EE288 Data Conversions/Analog Mixed-Signal ICs
Spring 2018

Lecture 22: OPAMP for ADC

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Agenda

- OPAMP Types
  - Telescopic
  - Folded-cascode
  - Gain-Boosting
  - Two-stage
  - Fully-differential

- Simulating OPAMP
  - DC, AC, stb, Transient

OPAMP Gain Requirement for N-bit ADC

OPAMP is always used in closed loop configuration.

OPAMP Closed-loop Response:

$$V_{\text{out}} = G \times V_{\text{in}} \left(\frac{1}{1 + \frac{1}{A \times \beta}} \right) \left(1 - e^{-\frac{t}{\tau}}\right)$$

Assume Gain Error should be less than ¼ LSB

$$\frac{1}{\beta A} < \frac{1}{2} LSB \quad \rightarrow \quad \frac{1}{\beta A} < \frac{1}{2} \frac{V_{FS}}{2^N}$$

$$A > \frac{2 \cdot 2^N}{\beta \cdot V_{FS}}$$

Resolution	Full Scale	Beta	Gain (dB)	Gain (dB)
N	V_{FS} (Volt)	β	$2 \cdot 2$^(N) /(β·V_{FS})	20log(x)
10	0.8	1	5120	74
10	0.8	0.5	10240	80
11	0.8	1	10240	80
11	0.8	0.5	20480	86
12	0.8	1	20480	86
12	0.8	0.5	40960	92
13	0.8	1	40960	92
13	0.8	0.5	81920	98
14	0.8	1	81920	98
14	0.8	0.5	163840	104

OPAMP Bandwidth Requirement for N-bit ADC

Assume Settling Error should be less than 1/2 LSB

$$e^{-t/\tau} < \frac{1}{2}\,LSB \quad \rightarrow \quad e^{-t/\tau} < \frac{1}{2}\frac{\boldsymbol{V_{FS}}}{\boldsymbol{2^N}} \quad \rightarrow \quad \frac{t}{\tau} > (\boldsymbol{N}+\boldsymbol{1})\boldsymbol{ln}(\boldsymbol{2}) - \boldsymbol{ln}(\boldsymbol{V_{FS}})$$

$$t = \frac{T_s}{2} = \frac{1}{2f_s}$$

$$\tau = \frac{1}{\omega_{-3dB}} = \frac{1}{2\pi\, f_{-3dB}} = \frac{1}{2\pi\,\beta\, f_u}$$

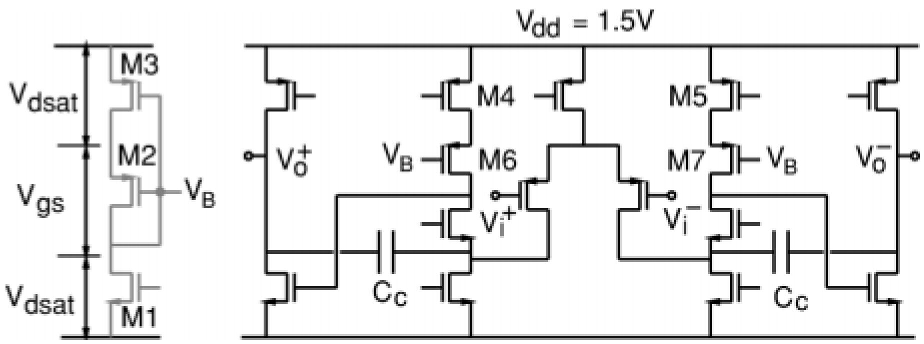
$$\frac{t}{\tau} = \frac{1}{2f_s}2\pi\,\beta\, f_u > \ (\boldsymbol{N}+\boldsymbol{1})\boldsymbol{ln}(\boldsymbol{2}) - \boldsymbol{ln}(\boldsymbol{V_{FS}})$$

$$f_u > \frac{f_s}{\pi\beta}[(\boldsymbol{N}+\boldsymbol{1})\boldsymbol{ln}(\boldsymbol{2}) - \boldsymbol{ln}(\boldsymbol{V_{FS}})]$$

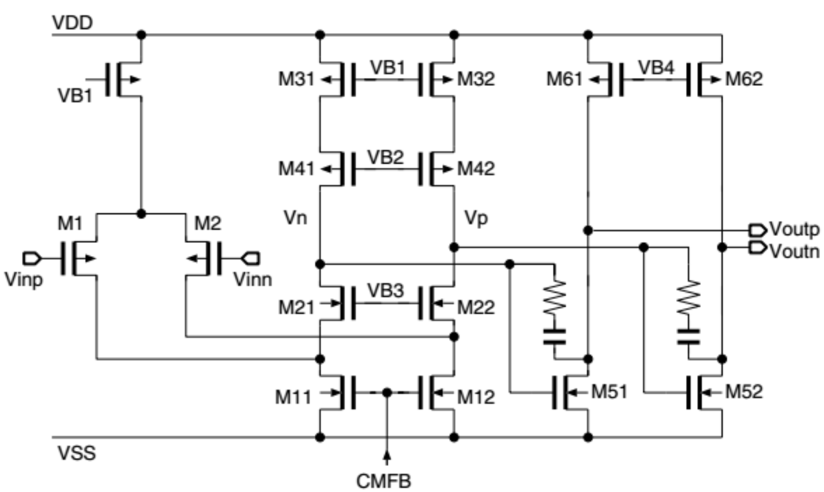
$$\boldsymbol{ln}(\boldsymbol{2}) = 0.\boldsymbol{693}$$

Resolution	Full Scale	Beta	Sampling Rate	UGB
N	V_{FS} (Volt)	β	fs	fu
10	0.8	1	5.00E+07	1.25E+08
10	0.8	0.5	5.00E+07	2.50E+08
11	0.8	1	5.00E+07	1.36E+08
11	0.8	0.5	5.00E+07	2.72E+08
12	0.8	1	5.00E+07	1.47E+08
12	0.8	0.5	5.00E+07	2.94E+08
13	0.8	1	5.00E+07	1.58E+08
13	0.8	0.5	5.00E+07	3.16E+08
14	0.8	1	5.00E+07	1.69E+08
14	0.8	0.5	5.00E+07	3.38E+08

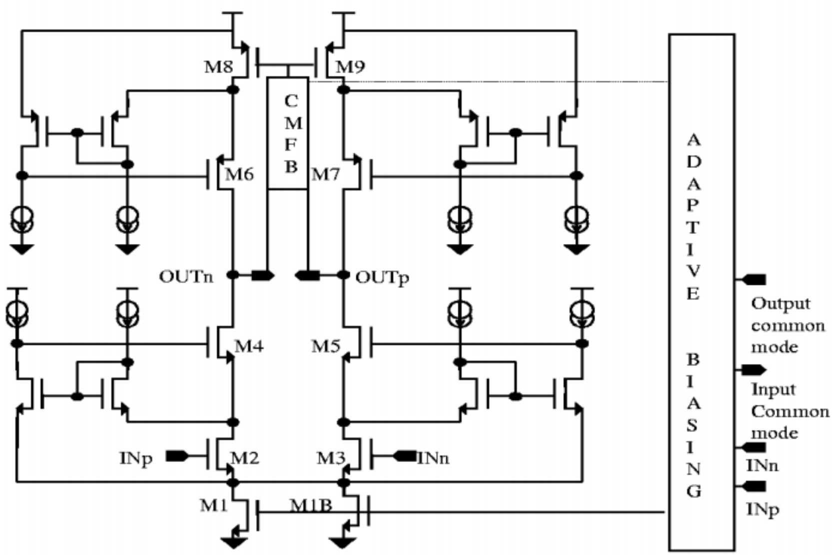
Example OPAMP Circuits



[Ref. 1]



[Ref. 2]



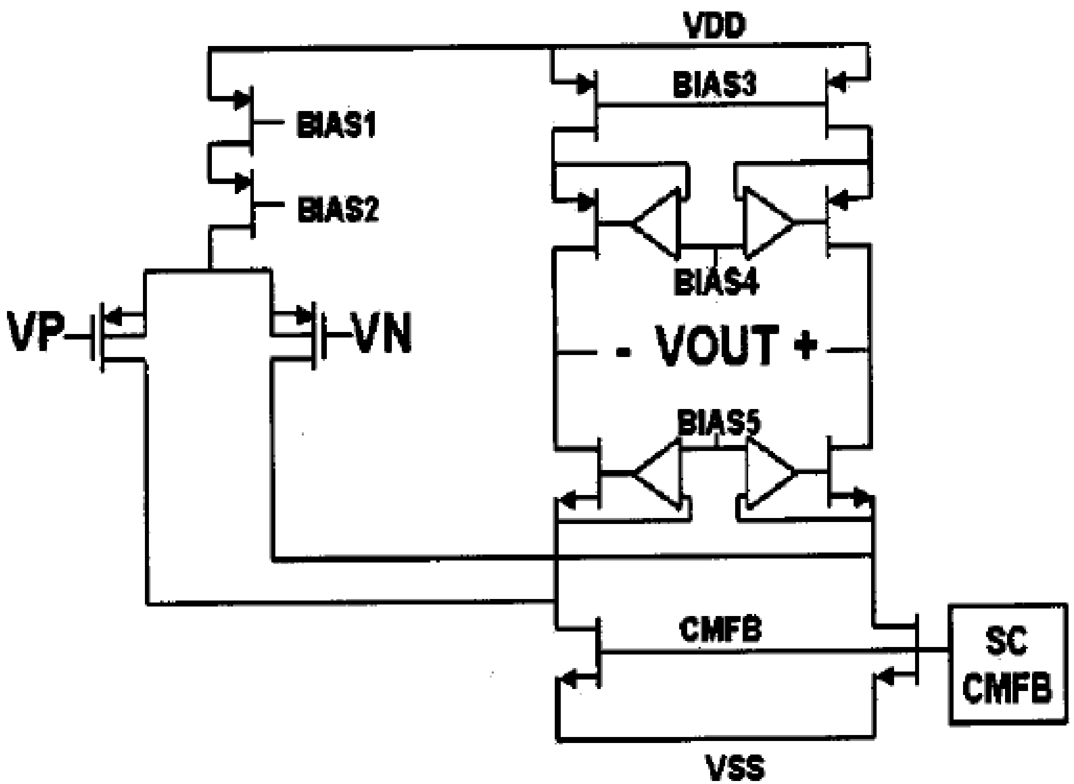
[Ref. 3]

Example OPAMP in 14-bit Pipelined ADC

IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 36, NO. 12, DECEMBER 2001

A 3-V 340-mW 14-b 75-Msample/s CMOS ADC With 85-dB SFDR at Nyquist Input

Wenhua (Will) Yang, *Member, IEEE*, Dan Kelly, *Member, IEEE*, Iuri Mehr, *Member, IEEE*, Mark T. Sayuk, *Member, IEEE*, and Larry Singer, *Member, IEEE*



