Transconductance enhancement method for operational transconductance amplifiers

Y.L. Li, K.F. Han, X. Tan, N. Yan and H. Min

An improved recycling structure for an operational transconductance amplifier is proposed. The proposed structure separates the AC path from the DC path, and achieves a significant boost in transconductance under the same power and area budget. A folded-cascode amplifier employing the improved recycling structure was implemented in SMIC standard 0.13 μm CMOS process. Simulation results show that the enhancement of transconductance leads to 230% improvement in gain-bandwidth product and 13 dB boost in gain compared with the conventional folded cascode.

Introduction: The operational transconductance amplifier (OTA) is a basic building block in analogue circuit systems, which can be a major source of power consuming. In an OTA, the ratio of transconductance to current consumption reflects the power efficiency of the amplifier [1]. To improve the power efficiency of an OTA, several methods have been presented [2, 3]. In this Letter, an improved recycling structure (IRS) is proposed to significantly enhance the transconductance of an OTA without increasing power or area consumption.

![Fig. 1 Recycling folded cascode](image1)

![Fig. 2 Improved recycling structure (IRS) and improved recycling folded cascode (IRFC)](image2)

Improved recycling structure: Shown in Fig. 1, is the recycling folded cascode (RFC) structure, which is proposed in [3]. The input pair is split into half (M1a, M1b and M2a, M2b) and the ratio of the current mirror (M3aM3b and M4aM4b) is set to three to maintain the correct summation of DC currents without increasing current or area consumption. Actually, since DC and AC currents share the same path, the boost of transconductance in the RFC is limited by DC currents; however, it still forms the basis of this work. The proposed IRS is shown in Fig. 2a. In the IRS, DC and AC currents have different paths. DC currents can flow through M3a, M3b, M3c, M4a, M4b and M4c, while almost no AC current flows through M3c, M11b and M4c, M12b since they show high impedance for AC signals. Thus, M3aM3b and M4aM4b form AC current mirrors, and M3c and M4c are DC paths. The separated DC and AC paths make it possible to increase more transconductance without extra DC current or area consumption. In order to keep DC current unchanged, the ratio of transistors are as follows: first, the input pair is split at the ratio of p(1− p). Next, the ratio M3a:M3b:M3c and M4a:M4b:M4c is pα(1− p)β(1− p), where α + β = 1. The ratio M11a:M11b and M12a:M12b is αβ. M3b and M4b are driven by a cross-coupled input pair, while M3c and M4c are biased with a constant gate voltage, which makes the DC current ratio I1:I2 = αβ. Thus, the ratio of current mirrors M3a:M3b and M4a:M4b is pα(1− p). Suppose the transconductance of the unsplit input pair is Gm, then the transconductance of the IRS is:

\[ G\text{m}_{\text{IRS}} = \left( p + p/\alpha \right) G\text{m} \]  

(1)

If we choose p = 1/2 and α = 1/6, then the transconductance is improved 250%. Moreover, since less current (pIb) instead of Ib flows through M1a, M2a, M3a and M4a, the output resistance of those MOSFETs is increased; thus, as a result of enhanced transconductance and output impedance, the gain is also increased. Based on the analysis in [3], the maximum slew rate (SR) of the IRS is:

\[ SR_{\text{IRS}} = p(1− \alpha)I_b/(\alpha C_L) \]  

(2)

where \( C_L \) is the load capacitor. Thus, SR is also improved with proper \( p \) and \( \alpha \). Other different OTA structures can also be modified using the IRS with enhanced transconductance. For example, the improved recycling folded cascode (IRFC) is shown in Fig. 2b. The size ratio of the transistors is similar to the IRS, except the ratio M3a:M3b:M3c and M4a:M4b:M4c, which is now (1 + p)α(1− p)β(1− p), since the folded cascode has ‘folded’ DC current. Suppose the transconductance of the FC is \( G\text{m} \), then the transconductance of IRFC is:

\[ G\text{m}_{\text{IRFC}} = \left[ p + (1 + p)/\alpha \right] G\text{m} \]  

