

Fully-Differential Opamp Design

Elyes Balti, *Member, IEEE*

Abstract—Operational amplifier is considered as the core of the analog building blocks [1]–[16]. High performance opamp must exhibit high gain, wide bandwidth, low power consumption and rail-to-rail output swings [17]–[25]. In this work, we propose to design a fully-differential opamp design to satisfy certain design requirements and specifications.

Index Terms—Cascode, Class-AB, Dual Diff-Pair, CMFB, ICMR

I. DESIGN SPECIFICATIONS

A. Requirements

In this project, the opamp design must satisfy the following specifications given by Table 1.1.

TABLE I: Opamp Design Specifications

Parameter	Specified value
Technology	TSMC 180-nm
Supply voltage, V_{DD}	1.8 V
Common-mode voltage, V_{CM}	0.9 V
Typical load	100 k Ω , 1 pF
Unity gain frequency (f_{un})	≥ 50 MHz
Open-loop gain (A_{OL})	≥ 60 dB
Closed-loop gain (A_{CL})	6 dB
Closed-loop bandwidth ($f_{3dB,CL}$)	≥ 20 MHz
Slew-rate (SR)	$\geq 100 \frac{V}{\mu s}$
Phase margin (ϕ_M)	60 deg
Output swing	$\geq 1.5 \cdot V_{DD}$
Power consumption	Minimum possible

To meet these requirements, the opamp design must include the following specifications:

- Two-stages: the first stage provides a high gain, while the second stage provides a high output swing (rail-to-rail) to drive a high load.
- The first stage does not necessarily provide high swing, but it has to provide high gain with minimum power consumption. The folded cascode amplifier is not suitable for the first stage since its gain is reduced 2 to 3 times compared to the telescopic and also the power consumption is higher, although it provides not only a wider ICMR and output swing, but also an excellent overlap of the ICMR and the output swing. Finally, the best candidate amplifier for the first stage is the cascode since it provides a high gain. The cascode also provides a higher bandwidth compared to the folded cascode since the last one has an additional pole due to the current summation at the node linking the bias source and the upper side of the cascode.

- The second stage is class-AB so that the output has a rail-to-rail swings (from 0 to V_{DD})
- Each stage has to be compensated separately, since this method is very robust compared to the method of using one compensation feedback loop for the two stages.
- Dual Diff-Pair CM Detector can be used in the first stage because it drives only small capacitive load and it does not affect the gain. However, it allows very limited output swings which is not required for the first stage.
- Since the second stage is class-AB, the practical CMFB method is the current injection.

B. Bias circuit

In this project, a current of $20\mu A$ is biasing the first stage. To generate such current value, A BMR circuit is designed and used as a bias circuit to feed the first stage. The process of biasing should take place with a constant transconductance g_m . To generate a current of $20\mu A$ for the process of 180 nm, I should determine first the corresponding size of the MOSFET given that V_{ov} is 90 mV. After the simulation and testing, I come up with the following MOSFET parameters' values so that to generate $20\mu A$.

TABLE II: Short-channel 180nm process MOSFET parameters

Parameter	NMOS	PMOS
V_{ov}	90 mV	90 mV
V_{THN} and V_{THP}	457 mV	463 mV
V_{GS} and V_{SG}	547 mV	553 mV
$V_{DS,sat}$ and $V_{SD,sat}$	60 mV	60 mV
Bias Current I_D	20 μA	20 μA
W/L	28/2	86/2
g_{mn} and g_{mp}	285 $\mu A/V$	260 $\mu A/V$
γ_{on} and γ_{op}	314 K Ω	437 K Ω