Amplifier in Flip-around THA

Example OPAMP in 14-bit Pipelined ADC

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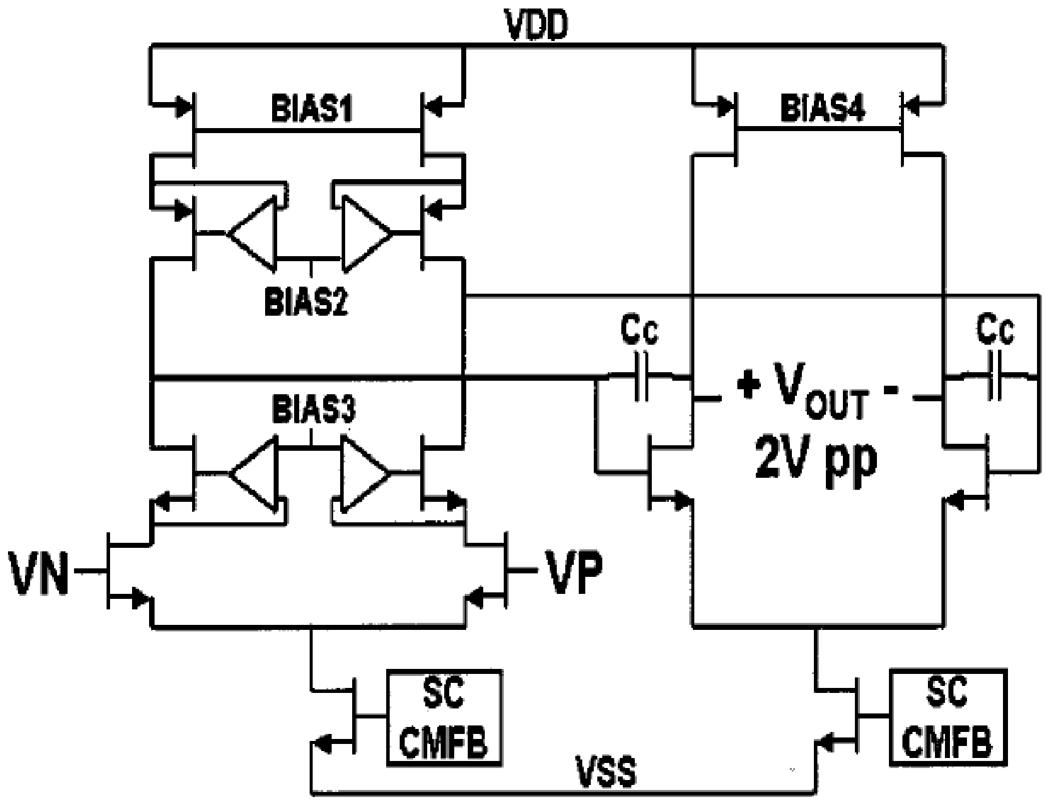
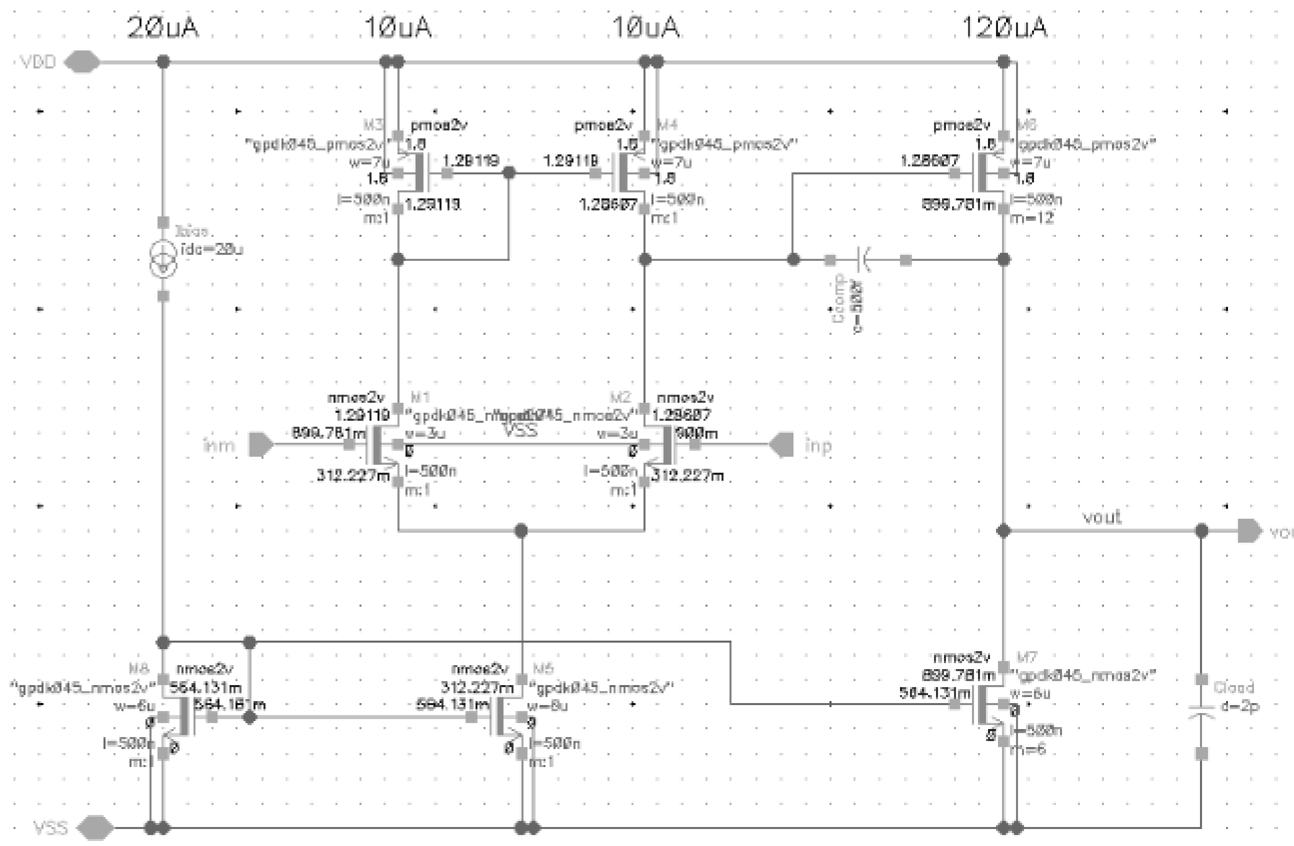


Amplifier in Stage 1

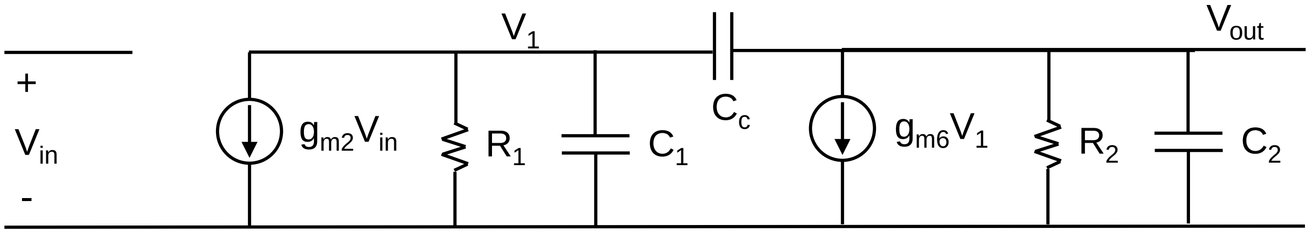
2-Stage OPAMP with NMOS Diff pair

Technology:
0.18um CMOS
VDD=1.8V
Lmin = 180nm
Use L $\geq$ 500nm
Ibias = 20uA



Spec:
DC gain = 60dB
GBW = 30MHz
PM = 60^{o}
SR = 20V/us
Cload = 2pF
Power < 300uW

Small-Signal Model of the OPAMP



By applying KCL, we can get the following approximate expression for 2 LHP poles and 1 RHP zero in the transfer function.

$p1 = -1/(R_1 g_{m6} R_2 C_c)$

$p2 = -g_{m6}/(C_1+C_2)$

$z = g_{m6}/C_c$

$Av = Av1\ Av2 = -g_{m2}R_1 g_{m6} R_2$

$GBW = UGB = Av \times p1 = g_{m2}/C_c$

For 60 deg PM, p2 > 2.2 GBW, and for 45 deg PM, p2 > 1.2 GBW

For z = 10 GBW, $g_{m6} = 10\ g_{m2}$ $\qquad$ $C_c > 0.22\ C_2$

Simulation Steps

1. DC Simulation

- Construct the OPAMP schematic
- Run a DC simulation
- Check the operating point information by choosing Results→Print →DC Operating Points
- Make sure that all transistors are in Saturation (region=2)

2. AC Simulation

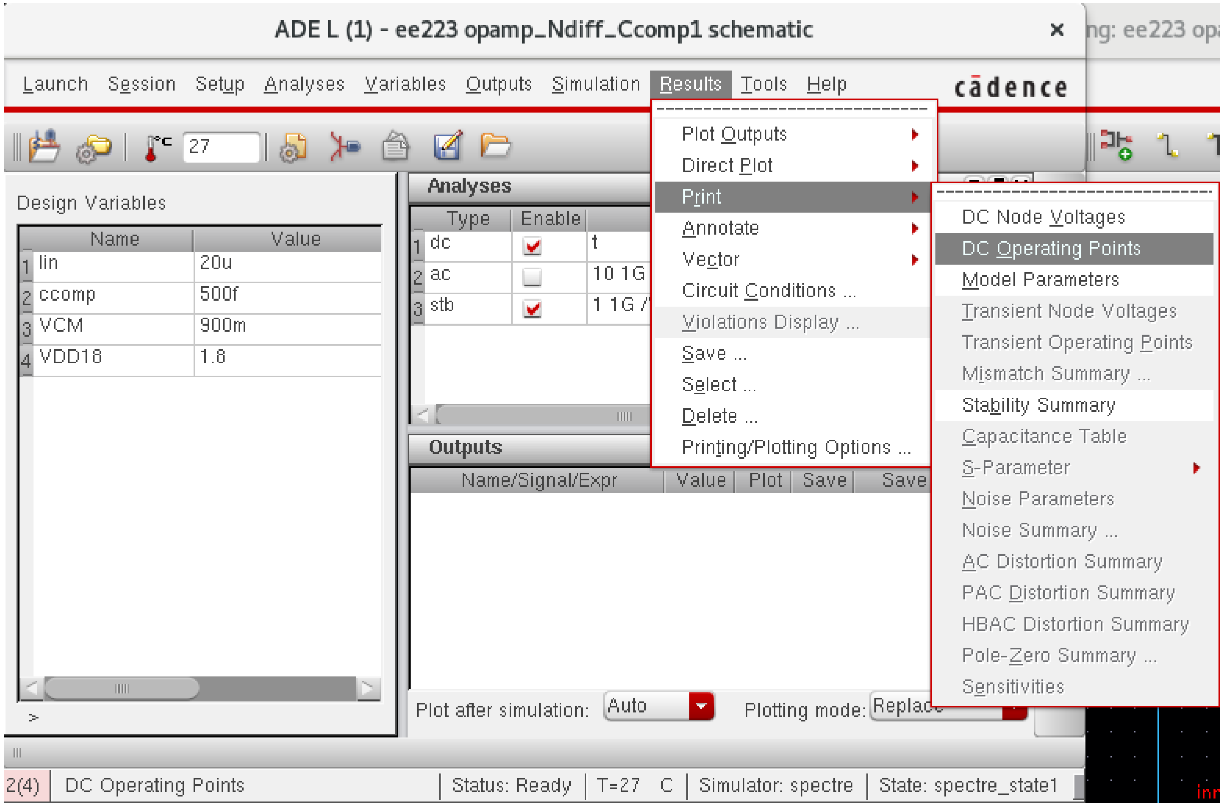
- Try RC Feedback approach to get the AC response
- Run stb analysis to check the stability

3. Transient Simulation

- Appy 10mV step pulse to check the small-signal transient response
- Appy 500mV step pulse to check the large-signal transient response

DC Operating Points

To get the DC operating point information after you run the dc simulation, Choose Results→Print →DC Operating Points and then click on the transistor in the schematic.



DC Gain Calculation from Operating Points

DC Gain = Av1 x Av2

Av1 = gm2 x (ro2//ro4) = gm2 / (gds2 + gds4)

Av2 = gm6 x (ro6//ro7) = gm6 / (gds6 + gds7)

From simulated DC operating point information of the circuit in slide 2,

gm2 = 125.9u	gds2 = 1.84u	gds4 = 3.53u
gm6 = 2.344m	gds6 = 41.6u	gds7 = 32.16u

Av1 = 125.8 / (1.84+3.53) = 23.4 = 27.4 dB

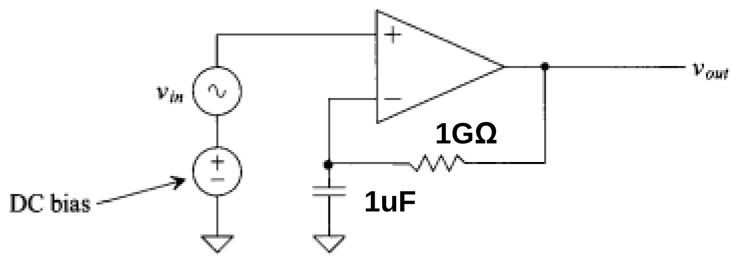
Av2 = 2344 / (41.6+32.16) = 31.8 = 30 dB

