ECEN326: Electronic Circuits
Fall 2022

Lecture 5: Operational Transconductance Amplifiers (OTAs)

Sam Palermo

Analog & Mixed-Signal Center

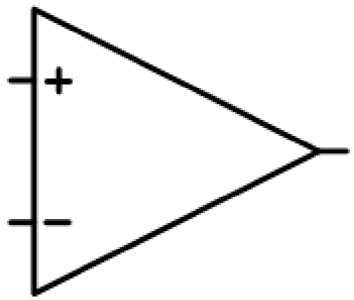
Texas A&M University

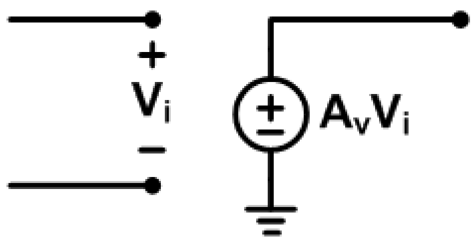
Announcements

- HW4 due Mar 8
- This material is related to Lab 7

OpAmps and OTAs

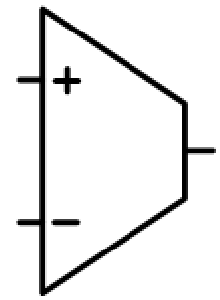
OpAmp

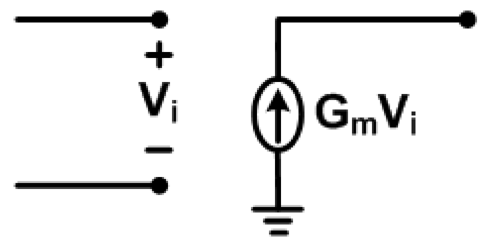




- High voltage gain
- High input impedance
- Voltage source output (low impedance)

