Design of a fully differential current mode opamp with improved input-output impedances and its filter applications

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Current Mode Analog Circuit Design

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WHY CURRENT MODE?

In recent years, current-mode approach has been extensively investigated. It has some advantages [1,2]:

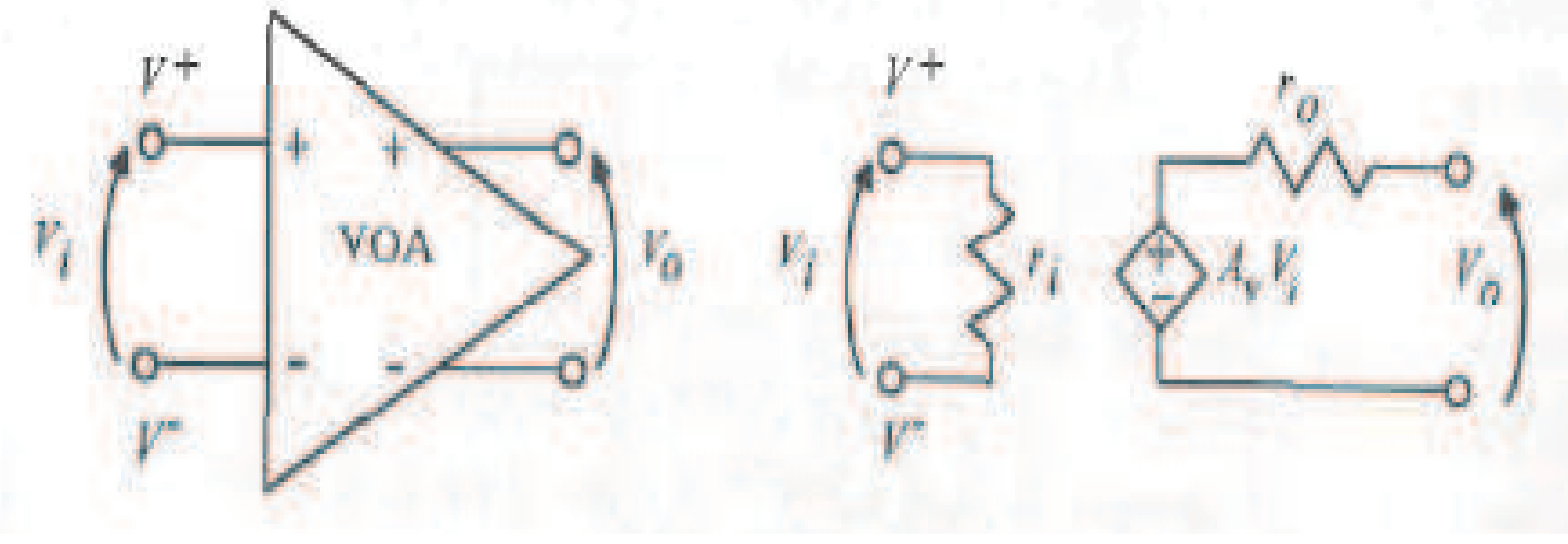
1. Wide bandwidth
2. Wide dynamic range
3. Simple circuitry
4. Low voltage design

OPERATIONAL AMPLIFIERS

1. Voltage opamp (VOA)
2. Current opamp (COA)
3. Current feedback opamp (CFOA)
4. Transconductance opamp (OTA)

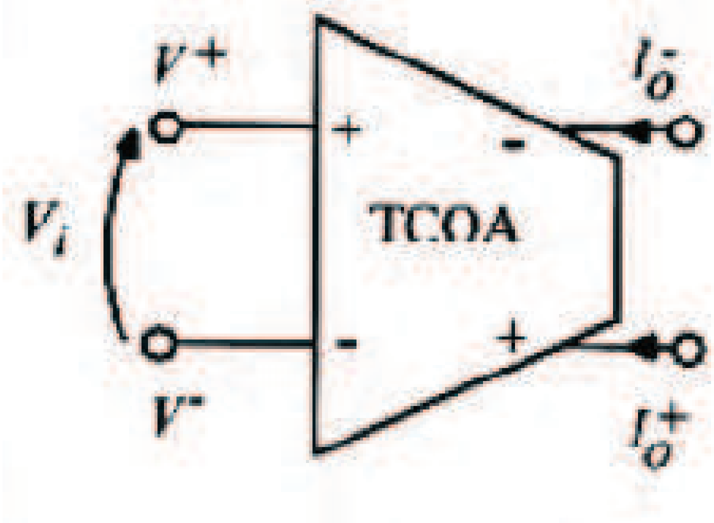
VOLTAGE OPAMP (VOA)

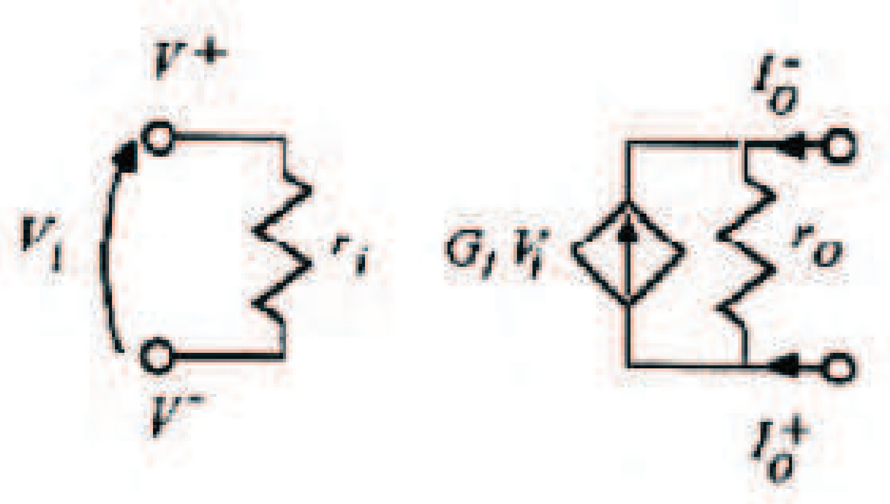
Voltage opamp(VOA): Voltage controlled voltage source with infinite voltage gain and input resistance, zero output resistance[3].



TRANSCONDUCTANCE OPAMP (OTA)

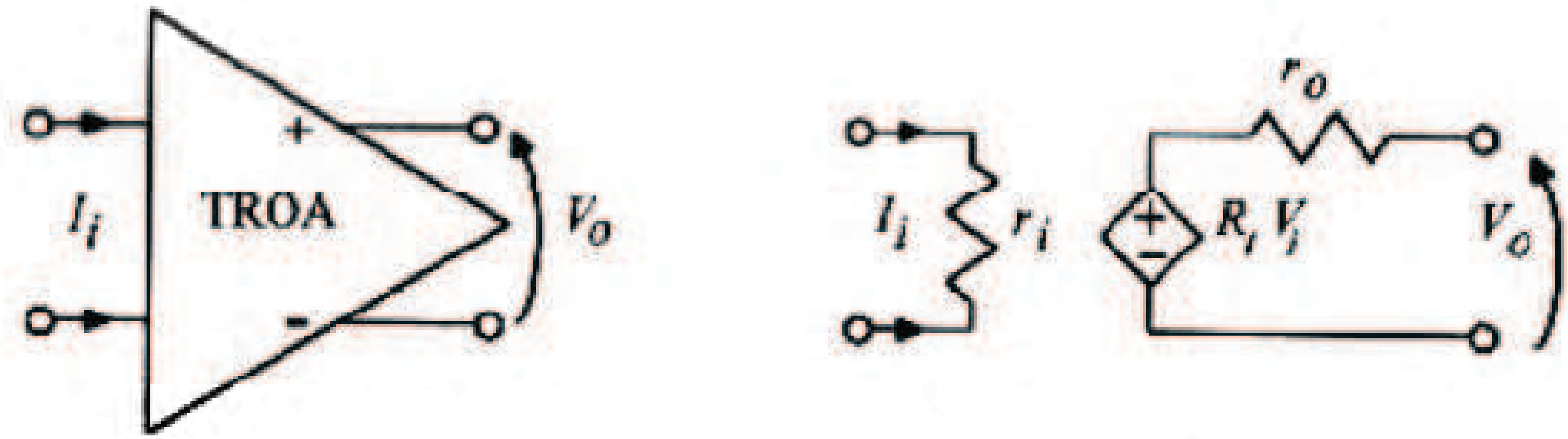
Transconductance opamp (OTA): voltage controlled current source with infinite transconductance gain, input and output resistances[3].



