

University of California  
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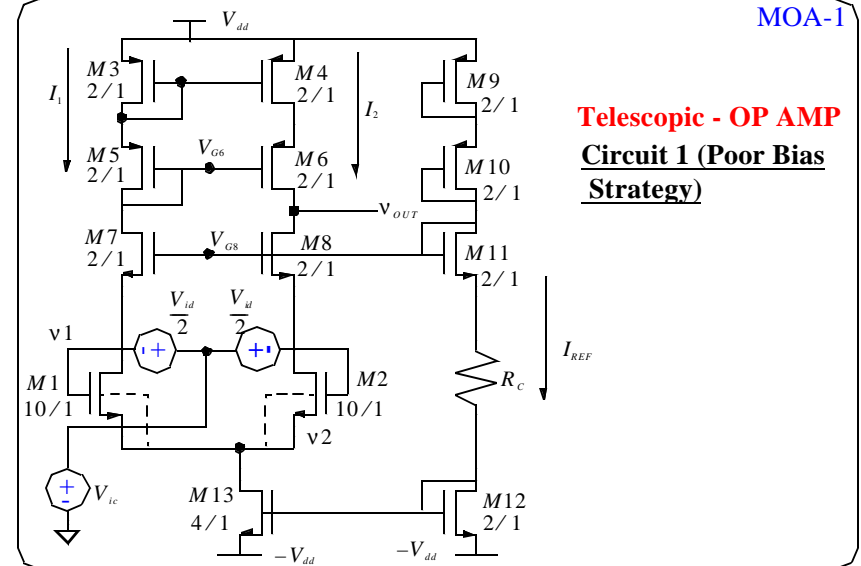
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EECS140

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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 :

MOA-2

**Telescopic 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,

$$V_{GS3} = V_{GS4} = V_{GS9} \quad (\text{all W/L's are equal also})$$

This also implies that,

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

similarly,

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

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,

$$V_{OUTMAX} = V_{G6} + V_T$$

But since,

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

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

$$V_{OUTMIN} = V_{G8} - V_T$$

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,

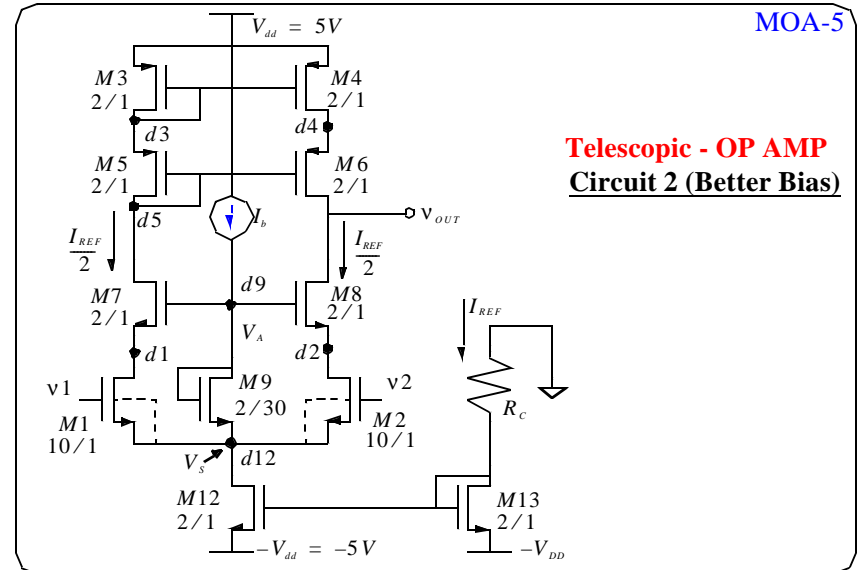
$$V_{OUTMAX} > V_{DD} - V_{GS} - V_{DSAT6}$$