Av = 27.4 dB + 30 dB = 57.4 dB ← Close to simulated gain

OPAMP AC simulation Setup

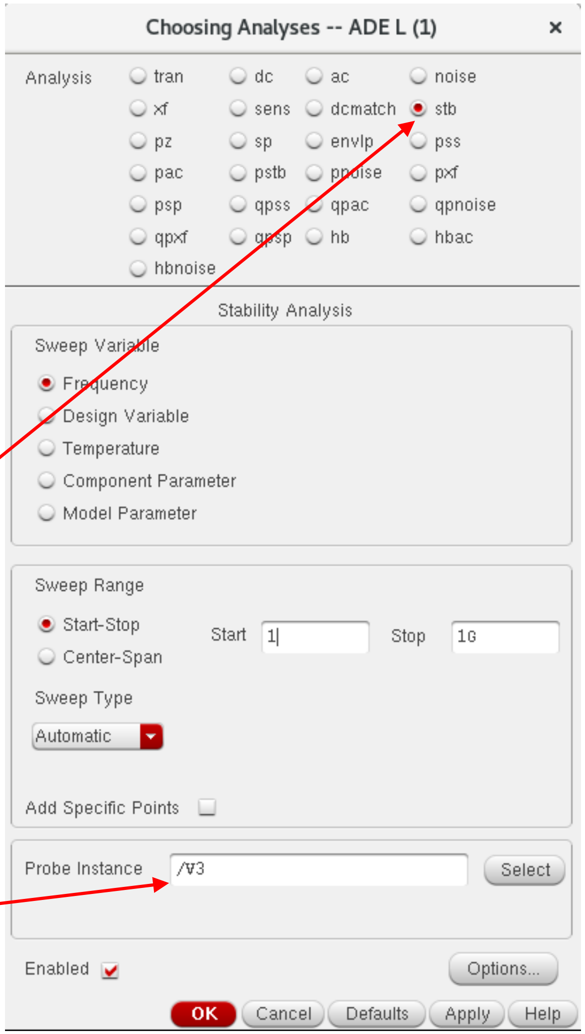
Two Simulation Approaches

1. RC Feedback



2. Stability analysis

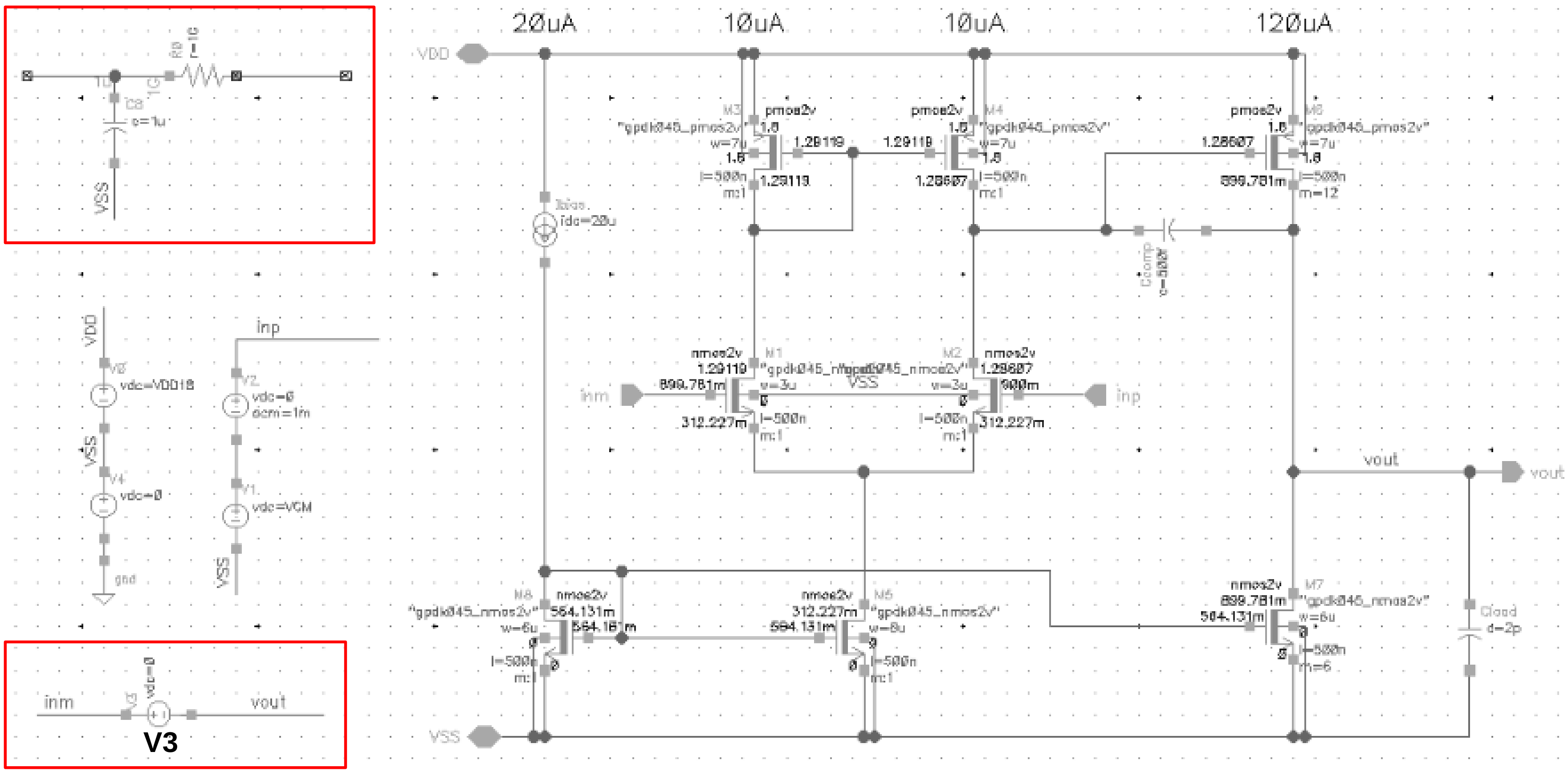
   Choose “stb” in Cadence Analysis



DC voltage source for probing. See previous page.

AC Simulation Test Bench

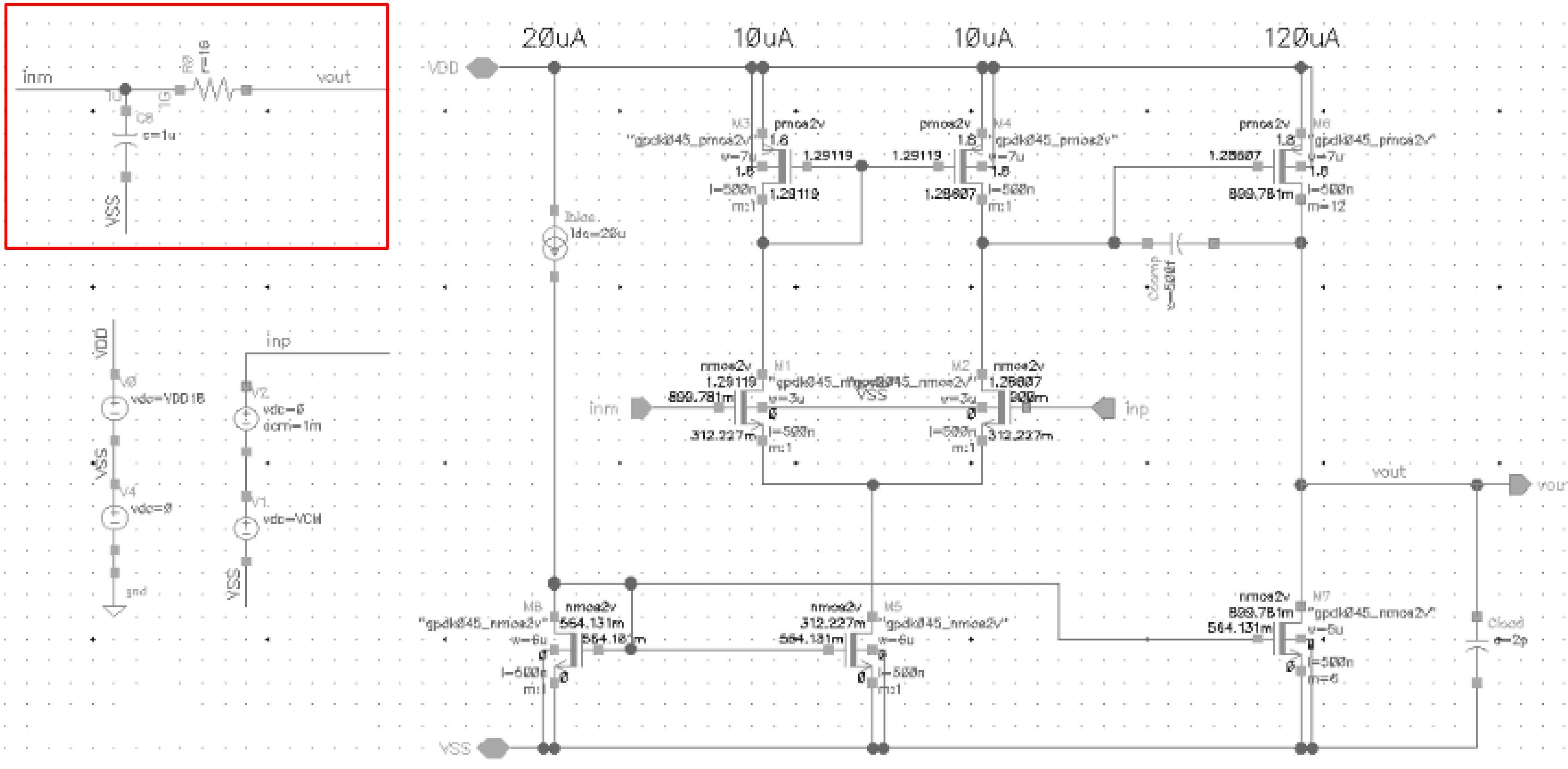
RC-Feedback approach



For stb analysis

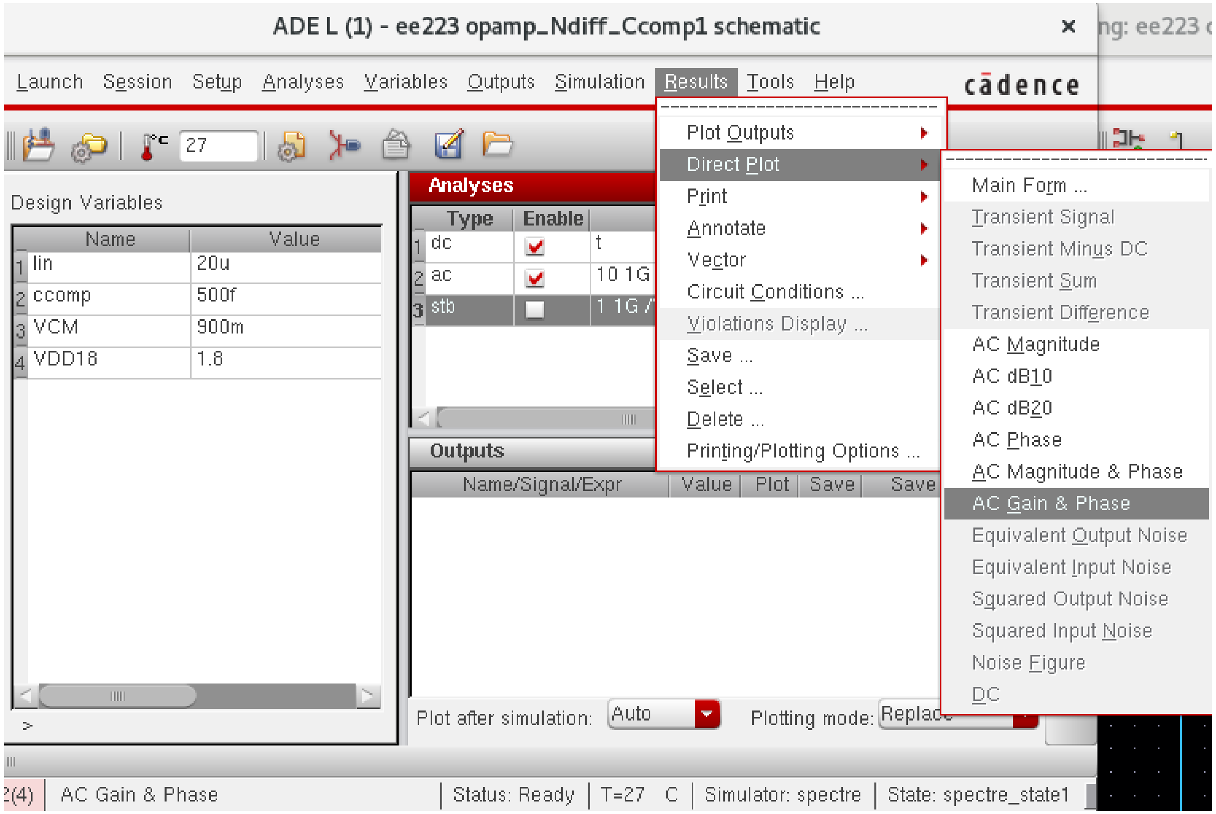
AC Simulation Test Bench using RC-feedback

