Transconductance-C Filters

A Prototype Filter Implementation

Talk Outline

- Introduction
- Transconductance Elements
- Filter Topologies
- Simulation Results
- Layout of Prototype Filter
- Conclusions

1. Introduction

Why monolithic continous-time filters?

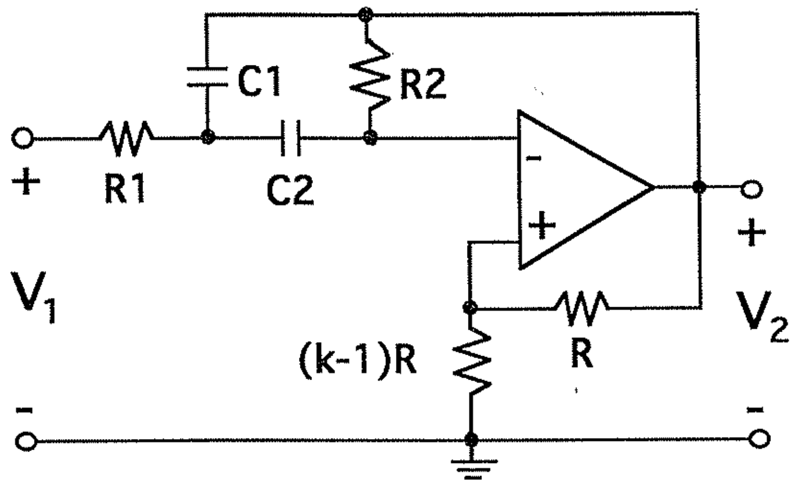
- Pre- and post filters for sampled-data systems
- Mixed analog digital systems
- Wide frequency range (<100MHz)
- Area and power efficient solution

Continuous-Time Filter Implementation Techniques

- RC-Active Circuits
- MOSFET-C Circuits
- Transconductance-C (Ota-C) Circuits

RC-active Filters

Example: 2nd Order Bandpass



Filter Characteristics

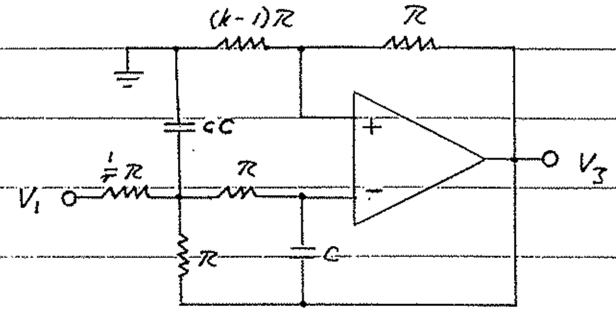
$$T_0 = -\frac{k\,R_2C_2}{R_1(C_1+C_2) - (k-1)\,R_2C_2}$$

$$\omega_0 = \frac{1}{\sqrt{R_1R_2C_1C_2}}$$

$$\frac{1}{Q_0} = \sqrt{\frac{R_1}{R_2}}\left(\sqrt{\frac{C_1}{C_2}} + \sqrt{\frac{C_2}{C_1}}\right) - (k-1)\sqrt{\frac{R_2\,C_2}{R_1\,C_1}}$$

Summary: Single-opamp negative feedback topologies (2nd order)

Lowpass

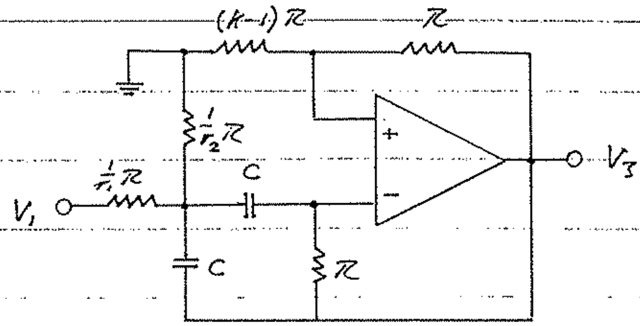


$$\omega_p = \frac{1}{RC}\sqrt{\frac{1-r(k-1)}{c}}$$

$$Q_p = \frac{\sqrt{c(1-r[k-1])}}{2+r-c(k-1)}$$

$$T(s=0) = -\frac{kr}{1-r(k-1)}$$

Bandpass

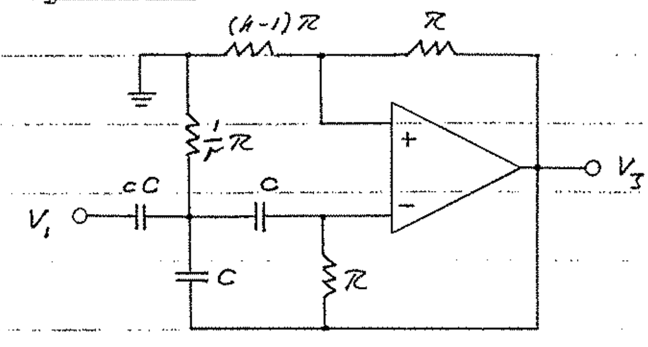


$$\omega_p = \frac{1}{RC}\sqrt{r_1+r_2}$$

$$Q_p = \frac{\sqrt{r_1+r_2}}{2-(r_1+r_2)(k-1)}$$

$$T(s=j\omega_p) = -\frac{k\cdot r_1}{2-(r_1+r_2)(k-1)}$$

Highpass



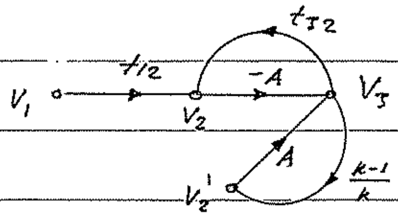
$$\omega_p = \frac{1}{RC}\sqrt{\frac{r}{1-c(k-1)}}$$

$$Q_p = \frac{\sqrt{r(1-c[k-1])}}{2+c-r(k-1)}$$

$$T(s\to\infty) = -\frac{kc}{1-c(k-1)}$$

Amplifier Finite Gain-Bandwidth Effects (neg. feedback topol.)

Voltage Transfer function:



$$T(s) = \frac{V_3}{V_1} = -\frac{A\,t_{12}}{1 + A\left(t_{32} - \frac{k-1}{k}\right)} \cdot \frac{\frac{k}{A}\hat{d}}{\frac{k}{A}\hat{d}}$$

$$\Rightarrow \quad T(s) = -\frac{k\,n_{12}}{\hat{d}\left(1+\frac{k}{A}\right) - k\left(\hat{d} - n_{32}\right)}$$

Example: 2^{nd} order Lowpass filter

$$\hat{d} = s^2 + s\frac{1}{RC}\left(1 + \frac{2+r}{c}\right) + \frac{1}{(RC)^2}\frac{1+r}{c}$$

$$n_{32} = s^2 + s\frac{1}{RC}\frac{2+r}{c} + \frac{1}{(RC)^2}\frac{1}{c}$$

$$n_{12} = \frac{1}{(RC)^2}\frac{r}{c}$$

Opamp: $A(s) \cong A_0 \frac{\omega_0}{s} = \frac{GB}{s}$ $\qquad$ GB: Gain-Bandwidth Pr.

$$\Rightarrow \quad T(s) = -\frac{k\frac{1}{(RC)^2}\frac{r}{c}}{\left(s^2 + s\frac{1}{RC}\left[1+\frac{2+r}{c}\right] + \frac{1}{(RC)^2}\frac{1+r}{c}\right)\left(1 + s\frac{k}{GB}\right) - k\left(s\frac{1}{RC} + \frac{1}{(RC)^2}\frac{r}{c}\right)}$$

Approx. Solution:

$$T(s) \cong -\frac{k\frac{1}{(RC)^2}\frac{r}{c}}{\left(1+s\frac{k}{GB}\right)\left(s^2\left[1+\frac{k^2}{GB\,RC}\right] + s\frac{1}{RC}\left[\frac{2+r-c(k-1)}{c} + \frac{k^2 r}{GB\,RC\,c}\right] + \frac{1}{(RC)^2}\frac{1-r(k-1)}{c}\right)}$$

Poles: neg. real: $\omega_{p3} \cong \frac{GB}{k}$

complex:

$$\omega_p \cong \frac{1}{RC}\sqrt{\frac{1-r(k-1)}{c}}\left(1 - \frac{k^2}{2\,GB\,RC}\right)$$

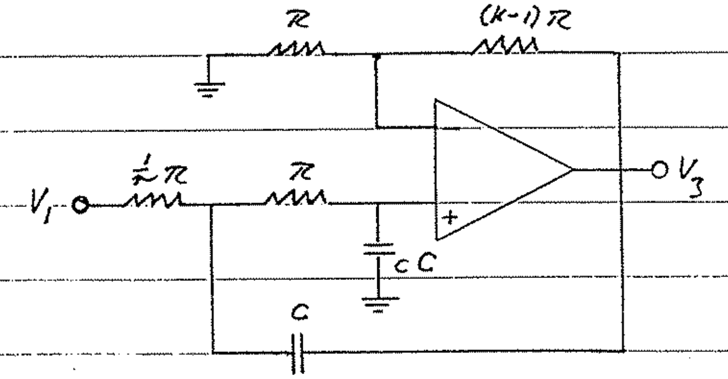
$$Q_p \cong \frac{\sqrt{c\,(1-r[k-1])}\left(1+\frac{k^2}{2GB\,RC}\right)}{2+r-c(k-1)+\frac{k^2 r}{GB\,RC}}$$

$$\omega_p \cong \omega_{p0}\left(1 - \frac{k^2}{2GB\,RC}\right)$$

$$Q_p \cong Q_{p0}\left(1 + \frac{k^2}{2GB\,RC}\,\frac{(2-r-c[k-1])}{(2+r-c[k-1])}\right)$$

Summary: Single-opamp positive feedback topologies (2nd order)

Lowpass

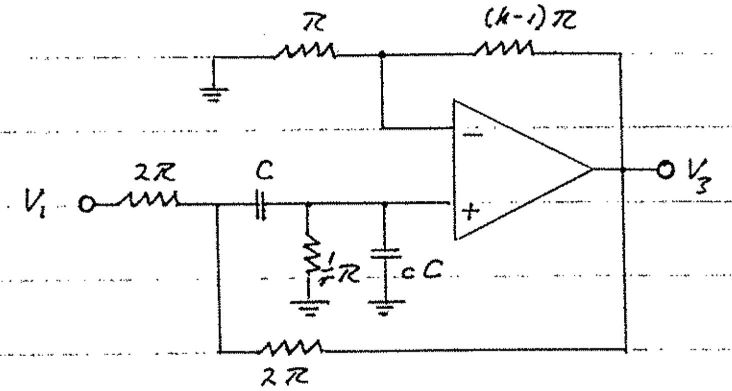


$$\omega_p = \sqrt{\frac{r}{c}}\,\frac{1}{RC}$$

$$Q_p = \frac{\sqrt{r\cdot c}}{c(1+r)-(k-1)}$$

$$T(s=0) = k$$

Bandpass

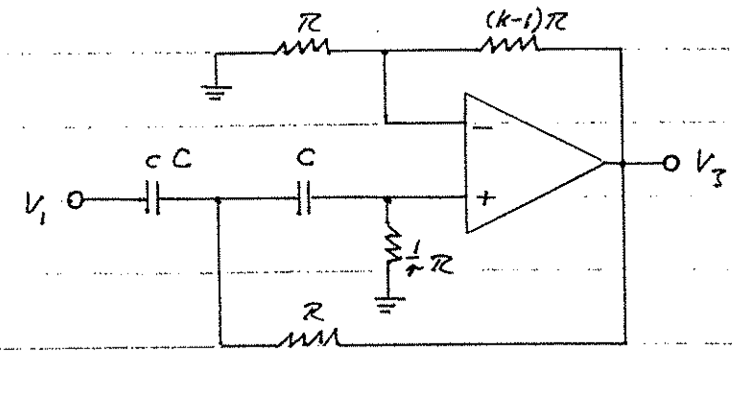


$$\omega_p = \sqrt{\frac{r}{c}}\,\frac{1}{RC}$$

$$Q_p = \frac{\sqrt{r\cdot c}}{r+c+\frac{1}{2}-\frac{1}{2}(k-1)}$$

$$T(s=j\omega_p) = \frac{k}{2(r+c)+1-(k-1)}$$

Highpass



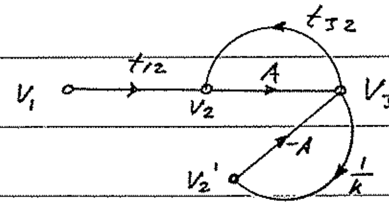
$$\omega_p = \sqrt{\frac{r}{c}}\,\frac{1}{RC}$$

$$Q_p = \frac{\sqrt{r\cdot c}}{r(1+c)-(k-1)}$$

$$T(s\to\infty) = k$$

Amplifier Finite Gain-Bandwidth Effects (pos. feedback topol.)

