NOVEL LOW-VOLTAGE CIRCUIT TECHNIQUES FOR FULLY-DIFFERENTIAL RESET- AND SWITCHED-OPAMPS

Sai-Weng Sin, Seng-Pan U [1], R.P.Martins [2]

Analog and Mixed Signal VLSI Laboratory (http://www.fst.umac.mo/lab/ans_vlsi),
Faculty of Science and Technology, University of Macau, Av. Padre Tomás Pereira S.J., Macao, China
E-mail - terryssw@ieee.org
(1 – Chipidea Microelectronics, Macao, on leave from University of Macau, E-mail - benspu@umac.mo)
(2 - on leave from Instituto Superior Técnico / UTL, E-mail - rmartins@umac.mo)

ABSTRACT

This paper proposes two novel techniques, namely low-voltage Switched-Capacitor Common-Mode Feedback (SC-CMFB) and cross-coupled passive input sampling branch that can be efficiently applied to very low-voltage reset- and switched-opamp architectures. The proposed CMFB circuit utilizes the inherent differential-pair of the opamps as the virtual ground common-mode (CM) voltage detector to avoid the traditional problems of floating switches, while the input sampling branch allows the direct passive interface from the external input signal to the 1st stage switched- and reset-opamp circuit, thus providing a new approach for very low-voltage implementation of fully-differential switched- and reset-opamps as well as saving opamps' power. Simulations with real switches and a fully-differential opamp in 1-V supply voltage are provided to verify the effectiveness of the proposed technique.

1. INTRODUCTION

As the technology advances, digital circuits have gained vast benefits from their constant evolution driven by the increased performances obtained from the downscaled supply voltages and also the reduced parasitic. However, analog circuits do not benefit from such technology trends mainly due to the very limited voltage headroom and also reduced output impedance as the channel length of CMOS transistors diminishes, as well as the problems associated with analog switches [1-3]. The main difficulties in very low-voltage circuit designs include the inability to turn on the floating switches, especially because the supply voltage is smaller than the sum of NMOS and PMOS threshold voltages, i.e. $V_{DD} < V_{thn} + |V_{thp}|$ [3]. Hence, in modern low-voltage designs, two state-of-the-art techniques are available to overcome the problem of turning-on the floating switches and they use either reset-opamps [2,3] or switched-opamps [1,4]. These two techniques do not require the generation of high voltage values on-chip and thus are truly compatible with future low-voltage deep-submicron CMOS processes. But, the design of very low-voltage analog circuits remains still very challenging, because (and especially in reset-opamp circuits) there is no efficient CMFB technique [2,3,5] to allow fully-differential operation (the traditional SC-CMFB circuit from Fig. 1 [6,7] cannot be applied due to floating switch problems), as well as the lack of a power efficient passive sampling interface to external continuous-time signals [1, 8-9] as illustrated next.

In this paper two novel low-voltage techniques are proposed to overcome such problems in reset- and switched-opamp circuits. Firstly, the proposed SC-CMFB technique utilizes the inherent opamps' differential-pair as the virtual ground common-mode voltage detector which can be effectively applied in a low-voltage environment without the problems of the floating switches, thus allowing fully-differential implementation of reset-opamp circuits (also applicable in switched-opamps), such that the traditional two single-ended opamps from Fig. 2 (that represents a reset-opamp S/H) can be replaced by a single fully-differential structure, thus saving half of the opamps' power. Secondly, the cross-coupled passive sampling technique allows direct passive interfaces (instead of traditional active)

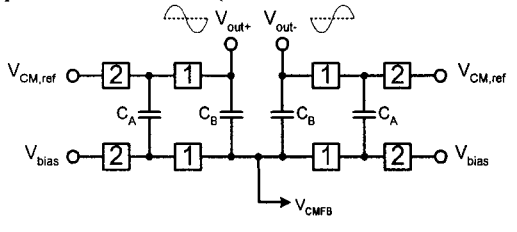

Figure. 1: Traditional SC-CMFB circuit.

