Quasi-Floating-Gate (QFG) Inverter-Based Class-AB Linear Transconductor for Low Voltage Applications

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Abstract. This paper presents a QFG inverter-based class-AB linear transconductance for low voltage applications. The circuit employs positive feedback to enhance the input impedance, and feed-forward technique to suppress the common-mode gain. The circuit is designed using 0.18 μm CMOS technology under 0.5 V supply. The simulation results show rail-to-rail input/output swing, suppressed common-mode response, and good linearity (less than -45 dB with input 0.4 V_{pp}, 5 MHz). The power dissipation is 110 μW.

Keywords: linear transconductor; feed-forward technique; class-AB; QFG-inverter; bulk-driven; 0.5V

1. Introduction

Operational transconductance amplifier (OTA) is a key building block in several analog and mixed signal processing systems, such as continuous-time G_{m}-C filters, oscillators and data converters. Several approaches have been proposed to realize OTA, and most of the major problems lie in limited input swing and moderate linearity [1]-[6]. Differential-pair with resistive source degeneration was employed and good linearity was achieved [1]. The linearity of the circuit depended on the linearity of the resistor. However, the circuit required large supply voltage and power dissipation. [2] proposed the resistive gate-degeneration technique. Although rail-to-rail input swing was achieved, the input impedance was quite low, and depended on the resistor employed. [3] used adaptive biasing method, and the linearity of the circuit was improved, but the input common-mode range was quite limited. Double differential pair (DDP) technique was proposed [4] and the third order harmonic distortion was cancelled. However, the circuit was unsuitable for low voltage operation since large supply voltage is required. [5-6] used pseudo-differential (PD) circuit, which is suitable for low voltage operation. However, the input common-mode range and linearity were limited.

Pseudo-differential (PD) structure is widely used to design low voltage OTA, since avoiding the voltage drop across the tail current source allows wider input and output swings. However, PD structure requires an extra common-mode feedback (CMFB) circuit to suppress the common-mode signal, thus degrading the PD performance, since CMFB behaves as an additional load. Furthermore, CMFB circuit has to be carefully designed to avoid stability problems, resulting in complex circuitry and more power consumption. Another alternative is to use common-mode feed-forward (CMFF) technique [7-8]. [8] proposed the feed-forward technique, which achieved enhanced differential-mode gain and suppressed common-mode gain. However, the circuit has limited input common-mode swing and possessed moderate linearity.

In this work, a low voltage class-AB OTA using the quasi floating gate MOSFET (QFG-MOS) is proposed. It is known that QFG-MOS is suitable for low voltage operation [9]. The circuit uses positive feedback to enhance the input impedance, and novel feed-forward circuitry to simultaneously suppress common-mode signals and enhance the differential-mode signals. The circuit exhibits large input/output swing with good linearity.

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2. The Proposed Linear OTA

2.1. Basic Structure of Class-AB Linear OTA

A basic structure of single-ended class-AB linear OTA is shown in Fig. 1(a). As seen, the circuit consists of a resistor \( R \) and a class-AB current mirror \( (M_{1N,P}-M_{2N,P}) \). The input voltage \( \nu_i \) is converted to current \( i_R \), through the resistor \( R \). The current \( i_R \) is then mirrored to output transistors \( (M_{2N,P}) \), and becomes the output current \( i_o \). Since the input impedance of current mirror is small, node A can be considered as ac ground. As a result, the transconductance \( G_m \) can be derived and shown as

\[
G_m = \frac{i_o}{\nu_i} = \frac{\beta}{R}
\]  

where \( \beta \) is the current gain of the CM \( (\beta=gm_2/gm_1) \).

From (1), one can notice that \( G_m \) can be very linear, since its value depends on the input resistor \( R \). In addition, the input voltage swing of the circuit can be very large, and is only limited by the supply voltage.

2.2. Differential OTA with Input Impedance Enhancement

The input impedance of the circuit in Fig. 1(a) is approximately equal to the resistor \( R \). Increasing \( R \) will increase the input impedance of the OTA. However, increasing \( R \) also decrease \( G_m \) of the circuit. To eliminate the correlation between the input impedance and transconductance, a positive feedback is incorporated into the differential OTA, as illustrated in Fig. 1(b). As seen, the proposed differential OTA consists of two matched resistors \( (R) \) and two matched current mirrors. The operation of the circuit can be explained as follows. When the input is differential signal (see solid signal), these voltages are converted to currents through resistors \( R \). These currents, which have the same amplitude but opposite phase, flow to each resistor, and are mirrored to the OutA and OutB terminals (with the current gain of \( \alpha \)), and positively fed back to the input nodes, thus enhancing the input impedance (at nodes \( \nu_{1i} \) and \( \nu_{2i} \)).