Voltage Transfer Function:



$$T(s) = \frac{A\, t_{12}}{1 + A\left(\frac{1}{k} - t_{32}\right)} \cdot \frac{\frac{k}{A}\hat{d}}{\frac{k}{A}\hat{d}}$$

$$\Rightarrow \quad T(s) = \frac{k \cdot n_{12}}{\hat{d}\left(1+\frac{k}{A}\right) - k\, n_{32}}$$

Example: 2nd order Lowpass filter

$$\hat{d} = s^2 + s\frac{1}{RC}\left(1 + r + \frac{1}{c}\right) + \frac{1}{(RC)^2}\frac{r}{c}$$

$$n_{32} = s\frac{1}{RC}\frac{1}{c}$$

$$n_{12} = \frac{1}{(RC)^2}\frac{r}{c}$$

Opamp: $A(s) \cong A_0 \frac{\omega_0}{s} = \frac{GB}{s}$ — GB: Gain-Bandwidth Pr.

$$\Rightarrow \quad T(s) = \frac{k \frac{1}{(RC)^2}\frac{r}{c}}{\left(s^2 + s\frac{1}{RC}\left[1 + r + \frac{1}{c}\right] + \frac{1}{(RC)^2}\frac{r}{c}\right)\left(1 + s\frac{k}{GB}\right) - s\frac{1}{RC}\frac{k}{c}}$$

Approx. Solution:

$$T(s) \cong \frac{k \frac{1}{(RC)^2}\frac{r}{c}}{\left(1 + s\frac{k}{GB}\right)\left(s^2\left[1 + \frac{k^2}{GB\, RC\, c}\right] + s\frac{1}{RC}\left[1 + r - \frac{(k-1)}{c}\right] + \frac{1}{(RC)^2}\frac{r}{c}\right)}$$

Poles: neg. real: $\omega_{p3} \cong \frac{GB}{k}$

complex:

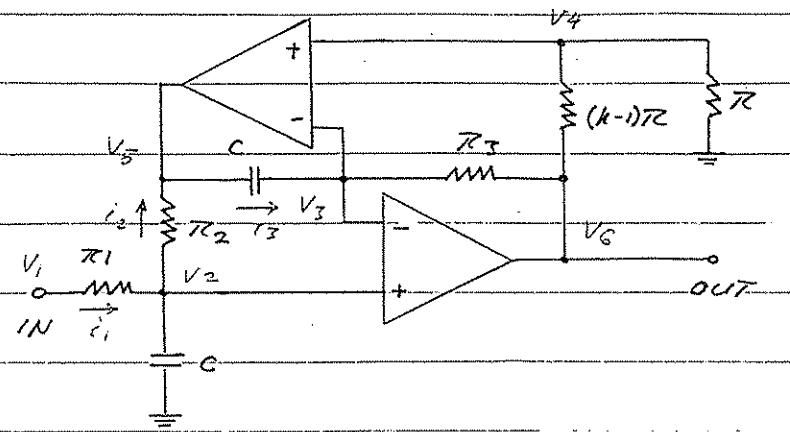
$$\omega_p \cong \frac{1}{RC}\sqrt{\frac{r}{c}}\left(1 - \frac{k^2}{2\, GB\, RC\, c}\right)$$

$$Q_p \cong \frac{\sqrt{rc}}{c(1+r) - (k-1)}\left(1 + \frac{k^2}{2\, GB\, RC\, c}\right)$$

$$\omega_p \cong \omega_{p0}\left(1 - \frac{k^2}{2\, GB\, RC\, c}\right)$$

$$Q_p \cong Q_{p0}\left(1 + \frac{k^2}{2\, GB\, RC\, c}\right)$$

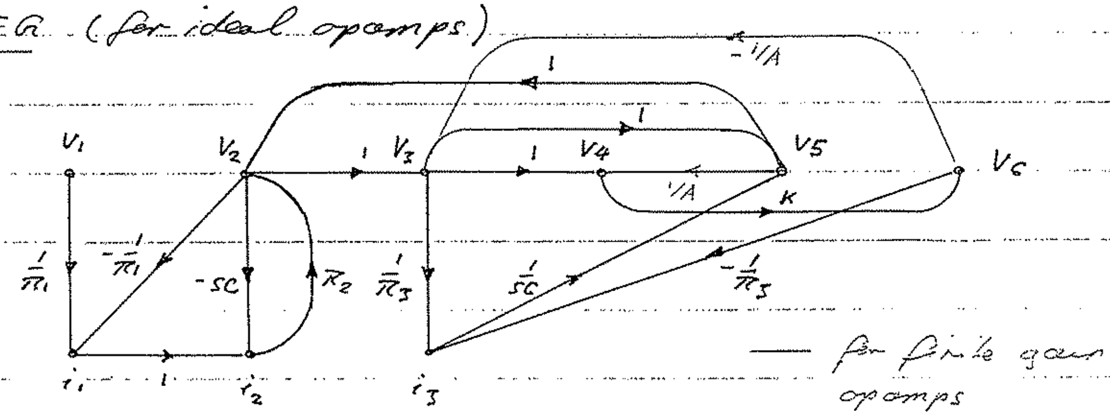
B) Sedra - Espinoza Bandpass Filter



assumption: opamps are ideal

Thus $V_2 = V_3 = V_4$

SFG (for ideal opamps)



$$T_{16}(s) = \frac{V_6}{V_1} = \frac{k \cdot \frac{R_2}{R_1}}{1 + \frac{R_2}{R_1} + sCR_2 - 1 + \frac{k}{sCR_3} - \frac{1}{sCR_3}} \times \frac{s\,\frac{1}{CR_2}}{s\,\frac{1}{CR_2}}$$

$$= \frac{k \cdot s\,\frac{1}{R_1 C}}{s^2 + s\,\frac{1}{R_1 C} + \frac{(k-1)}{R_2 R_3 C^2}}$$

Note: k must be larger than 1 otherwise we obtain a 1st order lowpass (k=1) or else the element (k-1)R becomes negative!

Filter Parameters: — **Sensitivities:**

Filter Parameters	Special Cases	Sensitivities
$\omega_p = \sqrt{\frac{(k-1)}{R_2 R_3}}\,\frac{1}{C}$	$k = 2$, $R_2 = R_3 = R$	$S^{\omega_p}_{R_2} = S^{\omega_p}_{R_3} = -\frac{1}{2}$
$Q_p = R_1 \sqrt{\frac{(k-1)}{R_2 R_3}}$	$\omega_p = \frac{1}{RC}$	$S^{Q_p}_{R_1} = 1$
$T(s = j\omega_p) = k$	$Q_p = \frac{R_1}{R}$	$S^{Q_p}_{R_2} = S^{Q_p}_{R_3} = -\frac{1}{2}$

Influence of amplifier gain-bandwidth product:

$$T_{16} = \frac{k \cdot s \frac{1}{R_1 C}\left[1 + \frac{1}{s R_3 C}\frac{1}{A}\right]}{s^2 + s\frac{1}{R_1 C} + \frac{(k-1)}{R_2 R_3 C^2} + \frac{k}{A}\left[\frac{s}{R_1 C} + \frac{s}{R_2 C} + s^2\right]}$$

Replacing $A(s)$ by $\frac{A_0 \omega_0}{s} = \frac{GB}{s}$ yields:

$$T_{16} = \frac{k \cdot s \frac{1}{R_1 C}\left[1 + \frac{1}{GB R_3 C}\right]}{s^3 \frac{k}{GB} + s^2\left[1 + \frac{k}{GB}\left(\frac{1}{R_1 C} + \frac{1}{R_2 C}\right)\right] + s\frac{1}{R_1 C} + \frac{(k-1)}{R_2 R_3 C^2}}$$

$$\cong \frac{k \cdot s \frac{1}{R_1 C}\left[1 + \frac{1}{GB R_3 C}\right]}{\left(s\frac{k}{GB} + 1\right)\left(s^2\left[1 + \frac{k}{GB}\frac{1}{R_2 C}\right] + s\left[\frac{1}{R_1 C} - \frac{k(k-1)}{GB R_2 R_3 C^2}\right] + \frac{(k-1)}{R_2 R_3 C^2}\right)}$$

Poles: $\omega_{p3} \cong \frac{k}{GB}$ neg. real pole

$$\omega_p \cong \sqrt{\frac{(k-1)}{R_2 R_3}}\cdot\frac{1}{C}\left(1 - \frac{1}{2}\frac{k}{GB R_2 C}\right)$$

$$Q_p \cong R_1\sqrt{\frac{(k-1)}{R_2 R_3}}\left(1 + \frac{1}{2}\frac{k}{GB R_2 C}\left[1 - 2(k-1)\frac{R_1}{R_3}\right]\right)$$

complex pole-pair

special case:

$k = 2$, $R_2 = R_3 = R$, $R_1 = Q_p R$ $\Rightarrow$

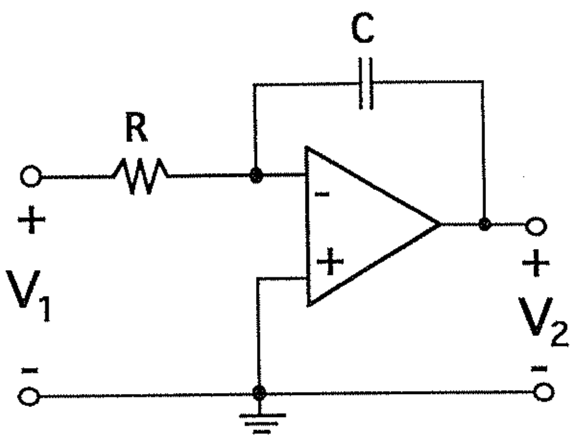
$$\omega_p = \omega_{po}\left(1 - \frac{\omega_{po}}{GB}\right)$$

$$Q_p = Q_{po}\left(1 + \frac{\omega_{po}}{GB}\left[1 - 2Q_{po}\right]\right)$$

MOSFET-C Filters

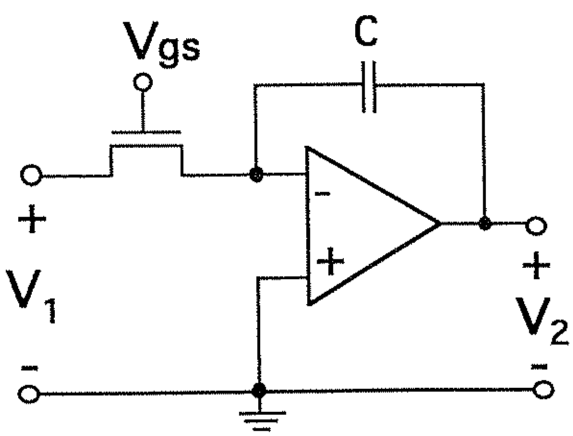
Example: Integrator

RC-active Implementation



$$T(s) = -\frac{1}{s\,RC}$$

MOSFET-C Implementation



$$T(s) = -\frac{g_{ds}}{s\,C}$$

where:

$$g_{ds} \cong \mu C_{ox}\frac{W}{L}\,[V_{gs} - V_T - V_{ds}]$$

RC-Active Filters

Properties

- Many filter topologies available
- Few active elements (op-amps)
- Excellent linearity and dynamic range (90dB)
- Frequency limited by op-amps (low MHz range)
- Passive elements require significant chip area (R_S: 10-100Ω C': 0.25-1fF/μm^2)
- Poor control over RC product (20%-60% variation)
- Discrete tuning possible (e.g. by employing C-arrays)

MOSFET-C Filters

Properties

- Few op-amps required
- Area efficient implementation of resistors
- Filter topologies limited (due to tuning)
- Frequency limited by op-amps (low MHz range)
- Poor linearity (due to nonlinearity of MOSFET resistors)
- MOSFET resistors require tuning
- Additional circuitry for automatic tuning

Transconductance-C (Ota-C) Filters

Properties

- Well-suited for high-frequencyapplications (<100MHz)
- Filter topologies limited (due to tuning)
- Many transconductance elements required
- Limited dynamic range (due to Ota nonlinearities)
- Transconductance elements require tuning
- Additional circuitry for automatic tuning

Comparison

Filter Type	Accuracy	Dynamic Range	Impl. Cost	Frequency Range
RC-Active	20%-60%	90dB	low	< 1MHz
MOSFET-C	approx. 1%	60dB	medium	< 1MHz
Transcond.-C	approx. 1%	60dB	medium	< 100MHz

2. Transconductance Elements

Voltage Controlled Current Source

Special Requirements

- High input impedance (>MΩ)
- High output impedance (>MΩ)
- Large input voltage swing (e.g. $1V_{p\text{-}p}$)
- Good linearity over entire range
- Wide bandwidth (<100MHz)
- Transconductance electrically tunable
- Wide tuning range

