

II. ULV DB-OTA CIRCUIT DESCRIPTION AND DESIGN

In this section, the operation of a digital-based differential circuit presented in [11] is firstly reviewed and then exploited to design an ULV DB-OTA.

A. Digital-Based Differential Circuit Description

The schematic of the proposed ULV DB-OTA is shown in Fig. 1 (a). The circuit is comprised by the *Differential-Mode (DM) amplifier*, the *Common-Mode (CM) extractor* loop, the *summing network* and the *output stage*, as in [11]. The main goal of this topology is to replace the classical DP stage with digital gates keeping the same functionality, i.e., to amplify the differential input signal $v_d = (V_{in+} - V_{in-})$ and to be insensitive to common mode input signal variations $v_{cm} = \frac{(V_{in+} + V_{in-})}{2}$. To reach these goals, the *DM Amplifier*, which is formed by two digital buffers, is used to sense the level of the input voltages w.r.t. the buffers tripping points (V_T) resulting in four possible logical outputs: $(X_{out+}, X_{out-}) = (0, 0), (1, 1), (1, 0), (0, 1)$.

As detailed in Fig. 1 (b.1), when $(X_{out+}, X_{out-}) = (0, 1), (1, 0)$ the *output stage* is activated and V_{out} is increased/decreased depending on v_d . Otherwise, when $(X_{out+}, X_{out-}) = (0, 0), (1, 1)$, the *CM Extractor* is turned on to correct the input CM signal. The truth tables which describe how the *CM Extractor* and the *output stage* work are shown in Fig. 1 (b.2) and (b.3), respectively.

Once it is sensed that the CM input signal must be corrected, the transistor MN_{cmp} (MP_{cmp}) is turned on and C_{CMP} is properly discharged (charged) and the generated V_{CM} signal is then subtracted from the input through the *summing network* ($V'_{in+(-)} = 0.5(V_{CMP} + V_{in+(-)})$). On the other hand, after the CM signal compensation, the v_d signal can be thus amplified charging or discharging C_{OUT} through the transistors MP_{out} and MN_{out} . A detailed analysis of the circuit dynamic can be found in [11].

B. ULV DB-OTA Design

The proposed ULV DB-OTA has been designed in 180nm following digital design criteria. Under this perspective, CMOS static logic is adopted for most the gates in Fig.1. Moreover, as usual in ULP digital design, the power supply voltage is set to the Minimum Energy Point (MEP) [2], which turns out to be about $V_{DD} = 300mV$ for the target technology and switching activity.

The strength of the *output stage* is set by considering the maximum capacitive load (80pF in the proposed design) and slew rate requirements, taking into account also that a minimum capacitive load (10pF in the proposed design) is needed in the DB-OTA for low-distortion analog signal reconstruction. The strength of the other gates is consequently designed as cascaded drivers. Minimum-size devices have been used in the *CM extractor* stage and the capacitance C_{CMP} has been set in view of the closed-loop stability requirements [11] and to reduce Total Harmonic Distortion (THD).

Two parts of the circuit deserve a special care due to their analog function, i.e. the *summing network* and the first

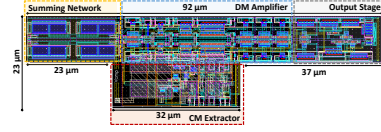


Fig. 2. DB-OTA layout. Total area of $1,426 \mu m^2$.

