Current Mode Analog Circuit Design

Current Operational Amplifiers

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Operational Amplifier Concept

- Amplifiers with high open loop gain are named as operational amplifiers.
- Operational amplifiers are the most common, useful and flexible building blocks for analog signal processing applications.
- By using the op-amps in closed-loop configurations with negative feedback, transfer functions can be implemented easily.
- Although voltage mode operational amplifiers are the most popular building blocks, current mode operation is becoming more popular especially in recent years.

Operational Amplifier Concept

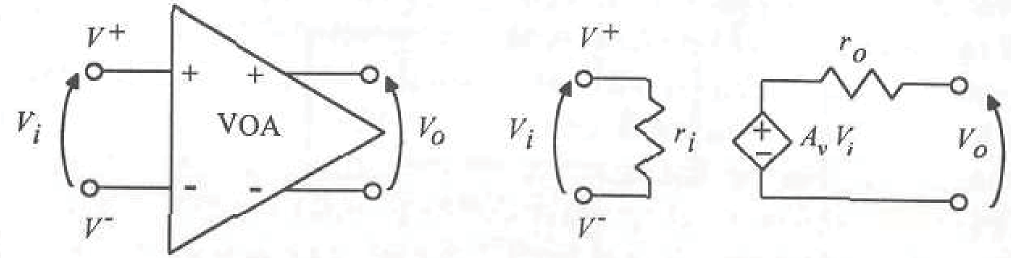
There are four different types of op-amps:

1. **Voltage op-amp (VOA):** voltage controlled voltage source with infinite voltage gain and input resistance, zero output resistance.
2. **Current op-amp (COA):** current controlled current source with infinite gain and output resistance, zero input resistance.
3. **Transresistance op-amp (TROA):** a current controlled voltage source with infinite transresistance gain and zero input and output resistances.
4. **Transconductance op-amp (TCOA):** voltage controlled current source with infinite transconductance gain, input and output resistances.

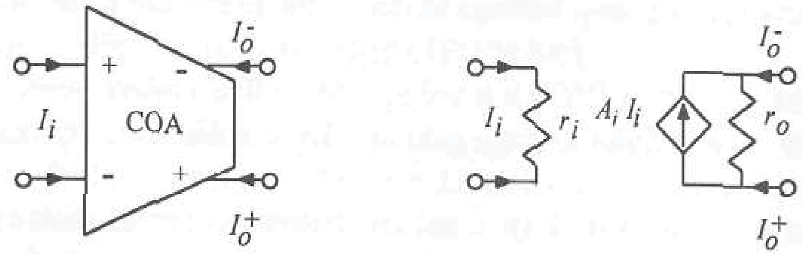
- The most commonly used operational amplifier is the voltage op-amp. This is mostly because of the tradition of using voltage mode operations. Voltage operational amplifier is the most commonly found operational amplifier.
- In recent years the current mode approach has attracted big attention. By using the current-mode approach, speed is maximized because the capacitors are driven by currents rather than by voltages. Another advantage of current mode approach is the low-voltage operation capability. The signal range depends on the impedance level chosen by the designer and is no longer restricted by the supply voltage.

Operational Amplifier Concept

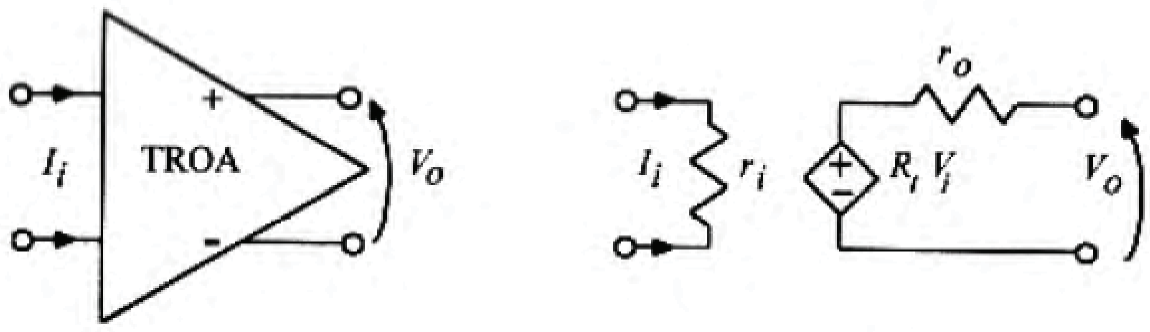
Circuit symbol of the voltage operational amplifier (VOA) and equivalent circuit



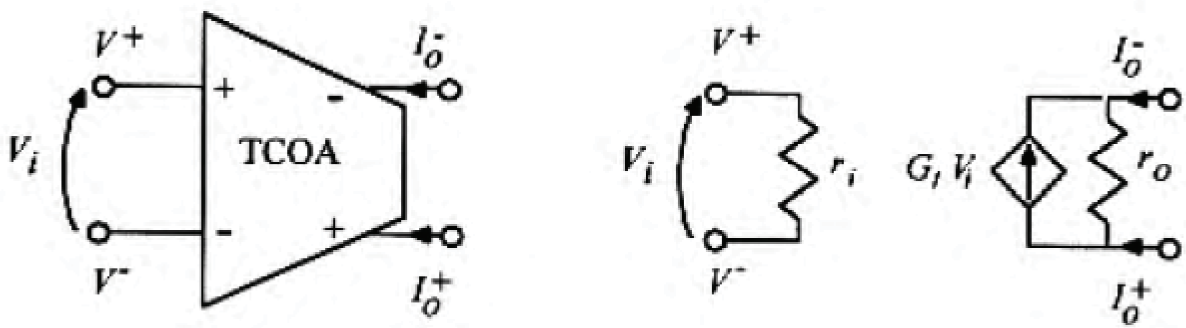
Circuit symbol of the current operational amplifier (COA) equivalent circuit



Operational Amplifier Concept



Transresistance op-amp symbol and equivalent circuit



Transconductance op-amp symbol and equivalent circuit

Operational Amplifier Concept

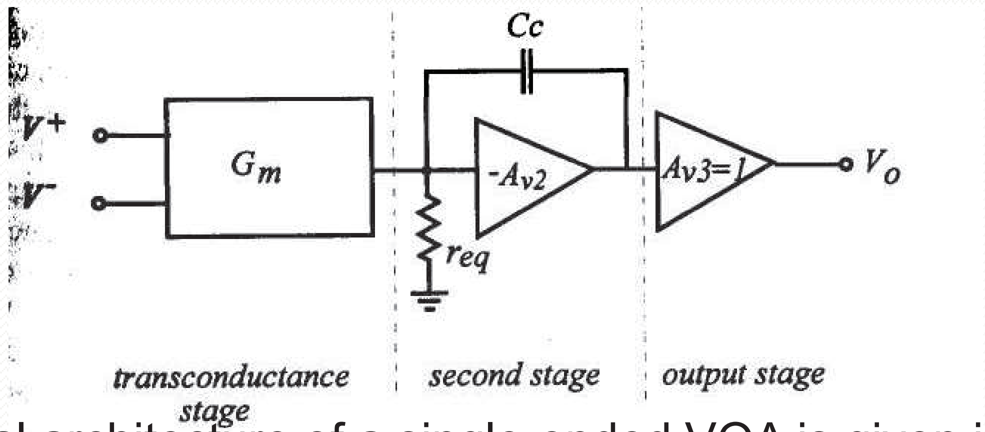
Ideal op-amps and their characteristics

Op-amp type	r_i	r_o	Open-loop gain
VOA	∞	0	$A_V = V_o/V_i$
COA	0	∞	$A_i = I_o/I_i$
TROA	0	0	$R_t = V_o/I_i$
TCOA	∞	∞	$G_t = I_o/V_i$

four possible types of closed-loop amplifiers which differ in combinations of input source and output drive

- voltage to voltage (V-V) amplifier
- current to current (I-I) amplifier
- voltage to current (V-I) amplifier
- current to voltage (I-V) amplifier

Voltage Operational Amplifier



A typical architecture of a single-ended VOA is given in the figure. It is made up of a transconductance input stage, a second gain stage and an output stage.

