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EECS140

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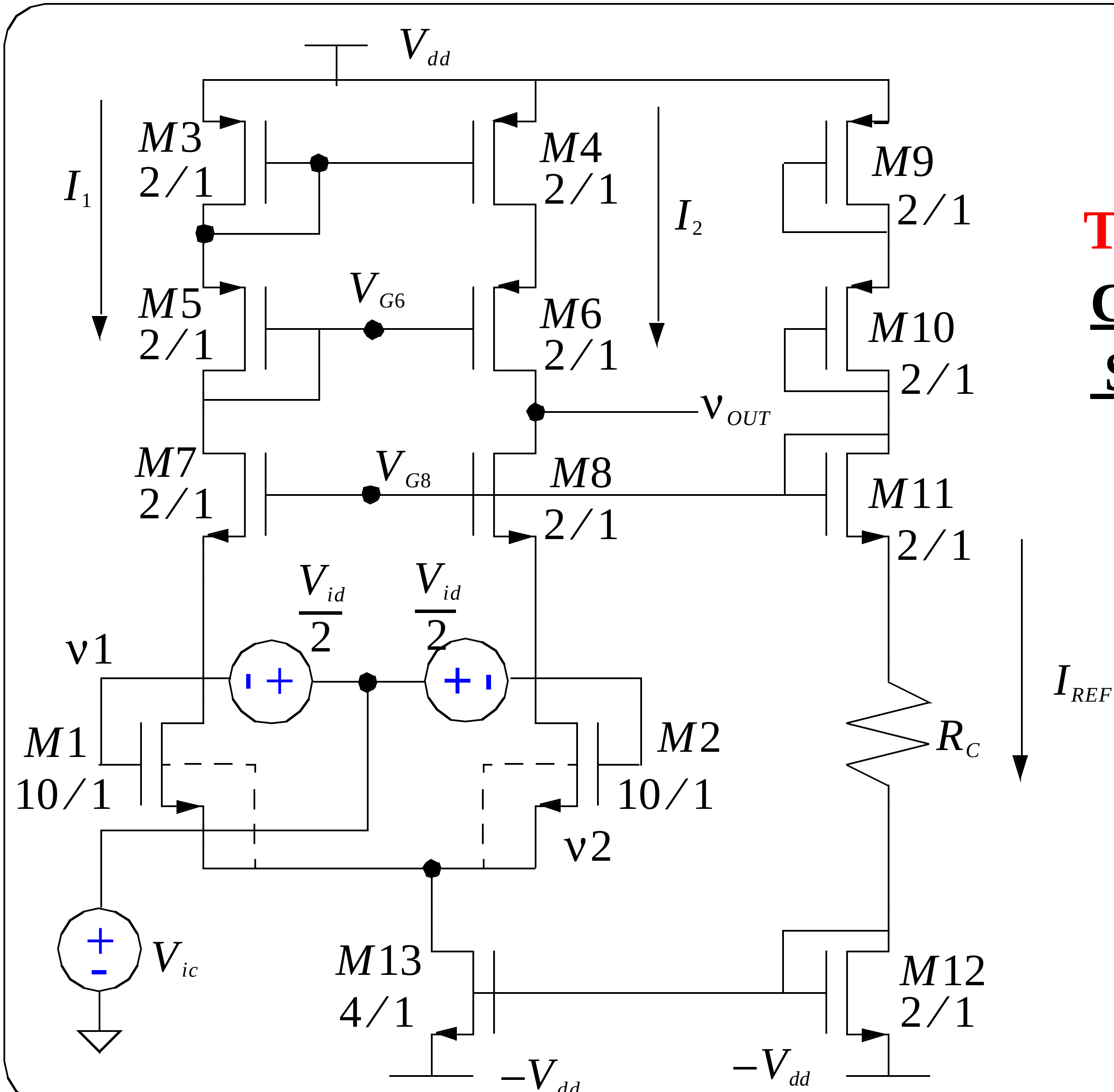
Analog Circuit Design

More
on Op Amps
TELESCOPIC and FOLDED CASCODE

MOA-1



Telescopic - OP AMP

Circuit 1 (Poor Bias Strategy)

Circuit 1 :

Telecopic OP AMP with “BAD” Bias of cascode :

The currents are balanced so that all transistors have,

$$I_{DS} = I_{REF}$$

except for M13 which has,

$$I_{DS13} = 2 \cdot I_{REF}$$

Since,

$$I_1 = I_2 = I_{REf}$$

then,

$$V_{GS3} = V_{GS4} = V_{GS9}$$ (all W/L’s are equal also)

This also implies that,

$$V_{DS4} = V_{DS3}$$

similarily,

$$V_{DS5} = V_{DS6}$$

So if the input has,

$$V_{id} = 0$$

MOA-3

then,

$$V_{OUT} = V_{DD} - 2 \cdot V_{To} - 2 \cdot V_{DSAT} = V_{G6} \quad (\text{if } \gamma = 0)$$

The gate of M8 is also at,

$$V_{DD} - 2 \cdot V_{To} - 2 \cdot V_{DSAT}$$

due to its connection to M11, so,

$$V_{OUT} = V_{G6} = V_{G8}$$

The swing in the positive direction will be,

$$V_{OUT,MAX^+} = V_{G6} + V_T$$

But since,

$$V_{OUT} = V_{G6}$$

this means the swing is only 1 V_T in the positive direction. In the negative direction,

$$V_{OUT,MIN^-} = V_{G8} - V_T$$

but since,

$$V_{OUT} = V_{G8}$$

the swing is only V_T again.

MOA-4

Thus the total swing is only $2V_T$ ... not too good.

In the positive direction we could use a high swing configuration as was described for the cascoded current source.

On the low side we can use a better circuit.

Circuit 2 :

Telescopic with a cascode bias that gives a better swing in the negative direction.

