

A transconductance enhancement technique for bulk-driven OTAs working in weak inversion

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Abstract: A proposed transconductance enhancement technique for bulk-driven OTAs working in weak inversion is presented in this paper. The basic idea is to use a bulk-driven input differential pair employing the auxiliary amplifier and positive feedback technique to enhance transconductance, which improves the enhancement ratio of transconductance from $(n + 1)/(n - 1)$ to $(n + 2)/(n - 1)$. The proposed amplifier based on the mentioned technique is simulated on UMC 180 nm process with the help of Spectre. The simulation results demonstrate that the transconductance of the bulk-driven OTAs working in weak inversion improves almost 50% with just a little increased power consumption compared to the conventional counterparts.

Keywords: transconductance enhancement, bulk-driven, weak inversion, positive feedback differential pair, OTA

Classification: Integrated circuits

References

- [1] S. Chatterjee, *et al.*: “0.5-V analog circuit techniques and their application in OTA and filter design,” *IEEE J. Solid-State Circuits* **40** (2005) 2373 (DOI: [10.1109/JSSC.2005.856280](https://doi.org/10.1109/JSSC.2005.856280)).
- [2] E. Lopez-Morillo, *et al.*: “A 1.2-V 140-nW 10-bit sigma-delta modulator for electroencephalogram applications,” *IEEE Trans. Biomed. Circuits Syst.* **2** (2008) 223 (DOI: [10.1109/TBCAS.2008.2001868](https://doi.org/10.1109/TBCAS.2008.2001868)).
- [3] L. H. C. Ferreira, *et al.*: “An ultra-low-voltage ultra-low-power CMOS miller OTA with rail-to-rail input/output swing,” *IEEE Trans. Circuits Syst. II, Exp. Briefs* **54** (2007) 843 (DOI: [10.1109/TCSII.2007.902216](https://doi.org/10.1109/TCSII.2007.902216)).
- [4] G. Raikos and S. Vlassis: “0.8 V bulk-driven operational amplifier,” *Analog Integr. Circuits Signal Process.* **63** (2010) 425 (DOI: [10.1007/s10470-009-9425-4](https://doi.org/10.1007/s10470-009-9425-4)).
- [5] G. Raikos and S. Vlassis: “Low-voltage bulk-driven input stage with improved transconductance,” *Int. J. Circ. Theor. Appl.* **39** (2011) 327 (DOI: [10.1002/cta.637](https://doi.org/10.1002/cta.637)).
- [6] J. M. Carrillo, *et al.*: “1-V rail-to-rail CMOS OpAmp with improved bulk-driven input stage,” *IEEE J. Solid-State Circuits* **42** (2007) 508 (DOI: [10.1109/](https://doi.org/10.1109/)

- JSSC.2006.891717).
- [7] L. H. C. Ferreira and S. R. Sonkusale: “A hybrid multi-tanh bulk-driven input stage OTA for Low-THD biomedical Gm-C applications,” 2012 IEEE International Symposium on Circuits and Systems (ISCAS) (2012) 838 (DOI: [10.1109/ISCAS.2012.6272171](https://doi.org/10.1109/ISCAS.2012.6272171)).
 - [8] L. H. C. Ferreira and S. R. Sonkusale: “A 60-dB gain OTA operating at 0.25-V power supply in 130-nm digital CMOS process,” IEEE Trans. Circuits Syst. I, Reg. Papers **61** (2014) 1609 (DOI: [10.1109/TCSI.2013.2289413](https://doi.org/10.1109/TCSI.2013.2289413)).
 - [9] G. Raikos and S. Vlassis: “0.8 V bulk-driven operational amplifier,” Analog Integr. Circuits Signal Process. **63** (2010) 425 (DOI: [10.1007/s10470-009-9425-4](https://doi.org/10.1007/s10470-009-9425-4)).
 - [10] T. H. Lin, *et al.*: “A 0.8-V 0.25-mW current-mirror OTA with 160-MHz GBW in 0.18-um CMOS,” IEEE Trans. Circuits Syst. II, Exp. Briefs **54** (2007) 131 (DOI: [10.1109/TCSII.2006.886465](https://doi.org/10.1109/TCSII.2006.886465)).

1 Introduction

With the development and applications of CMOS process, especially in portable and biomedical applications, decreasing of the minimum dimensions in CMOS technologies and reducing of the power supply voltage accordingly in integrated circuits (ICs) become more and more necessary. In addition, low-voltage and low-power analog and mixed signal ICs are required. To achieve the goal of reducing the supply voltage, we have an excellent choice which is to use bulk-driven OTAs operating in weak inversion region [1, 2]. The mentioned technique is not only used to overcome the issues of the reduction of input voltage range, but also can provide high g_m/I ratio, leading to high energy efficiency. Recently, there have been some works where bulk-driven transistors operating in weak inversion are utilized providing reliable low-voltage and low-power amplifiers [3].