Basic Implementation

MOS Transistor

Major Drawback

Poor Linearity

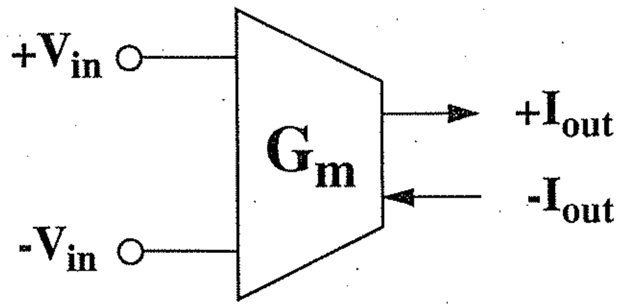
Remedies

Fully-differential implementation

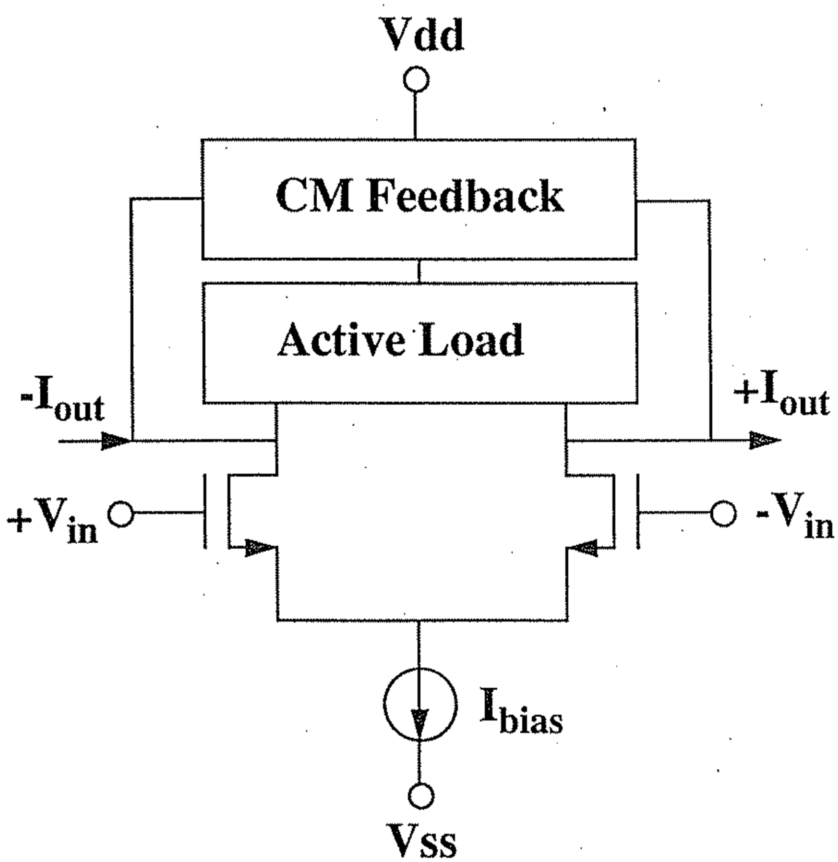
Additional compensating circuitry

Fully-differential transconductance element

Symbol

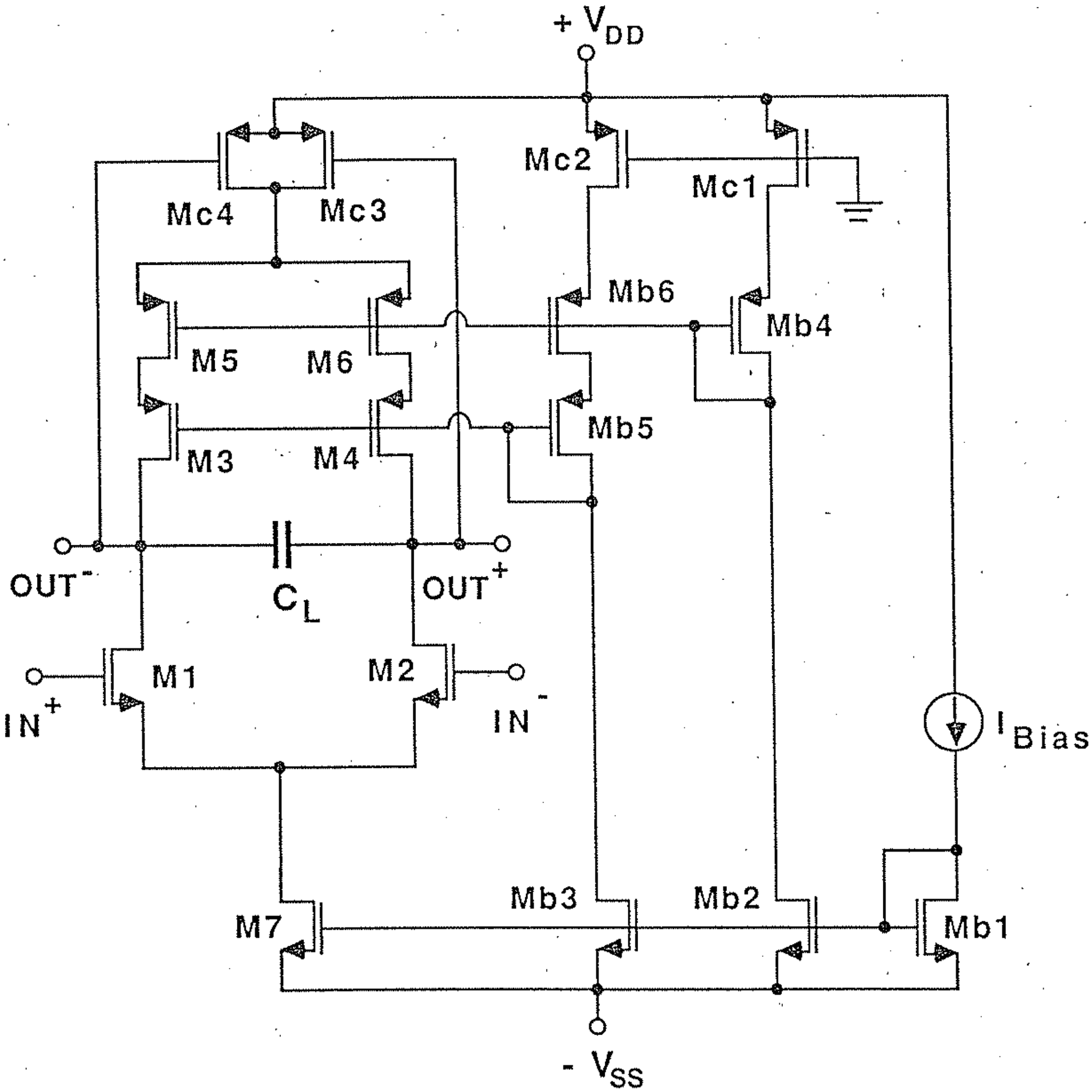


Implementation by CS Pair

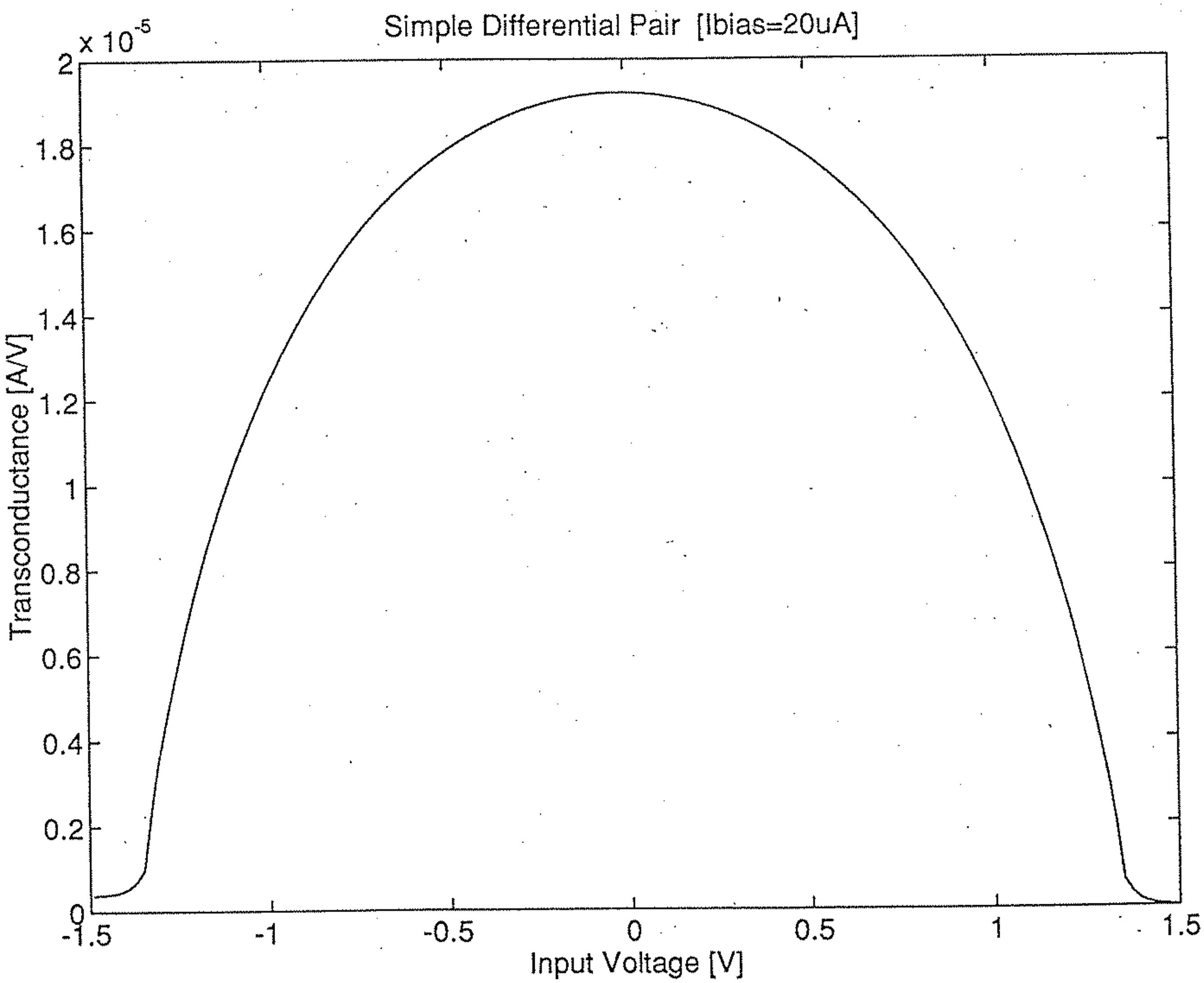


Fully-Differential Transconductance Amplifier

Version 0: Simple Source-Coupled Differential Pair

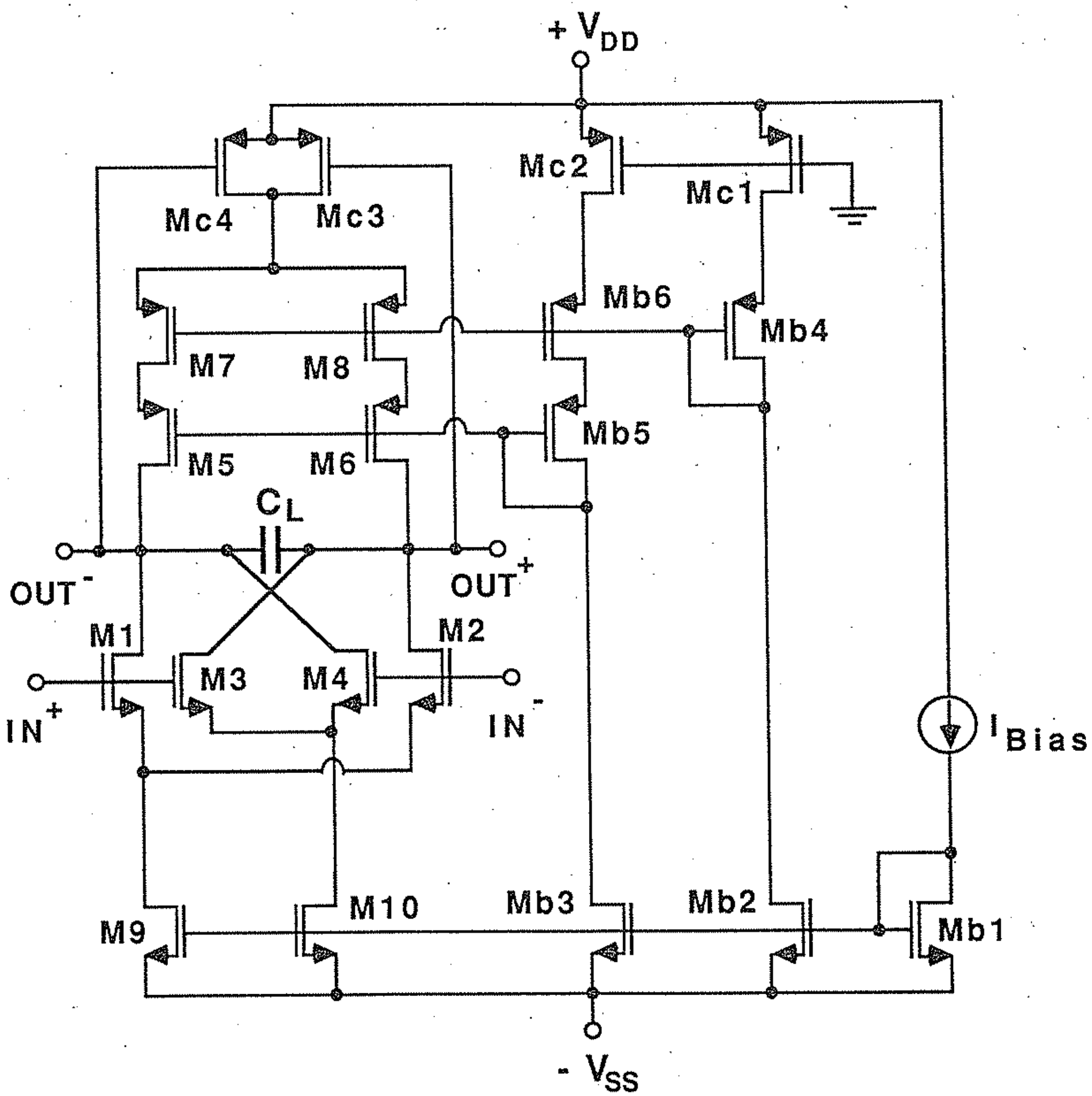


$$G_M = \frac{1}{2} g_{m1}$$

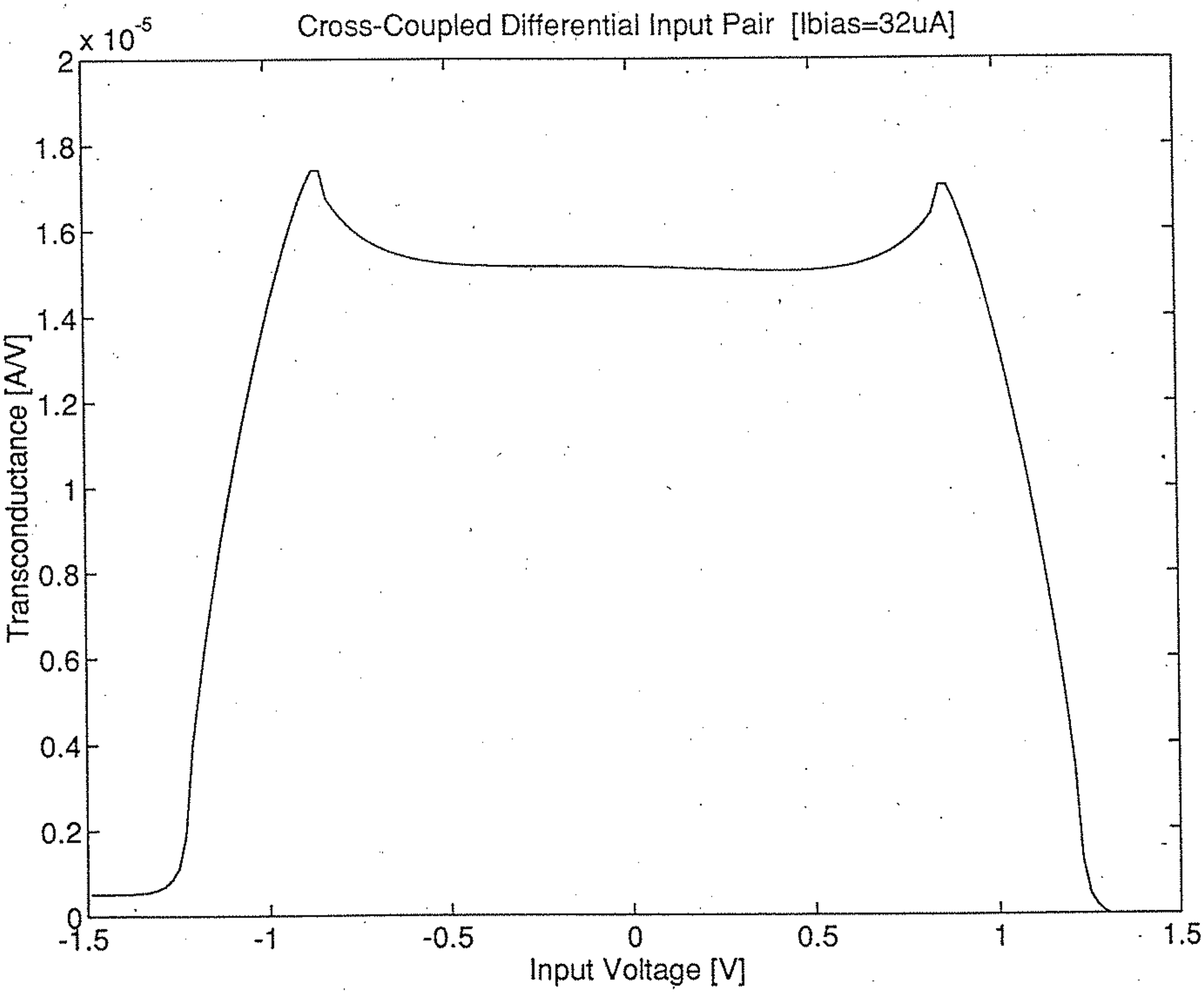

