Current-mode building blocks: Current-mode Analog amplifiers, input stages, output stages

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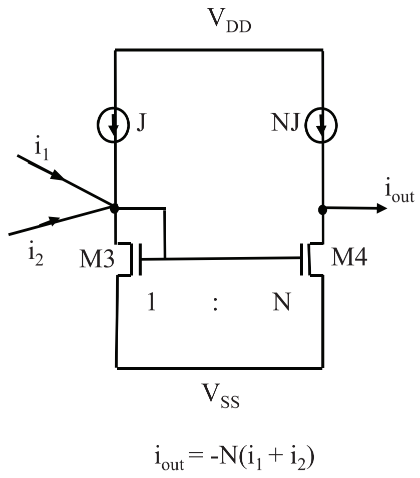
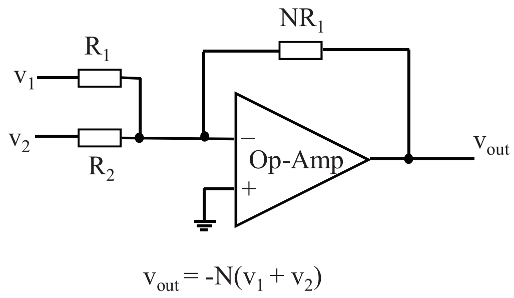
Current-mode Circuits

- Circuits are classified as current mode if the information medium is represented by time-varying currents.

Current-mode circuits have [2]:

–Higher Band-width
–Lower Supply Voltages
–Linearity and Wide Dynamic Range
–Topological Simplicity





Current and voltage summation

Why higher band-width?

Because the signal is represented by current instead of voltage, the node impedances are need to be lowered. So that poles of the circuits go to the higher frequencies.

$$f_{pole} \uparrow = \frac{1}{2\pi R_{node} C_{node}} \downarrow$$

Current-mode Circuits

Why Lower Supply Voltages?

- ❑ In a voltage-mode circuit, the carried signal is limited by the supplied voltage values. When the signal is carried by current, because of low impedance values, voltage levels are low according to the voltage mode one.

- ❑ An important advantage of lowered voltage supply is the lowered power consumption.

- ❑ New process technologies need lower supply voltages.

Why better linearity and Wide Dynamic Range in current mode?

- ❑ Voltage mode circuits are high-gain circuits (e.g. OPAMP) and so that the linearity is a problem when the signal level is high.

- ❑ Current mode circuits are generally unity gain circuits (e.g. CCII) and for that type of blocks, the linearity is improved. Also “current” has wider dynamic range with respect to “voltage”

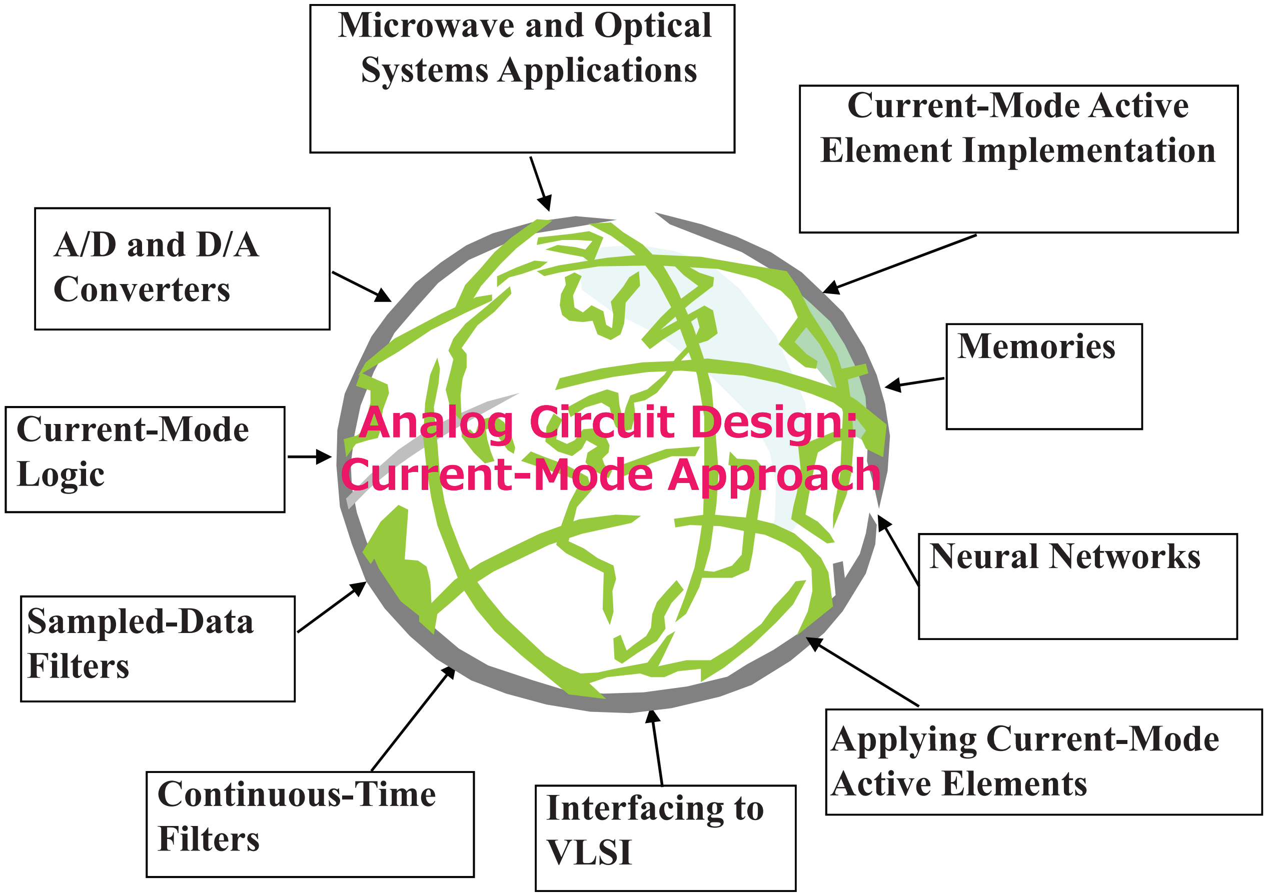
Current-mode Circuits

Why topological simplicity?

- In voltage-mode, we need high impedance nodes to have high voltage gain. For this reason we cascode the transistors. This results more complex circuit structures.

- However Current-mode circuits need lower node impedances which needs fewer transistors to implement.