Maximum voltage in the positive direction is given by M6 going linear when,

$$V_{OUT,MAX^+} > V_{DD} - V_{GS3} - V_{DSAT6}$$

Negative swing is limited by M8 going linear,

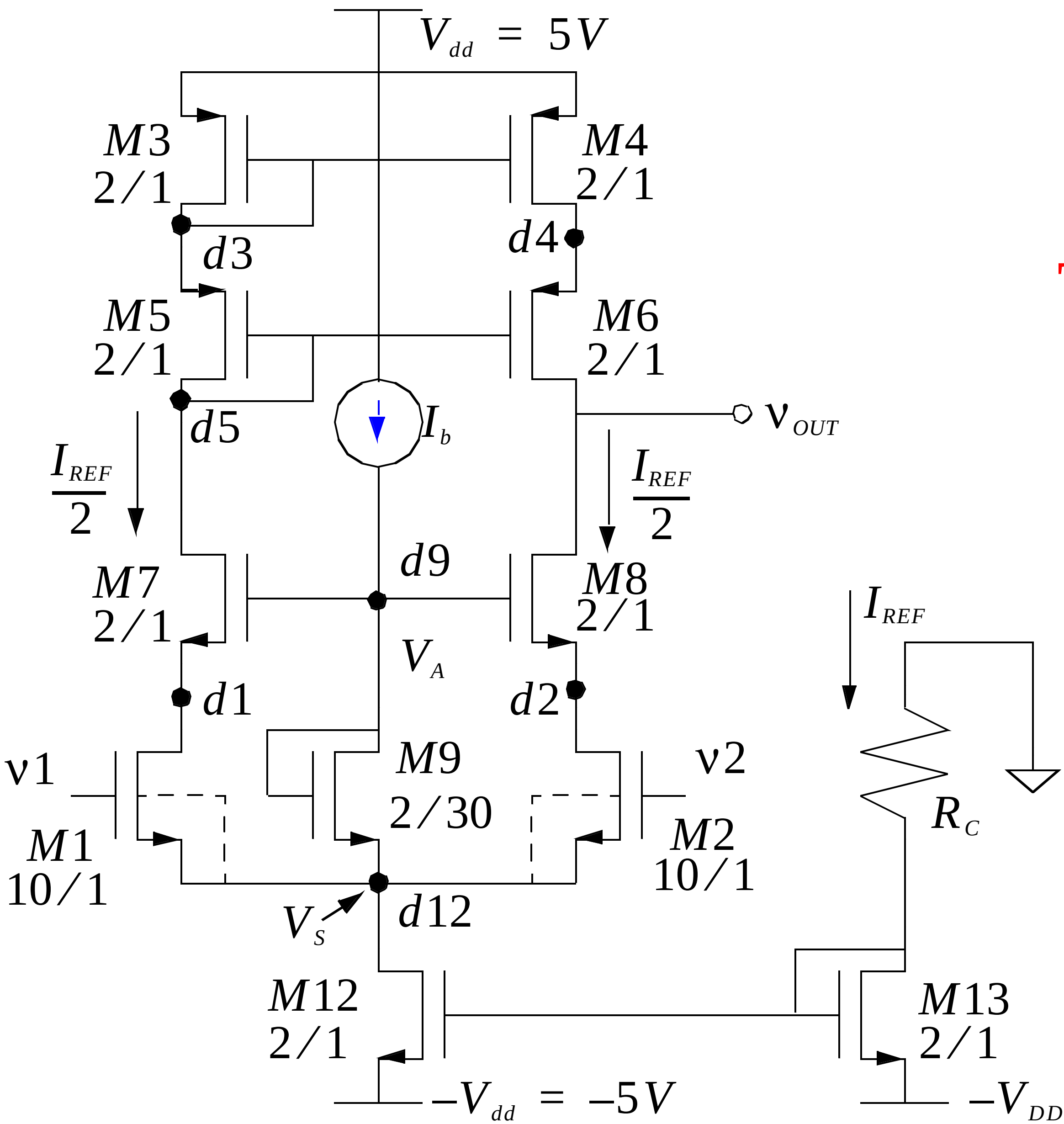
$$V_{OUT,MIN^-} = V_A - V_{T8}$$

Set V_A so that M1 & M2 are at the edge of saturation

MOA-5

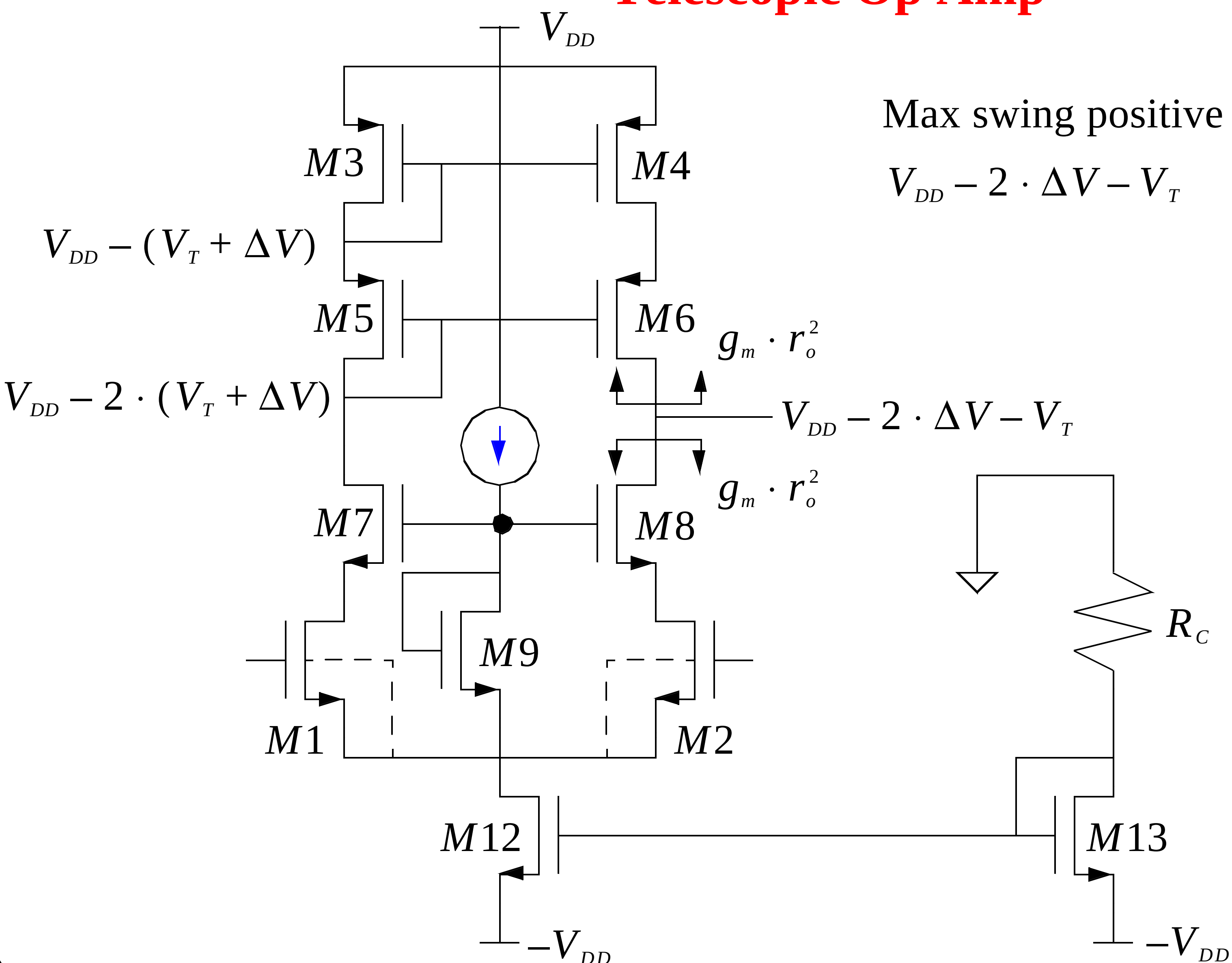
Telescopic - OP AMP

Circuit 2 (Better Bias)



Telescopic Op Amp

MOA-6



Max swing positive :

$$V_{DD} - 2 \cdot \Delta V - V_T$$

Telescopic Op Amp (Cont.)