Simple Differential Pair [Ibias=20uA]
x 10^-5
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Transconductance [A/V]
-1.5
-1
-0.5
0
0.5
1
1.5
Input Voltage [V]

Fully-Differential Transconductance Amplifier

Version1: Differential Pair with Cross-Coupled Inputs

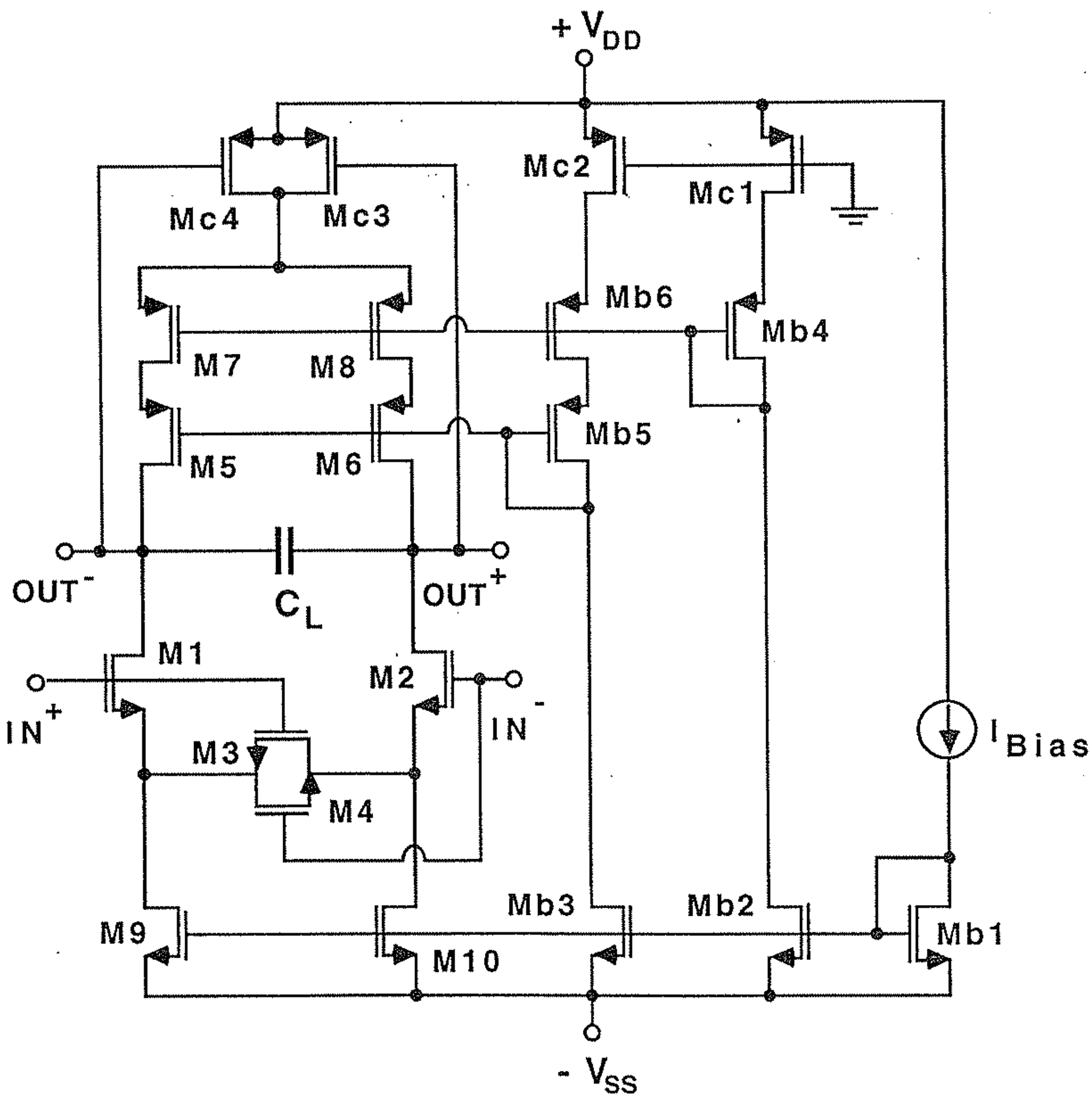


$$G_M = \frac{1}{2}\left(g_{m1} - g_{m3}\right)$$


Cross-Coupled Differential Input Pair [Ibias=32uA]
x 10^-5
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Transconductance [A/V]
-1.5
-1
-0.5
0
0.5
1
1.5
Input Voltage [V]

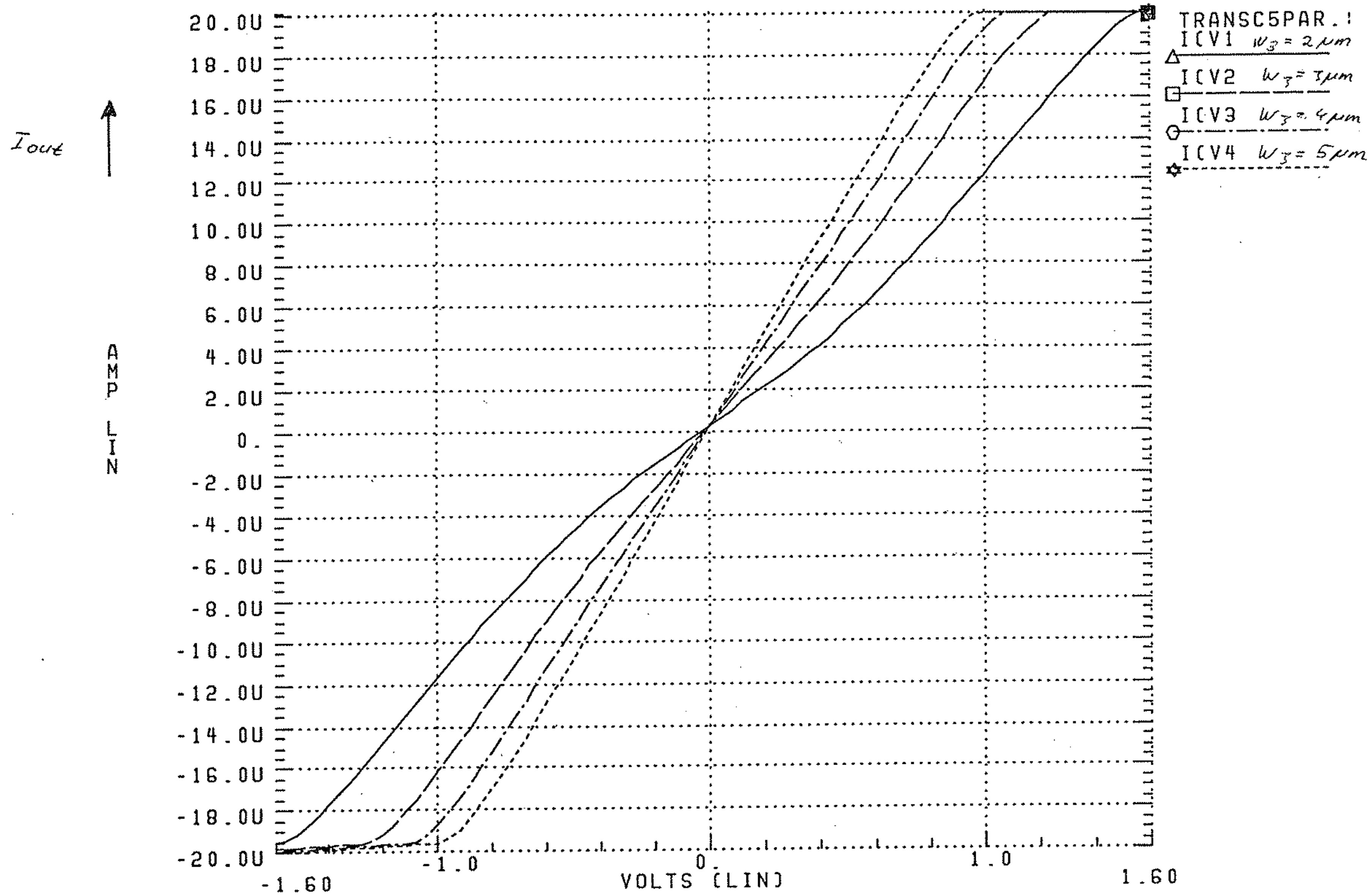
Fully-Differential Transconductance Amplifier

