A Novel Very Low-Voltage SC-CMFB Technique for Fully-Differential Reset-Opamp Circuits

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 a novel Switched-Capacitor (SC) Common-Mode Feedback (CMFB) technique that can be efficiently applied to very low-voltage reset-opamp architectures. The proposed CMFB circuit utilizes the inherent differential-pair existing in the opamps as the virtual ground common-mode voltage detector, thus providing a new approach for very low-voltage implementation of fully-differential opamps (instead of traditional two single-ended opamps operating in pseudo-differential mode) using traditional reset-opamps techniques, such that half of the opamps power can be saved. Simulations with real switches and a fully-differential opamp in 1-V supply voltage are provided to verify the effectiveness of the proposed technique.**

I. Introduction

The continuous downscaling of modern integrated circuits technology, as well as the increasing demand for battery-powered systems, imposes a significant stress in the design of analog integrated circuits with reduced supply voltage [1-6]. 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. $V_{DD} < V_{thn} + |V_{thp}|$ [6], and also the hard task of designing low-voltage opamps. Hence, in modern low-voltage designs, two state-of-the-art techniques are available to overcome the problem of turning-on the floating switches, using reset-opamps [4,6] and switched-opamps [2,7]. These two techniques do not require generation of on-chip high values of voltage and thus are truly compatible with future low-voltage deep-submicron CMOS processes.

On the other hand, the design of fully-differential circuits requires the use of CMFB circuits, which constitute even an

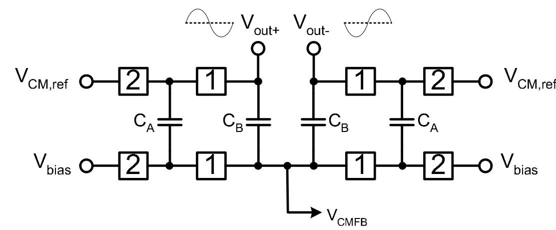

Fig. 1: Traditional SC-CMFB circuit.

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 [8,9] that is widely used in traditional applications. Obviously, this structure cannot be applied in low-voltage circuits because the two switches connected to the output nodes do not have enough overdrive voltage to turn on in 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 [2,7].

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). In [10] a CMFB circuit for a pseudo-differential stage (actually two single-ended opamps) 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

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techniques [4,6,10] 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 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.

In this paper a novel SC-CMFB technique is proposed which allows fully-differential implementation of reset-opamp circuits, such that the two single-ended opamp in Fig. 2 can be replaced by a single fully-differential one. The technique utilizes the inherent input differential pair of the opamps as the virtual ground CM voltage detector, controlling the opamp input CM level instead of the output, as in usual SC-CMFB circuits. By controlling the virtual ground CM level, the switches in CMFB can now be turned-on and architectures similar to the traditional SC-CMFB circuits can be applied.

II. VIRTUAL GROUND COMMON-MODE CONTROL

Before discussing the CMFB techniques, the possibilities of controlling the virtual ground CM level (instead of the one in the output) will be analyzed first. Fig. 2 shows an example of a low-voltage sample-and-hold (S/H) circuit using a reset-opamp implementation. Although the forgoing analysis is presented in a S/H circuit as an example, the principle can be equally applied to other low-voltage SC building blocks such as MDACs and integrators. The SC circuit from Fig. 2 utilizes a floating voltage source composed by switched-capacitor C_2, providing a level-shift function during reset phase $\phi 1$ (with an amount of V_2) such that the opamp output is always biased in the high-gain region to maximize the