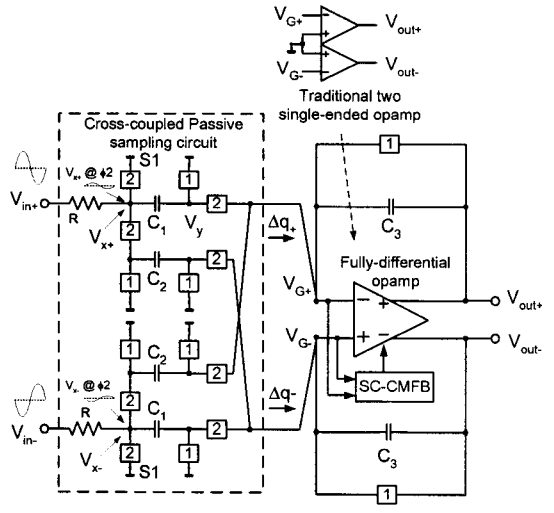

Figure 2: Fully-differential Reset-opamp S/H using the two proposed low-voltage techniques.

between the external world and the 1st stage reset- and switched-opamps (also shown in Fig. 2), further saving one extra-stage's opamp power.

2. NOVEL LOW-VOLTAGE CIRCUIT TECHNIQUES

2.1 Low-Voltage SC-CMFB Technique

The design of fully-differential circuits requires the use of CMFB circuits, which constitute even a higher limitation in low-voltage designs due to the small voltage swing margin available in the presence of a reduced supply voltage. For example, Fig. 1 shows a traditional SC-CMFB circuit [6,7] that is widely used in traditional designs. Obviously, this structure cannot be applied in low-voltage circuits because the two switches connected to the output nodes (V_{out+} & V_{out-}) do not have enough overdrive voltage to turn on at the presence of reasonable output voltage swings. In switched-opamp circuits, the opamps are switched off in one phase and the outputs of the opamp are pulled to a well-defined voltage (typically VDD or GND). As a result, the Common-Mode (CM) voltage in the next phase can be controlled by those well-defined voltages using SC-CMFB circuits in principle similar to traditional designs, thus allowing a fully-differential implementation in switched-opamp circuits [1,4].

However, the same principle is not applicable in reset-opamp architectures since the opamp output CM voltage is not defined in both phases (in one phase the opamp is reset, forcing the differential output to zero, but the CM output is still undefined).

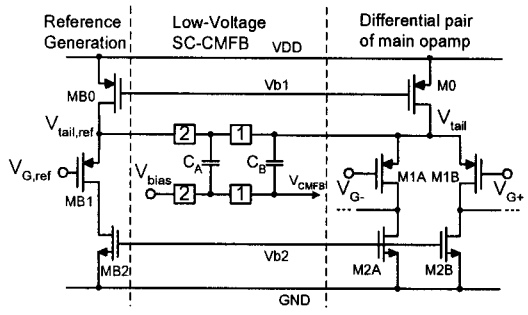

Figure 3. Proposed low-voltage SC-CMFB architecture.

In [5] a CMFB circuit for a pseudo-differential stage (actually two single-ended opamps as shown in Fig. 2) has been proposed, but it still does not allow the usage of fully-differential opamps since it requires a well-defined CM output voltage in the reset phase. Currently no CMFB circuit exists (due to the limited output voltage swing) to allow fully-differential implementation in very low-voltage reset-opamp circuits, thus all the traditional reset-opamp techniques [2,3,5] have utilized pseudo-differential stages as shown in the reset-opamp Sample-and-Hold (S/H) circuit of Fig. 2, which requires twice the number of opamps as well as doubles the power consumption. In addition, single-ended opamps are usually slower than their fully-differential counterparts due to the additional mirror pole created by the differential-to-single-end converter.