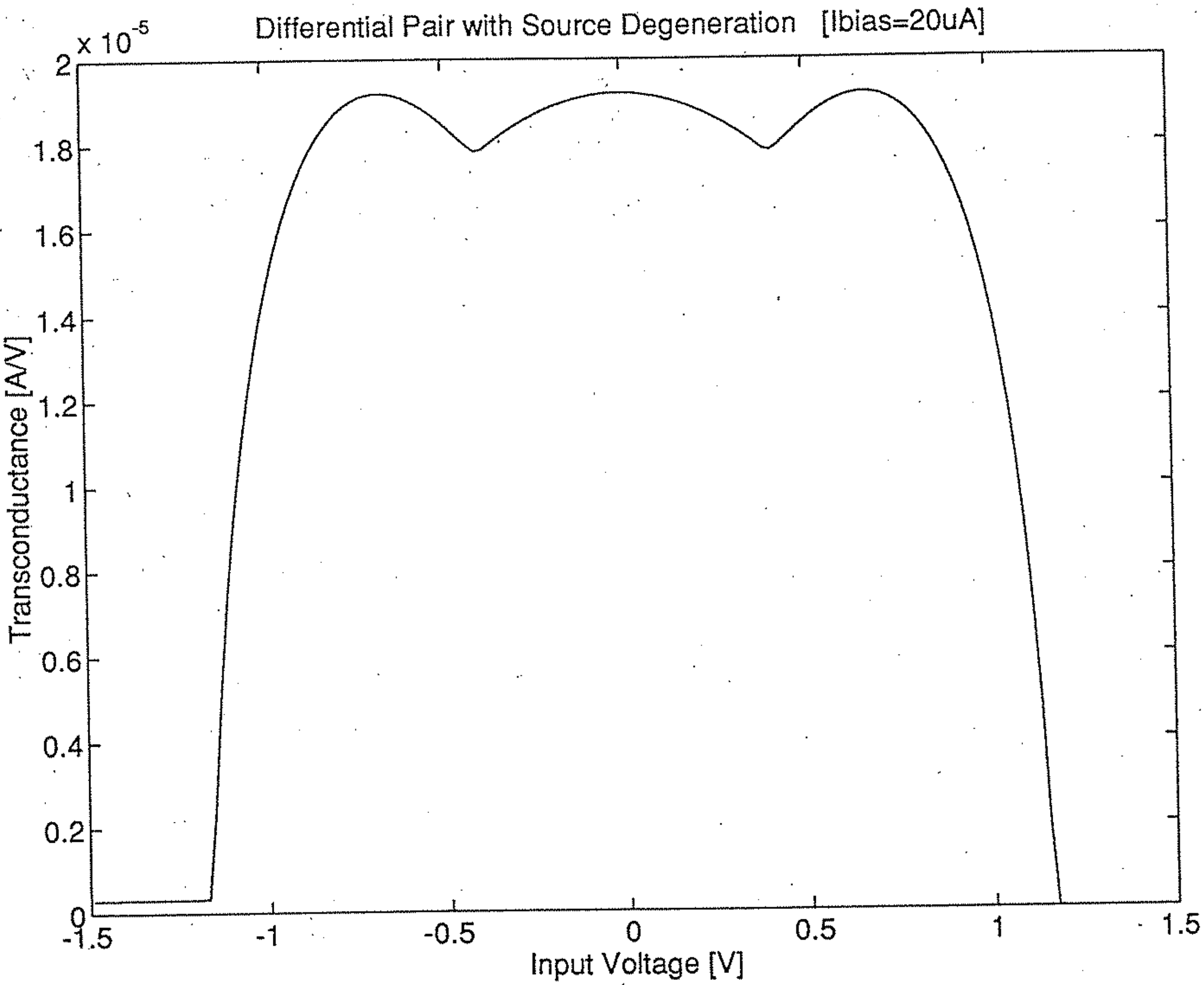
Version2: Differential Pair with Source Degeneration Devices



$$G_M = \frac{g_{m1}}{2 + g_{m1}/(g_{d3} + g_{d4})}$$

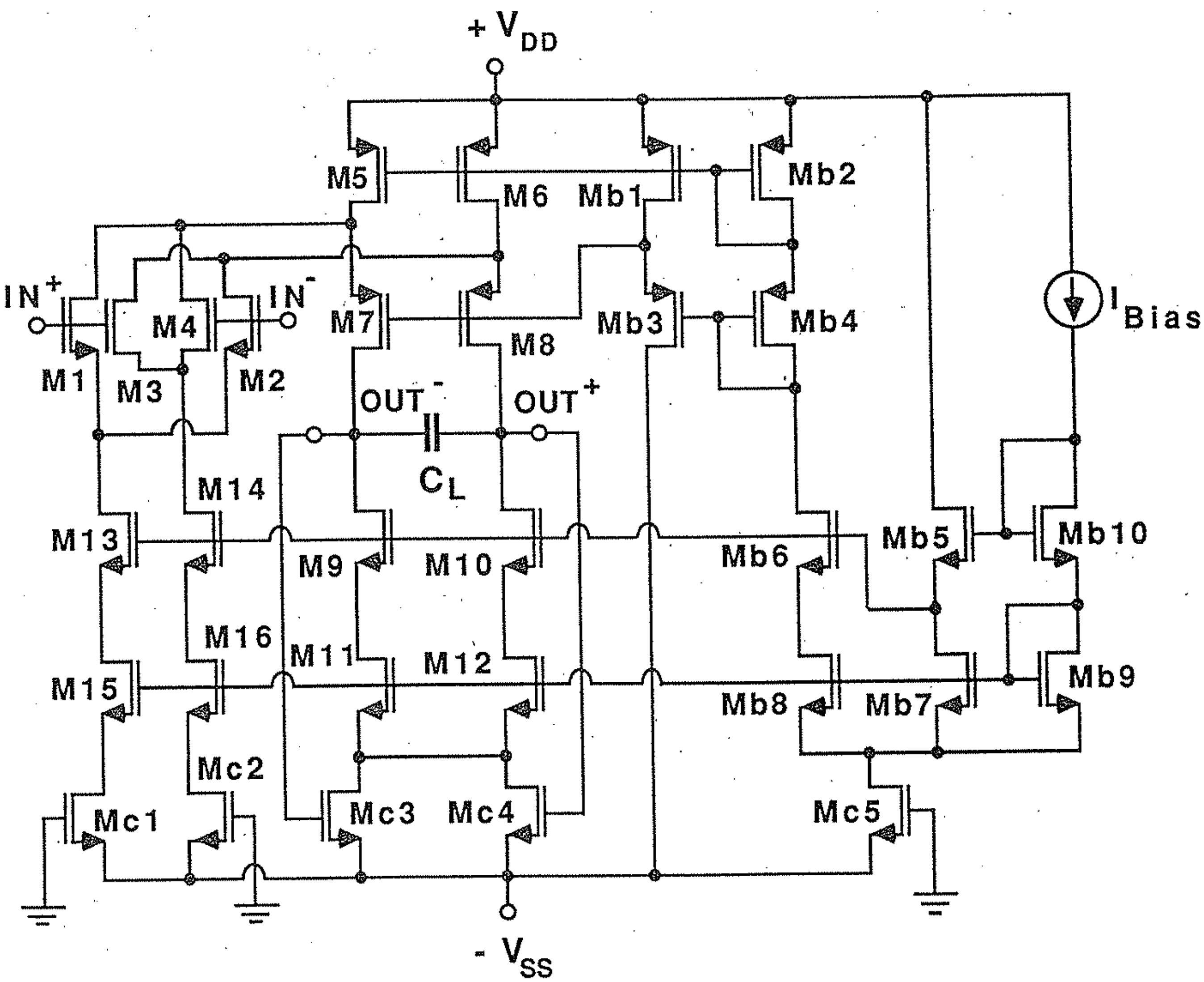
FULLY-DIFFERENTIAL TRANSCONDUCTANCE AMPLIFIER
20-OCT93 15:19:16




Differential Pair with Source Degeneration [Ibias=20uA]
x 10^-5
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Transconductance [A/V]
-1.5
-1
-0.5
0
0.5
1
1.5
Input Voltage [V]

Fully-Differential Transconductance Amplifier

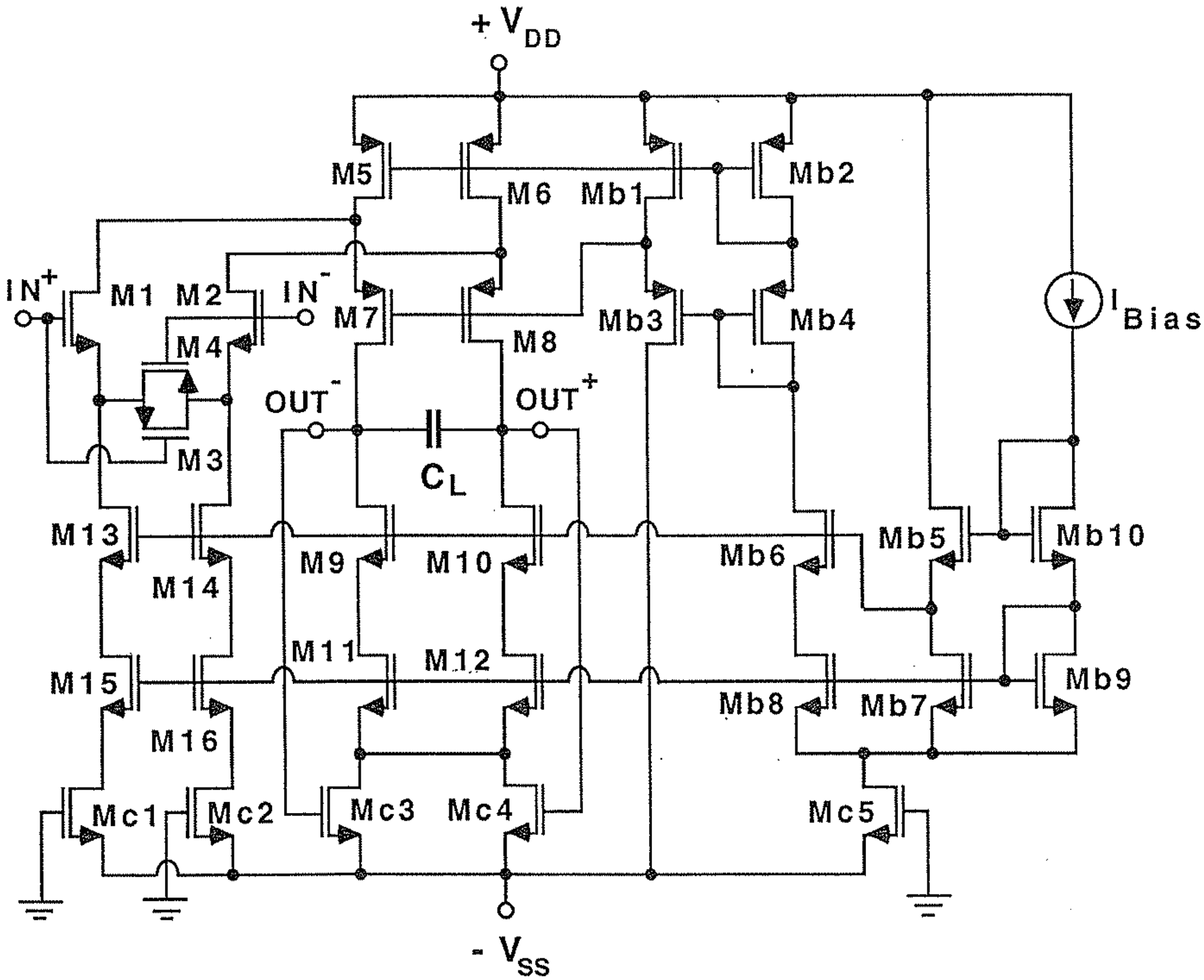
Version3: Folded Cascode with Cross-Coupled Inputs



$$G_M = \frac{1}{2}\,(g_{m1} - g_{m3})$$

Fully-Differential Transconductance Amplifier

Version4: Folded Cascode with Source Degeneration Devices

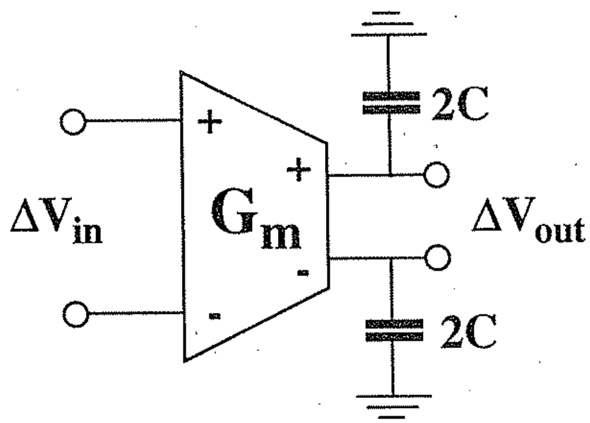


$$G_M = \frac{g_{m1}}{2 + g_{m1}/(g_{d3} + g_{d4})}$$

3. Filter Topologies

Basic building block

Ota-C Integrator



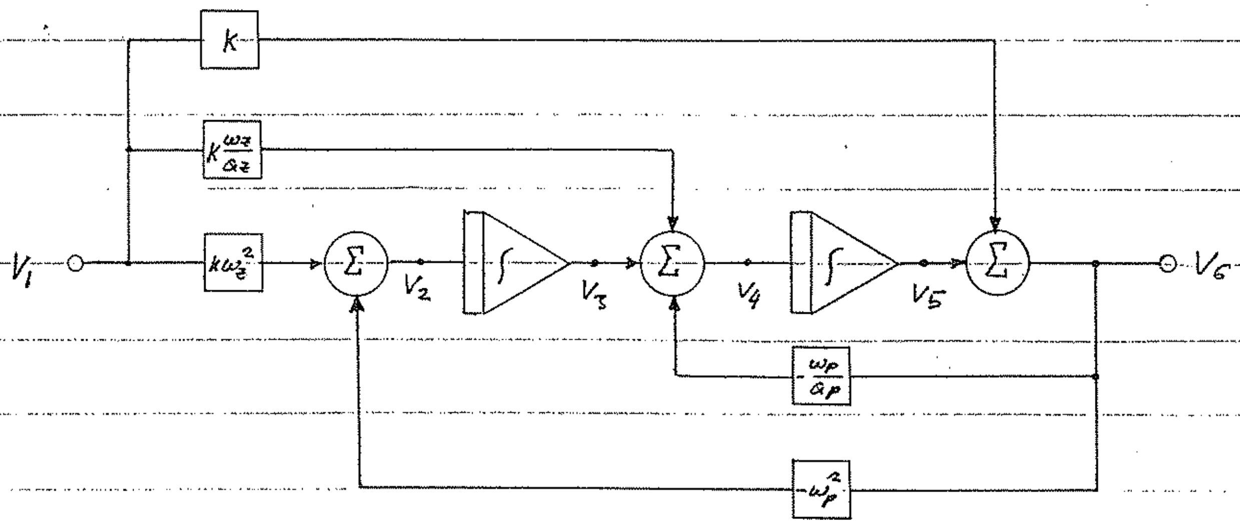
$$\frac{\Delta V_{out}}{\Delta V_{in}} = \frac{G_m}{sC}$$