RC-feedback approach

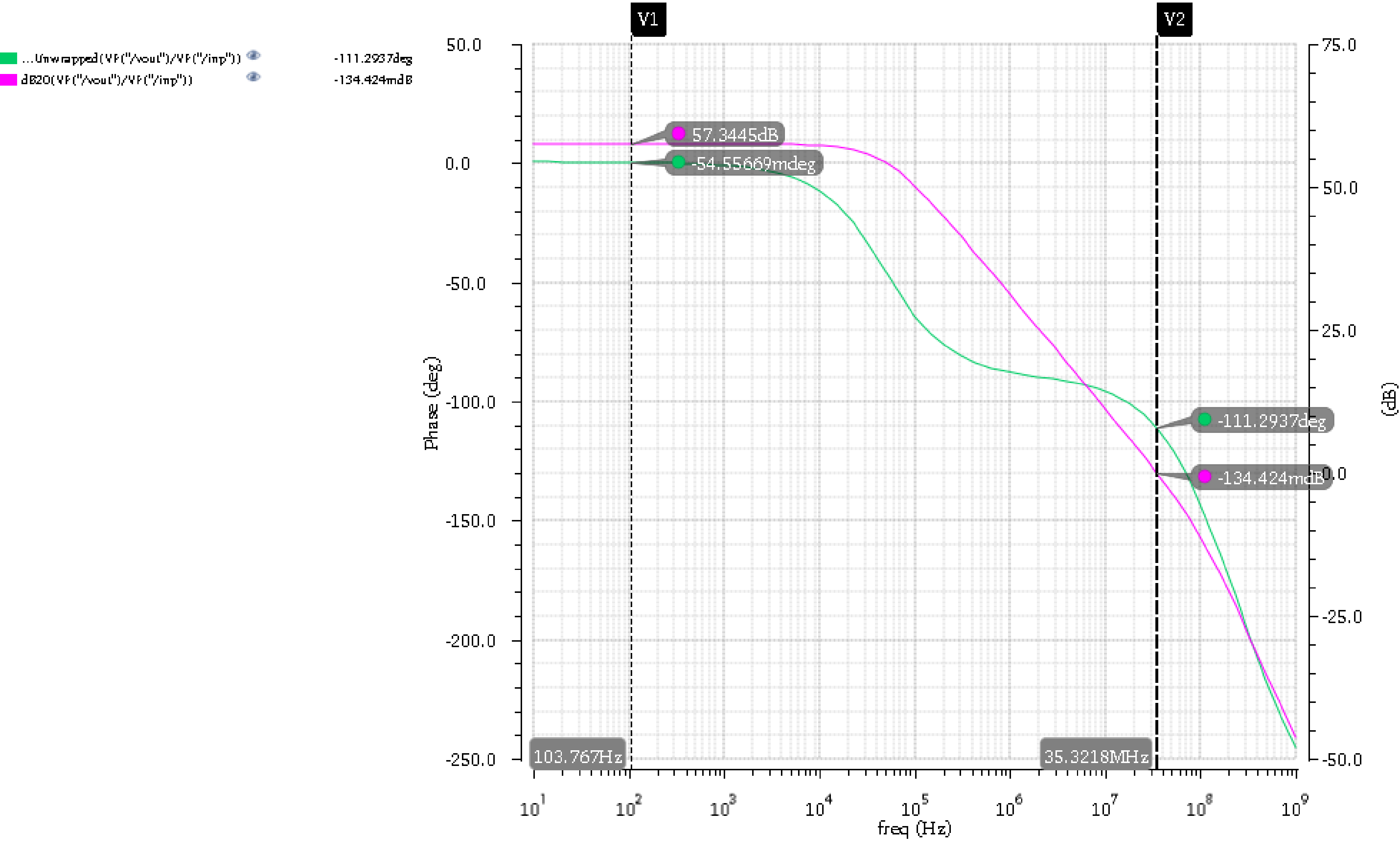


Plotting the AC simulation Results

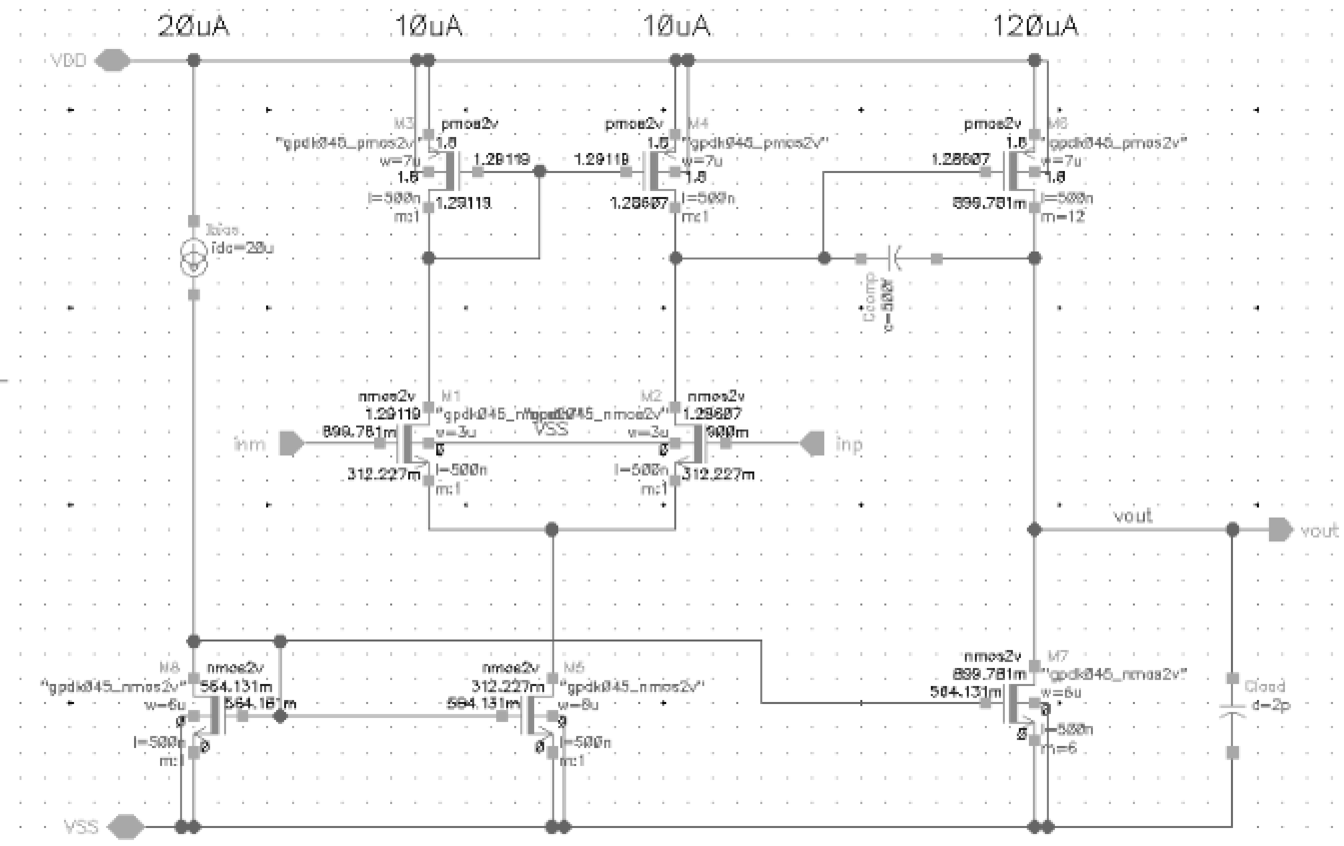
After running the AC simulation, choose Results→Direct Plot→AC Gain & Phase and then click on the output node (vout) and the input node (inp) to get the ac plot shown in next page.

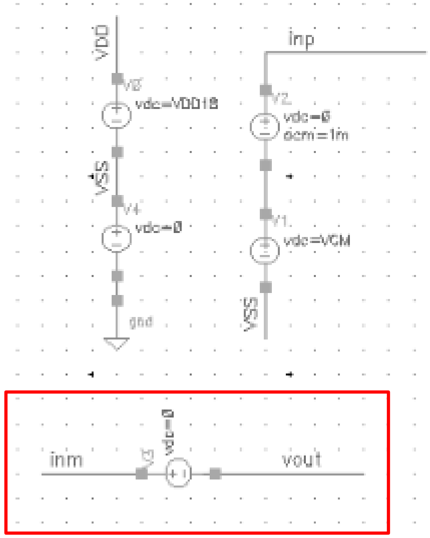


AC Simulation Result using RC Feedback



AC Simulation Test Bench using stb analysis

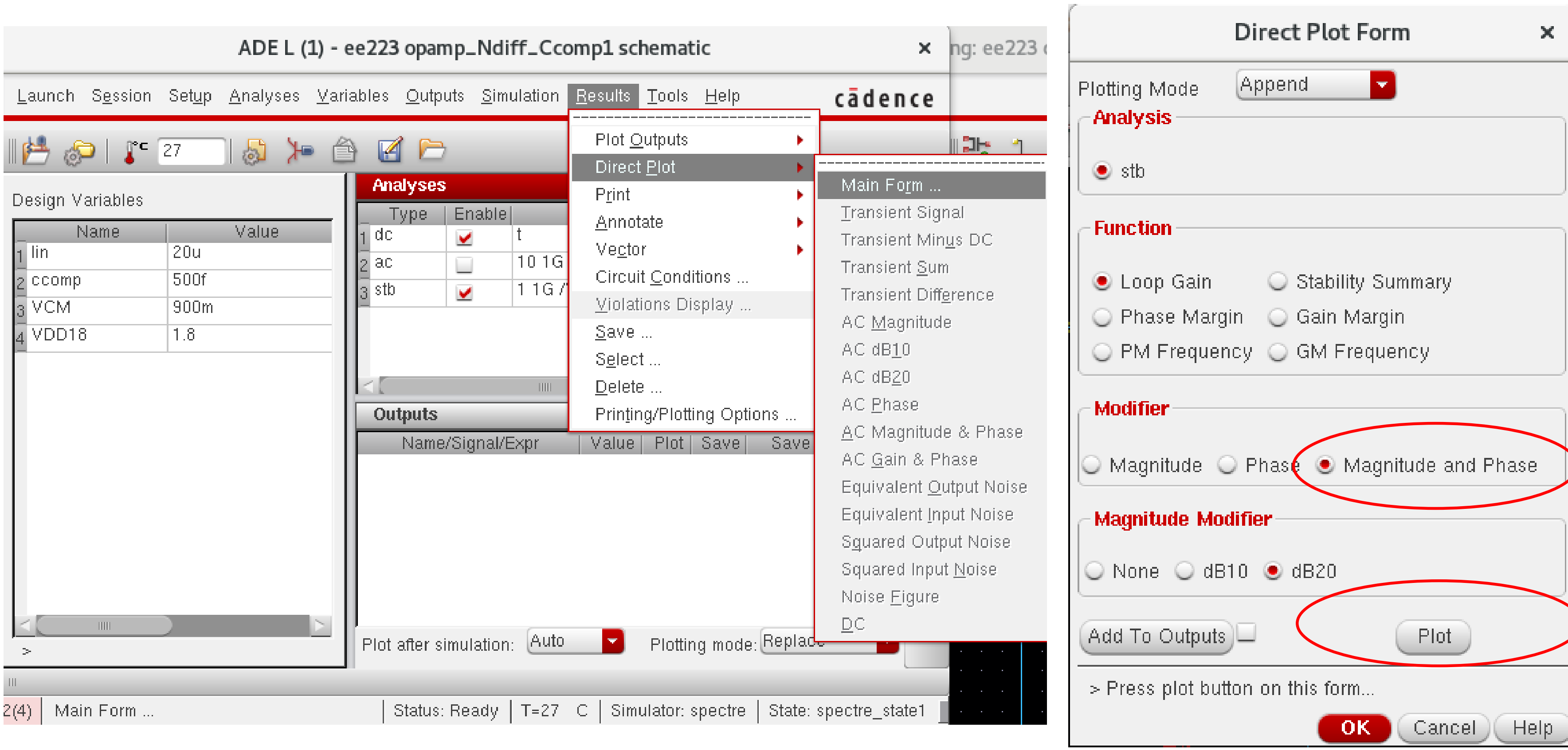




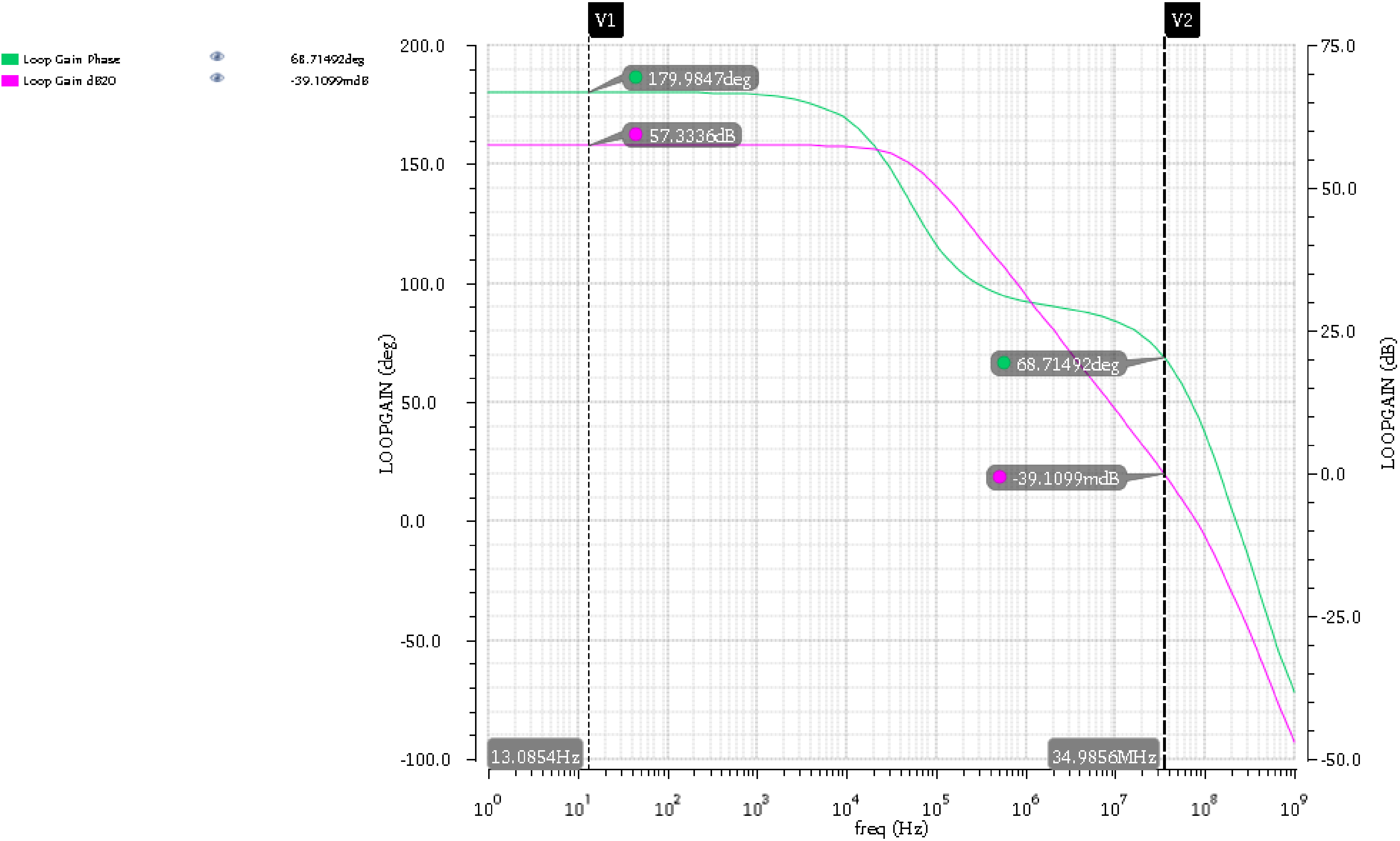
For stb analysis

AC simulation using stb analysis

After running the stb analysis, choose Results→Direct Plot→Main Form and then click on Plot to get the ac plot shown in slide 14