Negative swing is limited by M8 going linear,

$$V_{OUTMIN} = V_A - V_{T8}$$

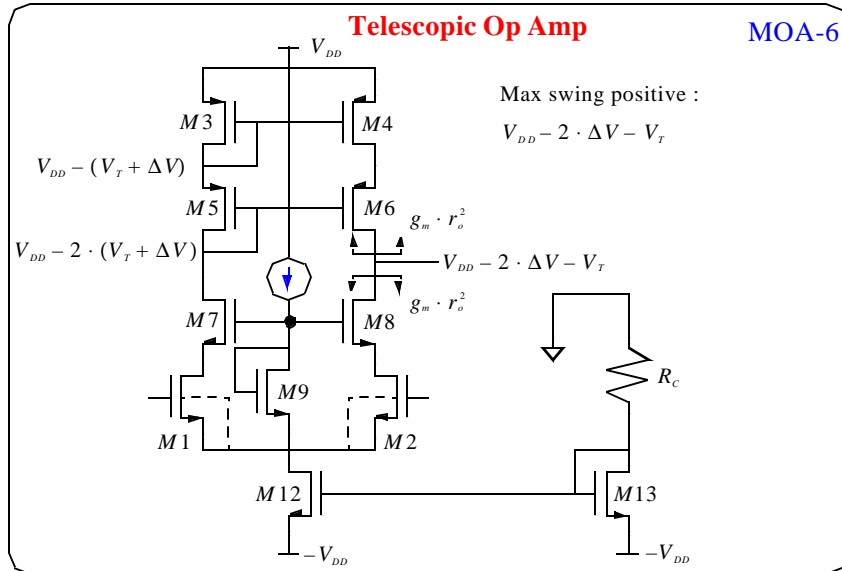
Set  $V_A$  so that M1 & M2 are at the edge of saturation