State-variable filter topologies

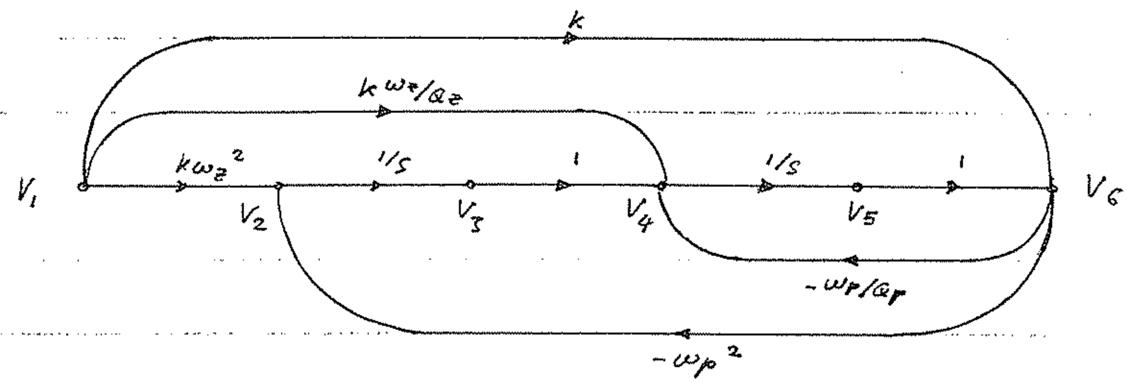
State - Variable Biquadratic Filters

General 2nd order Configuration

a) Block Diagram representation:



b) SFG representation: (in s-domain)



c) Voltage Transfer Function:

$$T_{16}(s) = \frac{V_6(s)}{V_1(s)} = k\,\frac{s^2 + s\,\omega_z/Q_z + \omega_z^2}{s^2 + s\,\omega_p/Q_p + \omega_p^2}$$

State-Variable Systems

The state space method is based on the description of system eq. in terms of n 1^{st} order differential (or difference) equations, which may be combined into a 1^{st} order vector matrix equation.

For linear, time-invariant systems, the state equation and the output equation are given by

$$\dot{\bar{x}}(t) = [A]\,x(t) + [B]\,u(t)$$
$$\bar{y}(t) = [C]\,x(t) + [D]\,u(t)$$

where:

$\bar{x}(t)$: state variable vector

$\bar{y}(t)$: output variable vector

$u(t)$: input vector

Example:

$$\dot{x}_1 = a_1 y + b_1 u$$
$$\dot{x}_2 = a_2 x_1 + a_3 y + b_2 u$$
$$y = x_2 + b_3 u$$

where:

$\bar{x} = (x_1, x_2)$

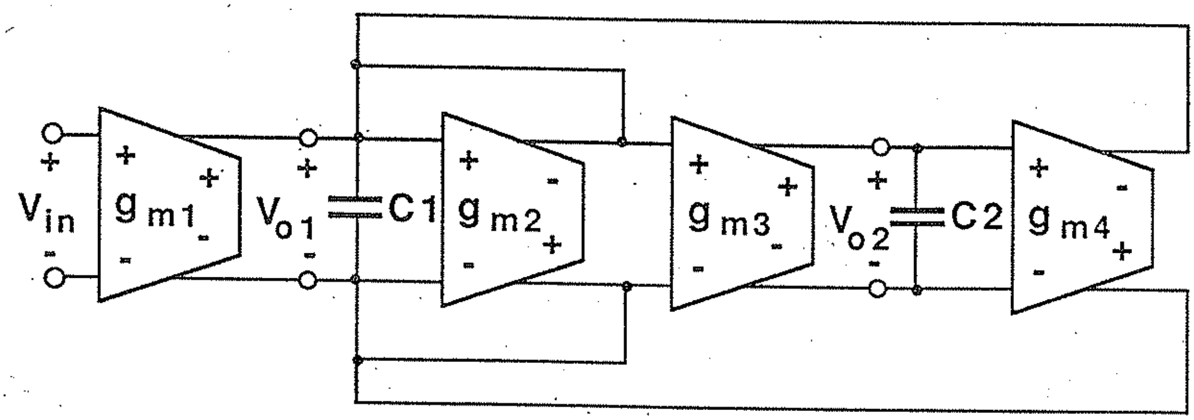
$\bar{y} = (y, 0)$

$\bar{u} = (u, 0)$

$$[A] = \begin{bmatrix} 0 & a_1 \\ a_2 & a_3 \end{bmatrix} \quad [B] = \begin{bmatrix} a_1 b_3 + b_1 & 0 \\ a_3 b_3 + b_2 & 0 \end{bmatrix}$$

$$[C] = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \quad [D] = \begin{bmatrix} b_3 & 0 \\ 0 & 0 \end{bmatrix}$$

2nd Order Ota-C Lowpass/Bandpass Filter



V_{o1} : Bandpass Output

V_{o2} : Lowpass Output

Pole Locations:

$$\omega_p = \sqrt{\frac{g_{m3} g_{m4}}{C_1 C_2}}$$

$$Q_p = \sqrt{\frac{g_{m3} g_{m4} C_1}{C_2}} \frac{1}{g_{m2}}$$

2nd Order Ota-C Lowpass / Bandpass Filter

a) Ideal System (Rout of OTA's are infinite)

Equations:

(1) $V_{o1} = V_{in} \frac{g_{m1}}{sC_1} - V_{o1} \frac{g_{m2}}{sC_1} - V_{o2} \frac{g_{m4}}{sC_1}$

(2) $V_{o2} = V_{o1} \frac{g_{m3}}{sC_2}$

(2) into (1) $\therefore$ $V_{o1} = V_{in} \dfrac{\frac{g_{m1}}{sC_1}}{\left(1 + \frac{g_{m2}}{sC_1} + \frac{g_{m3} g_{m4}}{s^2 C_1 C_2}\right)}$

Transfer functions:

$$\frac{V_{o1}}{V_{in}} = \frac{s \frac{g_{m1}}{C_1}}{s^2 + s \frac{g_{m2}}{C_1} + \frac{g_{m3} g_{m4}}{C_1 C_2}} \quad \text{2nd order BP}$$

$$\frac{V_{o2}}{V_{in}} = \frac{\frac{g_{m1} g_{m3}}{C_1 C_2}}{s^2 + s \frac{g_{m2}}{C_1} + \frac{g_{m3} g_{m4}}{C_1 C_2}} \quad \text{2nd order LP}$$

Poles:

$$\omega_p = \sqrt{\frac{g_{m3} g_{m4}}{C_1 C_2}}$$

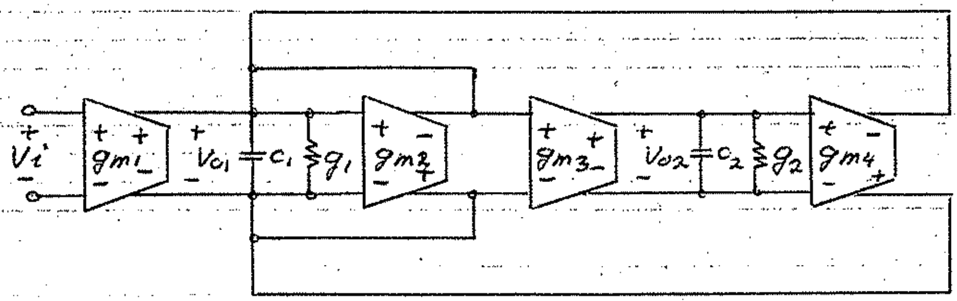
$$Q_p = \sqrt{\frac{C_1}{C_2}} \cdot \frac{\sqrt{g_{m3} g_{m4}}}{g_{m2}}$$

Trimming: use g_{m3} and g_{m4} for ω_p

use g_{m2} for Q_p

Fully-Differential Ota-C Biquad

Topology: for Lowpass and Bandpass



Transfer Functions:

$$\frac{V_{o1}}{V_i} = \frac{\frac{g_{m1}}{C_1}\left(s + \frac{g_2}{C_2}\right)}{s^2 + s\frac{g_{m2}}{C_1}\left[1 + \frac{g_1}{g_{m2}} + \frac{g_2}{g_{m2}}\frac{C_1}{C_2}\right] + \frac{g_{m3}g_{m4}}{C_1C_2}\left[1 + \frac{g_{m2}g_2 + g_1g_2}{g_{m3}g_{m4}}\right]}$$

$$\frac{V_{o2}}{V_i} = \frac{\frac{g_{m1}g_{m3}}{C_1C_2}}{s^2 + s\frac{g_{m2}}{C_1}\left[1 + \frac{g_1}{g_{m2}} + \frac{g_2}{g_{m2}}\frac{C_1}{C_2}\right] + \frac{g_{m3}g_{m4}}{C_1C_2}\left[1 + \frac{g_{m2}g_2 + g_1g_2}{g_{m3}g_{m4}}\right]}$$

$$\therefore \quad \omega_p = \sqrt{\frac{g_{m3}g_{m4}}{C_1C_2}}\sqrt{1 + \frac{g_{m2}g_2 + g_1g_2}{g_{m3}g_{m4}}}$$

$$Q_p = \sqrt{\frac{g_{m3}g_{m4}}{g_{m2}^2}\frac{C_1}{C_2}}\;\frac{\sqrt{1 + \frac{g_{m2}g_2 + g_1g_2}{g_{m3}g_{m4}}}}{1 + \frac{g_1}{g_{m2}} + \frac{g_2}{g_{m2}}\frac{C_1}{C_2}}$$

If $g_1, g_2 << g_m$

$$\therefore \quad \omega_p \cong \sqrt{\frac{g_{m3}g_{m4}}{C_1C_2}}$$

$$Q_p \cong \sqrt{\frac{g_{m3}g_{m4}}{g_{m2}^2}\frac{C_1}{C_2}}$$

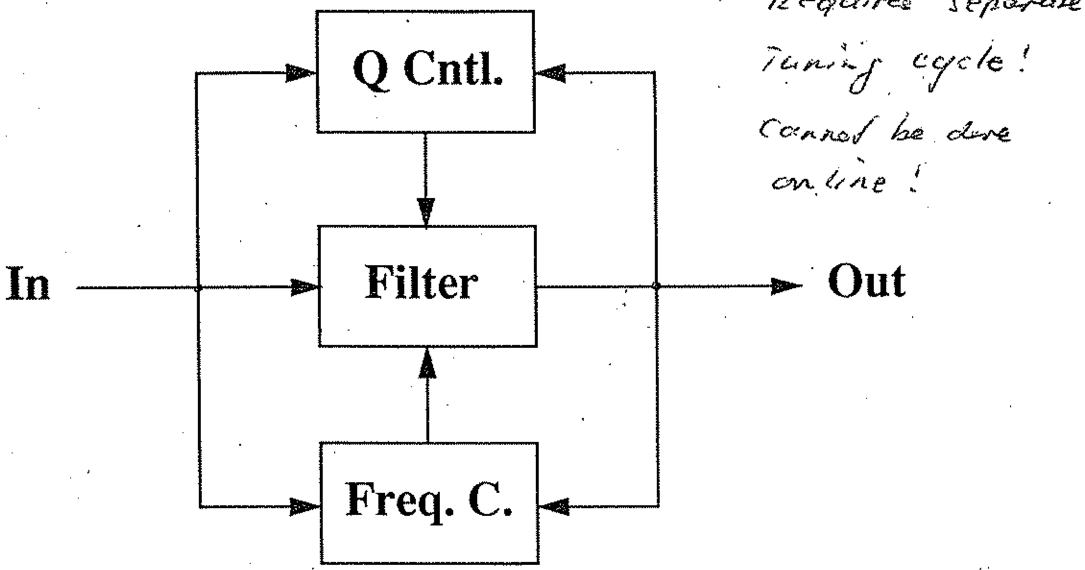
If $\frac{g_i}{g_m} = \varepsilon << 1 \quad i = 1, 2$

$$\omega_p = \omega_{p\,id}\left(1 + \frac{1}{2}\varepsilon\right)$$

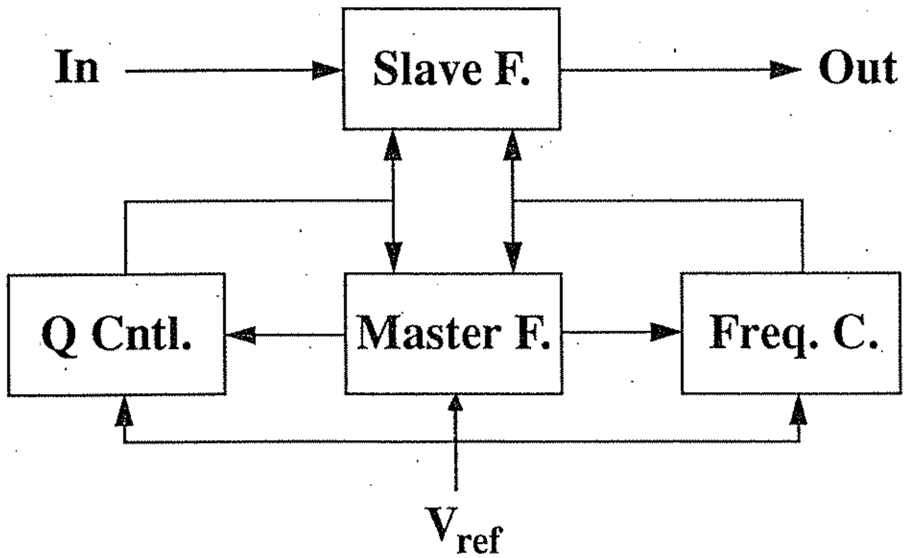
$$Q_p = Q_{p\,id}\left(1 - \frac{3}{2}\varepsilon\right)$$