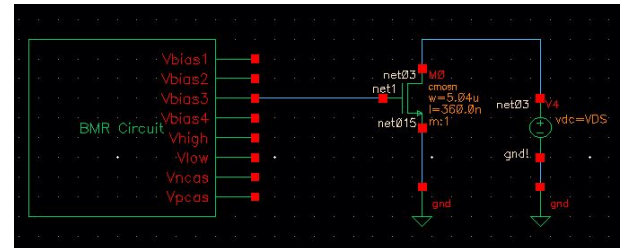


Fig. 1: NMOS testing for $20\mu A$

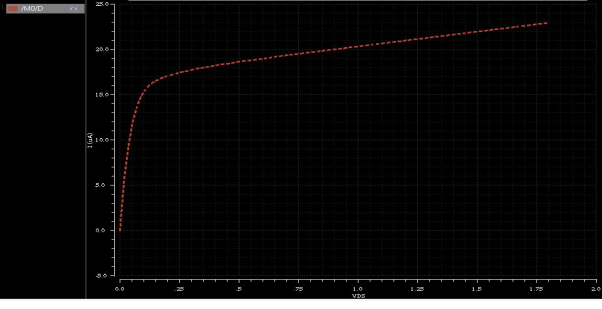


Fig. 2: NMOS bias current $I_D = 20 \mu A$

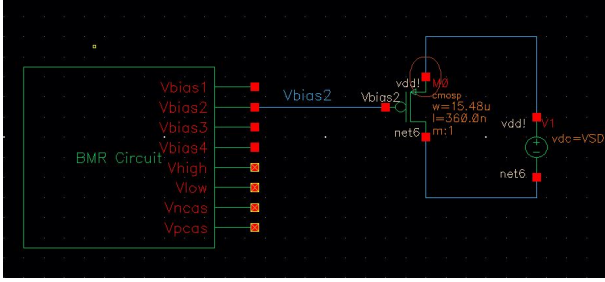


Fig. 3: PMOS testing for $20 \mu A$

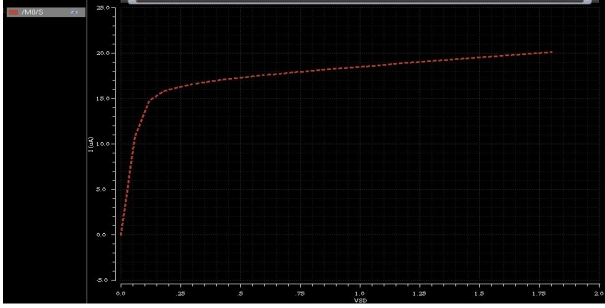


Fig. 4: PMOS bias current $I_D = 20 \mu A$

Each branch of the first stage is fed by $20 \mu A$, to satisfy this condition, the total bias current of the first stage is $40 \mu A$. To achieve this value, the size of the NMOS must be doubled to be $56/2$ and for the PMOS is $172/2$. Note that Vbias 2 and 3 feed PMOS and NMOS, respectively.

II. FIRST STAGE

A. Specifications

In this design, the first stage should provide a sufficient high gain. To satisfy this requirement, I suggest the cascode amplifier given by Fig. 2.1.

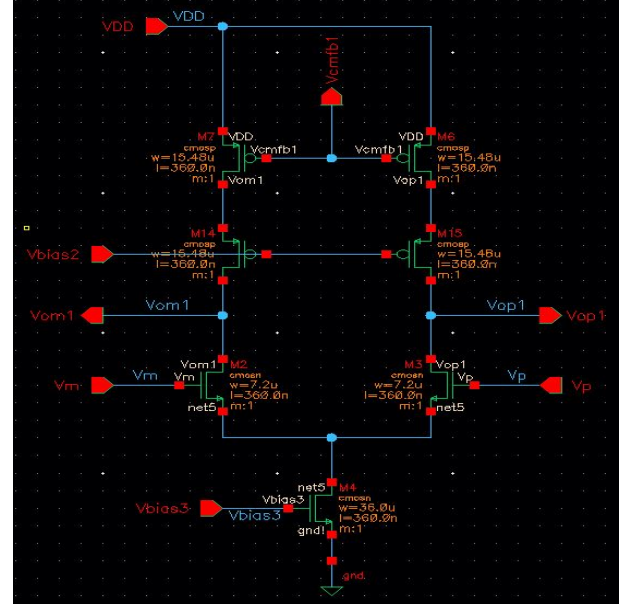


Fig. 5: First stage schematic

III. COMMON MODE FEEDBACK LOOP

The first stage has to be compensated separately to be stable. The appropriate common mode feedback (CMFB) loop is the dual diff-pair (DDP). The topology of the DDP should include the Miller compensation cap $C_{C,CM1}$. The schematic of the DDP CMFB is given by Fig. 2.3.