Current-mode Circuit Applications

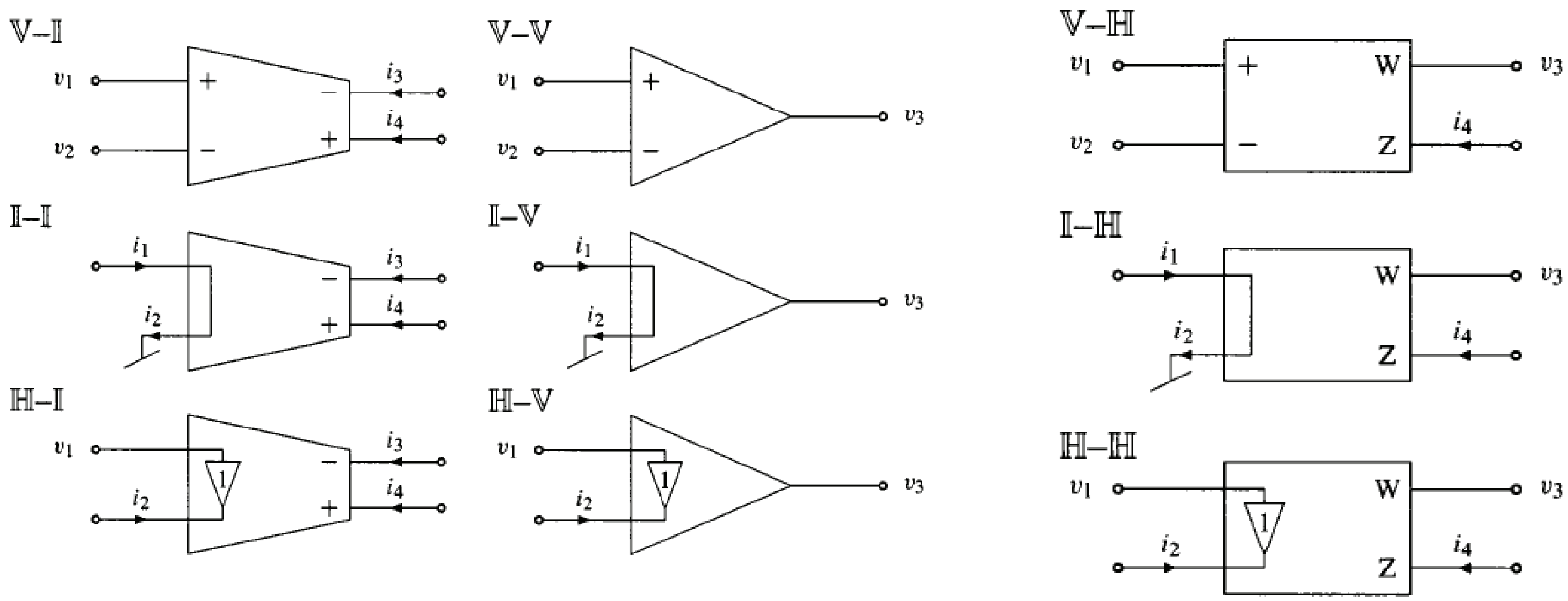


Universal Active Amplifiers

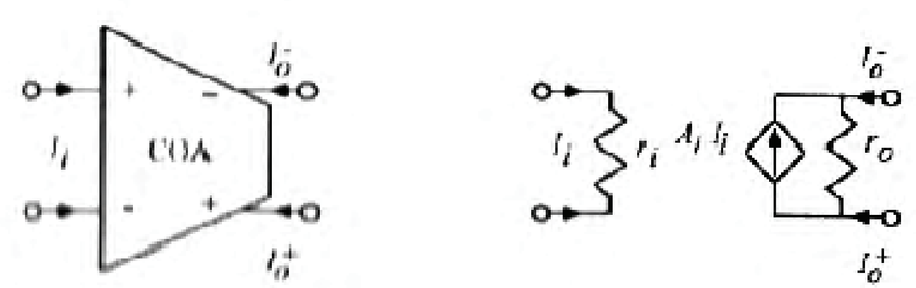
In below nine-universal active amplifiers are shown. Some of them are in Voltage-mode and some of them are in Current-mode.

Class	Gain Function	Operational Property	Literature Name
V-I	$i_3 = g_m(v_1 - v_2)$	$g_m R_{in} \to \infty$	Operational Transconductance Amplifier (OTA)
V-V	$v_3 = A_v(v_1 - v_2)$	$A_v \to \infty$	Operational Amplifier (OPAMP)
V-H	$v_3 = A_v(v_1 - v_2)$	$A_v \to \infty$	Operational Floating Amplifier (OFA)
I-I	$i_3 = A_i i_1$	$A_i \to \infty$	Current Operational Amplifier (COA)
I-V	$v_3 = r_m i_1$	$r_m / R_{in} \to \infty$	Operational Transresistance Amplifier (OTRA)
I-H	$v_3 = r_m i_1$	$r_m / R_{in} \to \infty$	Floating OTRA
H-I	$i_3 = A_i i_2$	$A_i \to \infty$	Current Feedback (CFB OTA)
H-V	$v_3 = r_m i_2$	$r_m / R_{in} \to \infty$	Current Feedback OPAMP
H-H	$v_3 = r_m i_2$	$r_m / R_{in} \to \infty$	Operational Floating Conveyor (OFC)

Universal Active Amplifiers



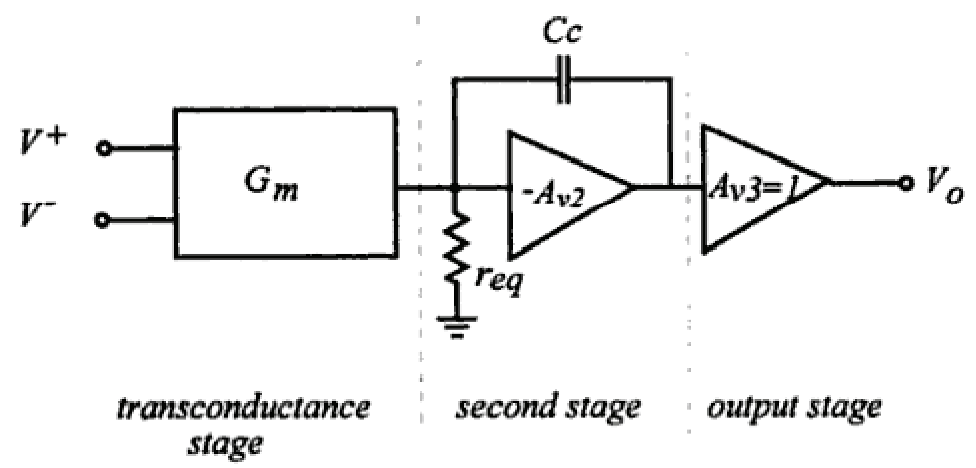
Current-mode Analog amplifiers (COA)

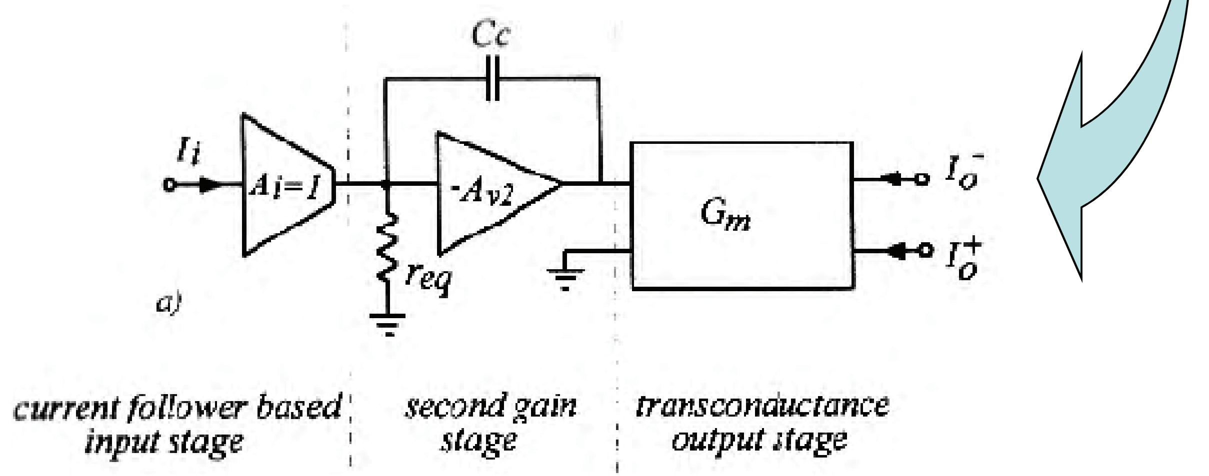


Current operational amplifier (COA) symbol and equivelant circuit

- Current opeational amplifier is the dual of voltage operational amplifier.
- Current op-amp (COA) is a current controlled current source (CCCS)
- It has ideally both infinite current gain and output resistance, and zero input resistance [1].

Current operational amplifiers (COA)





The adjoint theorem can be applied to voltage-mode operational amplifier to implement internal architecture of current-mode operational amplifier.

Current operational amplifiers (COA)

Performance parameters for the COA

Differential-mode gain

Differential mode gain can also be represented as open-loop gain which is important to set closed-loop transfer function.

$$A_d = \frac{I_o^+ - I_o^-}{I_i} \qquad A_d = r_{eq} A_{v2} \frac{I_o^+ - I_o^-}{V_{i3}} = r_{eq} A_{v2} G_{md}$$

Common-mode gain

Due to the duality with voltage amplifiers, the common mode gain is defined with respect to output common mode which is $(I_0^+ + I_0^-)/2$

$$A_c = \frac{I_o^+ + I_o^-}{2I_i} \qquad A_c = r_{eq} A_{v2} \frac{I_o^+ + I_o^-}{2V_{i3}} = r_{eq} A_{v2} G_{mc}$$

Current operational amplifiers (COA)

Performance parameters for the COA

Common mode rejection ratio (CMRR)

In voltage mode, CMRR depends on the input stage.

As expected from the duality principle, CMRR depends only on the performance of the output stage.

CMRR expresses the ability of the output stage to reject common mode signals coming from the input or supply lines and substrate.

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

Current operational amplifiers (COA)

Performance parameters for the COA

Input and output resistances

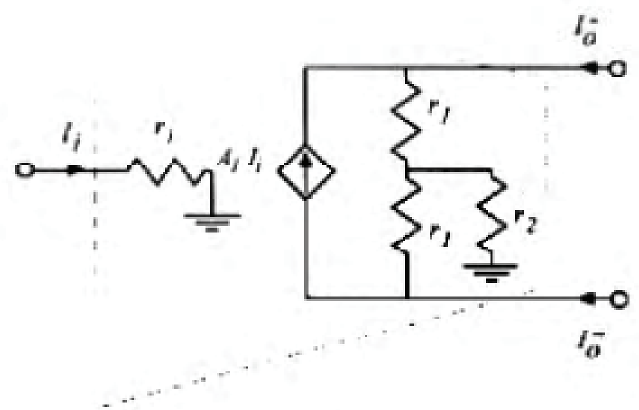
Ideally, the input resistance should be zero, the output resistance should be infinite.

The input resistance which is not zero in practice and may have large values in CMOS processes and so that it is responsible for a further pole in the loop gain transfer function.