MOA-7

$$V_A = V_S + V_{DSAT9} + V_{T9}$$

$$V_{DS2} = V_{DSAT2}$$ for setting M2 at EOS

$$V_{DS2} = V_A - V_{T8} - V_{DSAT8} - V_S$$

$$= V_S + V_{DSAT9} + V_{T9} - V_{T8} - V_{DSAT8} - V_S$$

$$V_{DS2} = V_{DSAT9} - V_{DSAT8} = V_{DSAT2}$$ for EOS

$$V_{DSAT9} = V_{DSAT2} + V_{DSAT8}$$

$$\left(\frac{W}{L}\right)_8 = \left(\frac{W}{L}\right)_7 \qquad \left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2$$

MOA-8

This means that,

$$V_A = V_S + V_{DSAT2} + V_{T8} + V_{DSAT8}$$

Since this will set,

$$V_{DS2} = V_{DSAT2}$$

To calculate the $(W/L)_9$ and I_B to do this we set,

$$V_{DS,9} = V_A - V_S = V_{DSAT2} + V_{T8} + V_{DSAT8}$$

since,

$$V_{DS,9} = V_{T9} + V_{DSAT9}$$

$$V_{DSAT9} = (V_{T8} - V_{T9}) + V_{DSAT2} + V_{DSAT8}$$

If we say,

$$V_{T8} \approx V_{T9}$$

then

$$\left(\frac{2 \cdot I_B}{k'_n \cdot \left(\frac{W}{L}\right)_9}\right)^{1/2} = \left(\frac{2 \cdot I_{DS2}}{k'_n}\right)^{1/2} \cdot \left(\frac{1}{\left(\frac{W}{L}\right)_8^{1/2}} + \frac{1}{\left(\frac{W}{L}\right)_2^{1/2}}\right)^2$$

MOA-9

so,

$$\left(\frac{W}{L}\right)_9 = \frac{I_B}{I_S} \cdot \left[\left(\frac{W}{L}\right)_8^{-1/2} + \left(\frac{W}{L}\right)_2^{-1/2}\right]^2$$

if,

$$\left(\frac{W}{L}\right)_2 = 10 \qquad \left(\frac{W}{L}\right)_8 = 2 \qquad I_B = 0.79\mu A \qquad I_S = 10.5\mu A$$

then,

$$\left(\frac{W}{L}\right)_9 \approx \frac{1}{15}$$

Gain and R_{out}

$$GM = g_{m1} \quad \text{(cascoding has no effect on } g_m\text{)}$$

$$R_{OUT} = [(g_{m6} \cdot r_{o4}) \cdot r_{o6}] \,||\, [(g_{m8} \cdot r_{o2}) \cdot r_{o8}]$$

$$A_{vd} = g_{m1} \cdot \left[\frac{g_{m6} \cdot g_{m8} \cdot (r_{o4} \cdot r_{o6} \cdot r_{o2} \cdot r_{o8})}{g_{m6} \cdot r_{o4} \cdot r_{o6} + g_{m8} \cdot r_{o2} \cdot r_{o8}}\right]$$

MOA-10

$$g_{m6} \cdot r_{o4} \cdot r_{o6} = \left(\frac{2 \cdot I_{DS}}{V_{DSAT6}}\right) \cdot \left(\frac{1}{\lambda_p \cdot I_{DS}}\right) \cdot \left(\frac{1}{\lambda_p \cdot I_{DS}}\right)$$

$$A_{vd} = \left(\frac{2 \cdot I_{DS}}{V_{DSAT1}}\right) \cdot \frac{2}{I_{DS}} \cdot \left(\frac{1}{V_{DSAT6} \cdot \lambda_p^2} \parallel \frac{1}{V_{DSAT8} \cdot \lambda_n^2}\right)$$

$$= \frac{4}{V_{DSAT1}} \cdot \left(\frac{1}{V_{DSAT6} \cdot \lambda_p^2 + V_{DSAT8} \cdot \lambda_n^2}\right)$$