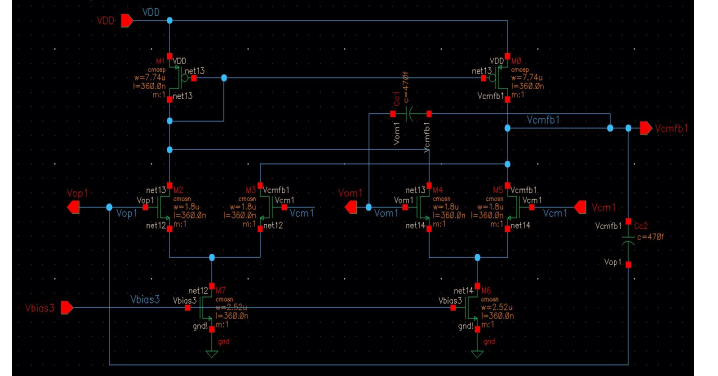


Fig. 6: DDP schematic

IV. SECOND STAGE

A. Specifications

In order to provide sufficient rail to rail output swing, the best candidate is the class-AB stage. I also introduce the Miller cap C_{CDM} to compensate the differential path with the zero nulling R_z to push the RHP zero out to infinity. The schematic is given by Fig. 3.1.

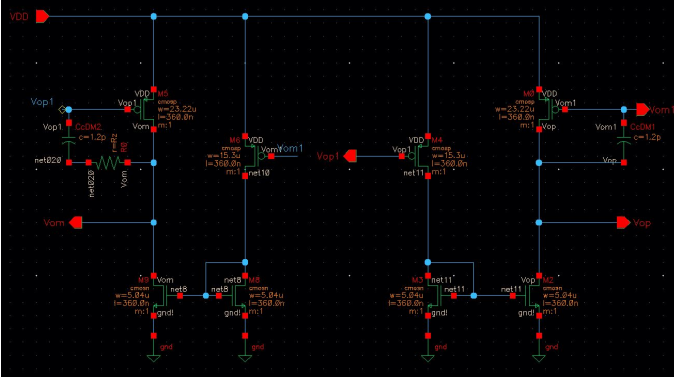


Fig. 7: Second stage schematic

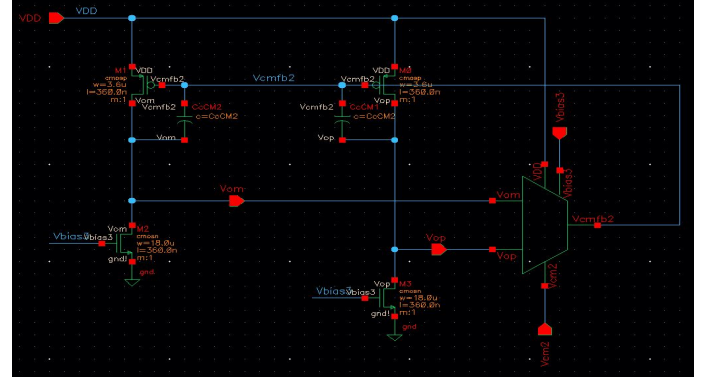


Fig. 9: Current injection schematic

B. Common mode feedback loop

The second stage has to be compensated separately to be stable. The appropriate common mode feedback (CMFB) loop is the current injection. The topology of the current injection should include the Miller compensation cap $C_{c,CM2}$ and also the error amplifier to match the output common mode voltage with the voltage reference ($V_{CM2} = 0.9$ V).

The bias current and widths are scaled down to save power ($I_{c0}=I_0/n$). Also both stages should have the same current density as follows:

$$\frac{I_0/2}{W_{pmos}} = \frac{I_{c0}/2}{W_{cpmos}} \quad (1)$$

For the current injection CM detector, 1/4 of the current branch injects or removes the current into or from the output nodes to control their CM-level. Also 3 by 1 of the DC current split for the bias current of the second stage I_2 used to avoid the potential instability. The schematic of the error amplifier and the symbol are given by Fig. 3.3 and Fig. 3.4, respectively.

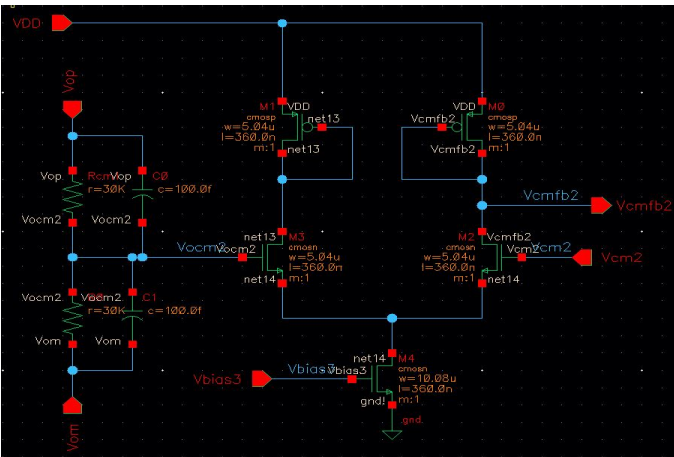


Fig. 8: Error amplifier schematic

The current injection and the relative symbol are given by Fig. 3.5 and Fig. 3.6, respectively.