Resistance req is the equivalent output resistance of the input stage and C_c is the compensation capacitor.

For this circuit, the DC open-loop gain and the pole frequency are given as;

$$A_v = G_m r_{eq} A_{v2}$$

$$w_0 = \frac{1}{r_{eq} A_{v2} C_c}$$

Current Feedback Operational Amplifier

❑Current feedback operational amplifier is an evolution in the architecture of the voltage-mode operational amplifiers.

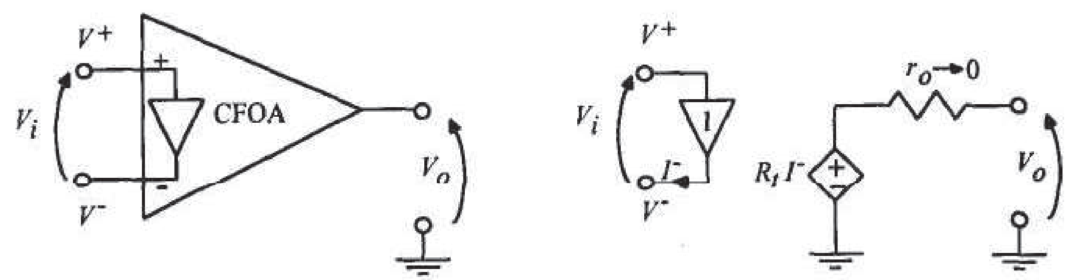
❑Figure shows the CFOA symbol and equivalent circuit.

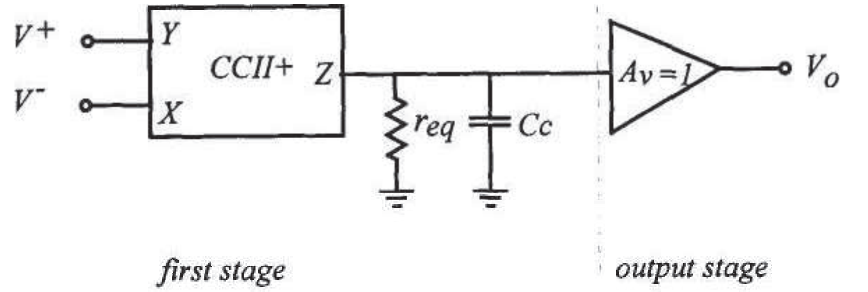
❑Like almost all current-mode circuits, a CFOA can be described in terms of the CCII and the architecture is given in Figure.

❑The DC open-loop transresistance gain (R_t) and the dominant-pole frequency (w_0) of the circuit is given as,

$$R_t = r_{eq}$$

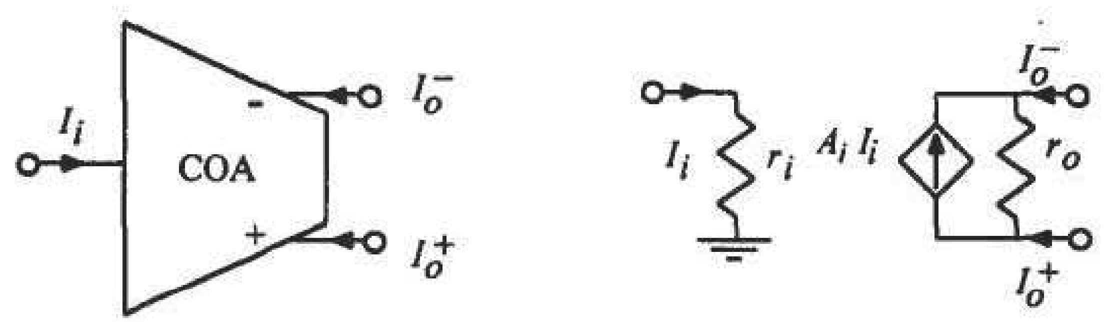
$$w_0 = \frac{1}{r_{eq} C_c}$$



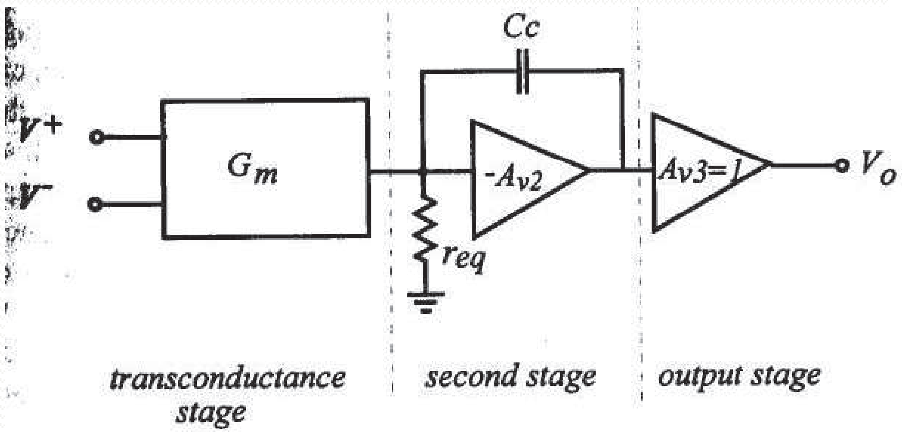


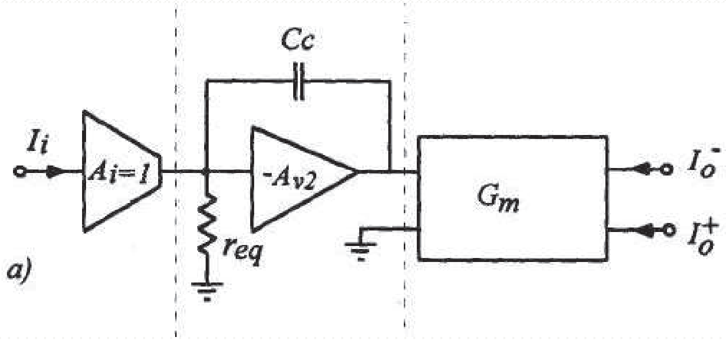
Current Operational Amplifier

- According to the adjoint network theorem, an ideal COA is the dual of an ideal VOA.
- The design of a VOA can be considerable simplified if a single output device is considered.
- A single ended VOA is able to drive the load and the feedback network simultaneously.
- With this observation in mind, a similar observation can be made for the input port of the COA.
- The COA only needs one input terminal to be connected to the input source and to the feedback network.
- The symbol and the circuit model of a single input COA is given in Figure.

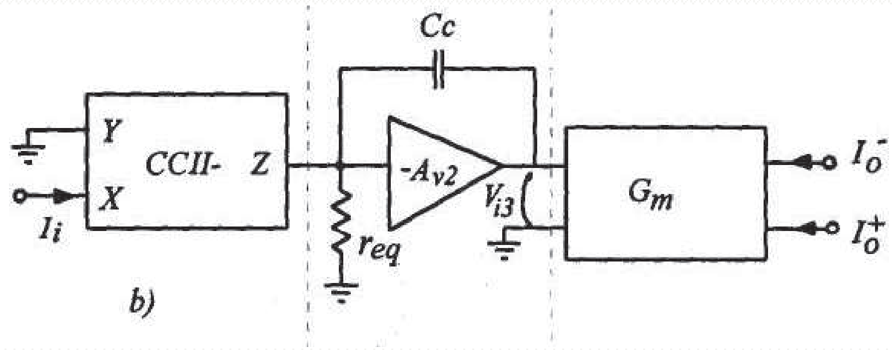


Current Operational Amplifier





The adjoint theorem can be applied to the VOA internal architecture given to obtain a possible internal architecture of the COA.