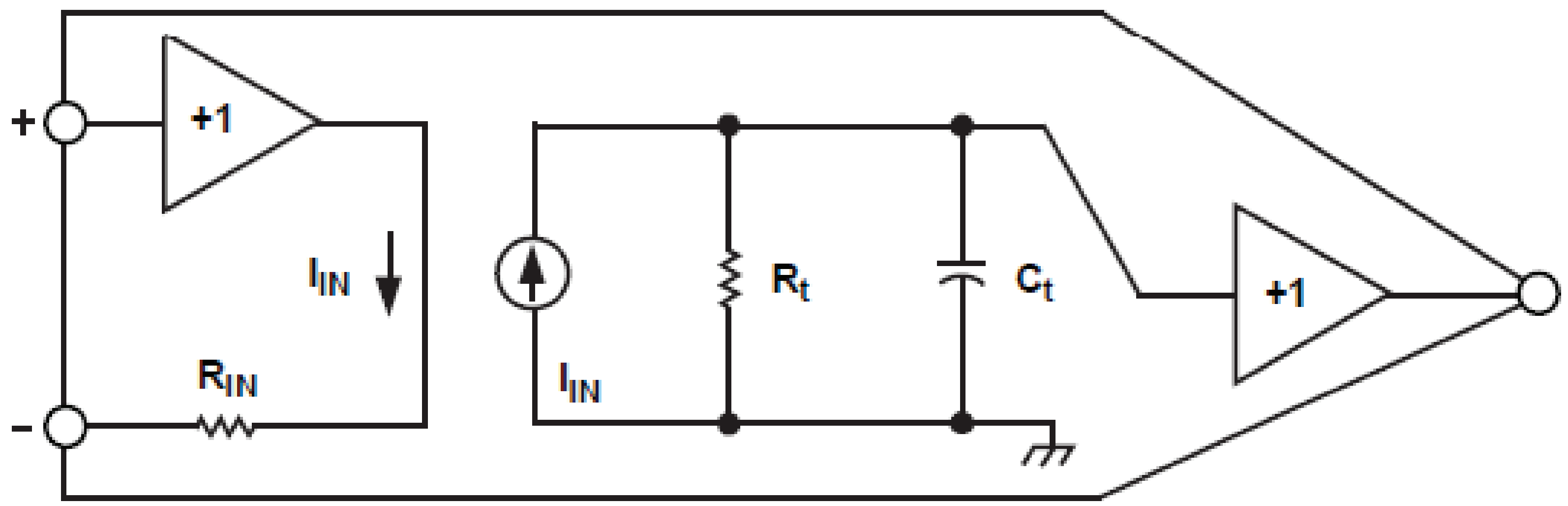


CURRENT FEEDBACK OPAMP (CFOA)

Current feedback opamp (CFOA): current controlled voltage source with infinite transresistance gain and zero input and output resistances.

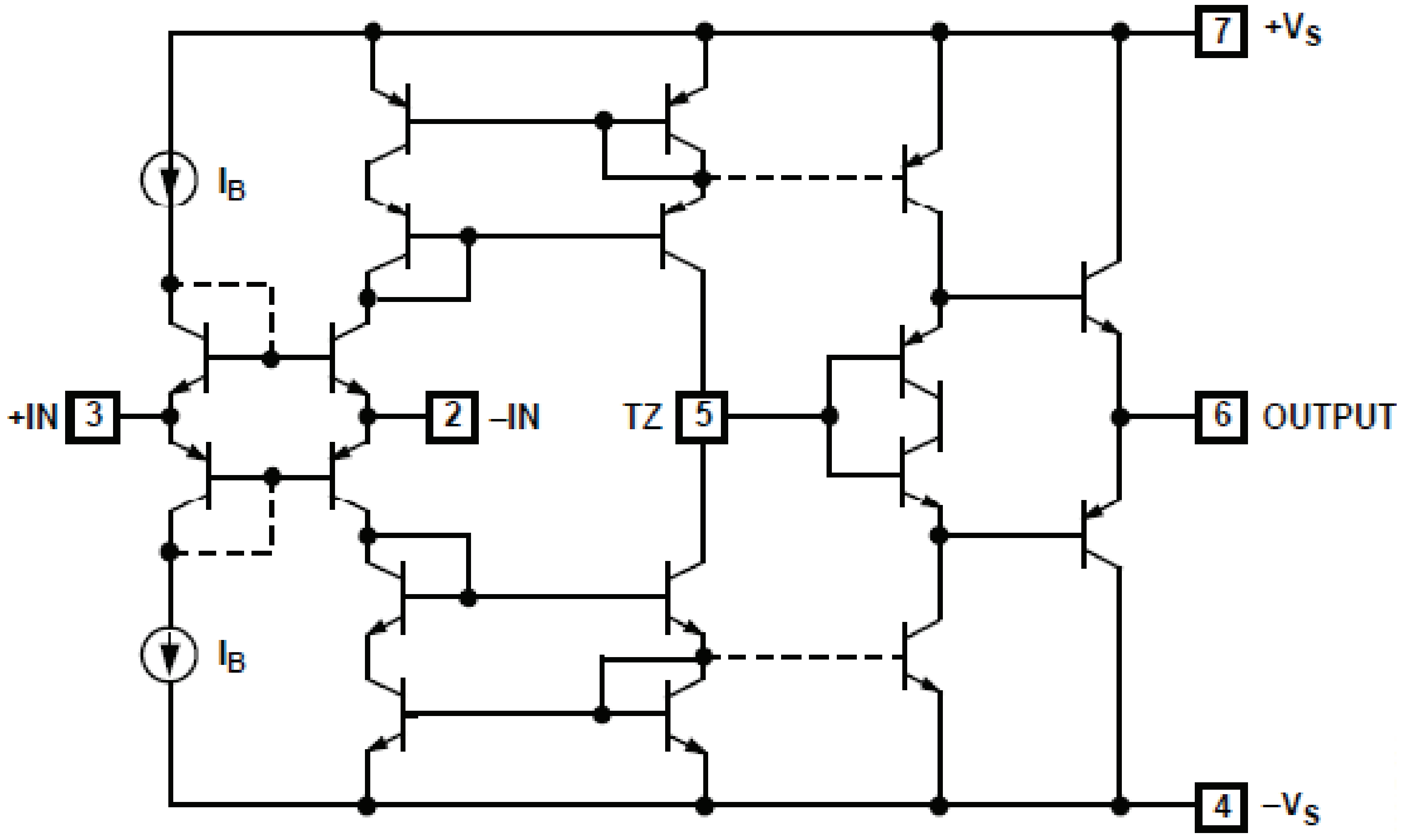


AD844 CFOA



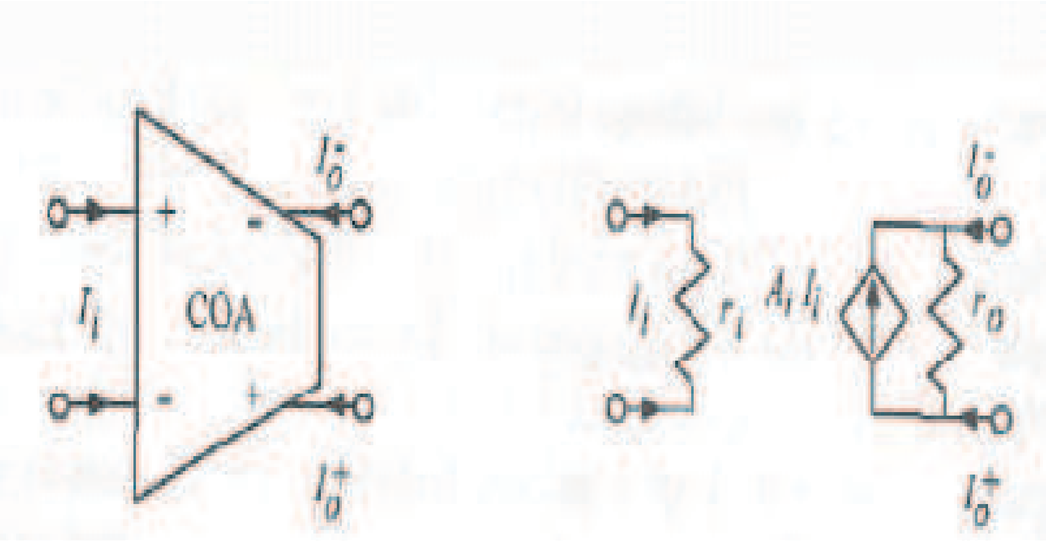
AD844 is a current feedback opamp. A CCII input stage is followed by a unity gain buffer which is the output stage[4].

AD844 CFOA



CURRENT OPAMP (COA)

Current opamp (COA): current controlled current source with <u>infinite current gain</u> and output resistance, zero input resistance[3].



