Improving Bulk Driven CMOS OTA Performance using Feedforward Technique

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ABSTRACT:
This paper presents an ultra-low-voltage ultra-low-power CMOS Operational Trans conductance Amplifier (OTA), using a novel feed-forward technique. The proposed topology is based on a bulk driven input differential pair, and inclusion of a gain-stage in the Miller capacitor feedback path to enhance the pole-splitting effect. The main objective of the proposed OTA is to utilize idle current source devices in small signal paths to improve the OTA performance. Not only the DC gain of the proposed OTA is enhanced by 10dB, its unity gains bandwidth (UGB) is also increased by factor of 3 with no extra power dissipation. The proposed OTA is designed and simulated in 180nm CMOS technology consuming only 386nW under the supply voltage of 400mV.

KEYWORDS: OTA, Low-power design, Bulk driven transistor, Pole splitting, Feedforward.

1. INTRODUCTION

The design of high performing analog integrated circuits that operate at low supply voltages is becoming increasingly important, particularly for applications such as medical electronic implants, as well as battery-powered portable electronic devices. The operational transconductance amplifier (OTA) still forms a vital analog buil ding block of such devices, and is the largest and most power consuming component in many of these applications [6].

Bulk driven MOSFET is one of the interesting approaches for low voltage analog circuits design. An inversion layer can be formed by assigning an adequate value to the gate to source voltage of a MOSFET, then applying the input signal to the bulk terminal. Therefore, the threshold voltage of a MOSFET can be reduced, or even removed from the signal path. The most important drawbacks of employing the bulk-driven method is to have a low DC gain and an extremely low unity gain bandwidth (UGB) owing to the fact that the body transconductance, g_{mb}, is approximately five times smaller than the gate transconductance, g_m [1].

A 0.4V, 386nW sub-threshold CMOS OTA is proposed in this paper. By using a new feed-forward technique, the DC gain and the unity gain bandwidth of the proposed OTA have been considerably increased to 88dB and 86 kHz, respectively.

2. PROPOSED CMOS OTA

Fig.1 illustrates the schematic of the proposed OTA which employs a feed-forward technique. As can be seen from the Fig.1, M_{3a}-M_{3b} and M_{4a}-M_{4b} form composite transistors. They are capable of biasing differential pair and common gate amplifier with the same value; thus there is no need to use additional biasing circuit. V_{ds3} of the composite transistor can be given by (1) [2].

$$V_{ds3a} = \frac{KT}{q} \ln\left(1 + 2\frac{(W/L)_{3b}}{(W/L)_{3a}}\right) \qquad (1)$$

In terms of dc analysis, voltages V_{ds3a} and V_{ds4a} are constant and equal. Hence, voltages V_{ds1} and V_{ds2} need to be constant and equal to optimize the matching of differential pair M_1 and M_2, and to reduce the differential offset voltage. Equation (2) should be satisfied to prevent no systematic offset in the proposed circuit

$$(W/L)_6 = \frac{2(W/L)_{3a}(W/L)_7}{2(W/L)_8 + (W/L)_5} \qquad (2)$$

In low frequency applications, flicker noise plays a tangible role on the performance of the circuit. To minimize the effect of this noise, the transistors sizes should be chosen to be rather large in the sub-threshold operation. In addition, the transistors operate in the weak inversion region, and since their role was illustrated by the authors in detail in [3], they will not be discussed here.

Obviously, discomfort of the right half plane (RHP) is the major drawback of the Miller frequency compensation technique. The RHP zero reduces the phase margin and causes the instability of OTA. To overcome the problem, the miller cascode frequency compensation technique can be employed to move the second pole to higher frequencies [4], or utilize the hybrid frequency compensation [5].