V. OPEN-LOOP STABILITY PERFORMANCE

The following table presents the design parameters that I come up with to achieve the opamp performance.

TABLE III: Design parameters

Parameter	Value
R_1	100K
R_2	200K
R_{CM}	30K
C_{cCM1}	0.94 pF
C_{cCM2}	0.1 pF
C_{cDM}	1.2 pF

The schematic of the two-stage opamp with **CMDM** probes is given by the following figure.

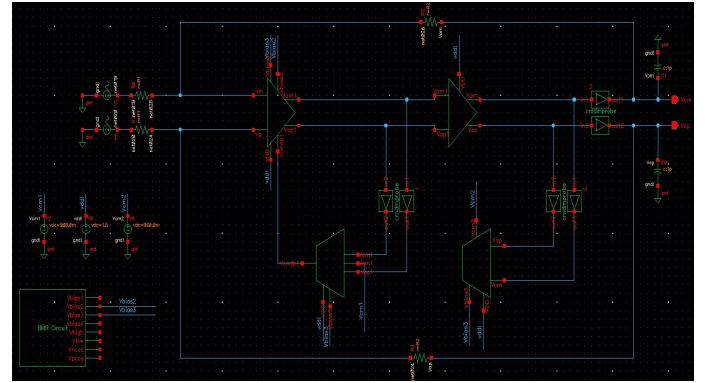


Fig. 10: Two-stage opamp

A. Differential open-loop gain

To measure the differential mode (DM) open-loop gain, I performed an **stb** analysis and I set the **CMDM 3** to -1. The simulation results show an agreement with the requirement detailed in the following table.

TABLE IV: DM open-loop gain results

Parameter	Value
$A_{v,DM}$	64.84 dB
ϕ_M	63.025 deg
f_{un}	59.408 MHz

The Bode plot of the magnitude and phase of the open-loop gain is given by the following figure.

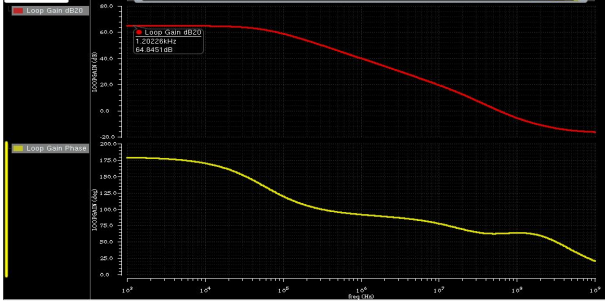


Fig. 11: DM open-loop gain Bode plot

B. First common mode open-loop gain

To evaluate the first CM open-loop gain, I performed an **stb** analysis and I set the **CMDM 1** to 1. The following table summarizes the main results.

TABLE V: First CM open-loop gain results

Parameter	Value
$A_{v,CM1}$	62.57 dB
ϕ_M	60.077 deg
f_{un}	51.055 MHz

The Bode plot of the magnitude and phase of the open-loop gain is given by the following figure.

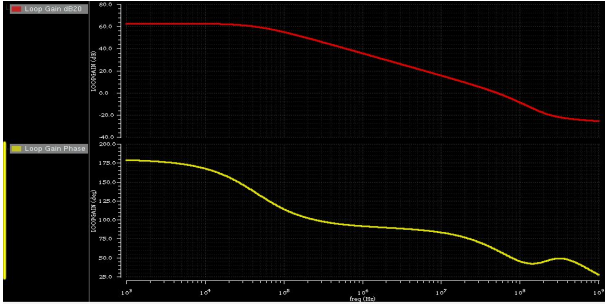


Fig. 12: First CM open-loop gain Bode plot

C. Second common mode open-loop gain

To evaluate the first CM open-loop gain, I performed an **stb** analysis and I set the **CMDM 2** to 1. The following table provides the main results of the open-loop gain of the second CM stage.