This may effect either stability or the closed-loop bandwidth.

$$r_{od} = 2r_1$$

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



Current operational amplifiers (COA)

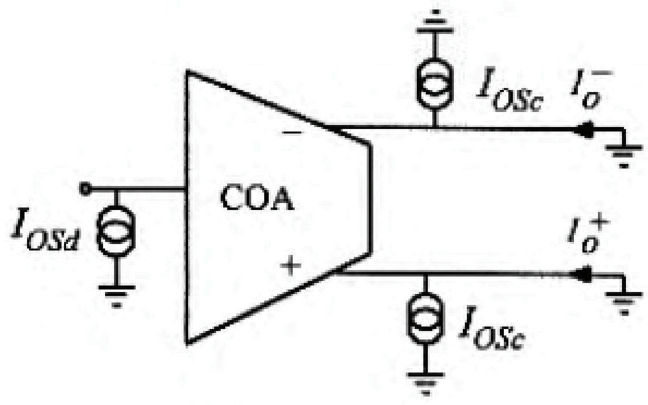
Performance parameters for the COA

Offset currents

Two offset current components can be mentioned.

I_{OSd} is the input current needed to set the differential output current to zero.

I_{OSc} is the output current which sets common mode output current to zero.

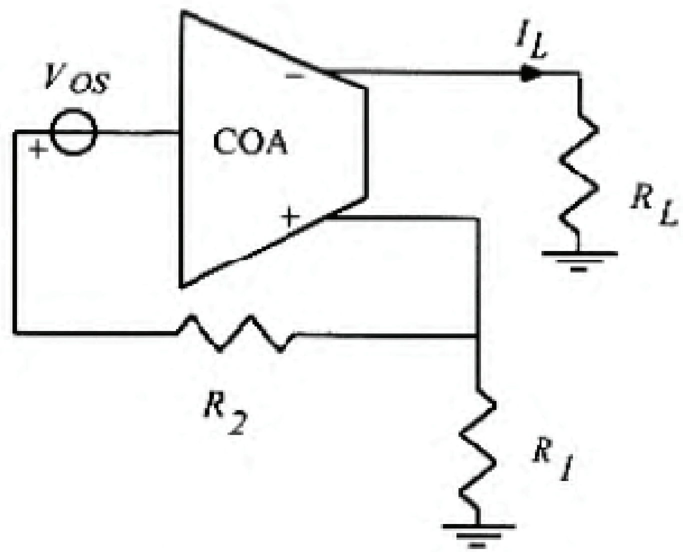


Current operational amplifiers (COA)

Performance parameters for the COA

Input offset voltage

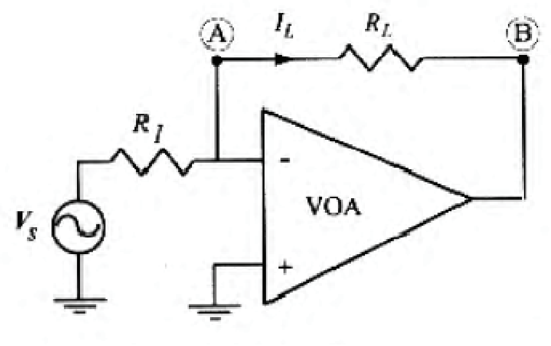
Any deviation voltage (VOS) of the input bias voltage causes DC current to flow load.



$$I_L = \frac{V_{OS}}{R_L}$$

Current amplifier realisation using Voltage OPAMPs – 1 [1]

- When there was <u>no integrated version</u> of current amplifiers, the only alternative way was to use a voltage amplifier.
- Several voltage to current amplifier, which includes voltage amplifier, has been designed.



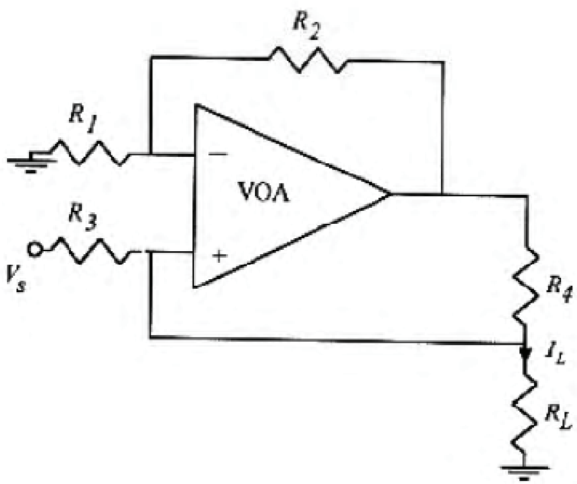
Feedback current source

- V_s and R_1 are fixed.
- The input impedance is low at the inverting terminal of the voltage amplifier.
- Although voltage gain of the amplifier varies with R_L, I_L is fixed.
- The circuit can be seen as current generator between A and B terminals.

Disadvantage:

- Current driven load, RL, is not ground referred.

Current amplifier realisation using Voltage OPAMPs – 2 [1]



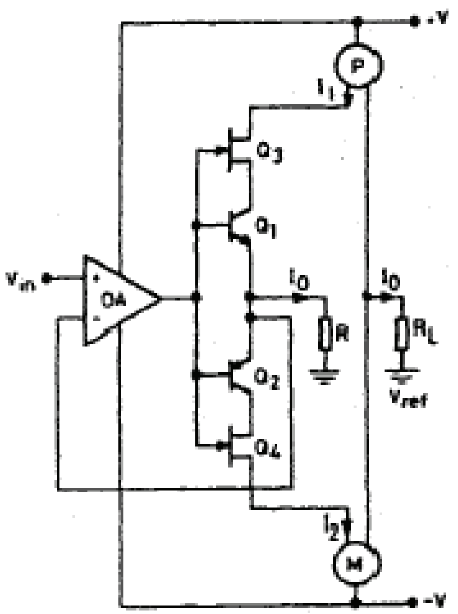
Howland current source

- This design solves the floating load problem.
- The circuit act as a current source: $I_L=V_s/R_3$ for the condition that $R_4/R_3=R_2/R_1$.
- Theoretically infinite output resistance, determined by the combined positive and negative feedback action of the VOA

Disadvantage:

Instability (Because of using positive feedback, the circuit requires very accurate resistor matching. If there is a small change in the $R_4/R_3=R_2/R_1$ condition, then output resistance would be negative and cause instability.)

Current amplifier realisation using Voltage OPAMPs – 3 [1]



Hart and Baker's class B voltage to current converter

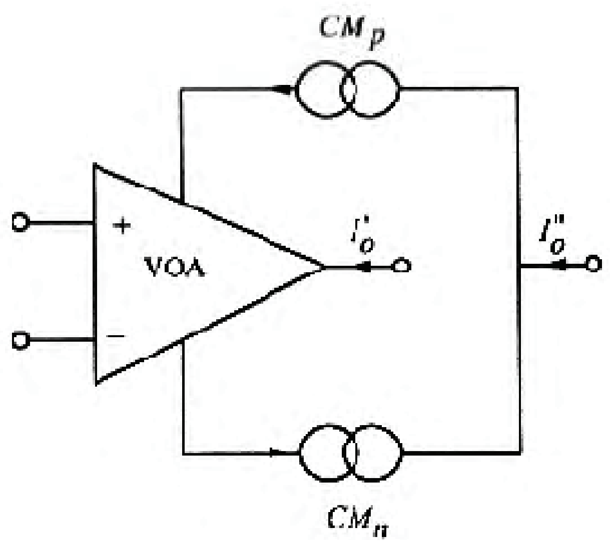
In this design, complementary current mirrors used to sense output current flowing through the collector.

Wilson current mirrors can be used for high output impedance and accurate current transfer performance.

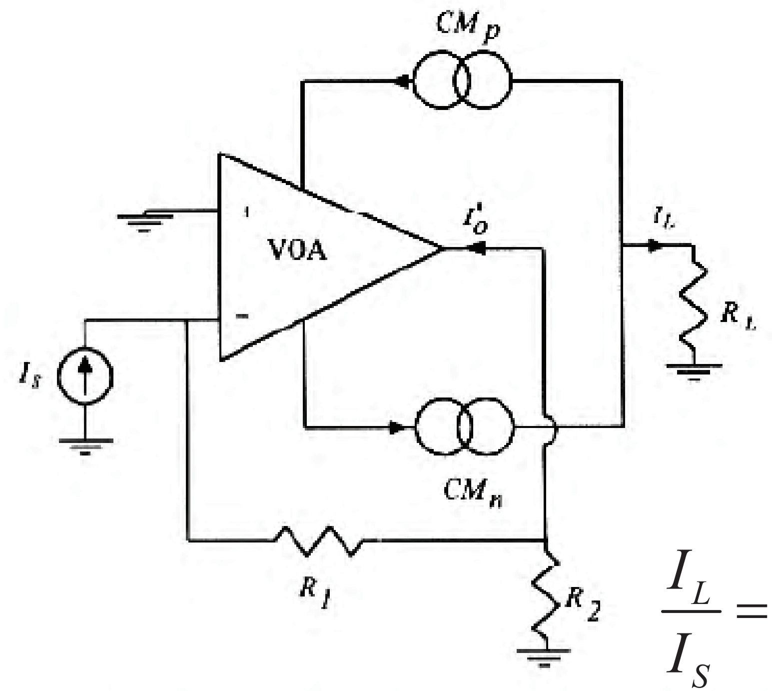
Disadvantage: The circuit operates in the class B mode. Therefore, there is a considerable distortion.

