FULL-WAVE RECTIFIER BASED ON DIFFERENTIAL DIFFERENCE CURRENT CONVEYOR FOR LV LP APPLICATIONS

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Abstract: In this paper, two full-wave voltage mode and current mode precision rectifiers based on bulk-driven quasi floating-gate (BD-QFG) differential difference current conveyor (DDCC) are presented. The rectifiers are capable to operate under ultra-low voltage (LV) of ±0.3 V and consume extremely low power (LP) in micro range. Moreover, these rectifiers enjoy circuit simplicity, whereas the voltage mode rectifier designed using only two BD-QFG DDCCs, and the current mode rectifier is constructed from only one BD-QFG DDCC and one SOD523 diode from NXP Semiconductor. Thus their circuits are suitable for IC fabrication. Both rectifiers yield better performance in view of the minimum number of devices, reduced power consumption and acceptable operation frequency. The performance of these rectifiers is investigated through PSPICE simulation program using 0.18 μm CMOS technology from TSMC.

Keywords: Bulk-driven quasi floating-gate, differential difference current conveyor, full-wave rectifier, low-voltage low-power

1. INTRODUCTION

Precision rectifiers are essential building blocks for analog signal processing. As well low power/low frequency rectifiers are needed in bionic implants for the deaf, hearing aids and speech recognition systems [1],[2]. The op-amp-based precision rectifiers exhibit significant distortion during the zero-crossing of transitional portion of circuit operation, due to their finite slew rate [3]. However, the second generation current conveyor has significant high slew rate in comparison with op-amp, and it has been successfully utilized to create precision rectifiers [4]-[6].

The differential difference current conveyor (DDCC) was firstly presented in 1996 [7]. It congregates the advantages of the differential difference amplifier (DDA) and the current conveyor (CCII). The BD-QFG technique has revealed as promising technique for low voltage low power analog circuit design [8]. Utilizing this technique, the limitations of BD and QFG MOSTs are suppressed and their performance is significantly enhanced [8, 9].

In this paper two ultra-LV LP full-wave rectifiers based on BD-QFG DDCC are introduced. The first can rectify the signals in voltage mode, where the input and output terminals possess high and low impedance, respectively, which are advantages for voltage mode operation. The second rectifier rectifies the signals in current mode, where the input and output terminals possess low and high impedance, respectively, which is advantages for current mode operation. Both rectifiers are able to operate with extremely low supply voltage of only ±0.3 V and consume very low-power in the micro range. Thus they are very useful to be used in low frequency portable and wearable electronic equipment where the low-power dissipation is highly desired.

The organization of this paper is as follows: in Section 2 the internal CMOS structure of the BD-QFG DDCC is presented. Besides, the operation principle of both ultra-LV LP BD-QFG DDCC based precision full-wave rectifiers are described; in Section 3 the simulation results are provided; eventually, Section 4 is the conclusion.
2. FULL-WAVE BD-QFG DDCC BASED RECTIFIERS

The schematic symbol of the DDCC is depicted in Fig. 1(a). The MOS internal structure of the ultra-LV LP BD-QFG DDCC is depicted in Fig. 1(b) [10]. The implementation of the BD-QFG MOST enables ultra-LV operation capability. Besides, the differential pair arrangement enables very small supply voltage requirement.

Ultra-LV LP voltage mode full-wave rectifier based on BD-QFG DDCC is shown in Fig. 2. The operation principle using conventional DDCC was firstly presented in [3]. The rectifier is very suitable for IC implementation. The input voltage \( V_{in} \) is connecting to the high impedance terminals \( Y_1 \) and \( Y_2 \) of BD-QFG DDCC1 and BD-QFG DDCC2, respectively. Two X terminals which possess low impedance are connected together to obtain the output voltage \( V_{out} \). The operation of this rectifier can be described as follow:

\[
\begin{align*}
V_{in} > 0; \text{BD-QFGDDCC1(ON)} & \Rightarrow V_{out} = V_Y = V_{in} \\
V_{in} < 0; \text{BD-QFGDDCC2(ON)} & \Rightarrow V_{out} = -V_Y = -V_{in}
\end{align*}
\]

It can be observed that the rectifier offers full-wave rectification of the input voltage signals. The DC offset output voltage can be controlled by tuning the voltage \( V_{of} \).

The proposed ultra-LV LP current mode full-wave rectifier is shown in Fig. 3. This rectifier is constructed from only one BD-QFG DDCC with one Schottky diode (D). It should be noted that extra two output terminals Z copy (ZC+) and negative Z copy (Z-) are required; however, these copies can be easily realized using the current mirror and cross-coupled techniques, respectively.

The operation principle of the proposed rectifier is very simple and it can be expressed as:

\[
\begin{align*}
I_{in} < 0; \text{D(OFF)} & \Rightarrow I_{out} = I_{Z-} = -I_{in} \\
I_{in} > 0; \text{D(ON)} & \Rightarrow I_{out} = (I_{Z+} + I_{ZC+}) - I_{Z-} = I_{Z+} = I_{in}
\end{align*}
\]

Therefore, the proposed rectifier provides full-wave rectification of the input current signal.
3. SIMULATIONS RESULTS

The operation of the BD-QFG DDCC based full-wave rectifiers has been investigated by PSPICE simulation program. The LV LP BD-QFG DDCC circuit was employed in CMOS using the 0.18 µm CMOS process from TSMC. The optimal transistors aspect ratios are as follow: for $M_1$-$M_4$ have $W/L=10/0.3$, $M_{b1}$-$M_{b4}$, and $M_{10}$ have $8/0.3$, $M_5$, and $M_6$ have $50/0.3$, $M_7$, $M_8$, and $M_{13}$ have $4/0.3$, $M_{1c}$, and $M_{10c}$ have $45/2$, $M_{11}$, and $M_{12}$ have $100/0.3$, $M_{11c}$, and $M_{12c}$ have $100/2$, $V_{DD}=V_{SS}=0.3$ V, and $I_{bias}=5$ µA.