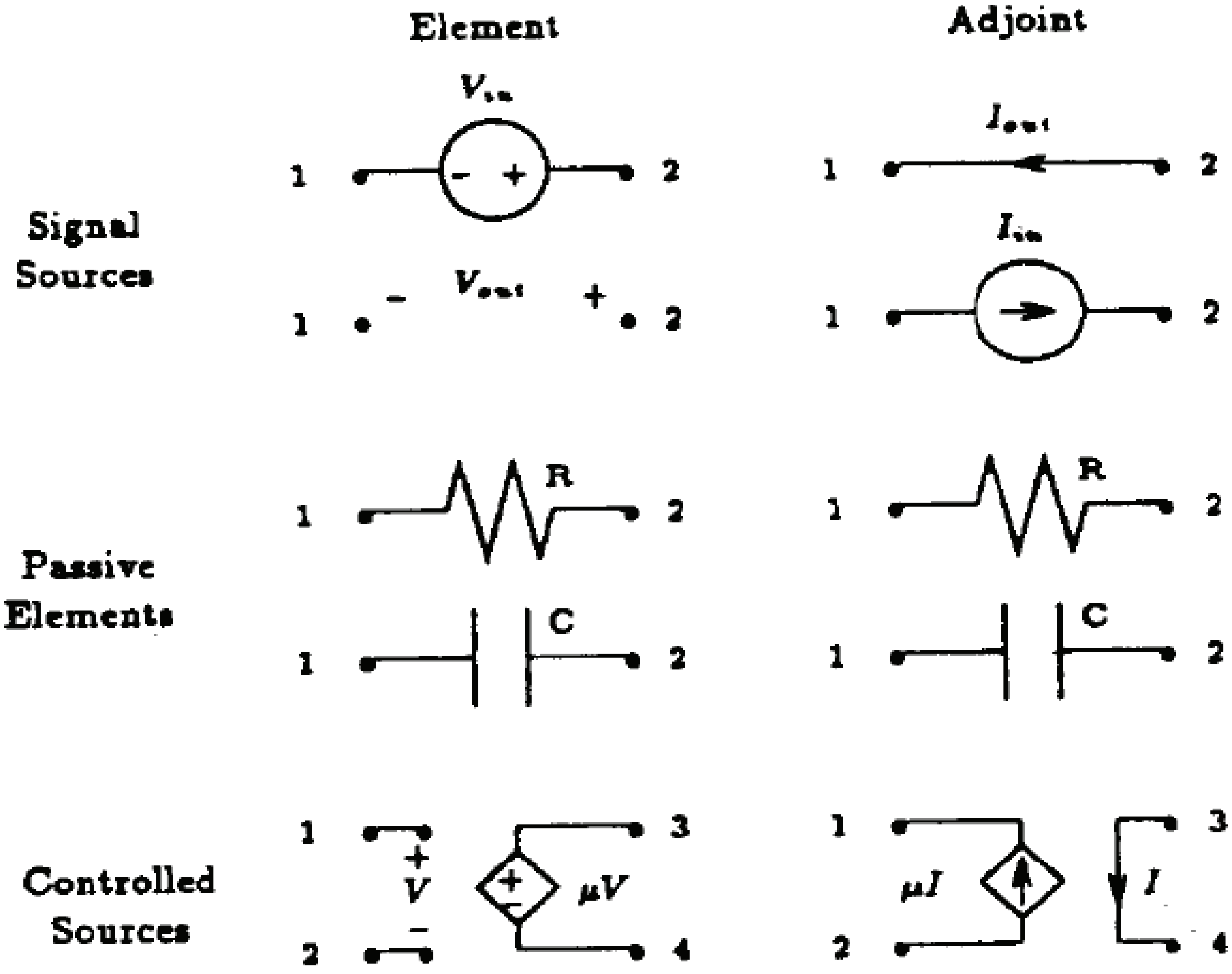
$$\begin{bmatrix} V_{IN+} \\ V_{IN-} \\ I_{O+} \\ I_{O-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ K & -K & 0 & 0 \\ -K & K & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{IN+} \\ I_{IN-} \\ V_{O+} \\ V_{O-} \end{bmatrix}$$

CURRENT OPAMP (COA)

The main advantage of using COA is its ability to replace with the voltage opamp when applying the adjoint network theorem in voltage mode to current mode transformation[5].

THE ADJOINT NETWORK THEOREM

Creating an alternative realization of a linear network having the same transfer function can be performed using the principle of adjoint networks[6]. This principle forms the basis of current-based circuits. A voltage mode circuit can be transformed to a current mode one by using the adjoint elements [7].


Element
Adjoint
Signal Sources
V_{in}
1
- +
2
I_{out}
1
2
1 -
V_{out}
+ 2
I_{in}
1
2
Passive Elements
R
1
2
R
1
2
C
1
2
C
1
2
Controlled Sources
1
+
V
-
2
+
-
μV
3
4
1
2
μI
I
3
4

THE ADJOINT NETWORK THEOREM

We can describe the adjoint transformation procedure as follows: Replace the input voltage source by a short circuit and call the current flowing through it the new output response variable.

Next connect a current source to the output port of the original circuit. This will be the new input and the transfer function of this “adjoint circuit” will be the ratio of two currents[5].

THE ADJOINT NETWORK THEOREM

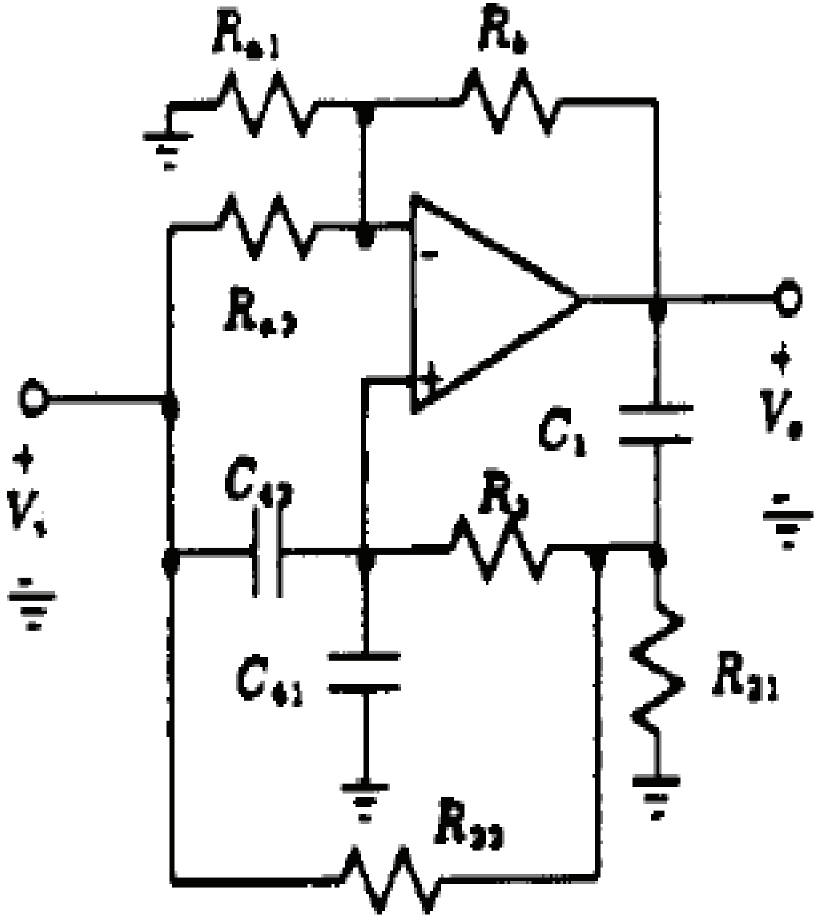
Finally replace each voltage-controlled voltage source(VCVS) by a current-controlled current source(CCCS). The input terminals of the CCCS should be connected to the output port of the VCVS and conversely, the output port of the CCCS is connected to the input port of the VCVS[5].

THE ADJOINT NETWORK THEOREM

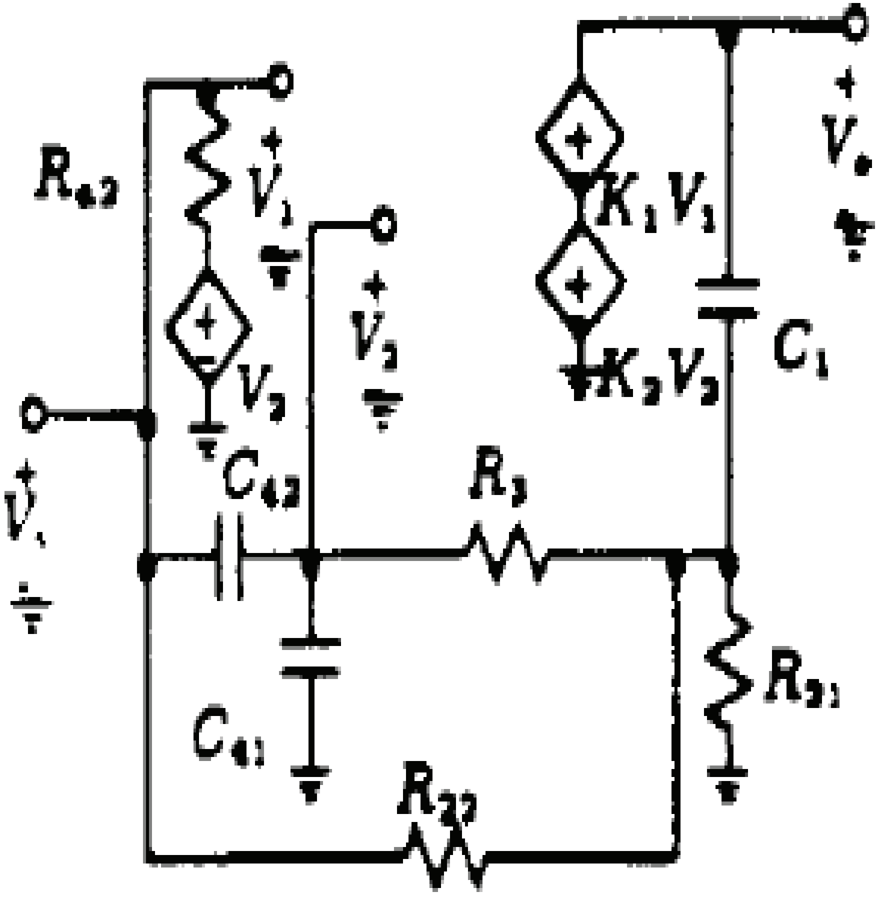
The resistors and capacitors are left unchanged. The result is an alternate circuit with the exact same transfer function[5].

Moreover two circuits have identical sensitivities to component variations[7].

