

Fundamentals of Analog & Mixed Signal VLSI Design

Exercise 10 (27.11.2024)

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Problem 1 Fully Differential Simple OTA

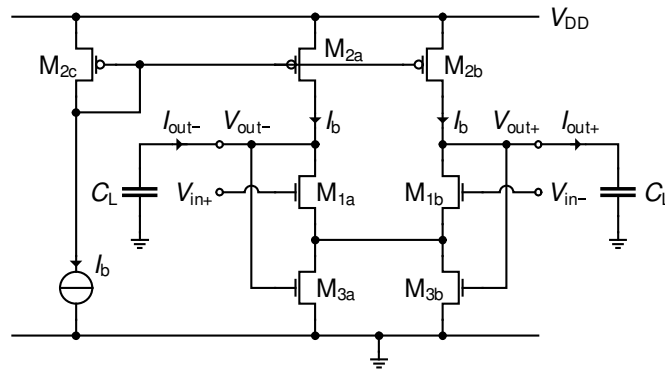


Figure 1: Schematic of the fully differential simple OTA.

In many mixed-signal circuits, the amplifiers are fully differential amplifiers. This means that not only the input is differential but they also have a differential output. There are many advantages of using fully-differential amplifiers, including:

- Reject any common-mode disturbances,
- Provide larger output swing,
- Avoid poles from current mirrors, thus achieving higher closed-loop speed.

However, the DC output common-mode voltage is not defined and needs to be stabilized and set at a common-mode voltage, which requires additional common-mode feedback (CMFB) circuits and hence additional power consumption. Therefore, the extra power consumption needed for the CMFB is an important specifications.

Additionally, the bandwidth of the closed-loop CMFB circuit needs to be sufficiently large to avoid both output to saturate for a long-time making the amplifier out of order for the differential signal. This means that the open-loop gain-bandwidth product of the CMFB circuit GBW_{cm} needs to be at least as high as the gain-bandwidth product in differential mode GBW_{dm} , i.e. $GBW_{dm} \leq GBW_{cm}$. Indeed, if the common-mode gain-bandwidth product GBW_{cm} is much smaller than GBW_{dm} , a fast and large common-mode signal at the amplifier input could saturate the amplifier outputs. Since the CMFB is slow, it takes time to recover, making the amplifier useless during this time. Requiring the GBW_{cm} to be as large as the GBW_{dm} will require a lot of power. Of course it depends on how the CMFB is implemented but usually fully-differential amplifiers consume about the double than their equivalent single-ended amplifiers.

Another limitation of the CMFB is matching. If there is mismatch in the CMFB circuit, the common-mode input signal generates a differential output voltage which translates into distortion. This feature is assessed by the common-mode rejection ratio $CMRR$ defined as the ratio of the differential voltage gain to the differential-to-common-mode voltage gain. Ideally, if there is no mismatch, the differential-to-common-mode voltage gain is zero resulting in an infinite $CMRR$.

Fig. 1 presents the schematic of a fully-differential simple OTA which does not need any additional current for the CMFB. Transistors M_{3a} and M_{3b} are connected to the positive and negative outputs to establish the output common-mode voltage. The output common-mode voltage is extracted from M_{3a} and M_{3b} which operate in the linear region. They change the voltage at the common-source node and therefore also at the output through the action of M_{1a} and M_{1b} .