To see the current dependence let,

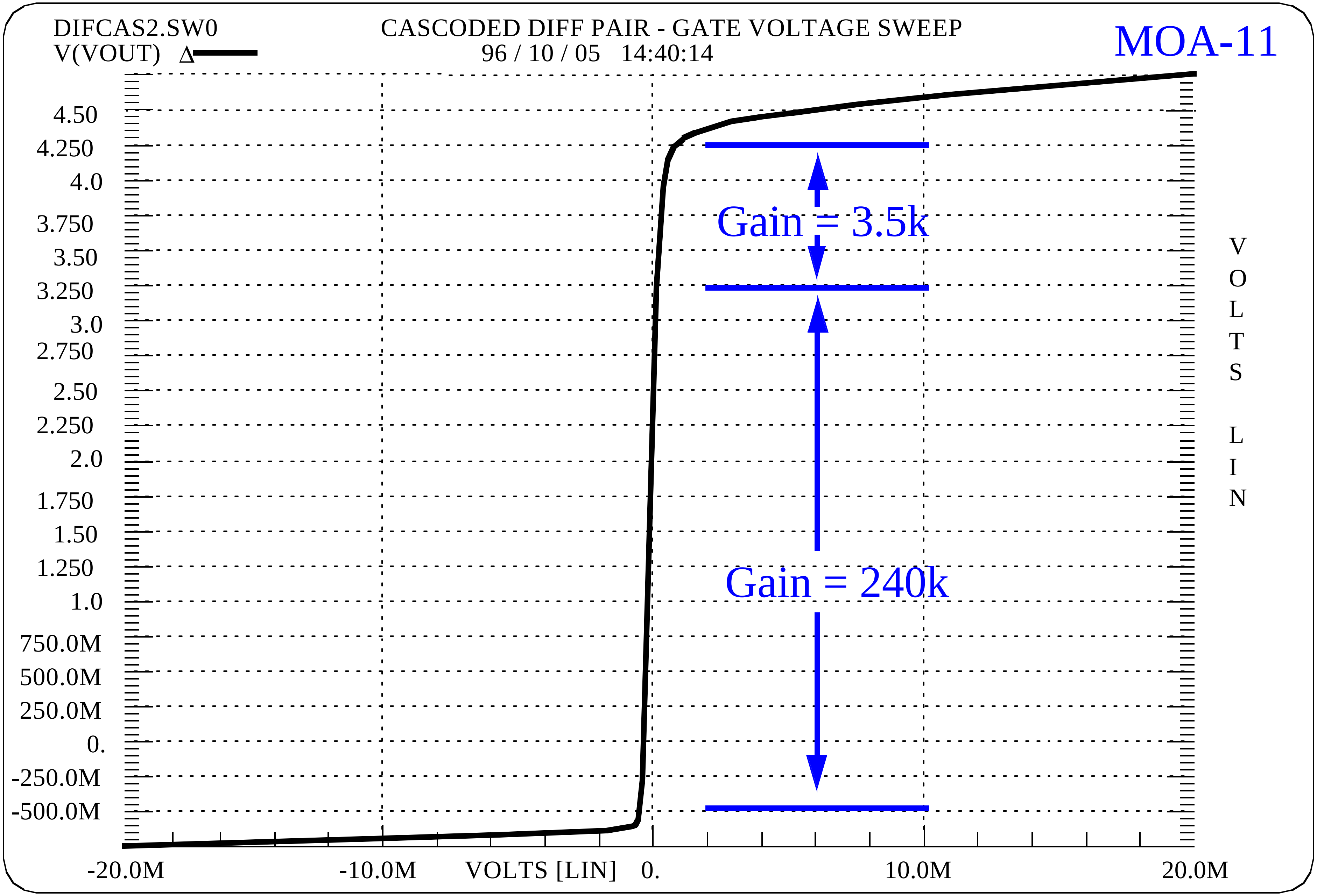
$$g_m = g_{m1} = g_{m6}$$

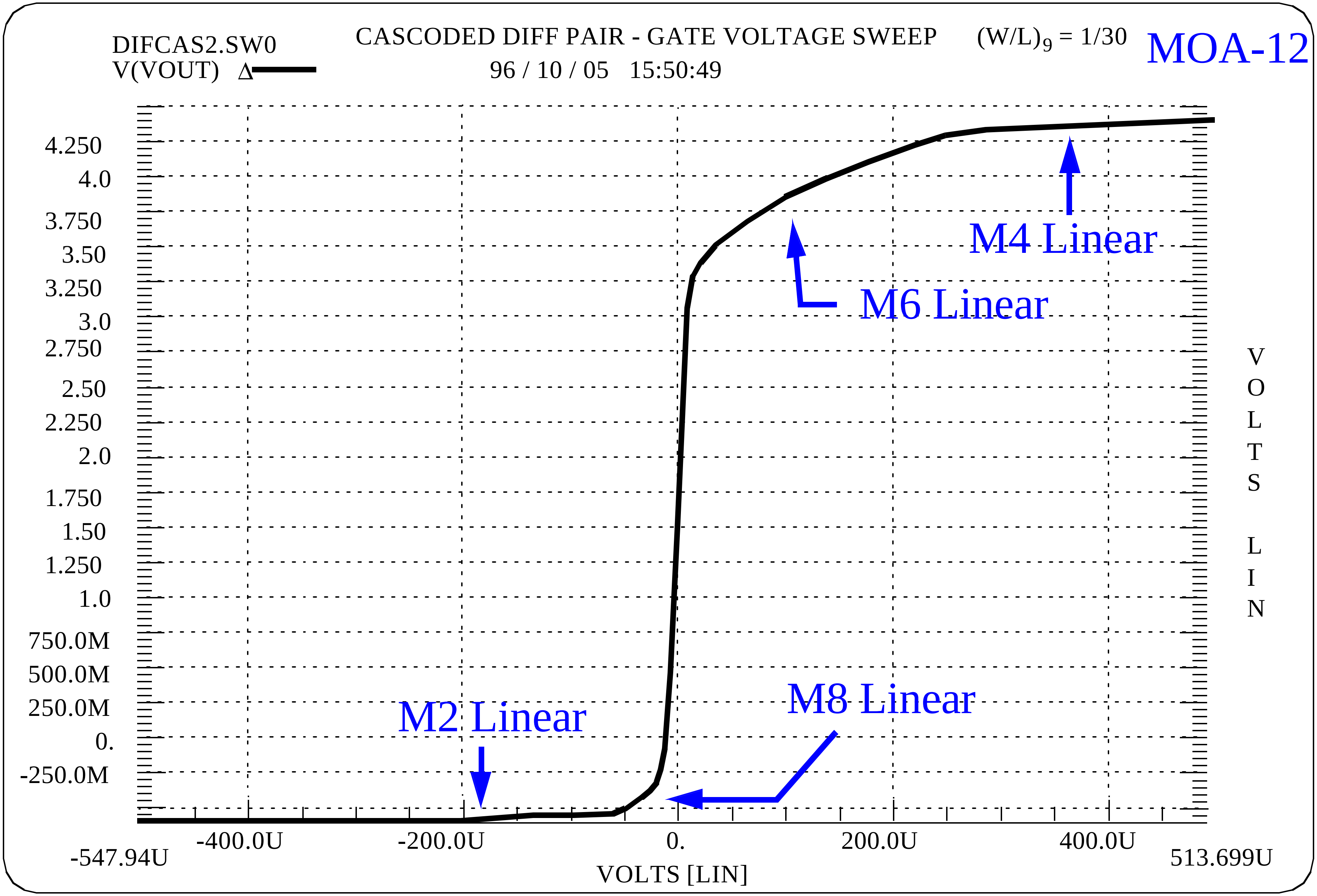
and,

$$r_o = r_{o4} = r_{o6} = r_{o2} = r_{o8}$$

$$A_{vd} \approx g_m^2 \cdot r_o^2 \sim \frac{I_{DS}}{I_{DS}^2} \sim \frac{1}{I_{DS}}$$

Gain keeps increasing as we decrease the current.


DIFCAS2.SW0
V(VOUT)
CASCODED DIFF PAIR - GATE VOLTAGE SWEEP
96 / 10 / 05 14:40:14
MOA-11
4.50
4.250
4.0
3.750
3.50
3.250
3.0
2.750
2.50
2.250
2.0
1.750
1.50
1.250
1.0
750.0M
500.0M
250.0M
0.
-250.0M
-500.0M
Gain = 3.5k
Gain = 240k
VOLTS LIN
-20.0M
-10.0M
VOLTS [LIN]
0.
10.0M
20.0M