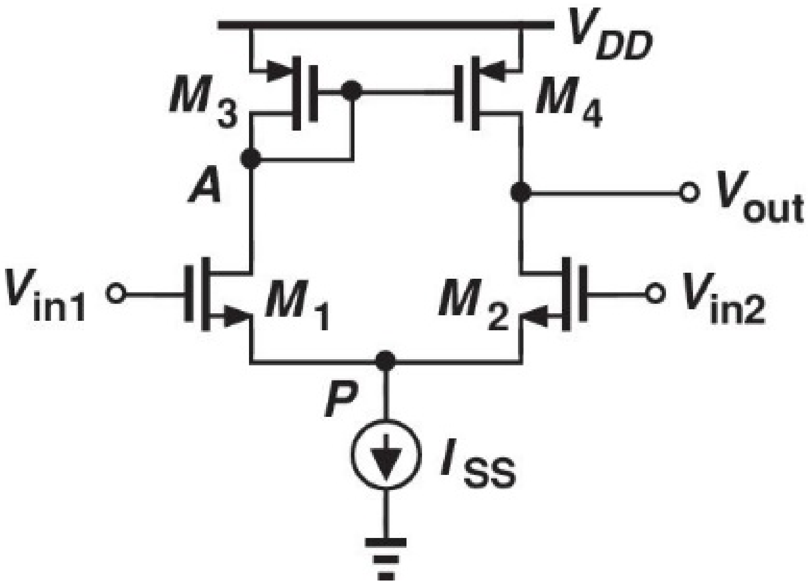
OTA





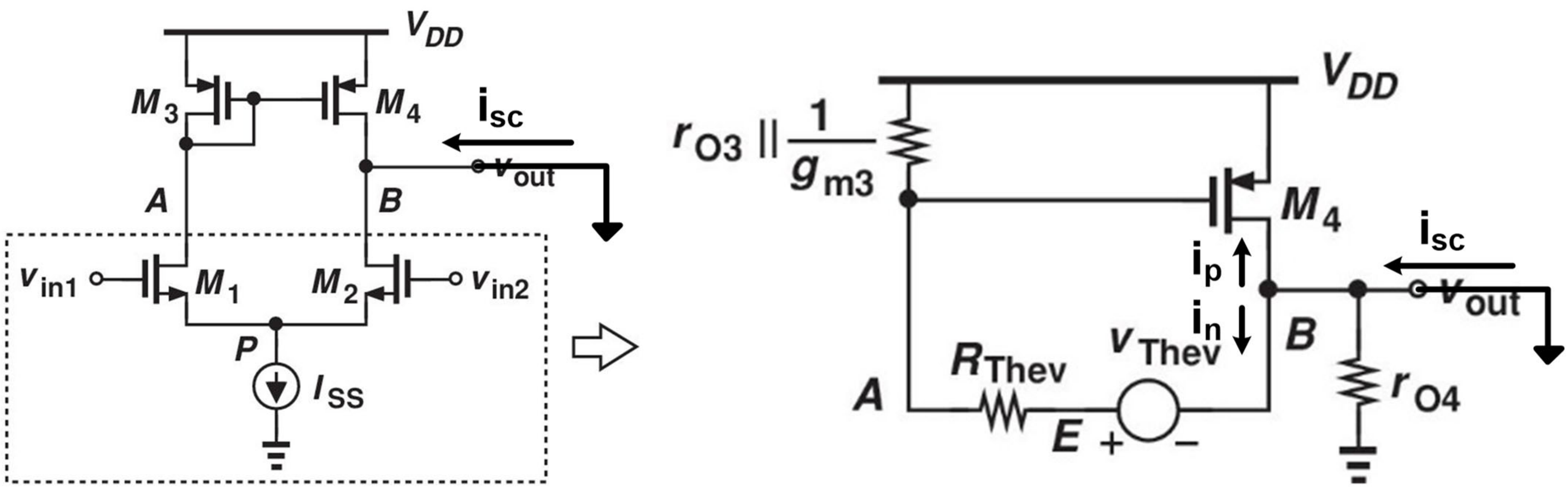
- High “voltage” gain
- High input impedance
- Current source output (high impedance)

Simple OTA



- Important Parameters
  - Transconductance
  - Output Resistance
  - Differential Gain
  - Common-Mode Input Range

Simple OTA Transconductance: Rigorous Analysis



From Lecture 3

$$v_{Thev} = -g_{mn} r_{ON} (v_{in1} - v_{in2}) \text{ and } R_{Thev} = 2r_{ON}$$

To find i_{sc}, we need to find i_p and i_n

$$i_p = g_{m4} v_A$$

$$v_A = \frac{\frac{1}{g_{m3}} \| r_{O3}}{\frac{1}{g_{m3}} \| r_{O3} + 2r_{ON}} \left(-g_{mn} r_{ON} (v_{in1} - v_{in2})\right) \approx -\frac{g_{mn}}{2g_{m3}} (v_{in1} - v_{in2})$$

$$i_p = g_{m4} v_A = -\frac{g_{mn}}{2} (v_{in1} - v_{in2})$$

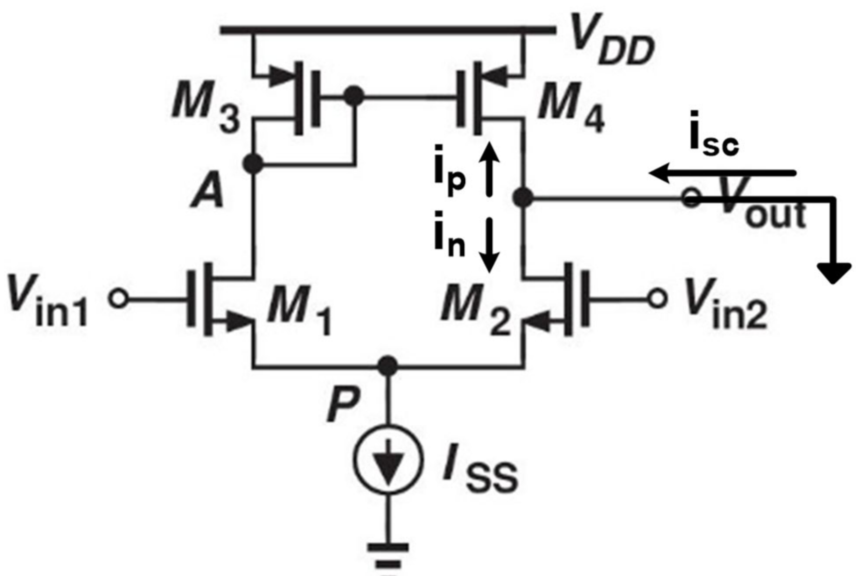
$$i_n = \frac{-g_{mn} r_{ON} (v_{in1} - v_{in2})}{2r_{ON} + \frac{1}{g_{m3}}} \approx -\frac{g_{mn}}{2} (v_{in1} - v_{in2})$$