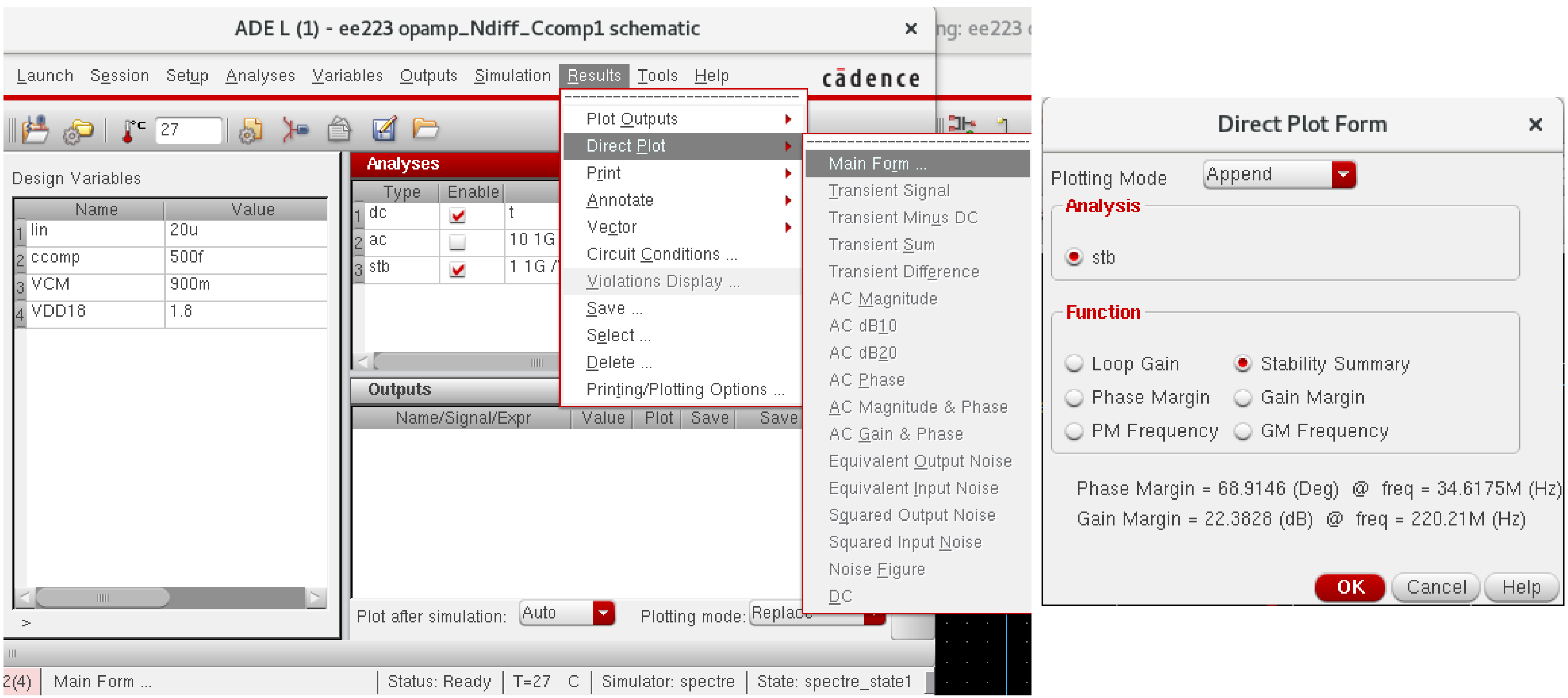


AC Simulation Result using stb analysis



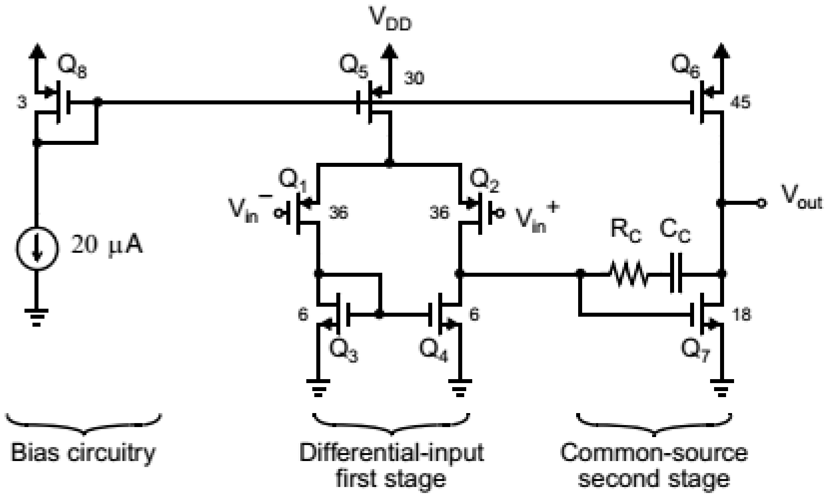
Stability Summary from stb analysis

After running the stb analysis, choose Results→Direct Plot→Main Form and then click on Stability Summary



Name	Value
lin	20u
ccomp	500f
VCM	900m
VDD18	1.8

Two-Stage OPAMP with RC Compensation



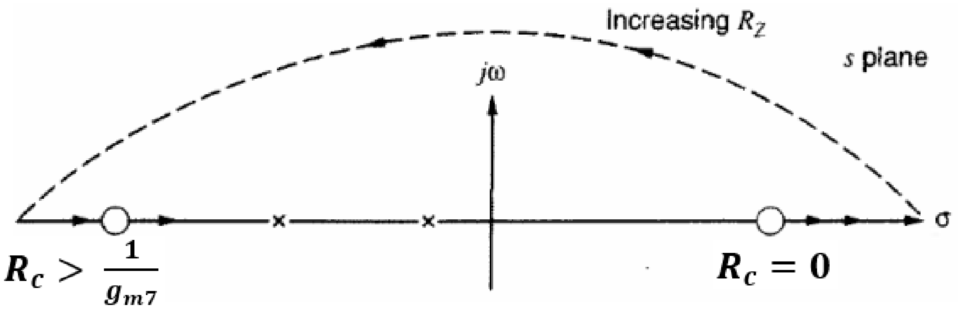
$$A(s) = \frac{A_0\left(1+\frac{s}{\omega_z}\right)}{\left(1+\frac{s}{\omega_{p1}}\right)\left(1+\frac{s}{\omega_{p2}}\right)}$$

$$\omega_z = \frac{-1}{C_c\left(\frac{1}{g_{m7}} - R_c\right)}$$

Choice of Rc

$$A(s) = \frac{A_0(1+\frac{s}{\omega_z})}{(1+\frac{s}{\omega_{p1}})(1+\frac{s}{\omega_{p2}})} \qquad \omega_z = \frac{-1}{C_c(\frac{1}{g_{m7}} - R_c)}$$

- $R_c = 0 \quad \rightarrow \quad \omega_z = \frac{-1}{C_c(\frac{1}{g_{m7}})} = \frac{-g_{m7}}{C_c} \quad \rightarrow$ RHP Zero ! Stability Issue
- $R_c = \frac{1}{g_{m7}} \quad \rightarrow \quad \omega_z = \infty$
- $R_c > \frac{1}{g_{m7}}$



$\rightarrow \quad \omega_z = \omega_{p2}$

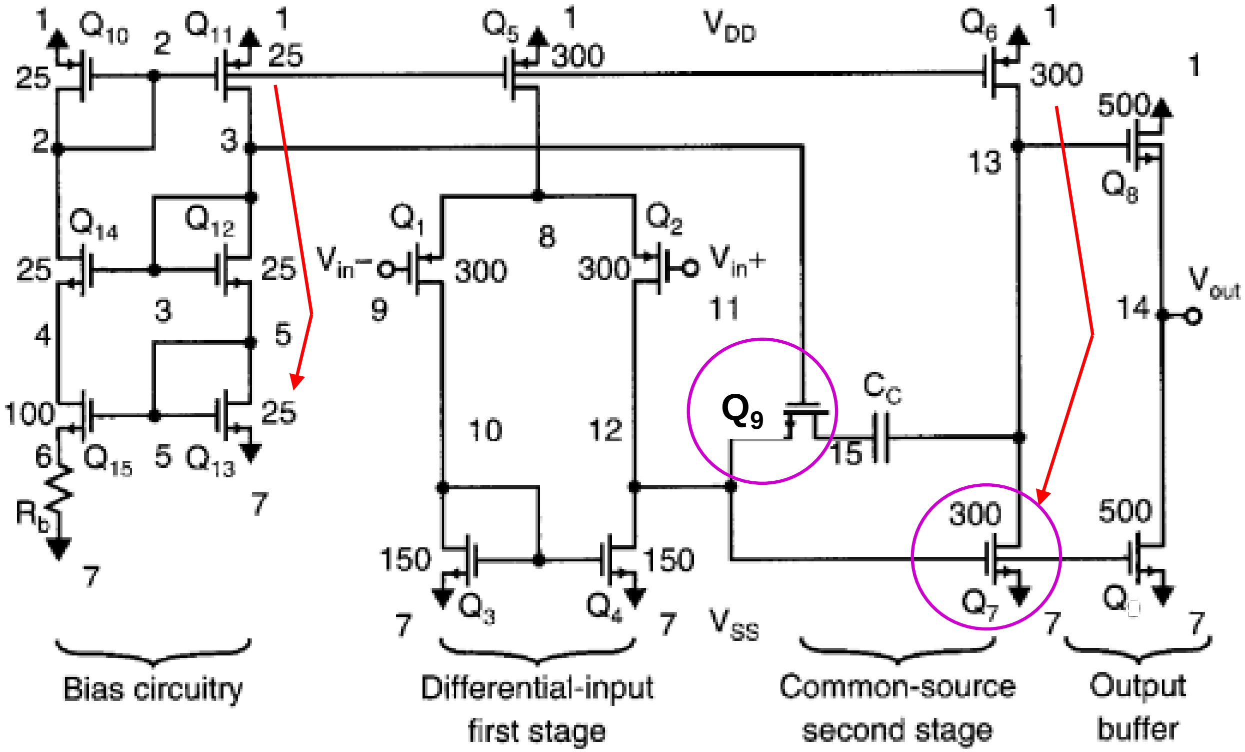
$$\frac{-1}{C_c(\frac{1}{g_{m7}} - R_c)} = \frac{g_{m7}}{C_1 + C_2} \quad \rightarrow \quad R_c = \frac{1}{g_{m7}}\left(1 + \frac{C_1 + C_2}{C_c}\right)$$

- $R_c \gg \frac{1}{g_{m7}} \qquad \omega_z \approx \frac{1}{R_c C_c} = \alpha\omega_u = \alpha\frac{g_{m1}}{C_c} \quad \rightarrow \quad \boxed{R_c = \frac{1}{\alpha g_{m1}}}$

Equation 1

$\alpha = 1.7$ from Caruson, Johns, Martin

Two-stage RC compensation



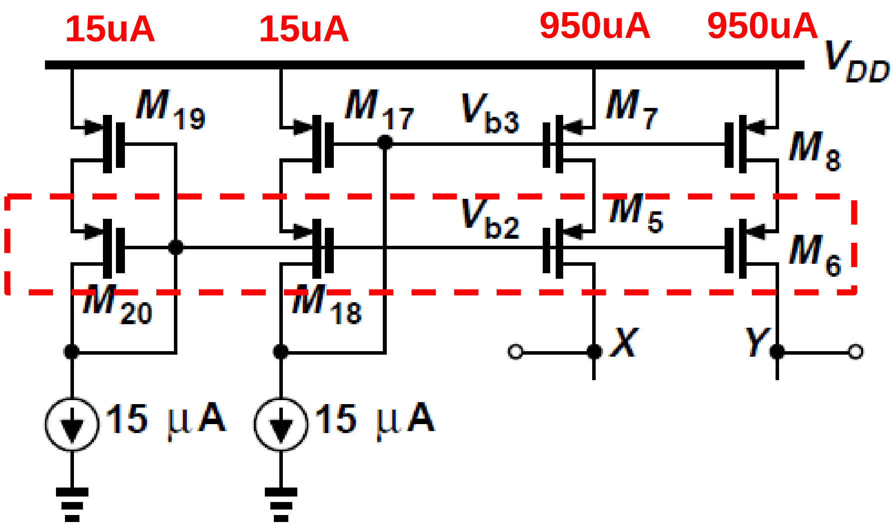
1. $\frac{(\frac{W}{L})_6}{(\frac{W}{L})_7} = \frac{(\frac{W}{L})_{11}}{(\frac{W}{L})_{13}}$

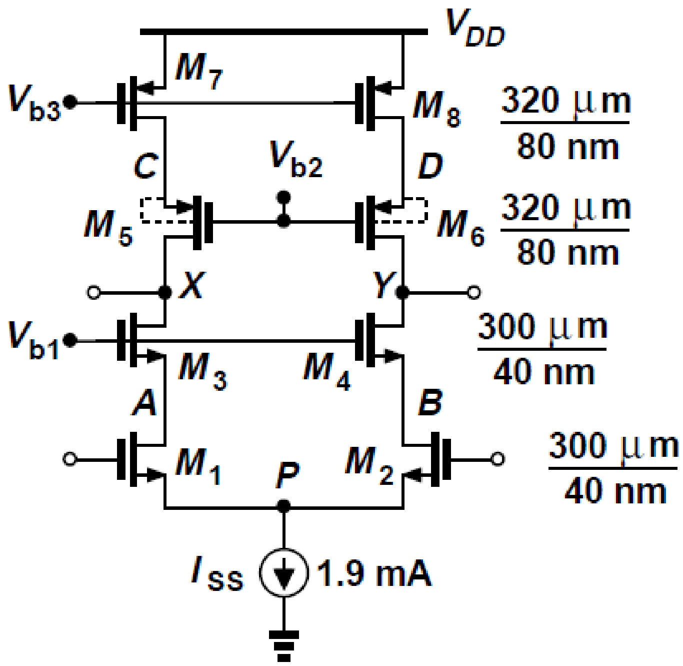
2. $(\frac{W}{L})_{12} = (\frac{W}{L})_{13}$

3. $(\frac{W}{L})_9 = 0.2\,(\frac{W}{L})_7$

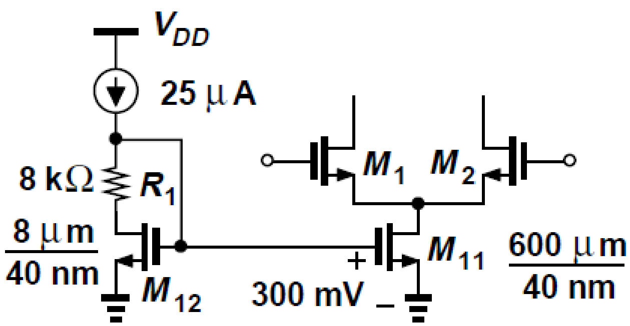
Bias Circuit

Key for cascode biasing : Maintain current density

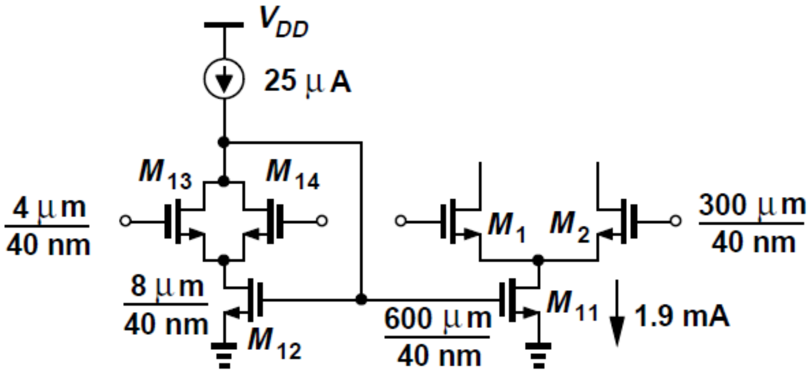




Bias for Tail Current Source

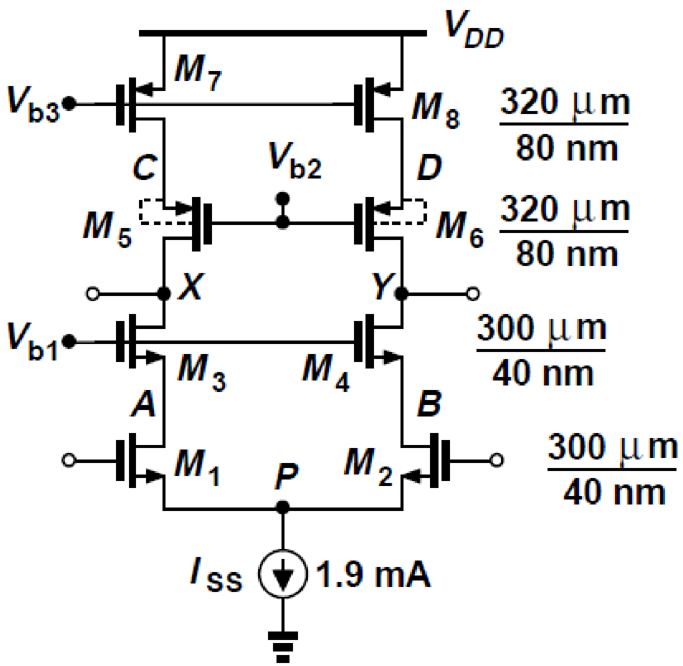


(a)

