Ultra-Low Voltage Low Power Bulk Driven Z Copy-Current Controlled-Current Differencing Buffered Amplifier

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Abstract—This paper presents Ultra Low Voltage (ULV) Low Power (LP) Z Copy-Current Controlled-Current Differencing Buffered Amplifier (ZC-CC-CDBA) with single voltage supply. The circuit is performed using bulk driven (BD) technique and it is capable to operate at ULV of 0.65V and consumes low power in the micro range. In addition to the topology simplicity, the proposed circuit offers high linearity and extended output voltage range. Eventually, to verify the functionality of the proposed circuit, current mode multi-function biquad filter using three ZC-CC-CDBAs with two grounded capacitors is included as an example of application. The simulations are performed in PSPICE environment using the 0.18µm CMOS technology from TSMC.

Index Terms—bulk driven, current differencing buffered amplifier, filter, low power circuit

I. INTRODUCTION

Minimizing the power consumption and reducing the supply voltage become essential demands in modern portable electronic devices and battery-powered implantable and wearable biomedical devices. Since low voltage (LV) LP operation either prolongs the battery life time or/and decreases device’s size using a smaller battery [1]. These requirements boost the efforts of designers to propose circuits capable to operate under LV LP conditions.

The main barrier in LV LP analog circuit design is the rather high threshold voltage of the MOST. Hence various techniques have been invented to reduce or even remove the threshold voltage from the signal path. Among the most interesting techniques are the non-conventional ones: Bulk Driven (BD), Floating Gate (FG) and Quasi-Floating Gate (QFG) MOST [2]-[4].

The aforementioned non-conventional techniques were successfully utilized to build numerous of modern LV LP active electronic elements [4]-[24]. Since these techniques enjoy the following design advantages: ULV LP operation capability, simple circuitry, and extended input voltage range. Moreover, their relatively lower transconductance value and narrower bandwidth in comparison to conventional gate driven MOST (GD) are attractive features in some applications, such as biomedical ones, since the amplitude and the frequency of the biological signals are extremely low.

The bulk driven (BD) principle was introduced for the first time in 1987 [5]. Although the transconductance of the BD MOST is the smallest among the non-conventional techniques, it is capable to process AC and DC signals, while the capacitively coupled gates of FG and QFG MOSTs prevent processing DC signals. Furthermore The BD MOST occupies smaller area on chip than FG and QFG MOSTs due to their input capacitors [4][17]. During the last decade various interesting and effective active elements were designed utilizing the BD technique, such as operational transconductance amplifiers (OTAs) [4], [6], and [7], operational amplifiers [8], and [9], voltage followers [10], and [11], second generation current conveyors (CCIs) [12], and [13], current differencing external transconductance amplifiers (CDeTAs) [14], winner take all circuit [15], differential-input buffered and external transconductance amplifiers (DBeTAs) [16] and Differential difference current conveyor (DDCC) [17].

The current differencing buffered amplifier (CDBA) principle was first published in 1999 [25]. Owing to its simplicity and capability to operate in current and voltage modes, it is considered as universal building block for analog signal processing with interesting application potentials. The capability of controlling the transfer parameters of the CDBA extends its applicability. Thus two controlling methods have been proposed: current controlled CDBA (CC-CDBA) [26]-[32], and digitally controlled CDBA (DC-CDBA) [33]. In several applications of the CDBA, There is a need for utilization of the output current signal flowing out of the output terminal to the working impedance [34]. However, this procedure is not easy to be achieved, since any attempt to use the output current affects the entire circuit performance. Therefore, providing copy of the output current is very useful in many applications. This copy can be performed by additional high impedance output terminal of the CDBA, thus this element can be named Z copy CDBA (ZC-CDBA) [35]. The CDBA building block has been widely used to design voltage mode or current mode filters [36]-[44]. Furthermore, various oscillators based on the CDBA were introduced in literature [26]-[28] [45] [46].
The purpose of this work is to introduce a new simple CMOS structure based on BD technique of the ZC-CC-CDBA capable to operate with ULV LP conditions. Thus the attractive features of this building block can be widely employed in LV LP applications.

This paper is organized as follows. Sect. II presents the principle and the internal structure of the novel ULV LP ZC-CC-CDBA based on the BD technique. In Sect. III, biquad multi-function current mode filter is introduced as an example of application. Sect. IV shows the simulation results, and Sect. V is the conclusion.