$$i_{sc} = i_p + i_n = -g_{mn} (v_{in1} - v_{in2})$$

$$G_m = \frac{i_{sc}}{v_{in1} - v_{in2}} = -g_{mn}$$

Simple OTA Transconductance: Informal Virtual Ground Approach

- As the differential circuit is not purely symmetric, we cannot formally assume a virtual ground at node P
- However, if the differential pair transistors M1 and M2 have high output resistance, a virtual ground can be approximated at node P to simplify the analysis



$$i_n = g_{m2} v_{in2}$$

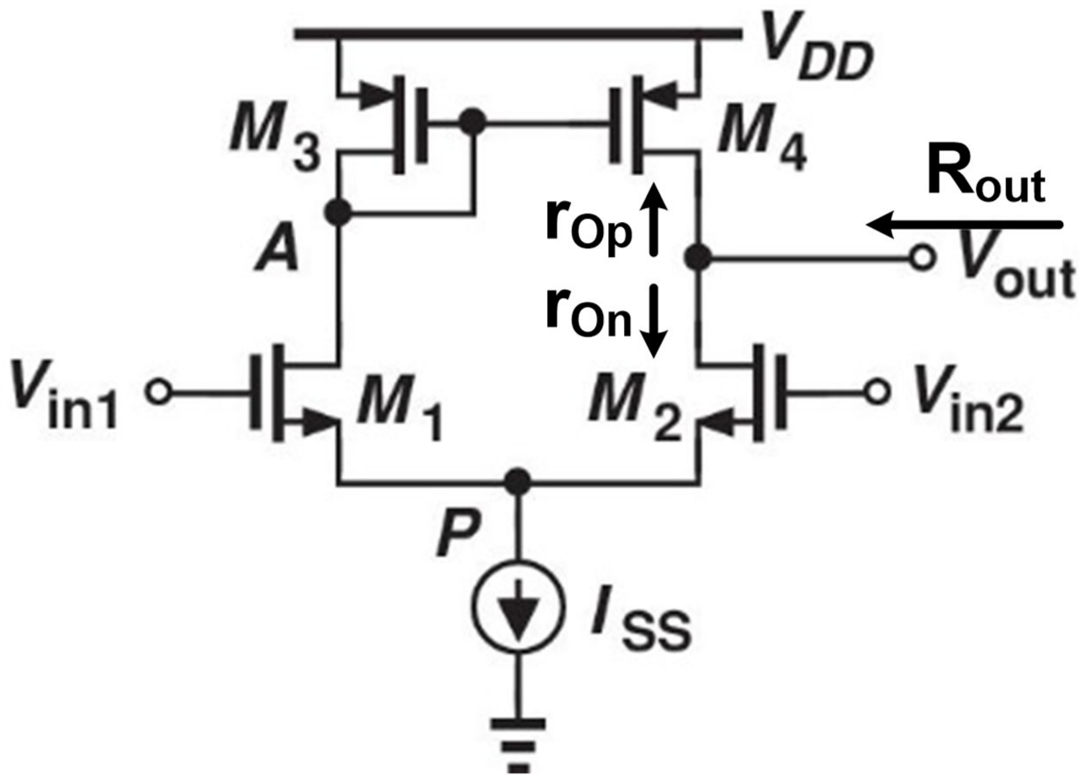
Assuming an ideal current mirror load

$$i_p = -g_{m1} v_{in1}$$

$$i_{sc} = i_p + i_n = -g_{m1} v_{in1} + g_{m2} v_{in2}$$

$$G_m = \frac{i_{sc}}{v_{in1} - v_{in2}} = \frac{-g_{m1} v_{in1} + g_{m2} v_{in2}}{v_{in1} - v_{in2}} = -g_{mn}$$