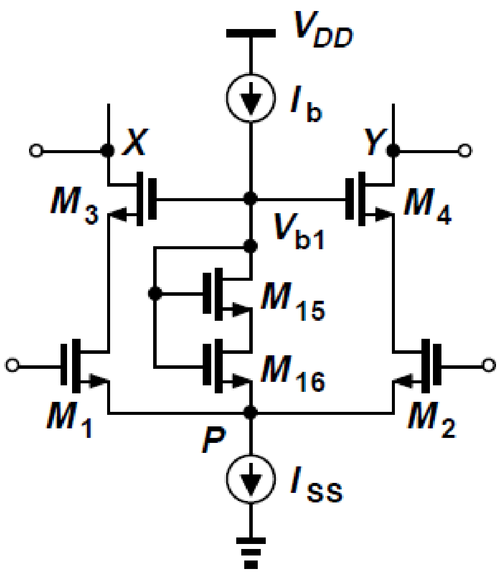


(b)

Bias for Vb1

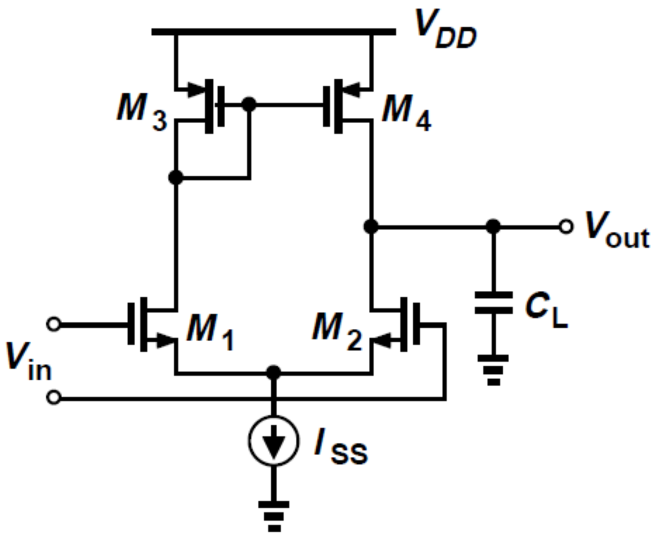


V_{DD}
M_7
V_{b3}
M_8
320 μm / 80 nm
C
V_{b2}
D
M_5
M_6
320 μm / 80 nm
X
Y
V_{b1}
300 μm / 40 nm
M_3
M_4
A
B
M_1
P
M_2
300 μm / 40 nm
I_{SS}
1.9 mA

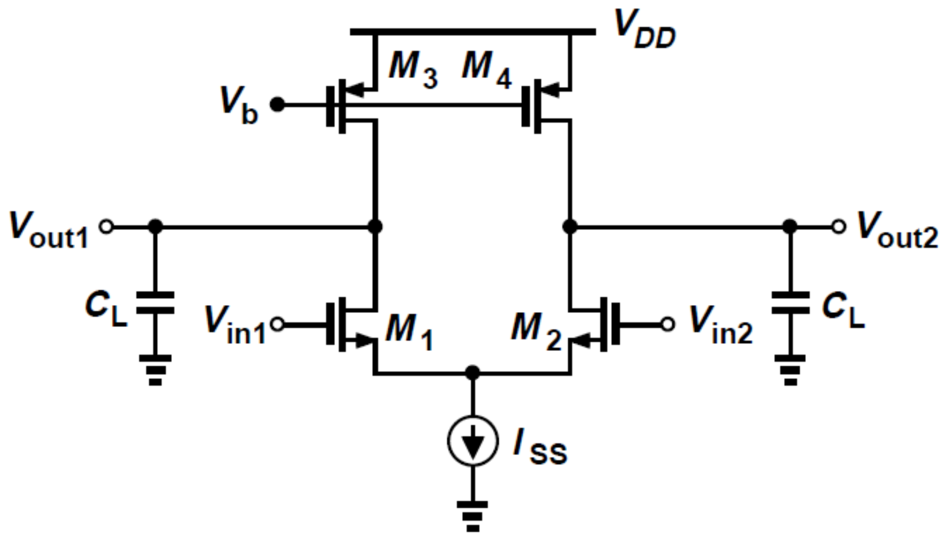


V_{DD}
I_b
X
Y
M_3
M_4
V_{b1}
M_{15}
M_{16}
M_1
M_2
P
I_{SS}

Single-Ended vs. Fully-Differential OPAMP



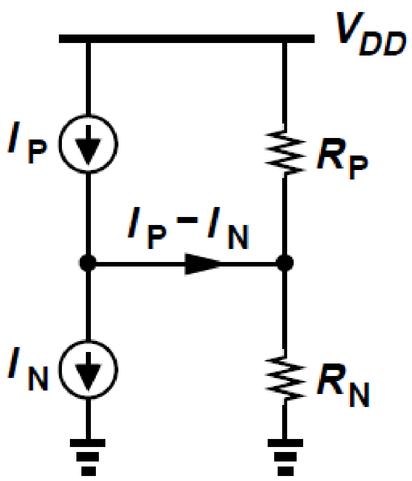
(a)

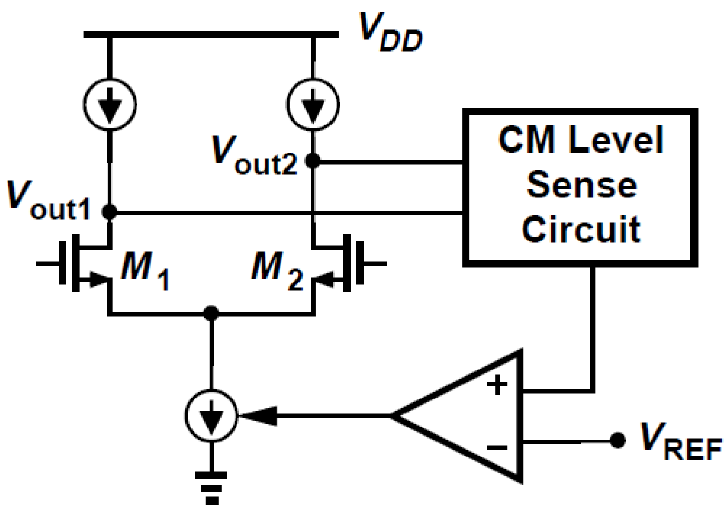


(b)

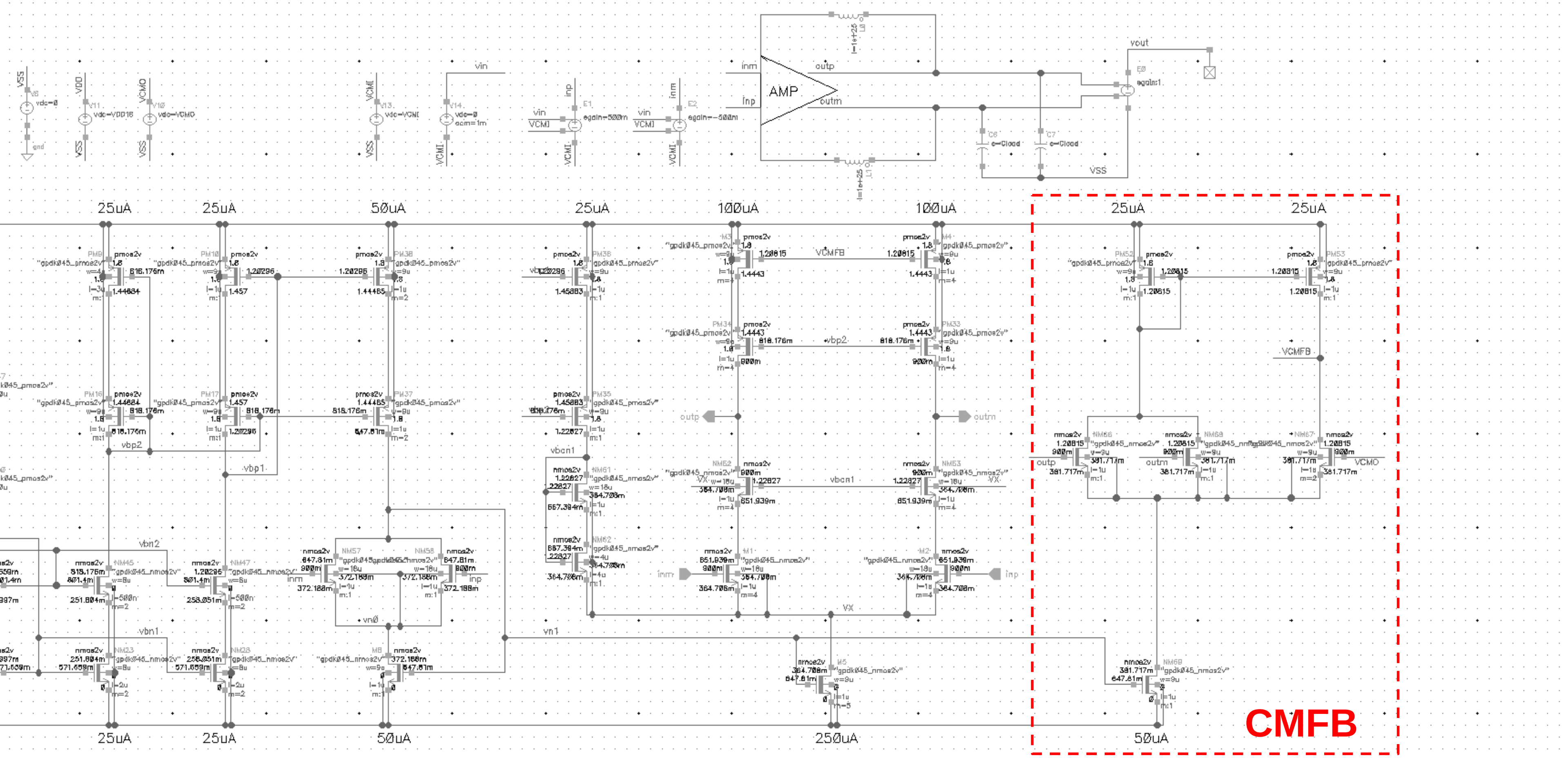
CMFB for Fully-Differential OPAMP

Random mismatches between the top and bottom current sources cause the CM level to fall or rise considerably
→ We need CMFB to set the voltage to the desired DC level