TABLE VI: Second CM open-loop gain results

Parameter	Value
$A_{v,CM2}$	25.445 dB
ϕ_M	63.673 deg
f_{un}	65.94 MHz

The Bode plot of the magnitude and phase of the open-loop gain is given by the following figure.

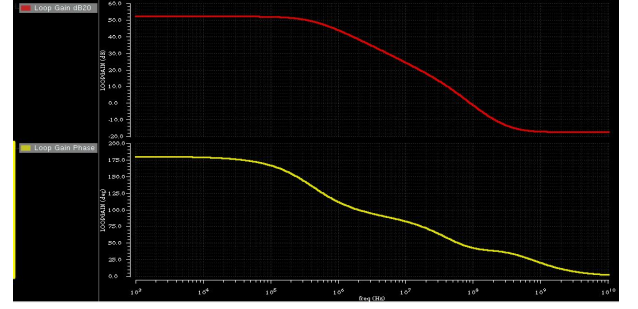


Fig. 13: Second CM open-loop gain Bode plot

VI. CLOSED-LOOP GAIN PERFORMANCE

To evaluate the closed-loop gain, the following steps must be achieved:

- 1) Remove all CMDM probes from the circuit.
- 2) For each loop (DM, CM1 and CM2), an AC voltage of 1V magnitude is introduced to the input.
- 3) Measure the output voltage of each loop.
- 4) Perform an **ac** analysis of each loop.

A. Differential closed-loop gain

The main results are detailed in the following table.

TABLE VII: DM closed-loop gain results

Parameter	Value
$A_{v,DM}$	6.013 dB
f_{3dB}	21.379 MHz

The Bode plot of the magnitude and phase of the closed-loop gain is given by the following figure.

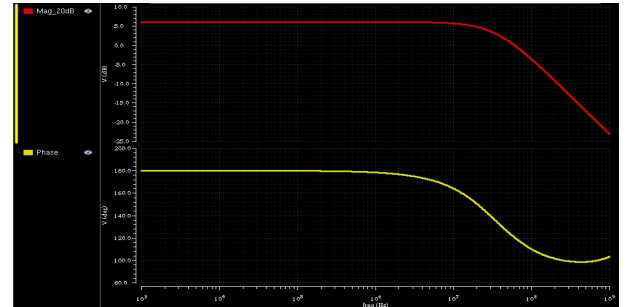


Fig. 14: DM closed-loop gain Bode plot

VII. FIRST COMMON MODE CLOSED-LOOP GAIN

The main results are detailed in the following table.

TABLE VIII: First CM closed-loop gain results

Parameter	Value
$A_{v,CM1}$	149.646 mdB
f_{3dB}	20.893 MHz

The Bode plot of the magnitude and phase of the closed-loop gain is given by the following figure.

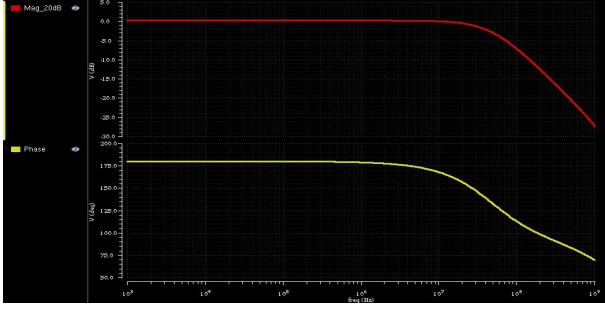


Fig. 15: First CM closed-loop gain Bode plot

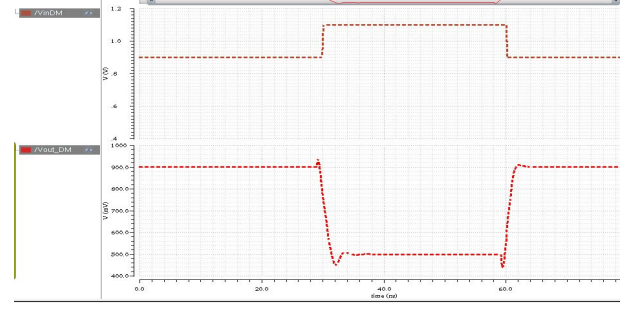


Fig. 17: DM transient response for input step = 200 mV

VIII. SECOND COMMON MODE CLOSED-LOOP GAIN

The main results are detailed in the following table.