Performance parameters for the COA

1. Differential mode gain: this parameter sets the accuracy of the closed-loop transfer function in low frequency operations. It is defined by:

$$A_d = \frac{i_o^+ - i_o^-}{i_i}$$

2. Common mode gain: This gain is defined with respect to the output common mode:

$$A_c = \frac{i_o^+ + i_o^-}{2i_i}$$

The output currents can be represented by the common mode and differential mode gain by:

$$i_o^+ = \left(\frac{1}{2}A_d + A_c\right)i_i \qquad i_o^- = \left(-\frac{1}{2}A_d + A_c\right)i_i$$

If the common-mode gain is zero, the output currents are equal in module and with opposite direction flow.

Performance parameters for the COA

3. Common mode rejection ratio: As expected from the duality principle, the common mode rejection ratio depends only on the performance of the output stage. It expresses the ability of the output stage to reject common mode signals coming from the input or spurious signals from the supply lines and the substrate. CMRR is defined by the following formula, which is the same as it is defined for voltage operational amplifiers.

$$CMRR = \frac{A_d}{A_c}$$

where A_d and A_c are the common mode and differential mode gains.

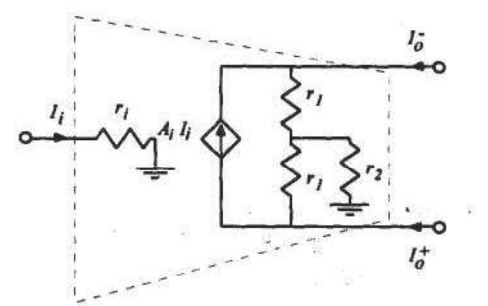
Performance parameters for the COA

4. Input and output resistances: The input and the output resistances are given below. Ideally, the input resistance and the output resistances should ideally be zero and infinite, respectively. The input resistance -which is not zero in practice and may have large values in standard CMOS processes- is responsible for a further pole in the loop gain transfer function which can greatly affect either stability or the closed-loop bandwidth.

The differential and common mode output resistances are easily defined by referring to the figure by:

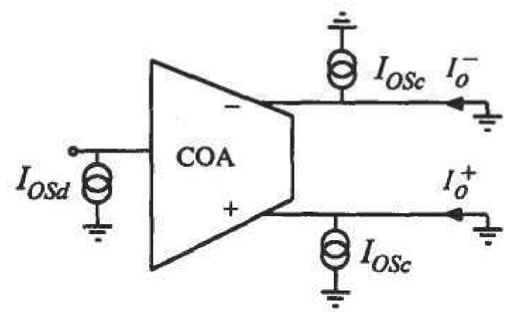
$$r_{od} = 2r_1$$

$$r_{oc} = \frac{r_1}{2} + r_2$$

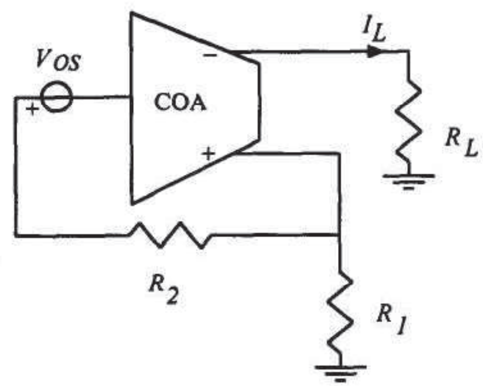


Performance parameters for the COA

5. Offset currents: There are two offset current components, differential and common mode offset currents. I_{OSd} is the input current needed to set the differential output current to zero and I_{OSc} is the output current which sets to zero the common mode output current.

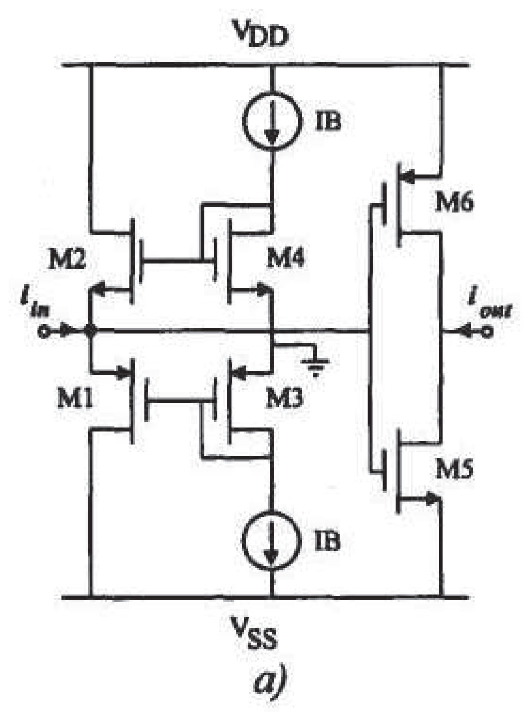


6. Input offset voltage: Ideally, the input bias voltage of a current amplifier is the reference voltage. Any deviation (offset voltage) of the input bias from the ideal value causes a DC current to flow through the resistor R_L.



Simple Current Amplifiers

The translinear loop, made up of transistors M1-M4, sets the input voltage equal to the ground under both AC and DC conditions. The input resistance and the current gain are equal to



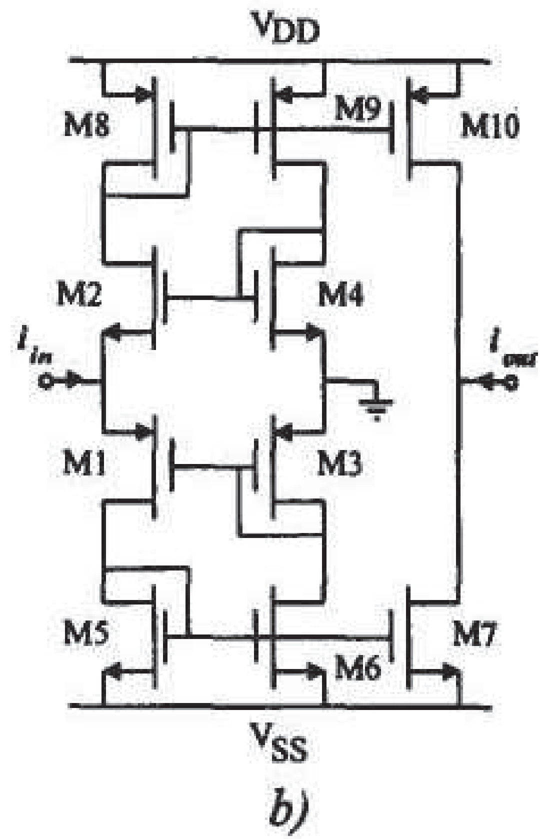
$$r_{in} \cong \frac{1}{g_{m1} + g_{m2}}$$

$$A = \frac{i_{out}}{i_{in}} = (g_{m5} + g_{m6})r_{in} = \sqrt{\frac{\beta_{5,6} I_{D5,6}}{\beta_{3,4} I_{D3,4}}}$$