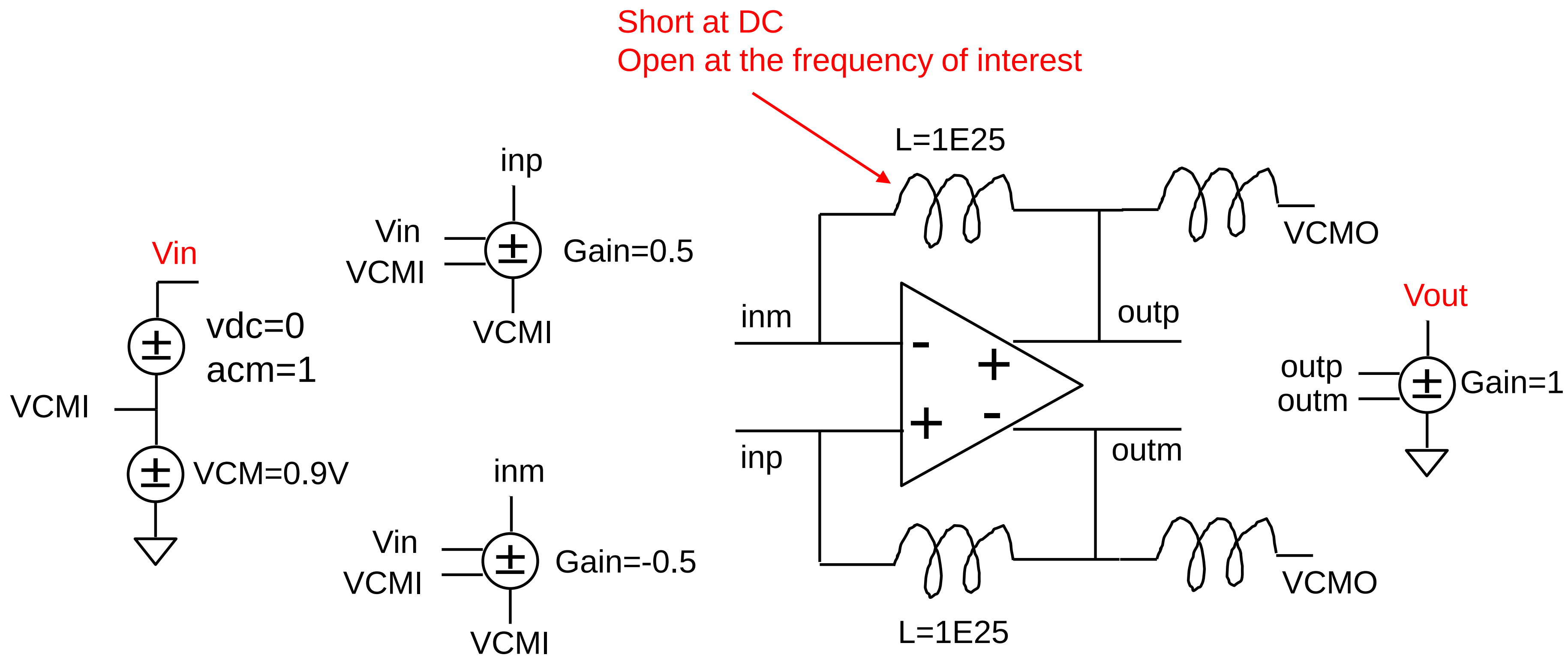


Fully Differential Telescopic OTA with CMFB Example 1



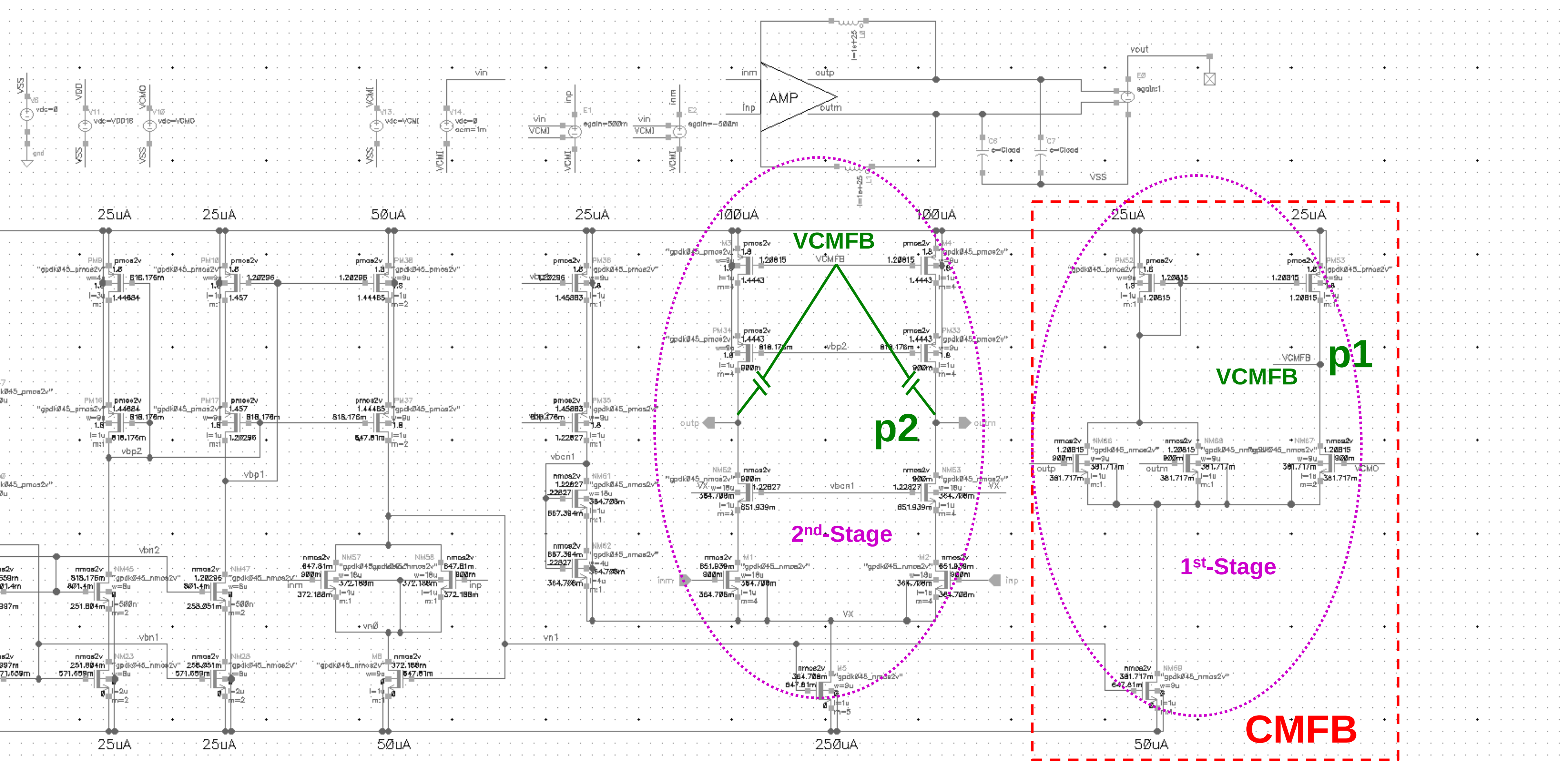
Test Bench for Fully Differential OPAMP

Test bench to simulate the open loop response of the fully-differential opamp
→ Use Inductor with large value

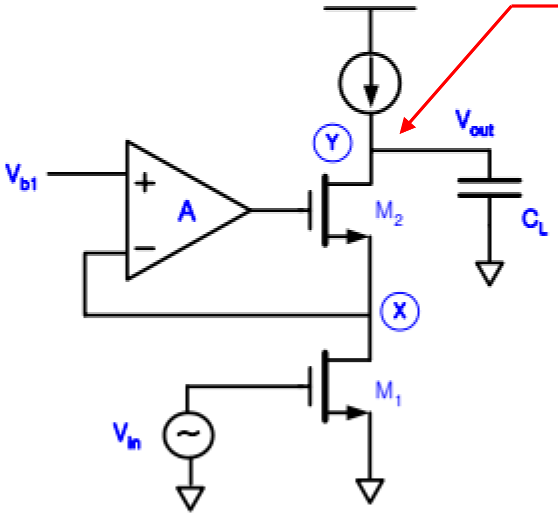


You may not need the inductor in the test bench
if you have a continuous-time CMFB.

Common-Mode Loop → Two-Stage



Gain-Boosting Cascode Amplifier



$$R_{out} = g_{m2}(A_{boost}+1)\cdot r_{ds1}\cdot r_{ds2} + r_{ds1} + r_{ds2}$$

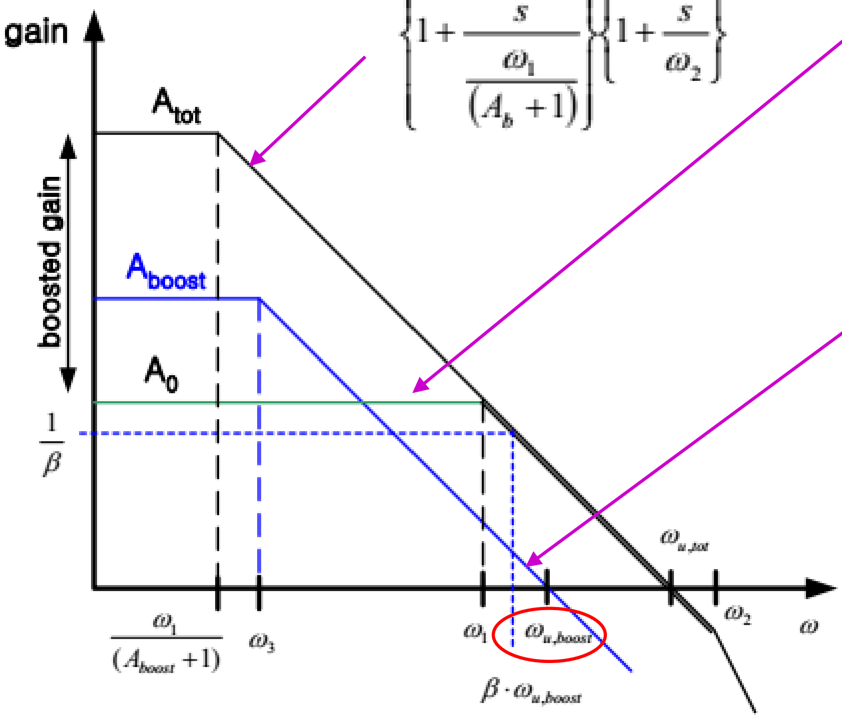
$$\cong g_{m2}(A_{boost}+1)\cdot r_{ds1}\cdot r_{ds2}$$

$$A_{tot} \approx (g_m r_{out})^2 A_{boost}$$

Chang-Hyuk Cho, PhD Thesis, Georgia Institute of Technology, 2005
"A Power Optimized Pipelined ADC Design in Deep Submicron CMOS Technology"

Gain-Boosting Cascode Amplifier

Total Amp $$\frac{V_{out}}{V_{in}} = \frac{A_0(A_{boost}+1)}{\left\{1+\dfrac{s}{\dfrac{\omega_1}{(A_b+1)}}\right\}\left\{1+\dfrac{s}{\omega_2}\right\}}$$



Original Cascode Amp

$$\frac{V_{out}}{V_{in}}(s) = \frac{A_0}{\left(1+\dfrac{s}{\omega_1}\right)\left(1+\dfrac{s}{\omega_2}\right)}$$

Gain Boosting Amp

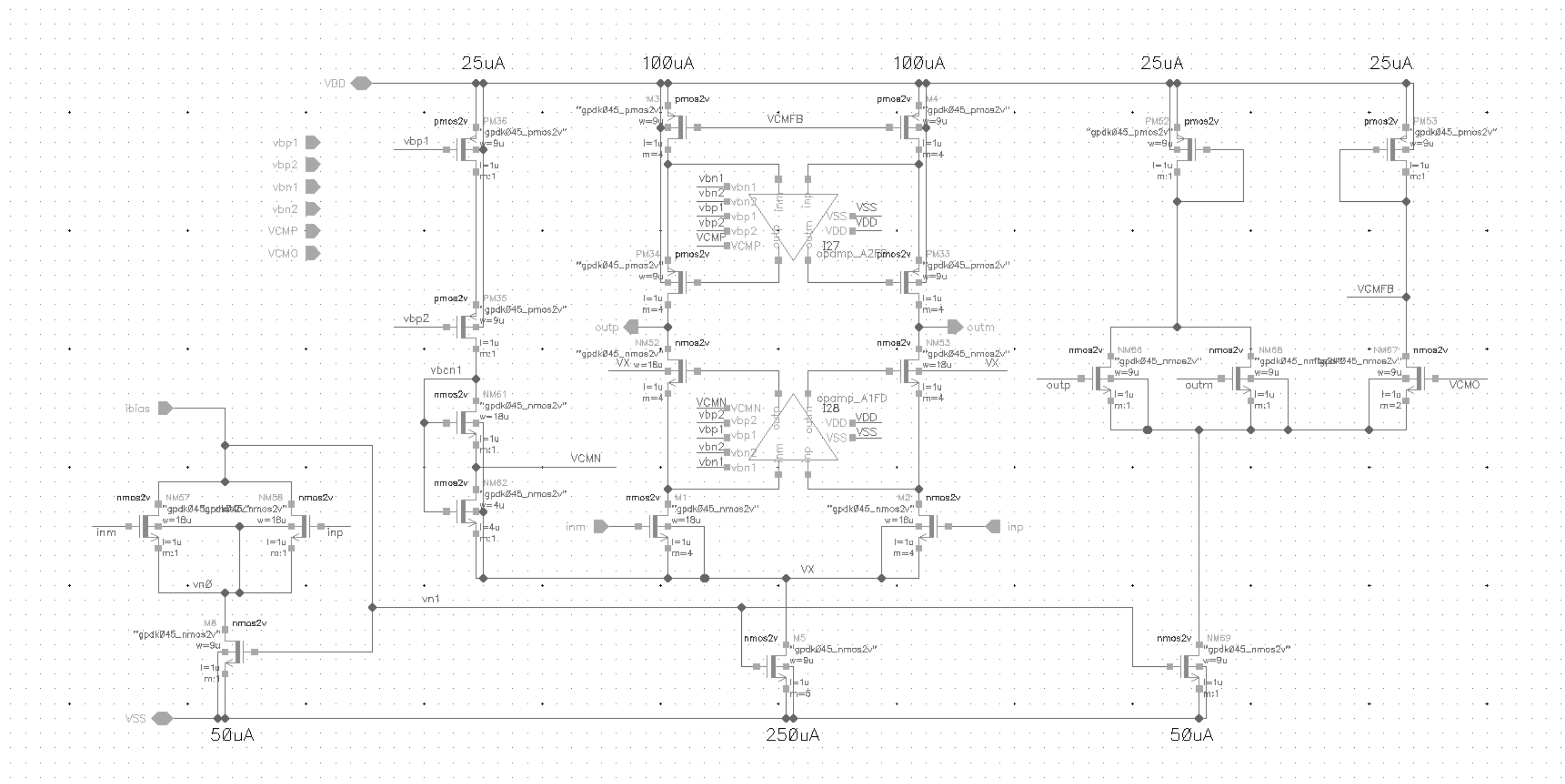
$$A_{boost}(s) = \frac{A_{boost}}{(1+\dfrac{s}{\omega_3})}$$