However, there still exist some issues associated with bulk-driven OTAs working in weak inversion. The transconductance (g_m) of bulk-driven OTAs working in weak inversion is ultra small, and the most significant issue is the bulk transconductance (g_{mb}) is substantially smaller. So that the unity-gain bandwidth (GBW), DC gain and noise performance of bulk-driven OTAs operating in weak inversion are limited. In recent years, many methods to increase the effective transconductance (G_m) in bulk-driven have been developed [4, 5, 6, 7, 8]. The partial positive feedback technique has been adopted by several recent works [1, 5, 6, 9] and some other papers improve the transconductance (g_m) by using an auxiliary amplifier [8, 10], where the enhancement ratio of transconductance is improved yet there is still the room for enhancement. This paper proposes a transconductance enhancement technique for bulk-driven OTAs working in weak inversion by utilizing an auxiliary amplifier and positive feedback technique, which enhances the enhancement ratio of transconductance from $(n + 1)/(n - 1)$ to $(n + 2)/(n - 1)$ with just a little increased power consumption.

This paper is organized as follows. The conventional positive feedback differential pair (CPFP) is discussed in Section 2. In Section 3, the enhanced positive feedback differential pair (EPFP) technique to improve the transconductance is described and the circuit performances including GBW, G_m enhancement ratio and transient response are discussed. To demonstrate the enhanced performances of proposed technique, two OTAs are designed and compared in Section 4. And the conclusions are given in Section 5. *Keep one copy of this template untouched for your reference and prepare your manuscript on another copy.*

2 The conventional positive feedback differential pair (CPFP)

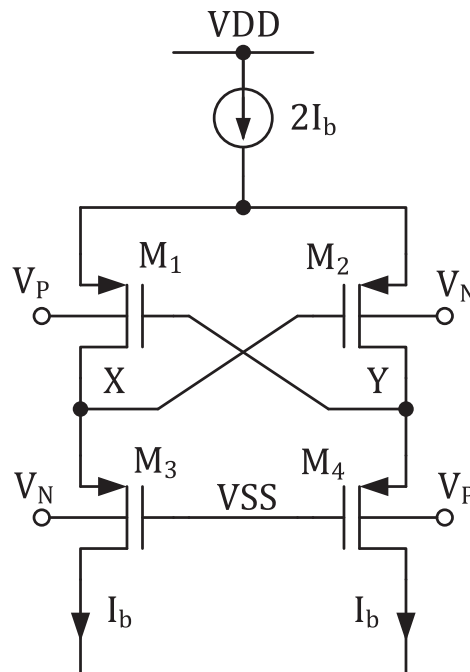


Fig. 1. Conventional positive feedback different-pair

CPFP is shown in Fig. 1 [7]. The bulk-driven differential pair consists of a current source $2I_b$ and two pairs of matched transistors, in which gates and bulks are split and biased as positive feedback source degeneration. The transistors $M1$ and $M2$ are configured as active loads, degenerating the sources of transistors $M3$ and $M4$. The G_m of CPFP can be given as,

$$G_m = \frac{n+1}{n-1} g_{mb1} \quad (1)$$

Where g_{mb1} is bulk transconductance and n the slope factor in weak inversion, which can be defined as,

$$n = 1 + \frac{g_{mb}}{g_m} = 1 + \eta \quad (2)$$

where g_m is bulk transconductance and g_{mb} is gate transconductance.

3 Enhanced positive feedback differential pair (EPFP)

To further the effective transconductance, an enhanced positive feedback differential pair is presented in this section, shown in Fig. 2, which uses an auxiliary

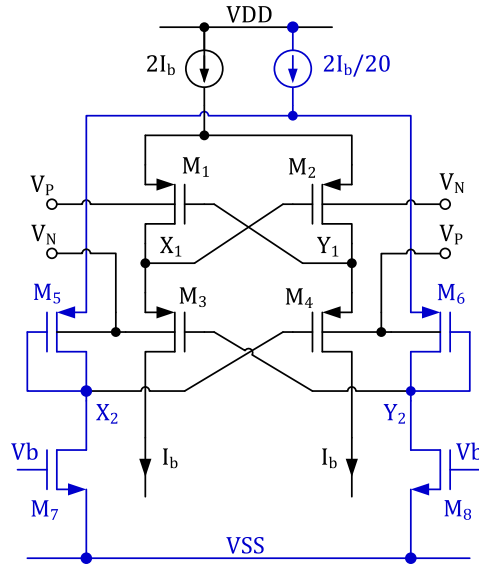


Fig. 2. Enhanced positive feedback different-pair

amplifier to make the gates terminal of M3 and M4 also be driven. The auxiliary amplifier consist of M5, M6, M7 and M8, while M5 and M6 are connected as diode. And the ac gain of auxiliary amplifier is expressed as,