Fig. 3 shows the proposed low-voltage SC-CMFB architecture, including the differential pair in the main opamp and the reference generation circuit [10]. And, although the forgoing analysis is performed in reset-opamp architectures, they can be equally applied in switched-opamp circuits. The proposed CMFB relies on controlling the virtual ground common-mode voltage potential, and due to the small signal swing at the virtual ground, the proposed techniques can avoid the floating switch problems that appeared in traditional SC-CMFB circuit. The operating principles of the proposed circuit is as follows: Besides performing the usual transconductance operation, the differential pair of the main opamp can also serve as the virtual ground CM level detector. As the CM-level bias current in M1A and M1B are fixed by the tail current source M0, $V_{GS1A,CM} = V_{GS1B,CM} = V_{GS1,CM}$ do not change and the differential pair reproduces the shifted version of virtual ground CM voltage at $V_{tail} = V_{G,CM} + |V_{GS1,CM}|$ and a half-version of conventional SC-CMFB circuit can be employed as shown in Fig. 3 (where V_{CMFB} is to be applied to the

gate of a pair of current source transistors in the main opamp). The floating switch problem is now solved since no signal swings are presented in the internal nodes of the CMFB. With such arrangement the virtual ground CM level can be stabilized, and with known-value of CM input voltage, as in usual case, the output CM potential can also be stabilized by the external passive feedback network.

2.2 Cross-Coupled Passive Sampling Circuit

The reason why switched-opamp circuits can alleviate the floating switch problems is related with the replacement of such switches by the previous stage opamps that switch-off in one phase, thus turning-off the output from the opamps and simulating the switching function [1]. Similarly in reset-opamp circuits, the previous stage opamps are reset in one phase to discharge the next stage sampling capacitors [2,3]. It becomes evident that both techniques require opamps in the previous stage to simulate the switches, and an extra effort must be devoted to design the front-end input sampling circuits, since there are no such opamps preceding the foremost front-end stages that interface with external input signals (except for bandpass applications, for which a input coupling capacitor can be used to solve this problem).

Although several input interfaces have been proposed [1, 8-9], they can only either provide Track-and-Reset (T/R) output signals as shown in Fig. 4 [8-9] (thus an extra opamp must be used to accurately reproduce the T/R output before the normal switched-capacitor processing), or extra clock phases are required with additional potential problems of direct signal feedthrough [1]. To alleviate such problems, Fig. 2 also shows the proposed low voltage cross-coupled passive sampling circuit in a differential configuration, thus avoiding the use of an active interface [11]. The resistor R provides resistive division with the on-resistance of switches S1 and attenuating the signal swings in node V_{x+},V_{x-} thus allowing the discharge operation of the sampling capacitor C_1 in phase $\phi 2$ without the floating switches' problem. However, with such attenuated signal swings the circuit exhibits direct signal feedthrough interference in this charge transfer phase which can be cancelled by the cross-coupling action if $C_1 = C_2$, as it can be deducted from the following equation:

$$\Delta q_+ - \Delta q_- = -C_1 V_{in}[\phi 1] - \frac{R_{on}}{R + R_{on}}(C_2 - C_1)V_{in}[\phi 2] \quad (1)$$

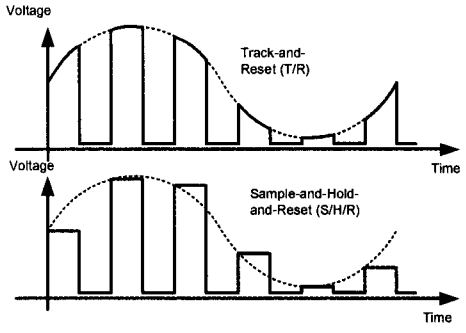

Figure 4: Track-and-Reset (T/R) vs. Sample-and-Hold-and-Reset (S/H/R).