ADJOINT NETWORK EXAMPLE

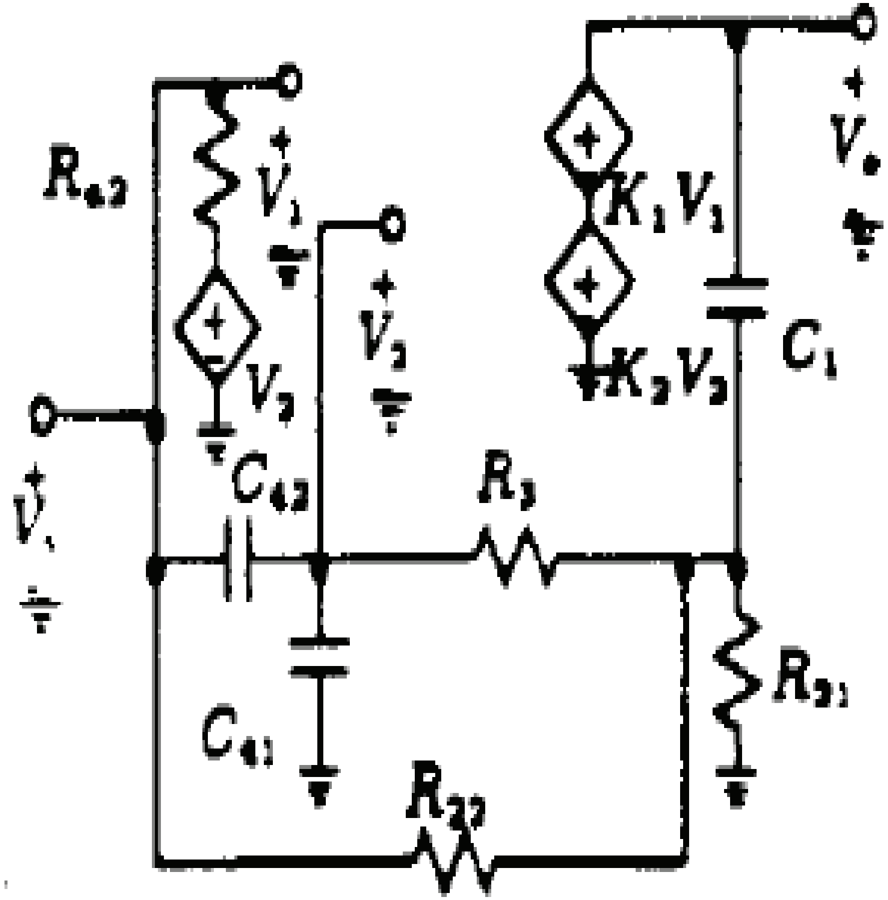


Low pass biquad (LPB)

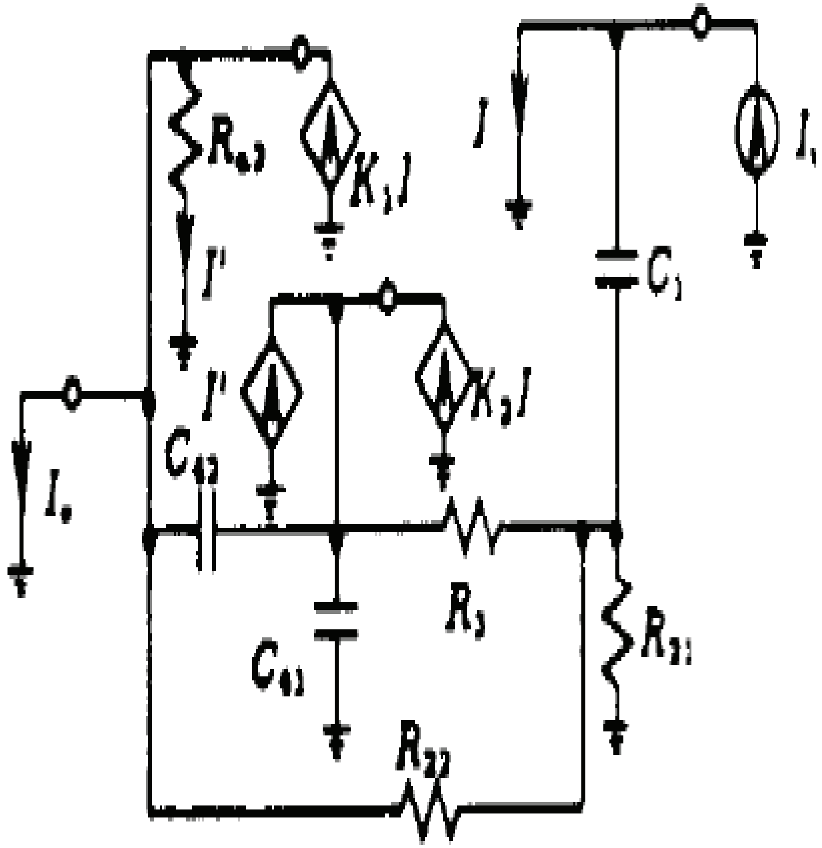


Equivalent VCVS representation

ADJOINT NETWORK EXAMPLE



Equivalent VCVS representation



Corresponding current-mode adjoint circuit

CURRENT OPAMP (COA)

It is not difficult to increase output resistance and current gain of a COA to a reasonable value. However, achieving a very low input resistance is a problem[8].

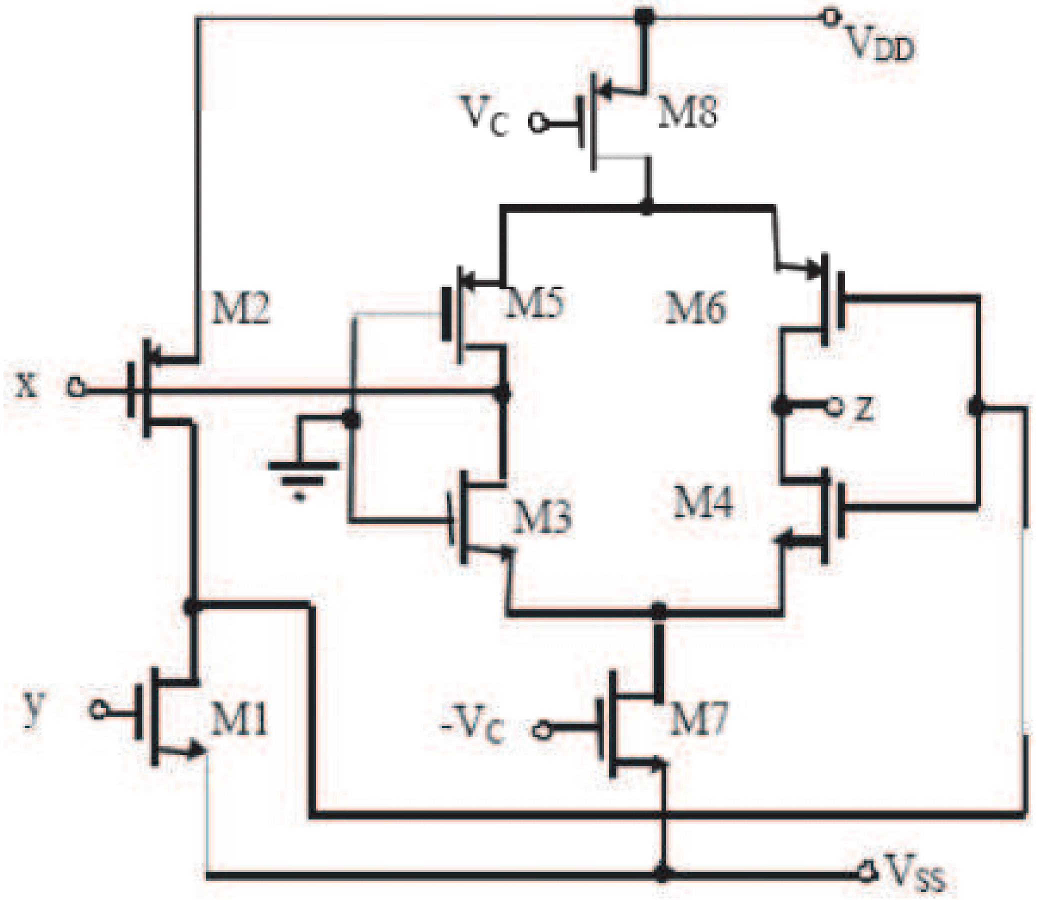
Some complicated negative feedback configurations have been suggested in [9,10] but it generally worsens the frequency response.

Positive feedbak is another solution to lower the input resistance[8,11,12].