Simple OTA Output Resistance

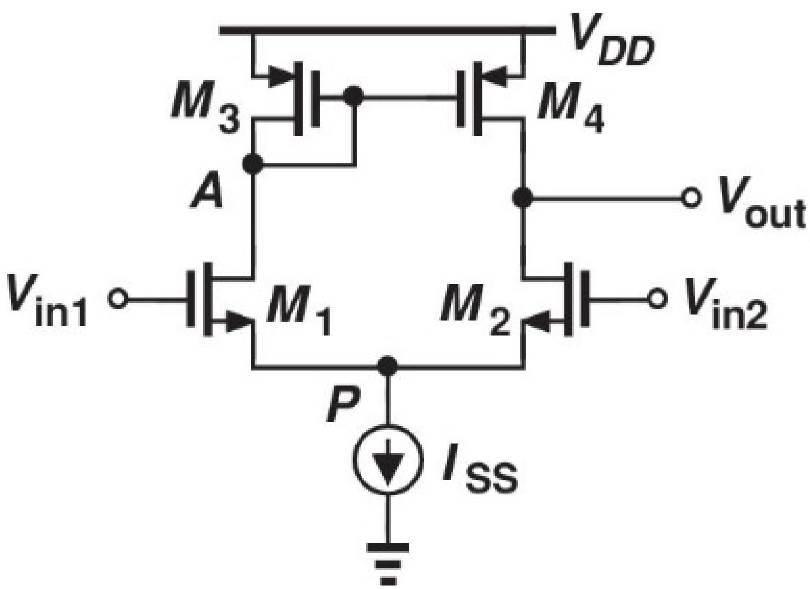


$$R_{out} = r_{Op} \| r_{On}$$

It is often useful to also use the output conductance

$$G_{out} = \frac{1}{R_{out}} = g_{op} + g_{on}$$

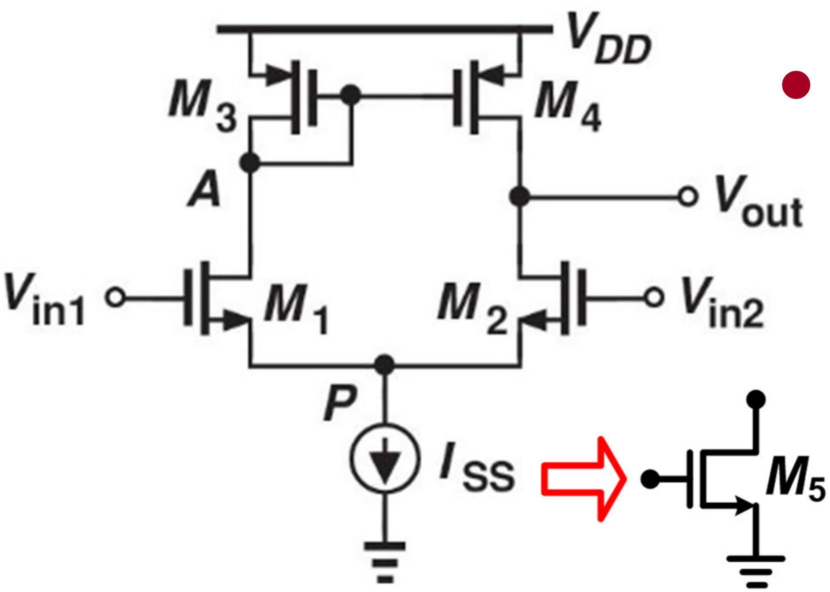
Simple OTA Differential Gain



$$A_v = -G_m R_{out} = -(-g_{mn})(r_{On} \| r_{Op})$$

$$A_v = g_{mn}(r_{On} \| r_{Op}) = \frac{g_{mn}}{g_{op} + g_{on}}$$

Simple OTA Common-Mode Input Range



- Common-mode input range set by transistor saturation conditions
  - Low-end set by tail current source saturation

$$V_{icm} \geq V_{DSAT5} + V_{GS1} = \sqrt{\frac{2I_{SS}}{\mu_n C_{ox} \frac{W}{L}_5}} + \sqrt{\frac{I_{SS}}{\mu_n C_{ox} \frac{W}{L}_1}} + V_{TH,n1}$$