$$V_{X2} = V_{in} g_{mb5} \frac{1}{g_{m5}} = \eta V_{in} \quad (3)$$

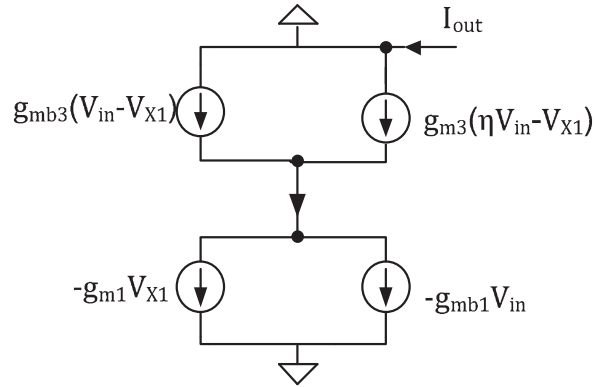


Fig. 3. Small-signal equivalent model of EPFP

The small-signal equivalent model of EPFP is shown in Fig. 3. Small-signal current constraint equation can be given as,

$$I_{out} = g_{mb3}(V_{in} - V_{X1}) + g_{m3}(\eta V_{in} - V_{X1}) \quad (4)$$

and

$$I_{out} = g_{m1}(-V_{X1}) + g_{mb1}(-V_{in}) \quad (5)$$

where g_{mb3} and g_{m3} are equal to g_{mb1} and g_{m1} . Therefore, from Eq. (2), Eq. (4) and Eq. (5), we can get G_m of EPFP which is expressed as,

$$G_m = \frac{n+2}{n-1} g_{mb1} \quad (6)$$

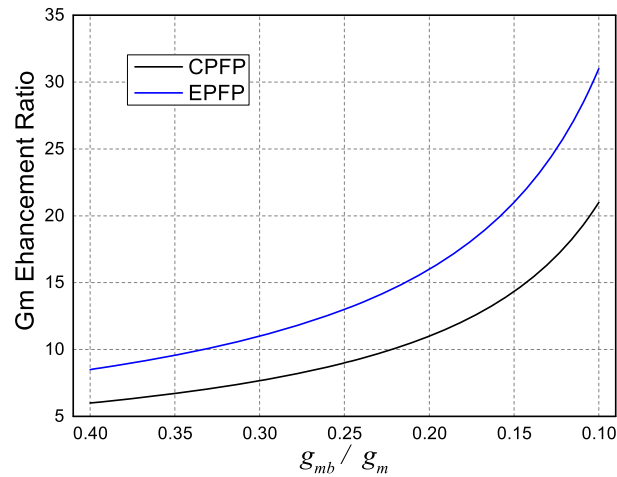


Fig. 4. Enhancement ratio of CPFP and EPFP versus g_{mb}/g_m

Fig. 4 shows the variation tendency of G_m enhancement ratio of CPFP and EPFP versus g_{mb}/g_m . As can be seen in Fig. 4, with the g_{mb}/g_m decreases, the G_m enhancement ratio of EPFP grows faster than that of CPFP, which demonstrates that EPFP has the advantage of meeting the needs of the technology scaling. Therefore, the EPFP shows better performance compared to CPFP in the aspect of the GBW.

4 Simulation results and discussion

In order to show the performance advantages of the proposed technique clearly, we prototype two OTA versions for comparison, one of them is a OTA using the conventional positive feedback differential pair (CPFP) which can be seen in Fig. 1; and the another is a OTA utilizing the enhanced positive feedback differential pair (EPFP) as shown in Fig. 2. The CPFP and EPFP are employed in two OTAs with a cascode structure providing high output impedance, which are realized in a UMC 180 nm standard CMOS process, where the threshold voltages of NMOS and PMOS devices have relatively large values 0.4 V and 0.47 V, respectively. The performance metrics is obtained correspond to Spectre simulation tools and the MOS model is used the BSIM3v3. The biasing current of CPFP and EPFP are 20 nA and 21 nA, which merely result in a little power dissipation but obtains a high enhancement ratio of transconductance. And the power supply is 0.6 V which allows all the NMOS and PMOS transistors working in weak-inversion region and the load capacitance is 15 pF.

Fig. 5 shows simulated AC response diagrams for two OTAs. The open loop gain of the CPFP and EPFP are 63.1 dB and 65.7 dB, which is obvious that the DC gain of EPFP is superior than that of CPFP. In addition, the unity-gain bandwidth (GBW) of the CPFP and EPFP are 4.92 kHz and 6.96 kHz respectively. The GBW of proposed EPFP is enhanced by almost 50% compared to CPFP as discussed previously, which also demonstrates the enhanced transconductance of the presented technique.