ARBEL GOLDMINZ OUTPUT STAGE

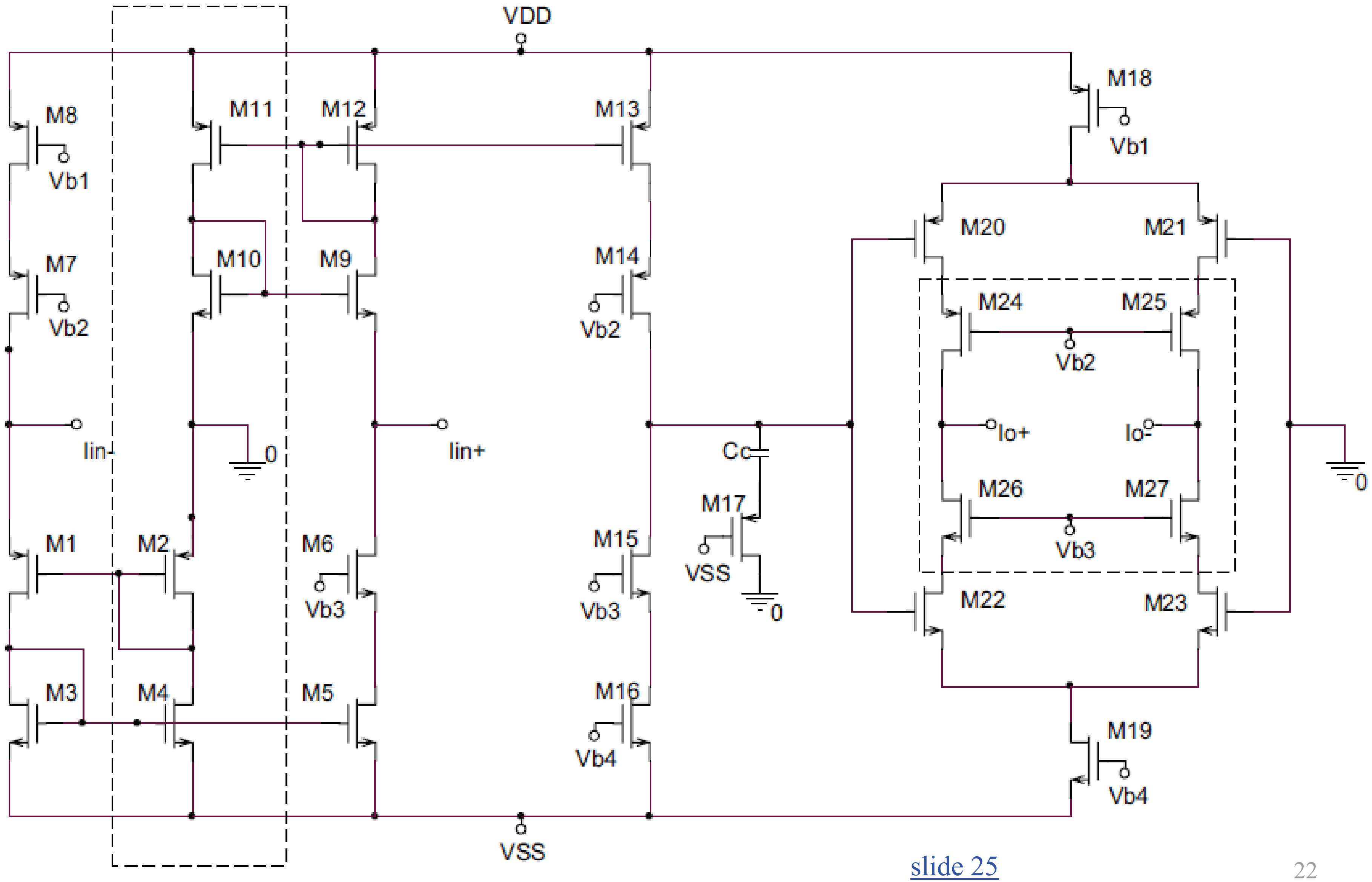
Arbel Goldminz output stage, which is the conventional current output stage, suffers from its output resistance[13]. An improved version of this stage is discussed in [8].

ARBEL GOLDMINZ OUTPUT STAGE



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

PROPOSED COA



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PROPOSED COA

Transistors	$W(\mu m)/L(\mu m)$
M1, M2	20/0.7
M3, M4, M5, M6	20/1
M7	10/0.7
M8	27/0.7
M9, M10	15/0.7
M11, M12, M13	20/1.4
M14	40/1.4
M15	20/0.7
M16	17.8/1.4
M17	12.5/1
M18	118/1
M19	47/1
M20, M21	75/1
M22, M23	40/0.7
M24, M25	100/1
M26, M27	60/0.7

Parameter	Value
$V_{DD} - V_{SS}$	±1.5 V
V_{b1}, V_{b2}	0.6 V, −0.3 V
V_{b3}, V_{b4}	0.3 V, −0.8 V
I_{D8}, I_{D16}	30 µA
I_{D18}, I_{D19}	100 µA

PROPOSED COA

The amplifier is configured from a differential input transimpedance stage followed by a differential output transconductance stage. Shown in dashed lines at the input stage, M2, M4 and M10, M11 compose positive feedback loops to reduce positive and negative input resistances, respectively[8]. The frequency response is not noteworthy affected since only four extra transistors are added.

slide 22

PROPOSED COA

If no positive feedback is applied to the inputs, the input resistances will be as shown:

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

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

And generally these values are not low enough.

PROPOSED COA

However, if some positive feedback is applied to the inputs, the input resistances will change as shown in [8]:

$$r_{\text{in}-} \cong \frac{1}{g_{m1}g_{m3}}\left[(g_{\text{ds1}} + g_{m3} + g_{\text{ds3}}) - \frac{g_{m1}g_{m4}}{g_{\text{ds4}} + g_{m2} + g_{\text{ds2}}}\right].$$

$$r_{\text{in}+} \cong \frac{1}{g_{m9}g_{m12}}\left[(g_{\text{ds9}} + g_{m12} + g_{\text{ds12}}) - \frac{g_{m9}g_{m11}}{g_{\text{ds11}} + g_{m10} + g_{\text{ds10}}}\right].$$

PROPOSED COA

The second terms mainly affect input resistance value . That is, if it is selected close to zero, r_{in} also goes near zero[8].

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

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

PROPOSED COA

Furthermore, these values must be always chosen as positive. Otherwise, because of the negative input resistances, the problem of stability will occur. To overcome that problem, the values can be choosen as follows, as suggested in [8].

$$g_{m3} = g_{m4},\ g_{m1} = g_{m2},\ g_{m11} = g_{m12},\ g_{m9} = g_{m10}$$

Selecting W/L ratios equal will make g_m s equal.

PROPOSED COA

Output resistance of traditional current output stage (Arbel Goldminz) is:

$$r_{\text{out}+} = r_{\text{out}-} \cong \left[\left(\frac{g_{m20} g_{\text{ds}21}}{g_{m21} + g_{m20}} \right) + \left(\frac{g_{m22} g_{\text{ds}23}}{g_{m23} + g_{m22}} \right) \right]^{-1}$$

M24, M25, M26 and M27 in dashed line are added to the conventional current output stage for getting very big output resistance values[8].

PROPOSED COA

The output resistance of the proposed COA is:

$$r_{\text{out}+} = r_{\text{out}-} \cong \left[\left(\frac{g_{m20} g_{\text{ds}21} g_{\text{ds}25}}{g_{m25}(g_{m21} + g_{m20})} \right) + \left(\frac{g_{m22} g_{\text{ds}23} g_{\text{ds}27}}{g_{m27}(g_{m23} + g_{m22})} \right) \right]^{-1}.$$

It is approximately $g_m r_o$ times bigger than the traditional Arbel Goldminz output stage[8].

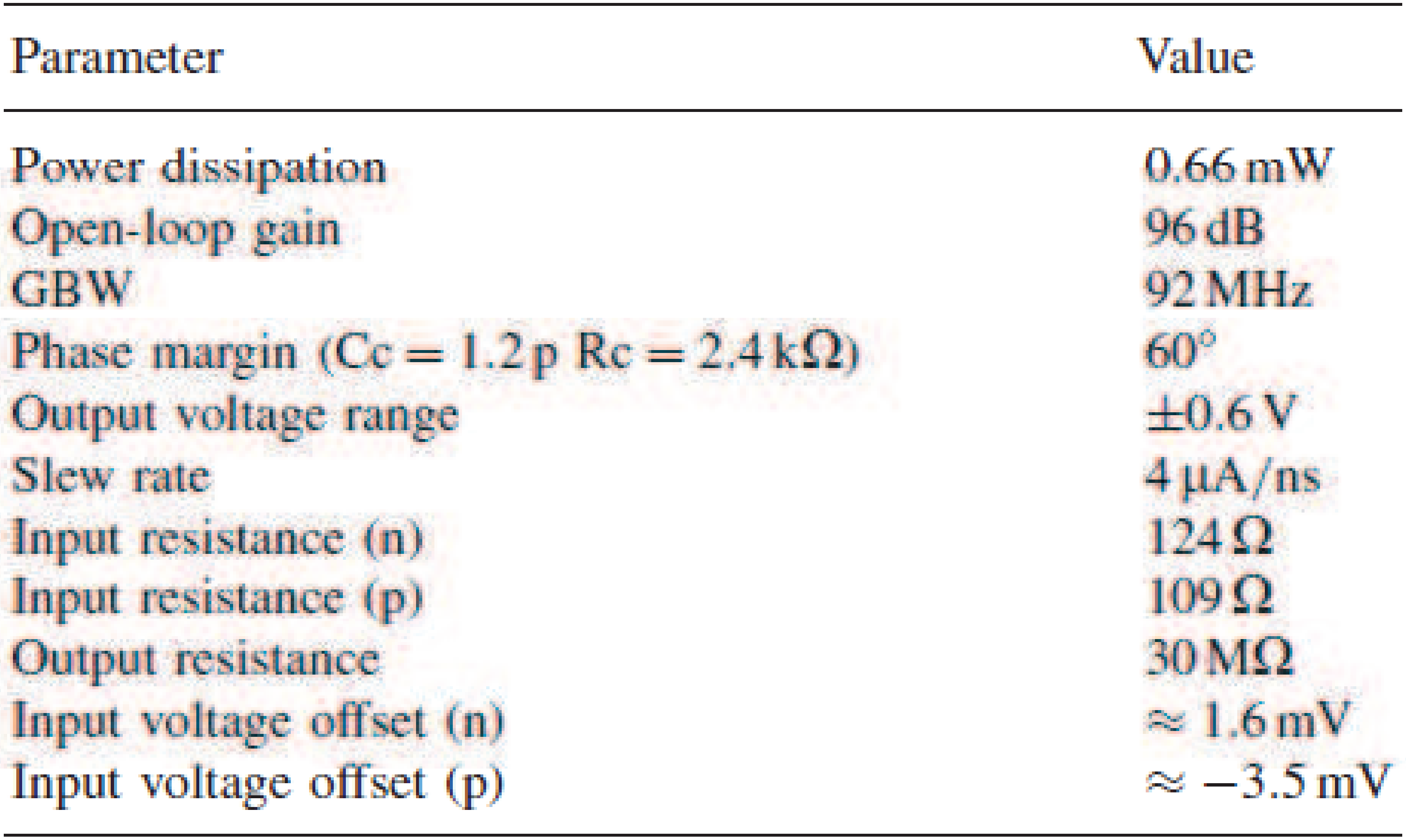
PROPOSED COA

M_{17} and C_C are used for compensation. M17 forms a resistor and improves the frequency response of the COA. The DC current gain and the gain-bandwidth product are given as follows[8]:

$$A_i(0) \cong \frac{g_{m20} g_{m22}}{2} \left[\frac{g_{ds14} g_{ds13}}{g_{m14}} + \frac{g_{ds15} g_{ds16}}{g_{m15}} \right]^{-1},$$