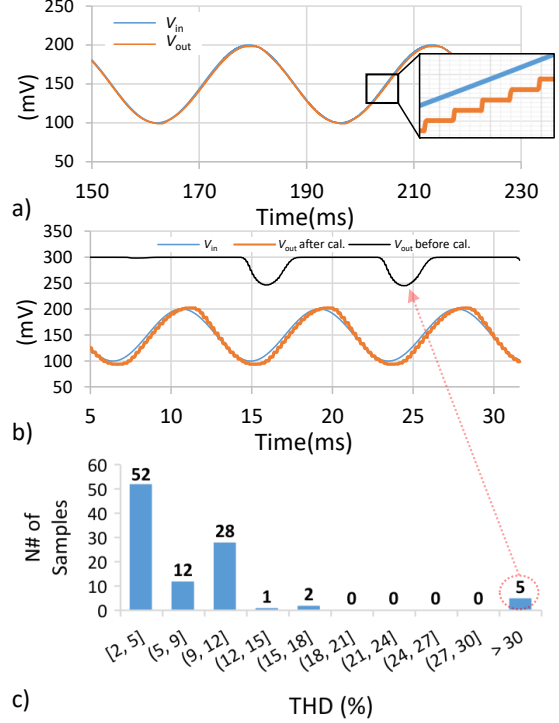


Fig. 3. a) V_{in} and V_{out} for $C_{out} = 80pF$, $V_{amp} = 50mV$ and $f_{in} = 30Hz$. b) V_{in} , V_{out} before calibration (black) and V_{out} after calibration (red) for $C_{out} = 80pF$, $V_{amp} = 50mV$ and $f_{in} = 120Hz$. c) 100 samples MC simulation for DB-OTA THD (%).

inverters of the *DM amplifier*: the *summing network* has been implemented using inverter-based pseudo-resistors as voltage dividers. Large area has been adopted in PMOS devices in Fig. 1 (a.1), to achieve a good matching leveraging Pelgrom's law [12].

For what concerns the *DM amplifier* in Fig. 1 (a.2), mismatch in the buffers V_T decides the DB-OTA input offset voltage and it has been mitigated by the calibration network in Fig. 1 (a.3). Such a calibration network includes four auxiliary pull-up (pull-down) branches, having pMOS (nMOS) devices with minimum length and binary weighted minimum width ($W_k = 2^k W_{min}, k = 0 \dots 3$) and driven by the same input signal, which can be individually enabled/disabled depending on an 8-bit digital calibration word so that to modify the trip point of the buffer and effectively compensate mismatch. It is worth mentioning that this calibration network is also able to work in low V_{DD} .

III. SIMULATIONS RESULTS

The proposed DB-OTA has been laid out in 180nm CMOS so that to match the delays of the non-inverting and inverting

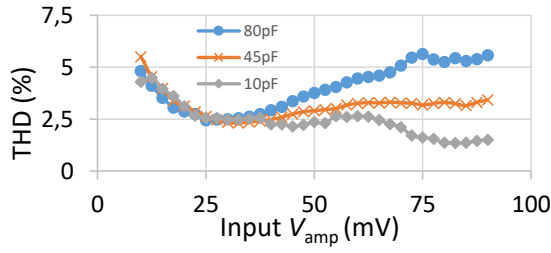


Fig. 4. THD (%) versus V_{amp}

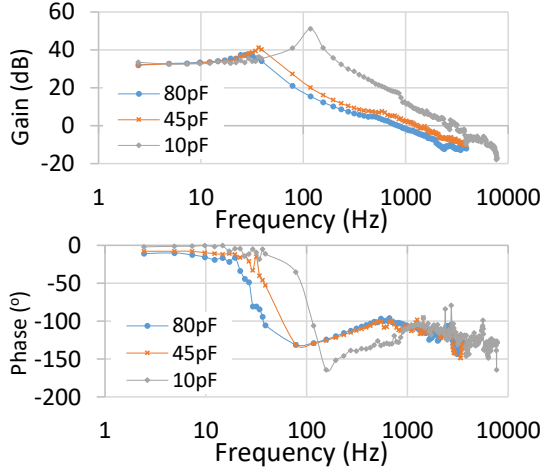


Fig. 5. ULV DB-OTA frequency response.

signal paths. The layout of the circuit, including the calibration network, occupies just $1,426 \mu\text{m}^2$ and it is shown in Fig. 2. The operation and performance of the DB-OTA have been tested by post-layout simulations performed in the voltage follower configuration and is then compared with ULV OTAs presented in recent literature.