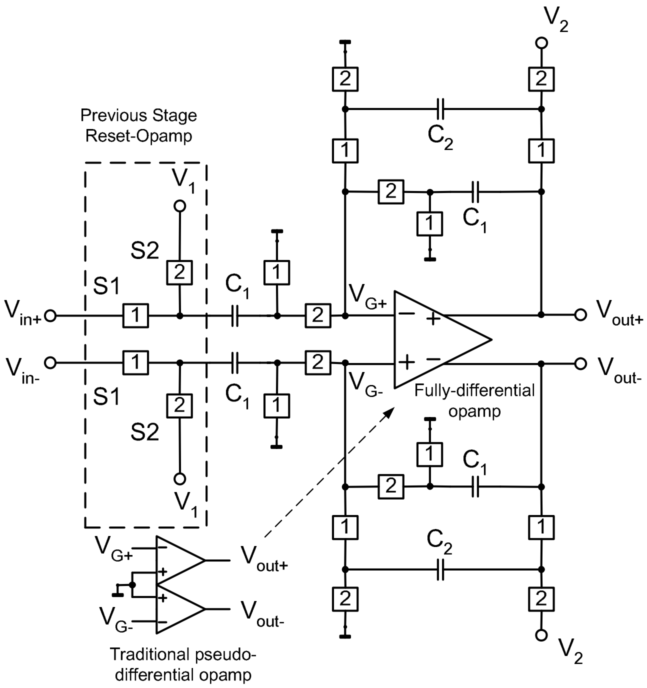

Fig. 2: Low-Voltage SC S/H circuit using fully-differential reset-opamp.

speed when the virtual ground potential is set at GND [4]. The floating switches S1 and switches S2 are used to simulate the previous stage reset-opamp with the reset level equal to V_1 at phase $\phi 2$, thus discharging the sampling capacitor in the forgoing stages [4]. The output of the SC circuit in Fig. 2 resets to a level equal to $V_{G,CM} + V_2$ in phase $\phi 1$, and performs a charge transfer operation to produce the output in phase $\phi 2$, where $V_{XXX,CM} = (V_{XXX+} + V_{XXX-})/2$. Considering only the CM components of all the signals, a simple mathematical relationship between input, virtual ground and output CM level in both phases can be easily derived as follows:

$$V_{out\_\phi 1,CM} = V_{G,CM} + V_2 \quad (1)$$

$$V_{out\_\phi 2,CM} = V_{in,CM} + 3V_{G,CM} + (V_2 - V_1) \quad (2)$$

If both the previous and present reset-opamp stages are similar, then in phase $\phi 2$ the voltage $V_1 = V_{G,CM} + V_2$ and (2) can be immediately simplified to

$$V_{out\_\phi 2,CM} = V_{in,CM} + 2V_{G,CM} \quad (3)$$

Assuming $V_{in,CM}$ has a known voltage value (as in usual cases), Eq. (1) and (3) represent one equation for each phase, with two unknown variables $V_{out,CM}$ and $V_{G,CM}$, i.e. only one constraint derived by the external SC networks for each phase. If a common-mode feedback (implying another constraint equation) is applied such that either $V_{out,CM}$ (the traditional CMFB method) or $V_{G,CM}$ (the proposed one) are defined, then the other unknown variable can also be determined. These simple equations clearly show how the control of the virtual ground CM level can lead to the stabilization of opamps output CM level. Compared with the traditional output CM level control, this proposed method can be implemented easily in low-voltage applications due to two main reasons: (a) the signal swing in the virtual ground is much smaller than the one in the output due to the opamp's differential feedback; (b) the output CM level is usually different in the two phases in low-voltage circuits and thus difficult to control, while the virtual ground is usually fixed in both phases to allow a suitable biasing of the input differential pair. However, stabilizing the output CM by controlling the virtual ground CM level is not as accurate as the traditional direct control method since any inaccuracy in the virtual ground CM voltage will be amplified by $1/\beta$ to the output CM voltage (with β as the feedback factor). In fact, in most applications this is not too relevant since the CM output voltage is not required to be so accurate as the differential mode signal.

III. THE NOVEL LOW-VOLTAGE SC-CMFB CIRCUITS

Fig. 3 shows the proposed low-voltage SC-CMFB architecture, including the differential pair in the main opamp and the reference generation circuit. In addition to perform 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

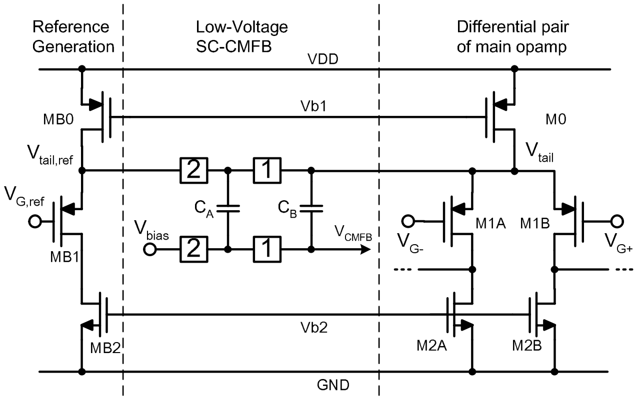

Fig. 3: The proposed low-voltage SC-CMFB architecture.