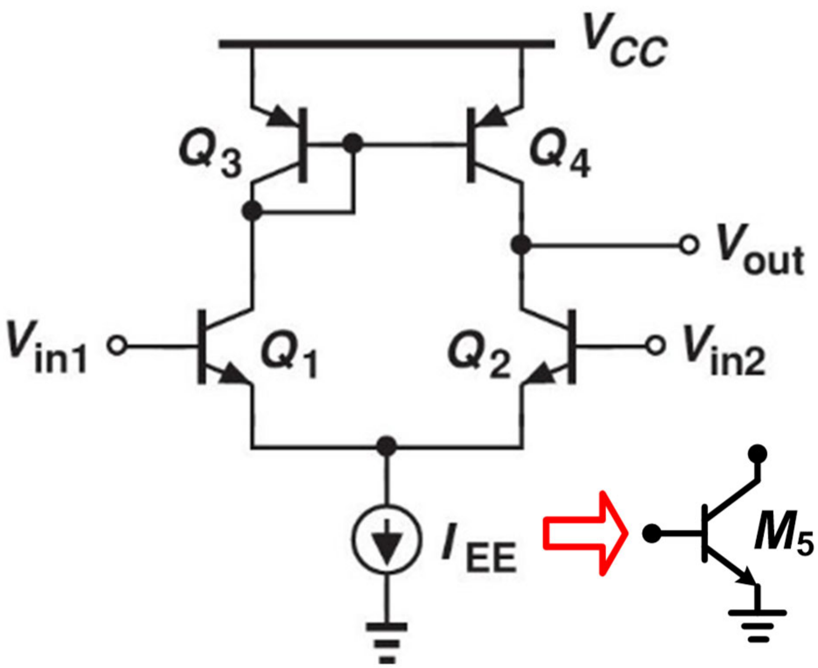
- High-end set by differential pair saturation

$$V_{icm} \leq V_{ocm} + V_{TH,n1} = V_{DD} - |V_{GS3}| + V_{TH,n1} = V_{DD} - \left(\sqrt{\frac{I_{SS}}{\mu_p C_{ox} \frac{W}{L}_3}} + |V_{TH,p3}| \right) + V_{TH,n1}$$

$$\sqrt{\frac{2I_{SS}}{\mu_n C_{ox} \frac{W}{L}_5}} + \sqrt{\frac{I_{SS}}{\mu_n C_{ox} \frac{W}{L}_1}} + V_{TH,n1} \leq V_{icm} \leq V_{DD} - \left(\sqrt{\frac{I_{SS}}{\mu_p C_{ox} \frac{W}{L}_3}} + |V_{TH,p5}| \right) + V_{TH,n1}$$

Bipolar Simple OTA

- Following a similar procedure



$$G_m = -g_{mn}$$
$$R_{out} = r_{On} \| r_{Op}$$
$$A_v = g_{mn}\left(r_{On} \| r_{Op}\right) = \frac{g_{mn}}{g_{on} + g_{op}}$$