Filter Tuning

Direct Tuning



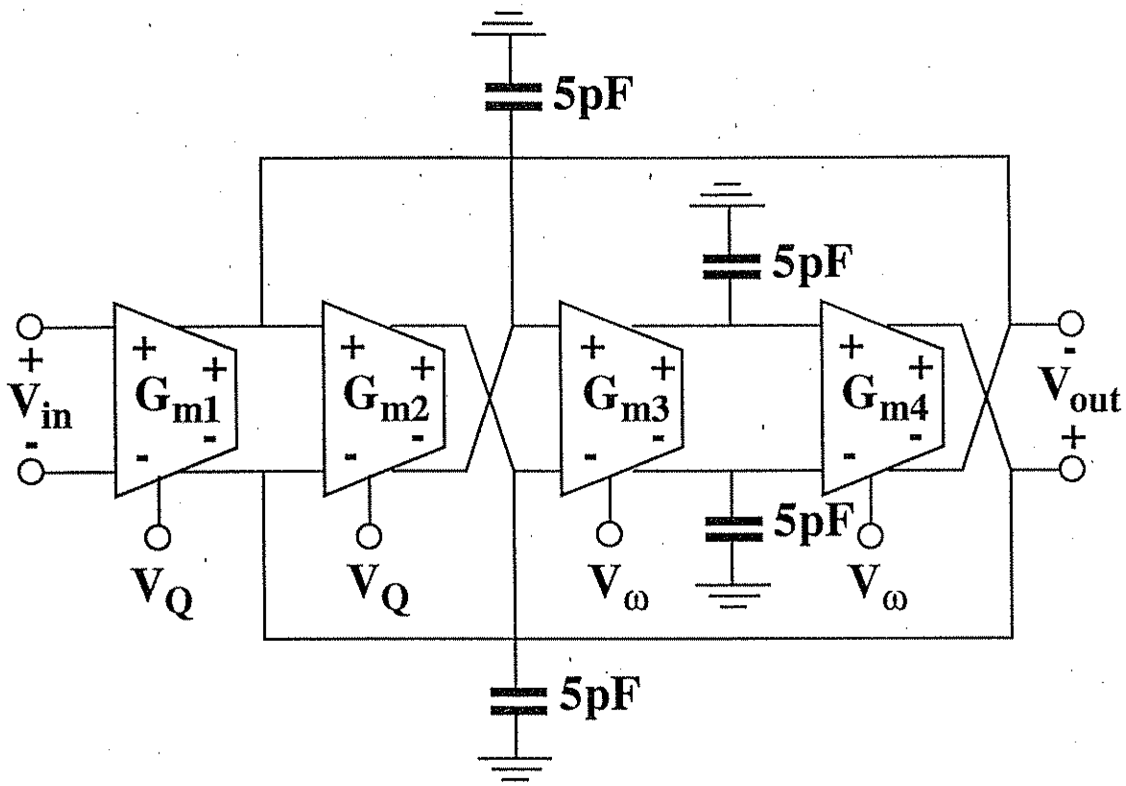
Master-Slave Tuning



4. Simulation Results

Test Circuit

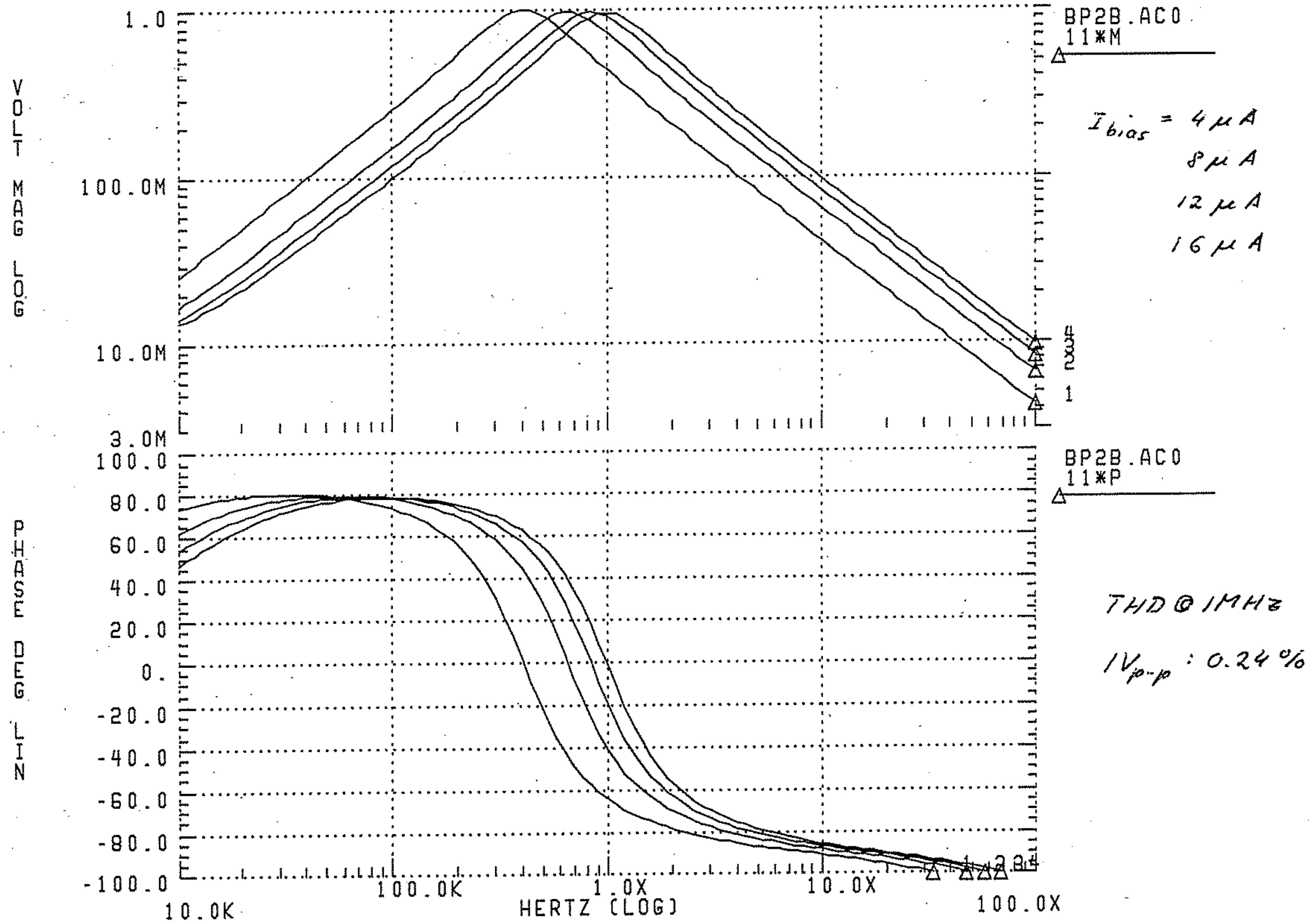
2nd Order Bandpass

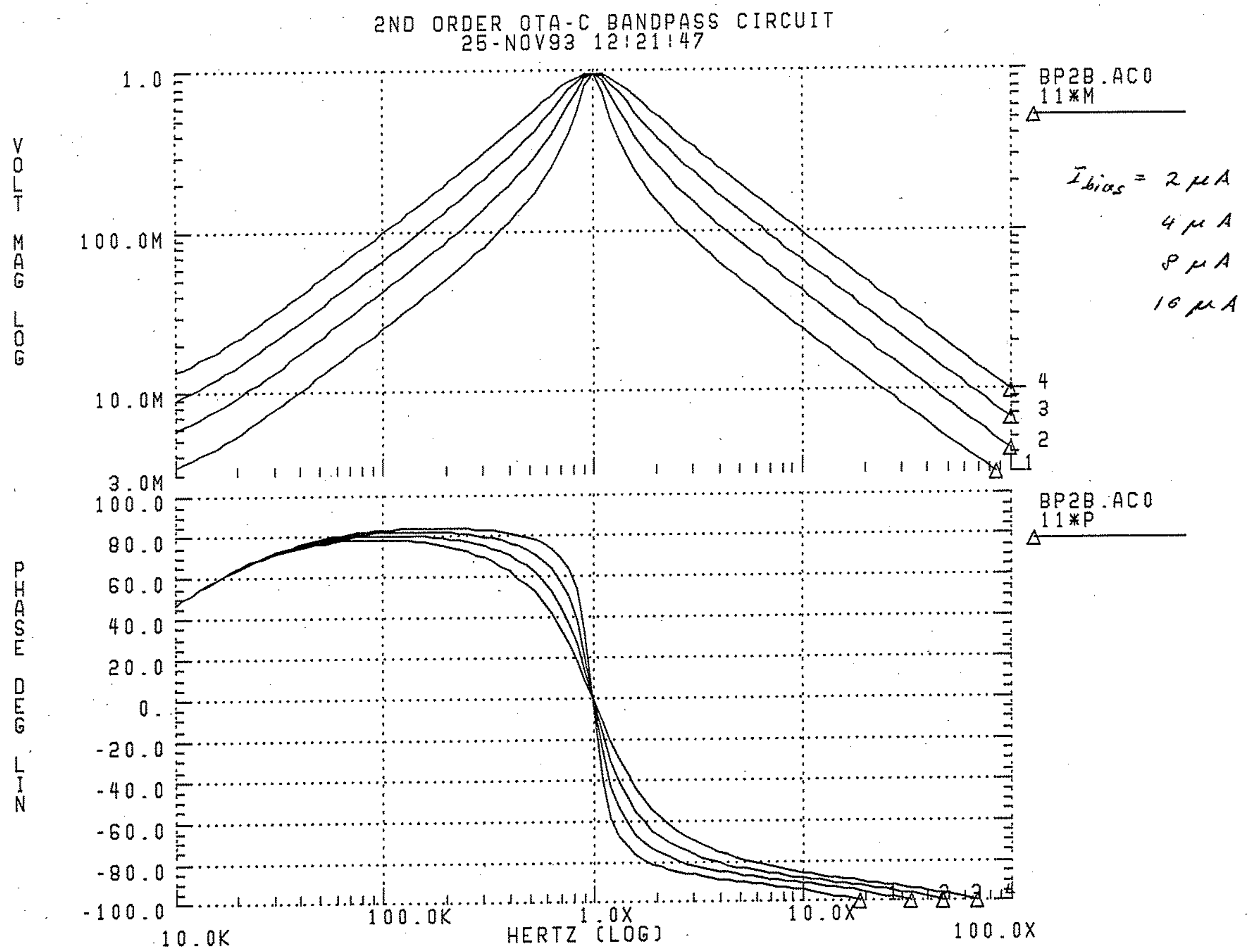


nominal bias: G_{mi}=16μA/V   i=1,2,3,4

ω_p=2Π*1MHz
Q_p=1

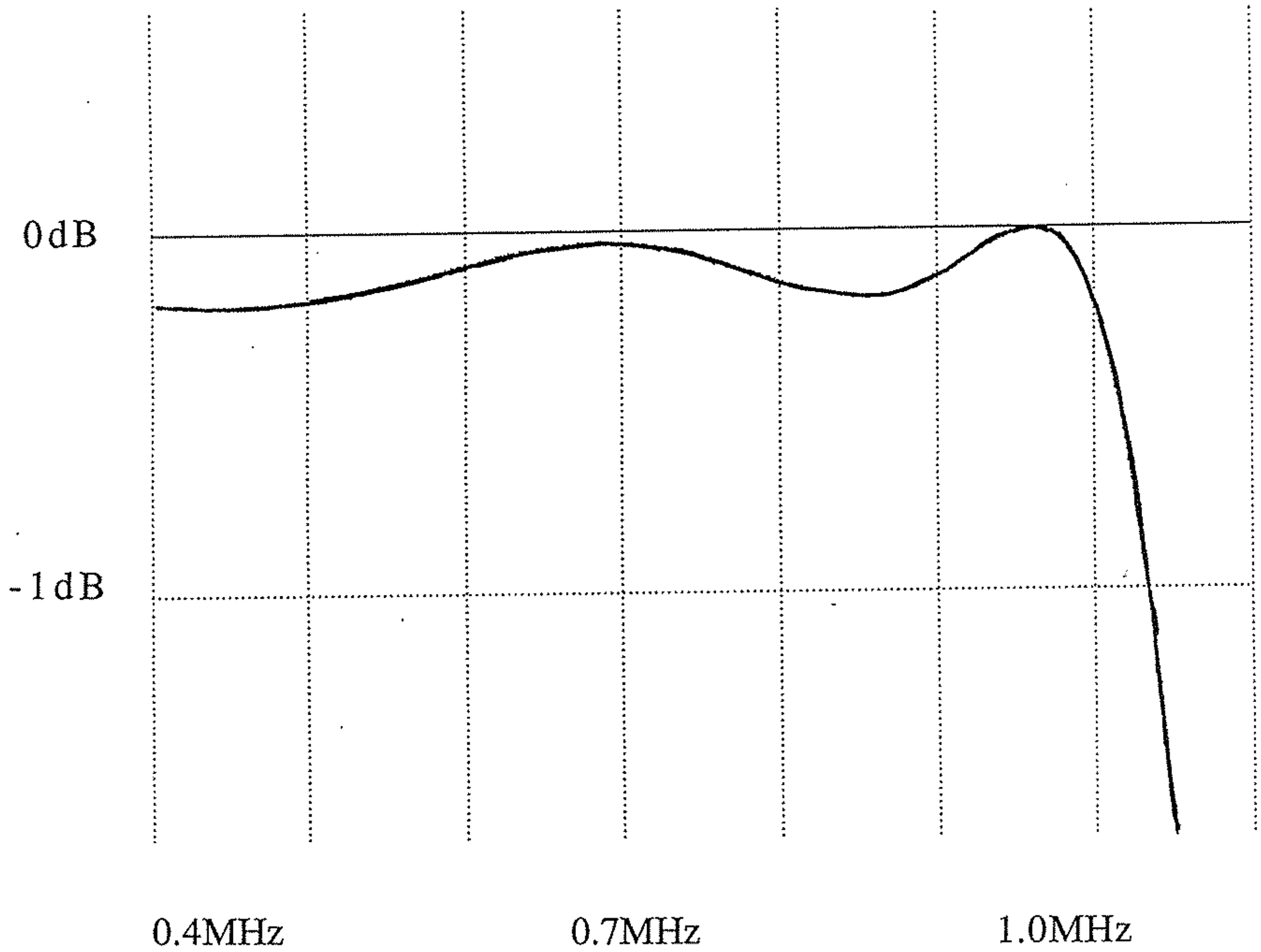
2ND ORDER OTA-C BANDPASS CIRCUIT
25-NOV93 12:21:47