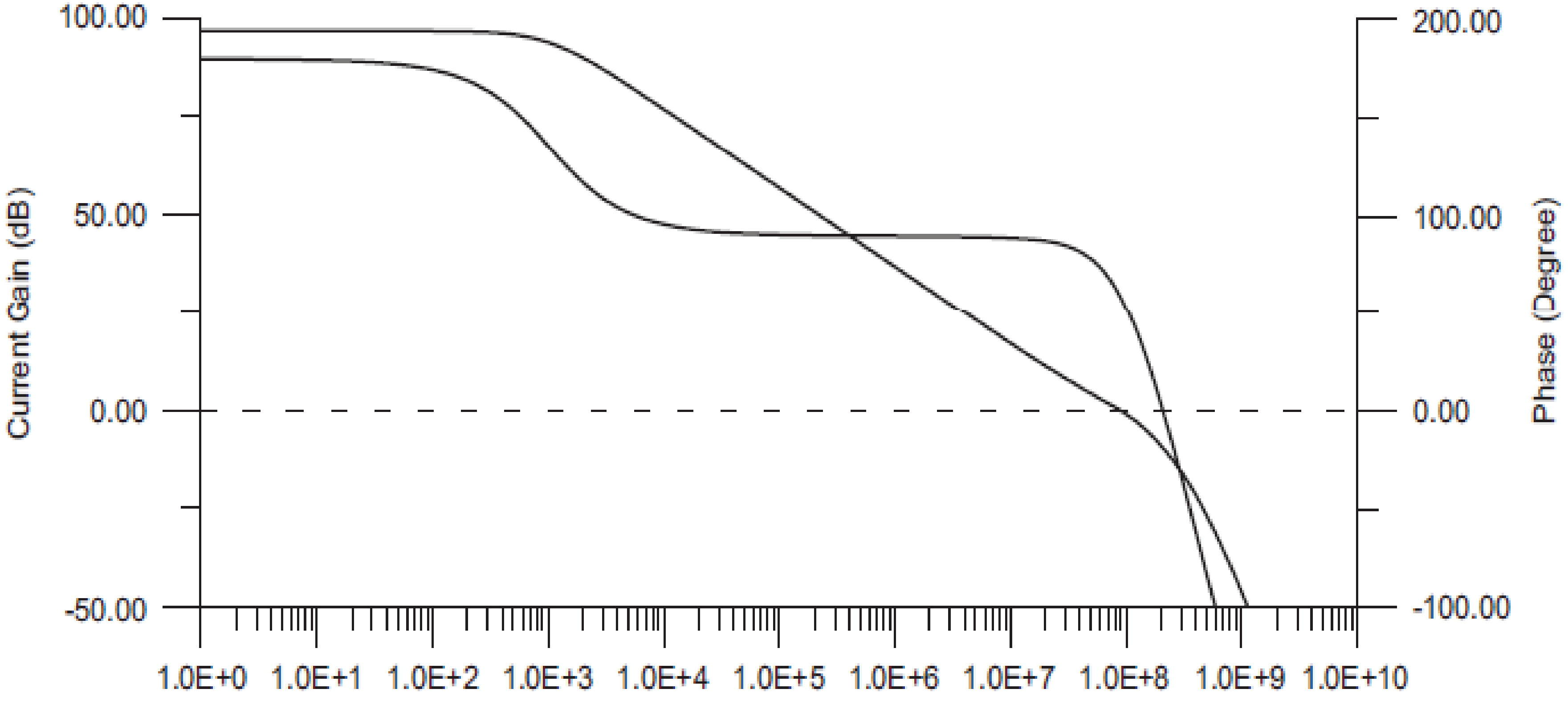
$$f_{GBW} \cong \frac{1}{2\pi} \frac{g_{m20} + g_{m22}}{2Cc}.$$

PERFORMANCE OF THE PROPOSED COA



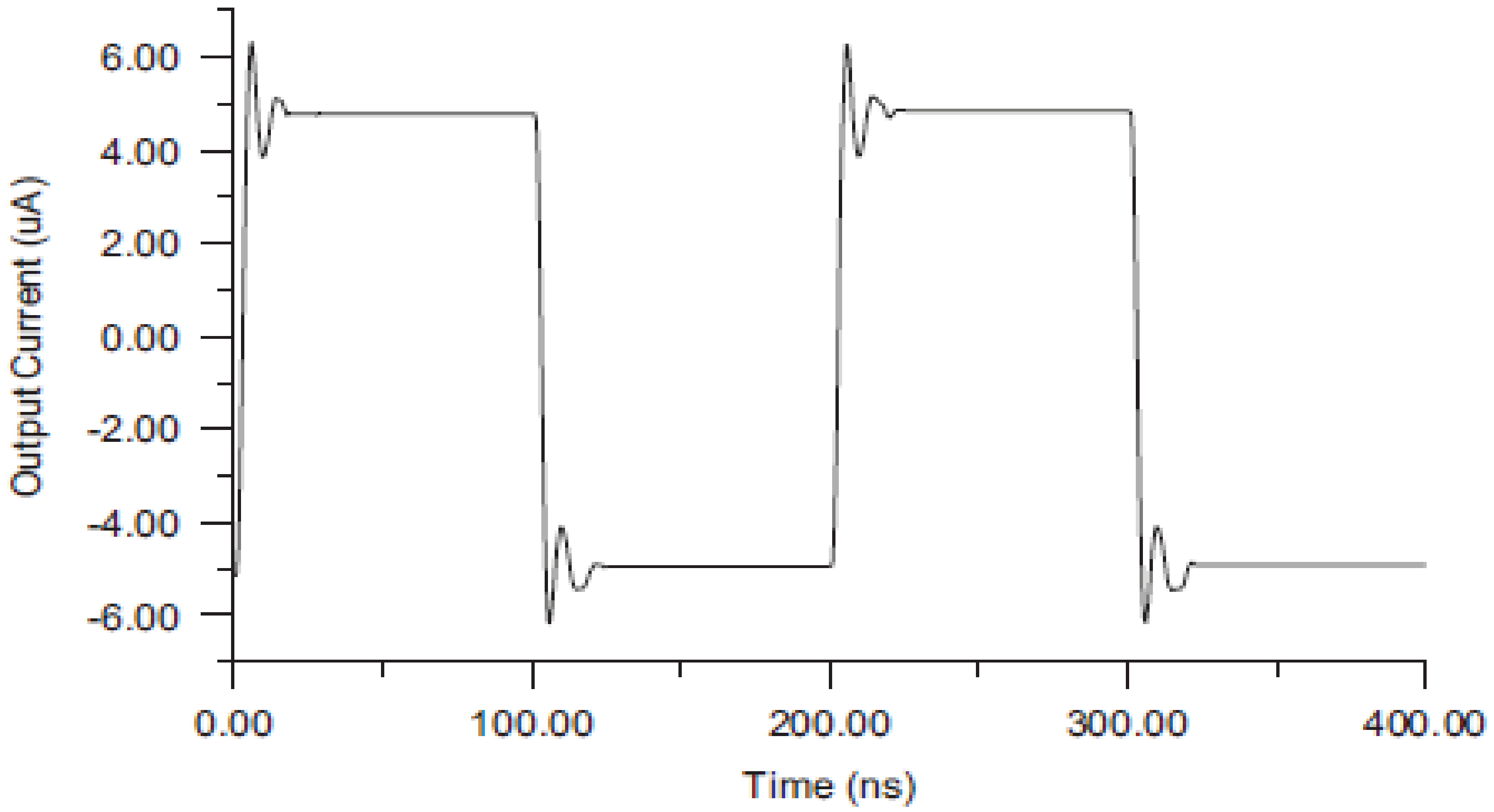
Parameter	Value
Power dissipation	0.66 mW
Open-loop gain	96 dB
GBW	92 MHz
Phase margin ($Cc = 1.2\,p$ $Rc = 2.4\,k\Omega$)	60°
Output voltage range	±0.6 V
Slew rate	4 µA/ns
Input resistance (n)	124 Ω
Input resistance (p)	109 Ω
Output resistance	30 MΩ
Input voltage offset (n)	≈ 1.6 mV
Input voltage offset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

PERFORMANCE OF THE PROPOSED COA



Open-loop frequency response of the COA.

PERFORMANCE OF THE PROPOSED COA



Response of the COA in unity-gain feedback to a ±5μA input step ($f = 5\,\text{MHz}$).

PERFORMANCE OF THE PROPOSED COA

- ✓ 0.35μ model parameters was used in spice simulations.
- ✓ Threshold voltages of the mosfets are nearly 0.5V and -0.7V for NMOS and PMOS respectively.
- ✓ As a result of the class A operation, speed of the COA is limited by quiescent current.