TABLE IX: Second CM closed-loop gain results

Parameter	Value
$A_{v,CM2}$	213.508 mdB
f_{3dB}	22.9087 MHz

The Bode plot of the magnitude and phase of the closed-loop gain is given by the following figure.

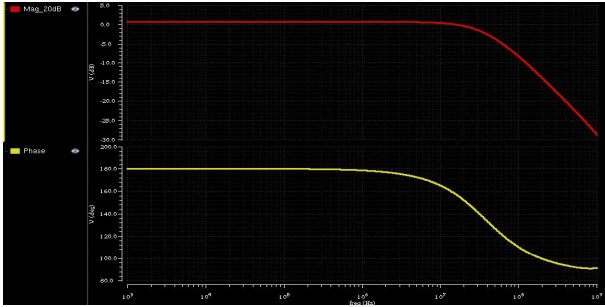


Fig. 16: Second CM closed-loop gain Bode plot

X. COMMON MODE STEP RESPONSE

The following table provides the parameters of the CM step input.

TABLE XI: CM step input parameter

Parameter	Value
Amplitude	100 mV
rise	0.1 ns
fall	0.1 ns

The following figure shows the variations of the common mode input and output voltages.

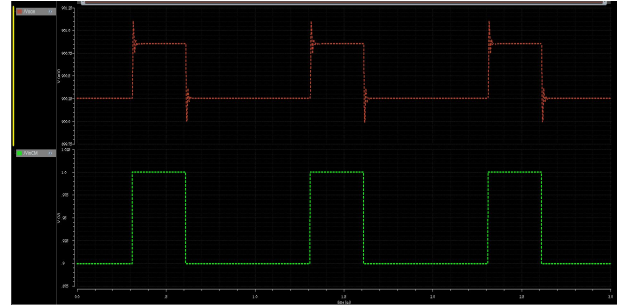


Fig. 18: CM transient response

IX. TRANSIENT RESPONSES

A. Differential step response

To evaluate the differential step response, I introduce a differential step of the following characteristics:

TABLE X: Differential step input parameter

Parameter	Value
Amplitude	200 mV
rise	0.1 ns
fall	0.1 ns

The following figure shows the variations of the differential input and output voltages.

A. Small and large step inputs

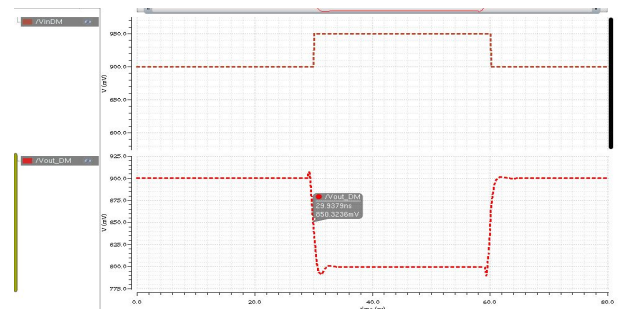


Fig. 19: Small input step = 50 mV

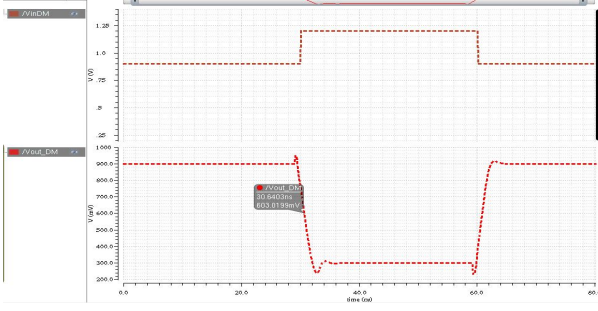


Fig. 20: Large input step = 300 mV

As the differential input step voltages increases, the slew-rate appears and varies. From the figures, as the differential step increases, I noted that the low-to-high settling times decrease while the high-to-low settling times increase. The table below summarizes the values of settling times (high-to-low and low-to-high) with respect to the differential input step voltage.

TABLE XII: DM input step voltage vs Settling times

DM input step	Settling times
50 mV	29.933 ns
300 mV	30.64 ns

XI. METRICS CHARACTERIZATION

A. Slew rates

The following table summarizes the dependence of the slew-rates on the differential step input voltages

TABLE XIII: Slew-rates vs DM input step voltage

DM input step	$SR^+ V/\mu s$	$SR^- V/\mu s$
50 mV	137.93	108.69
300 mV	301.51	265.01

B. CMRR

For fully-differential opamp, the CMRR metric is not defined. Thereby, CMRR is infinity. However, the CMRR makes sense for the case of single-ended differential opamp.