On the contrary, when the input is common-mode signal (see dotted signal), the common-mode currents flow through nodes A and B with the same amplitude and phase. As a result, these two currents are added constructively, thus reducing the input impedance. From Fig. 1(b), differential \( (Z_{idm}) \) and common-mode \( (Z_{icm}) \) input impedances at nodes \( \nu_{1i} \) and \( \nu_{2i} \) can be calculated as

\[
Z_{idm} = r_{OAB}[1+r_{OAB}(1-\alpha)/R] \quad \text{and} \quad Z_{icm} = r_{OAB}[1+r_{OAB}(1+\alpha)/R], \]

respectively.

2.3. The Proposed Feed-forward Amplifier

The differential OTA in Fig. 1(b) is known as Pseudo-differential amplifier (PDA). One can see that the differential-mode transconductance \( (G_{dm}) \) is the same as the common-mode transconductance \( (G_{cm}) \), making the OTA prone to interferences and supply noises. To suppress the common-mode response, a newly developed feed-forward circuitry has been proposed. The technique employs feed-forward amplifier (FFA) and body-driven as shown in Fig. 2(a). As seen, FFA consists of two independent CMOS inverters \( (M_{2AN,P} \text{ and } M_{2BN,P}) \) and inverting amplifiers \( (-A) \), which serves two purposes: 1) to suppress the common-mode current signals \( (i_{o1} \text{ and } i_{o2}) \), and 2) to enhance the differential transconductance \( (G_{dm}) \) of the system.

The operation can be explained as follows. In case of the common-mode input signals \( (\nu_{in A,B}=\nu_{icm}) \), FFA will amplify \( \nu_{oA,B} \) and negatively feed forward the amplified signals to the body terminals of \( M_{2AN,P} \text{ and } M_{2BN,P} \). Since the input signals and amplified signals have opposite phase, the common-mode output current
is then suppressed. On the contrary, in case of the differential-mode signals \((V_{inA} = -V_{inB})\), the input signals at the gate and amplified signals at the body are in phase, thereby increasing the differential-mode output currents and differential transconductance \((G_{dm})\).

From Fig. 2(a), the differential-mode \((G_{dm})\) and common-mode \((G_{cm})\) transconductance gains can be derived and shown as

\[
G_{dm} = g_{m2N,P} + A \cdot g_{mb2N,P} \tag{2}
\]

\[
G_{cm} = g_{m2N,P} - A \cdot g_{mb2N,P} \tag{3}
\]

where \(A\) is the voltage gain of the inverting amplifier, \(g_{m2N,P}\) and \(g_{mb2N,P}\) are the gate and the body transconductances of \(M_{2AN,P}(M_{2BN,P})\), respectively.

From Eqs. (2) and (3), one can see that if \(A\) is set to \(g_{m2N,P}/g_{mb2N,P}\), \(G_{dm}\) will be equal to \(2g_{m2N,P}\) while \(G_{cm}\) will become zero, respectively.

![Fig. 2: Proposed class-AB linear OTA (a) feed-forward amplifier technique (b) circuit implementation.](image)

2.4. Circuit Implementation

The circuit implementation of the proposed OTA is illustrated in Fig. 2(b). As seen, the circuit consists of two matched current mirrors \((M_{1AN,P}-M_{2AN,N})\), two matched resistors \((R)\), two matched positive feedback transistors \((M_{3AN,P}-M_{3BN,N})\) and feed-forward amplifier \((M_{2AN,P}-M_{2BN,P}\) and \(M_{4AN,P}-M_{4BN,P}\)). Transistors \(M_{1AN,P}-M_{1BN,P}\) form the current mirror \(A\) and \(M_{1BN,P}-M_{2BN,P}\) form the current mirror \(B\). The current gain with the ratios of \(\alpha\) and \(\beta\) can be achieved by adjusting the aspect ratios of \(M_{1AN,P}, M_{3AN,P}\) \((M_{1BN,P}, M_{3BN,P})\) and \(M_{1AN,P}\) \((M_{1BN,P}, M_{3BN,P})\), respectively. Feed-forward Transistors \(M_{1AN,P}\) and \(M_{1BN,P}\) consist to be the FFA, which has the voltage gain approximately equal to \(g_{mn}/g_{mb4}\). It is noticed that QFG-inverters (resistors \(R_G\), capacitors \(C_G\), and CMOS inverters) is employed so that the circuit can operate under the low voltage environment.