In the proposed OTA, a new feed-forward technique is presented which exploits the bulk of idle device to create another signal path. The input signal is directly and simultaneously applied to the bulk of both nMOS current source transistors of the first stage, (M3a, M4a). Compared to other transistors, these devices carry a large amount of DC current which results in achieving a higher body transconductance (g_{mb}). However, it is possible to apply the input signal to the gate of both M3a, M4a to obtain a much higher transconductance as well, but it surely deteriorates the biasing of these transistors; thus, complex biasing circuit needs to be implemented to overcome this important issue.

In term of circuit analysis, the proposed feed-forward technique creates two small signal paths from the input to the output of the first stage. One path is generated from the input transistor, M2 or M1, similar to the conventional topology and the other path is resulted from M4a or M3a, where these paths forma cascode configuration.

In other words, the overall transconductance of the first stage is enhanced from g_{mb1} to $g_{mb1}+g_{mb4a}$ which results in a remarkable enhancement in term of DC gain compared to the conventional bulk driven form. Applying the proposed technique does not change the dominant pole located at the output of the first stage. Due to employing the pole-splitting effect, the dominant and non-dominate poles are significantly separated; therefore, the unity gain bandwidth of the OTA can be given by:

$$\omega_t = A_{dc}.\omega_p \tag{3}$$

where A_{dc} and ω_p are total gain and dominant pole located at the output of the first stage, respectively.

Since the dominant pole is not changed and according to (3), the DC gain of the OTA is dramatically increased, the unity gain-bandwidth is considerably boosted as well. It is worth mentioning that these improvements are achieved without consuming extra DC power or limiting other OTA parameters. Now, the open loop gain of the proposed OTA can be calculated as:

$$A_0 = \frac{(g_{mb1}+g_{mb4a})g_{m6}}{g_{o67}\left(\frac{g_{oB}+g_{o9}}{g_{m4b}+g_{mb4b}+g_{o4b}}g_{o24a}+\frac{g_{o11}.g_{o9}}{g_{m11}+g_{mb11}}\right)} \tag{4}$$

where g_{oi} is output conductance of transistor M_i, and g_{oij} shows the parallel conductance of M_i and M_j transistors.

It is discussed in [2] that the input transistors M_1 and M_2 never become thoroughly cut off, and the current of M_5 cannot flow into one of paths; thus, a complex approach needs to be considered to determine the slew rate value. The slew rate value can be obtained from the expressions associated with the compensation capacitor C_c,:

$$SR = \frac{I_{DS2} - I_{DS1}}{C_c}. \tag{5}$$

Therefore, slew rate can be obtained from the operating point analysis given by the simulations.