Current amplifier realisation using Voltage OPAMPs – 4 [2]

- In the supply current sensing technique, the output current equals to the sum of the current in the supply of the VOA.
- In most current converter topologies, current mirrors are used for sensing the signal currents of the supply rails of the VOA and summing them at the output impedance.

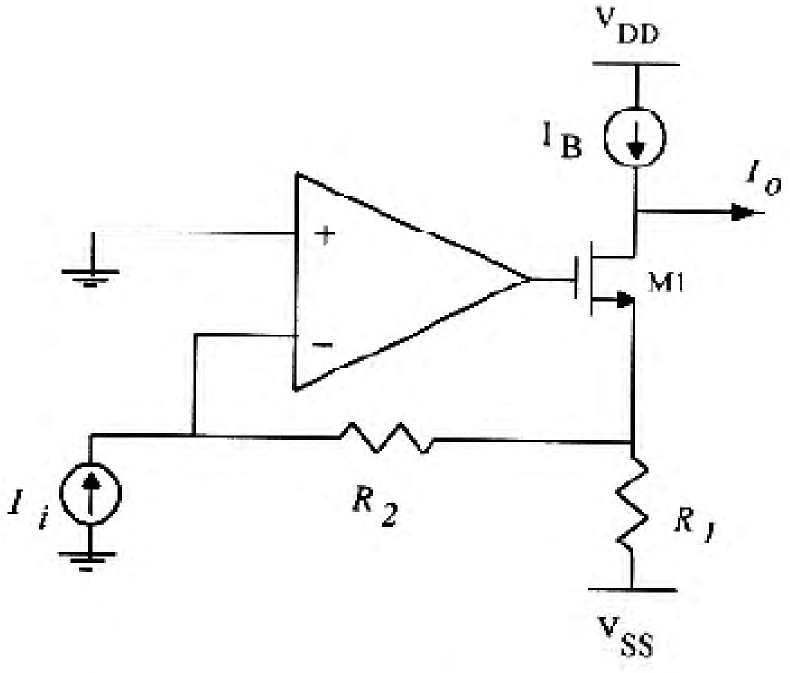


Supply current sensing technique



$$\frac{I_L}{I_S} = -\left(1 + \frac{R_2}{R_1}\right)$$

Current amplifier realisation using Voltage OPAMPs – 5 [2]



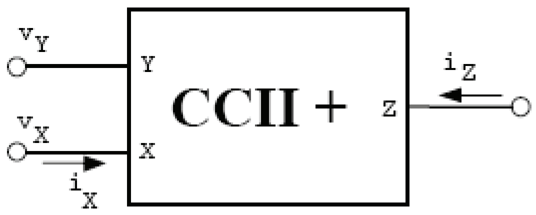
Simple Class-A current amplifier

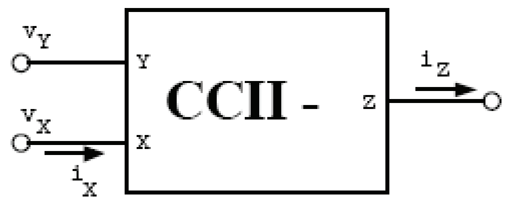
- M1 and current generator IB make up the current output stage.
- This circuit exhibits hign accuracy and linearity.
- But it has a very low power conversion efficiency (Class-A operation).

$$\frac{I_L}{I_S} = -\left(1 + \frac{R_2}{R_1}\right)$$

Current-Conveyors [1]

- Designers have developed several variations of current conveyor. They have been called the second-generation and the third-generation current conveyor (CCII, CCIII).
- The most successful type is CCII. But, in some cases a disadvantage of CCII can be observed.
- Current conveyors facilitates a voltage tracking input in addition to its current converter properties.
- x and y are input terminals, z is the output terminal.





$$i_y = a \cdot i_x$$

$$V_x = V_y$$

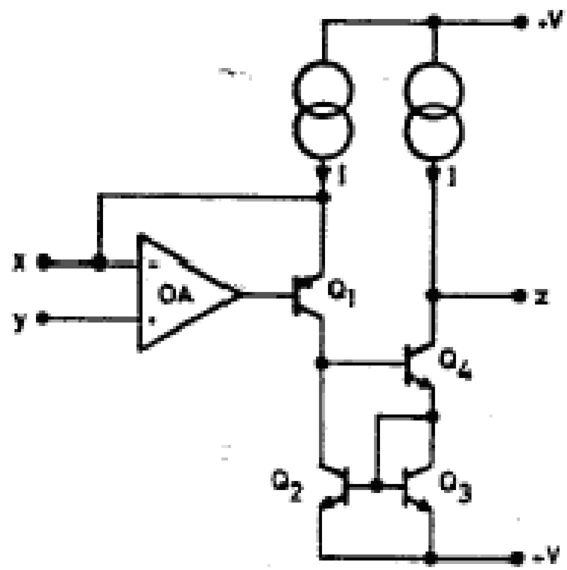
$$i_z = \pm i_x$$

In the first generation current conveyor, CCI, a=1. Thus, an impedance connected at terminal x is also reflected to y terminal.

In the second generation current conveyor, CCII, a=0. The terminal y draws zero current.

Current-Conveyors [1]

How to implement by using voltage operational amplifiers?

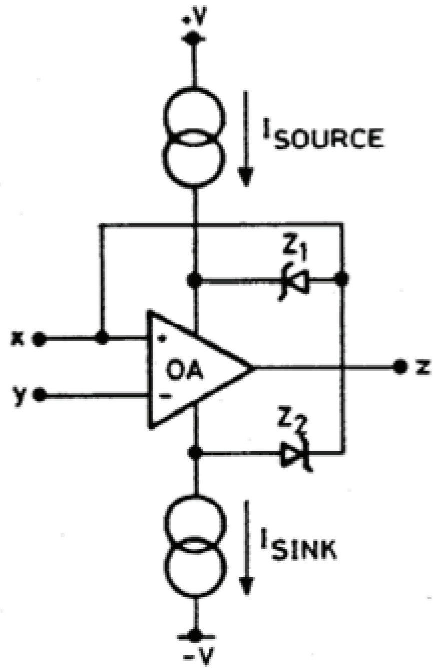


Current conveyor realization using VOA (Single ended CCII+ current-conveyor)

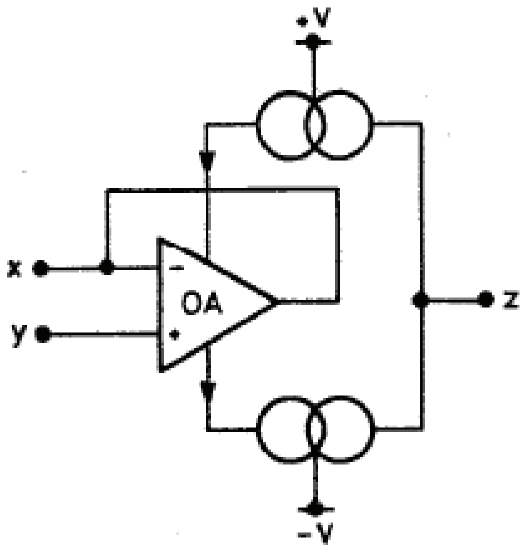
- ❑ A single opamp and current mirror can be used to implement current conveyor.
- ❑ The circuit is limited to Class A output operation and requires matching between the two current sources.

Current-Conveyors [1]

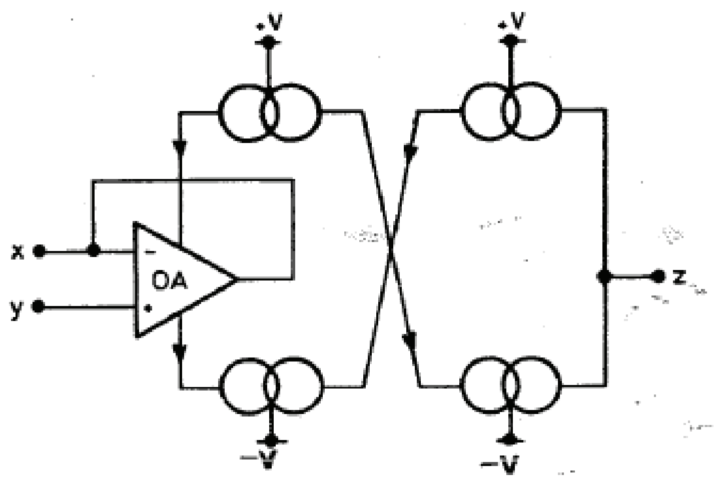
Different techniques to implement current conveyors



CCII- based upon floating VOA structure, Isource=Isink, V(z1)=V(z2)



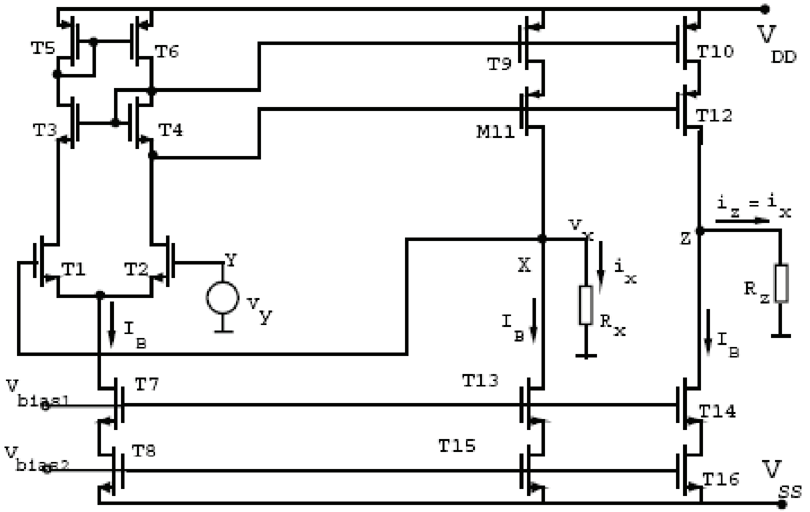
CCII+ based upon VOA supply current sensing.