II. ULV LP ZC-CC-CDBA

The ZC-CC-CDBA is a five terminal active element; two low impedance input terminals (p, n), two high impedance output terminals (z, zc), and one low impedance output terminal (w). The schematic symbol of the ZC-CC-CDBA and its equivalent circuit are depicted in Fig. 1(a) and (b), respectively.

\[
\begin{bmatrix}
V_p \\
V_n \\
I_p \\
I_n \\
V_z \\
V_{zc}
\end{bmatrix}
= \begin{bmatrix}
R_p & 0 & 0 & 0 & I_p \\
0 & R_n & 0 & 0 & I_n \\
1 & -1 & 0 & 0 & V_z \\
0 & 0 & 1 & 0 & V_{zc}
\end{bmatrix}
\begin{bmatrix}
V_w \\
I_{bias}
\end{bmatrix}
\]

\[I_{bias} = I_p - I_n\]  

(1)

The MOS internal structure of the proposed ZC-CC-CDBA is depicted in Fig. 2. Transistors M13, M14, M15, and M16 act as an active load. Transistors M13, M14, M15 construct BD flipped voltage follower differential structure (BD-DFVF) [47].

Owing to use the BD flipped voltage follower structure in the proposed circuit, the minimum power supply voltage \(V_{DD,min}\) can be given by:

\[V_{DD,min} = V_{GS} + V_{DSsat}\]  

(2)

whereas \(V_{GS}\) and \(V_{DSsat}\) are the gate-source and the drain-source voltage of The MOST, respectively. It is obvious from (2) that the proposed circuit is capable to operate under ULV conditions.

Moreover, the parasitic input resistances \(R_p, R_n\) can be described by:

\[R_{p,n} = \frac{1}{g_{m3.7} g_{mb1.5} f_{d3.7}}\]  

(3)

Figure 1. ZC-CC-CDBA: (a) schematic symbol, (b) equivalent circuit.

Figure 2. The proposed MOS structure of the ZC-CC-CDBA.
These resistances $R_p$ and $R_n$ can be adjusted via the bias current $I_{bias}$ as it is shown in Fig. 3. Hence designers started to utilize these resistances instead of the passive resistors in several applications.

III. APPLICATION EXAMPLE

A current mode universal filter based on ZC-CC-CDBA is introduced in this section to confirm the functionality of the proposed circuit [32]. The multi-function current mode filter is depicted in Fig. 4. This filter performs three functions simultaneously: low pass, high pass, and band pass with high output impedance property. The parasitic resistances ($R_{p1}$, $R_{n1}$) of the ZC-CC-CDBA1, ($R_{p2}$, $R_{n2}$) of the ZC-CC-CDBA2, and ($R_{p3}$, $R_{n3}$) of the ZC-CC-CDBA3 can be tuned via bias currents: $I_{B1}$, $I_{B2}$, and $I_{B3}$, respectively. The output currents $I_{BP}$, $I_{AP}$ and $I_{LP}$ of this filter are flowing out the $zc1$, $zc2$ and $zc3$ terminals, respectively. These currents are flowing into the working impedances directly.

![Current mode biquad filter based on ZC-CC-CDBA.](image)

Figure 4.

The transfer functions of the filter are given by:

\[
\frac{I_{BP}}{I_{m}} = \frac{S^2}{S^2 + S \left( \frac{1}{C_1 R_{p1}} + \frac{1}{C_2 R_{p2} R_{n3}} \right)}
\]

\[
\frac{I_{AP}}{I_{m}} = \frac{-S/C_1 R_{p2}}{S^2 + S \left( \frac{1}{C_1 R_{p1}} + \frac{1}{C_2 R_{p2} R_{n3}} \right)}
\]

\[
\frac{I_{LP}}{I_{m}} = \frac{-1/C_1 C_2 R_{p2} R_{n3}}{S^2 + S \left( \frac{1}{C_1 R_{p1}} + \frac{1}{C_2 R_{p2} R_{n3}} \right)}
\]

The pole frequency ($\omega_h$) and the quality factor (Q) of the filter are described by:

\[
\omega_h = \frac{1}{\sqrt{C_1 C_2 R_{p2} R_{n3}}}
\]

\[
Q = R_{p1} \sqrt{\frac{C_1}{C_2 R_{p2} R_{n3}}}
\]

It is obvious from (7) and (8), that the quality factor can be adjusted independently from the pole frequency by adjusting the value of $R_{p1}$ via $I_{B1}$.

IV. SIMULATION RESULTS

A. ULV LP ZC-CC-CDBA Simulation Results:

The performances of the proposed circuit are verified by PSPICE simulator using 0.18 $\mu$m CMOS technology from TSMC; its PSPICE model parameters can be found in [48]. The optimal transistors aspect ratios of the proposed circuit ZC-CC-CDBA shown in Fig. 2 are listed in Table I.