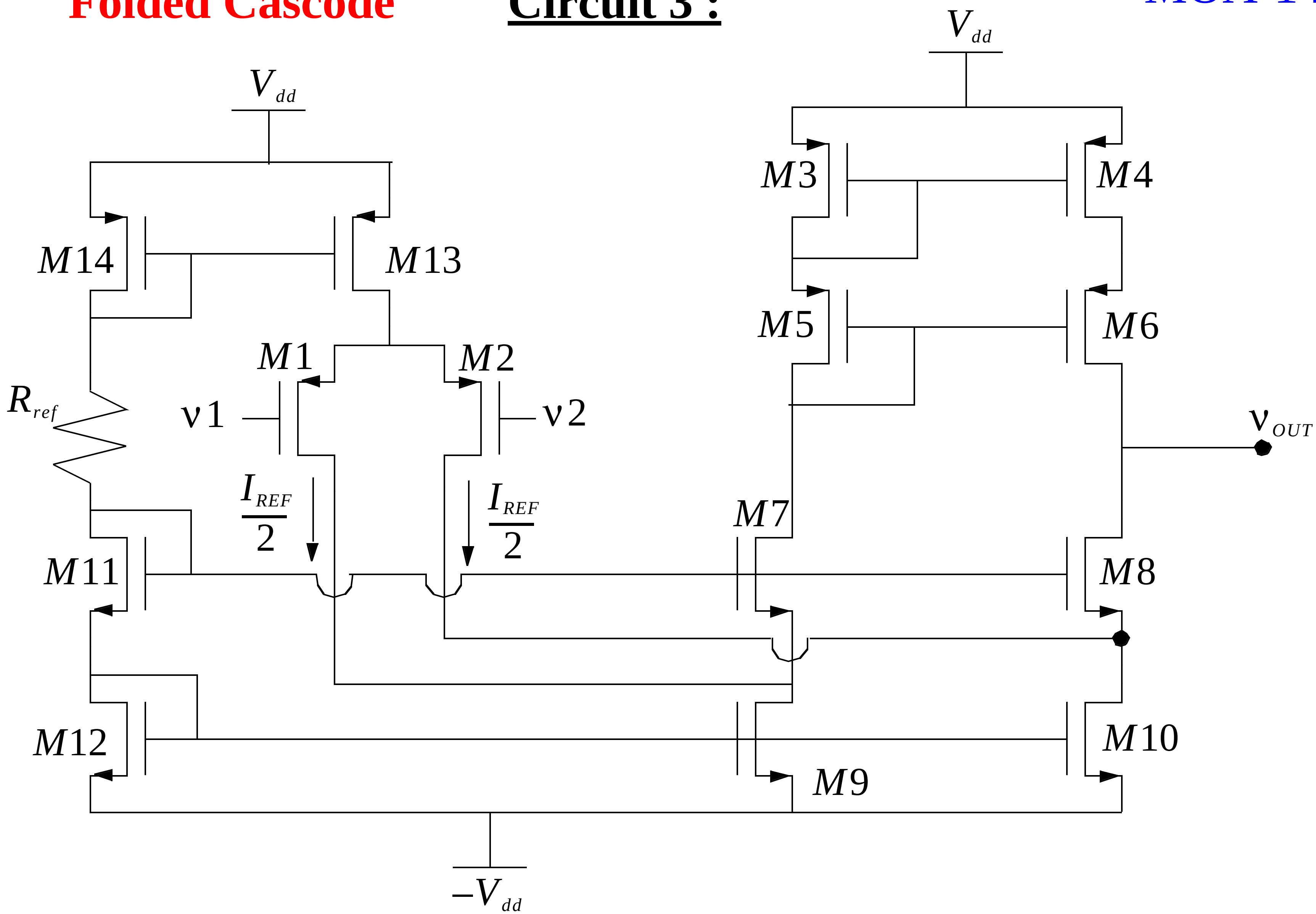

DIFCAS2.SW0
V(VOUT)
CASCODED DIFF PAIR - GATE VOLTAGE SWEEP
(W/L)9 = 1/30
MOA-12
96 / 10 / 05 15:50:49
4.250
4.0
3.750
3.50
3.250
3.0
2.750
2.50
2.250
2.0
1.750
1.50
1.250
1.0
750.0M
500.0M
250.0M
0.
-250.0M
M4 Linear
M6 Linear
M8 Linear
M2 Linear
V O L T S L I N
-547.94U
-400.0U
-200.0U
0.
200.0U
400.0U
513.699U
VOLTS [LIN]

MOA-13

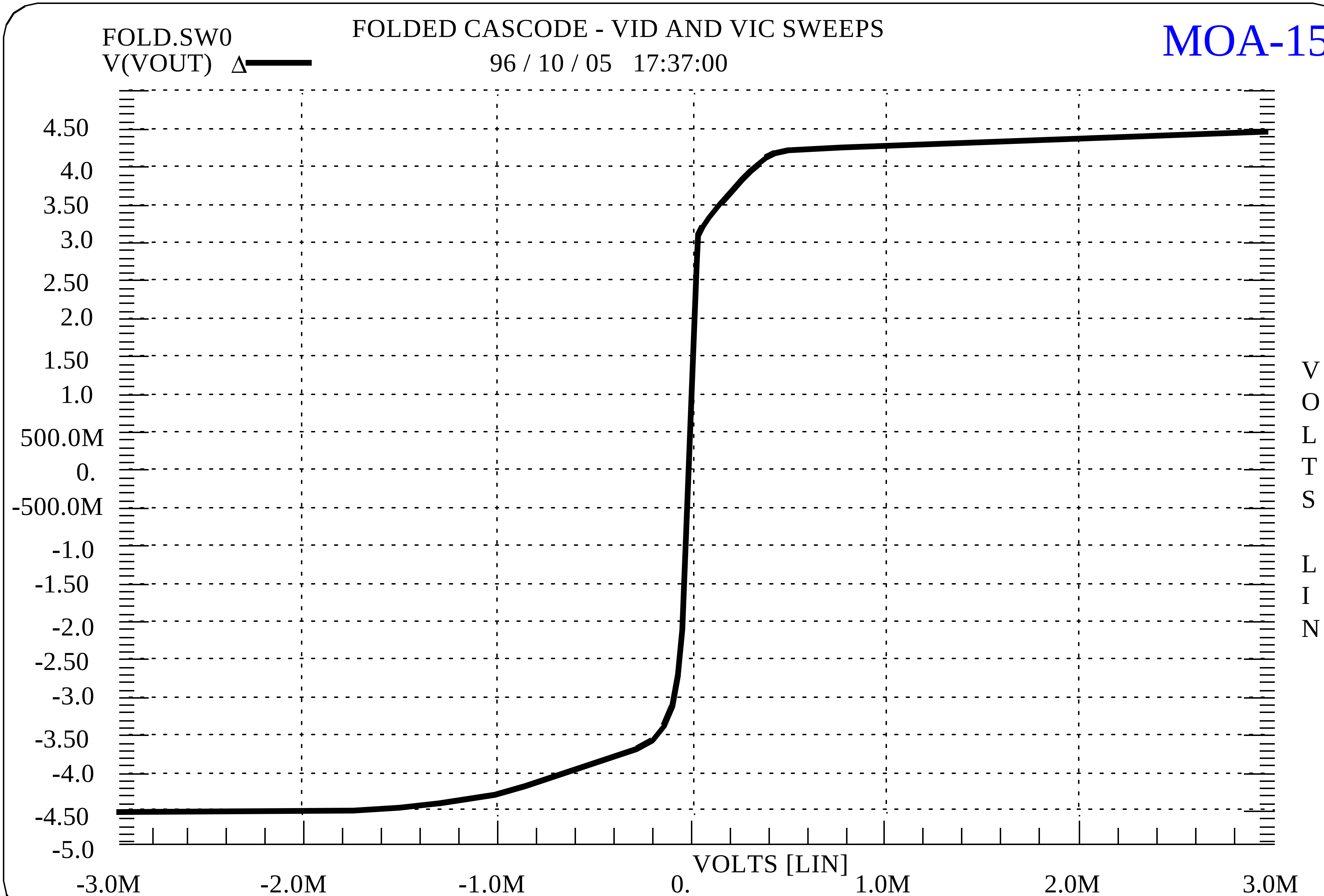
```
*****
diff pair - gate voltage sweep

*****
* reading file: /bobtools/commercial/hspice/hspice.ini
*
.model nch nmos level = 1 tox = 170 vto = 0.7 kp = 90.0e-6 lambda = 0.01
+ gamma = 0.5 phi = 0.6 capop = 0 cgso=5.e-10 cgdo=5.e-10 cgbo=4.e-10 cj=1e-4

.model pch pmos level = 1 tox = 170 vto = -0.7 kp = 30.0e-6 lambda = 0.01
+ gamma = 0.5 phi = 0.6 capop = 0 cgso=3.e-11 cgdo=3.e-11 cgbo=4.e-10 cj=6e-4

.option nopage post=2   nomod

*name drain gate source bulk model
m1  d1  vi1  vs  vs  nch  l=1u  w=10u
m2  d2  vi2  vs  vs  nch  l=1u  w=10u
m3  d3  d3  vdd   vdd  pch   l=1u   w=2u
m4  d4  d3  vdd   vdd  pch   l=1u   w=2u
m5  d5  d5  d3  vdd  pch   l=1u   w=2u
m6   vout  d5  d4  vdd  pch   l=1u   w=2u
m7  d5  d9  d1  vdd-  nch  l=1u   w=2u
m8  vout  d9  d2  vdd-  nch  l=30u  w=2u
m12  d12  d12 vdd-  vdd-  nch  l=1u   w=2u
m13  vs  d12  vdd-  vdd-  nch  l=1u   w=2u

rref   0   d12   180k
r9   d9   vdd   5x

vic    vic    0    0
vid1    vi1    vic    0.0
evid2    vic    vi2    vi1    vic    1              *other half of the vid input
vdd    vdd    0     5.0
vdd-   vdd-  0    -5.0

.dc vid1 -.02  .02  .00001                                 *sweep the input voltage
*.dc vid1 -5  5  .1                                     *sweep the input voltage
*.print dc v(out)
*.print dc i(m1)                                  * i is the ids of m1
*                                                  * von=1v9  vdsat=1x9  gds=1x8
*.print dc 1v9(m1)  1v10(m1)  1x7(m1)    * plots gm=1x7 gmbs=1x9 gds=1x8
.op                                               *initial operating point
.tf v(vout,0)  vid1
*.measure tot_power avg power                *makes it do the power calculation

.end
```