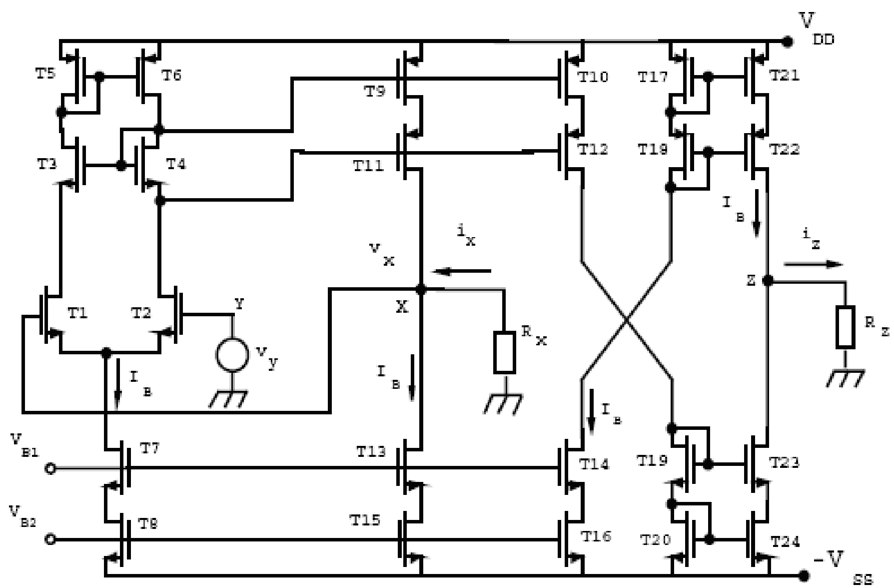
CCII- based upon VOA supply current sensing and using cross-coupled mirrors.

Current-Conveyors

CMOS implementation of Current Conveyor.

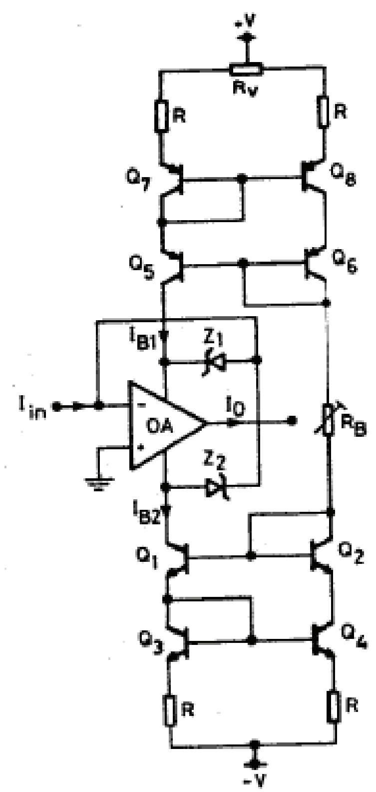


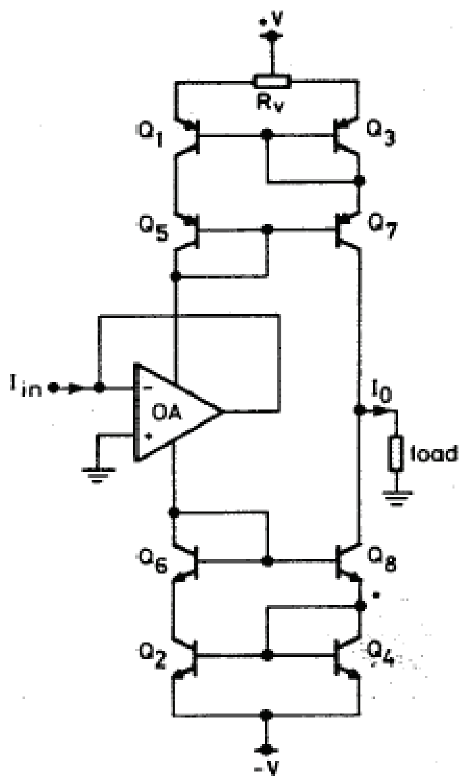
- ❑ Examples of CMOS CCII+ and CCII-



- ❑ A more detailed investigations on the CCIIs will be given in the following seminars.

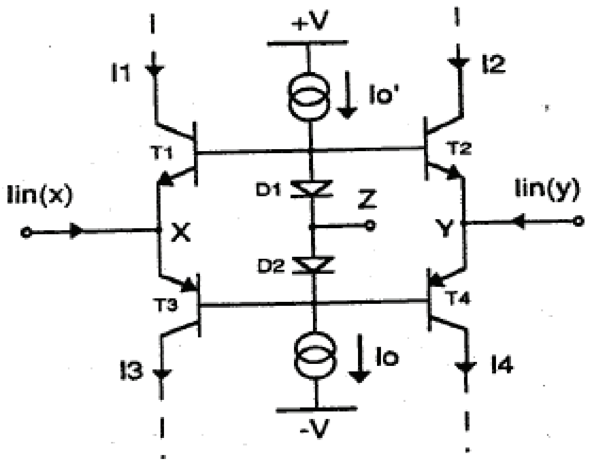
Current Follower [1]





- ❑ Current follower is a circuit with very low input impedance and very high output impedance.
- ❑ When the current follower is used with a signal source, it is expected to drive load with that current value due to the short circuit from input the output.

Input Stages [1]



- The circuit given here is made up of a translinear loop (T1-T4) and two diodes.
- Assuming that the input currents Iin(x) and Iin(y) are purely differential and much smaller than the bias currents Io nd Io', if Iin>0 then

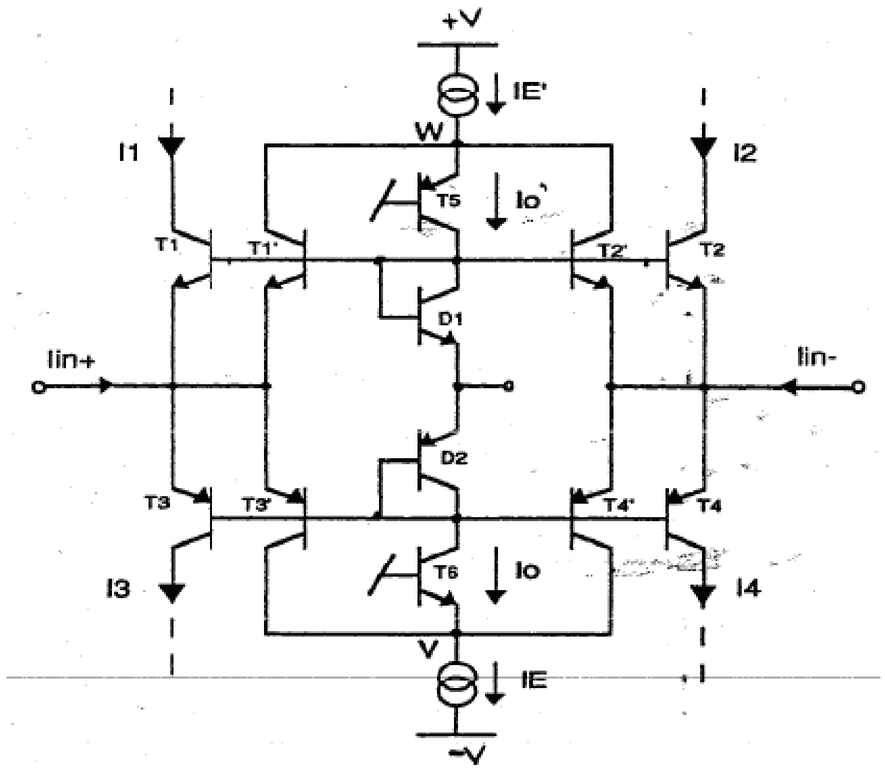
$$I_2 = I_3 = I_o + I_{in}/2$$
$$I_1 = I_4 = I_o - I_{in}/2$$

If input current is common and I_{in}>0, then

$$I_1 = I_2 = I_o - I_{in}/2$$
$$I_3 = I_4 = I_o + I_{in}/2$$

- This is also a realization for a current conveyor.