<table>
<thead>
<tr>
<th>Transistor</th>
<th>W/L [µm/µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M_{b1}, M_{b2}, M_{b3}, M_{b4}, M_{b5}</td>
<td>15/1.5</td>
</tr>
<tr>
<td>M_{b6}, M_{b7}, M_{b8}</td>
<td>80/3</td>
</tr>
<tr>
<td>M_{b9}</td>
<td>30/3</td>
</tr>
<tr>
<td>M_{b10}</td>
<td>8/0.3</td>
</tr>
<tr>
<td>M_{b11}, M_{b12}</td>
<td>40/2</td>
</tr>
<tr>
<td>M_{b13}, M_{b14}</td>
<td>40/3</td>
</tr>
<tr>
<td>M_{b15}</td>
<td>80/1</td>
</tr>
<tr>
<td>M_{b16}</td>
<td>20/3</td>
</tr>
<tr>
<td>M_{b17}</td>
<td>30/3</td>
</tr>
<tr>
<td>M_{b18}</td>
<td>15/3</td>
</tr>
</tbody>
</table>

All the simulations are performed for $I_{bias}$=3 $\mu$A, $I_p$=4 $nA$ with an extremely low voltage supply of 0.65 V. The DC curves $I_{BP}$ versus $I_p$ and $I_{LP}$ are depicted in Fig. 5. Thanks to utilizing enhanced BD current mirror, the proposed circuit offers high linearity of $I_p$ versus $I_p$ with extremely low current offset whose value is less than 0.05 $\mu$A. The DC curves $I_p$ versus $I_p$ for various values of $I_{bias}$ are shown in Fig. 6, whereas the current $I_{bias}$ vary from -3 $\mu$A to 3 $\mu$A with a step of 1 $\mu$A.

![DC curves $I_p$ versus $I_p$ for various values of $I_{bias}$.](image)

Figure 5.

![DC curves $I_p$ versus $I_p$ for various values of $I_{bias}$.](image)

Figure 6.
The frequency responses of the current gains \(I_{z,zc}/I_n\) and \(I_{z,zc}/I_p\) are shown in Fig. 7. The current gains are unity at low frequencies. The cutoff frequencies of these gains are 2.4 MHz and 5.15 MHz of \(I_{z,zc}/I_n\) and \(I_{z,zc}/I_p\), respectively. The frequency dependence of the parasitic impedance of the \(z\) terminal is shown in Fig. 8. The impedance of \(z\) terminal is very high about 2.67 MΩ at low frequencies.

The DC curve \(V_z\) versus \(V_w\) is shown in Fig. 9. Besides, the voltage error \((V_z - V_w)\) is depicted. The high linearity and the wide range operation can be observed. Furthermore, in the range from 0.04 V to 0.58 V, the voltage error is less than 1 mV.

The power consumption of the proposed circuit is extremely low (5.6 µW to 56 µW) for \(I_{Bias}=1 \mu A\) to \(I_{Bias}=10 \mu A\), respectively.

The frequency responses of the parasitic impedance of \(w\) terminal is depicted in Fig. 11. The value of this impedance at low frequencies is 1 kΩ. The most important features of the proposed ZC-CC-CDBA are listed in Table II.

The frequency response of the parasitic impedance of \(w\) terminal is depicted in Fig. 11. The value of this impedance at low frequencies is 1 kΩ. The most important features of the proposed ZC-CC-CDBA are listed in Table II.

**B. Simulation Results of the Current Mode Biquad Filter Based on ZC-CC-CDBA:**

The simulation results of the multi-function current mode biquad filter shown in Fig. 4 are depicted in Fig. 12, 13 and 14. The components of the filter are \(C_1=5\) nF and \(C_2=10\) nF. That yields the pole frequency of 950 Hz, while the calculated pole frequency from (7) is 1 kHz. Thus the deviation is 5.2%. This error comes from the non-ideal parasitic properties of the ZC-CC-CDBA. The frequency responses of the current gains of the filter...
shown in Fig. 4 are presented in Fig. 12 for $R_{load} = 1 \, \Omega$. It is obvious that this filter can provide low pass, band pass and high pass functions simultaneously, without any change in the circuit topology. The band pass gain responses for various values of $I_{B1}$ are depicted in Fig. 13. It can be observed that by adjusting the $R_{B1}$ value via $I_{B1}$, the quality factor can be tuned independent from the pole frequency as it was clarified in (7) and (8). Moreover, Fig. 14 depicts the band pass filter gain responses for ($I_{B1} = I_{B2} = I_{B3} = 0.5 \, \mu A$, $1 \, \mu A$ and $1.5 \, \mu A$), it is noticeable that the pole frequency can be adjusted without affecting the quality factor as it was described in (7) and (8).

Figure 12. Frequency response of the proposed filter.

Figure 13. The response of the band pass filter for different $I_{B1}$ values.

Figure 14. The response of the band pass filter for different values of $I_{B1}$, $I_{B2}$ and $I_{B3}$.

V. CONCLUSIONS

This paper presents a new ULV LP bulk driven based ZC-CC-CDBA capable to operate under single supply voltage of only 0.65 V. Besides, the proposed circuit enjoys circuit simplicity, high linearity, extended output voltage range and tunable parameters. Furthermore, additional copy of the difference current ($I_{C1} - I_{C2}$) is available through $z_c$ terminal. This additional terminal solves the problem of utilizing output current to drive the working impedance directly. Eventually, as an example of application a multi-function current mode filter is presented to prove the functionality of the proposed circuit. Thanks to the tunable parameters of the circuit the quality factor and the pole frequency are adjustable independently.

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