Simple Current Amplifiers

This circuit provides a very low input resistance because of the positive feedback loop in the input stage. The input resistance is

$$r_{in} \cong \left[\frac{1}{g_{m1}}\left(\frac{1}{g_{m5}r_{d1}//r_{d5}}+\frac{1}{g_{m3}r_{d3}//r_{d6}}\right)\right]//\left[\frac{1}{g_{m2}}\left(\frac{1}{g_{m8}r_{d8}//r_{d2}}+\frac{1}{g_{m4}r_{d4}//r_{d9}}\right)\right]$$



The current gain is now given by the aspect ratios

$$A=\frac{i_{out}}{i_{in}}=\frac{(W/L)_7}{(W/L)_5}=\frac{(W/L)_{10}}{(W/L)_8}$$

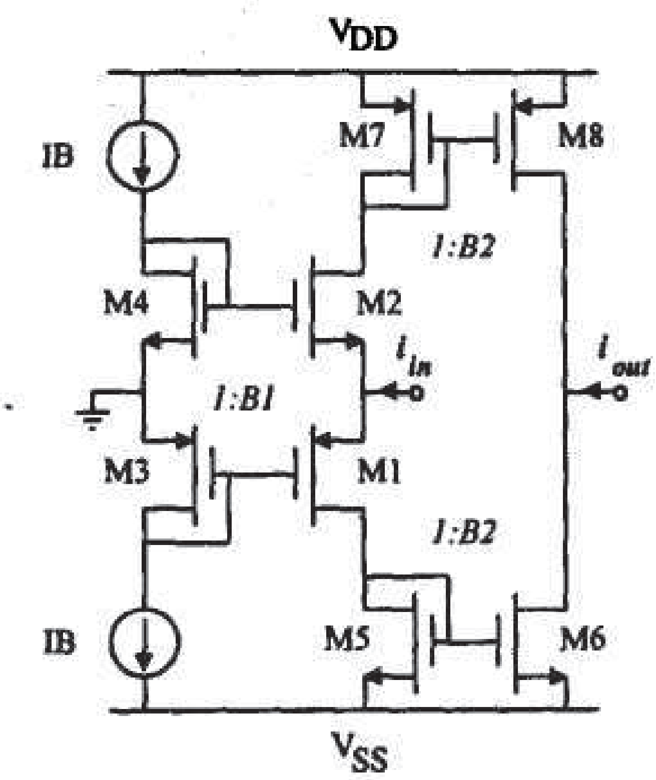
Although these two circuits provide accurate input resistance and gain, the quiescent current is controlled well only in the input stage for the first, and there is no current control at all in the second. As a result, most of the performance parameters (frequency response, power dissipation, etc.) are not well-defined.

Simple Current Amplifiers

A better solution for current amplifier is given here. In this circuit, the quiescent current is set by aspect ratios. Typical values for the current mirror ratios are 0.1 to 1 for B1 and 5 to 10 for B2. The input resistance and the current gain are found as

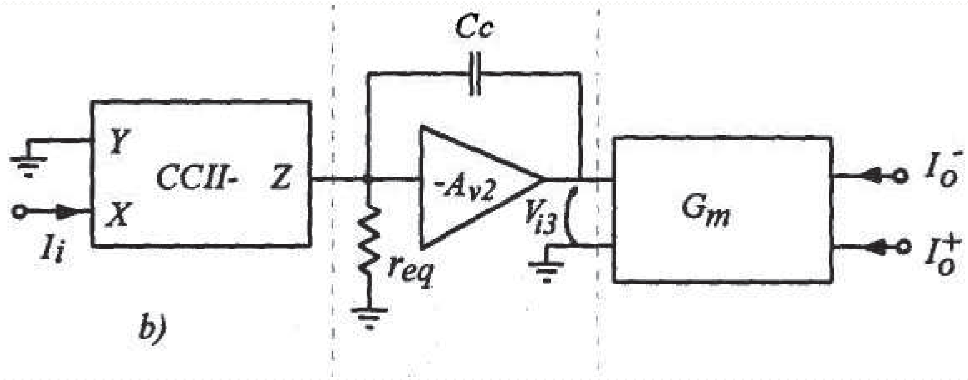
$$r_{in} \cong \frac{1}{g_{m1} + g_{m2}}$$

$$A = \frac{i_{out}}{i_{in}} = \frac{(W/L)_6}{(W/L)_5} = \frac{(W/L)_8}{(W/L)_7} = B2$$



The three amplifiers shown above cannot be used as current operational amplifiers, because they only have single output and their open-loop gain is not high enough. It is also important to know that these amplifiers are strictly current mode, and their gain typically do not exceed 20 dB.

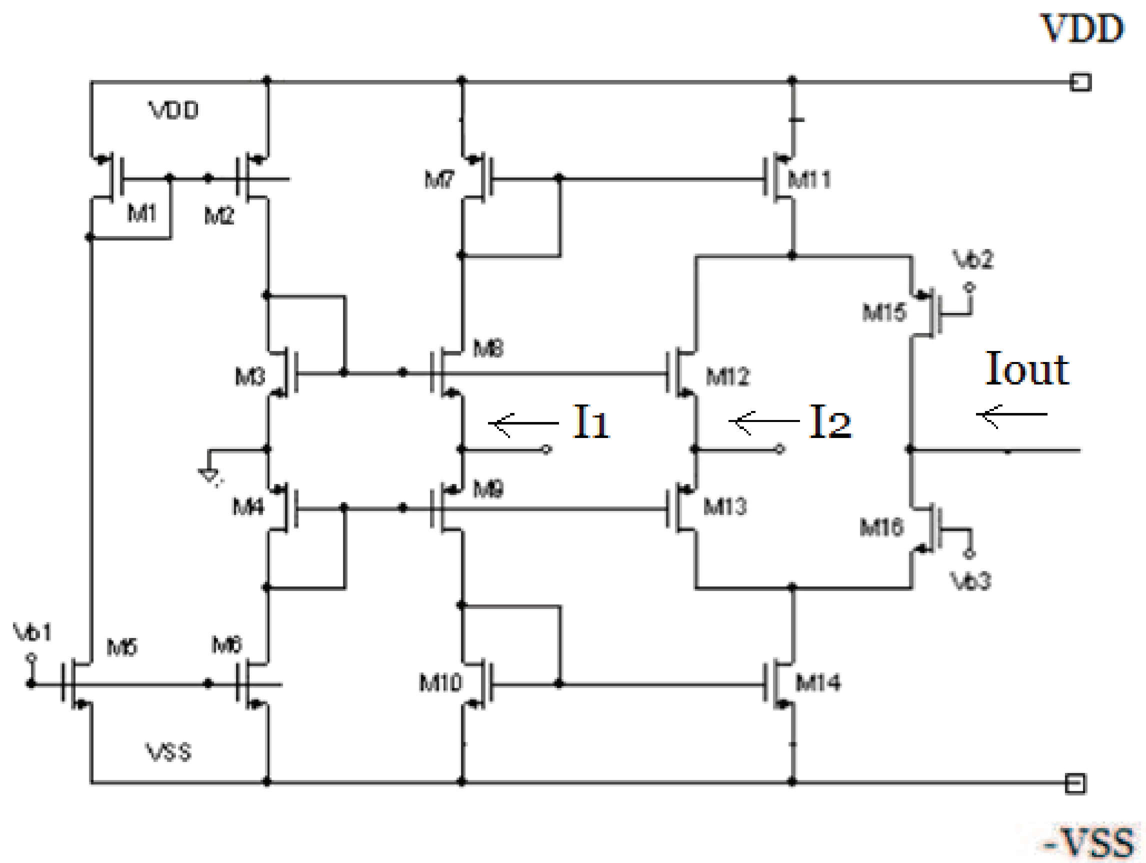
Building Blocks for Current Operational Amplifiers