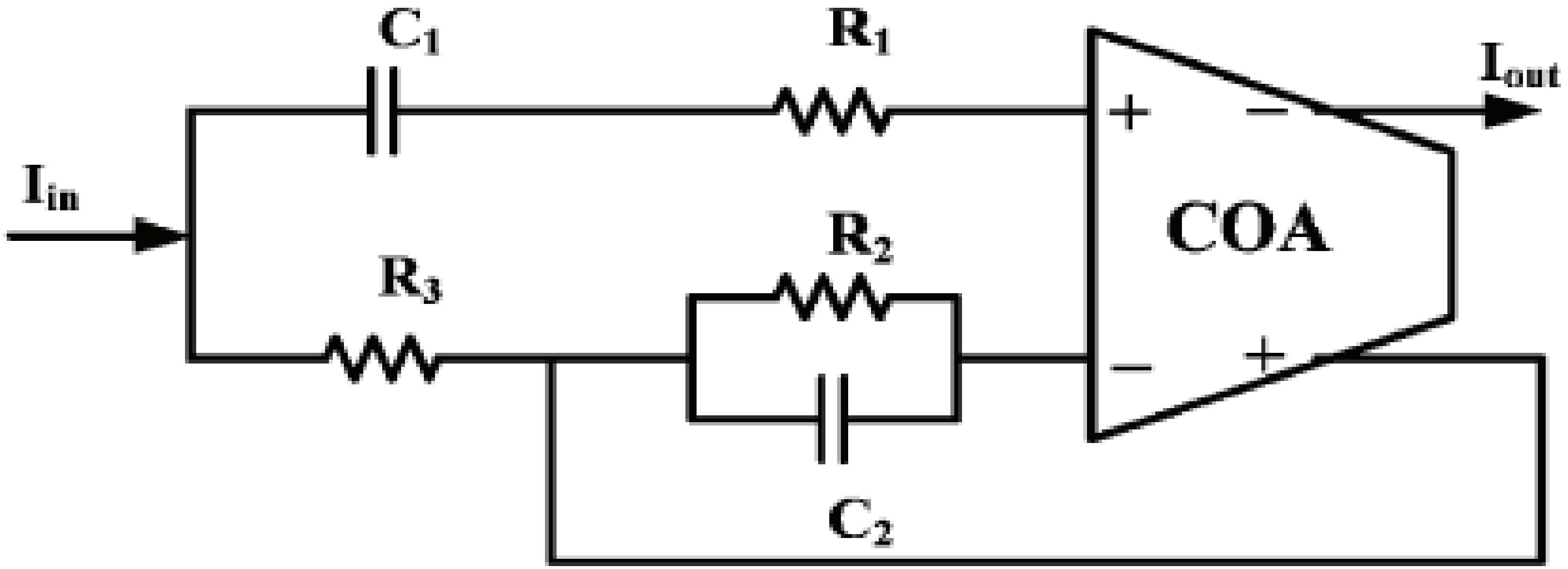
COA BASED FILTERS

Two second-order low-pass (LP) and high pass (HP) filter configurations are proposed. Single COA is used for each realization and matching conditions are:

$R_1 = R_3 = R_{LP}$, $C_1 = C_2 = C_{LP}$ for LP filter,

$R_4 = R_5 = R_{HP}$, $C_4 = C_6 = C_{HP}$ for HP filter.

COA BASED LOW-PASS FILTER



$$\frac{i_{\mathrm{out-LP}}}{i_{\mathrm{in}}} = \frac{\dfrac{1}{2R_{\mathrm{LP}}R_2C_{\mathrm{LP}}^2}}{s^2 + s\dfrac{1}{R_2C_{\mathrm{LP}}} + \dfrac{1}{2R_{\mathrm{LP}}R_2C_{\mathrm{LP}}^2}}.$$

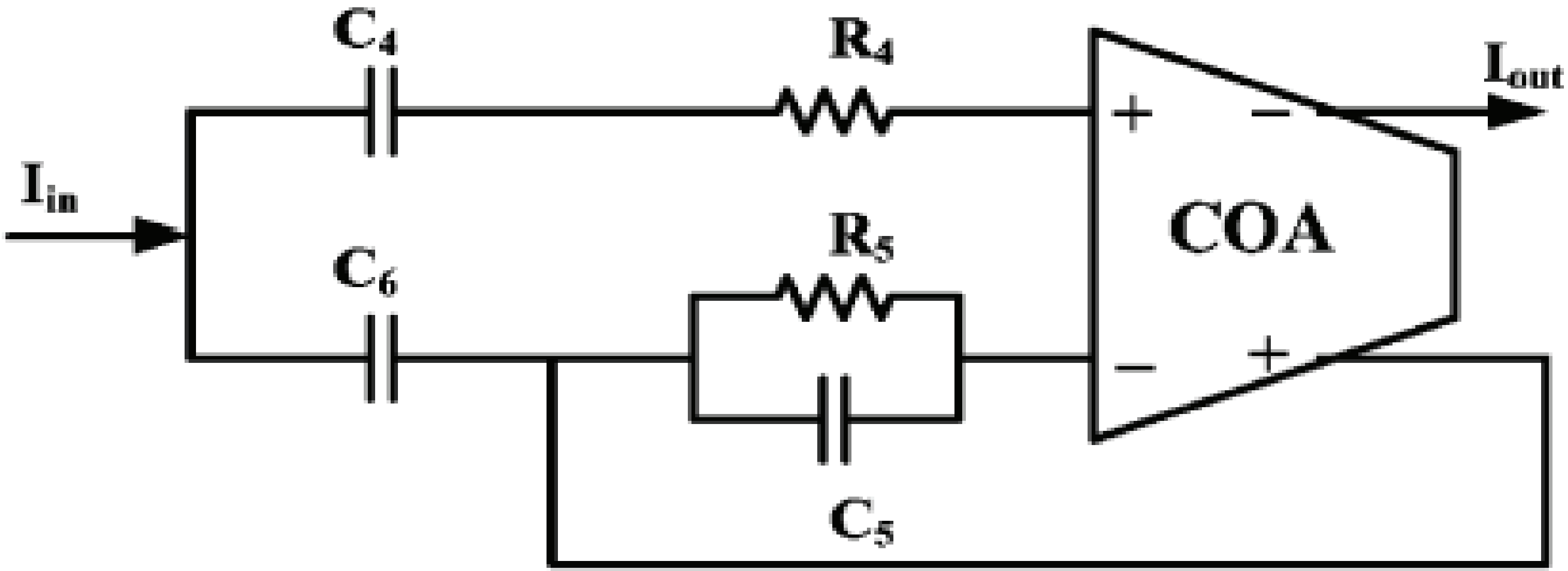
COA BASED LOW-PASS FILTER

$$\frac{i_{\text{out-LP}}}{i_{\text{in}}} = \frac{\dfrac{1}{2R_{\text{LP}}R_2C_{\text{LP}}^2}}{s^2 + s\dfrac{1}{R_2C_{\text{LP}}} + \dfrac{1}{2R_{\text{LP}}R_2C_{\text{LP}}^2}}.$$

$$w_0 = \sqrt{\frac{1}{2R_{\text{LP}}R_2C_{\text{LP}}^2}}, \quad Q = \sqrt{\frac{R_2}{2R_{\text{LP}}}}.$$

$$S_{R_{\text{LP}}}^{w_0} = S_{R_2}^{w_0} = -1/2,\ S_{C_{\text{LP}}}^{w_0} = -1,\ S_{R_2}^{Q} = 1/2,\ S_{R_{\text{LP}}}^{Q} = -1/2,$$

COA BASED HIGH-PASS FILTER



$$\frac{i_{\text{out-HP}}}{i_{\text{in}}} = \frac{s^2}{s^2 + s\frac{1}{R_{\text{HP}}C_{\text{HP}}} + \frac{2}{R_{\text{HP}}^2 C_{\text{HP}} C_5}}$$

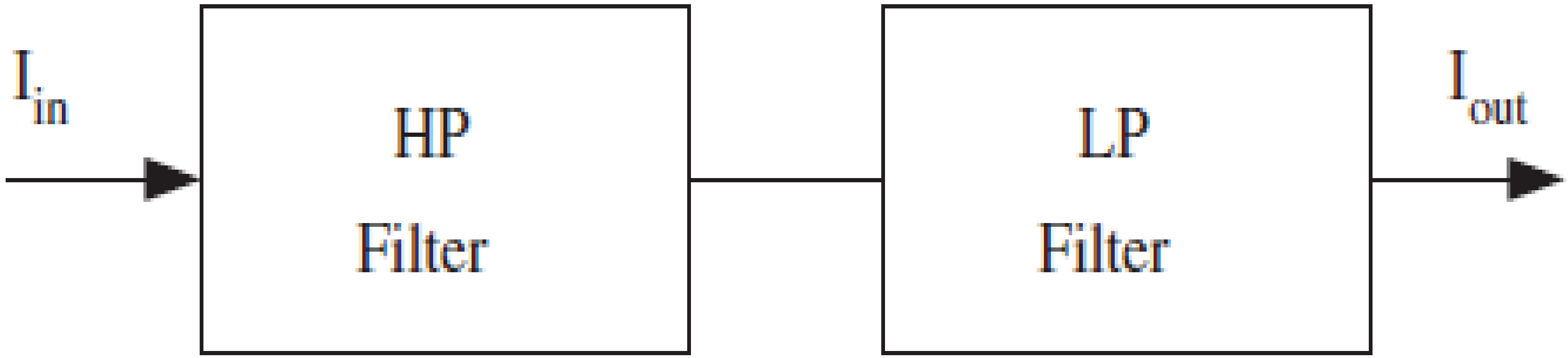
COA BASED HIGH-PASS FILTER

$$\frac{i_{\text{out}-\text{HP}}}{i_{\text{in}}} = \frac{s^2}{s^2 + s\frac{1}{R_{\text{HP}}C_{\text{HP}}} + \frac{2}{R_{\text{HP}}^2 C_{\text{HP}} C_5}}$$

$$w_0 = \sqrt{\frac{2}{R_{\text{HP}}^2 C_{\text{HP}} C_5}}, \quad Q = \sqrt{\frac{C_{\text{HP}}}{2C_5}}.$$

$$S_{C_{\text{HP}}}^{w_0} = S_{C_5}^{w_0} = -1/2, S_{R_{\text{HP}}}^{w_0} = -1, S_{C_{\text{HP}}}^{Q} = 1/2, S_{C_5}^{Q} = -1/2.$$