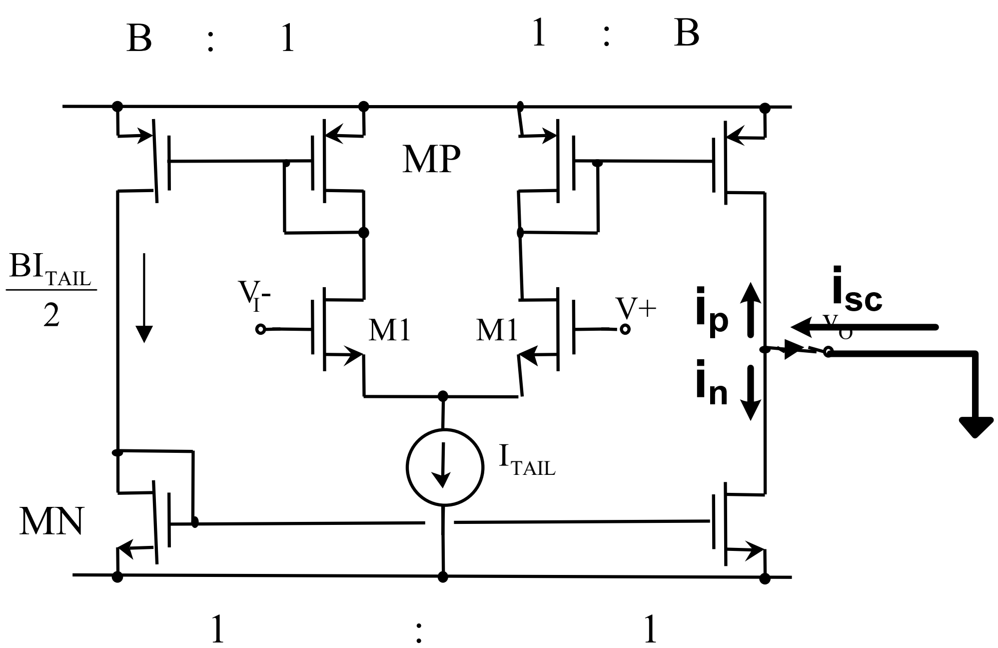
- Low-end V_{icm} set by keeping tail current source in active mode

$$V_{icm} \geq V_{CE,sat} + V_{BE,on} \approx 0.3V + 0.7V = 1V$$

- High-end V_{icm} set by keeping differential pair in active mode

$$V_{CE1} = V_{CC} - V_{BE,on} - \left(V_{icm} - V_{BE,on}\right) \geq V_{CE,sat}$$
$$V_{icm} \leq V_{CC} - V_{CE,sat} \approx V_{CC} - 0.3V$$

3 Current Mirror OTA



$$i_p = -Bg_{m1}v^+$$

$$i_n = Bg_{m1}v^-$$

$$i_{sc} = i_p + i_n = -Bg_{m1}v^+ + Bg_{m1}v^-$$

$$G_m = \frac{i_{sc}}{v^+ - v^-} = \frac{-Bg_{m1}v^+ + Bg_{m1}v^-}{v^+ - v^-} = -Bg_{m1}$$

$$R_{out} = \frac{r_{Op}}{B} \Bigg\| \frac{r_{O1}}{B} = \frac{1}{B}\left(r_{Op} \| r_{O1}\right)$$

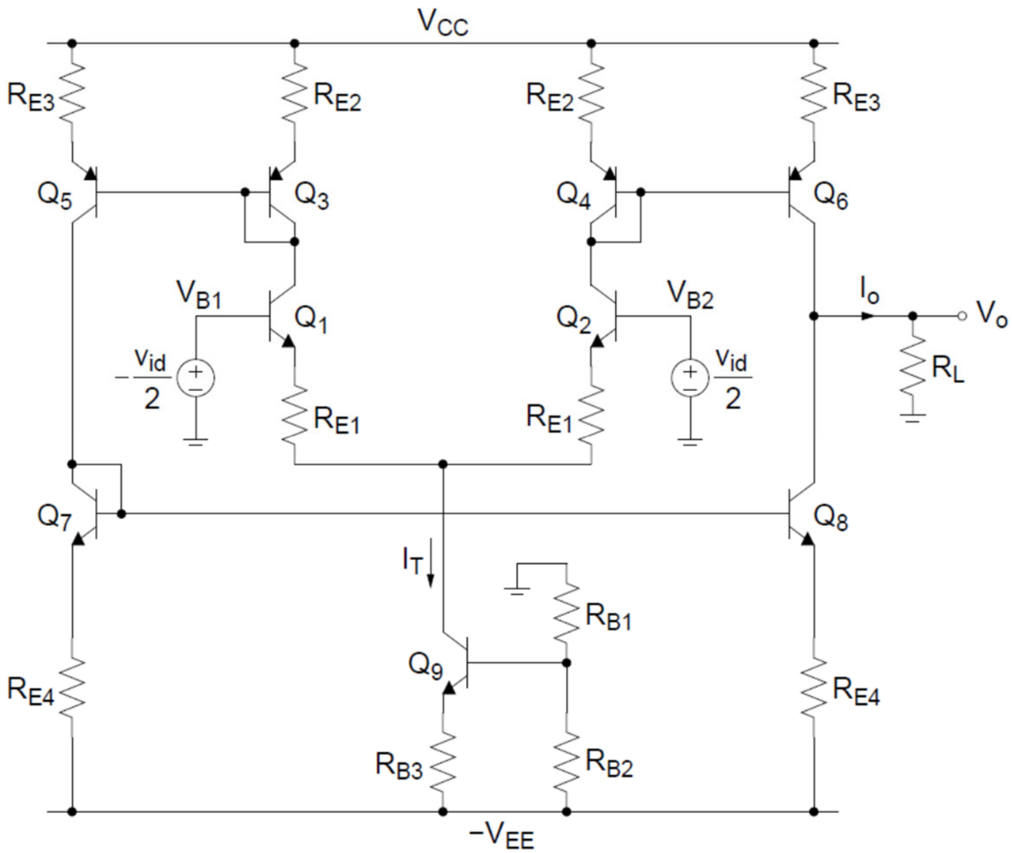
$$G_{out} = B\left(g_{op} + g_{o1}\right)$$