MOA-5

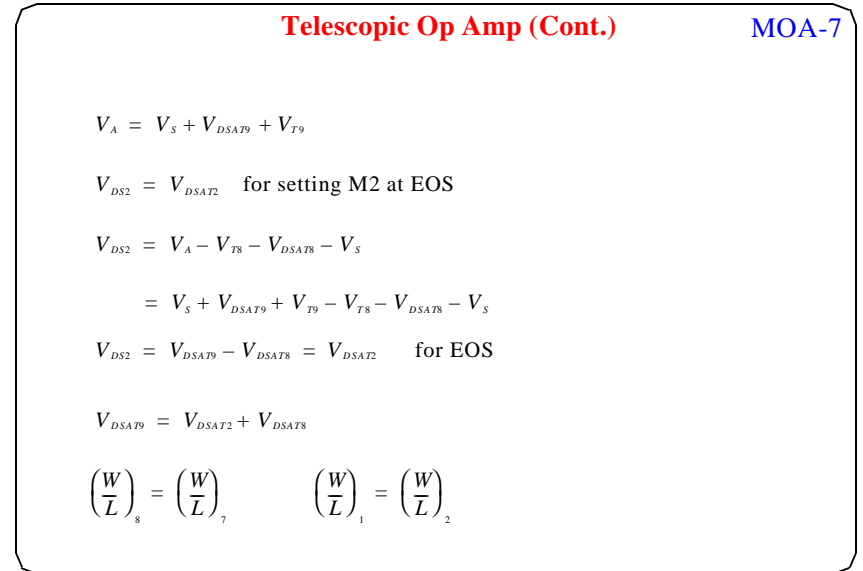


**Telescopic - OP AMP  
Circuit 2 (Better Bias)**

MOA-6



MOA-7



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,

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

then,

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

Gain and  $R_{out}$

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

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