- What is approximately the level of the common-mode output voltage $V_{oc} \triangleq (V_{out+} + V_{out-})/2$?
- Derive the differential-mode transconductance G_{md} and the differential gain-bandwidth product GBW_{dm} assuming the transistors in the left branch are perfectly matched to those in the right branch.
- Calculate the common-mode transconductance G_{mc} in open-loop. To do this you need to disconnect the gates of M_{3a} and M_{3b} from the outputs. The open-loop common-mode transconductance is then obtained by applying a common-mode voltage at the gates of M_{3a} and M_{3b} and measuring the common-mode output current.
- How do they compare?
- Calculate the small-signal differential DC voltage gain $A_{vd} \triangleq \Delta V_{od} / \Delta V_{id}$ where $V_{id} \triangleq V_{in+} - V_{in-}$ and $V_{od} \triangleq V_{out+} - V_{out-}$ are the input and output differential voltages assuming the transistors in the left branch are perfectly matched to those in the right branch.
- Calculate the small-signal common-mode DC voltage gain $A_{vc} \triangleq \Delta V_{oc} / \Delta V_{ic}$ where $V_{ic} \triangleq (V_{in+} + V_{in-})/2$ and $V_{oc} \triangleq (V_{out+} + V_{out-})/2$ are the input and output common-mode voltages assuming the transistors in the left branch are perfectly matched to those in the right branch.
- Calculate the common-mode to differential-mode voltage gain $A_{cd} \triangleq \Delta V_{od} / \Delta V_{ic}$ assuming there is a G_m -mismatch between M_{1a} and M_{1b} .
- Calculate the corresponding $CMRR$.
- Propose a way to improve the CMFB offering a better control on the output common-mode voltage without increasing the current consumption.

Problem 2 Fully Differential Folded Cascode OTA

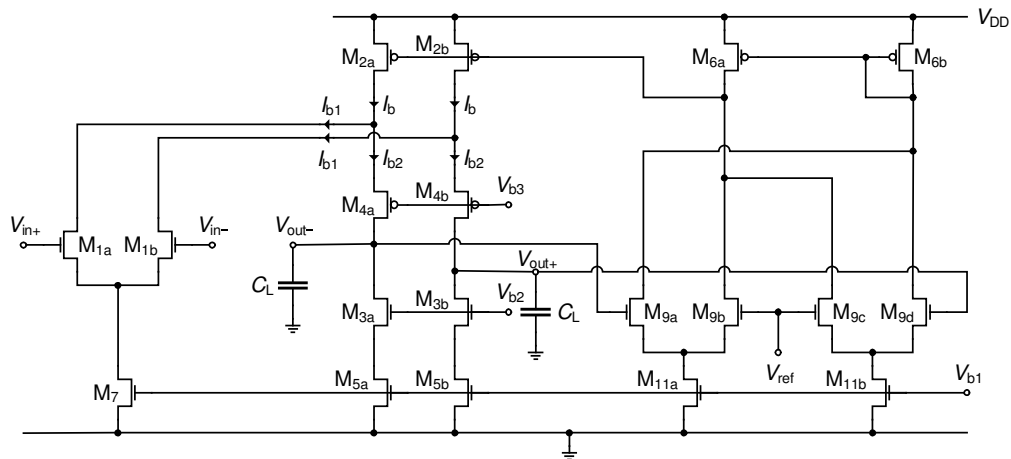


Figure 2: Schematic of the fully differential folded cascode OTA including the CMFB circuit.

Fig. 2 presents a fully differential folded-cascode OTA. The common-mode voltage is extracted by differential pairs M_{9a} - M_{9b} and M_{9c} - M_{9d} and compared to the common-mode reference voltage V_{ref} . If the output common-mode voltage is different from V_{ref} , it is then adjusted by means of the current sources M_{2a} - M_{2b} to bring it back to V_{ref} . To analyze the CMFB, we will derive the open-loop gain (actually transconductance) by opening the loop at the input of the CMFB circuit (i.e. disconnecting the gates of M_{9a} and M_{9d}).

- What is the level of the common-mode output voltage $V_{oc} \triangleq (V_{out+} + V_{out-})/2$?
- Derive the differential-mode transconductance G_{md} and the differential gain-bandwidth product GBW_{dm} assuming the transistors in the left and right branches are perfectly matched.
- Calculate the DC open-loop common-mode transconductance $G_{mc} \triangleq \Delta I_{out} / \Delta V_{in}$ and gain bandwidth product GBW_{cm} assuming again that the transistors in the left and right branches are perfectly matched.
- How do they compare?
- What is the total current consumption for $GBW_{cm} > GBW_{dm}$? How much is the current penalty compared to the single-ended case?