Fig. 4 shows the rectified waveforms obtained from the voltage mode rectifier. These simulations are performed with capacitive load of 5 pF. The rectifier was excited by a voltage source with a magnitude of [50, 75, 100, 125 and 150] mV and a frequency of 100 kHz. It is obvious here that the rectifier can rectify a wide range of input voltage amplitudes. The rectified output current waveforms of the current mode rectifier are depicted in Fig. 5. The simulations are carried out using SOD523 diode from NXP Semiconductor. Multiple input current signals have 1 kHz frequency and different amplitudes of 2, 4, 6, and 8 µA were applied to the input of the rectifier. Hence, The wide range precision operation of the rectifier is verified.

**Figure. 4:** Transient analysis of output waveforms of the voltage mode rectifier with 100 kHz and various amplitudes of the input signal.

**Figure. 5:** Transient analysis of output waveforms of the current mode rectifier with 1 kHz and various amplitudes of the input signal.

To measure the quality of the rectification process as a function of the amplitude and the frequency of the input signal two types of characteristics are proposed [11],[12]. The first is $P_{AVR}$ (AVR =Average Value Ratio) which is the ratio of the average value of the rectified output signal $V_{out}$ and the average value of the sinusoidal input signal after its ideal full-wave rectification $V_{ideal}$:

$$P_{AVR} = \frac{1}{T} \int_{0}^{T} V_{out}(t) dt$$

$$= \frac{2}{\pi} V_{m}$$

(3)

where $T$ and $V_{m}$ are the period and amplitude of the sinusoidal input voltage signal. The ideal operation of the rectifier is then characterized by the value $P_{AVR}=1$. With increasing the frequency and decreasing the amplitude of the input signal, the deviation from the ideal operation is indicated by a change, mostly a decrease in $P_{AVR}$ below one.

The second type of characteristic is defined more rigorously as a ratio of two RMS values, the RMS of the difference of the real and ideal output signals, $V_{out}$ and $V_{ideal}$, and the RMS value of the ideal signal:

$$P_{RMSE} = \frac{1}{\sqrt{2}} \frac{1}{T} \int_{0}^{T} [V_{out}(t)-V_{ideal}(t)]^2 dt$$

(4)
The subscript RMSE is an abbreviation of the term “Root Mean Square Error”. For ideal circuit operation, i.e., $V_{out}(t)=V_{ideal}(t)$, the result is $P_{RMSE}=0$, while in the case of total attenuation of the output signal $P_{RMSE}=1$. For extra high distortions, when the mutual energy of signals $V_{out}$ and $V_{ideal}$ can be negative, one can obtain $P_{RMSE}>1$. Fig. 6 shows the $P_{AVR}$ (a) and $P_{RMSE}$ (b) versus frequency in range of 50 kHz up to 500 kHz for three amplitudes of the input voltage [50,100,150] mV of the voltage mode rectifier. It is evident that with increasing frequency and/or decreasing the amplitudes of the input signal the $P_{AVR}$ value decreased below the ideal unity value whereas the $P_{RMSE}$ increased above the zero value.

Figure. 6: AVR (Average Value Ratio) (a) and RMS error (b) versus frequency for three amplitudes of the input voltage [50, 100, 150] mV of the voltage mode rectifier shown in Fig. 2.

Moreover, the $P_{AVR}$ and $P_{RMSE}$ versus frequency for the current mode rectifier are depicted in Fig. 7(a) and (b), respectively. The rectifier has excited with three input signals have different amplitudes [2.5, 5, 7] µA, with frequency range of 2 kHz to 12 kHz. The analysis of these curves reveals that the operation of the rectifier is close to the ideality. Moreover, with increasing frequency and/or decreasing the amplitudes of the input signal the $P_{AVR}$ value decreased below the ideal unity value.

Figure. 7: AVR (Average Value Ratio) (a) and RMS error (b) versus frequency for three amplitudes of the input current [2.5, 5, 7] µA of the current mode rectifier shown in Fig. 3.

4. CONCLUSION

This work presents two ultra-LV LP full-wave precision rectifiers based on BD-QFG DDCC. Where one operates in voltage mode and the other operates in current mode. Thanks to employing BD-QFG DDCC, these rectifiers can operate with extremely low voltage of ±0.3 V and consume low power of 36 and 44 µW, respectively. Moreover, these rectifiers enjoy circuit simplicity with minimum number of devices and high input amplitudes range. The functionality and quality of both rectifiers have been proved by $P_{AVR}$ and $P_{RMSE}$ characteristic. The proposed rectifiers can rec-
tify signals with frequencies from fraction of a hertz to several kilohertz. Hence, these rectifiers are expected to find many applications in biomedical field.

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