M0, $V_{GS1A,CM} = V_{GS1B,CM} = V_{GS1,CM}$ does not change and the differential pair reproduces the shifted version of virtual ground CM voltage at $V_{tail} = V_{G,CM} + |V_{GS1,CM}|$. The reference generation circuit simulates the biasing condition of the differential pair, also reproducing $V_{tail,ref} = V_{G,ref} + |V_{GSB1}|$, in which $V_{G,ref}$ represents the desired virtual ground potential. The reference generation circuit can be a scaled-down version of the differential pair, thus consuming negligible power and silicon area. Since both the reference and virtual ground CM levels are now defined, a conventional SC-CMFB circuit can be employed, and only half of the circuit in Fig. 1 is required as the CM level is already reproduced as V_{tail}. V_{CMFB} has a similar meaning as in conventional SC-CMFB, which is to be applied to the gate of one pair of current source transistors in the main opamp, providing adjustment of the output CM level and also through the connection of an external SC network to the virtual ground CM potential. The 4 switches in the SC-CMFB can be easily turned on since no signal swings are presented in any nodes of the SC-CMFB circuit.

IV. SIMULATION RESULTS

In order to verify the effectiveness of the proposed circuit, simulation results using Spectre simulator with 1-V supply voltage, real switches (0.35 μm CMOS process with $V_{thn} = 0.56V$ and $V_{thp} = -0.73V$) and fully-differential opamps are provided for the SC S/H circuits shown in Fig. 2. A modified version of the opamp in [2,4] (fully-differential with PMOS input pair) is used and shown in Fig. 4, and actually this is the most frequently used opamp in reset- and switched-opamp circuit applications. For a normal operation of the PMOS input pair the virtual ground reference CM level $V_{G,ref}$ is set to GND, and V_2 (from Fig. 2) is set to 0.2V thus avoiding the opamp output stage to enter in the triode region.

Designing CMFB for two-stage opamps is always more difficult than in single-stage architectures (even in traditional circuits) due to 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

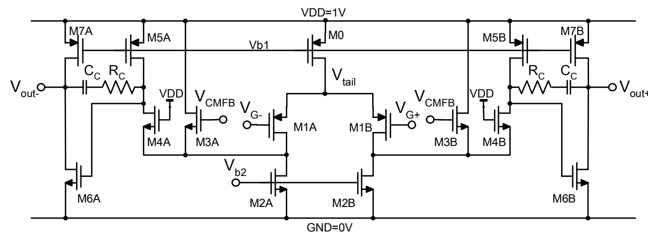

Fig. 4: The low-voltage two-stage fully-differential opamp.

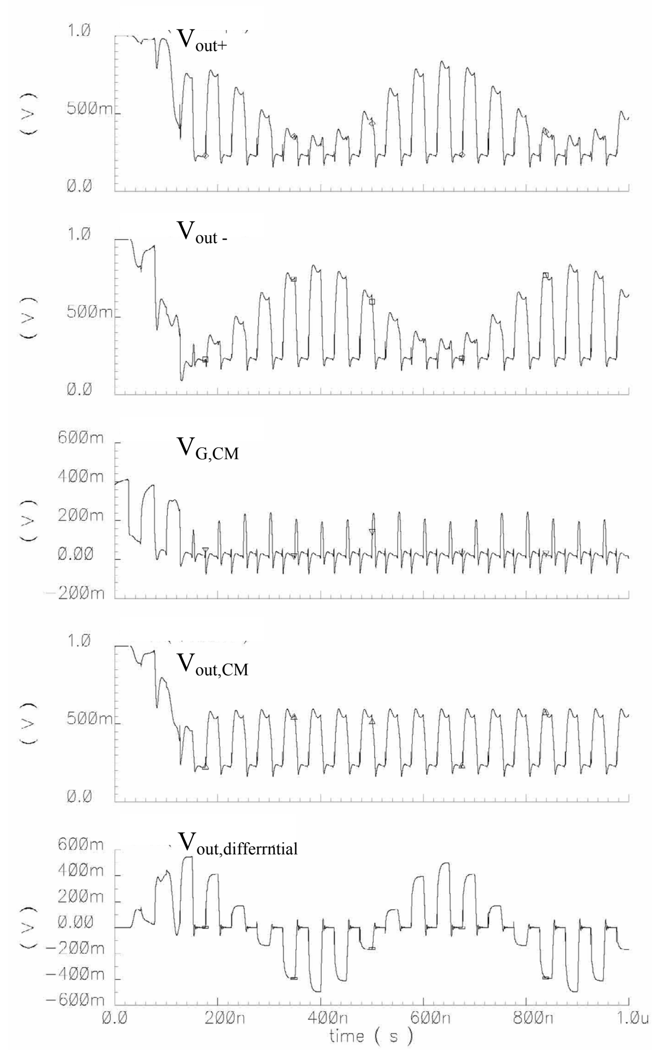

Fig. 5: Simulated transient waveform of the SH circuit (Fig. 1) with the proposed SC-CMFB.