2ND ORDER OTA-C BANDPASS CIRCUIT
25-NOV93 12:21:47
VOLT MAG LOG
1.0
100.0M
10.0M
3.0M
BP2B.AC0
11*M
I_{bias} = 2 μA
4 μA
8 μA
16 μA
4
3
2
1
PHASE DEG LIN
100.0
80.0
60.0
40.0
20.0
0.
-20.0
-40.0
-60.0
-80.0
-100.0
BP2B.AC0
11*P
10.0K
100.0K
1.0X
10.0X
100.0X
HERTZ (LOG)

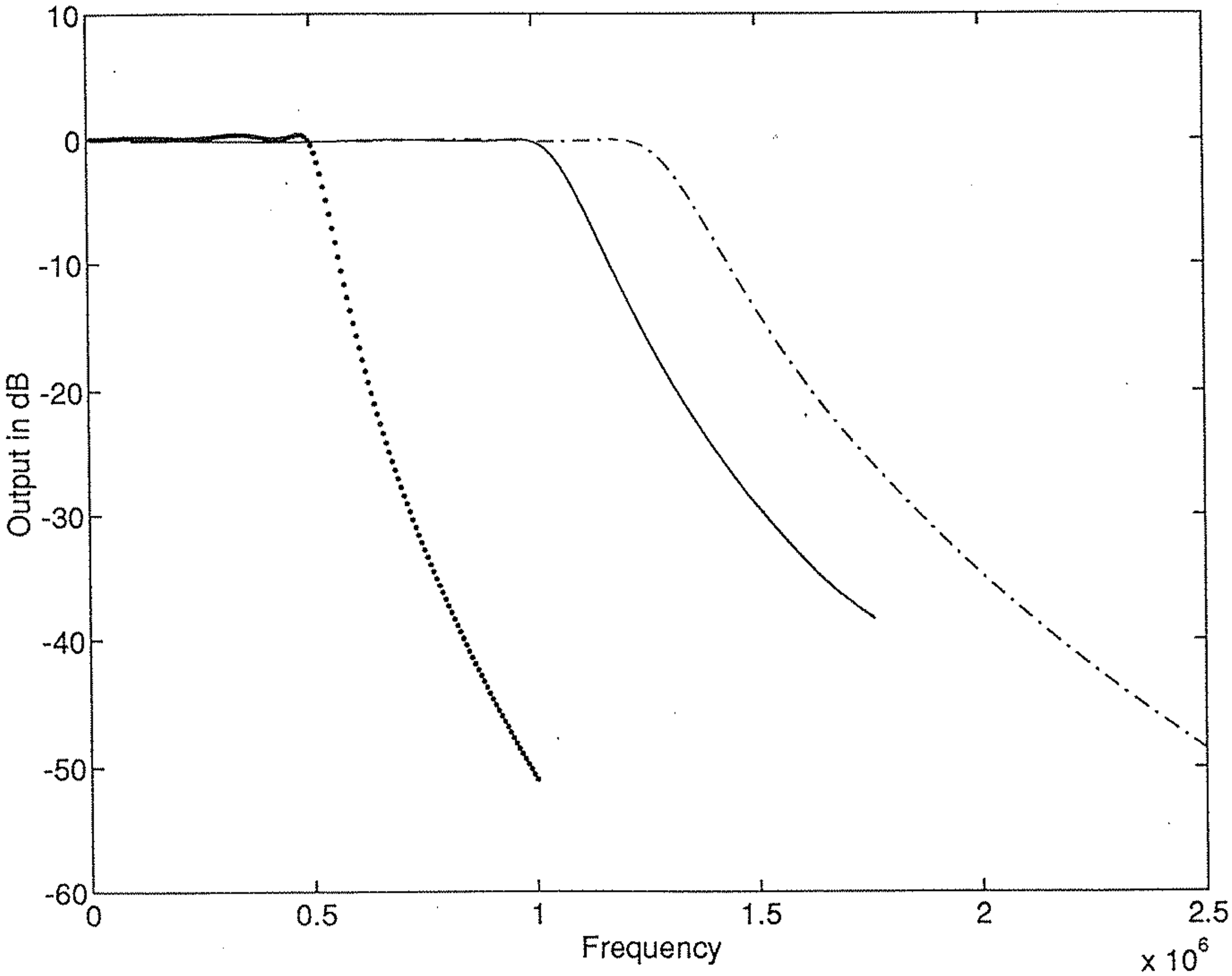
6th Order Ota-C Lowpass Filter

Passband Response

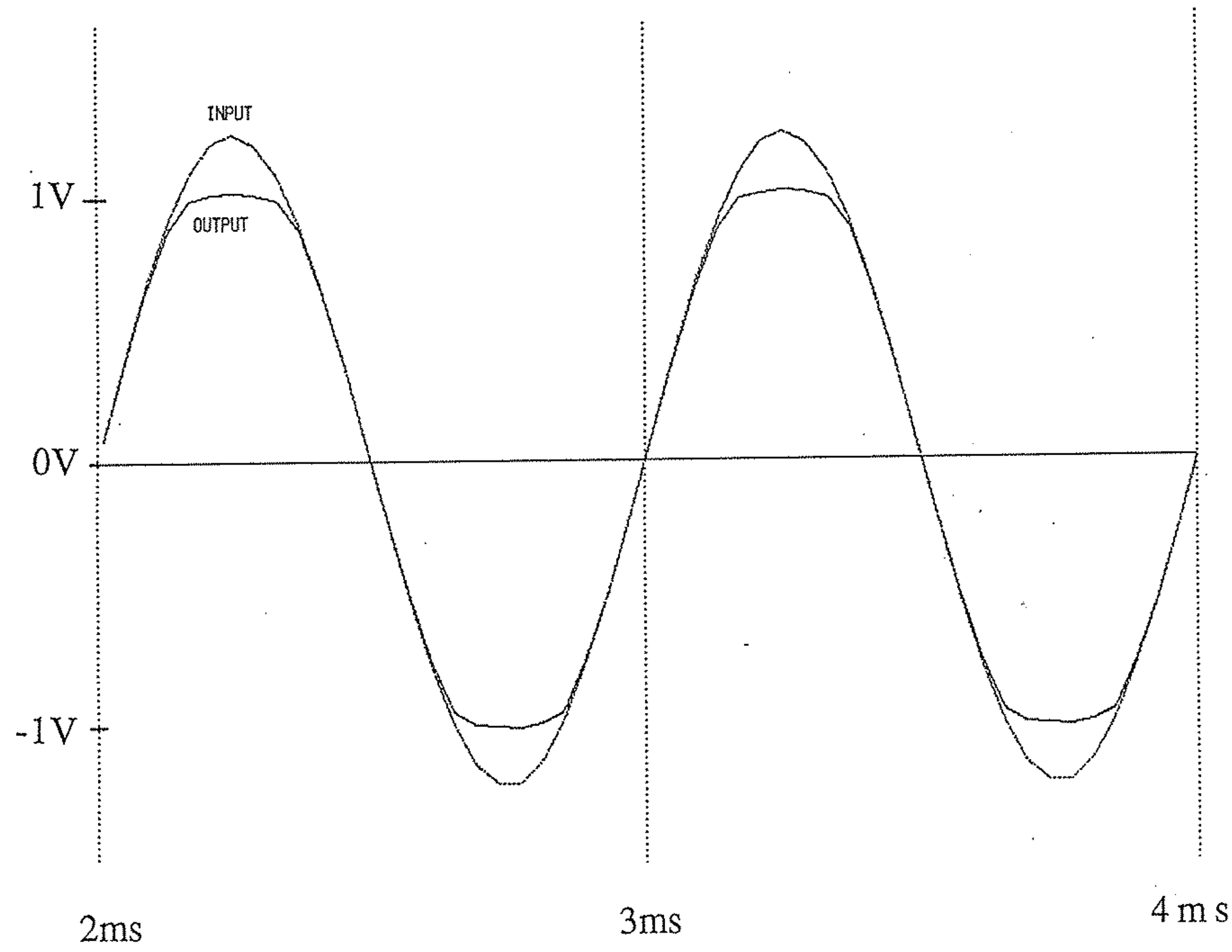


Filter Tuning Range

Ib1=4µm, Ib2=16µm, Ib3=24µm,



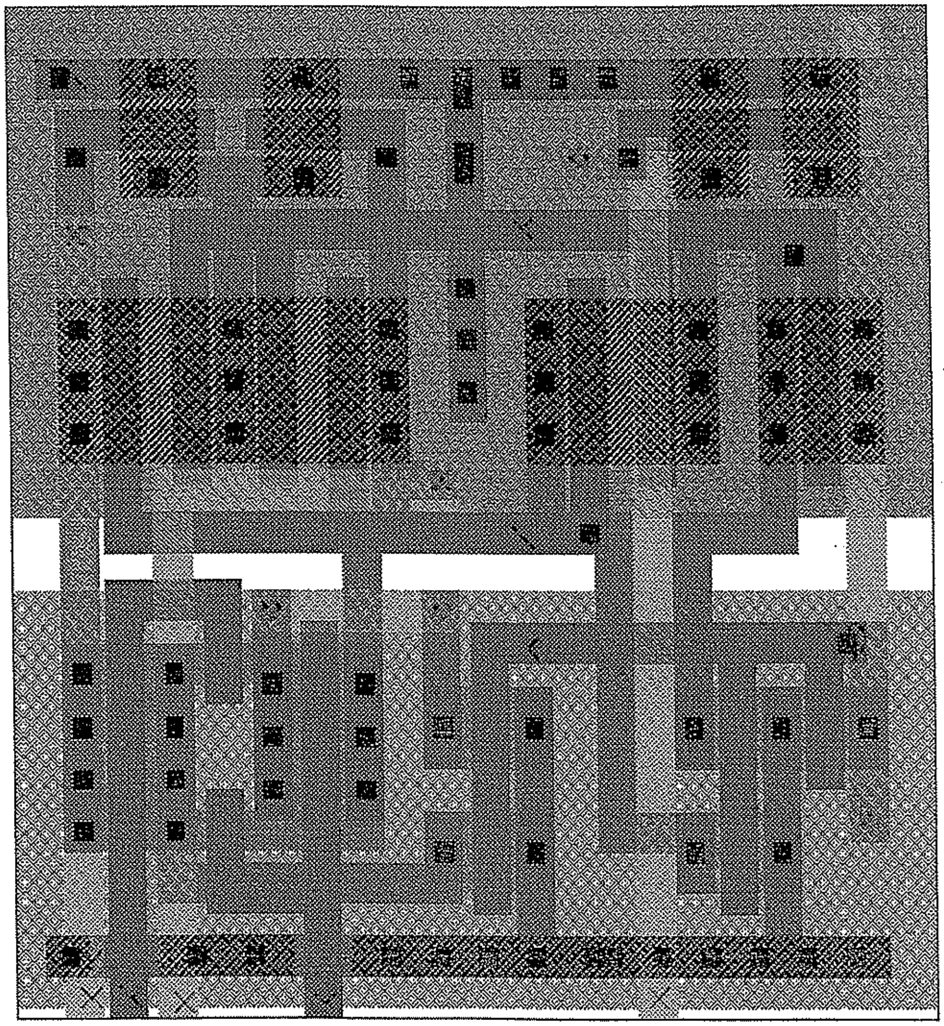
Swing Limitation



5. Layout of Prototype Filter

Transconductance Element (1.2μm CMOS)

(size: 85μmx88μm)



6. Conclusions

- Simple design procedure (for state variable topologies)
- Power and area efficient filter implementation
- Well suited for high frequency applications ($\omega_p = G_m/C$)
- Dynamic range limited by transconductors (Large input swing ---> THD < 60dB)
- Transconductors require tuning
- Accuracy depending on device matching (for on-line master-slave tuning)
- Additional circuitry for automatic tuning required