As it can be seen from the figure above, a COA is made up of three stages:

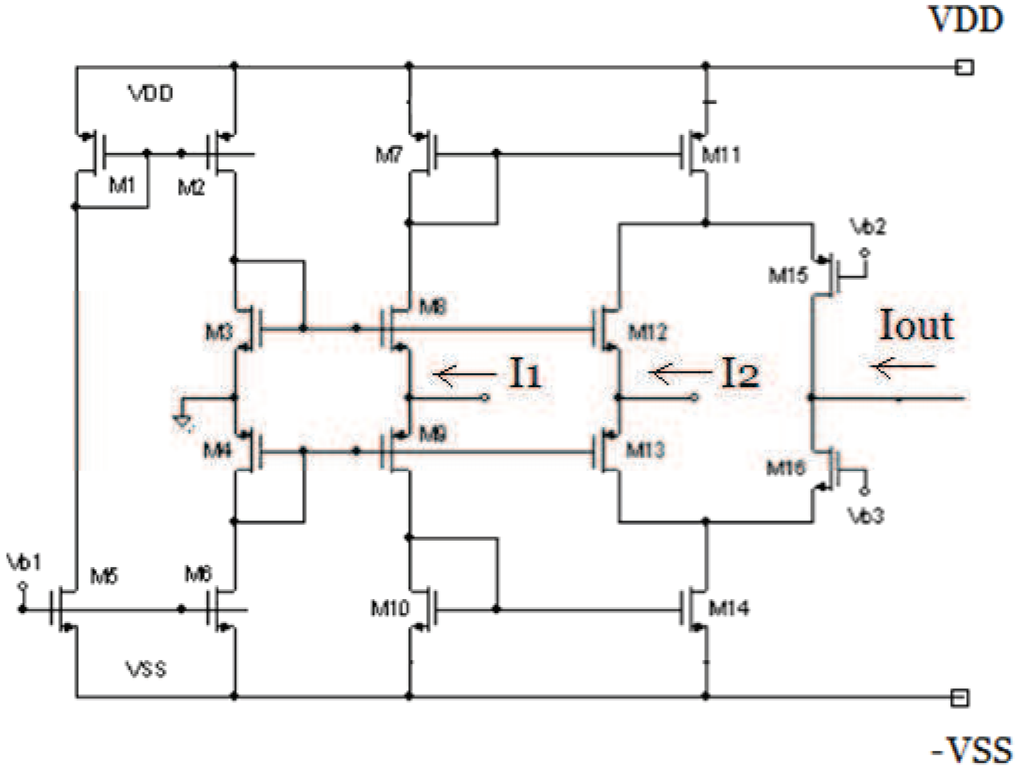
1. The input stage is a second generation current conveyor
2. There is a voltage gain stage between the input stage and the output stage.
3. The output stage is a transconductance stage with dual current output.

Differential input stage



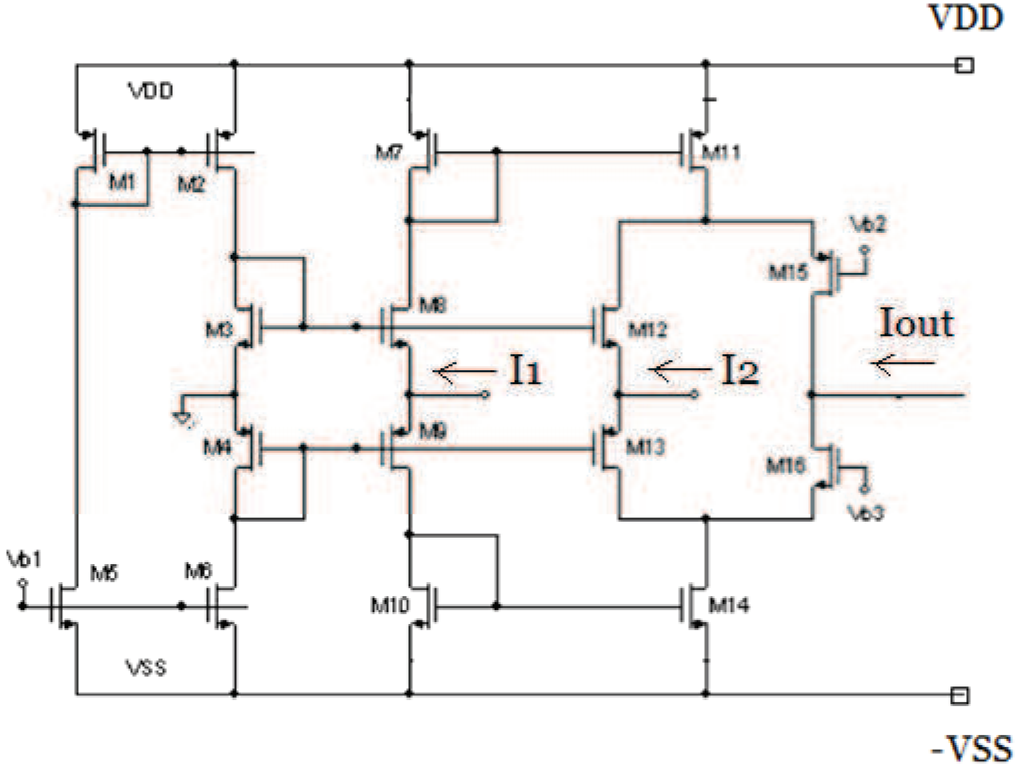
Aspects of the M8 and M9 should be chosen two times of the M3, M4 and M12, M13 transistors in order to operate the input stage correctly.

Differential input stage



- M1-M6 biasing transistors
- I1 = 0, I2 = 0, current through transistors M3, M4 are equal to M12, M13 and M15, M16, adequate Vb1, Vb2.
- Current through M8, M9 and M11,M14 two times of the M3, M4
- Iout = 0

Differential input stage



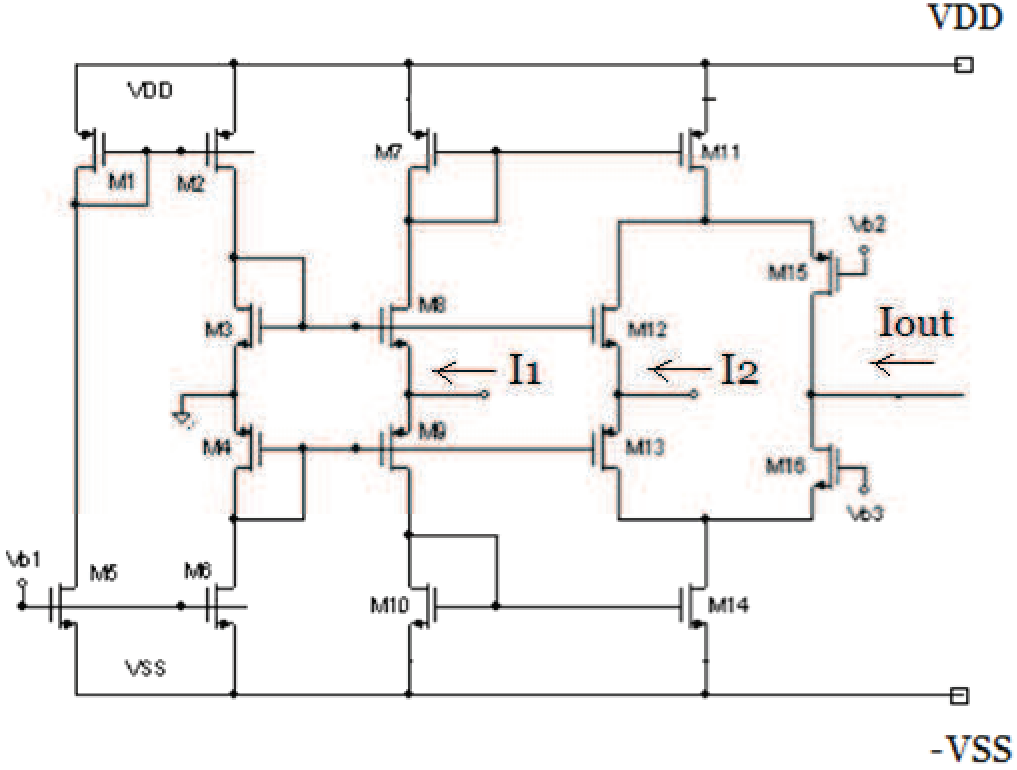
Phase I:

