower configuration of the three OTAs is shown in Fig. 3. An external load capacitor of 47 pF (pad, board and test probe), the overall load capacitance is $C_L \approx 70 \text{ pF}$. The input signal was a 1 MHz 0.5 V periodic square wave, whose DC level was -0.6 V. Table 1 summarizes the main measured performance parameters. Note an improved SR by a factor of 28 versus the FC OTA.

Table 1: Measured performance summary ($C_L = 70 \text{ pF}$)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fig. 1a</th>
<th>Fig. 1b</th>
<th>Fig. 1c</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR+</td>
<td>0.26 V/μs</td>
<td>0.48 V/μs</td>
<td>7.27 V/μs</td>
</tr>
<tr>
<td>SR-</td>
<td>-0.86 V/μs</td>
<td>-1.5 V/μs</td>
<td>-18.8 V/μs</td>
</tr>
<tr>
<td>THD @25kHz, 0.5Vpp</td>
<td>-37.81 dB</td>
<td>-44.54 dB</td>
<td>-47.85 dB</td>
</tr>
<tr>
<td>DC gain (*)</td>
<td>60.26 dB</td>
<td>68.37 dB</td>
<td>75.06 dB</td>
</tr>
<tr>
<td>PM (*)</td>
<td>89º</td>
<td>86.2º</td>
<td>76.3º</td>
</tr>
<tr>
<td>GBW</td>
<td>480 kHz</td>
<td>950 kHz</td>
<td>3.4 MHz</td>
</tr>
<tr>
<td>CMRR @ DC</td>
<td>97 dB</td>
<td>111 dB</td>
<td>112 dB</td>
</tr>
<tr>
<td>PSRR+ @ DC</td>
<td>73 dB</td>
<td>82 dB</td>
<td>89 dB</td>
</tr>
<tr>
<td>PSRR- @ DC</td>
<td>93 dB</td>
<td>104 dB</td>
<td>105 dB</td>
</tr>
<tr>
<td>Eq. input noise @1MHz</td>
<td>49 nV/√Hz</td>
<td>35 nV/√Hz</td>
<td>22 nV/√Hz</td>
</tr>
<tr>
<td>Power</td>
<td>80 nW</td>
<td>80 μW</td>
<td>100 μW</td>
</tr>
<tr>
<td>Area</td>
<td>0.020 mm²</td>
<td>0.024 mm²</td>
<td>0.026 mm²</td>
</tr>
</tbody>
</table>

(*) Simulation

In order to compare with other class AB amplifiers, two conventional figures of merit (FoM) are used: $\text{FoM}_{\text{CL}} = SR \cdot C_{L} / I_{\text{app}} = \frac{\text{Input/Load}}{\text{Current}}$, where $I_{\text{app}}$ is the total static current consumption, and $\text{FoM}_{\text{CL}} = \text{GBW} \cdot C_{L} / I_{\text{app}}$ (MHz pF/mA). Note that the proposed OTA shows competitive small-signal and large-signal performance.

Fig. 2 Microphotograph of the OTAs of Fig. 1

Fig. 3 Measured transient response of the OTAs of Fig. 1

Fig. 5 Performance comparison

Conclusion: Proper biasing of the differential pair active load in the RFC OTA can provide dynamic current boosting in a simple way. Together with an adaptive biasing current source, efficient super class AB operation can be achieved.

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References


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