Input Stages [1]



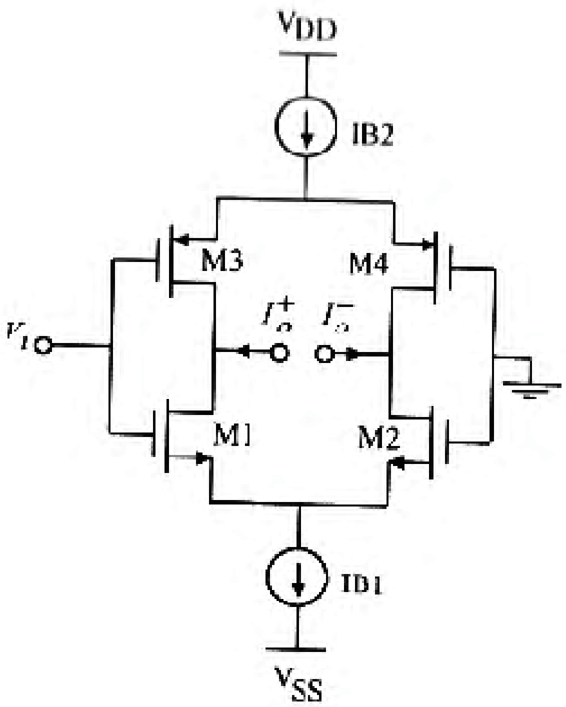
High CMRR dfferential input cell

$$I_E = 3 \cdot I_o$$

- When a common mode input current is applied (Iin>0), I1 and I2 will decrease.
- Then if output impedance of IE' is large enough, W terminal would be higher, so V_{BE} voltages of T1 and T2 increase.
- Thus, input voltage is kept almost stationary.

Output Stages [2]

Arbel Goldminz Output Stage: A well-known output stage which can be used in COA outputs.

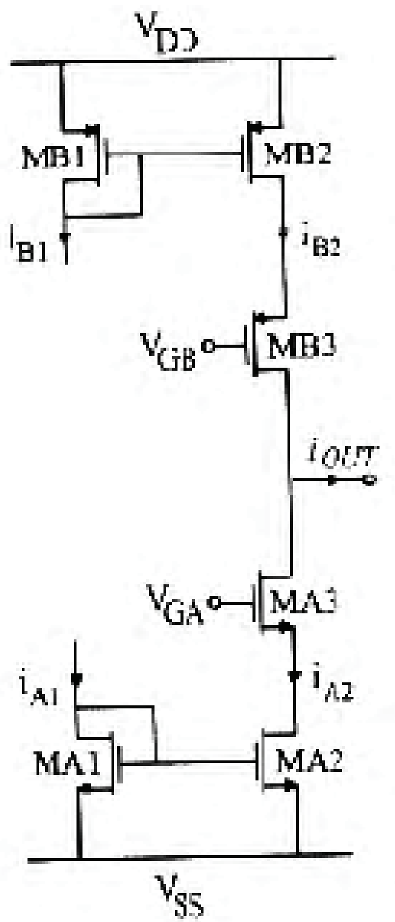


- It is suitable for two opposit phase outputs.
- Main advantage is high output impedance.

$$G_m = \frac{i_o^+}{v_i} = -\frac{i_o^-}{v_i} = \frac{1}{2}\left(g_{m1,2} + g_{m3,4}\right)$$

Output Stages [2]

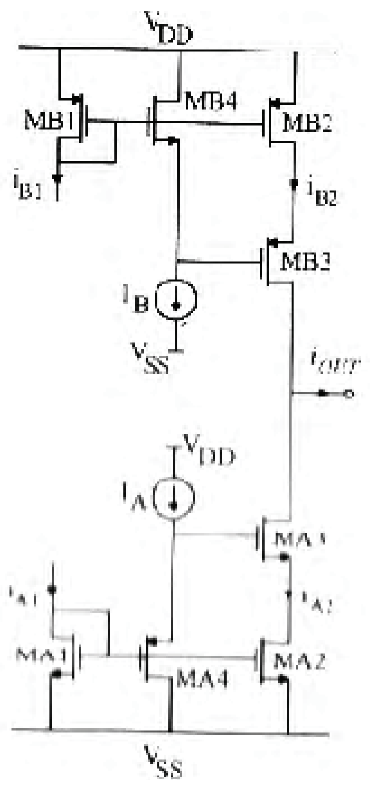
Cascoded current output stage

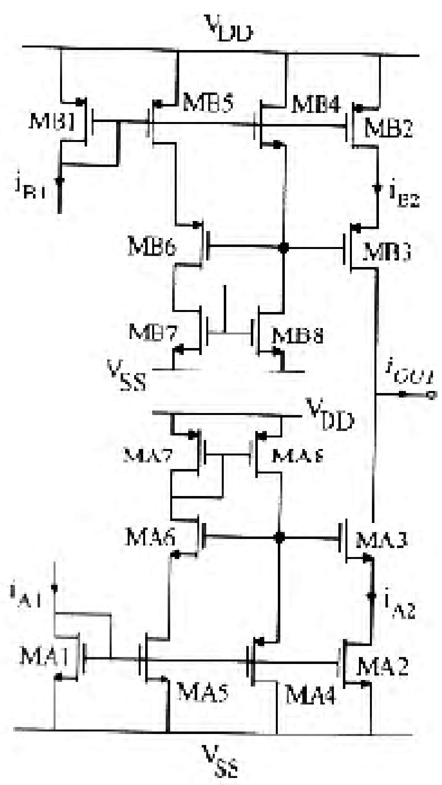


- In this output stage, high output resistance and high output current swing is achieved.
- However, it has the problem of channel length modulation in the output transistors MA2 and MB2

Output Stages [2]

Cascoded current output stage
with dynamic matching

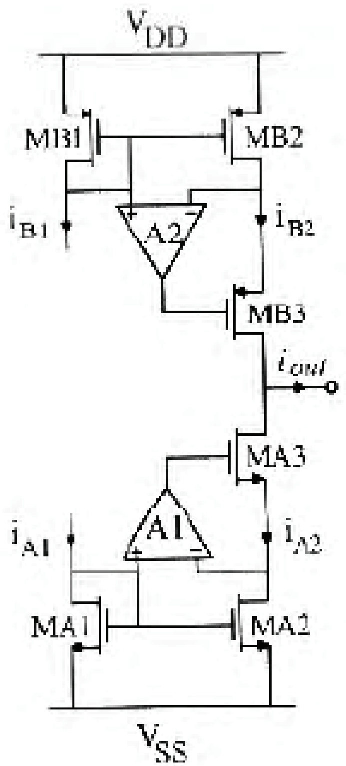




- ❑ Channel length modulation problem can be solved by using cascoded mirror with dynamic matching.
- ❑ MA4 and MB4 helps decreasing the nonlinearity which is caused by the channel length modulation.

Output Stages [2]

Gain boosted cascoded current output stage



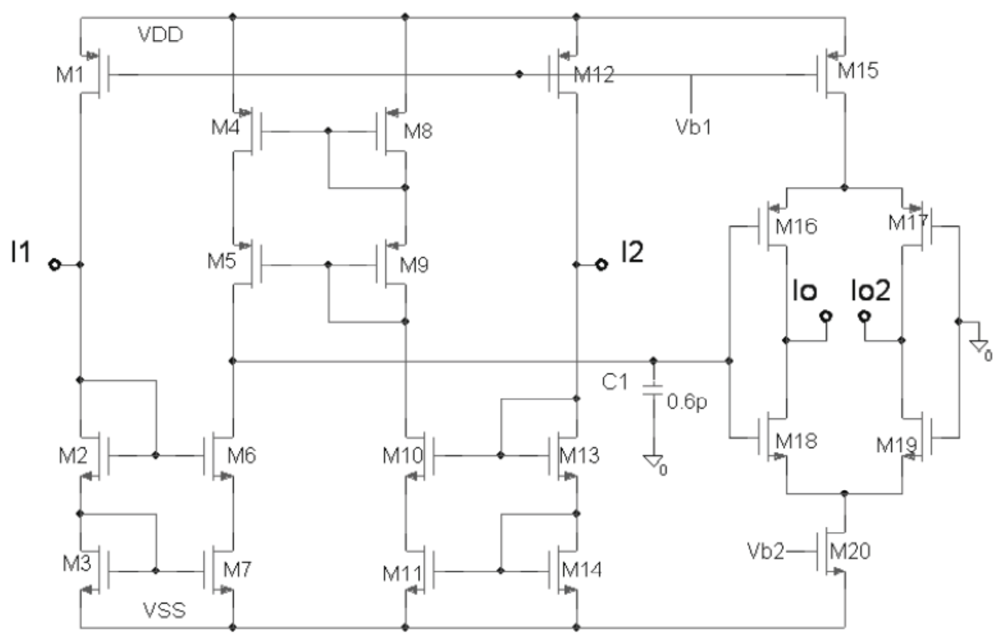
- The two current mirrors are composed of transistors MA1-MA3 and MB1-MB3 and two voltage amplifiers A1 and A2.
- The drain voltages of MA1, MA2 and MB1, MB2 are almost equal even for large currents.
- Thus a current output stage with high linearity performance is achieved.
- The use of voltage amplifiers also increases the output resistance to a larger value given by

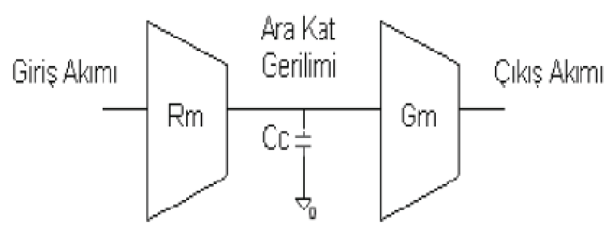
$$r_0 \cong (g_{mA3} r_{dA2} r_{dA3} A_1) // (g_{mB1} r_{dB2} r_{dB3} A_2)$$

Design Example:
CMOS COA – 1 [3]

A. Uygur, H. Kuntman, Basit ve Kullanışlı Bir Akım İşlemsel Kuvvetlendiricisi Tasarımı, ELECO’2004: Elektrik-Elektronik ve Bilgisayar Mühendisliği Sempozyumu, Bildiri Kitabı (Elektronik-Bilgisayar), s. 6-10, EMO Bursa Şubesi, 8-12 Aralık 2004, Bursa.