- $I_1 > 0$, $I_2 = 0$, currents through transistors M9, M10, M14, M16 increase,
- Current through M12, M13 constant
- Difference current flows through output over M16
- $I_{out} > 0$

Phase II:

- $I_1 < 0$, $I_2 = 0$, currents through transistors M8, M7, M11, M15 increase,
- Current through M12, M13 constant
- Difference current flows through output over M15
- $I_{out} < 0$

Differential input stage



Phase III:

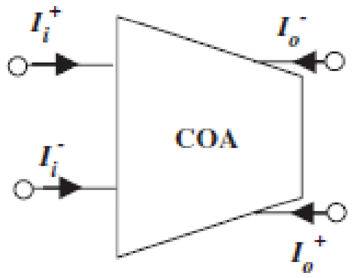
- ❑I1 =0, I2 > 0, current through transistor M13 increases,
- ❑Current through M11, M14 constant
- ❑Currents through M12, M16 decreases
- ❑Difference current flows through output over M15
- ❑Iout < 0

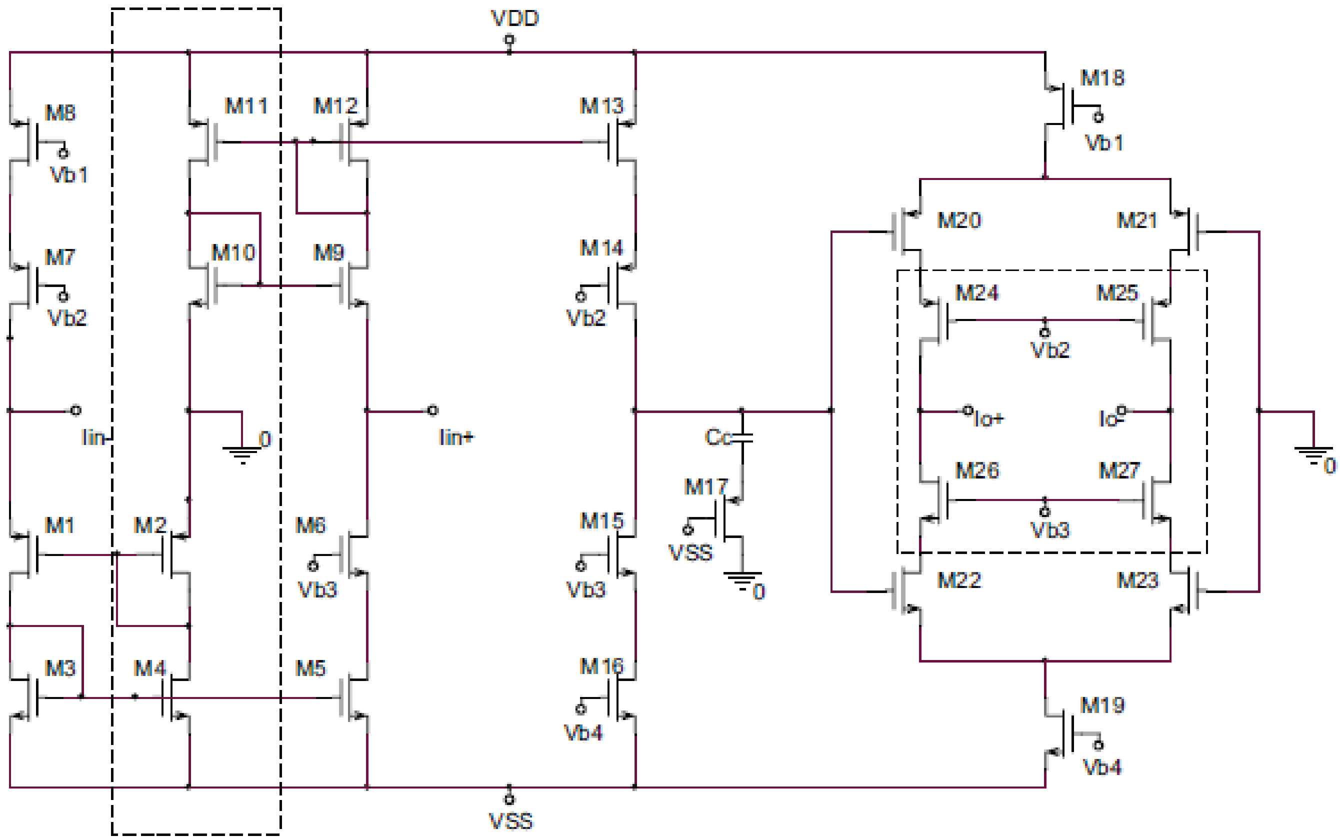
Phase IV:

- ❑I1 =0, I2 < 0, current through transistors M12 increases,
- ❑Current through M11, M14 constant
- ❑Currents through M13, M15 decreases
- ❑Difference current flows through output over M16
- ❑Iout > 0

Current Operational Amplifier

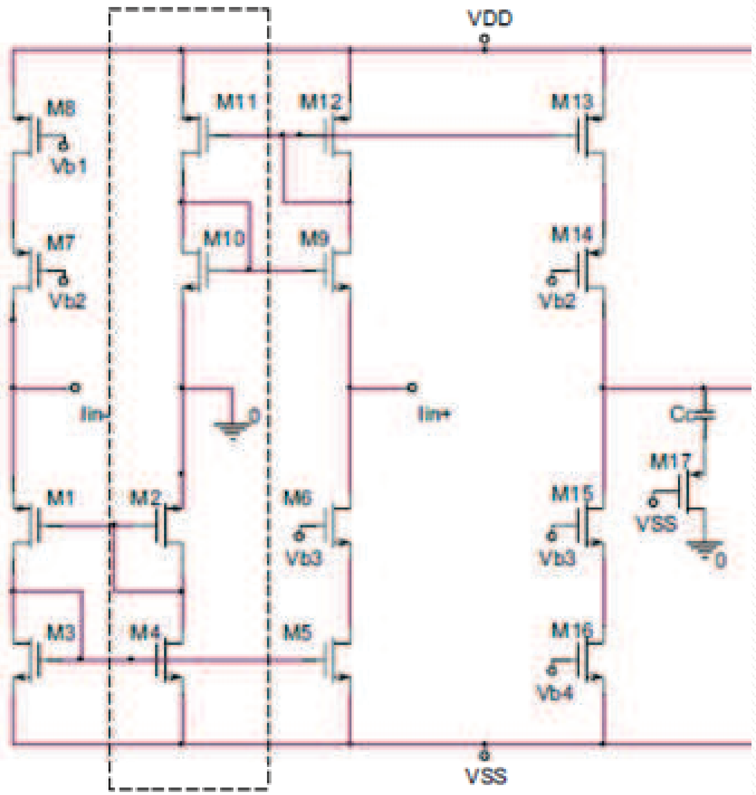
Current Operational Amplifier, M. Altun, H. Kuntman, 2008.