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 wrong 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 [2]. 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).

The input signal (f_{in} = 2 MHz) of the S/H circuits (sampling rate f_s = 20 MHz) has the CM voltage of $V_{in,CM}$ = 0.5V with $1V_{pp}$ differential signal swing. According to (1) and (3), with a normal operation of the proposed CMFB circuit, the output CM voltage in phase $\phi1$ is $V_{out,CM} = 0.2V$ while that in phase $\phi2$ is $V_{out,CM} = 0.5V$. Fig. 5 presents the transient simulation results, where the waveforms clearly show that the S/H circuit correctly reproduces the output differential voltage $V_{out,differential}$, after some initial transients disappeared. Also, it demonstrates that the proposed CMFB circuit works as expected with the output CM level $V_{out,CM}$ eventually settled to 0.237V or 0.55V in phase $\phi1$ or phase $\phi2$ respectively, while the virtual ground CM voltage $V_{G,CM}$ settled at 0V in both phases. Important to notice also is the fact that the common-mode charge injection errors will affect the output CM level accuracy, and the accumulated CM error in certain applications can cause opamp saturation (e.g. 1.5b MDACs in pipelined ADCs which multiply this error by 2 per stage [6]). Similar situations also occur in traditional pseudo-differential reset-opamp circuits but solutions have already been presented [6] to reduce the CM gain to 1 per stage, thus alleviating the CM error accumulation problem.

In addition to the transient simulation an FFT analysis has also been performed on the differential output voltage to evaluate the Total Harmonic Distortion (THD). An input signal of f_{in} = 9.123 MHz (at near-Nyquist rate for f_s = 20 MHz) with 1-V_{pp} differential swing was used in the simulation analysis leading to the results shown in Fig. 6. The output spectrum shows a THD of -76.8 dB, revealing that the proposed CMFB technique can be applied in low-voltage circuits being able to provide better than 10-bit linearity.

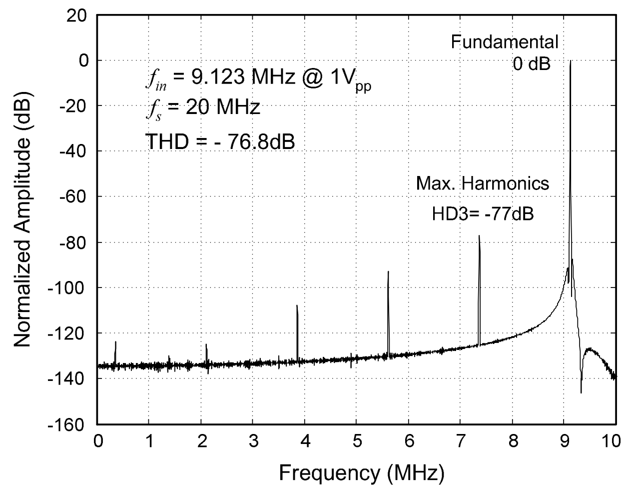

Fig. 6: Output spectrum of the SH circuit with proposed CMFB.

V. CONCLUSION

A novel low-voltage SC-CMFB technique for fully-differential reset-opamp circuits has been proposed. In contrast to controlling the output CM level as in traditional CMFB circuits, the new technique utilizes an inherent common-mode voltage detector that is formed by the differential pair of the main opamp to stabilize the virtual ground CM voltage, and thus controlling the output CM voltage through the external SC-network. As such, it can be employed in reset-opamp circuits without the usual floating switches design difficulties. Also, fully-differential opamps can be used, saving half of the opamps power, when compared with traditional implementations using 2 singled-ended opamps in pseudo-differential mode. Simulation results show a -76.8 dB THD (>10 bit linearity) for the fully-differential reset-opamp SH circuit, demonstrating the effectiveness of such CMFB technique.

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