COA BASED BAND-PASS FILTER



$$\frac{i_{out}}{i_{in}} = \frac{\dfrac{1}{2R_{LP}R_2C_{LP}^2}}{s^2 + s\dfrac{1}{R_2C_{LP}} + \dfrac{1}{2R_{LP}R_2C_{LP}^2}} \cdot \frac{s^2}{s^2 + s\dfrac{1}{R_{HP}C_{HP}} + \dfrac{2}{R_{HP}^2C_{HP}C_5}}$$

COA BASED BAND-PASS FILTER

For C_{LP}=7.5pF, R_{LP}=R_2=5kΩ

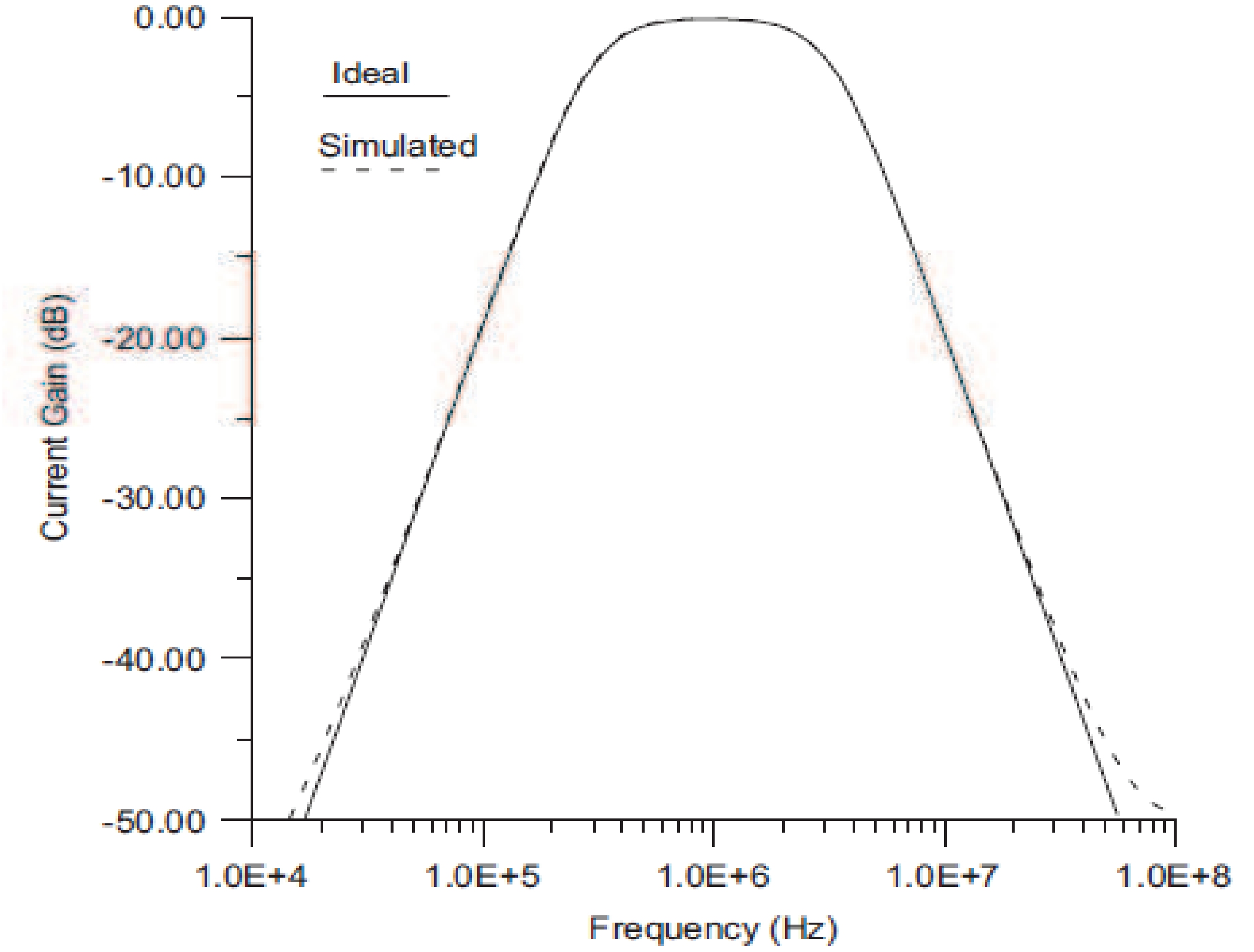
$f_{0LP} \approx$ 3.0MHz, Q = 0.707

For C_{HP}=C_5=15pF, R_{HP}=50kΩ

$f_{0HP} \approx$ 300.1 kHz, Q = 0.707

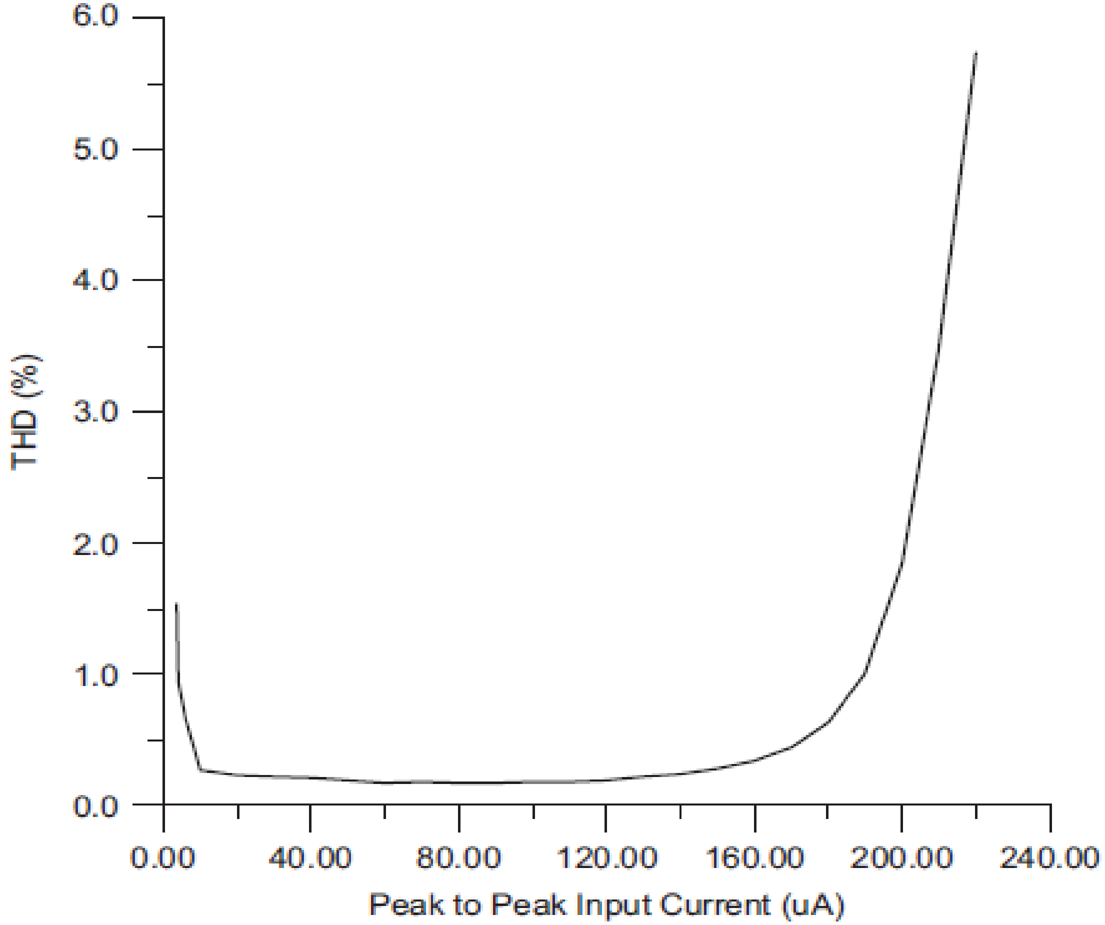
So $f_{0BP} \approx$ 1MHz, Q = 0.707 (flat response)

COA BASED BAND-PASS FILTER



Simulated and ideal band-pass filter responses.

COA BASED BAND-PASS FILTER



Total harmonic distortion (THD) values of the filter versus input peak to peak current at 1 MHz frequency.

CONCLUSION

A very accurate, fully differential COA is proposed in [8]. A novel approach is used in input resistance improvement and also very high output resistance is achieved by modifying traditional current output stage. Due to the simple circuitry, 92MHz GBW is obtained. Moreover, a very high DC gain and ±0.6V output voltage swing are obtained. A new COA-based fourth-order BP filter is proposed as an application. Simulation results are the evidences of accuracy of the proposed fully differential COA.

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Thanks…