Current Operational Amplifier, M. Altun, H. Kuntman

The amplifier is configured from a differential input transimpedance stage followed by a differential output transconductance stage.



- ❑ M2, M4 and M10, M11 compose positive feedback loops to reduce positive and negative input resistances, respectively.
- ❑ Eqs. (1) and (2) show input resistances without positive feedback loops and generally their values are not low enough.

$$r_{\text{in}-} \cong \frac{1}{g_{m1}},$$

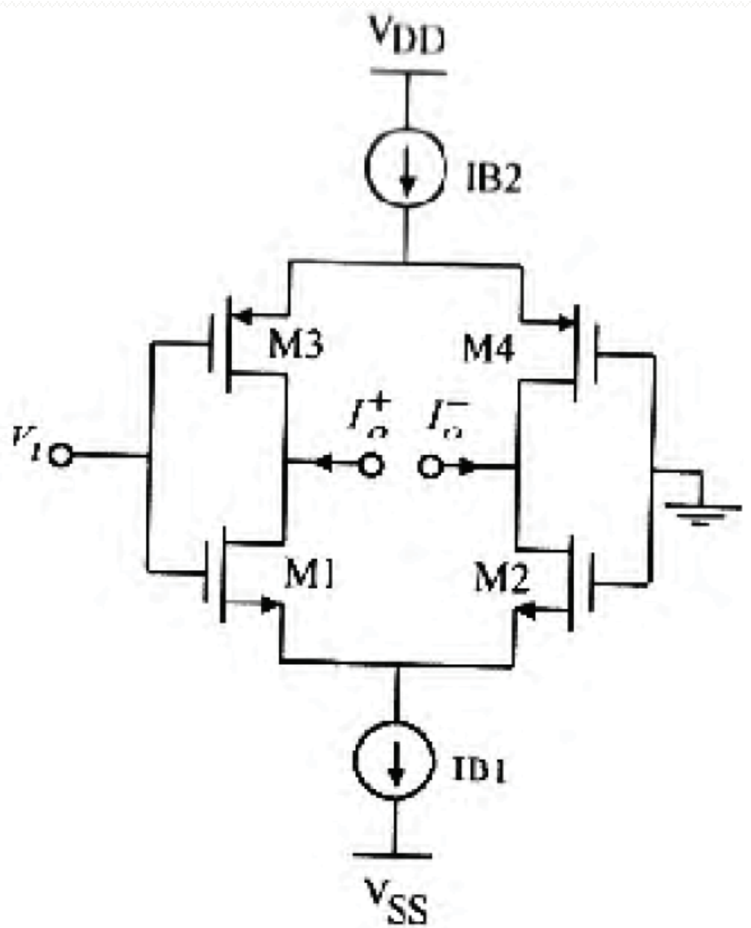
$$r_{\text{in}+} \cong \frac{1}{g_{m9}}.$$

Current Operational Amplifier, M. Altun, H. Kuntman

$$r_{\text{in}-} \cong \frac{1}{g_{m1}g_{m3}}\left[(g_{\text{ds}1} + g_{m3} + g_{\text{ds}3}) - \frac{g_{m1}g_{m4}}{g_{\text{ds}4} + g_{m2} + g_{\text{ds}2}}\right],$$

$$r_{\text{in}+} \cong \frac{1}{g_{m9}g_{m12}}\left[(g_{\text{ds}9} + g_{m12} + g_{\text{ds}12}) - \frac{g_{m9}g_{m11}}{g_{\text{ds}11} + g_{m10} + g_{\text{ds}10}}\right].$$

- The second terms mainly affect input resistance value. If we select its value close to zero, *rin also goes closer zero*.
- *Moreover, its value must larger* than zero to overcome the stability problem.
- If we choose *gm3 = gm4, gm1 = gm2 and gm11 = gm12, gm9 = gm10, then* we will both overcome stability problem and obtain very low input resistances.
- Consequently we come such a decision that $(W/L)_{M3}=(W/L)_{M4}$, $(W/L)_{M1}=(W/L)_{M2}$, $(W/L)_{M11}=(W/L)_{M12}$, $(W/L)_{M9} = (W/L)_{M10}$.



Conventional Arbel-Goldminz Output Stage

Output resistance of conventional current output stage (Arbel Goldminz output stage) is given by:

$$r_{out+} = r_{out-} \cong \left[\left(\frac{g_{m20} g_{ds21}}{g_{m21} + g_{m20}} \right) + \left(\frac{g_{m22} g_{ds23}}{g_{m23} + g_{m22}} \right) \right]^{-1}$$

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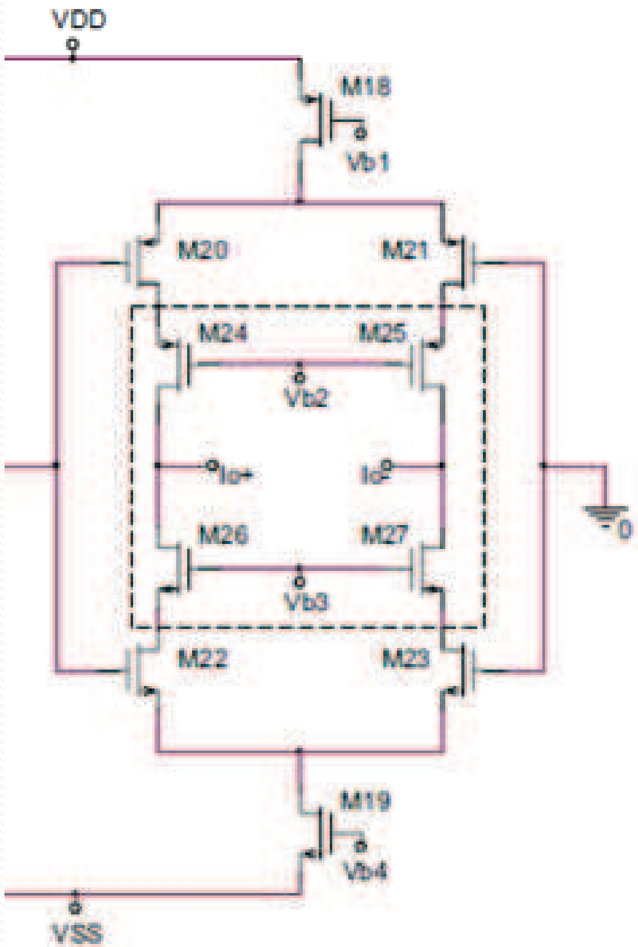

Improved Arbel-Goldminz Output Stage

❑M24, M25, M26 and M27 in dashed line are added to the conventional current output stage for getting larger output resistance values.