C. PSRR

For fully-differential opamp, the PSRR metric is not defined. Thereby, PSRR is infinity. However, the PSRR makes sense for the case of single-ended differential opamp.

XII. PVT CHARACTERIZATION

A. Temperature variations

I run a temperature sweeping to control the transient response of the differential output voltage. The following figure illustrate the thermal impact.

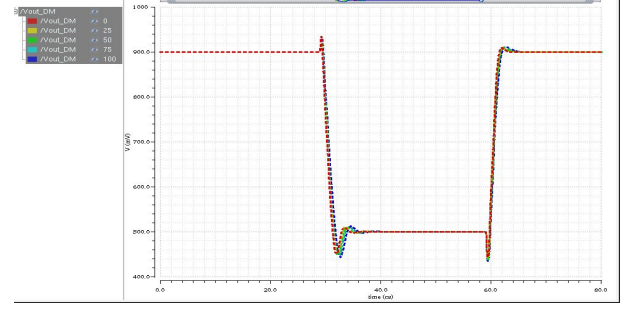


Fig. 21: Temperature variations vs transient DM output voltage

I observe that the temperature variations affect the transient response of differential output voltage. In fact, this impact is negligible for positive slew-rate while charging the capacitors. Nevertheless, as the temperature increases, the charging is longer, while the capacitor gets charged faster for lower temperature value. However, the thermal impact becomes pronounced for negative slew-rate (capacitors discharging). For higher values of temperature, the capacitors take so long for discharging, whereas, the discharging is faster for lower values of temperature.

XIII. SUPPLY VOLTAGE VARIATIONS

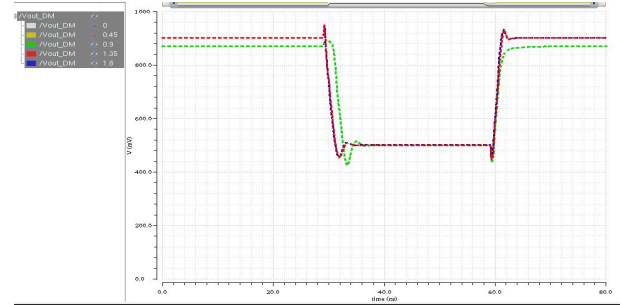


Fig. 22: Supply voltage variations vs transient DM output voltage

The figure above illustrates the dependence of the transient response against the supply voltage variations. For the case of no supply voltage ($V_{DD} = 0$ V), the MOSFETS are in cut-off region and the total opamp is in OFF-state, and the response is flat. For a supply voltage of 0.45 V, the response is very low, since the gain is deteriorated because many MOSFETs are still in cut-off or operating in triode region. As the supply voltage becomes higher than 900 mV, the two-stage opamp exhibits various response. The capacitors are charging and discharging faster for higher supply voltages. For lower supply voltages, the capacitors are slowly charging but they are discharging at a rate similar to the case of high supply voltages.

XIV. CONCLUSION

In this project, the design of the two-stage fully-differential opamp is achieved. The stability analysis of the open-loop gain for the two-stage common modes and the differential mode are studied. Based on the design parameters, the open-loops (CM1, 2 and DM) are stable and achieve a phase

margin greater than 60 deg. Also the first common and the differential modes loop-gain achieve sufficient gains greater than 60 dB. In addition, the differential closed-loop achieves a gain of 6 dB and cut-off frequencies higher than 20 MHz, while the CMFB closed-loop achieves gains closer to zeros which confirm the system stability against the common mode disturbance. Furthermore, the design shows slew-rates for various differential input steps higher than 100 V/ μ s. Based on those results, the proposed design met the requirements for an opamp of high performance. Furthermore, a framework analysis of the transient responses (common and differential modes) are provided and the opamp design is characterized based on various input steps, slew-rates and PVT variations.