Then, if $C_1 = C_2$, only the desired sampled differential input voltage $V_{in}[\phi 1]$ is transferred into the virtual ground. In addition, the proposed sampling circuit is insensitive to the non-linearity error produced by the modulation of the switches' (S1) on-resistance in phase $\phi 2$, because the even harmonics is in common-mode and they are cancelled by the fully-differential operation, while the odd harmonics are similar to the attenuated signal feedthrough and thus cancelled by the action of the cross-coupled passive sampling branch.

3. SIMULATION RESULTS

In order to verify the effectiveness of the two proposed techniques the SC reset-opamp S/H circuit from Fig. 2 was simulated, with the parameters of 0.35 μm CMOS process with Vthn = 0.56V and Vthp = -0.73V, using Spectre simulator with 1-V supply voltage and real switches. The S/H circuit can be used as the front-end stage of a reset-opamp pipelined ADC, employing the proposed cross-coupled sampling circuit to sample the input signal and also the low-voltage CMFB circuit. A modified version of the opamp presented in [1,2] (fully-differential with PMOS input pair), with the circuit architecture of Fig. 5, was used in the simulation and 1% mismatches were introduced between C_1 and C_2, and also between the switch pair designated by S1.

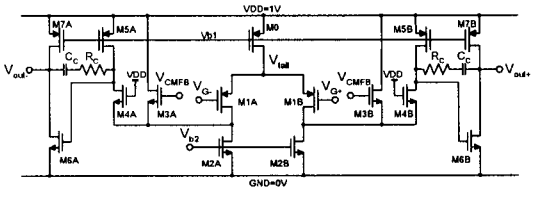

Figure. 5: The low-voltage two-stage fully-differential opamp.

Designing CMFB for two-stage opamps is always more difficult than the case of a single-stage (even in traditional circuits) since the CM level of the two pairs of high-impedance nodes (namely the drains of M4A, M4B, M6A and M6B) must be stabilized. Simultaneously controlling the output CM level in a two-stage opamp requires a feedback point located in the first stage, but V_{CMFB} cannot be directly applied to the gate of any current source transistor due to the opposite polarity. An additional pair of NMOS current sources with the source tied to the folding node of the first stage is added to provide CMFB control on both stages with proper polarity [1]. With such configuration, the nominal value of V_{CMFB} is set to V_{bias} = VDD, thus further simplifying the reference voltage generation used in SC-CMFB circuit (from Fig. 3).

Fig. 6 shows the FFT simulation results obtained through the Spectre simulator. With $1V_{pp}$ differential input signal @ 9.123MHz with 20MHz sampling rate, the S/H utilizing the 2 proposed techniques clearly achieves good performance of -73.4 dB THD, thus proving the efficiency of the proposed techniques.

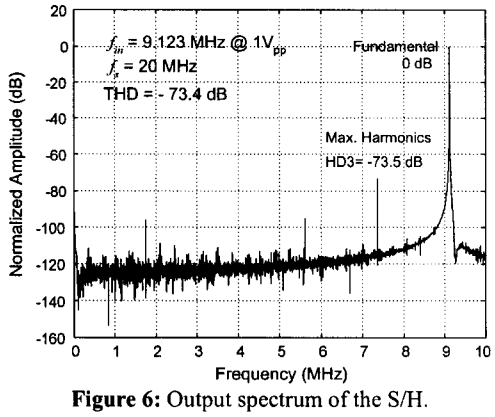

Figure 6: Output spectrum of the S/H.

4. CONCLUSIONS

Two novel low-voltage techniques for fully-differential reset- and switched-opamp circuits have been proposed. The novel SC-CMFB technique saves half of the opamp power by allowing fully-differential implementation of the reset-opamp circuits, while the cross-coupled passive sampling branches serve as a passive solution to the traditional active interface, thus further saving one-stage opamp power. Simulation results show a -73.4 dB THD (>10 bit linearity) for the fully-differential reset-opamp SH circuit, demonstrating the effectiveness of the proposed technique.

5. ACKNOWLEDGEMENT

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