A. Post-Layout Simulated Performance

The time-domain input and output waveforms of the proposed DB-OTA at $V_{DD} = 300\text{mV}$, with sine wave input at 30Hz frequency, 50mV peak amplitude and $C_{out} = 80\text{pF}$ capacitive load are reported in Fig.3(a) and reveal the operation of the circuit as an opamp and less than 2% THD and 2nW power consumption. A zoom in the waveform shows the step-wise changes in v_{out} resulting from digital operation. Fig. 4 depicts THD versus V_{amp} for three different $C_{out} = 80, 45, 10\text{pF}$ keeping $f_{in} = 120\text{Hz}$.

1) *Frequency Response*: The frequency response of the circuit has been tested by time-domain, large-signal simulations, since small signal analysis cannot be adopted in view of the digital operation of the circuit. For this purpose, the DB-OTA has been tested in the voltage follower configuration with 50mV-peak-amplitude sine wave input at different frequencies f_0 , and the differential amplification frequency response $A_d(f) = \frac{V_{out}(f)}{V_d(f)}$ has been estimated in magnitude and phase taking the ratio of the Fast Fourier Transform (FFT) at the fundamental frequency f_0 of the output and of the

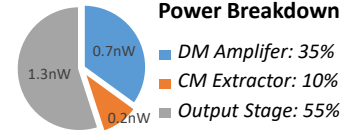


Fig. 6. ULV DB-OTA Power Breakdown

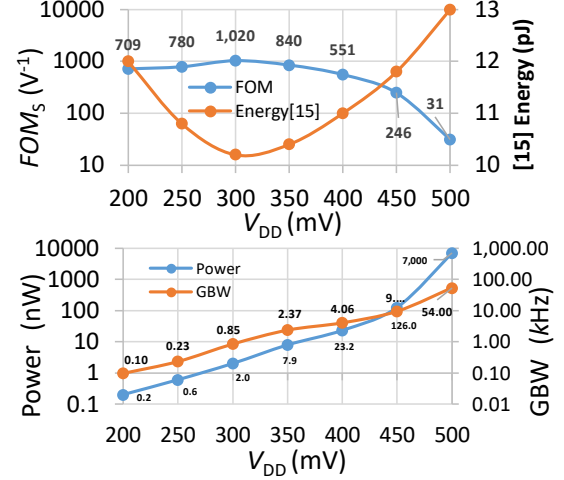


Fig. 7. V_{DD} versus FOM_S , Power and GBW.

differential voltage. The DB-OTA frequency response reported in Fig.5 exhibit 35dB DC gain and 0.85, 1.3 and 2.48kHz Gain Bandwidth Product (GBW) with phase margin $76^\circ, 68.5^\circ$ and 57° under $C_{out} = 80, 45$ and 10pF load, respectively.

2) *Process Variations and Calibration*: The uncalibrated DB-OTA has been tested under process variations for $V_{amp} = 50\text{mV}$, $C_{out} = 80\text{pF}$ and $f_{in} = 120\text{Hz}$ by Montecarlo (MC) simulations performed on 100 samples and the output THD has been considered to evaluate the signal quality degradation. The histogram of the output THD reported in Fig.3(c) reveals a noticeable number of samples exceeding 10% THD due to the spread of the trip voltages of the *DM amplifier* ΔV_T , which leads to high input offset voltage and results in the output saturation, as shown in Fig.3(b). From the same figure, however, the offset can be completely compensated by the proposed calibration network turning the DB-OTA back to work properly.