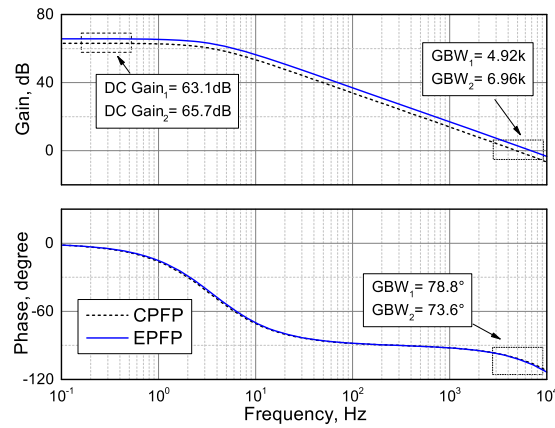


Fig. 5. AC response of CPFP and EPFP

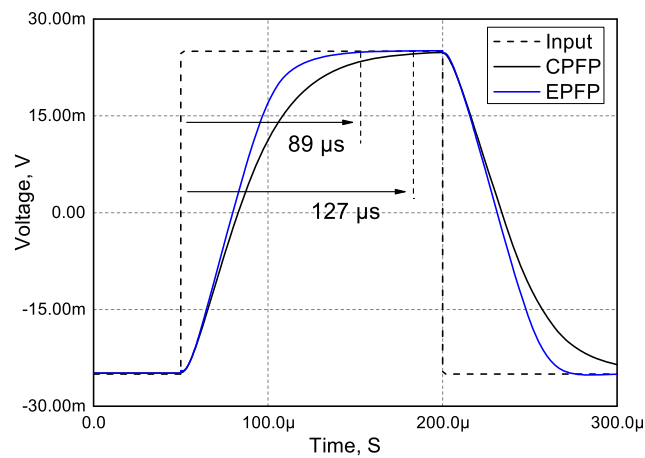


Fig. 6. The transient response of CPFP and EPFP

For the small signal transient analysis shown in Fig. 6. A square wave of 50 mV is generated by a function generator at 3.3 kHz. The 1% rise settling times for the two OTAs are 127 μs and 89 μs respectively. It is clearly that the OTA with the enhanced positive feedback differential pair (EPFP) has shorter settling time in two OTAs, which indicates the enhanced transconductance of the proposed technique. To study robustness to mismatch and process variations, Monte Carlo analysis with over 1000 runs was performed. The results are shown in Table I. Note that there are a consistent 65.7 dB dc gain and 6.94 kHz in gain-bandwidth by EPFP, proving the feasibility of the presented approach even under mismatches and process variations. Also, the value of phase margin standard deviation of CPFP and EPFP is 0.7 which demonstrates that the EPFP almost maintain the same circuit stability.

Table II sums up a list of CPFP and EPFP benchmark indicators used to evaluate this work. The superiority of the EPFP is clearly from the form. The figure-of-merit (FoM) is used for OTA performance comparisons and is expressed as

$$FoM = 100 \times \frac{GBW \times C_L}{I} \quad (7)$$

Table I. Monte carlo simulation results of CPFP and EPFP (1000 runs)

Parameter	CPFP	EPFP
Open loop gain average (dB)	63.1	65.7
Open loop gain standard (dB)	0.80	0.75
Unity gain frequency average (kHz)	4.90	6.94
Unity gain frequency standard deviation (kHz)	0.08	0.10
phase margin average (°)	78.8	73.6
phase margin standard deviation (°)	0.6	0.7
Offset standard deviation	2.90	2.33

Table II. Performance summary of the OTAs with CPFP and EPFP

Parameter	CPFP	EPFP
Voltage supply (V)	0.6	0.6
C_L (pF)	15	15
GBW (kHz)	4.92	6.96
Open loop gain (dB)	63.1	65.7
Power of the input pair (nW)	12	12.6
Power of the OTAs (nW)	24	24.6
Phase margin (°)	78.8	73.6
1% settling time (μs)	127	89
FoM (V^{-1})	185	255

where I represents the current consumption of the OTA. This FoM is used to present the bandwidth and the drive capability of the OTA. According to these results, the EPFP OTA using the proposed enhanced positive feedback differential pair has the higher FoM. The proposed OTA design technique is suitable for a wide range of low-voltage and low-power analog applications.

5 Conclusion

In this paper, a transconductance enhancement technique for bulk-driven OTAs working in weak inversion is presented, which improves the enhancement ratio of transconductance from $(n+1)/(n-1)$ to $(n+2)/(n-1)$. Simulation results demonstrate that the transconductance is enhanced almost 50% by using the proposed technique with just a little increased power consumption. Whats more, the FoM of the OTAs with the enhanced positive feedback differential pair (EPFP) is higher than the conventional transconductance enhancement approach.

Acknowledgments

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