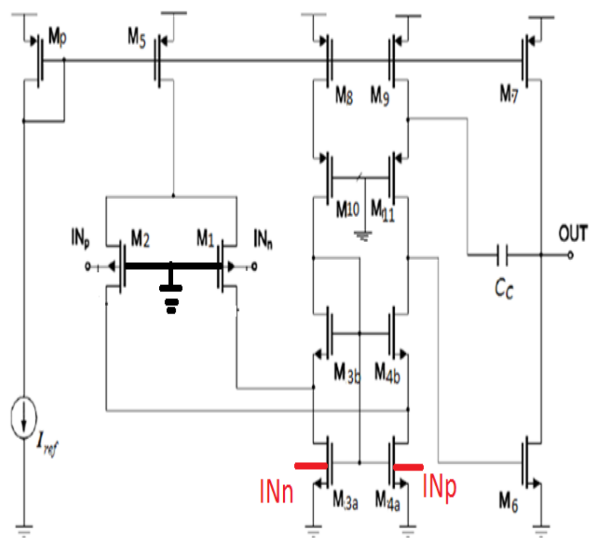

Fig. 1. Schematic of the proposed feedforward OTA circuit

3. SIMULATION RESULTS

The HSPICE software using BSIM3v3 model is utilized to simulate the proposed and conventional OTAs according to the standard 180nm CMOS process. Fig. 2 represents the simulated open loop gain and the phase of the OTAs before and after applying the feed-forward technique. The simulation result confirms the increasing DC gain of the proposed OTA by 10dB whose value reaches 88dB. Beside, a considerable enhancement in the unity-gain bandwidth to the value of 86 kHz and a phase margin of 55^o can be seen in Fig. 2. The common mode rejection ration (CMRR) of the proposed OTA is more than 100dB, and it is also capable of having rail to rail output swing. The presented topology employing the feed-forward technique and weak inversion transistors is capable of working with a power supply of 400 mV, and consumes only 386nW.The simulated power spectral density shows that the input referred noise of the proposed OTA has decreased by a factor of 10 compared to that of the conventional OTA and its value is as low as 20nV/$\sqrt{Hz}$ @10mHz. The designed system demonstrates a relatively suitable response in different process corners. The slew rate of the proposed OTA is 25mV/s. The OTAs drive a capacitive load of 15pF, and to compensate the frequency response, the miller capacitor is chosen to be 2.5pF. It is worth mentioning that the DC gain, unity gain bandwidth, and noise performance of the proposed OTA has improved without consuming extra power and deteriorating other OTA parameters and in fact, the applied technique is the simplest and the most efficient method to improve the OTA performance. The whole performance of the OTAs is tabulated in Table 1. A figure of merit (FOM) is used to evaluate the OTA performance [3]:

$$\text{FoM}=\frac{(\text{Gain})(\text{Unity gain freq.})}{(\text{Power supply})(\text{Power consumption})}. \quad (6)$$

As can been seen from the Table 1, a considerable FOM is produced for the proposed OTA while the supply voltage is as low as 0.4V. Considering the slew rate and power spectral density of input referred noise of the OTA, a new FOM can be defined in which the efficiency of the proposed OTA can be highlighted better.

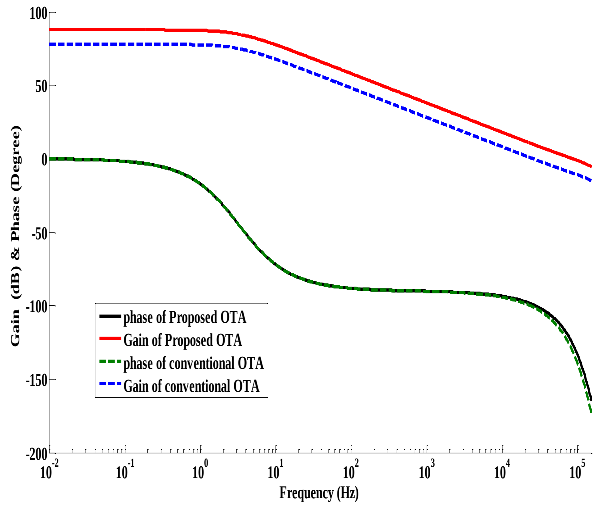

Fig. 2. simulation result of gain and phase of the OTA before and after applying the feed-forward technique.

Table 1. Comparison results for before and after applying the feed-forward technique.

	Proposed OTA	Conventional OTA	[7]	[8]	[9]	[10]
Gain (dB)	88	78	88.5	62	90	60
UGB (Khz)	86	26	83.88	540	113	1.88
V_{dd}(V)	0.4	0.4	0.5	0.9	1	0.25
SR (mV/s)	25	22	52	N/A	N/A	0.64
P_{dc} (nW)	386	386	1020	9900	8400	52
FOM#	49	13.1	14.47	3.76	1.21	8.68

(dB.kHz / V.nW)

4. CONCULSION

A new feed-forward technique was introduced to improve OTA parameters. Employing idle devices in small signal path resulted in enhancing DC gain and unity gain bandwidth of the proposed OTA. The OTA represented gain and UGB of 88dB and 86 kHz, respectively, while those of the conventional OTA were 78dB and 26 kHz, respectively. In constant power dissipation, the applied technique was the simplest and the most efficient method to improve OTA parameters. The total power consumption of the OTA is as low as 386nW. This ultra-low power ultra-low voltage architecture is very useful in bio-medical applications in which the power budget is limited.

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