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

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,

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

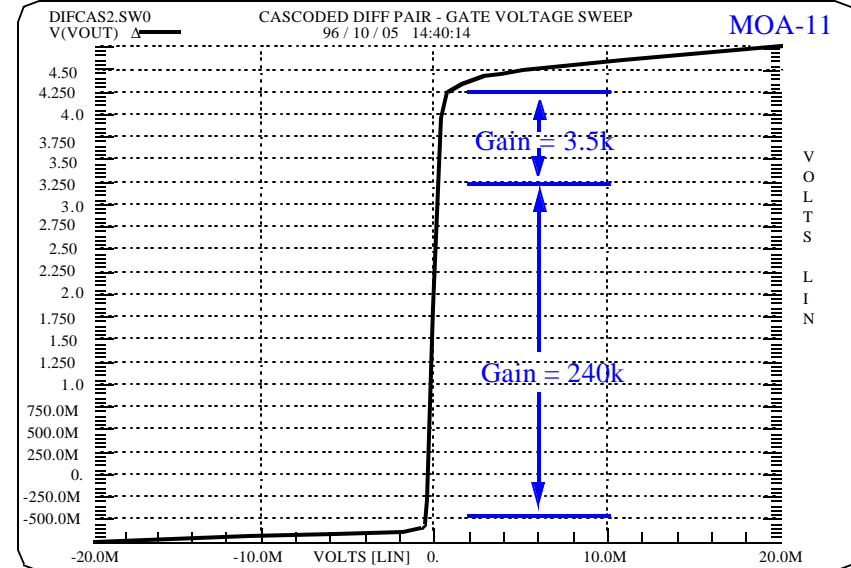
and,

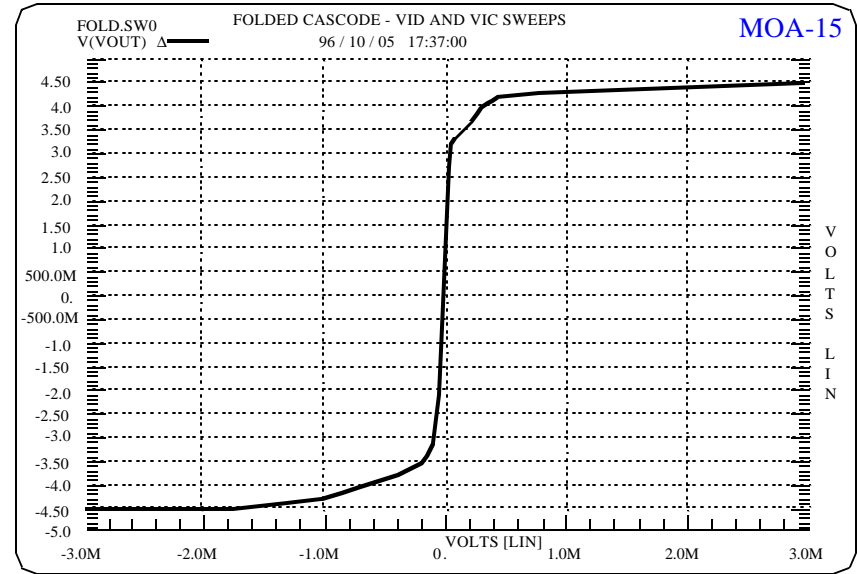
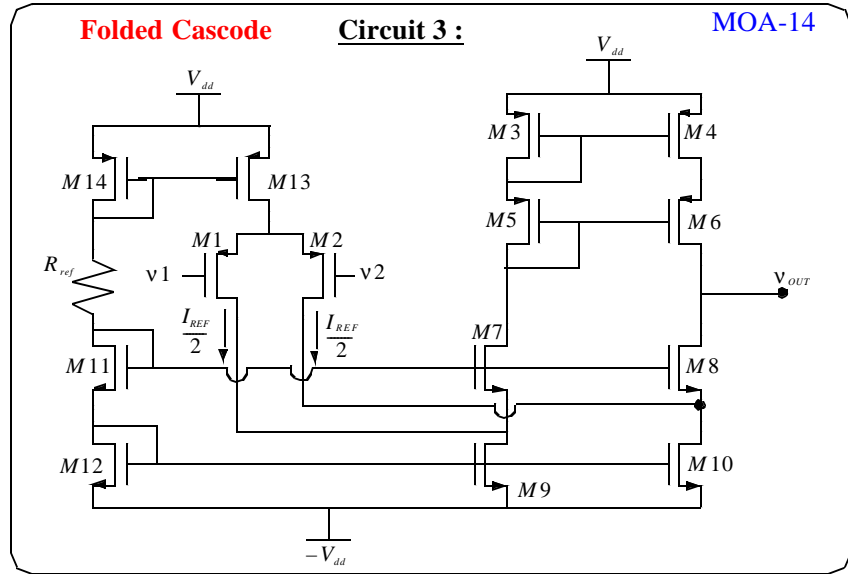
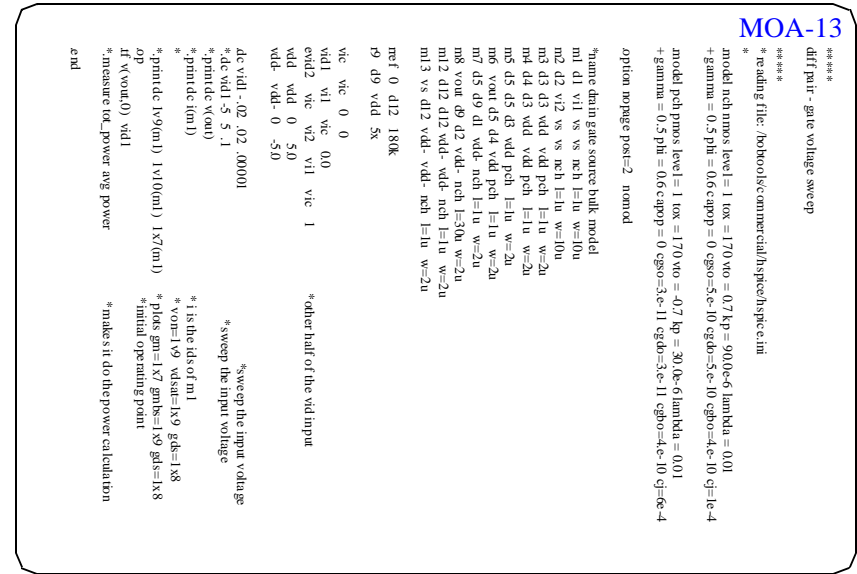
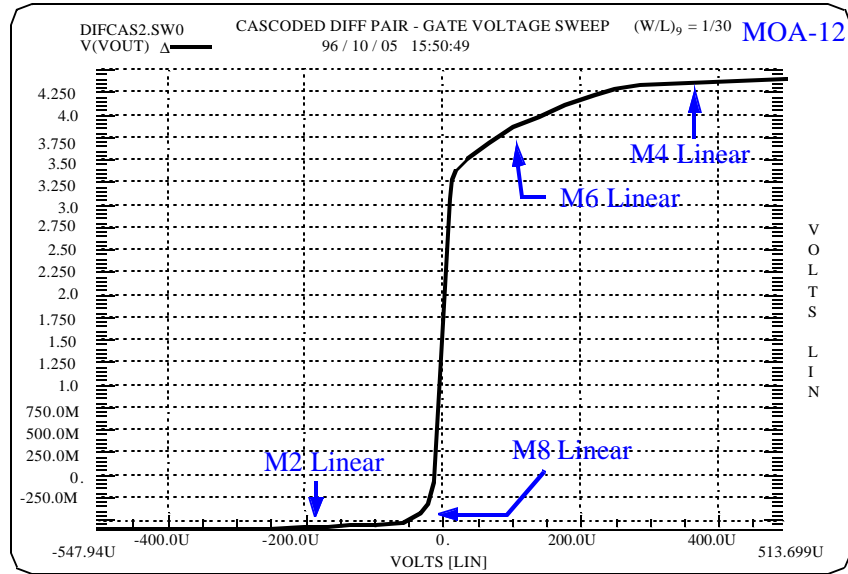
$$r_o = r_{o4} = r_{o6} = r_{o2} = r_{o8}$$