Straightforward small signal analysis shows that \(G_{dm}\) and \(G_{cm}\) can be derived and shown as

\[
G_{dm} = \frac{\beta}{R} \left( \frac{g_{m1}}{g_{m1} + sC_{A(B)}} \right) \left( 1 + \frac{g_{mb2}}{g_{mb4} + sC_{C(D)}} \right) \tag{4}
\]

\[
G_{cm} = \frac{\beta}{R} \left( \frac{g_{m1}}{g_{m1} + sC_{A(B)}} \right) \left( 1 - \frac{g_{mb2}}{g_{mb4} + sC_{C(D)}} \right) \tag{5}
\]

where \(g_{m1} = g_{m1N} + g_{m1P}, g_{mb1} = g_{mb1N} + g_{mb1P}, g_{mb2} = g_{mb2N} + g_{mb2P}, C_{A(B)}\) and \(C_{C(D)}\) are total parasitic capacitances at nodes \(A(B)\) and \(C(D)\), respectively.

It is noted that the choice of \(\alpha\) requires precaution. A large value of \(\alpha\) can result in a large input impedance of the OTA. However, large value of \(\alpha\) can drive the circuit unstable. In practice, \(\alpha\) should be set a little bit larger than one to compensate for the loss as a result of the imperfection of the current mirror not being able to perfectly mirror the current from the input to the output. In this work, \(\alpha\) is set to 1.5. The value of \(\beta\) plays role in determining the current gain, because it is part of the OTA circuit. As seen in Eq. (4), large value of \(\beta\) results in high transconductance gain. However, it is noted that large \(\beta\) requires large transistors,
thus large standby current and parasitic capacitors, which can degrade frequency performance of the system. In this work, $\beta$ is set to 6.

3. Simulation Results

To verify the circuit performance, Spectre is used to simulate the proposed circuit, using a 0.18 $\mu$m CMOS process under the supply voltage of 0.5 V. In this work, the bias currents of all transistors are chosen to optimize both gain and power dissipation. $Z_{dgm}$ and $Z_{icm}$ are found to be 1.5 M$\Omega$ and 20 k$\Omega$, respectively.

Fig. 3 shows the transconductance and output current as a function of the input differential voltage for different value of resistors. As seen, the transconductance is nearly constant (less than 0.25 % variation) and output currents vary with the input voltage linearly over an entire range of the input signal. Fig. 4 shows total harmonic distortion (THD) versus the amplitude of the input voltage at 5 MHz. As seen, THD of the circuit remains lower than -45 dB for the input amplitude up to 0.4 Vpp.

Fig. 5 shows the frequency response of the proposed OTA for both differential-mode and common-mode input signals. In case of differential-mode input signal, the DC transconductance gain of the OTA without feed-forward (Fig. 1(a)) is found to be 135 $\mu$A/V (dotted line), and increases to 245 $\mu$A/V (solid line), when feed-forward circuitry is incorporated into the circuit. The common-mode transconductance gain is suppressed, and found to be only 9 $\mu$A/V. The bandwidth of the differential-mode and common-mode are nearly the same, and equal to 10 MHz. The power dissipation of the proposed PDA is 110 $\mu$W.

![Fig. 3: Transconductance and output current versus input voltage.](image)

![Fig. 4: THD of the proposed OTA (5 MHz).](image)
Fig. 5: Frequency response of OTA.

4. Conclusions

In this paper, a QFG inverter-based class-AB linear transconductance is proposed. The QFG-inverter is employed, enabling the circuit to operate under low voltage supply. Feed-forward technique is used to suppress the common-mode response. The circuit demonstrates wide input/output swing and good linearity over an entire range of the input signal. The differential-mode gain is increased, while the common-mode gain is suppressed.

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6. References