$$A_v = g_{m1}\left(r_{Op} \| r_{O1}\right)$$

- While G_m has increased by the current mirror factor B, the voltage gain remains the same due to the output resistance being reduced by B^{-1}

- Common-mode input range expression remains the same as the previous simple OTA

Bipolar 3 Current Mirror OTA w/ Degenerated G_m (Lab 7)



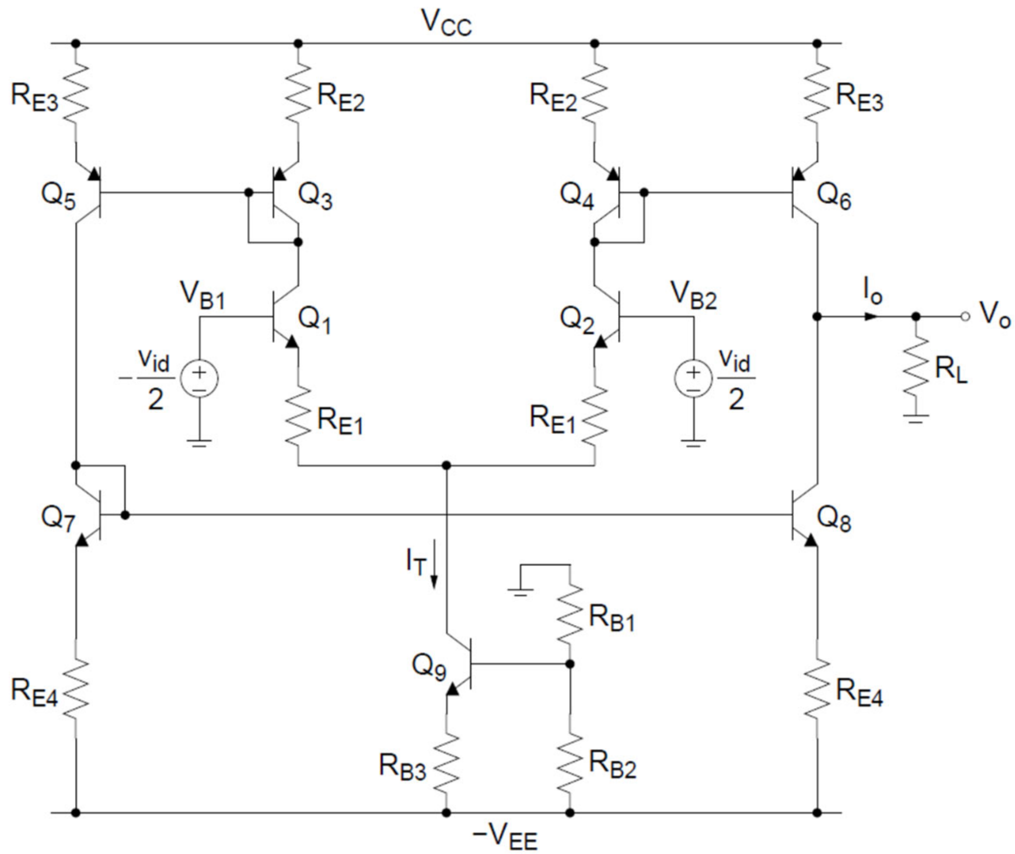
- In order to improve the distortion performance, emitter resistors have been added in the input differential pair
- In order to improve the output resistance, emitter resistance has been added to all the current mirror/source transistors