❑Compared to the conventional one, proposed output stage approximately offers *gm x ro times higher output resistance*.

$$r_{out+} = r_{out-} \cong \left[\left(\frac{g_{m20} g_{ds21} g_{ds25}}{g_{m25}(g_{m21} + g_{m20})} \right) + \left(\frac{g_{m22} g_{ds23} g_{ds27}}{g_{m27}(g_{m23} + g_{m22})} \right) \right]^{-1}.$$

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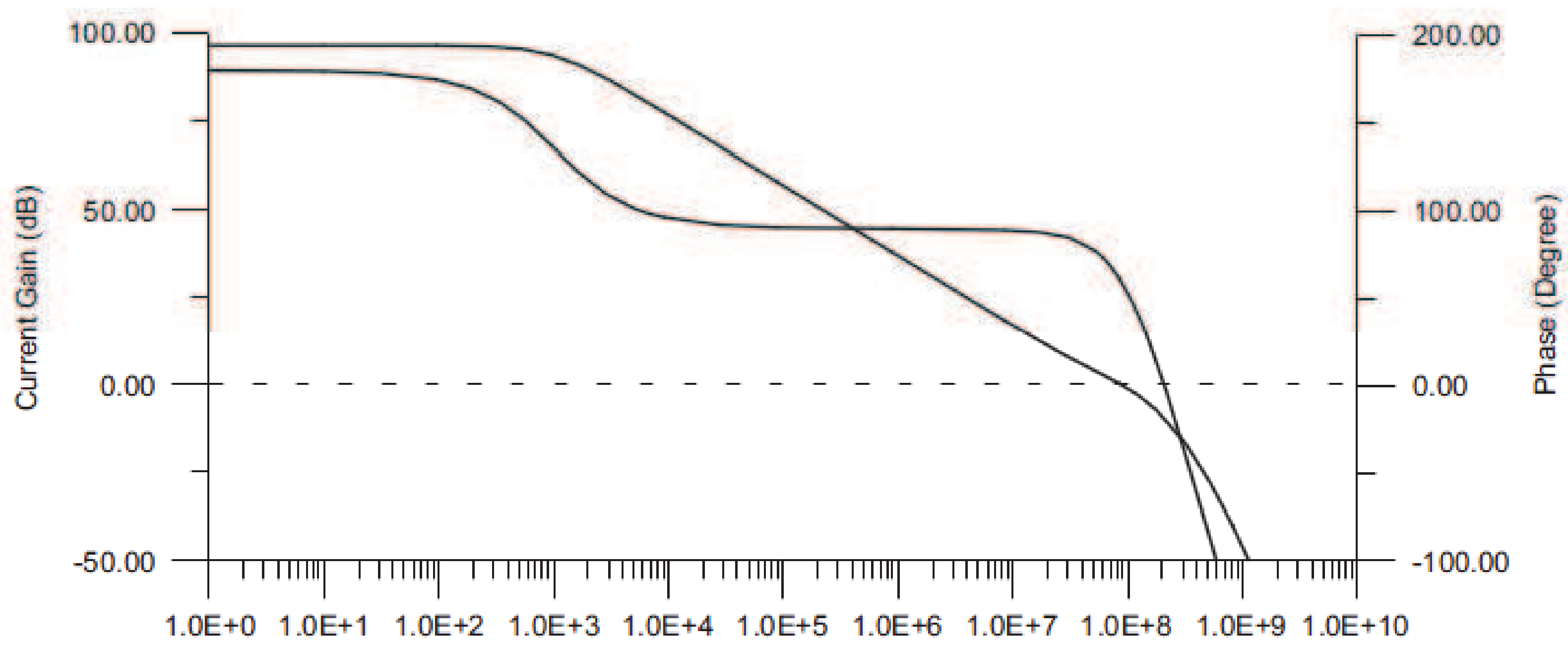
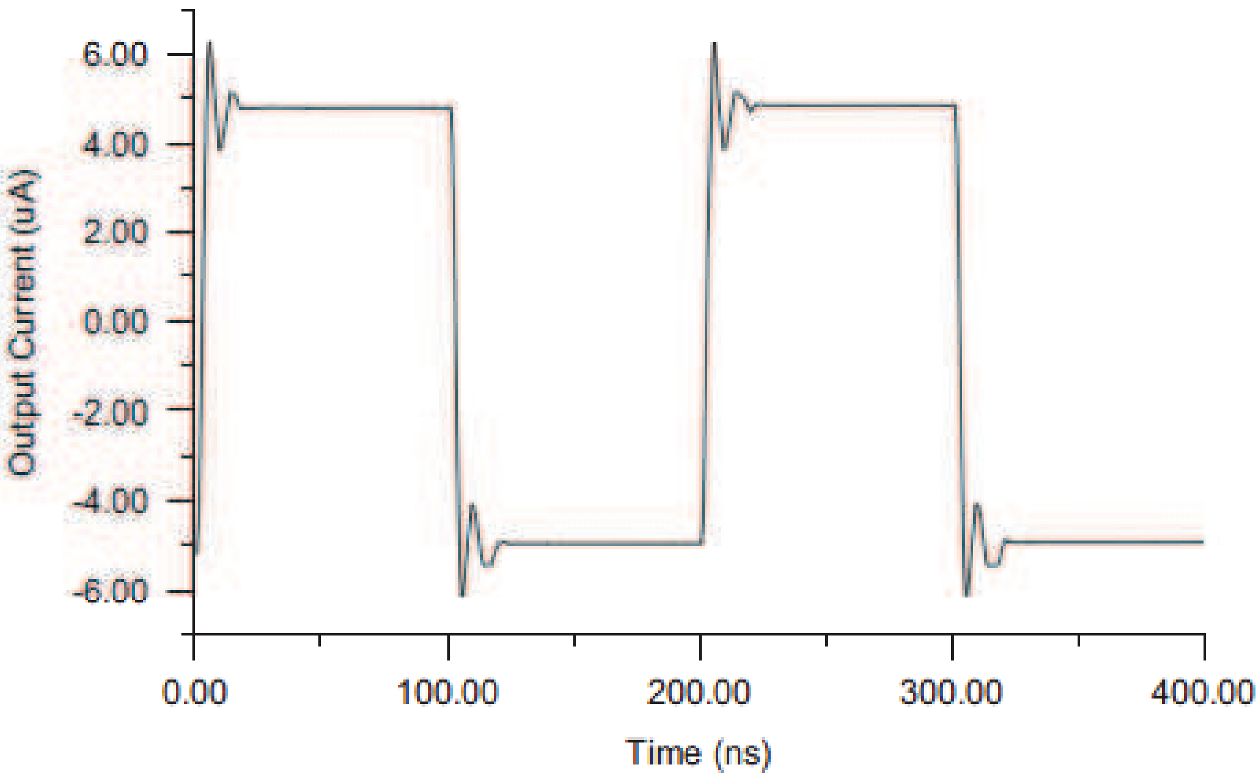


Open-loop frequency response of the COA.

Current Operational Amplifier, M. Altun, H. Kuntman



Response of the COA in unity-gain feedback to a $\pm 5\mu A$ input step ($f = 5\,MHz$).

Table 3. Performance parameters of the COA

Parameter	Value
Power dissipation	0.66 mW
Open-loop gain	96 dB
GBW	92 MHz
Phase margin (Cc = 1.2 p Rc = 2.4 kΩ)	60°
Output voltage range	±0.6 V
Slew rate	4 μA/ns
Input resistance (n)	124 Ω
Input resistance (p)	109 Ω
Output resistance	30 MΩ
Input voltage offset (n)	≈ 1.6 mV
Input voltage offset (p)	≈ −3.5 mV

References

- G. Palmisano, G. Palumbo, S. Pennisi, "**CMOS current amplifiers**", Kluwer Academic Publishers, 1999
- C. Toumazou, F.J. Lidgey, D.G. Haigh (ed.), "**Analog IC design: the current-mode approach**", Peter Peregrinus Ltd., 1998.
- A. Uygur, H. Kuntman, **Seventh-order elliptic video filter with 0.1 dB pass band ripple employing CMOS CDTAs,** Int. J. Electron. Commun. (AEÜ) 61 (2007) 320 – 328.
- M. Altun, H. Kuntman , **Design of a fully differential current mode operational amplifier with improved input–output impedances and its filter applications** Int. J. Electron. Commun. (AEÜ) 62 (2008) 239 – 244