(3)

If we choose \( p = \alpha = 1/2 \), then the transconductance is improved 250% compared to the FC. The maximum slew rate of the IRFC is:

\[ SR_{\text{IRFC}} = (1 + p)[2(1 - \alpha(1-p))I_b/(\alpha(1-p)C_L)] \]  

(4)

Theoretically, with proper \( p \) and \( \alpha \), the slew rate of the IRFC has a greater upper-bound. In practice, negative slew rate (SR–) is restricted by the size and biasing of M10; while positive slew rate (SR+) is limited by supply voltage, since M6 is likely to enter the linear region in the transient response.

Implementation and results: Three amplifiers, including an FC, an RFC and an IRFC, were designed with the same power and area budget in SMIC standard 0.13 μm technology using a single 1.2 V supply voltage. For the RFC, \( p \) and \( \alpha \) were set to 1/2. The current budget of amplifiers is 260 μA and area is 16 × 67 μm². As shown in Fig. 3, the three amplifiers were used as a unity gain amplifier, where \( C_1 = 1 \) pF, \( R_1 = 500 \) kΩ and \( C_0 = 7 \) pF. The simulated open-loop AC response is shown in Fig. 4, and the simulated transient response to 5 MHz 600 mVpp step input is shown in Fig. 5. The simulation results of key parameters of three OTAs are listed in Table 1. It can be seen that the IRFC achieves a 230% improvement in gain-bandwidth product (GBW) compared to the FC, and a 60% improvement compared to the RFC, owing to the enhancement of transconductance. The boost of transconductance is slightly less than the theoretical value of 250% because of the finite AC impedance of DC paths. Also, the DC gain of the IRFC is 13 dB higher than the FC and 4 dB higher than the RFC. The SR+ of the IRFC is better than the RFC, while the SR– of the IRFC is limited by low supply voltage, so no SR– improvement compared to the RFC is observed. The phase margin of the RFC and the FC at 83 MHz drop to 74.1° and 78.7°, respectively, thus the IRFC shows a slight degradation of less than 10° as a result of decreased transconductance of M3b and M4b.
Fig. 3 Unit gain amplifier

Fig. 4 Open-loop AC response of FC, RFC and IRFC

Fig. 5 Transient response of FC, RFC and IRFC to 5 MHz, 600 mVpp step

Table 1: Performance summary of FC, RFC and IRFC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FC</th>
<th>RFC</th>
<th>IRFC</th>
</tr>
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<tbody>
<tr>
<td>Bias current (μA)</td>
<td>260</td>
<td>260</td>
<td>260</td>
</tr>
<tr>
<td>Area (μm²)</td>
<td>16 × 67</td>
<td>16 × 67</td>
<td>16 × 67</td>
</tr>
<tr>
<td>C_L (pF)</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>GBW (MHz)</td>
<td>24.6</td>
<td>50</td>
<td>83</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>56.8</td>
<td>65.6</td>
<td>70.2</td>
</tr>
<tr>
<td>Phase margin (deg)</td>
<td>87</td>
<td>80.6</td>
<td>70</td>
</tr>
<tr>
<td>SR+ (V/μs)</td>
<td>12.4</td>
<td>20.1</td>
<td>21.2</td>
</tr>
<tr>
<td>SR- (V/μs)</td>
<td>11.6</td>
<td>25</td>
<td>38.4</td>
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<tr>
<td>FoM (MHzpF/μA)</td>
<td>662</td>
<td>1346</td>
<td>2235</td>
</tr>
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</table>

Conclusion: An improved recycling structure is proposed to enhance transconductance of OTAs without increasing power or area consumption. The IRS can be adopted by most classic-structure OTAs to boost transconductance. Three amplifiers, including the FC, the RFC and the IRFC, were designed with the same power and area consumption. Simulation results show that the transconductance enhancement of the IRFC leads to a 230% improvement in GBW compared to the FC and 60% improvement compared with the RFC. Also, the DC gain of the IRFC has a 13 dB improvement compared to the FC and 4 dB improvement compared to the RFC.

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