Folded Cascode Circuit 3 :

MOA-14



MOA-15


FOLD.SW0
V(VOUT)
FOLDED CASCODE - VID AND VIC SWEEPS
96 / 10 / 05 17:37:00
4.50
4.0
3.50
3.0
2.50
2.0
1.50
1.0
500.0M
0.
-500.0M
-1.0
-1.50
-2.0
-2.50
-3.0
-3.50
-4.0
-4.50
-5.0
VOLTS LIN
VOLTS [LIN]
-3.0M
-2.0M
-1.0M
0.
1.0M
2.0M
3.0M

MOA-16

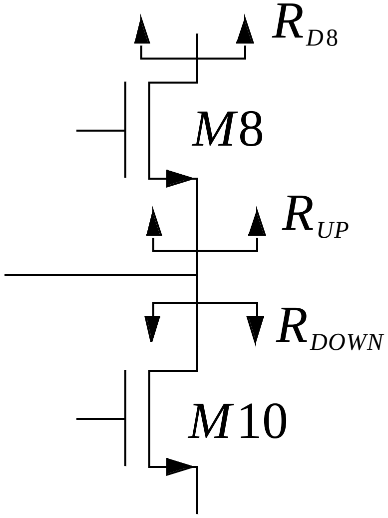
```
*****
folded cascode - vid and vic sweeps

*****
* reading file: /bobtools/commercial/hspice/hspice.ini
*
.model nch nmos level = 1 tox = 170 vto = 0.7 kp = 90.0e-6 lambda = 0.01
+ gamma = 0.5 phi = 0.6 capop = 0 cgso=5.e-10 cgdo=5.e-10 cgbo=4.e-10 cj=1e-4

.model pch pmos level = 1 tox = 170 vto = -0.7 kp = 30.0e-6 lambda = 0.01
+ gamma = 0.5 phi = 0.6 capop = 0 cgso=3.e-11 cgdo=3.e-11 cgbo=4.e-10 cj=6e-4

.option nopage post=2   nomod

*name drain gate source bulk model
m1  d1  vi1  vs  vs  pch  l=1u  w=10u
m2  d2  vi2  vs  vs  pch  l=1u  w=10u
m3  d3  d3  vdd   vdd  pch   l=1u   w=2u
m4  d4  d3  vdd   vdd  pch   l=1u   w=2u
m5  d5  d5  d3  vdd  pch   l=1u   w=2u
m6   vout  d5  d4  vdd  pch   l=1u   w=2u
m7  d5  d11  d1  vdd-  nch  l=1u   w=2u
m8  vout  d11  d2  vdd-  nch  l=1u  w=2u
m9  d1  d12  vdd-  vdd-  nch  l=1u  w=2u
m10  d2  d12  vdd-  vdd-  nch  l=1u  w=2u
m11  d11  d11  d12  vdd-  nch  l=1u  w=2u
m12  d12  d12 vdd-  vdd-  nch  l=1u   w=2u
m13  vs  d14  vdd  vdd  pch  l=1u   w=2u
m14  d14  d14  vdd  vdd  pch  l=1u   w=2u
rref   d11   d14   270k

vic    vic    0    0
vid1    vi1    vic    0.0
evid2    vic    vi2    vi1    vic    1                 *other half of the vid input
vdd    vdd    0     5.0
vdd-   vdd-  0    -5.0

.dc vid1 -20m  20m  .01m                                      *sweep the input voltage
*.dc vid1 -.2  .2  10m                                    *sweep the input voltage
*.print dc v(out)
*.print dc i(m1)                                  * i is the ids of m1
*                                                  * von=1v9  vdsat=1x9  gds=1x8
*.print dc 1v9(m1)  1v10(m1)  1x7(m1)     * plots gm=1x7 gmbs=1x9 gds=1x8
.op                                               *initial operating point
.tf v(vout,0)  vid1
*.measure tot_power avg power                 *makes it do the power calculation

.end
```

Folded Cascode (Cont.)

MOA-17

Upper and lower cascodes could be biased for high swing thus max swing could be within $2V_{DSAT}$ of each rail.

$$GM = gm \cdot \frac{R_{DOWN}}{R_{UP} + R_{DOWN}}$$



There is some current splitting at the point of the folding. However when calculating GM the output (drain of M8) is grounded so R_{UP} is about $1/g_m$ with R_{DOWN} being r_o .

Folded Cascode (Cont.)

