An Ultra Low-Power Fully Differential Operational Transconductance Amplifier (FD-OTA) Operating in Weak-inversion Region and Its Applications

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Abstract- A low-power, low-voltage CMOS fully differential operational transconductance amplifier (OTA) operating in weak inversion region is presented in this paper. The proposed element allows the use of very small current for low-power and low-voltage features. The performances are examined through PSPICE simulations, displaying usabilities of the new active element. The power consumption is about 35.5pW at ±0.75V. The description includes examples as a current-mode full-wave rectifier and current splitter.

I. INTRODUCTION

An OTA has received considerable attention as active components, because the transconductance can be adjusted electronically, especially suitable for analog circuits [1]. The flexibility of the mentioned device to operate in both current and voltage-modes allows for a variety of circuit designs. In the most of modern high-performance analog integrated circuits, a fully differential circuit is needed since it can extend the dynamic range over one order of magnitude through the cancellation of even harmonics, as well as the suppression of all undesirable common mode (CM) signals [2].

In the last decade, there has been much effort to reduce the supply voltage of electronic circuits. This is due to the demand for portable and battery-powered equipment. Since a low-voltage operating circuit becomes necessary, the operation of MOS devices in weak-inversion region is ideally suited for this purpose. The features of this technique are that: higher voltage gain that results from operation below the strong-inversion region [3-7]; lower device power consumption resulting from the low value of quiescent drain current: decrease in distortion over operation in the strong-inversion region [6-7]: higher output resistance of the devices of the input stage resulting from the low drain currents that often lead to operation below the strong-inversion region [7]. Recently, a large number of the OTAs using this technique have been proposed [8-16]. Unfortunately, these circuits employed complicated internal constructions due to requiring specific bias sources. Consequently, these configurations still consume power consumption in nW-range, and occupy large area of monolithic chip.

The aim of this paper is to propose the implementation of low-power fully differential CMOS OTA (FD-OTA) operating in weak-inversion region and using simple architecture to achieve less power consumption. The performances of proposed OTA are proved by PSPICE simulations, they show good agreement as mentioned. The application examples as a current-mode full wave rectifier and current splitter are included. The maximum power consumptions are restricted in pW-level.

II. CIRCUIT CONFIGURATION

A. Operational of MOS device in weak-inversion region

If a MOS (using EKV model) operates in weak inversion or subthreshold region, the drain current for the NMOS-type equation will be expressed as in (1)

\[ I_{D,NMOS} = I_s e^{\frac{V_{th} - V_s}{V_T}} e^{-\frac{V_T}{V_T} \frac{V_{th} - V_s}{V_T}} , \]

where \( V_{th} \) is threshold voltage, while \( I_s, n, V_T \) are correspondent to specific current, subthreshold slope, and thermal voltage (about 25mV at room temperature), respectively. From (1), if the NMOS-type operates saturation region, the drain current has a square law in voltage to current conversion.

B. Basic Concept of FD-OTA

An ideal FO-OTA has infinite input and output impedances. The output current of an FO-OTA is given by

\[ I_o = g_o (V_1 - V_2) , \]
where $g_m$ is the transconductance of the FO-OTA. For a MOSFET operating in weak-inversion mode can be expressed by

$$g_m = \frac{I_g}{2nV_T}.$$ (3)

$V_T$, $n$ and $I_g$ are the thermal voltage, subthreshold slope and the input bias current, respectively. The transconductance of CMOS OTA operating in the mode is differed from those in saturation region, where $g_m$ is square-rooting function of $I_g$.

The symbol and equivalent circuit of the FO-OTA are illustrated in Figs. 1(a) and (b), respectively.

### C. Proposed FD-OTA

A simple differential pair amplifier is employed to achieve simpler circuit description of the proposed FD-OTA as shown in Fig. 2. From Fig. 2, $M_1$ and $M_2$ function as a differential amplifier to convert an input voltage to an output current and are biased to work in weak-inversion region. $M_3$ to $M_{16}$ operate as a simple current mirror, where $I_B$ is an input bias current.

When $V_\text{in}$ is applied, this makes $I_1$ and $I_2$ flowing in $M_1$ and $M_2$, respectively. The following currents can be obtained

$$I_1 = I_e e^{\frac{V_\text{in} - I_0}{V_T}} e^{\frac{V_g}{V_T}},$$ (4)

$$I_2 = I_e e^{\frac{V_\text{in} - I_0}{V_T}} e^{\frac{V_g}{V_T}}.$$ (5)

Due to

$$I_g = I_1 + I_2,$$ (6)

and

$$I_o = I_1 - I_2.$$ (7)

Substituting (4), (5) and (6) into (7), it yields

$$I_o = I_g \tanh(V_\text{in} / 2nV_T).$$ (8)

Since $\tanh(V_\text{in} / 2nV_T) \cong V_\text{in} / 2nV_T$, we will obtain

$$I_o = I_g \frac{V_\text{in}}{2nV_T},$$ (9)

or

$$I_o = g_m V_\text{in},$$ (10)

where $g_m$ is equal to (3).