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

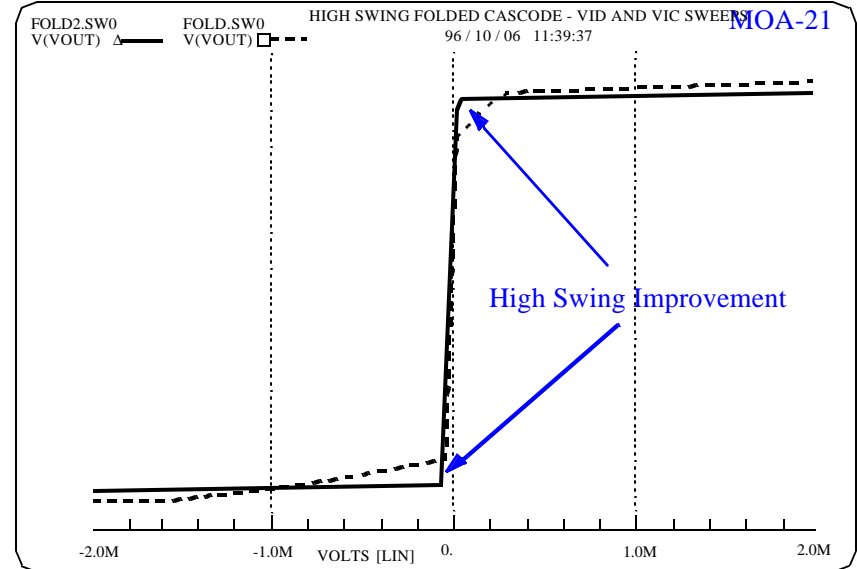
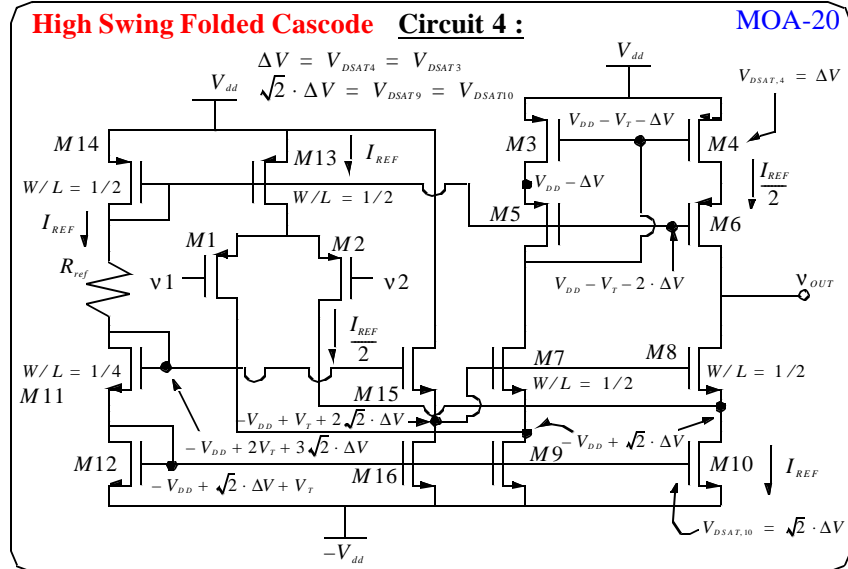
Gain keeps increasing as we decrease the current.

MOA-11









### Circuit 4 : MOA-22

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

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

$$R_D \rightarrow 0$$

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

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

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

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

$$R_{OUTSS} \approx \frac{r_o}{3}$$