$$\omega_1 \ll \omega_3 \cdot (A_{boost}+1)$$

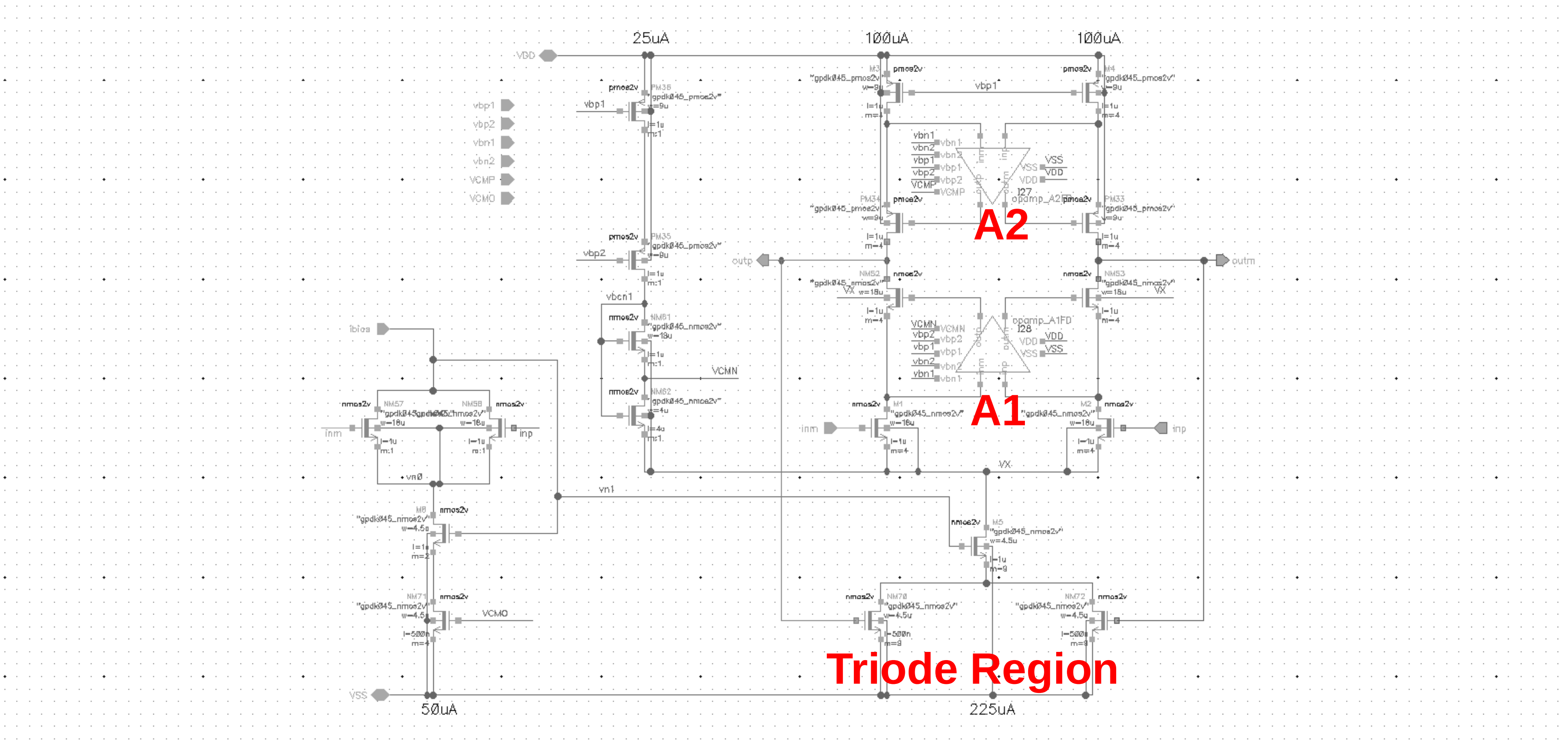
$$\beta \cdot \omega_{u,tot} < \omega_{u,boost} < \omega_2$$

Unity Gain frequency of the gain boosting amp should be Larger than -3dB frequency of the original amp and Lower than first non-dominant pole of the original amp

CMFB Example 2

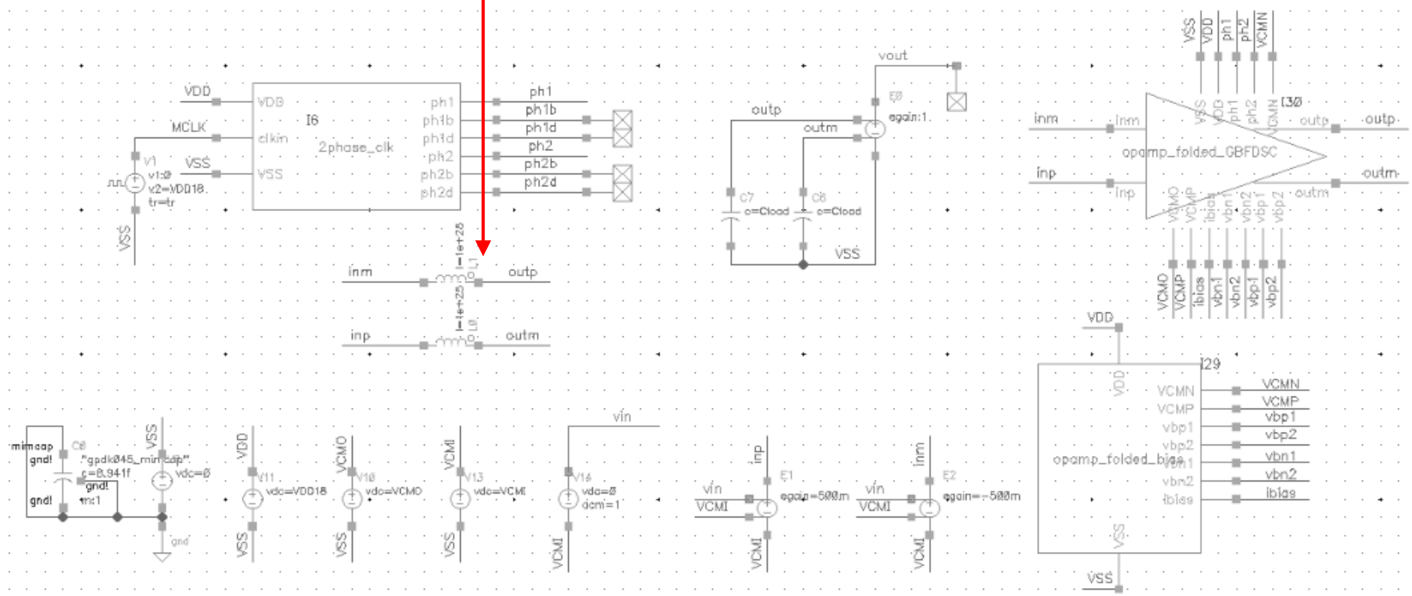


CMFB Example 3

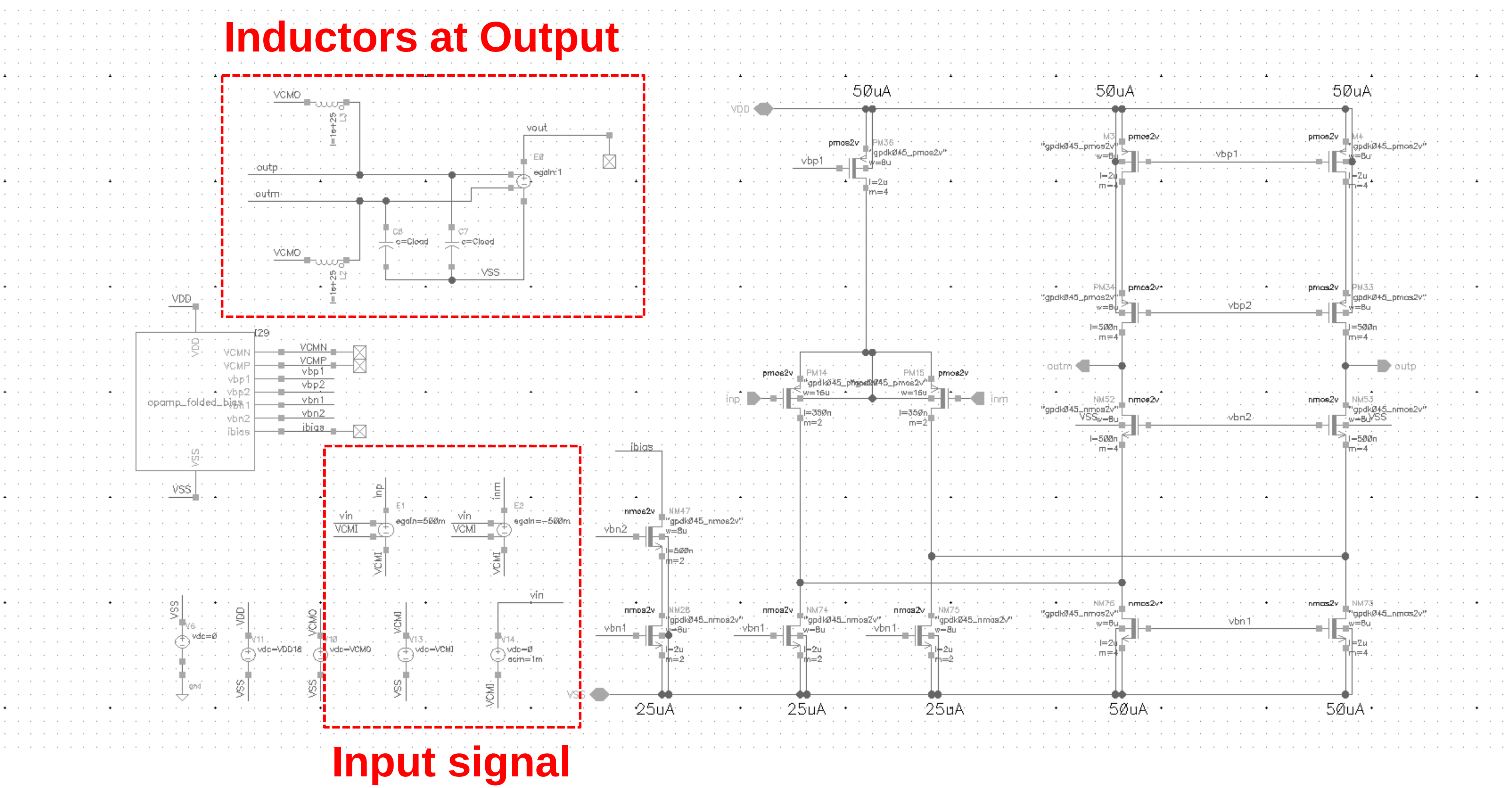


Test Bench for Fully-Differential AMP ac simulation

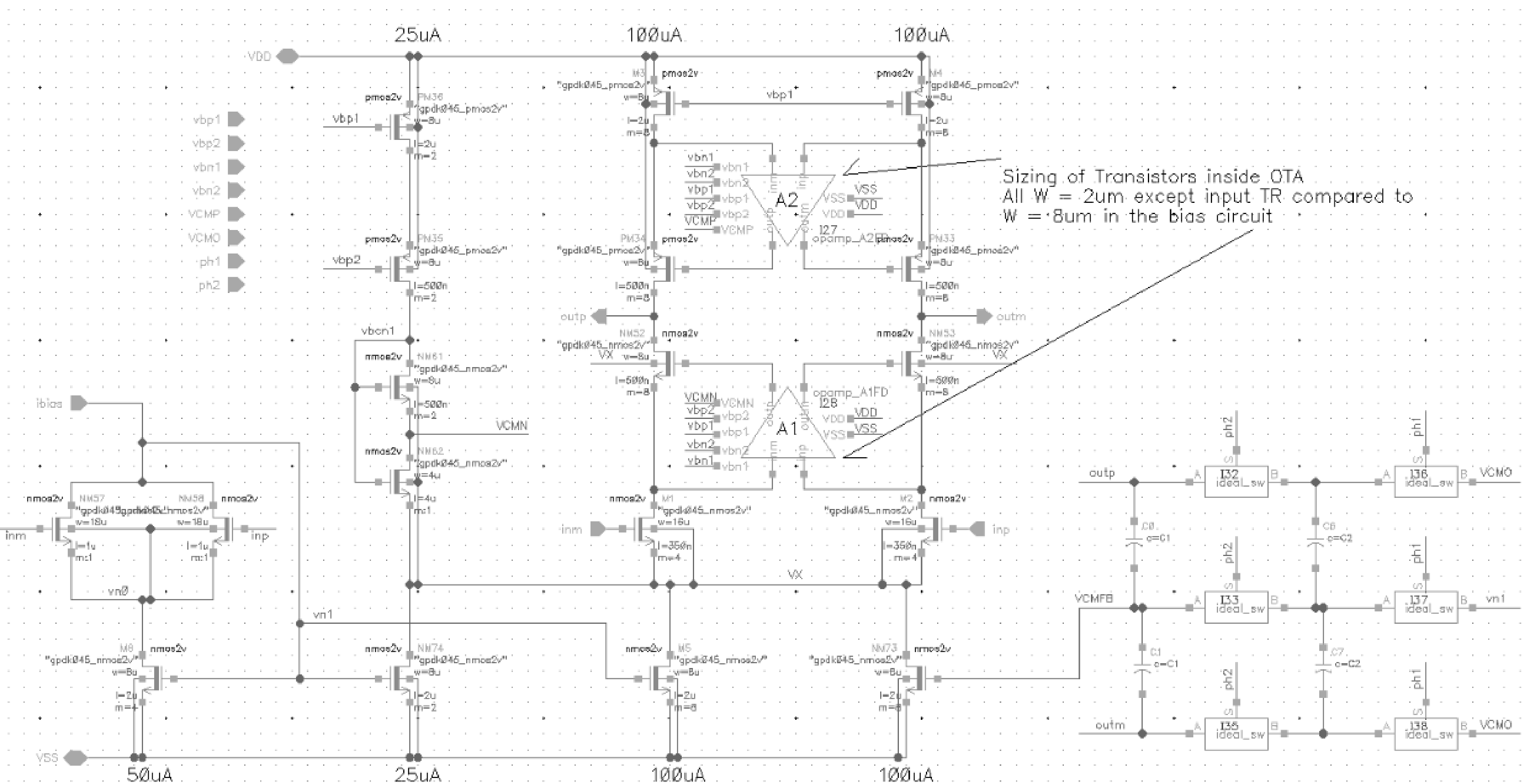
Inductors to set the DC bias point in unity gain feedback.



Test Bench For AC simulation of Cascode Amp



Gain-Boosted Telescopic OPAMP with SC CMFB



Gain-Boosted Folded-Cascode AMP with SC CMFB