### III. SIMULATION RESULTS

To prove the performances of the proposed FD-OTA, the PSPICE simulation program was used. The NMOS and PMOS were simulated by using the EKV version 2.6 parameters for 0.5µm CMOS technology [17] with ±0.75V supply voltages. A wide range of the transconductance controllability can be achieved as shown in Fig. 3, when $I_g$ is varied from 1pA - 1.2µA. The bandwidths of the output terminals are shown in Fig. 4. The −3dB responses of $I_{o+}/V_1, I_{o-}/V_1, I_{o+}/V_2$ and $I_{o-}/V_2$ are respectively located at 250kHz, 320kHz, 230kHz and 270kHz. The summarized characteristics of the FD-OTA can be seen in Table 1.

### IV. APPLICATION EXAMPLES

To validate the proposed FD-OTA configuration, some applications are stated in this section, as followed.

#### A. Precision Rectifier

The first application of proposed FD-OTA is a current-mode full-wave rectifier, shown in Fig. 5. It consists of only 2 FD-OTAs. Considering the circuit in Fig. 5, and using the FD-OTAs properties, it yields the output currents as follows

$$i_0^+ = \begin{cases} i_{n}\tanh\left(\frac{V_\text{in}}{2nV_T}\right) & \text{if } i_{n} > 0, \\ 0 & \text{if } i_{n} < 0 \end{cases}.$$ (11)
From (11)-(14), if $V_C \gg 2V_T$, we can use Taylor’s series and it can be approximately reduced that
\[ \tanh \left( \frac{V}{2V_T} \right) \approx 1. \] (15)

The output currents of FD-OTAs are reduced to
\[
i_{o1} = \begin{cases} i_{in} & \text{if } i_{in} > 0, \\ 0 & \text{if } i_{in} < 0, \\ \end{cases} \quad (16)
\]
\[
i_{o2} = \begin{cases} -i_{in} & \text{if } i_{in} < 0, \\ 0 & \text{if } i_{in} > 0, \\ \end{cases} \quad (17)
\]
\[
i_{o3} = \begin{cases} 0 & \text{if } i_{in} < 0, \\ i_{in} & \text{if } i_{in} > 0, \\ \end{cases} \quad (18)
\]
and
\[
i_{o4} = \begin{cases} 0 & \text{if } i_{in} > 0, \\ -i_{in} & \text{if } i_{in} < 0, \\ \end{cases} \quad (19)
\]

The output currents $i_p$ and $i_N$ can be shown to be
\[
i_p = i_{o1} + i_{o3} = |i_{in}| \quad \text{when } V_C \gg 2V_T, \] (20)
and
\[
i_N = i_{o2} + i_{o4} = -|i_{in}| \quad \text{when } V_C \gg 2V_T. \] (21)

From (20) and (21), we found that the output currents are the absolute value of input current and temperature-insensitive. In addition, the directions can be electronically changed by $cV$. Fig. 6 depicts DC transfer characteristics. It is clearly seen that it is linear in range of $-50 \mu A \leq i_{in} \leq 50 \mu A$, and does not have an offset current. A transient response at output as an absolute current is shown in Fig. 7. Fig. 8 shows the output current relative to temperature variations to be $27^\circ C$, $50^\circ C$ and $100^\circ C$. It is clearly observed that the output current is almost not dependent on the temperature variations. Fig. 9 shows the temperature stability of the output current. It should be remarked that the output deviation is less than 3%.

\[ i_{o1} = \begin{cases} i_{in} & \text{if } i_{in} > 0, \\ 0 & \text{if } i_{in} < 0, \\ \end{cases} \quad (22)
\]
\[ i_{o2} = \begin{cases} -i_{in} & \text{if } i_{in} < 0, \\ 0 & \text{if } i_{in} > 0, \\ \end{cases} \quad (23)
\]
\[ i_{o3} = \begin{cases} 0 & \text{if } i_{in} < 0, \\ i_{in} & \text{if } i_{in} > 0, \\ \end{cases} \quad (24)
\]
and
\[ i_{o4} = \begin{cases} 0 & \text{if } i_{in} > 0, \\ -i_{in} & \text{if } i_{in} < 0, \\ \end{cases} \quad (25)
\]

The output currents $i_1$ and $i_2$ can be expressed to be
\[
i_1 = i_{o1} + i_{o4} = \begin{cases} i_{in} & \text{if } i_{in} > 0 \text{ when } V_C \gg n2V_T, \\ -i_{in} & \text{if } i_{in} < 0 \text{ when } V_C \gg n2V_T. \] (26)
W. We found that the output currents $i_s$ and $i_{s2}$ are in 180° phase difference and temperature-insensitive. Fig. 11 depicts DC transfer characteristics. It is clearly seen that it is linear in range of $-50\mu A \leq i_s \leq 50\mu A$. The transient response is shown in Fig. 12. Fig. 13 shows the output current versus temperature variations, we found that the output current is almost not dependent on the temperature variations.

V. CONCLUSIONS

The building block, called the FD-OTA implemented by using CMOS transistors operating in weak inversion region, has been introduced via this paper. The internal construction is very simple to obtain less power consumption and chip area. The usabilities have been proven by the simulation and application examples. The application circuits consume power consumptions in pW level, which is suitable to design in ultra-low power operating circuit. Our future work is to find more applications of the FD-OTA, emphasizing on the current-mode applications such as signal generator, filter, and etc.

REFERENCES