REFERENCES

- [1] E. Balti and M. Guizani, "Mixed rf/fso cooperative relaying systems with co-channel interference," *IEEE Transactions on Communications*, vol. 66, no. 9, pp. 4014–4027, 2018.
- [2] E. Balti and B. K. Johnson, "Tractable approach to mmwaves cellular analysis with fso backhauling under feedback delay and hardware limitations," *IEEE Transactions on Wireless Communications*, vol. 19, no. 1, pp. 410–422, 2020.
- [3] E. Balti, M. Guizani, B. Hamdaoui, and B. Khalfi, "Mixed rf/fso relaying systems with hardware impairments," in *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, 2017, pp. 1–6.
- [4] E. Balti, "Analysis of hybrid free space optics and radio frequency cooperative relaying systems," Master's thesis, 2018.
- [5] E. Balti, M. Guizani, B. Hamdaoui, and B. Khalfi, "Aggregate hardware impairments over mixed rf/fso relaying systems with outdated csi," *IEEE Transactions on Communications*, vol. 66, no. 3, pp. 1110–1123, 2018.
- [6] E. Balti and B. K. Johnson, "On the joint effects of hpa nonlinearities and iq imbalance on mixed rf/fso cooperative systems," 2020.
- [7] E. Balti, M. Guizani, and B. Hamdaoui, "Hybrid rayleigh and double-weibull over impaired rf/fso system with outdated csi," in *2017 IEEE International Conference on Communications (ICC)*, 2017, pp. 1–6.
- [8] E. Balti and B. K. Johnson, "Stochastic geometry analysis of uplink cellular networks with fso backhauling: Cooperative relaying vs. reflecting surfaces," 2020.
- [9] E. Balti, "Adaptive gradient search beamforming for full-duplex mmwave MIMO systems," 2020.
- [10] E. Balti, N. Mensi, and D. B. Rawat, "Temporal csi correlation in mixed rf/fso cooperative relaying systems under joint effects of hpa nonlinearities and iq imbalance," 2021.
- [11] E. Balti and B. L. Evans, "Adaptive self-interference cancellation for full-duplex wireless communication systems," 2021.
- [12] N. Mensi, D. B. Rawat, and E. Balti, "Securing v2i communications in 5g and beyond wireless system using gradient ascent approach," 2021.
- [13] Y. Maalej and E. Balti, "Cuda-accelerated application scheduling in vehicular clouds under advanced multichannel operations in wave," 2020.
- [14] N. Mensi, D. B. Rawat, and E. Balti, "Pls for v2i communications using friendly jammer and double kappa-mu shadowed fading," 2020.
- [15] Y. Maalej, A. Abderrahim, M. Guizani, B. Hamdaoui, and E. Balti, "Advanced activity-aware multi-channel operations in vanets for vehicular clouds," in *2016 IEEE Global Communications Conference (GLOBECOM)*, 2016, pp. 1–6.
- [16] N. Mensi, D. B. Rawat, and E. Balti, "Physical layer security for v2i communications: Reflecting surfaces vs. relaying," 2020.
- [17] E. Balti, "Hybrid precoding for mmwave v2x doubly-selective multiuser mimo systems," 2021.
- [18] E. Balti, M. Guizani, B. Hamdaoui, and Y. Maalej, "Partial relay selection for hybrid rf/fso systems with hardware impairments," in *2016 IEEE Global Communications Conference (GLOBECOM)*, 2016, pp. 1–6.
- [19] E. Balti and B. K. Johnson, "Asymmetric rf/fso relaying with hpa nonlinearities and feedback delay constraints," 2019.
- [20] E. Balti and N. Mensi, "Zero-forcing max-power beamforming for hybrid mmwave full-duplex mimo systems," in *Proc. Int. Conf. on Adv. Systems and Emergent Tech.*, 2020, pp. 344–349.
- [21] E. Balti and B. K. Johnson, "Sub-6 ghz microstrip antenna: Design and radiation modeling," 2019.
- [22] E. Balti and M. Guizani, "Impact of non-linear high-power amplifiers on cooperative relaying systems," *IEEE Transactions on Communications*, vol. 65, no. 10, pp. 4163–4175, 2017.
- [23] E. Balti and B. K. Johnson, "Mmwaves cellular v2x for cooperative diversity relay fast fading channels," 2020.
- [24] N. Mensi, D. B. Rawat, and E. Balti, "Gradient ascent algorithm for enhancing secrecy rate in wireless communications for smart grid," *IEEE Transactions on Green Communications and Networking*, pp. 1–1, 2021.
- [25] E. Balti and B. K. Johnson, "Rate and power adaptation for multihop regenerative relaying systems," 2021.