3) *Power Consumption and Figure of Merit (FOM)*: For all C_{out} values here explored the power consumption was found to be always lower than 2 nW. Fig. 6 shows the DB-OTA power breakdown for $C_{out} = 80\text{pF}$, at which it can be seen that 45% of the total power is used to process the input signal while the rest is used to charge C_{out} . The energy efficiency of the proposed DB-OTA under low V_{DD} has been also analyzed in Fig. 7 where the power, the GBW and the small signal figure of merit $FOM_S = 100 GBW C_{out} (I_{DD})^{-1}$ are plotted at different V_{DD} . It is interesting to note that there is a peak for FOM_S around $V_{DD} = 300\text{mV}$, which coincides with the energy-efficient V_{DD} optimum in digital sub- or near-threshold designs, regarding their most energy efficient V_{DD} , i.e., their Minimum Energy

TABLE I
COMPARISON WITH STATE-OF-THE-ART ULTRA-LOW-VOLTAGE OPERATIONAL TRANSCONDUCTANCE AMPLIFIER

Performance	[10] ⁺	[6] ⁺	[13] ⁺	[14] ⁺	[9] [*]	[5] [*] MC-OTA	[5] [*] FFC-OTA	This work[*]	Unit
Technology	65	130	180	350	65	130	130	180	nm
Supply Voltage	0.35	0.25	0.5	0.6	0.3	0.3	0.3	0.3	V
DC Gain	43	60	52	69	60	46.2	49.8	35	dB
GBW	3600	1.88	1,200	11.4	70	2,450	9,100	0.85	kHz
Slew Rate	5600	0.7	2,890	14.6	25	2,400	3,800	0.5	$\frac{V}{ms}$
THD	0.6	0.2	1	0.08	-	-	-	3	%
Phase Margin	56	52.5	-	65	53	52	76	76	°
C _{out}	3	15	20	15	5	2	2	80	pF
Power	17,000	18	110,000	550	51	1,800	1,800	2	nW
Dia Area	5,000	83,000	26,000	60,000	3,000	-	-	1,426	μm^2
FOM _S	19	29	0.11	0.18	2.05	81	303	1020	V ⁻¹
FOM _L	34.6	14.6	26.27	23.9	73.4	80	140	600	-

⁺experimental; ^{*}simulation;

Point (MEP). To illustrate, in Fig. 7 the notch filter MEP designed in [15] is also plotted. This result is expected since the DB-OTA processes the analog input information digitally.

B. Comparison with the State of the Art

Based on the post-layout simulation, compared to ULV OTAs proposed in recent literature, whose performance is summarized in Tab. I, the ULV DB-OTA presented here is able to drive the highest C_{out} (x4 larger than [13]) at the lowest power consumption (x9 lower than [6]) and shows itself as the most power-efficient topology for CMOS technology considering FOM_S as a benchmark (x3.35 larger than [5] FFC-OTA). The comparison in terms of both FOM_S and FOM_L is also illustrated in Fig. 8 including the performance of the proposed circuit samples after calibration and reveals that state-of-art performance is achieved even considering process variations. Moreover, the results of preliminary transistor-level simulations performed on the circuit ported to 40nm CMOS are also shown in Fig.8, demonstrating a further improved performance in finer technology, as expected for digital circuits and as not observed in traditional analog OTAs.

IV. CONCLUSION

By processing the analog input signal digitally with static logic gates, the ULV DB-OTA presented here has achieved at V_{DD} = 300mV a FOM_S = 1020V⁻¹ consuming only 2 nW and 1,426 μm^2 of silicon area. The DB-OTA maximum energy-efficient point has been demonstrated as well as its scalability. Through this implementation, this work moves forward against the common statement which states that, in general, analog integrated circuits do not take advantage of CMOS technology scaling.

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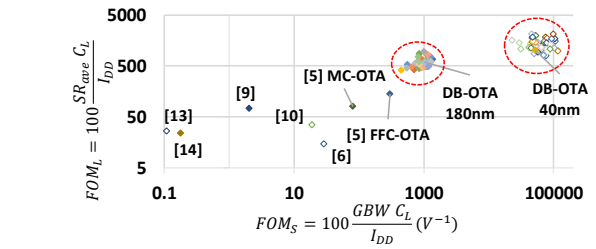


Fig. 8. State-of-art plot for ULV OTA.

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