- A CMOS COA and its performance summary is given.
- Low impedance inputs are performed with diode connected transistors.
- High impedance outputs are obtained with Arbel Goldminz Output Stage.

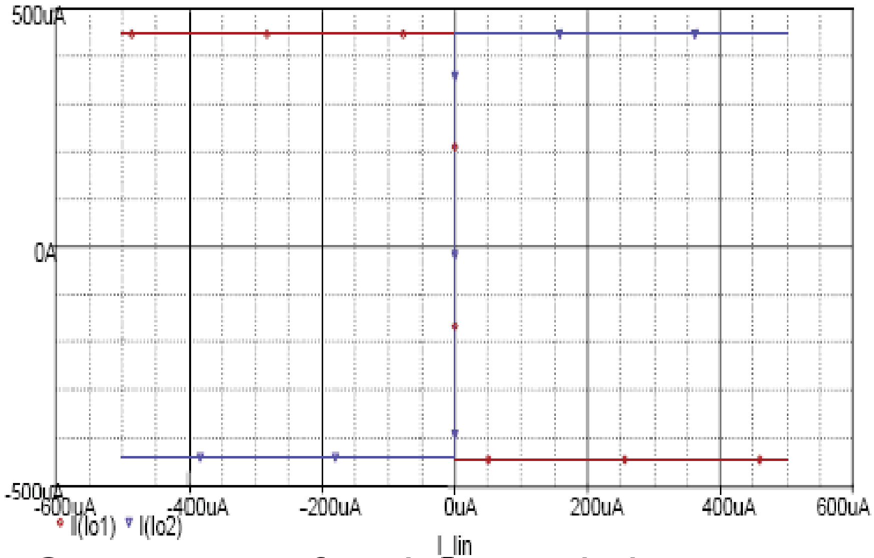




$$K_{dm} = R_A\left(\frac{gm_{16} + gm_{18}}{2}\right)$$

$$f_p = \frac{1}{2\pi R_A C_A}$$

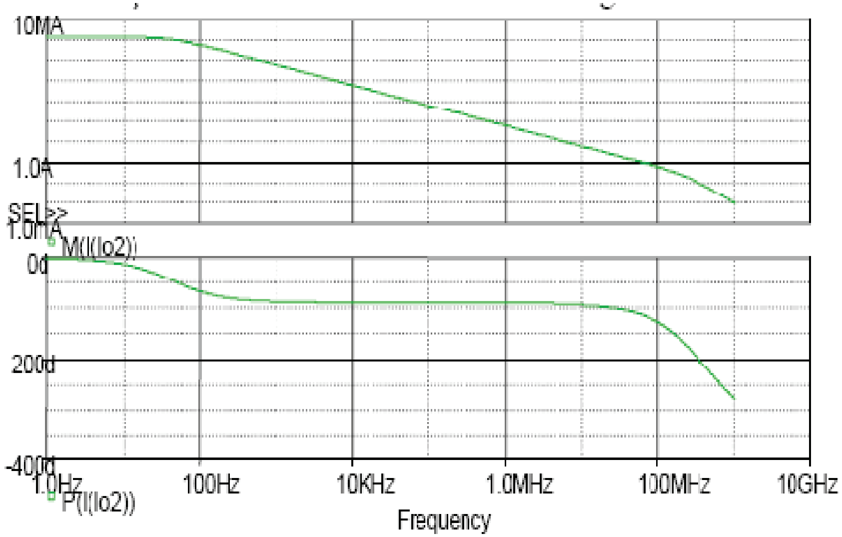
Design Example: CMOS COA – 1 [3]



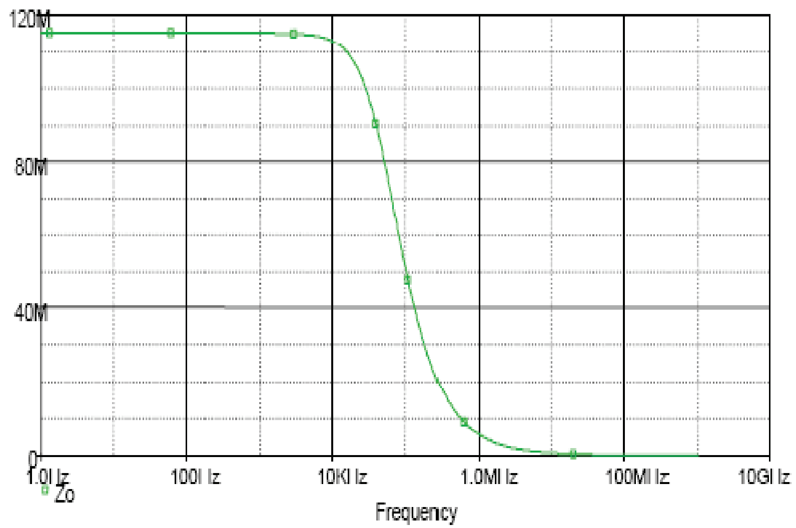
Current transfer characteristics

Besleme	+2.5V -2.5V
Kompanzasyon kapasitesi	(1 adet) 0.6pF
Birim kazanç band genişliği	60MHz
Faz payı	68°
Açık çevrim kazancı	123dB
Giriş akımı salınımı	≈ +100μA -400μA
Giriş dengesizlik akımı	-0.2μA
Güç tüketimi	4.7mW
Yükselme eğimi	100μA/11ns
Giriş Direnci	2kΩ
Çıkış Direnci	115MΩ

Performance summary



Simulated open-loop characteristics

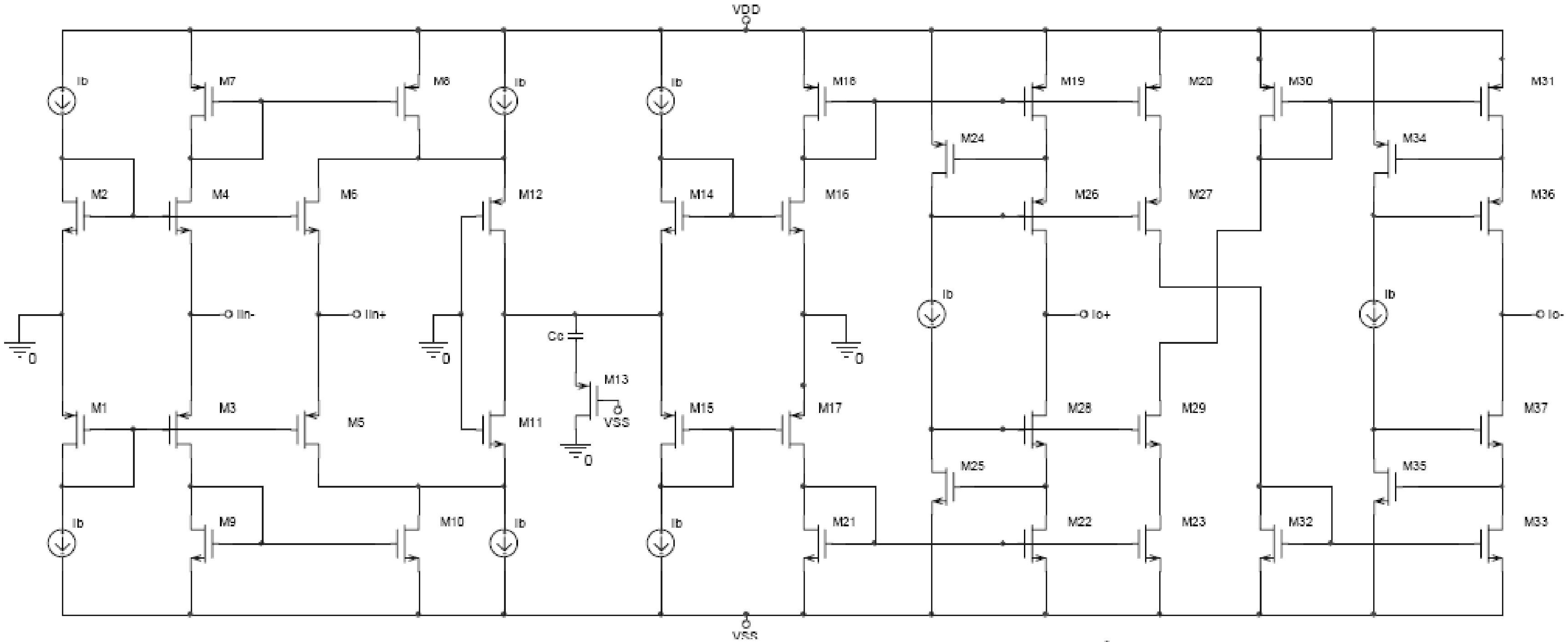


Simulated Output resistance

Design Example: CMOS COA - 2 [4]

M. Altun, H. Kuntman, “A High-Drive Fully Differential Current Mode Operational Amplifier Providing High Output Impedance And Filter Application”, Proceedings of ELECO 2007: The 5th International Conference on Electrical and Electronics Engineering, Electronics, pp. 44-47, 5-9 December 2007, Bursa, Turkey.