MOA-18

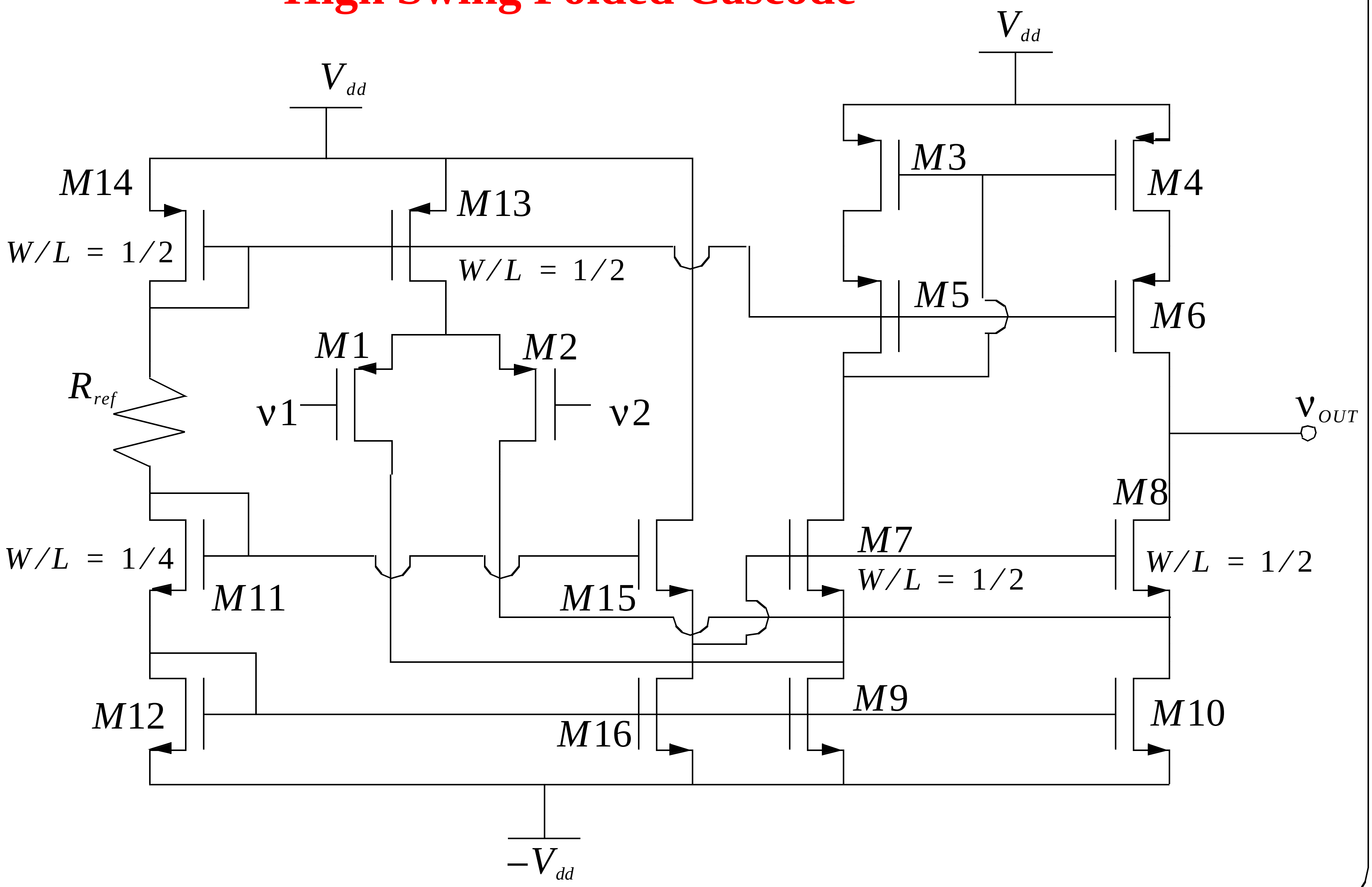
There is a loss in R_{out} as well since M10 must sink DC current from both M2 and M8, thus reducing its r_o