- Another CMOS COA example is shown.
- Circuit has improved input and output impedances and AC characteristics.
- Both input and output have Class-AB operation.



$$r_{in+} \cong \frac{1}{g_{m5} + g_{m6}}$$

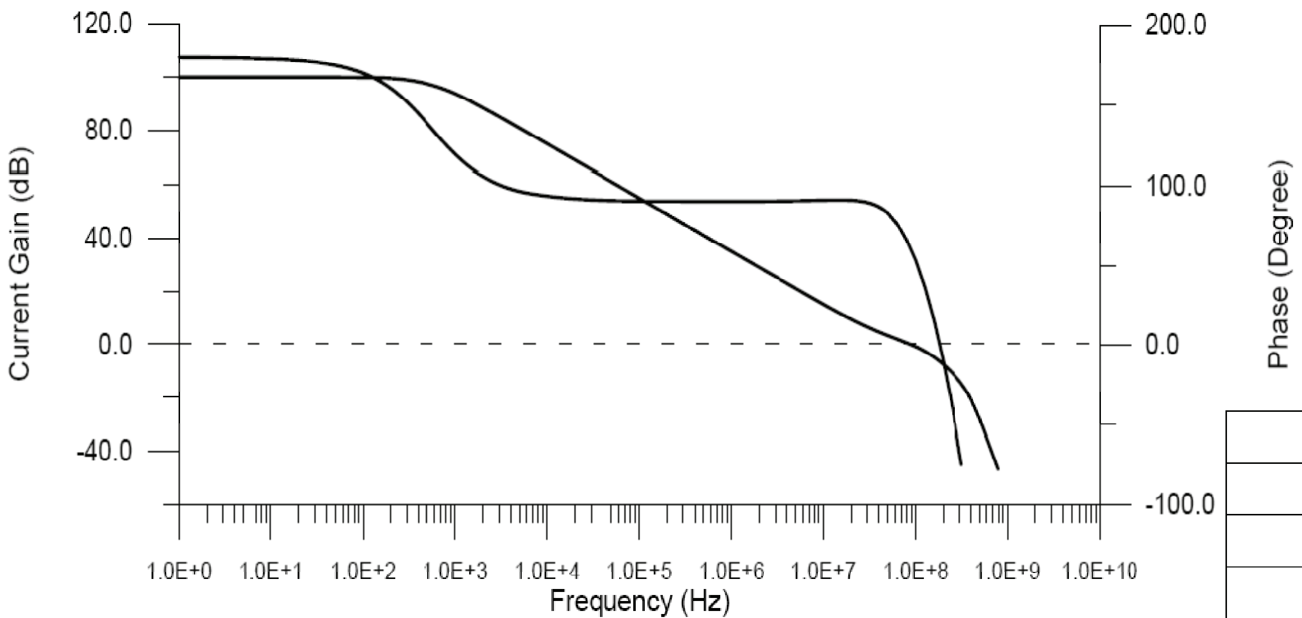
$$r_{in-} \cong \frac{1}{g_{m3} + g_{m4}}$$

$$r_{out+} = r_{out-} \cong \left[\frac{g_{ds26} g_{ds19} g_{ds24}}{g_{m26} g_{m24}} + \frac{g_{ds28} g_{ds22} g_{ds25}}{g_{m28} g_{m25}} \right]^{-1}$$

$$A_i(0) \cong \left[g_{m16} + g_{m17} \right] \left[\frac{g_{ds12} g_{ds8}}{g_{m12}} + \frac{g_{ds11} g_{ds10}}{g_{m11}} \right]^{-1}$$

$$f_{GBW} \cong \frac{1}{2\pi} \frac{g_{m16} + g_{m17}}{Cc}$$

Design Example: CMOS COA- 2 [4]



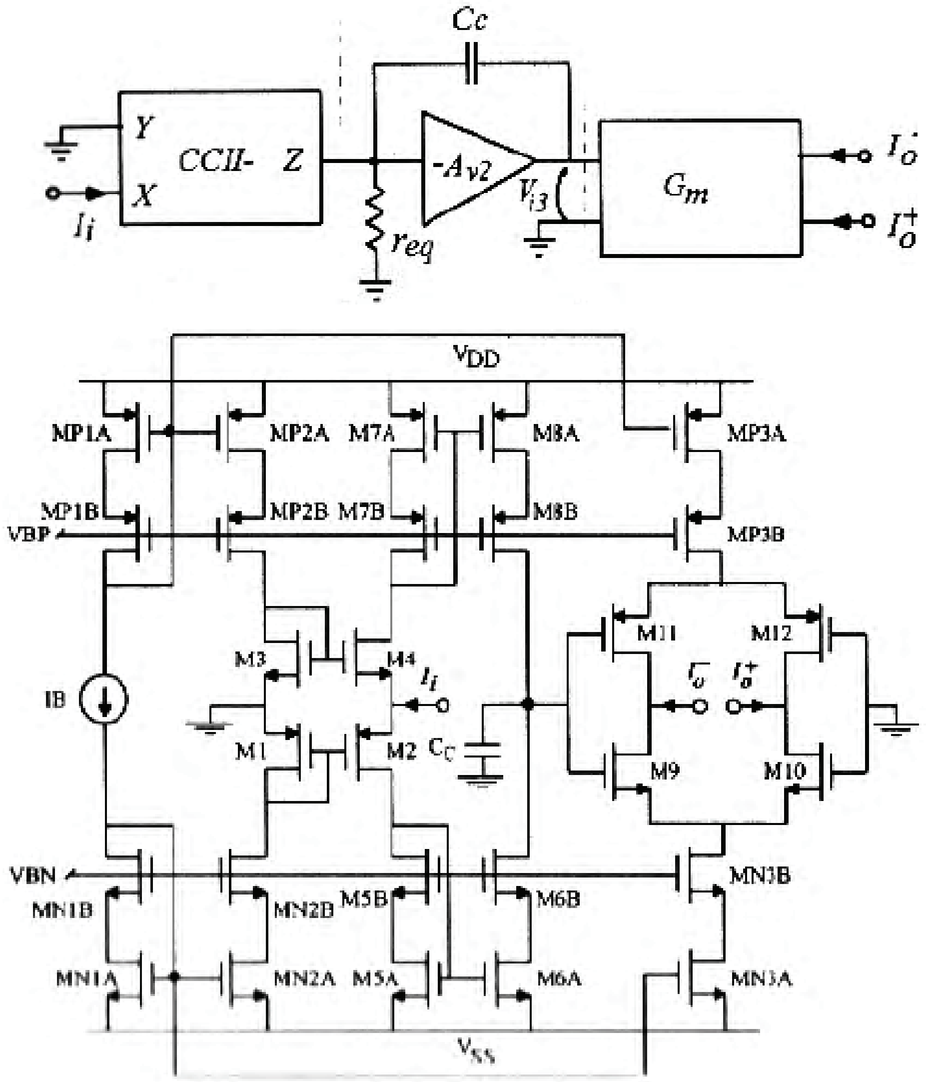
Simulated open-loop characteristics

Parameter	Value
Power Dissipation	0.72 mW
Open-Loop Gain	100 dB
GBW	85 MHz
Phase Margin (Cc=1.5p Rc=2.2kΩ)	62°
Output Voltage Range	±1 V
Output Current Range	±250 μA
Slew Rate	100uA/ns
Input Resistance (n, p)	1.6 kΩ
Output Resistance	6.1 GΩ
Input Voltage Offset (n,p)	≈ 0.1mV

Performance summary

Design Example: CMOS COA - 3 [5]

E. Bruun, "Bandwidth optimization of a low power high speed CMOS current op-amps," *Analog Integrated Circuits Signal Process.*, vol. 7, pp. 11–19, Jan. 1995.



Technology	2 µm
V_{DD}-V_{SS}	3 V
DC Power	≅90µW
Gain	96 dB
GBW	128 MHz
M_ϕ	---

In this example, class-AB current conveyor is used as the input stage, floating current source is used as the output stage.

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[5] E. Bruun, "Bandwidth optimization of a low power high speed CMOS current op-amps," Analog Integrated Circuits Signal Process., vol. 7, pp. 11–19, Jan. 1995.