	CASCODE	*FOLDED CASCODE*
A_v	336K	125K
R_{OUT}	2,446KΩ	1,486KΩ

same currents,
same device size
from examples

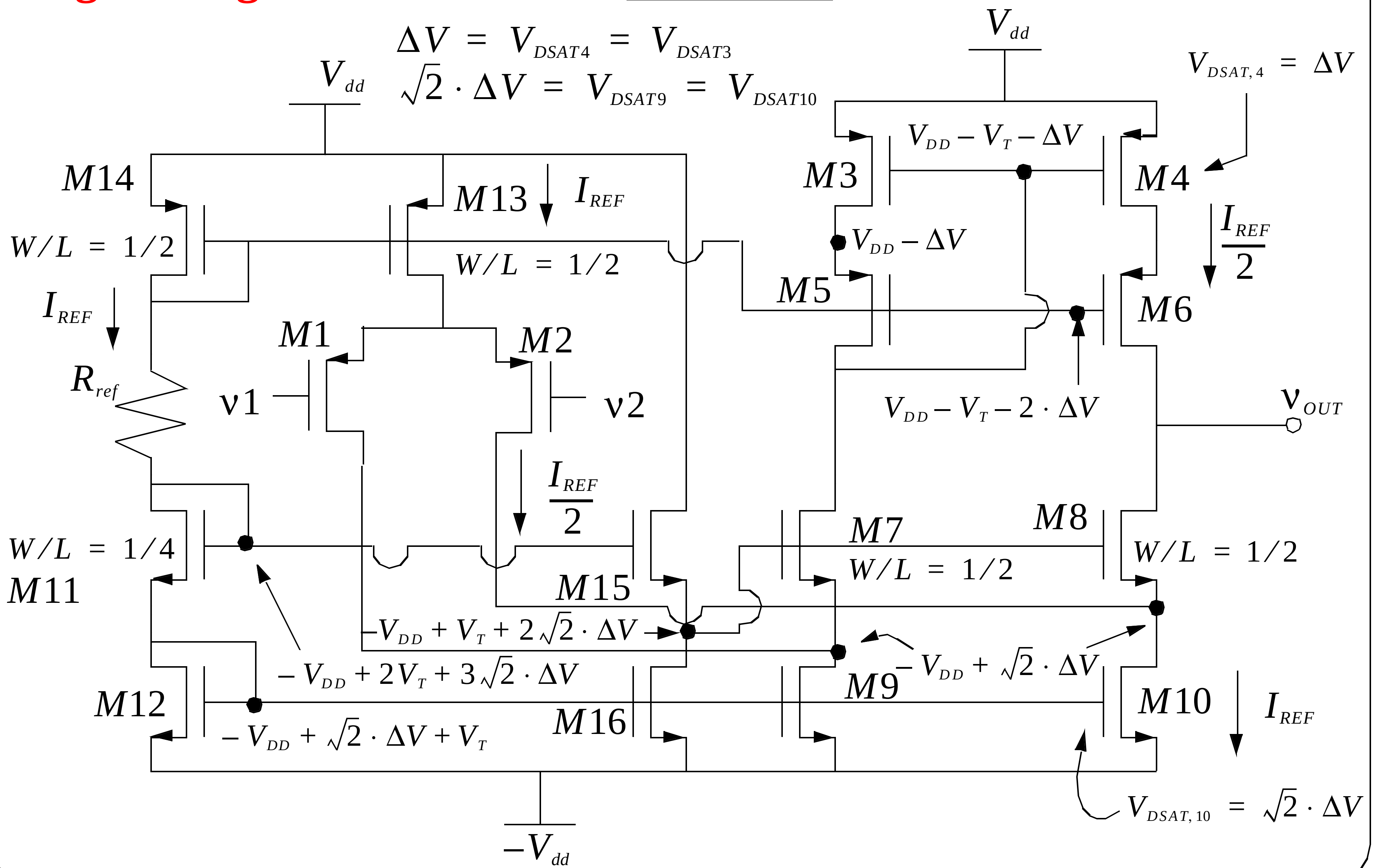
High Swing Folded Cascode

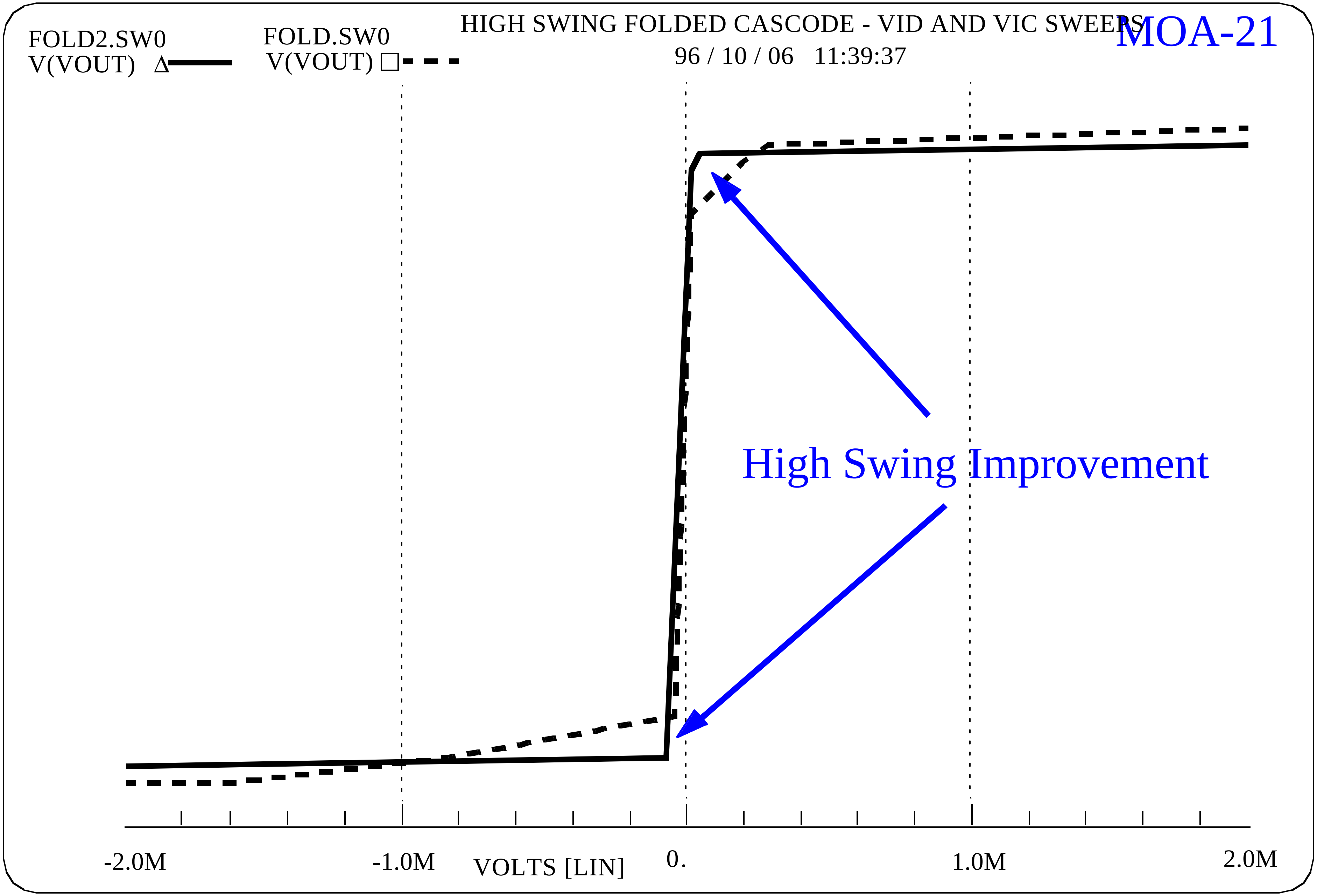
MOA-19



High Swing Folded Cascode **Circuit 4 :** MOA-20

$$\Delta V = V_{DSAT4} = V_{DSAT3}$$
$$\sqrt{2} \cdot \Delta V = V_{DSAT9} = V_{DSAT10}$$




HIGH SWING FOLDED CASCODE - VID AND VIC SWEEPS
MOA-21
FOLD2.SW0
V(VOUT)
FOLD.SW0
V(VOUT)
96 / 10 / 06 11:39:37
High Swing Improvement
-2.0M
-1.0M
VOLTS [LIN]
0.
1.0M
2.0M

Circuit 4 :

M15-M16 perform level shift to bias M9 and M10 at the edge of linear.
M7 and M8 have 1/2 sized W/L because the current is Iref/2.
The connection to M5 from M14 sets the M3 at the edge of linear operation.
The W/L's are 1 unless otherwise shown. This is smaller than you would want to use, but this was done to show the ratioing that is required to place the output in high swing.
The Gain and Rout calculations are the same as for circuit 3 and are carried out as described by DP-21 to DP-23.

High Swing Folded Cascode (Cont.)

MOA-23

$$R_{O,UP} = \frac{r_{o8} + R_D}{1 + (1+\chi) \cdot r_{o8} \cdot g_{m8}}$$

$$R_D \to 0$$

$$R_{O,UP} = \frac{1}{\frac{1}{r_{o8}} + (1+\chi) \cdot g_{m8}} \approx \frac{1}{(1+\chi) \cdot g_{m8}}$$

$$R_D \approx g_m \cdot r_o^2 \qquad \chi = 0$$

$$R_{O,UP} \approx \frac{g_{m6} \cdot r_{o4} \cdot r_{o6}}{r_{o8} \cdot g_{m8}} \approx r_o$$

$$R_{O,UP} = \frac{r_{o8} + g_{m6} \cdot r_{o4} \cdot r_{o6}}{1 + (1+\chi) \cdot r_{o8} \cdot g_{m8}}$$

$$R_{OUT,S8} \approx \frac{r_o}{3}$$