Assuming a 1 : 1 ratio for all the current mirrors,

G_m is set by the degnerated G_m of the input transistors

$$G_m = -\frac{\alpha}{r_{e1} + R_{E1}} \approx -\frac{1}{r_{e1} + R_{E1}}$$

Bipolar 3 Current Mirror OTA w/ Degenerated G_m (Lab 7)

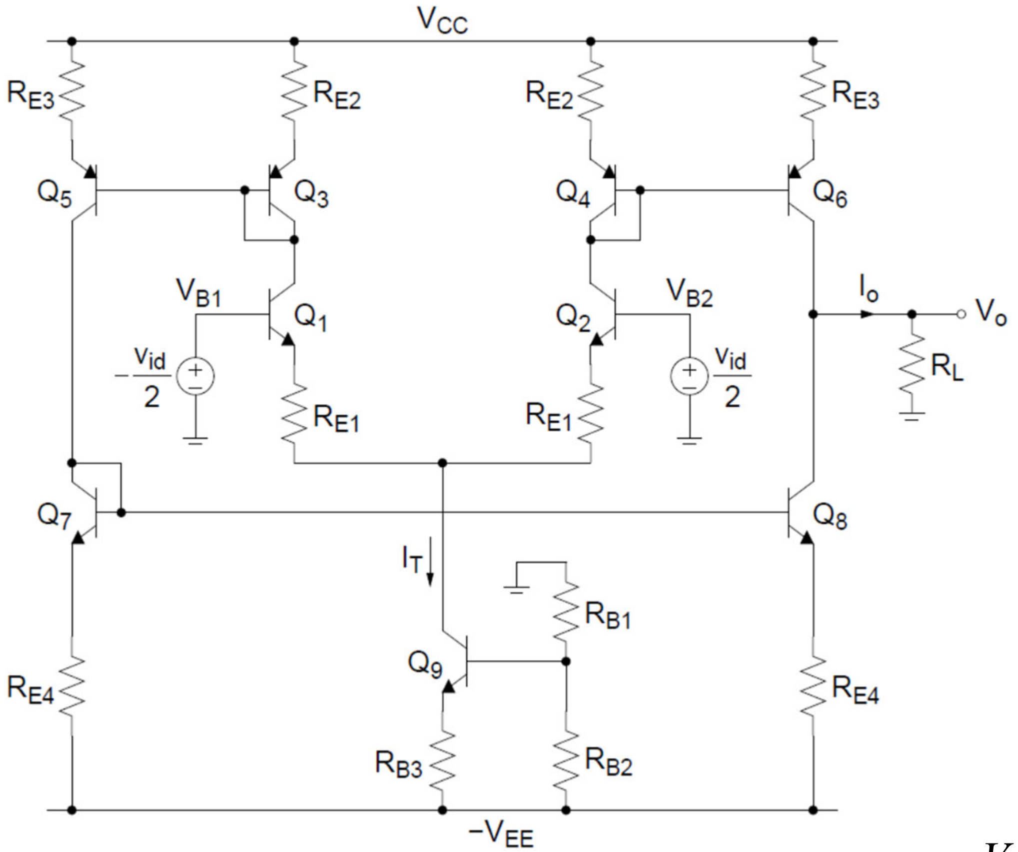


$$R_{out} \approx \left(g'_{m6} r_{o6} R'_{E3} + r_{o6}\right) \| \left(g'_{m8} r_{o8} R'_{E4} + r_{o8}\right)$$

$$g'_{m6} = g_{m6} \frac{r_{\pi 6}}{r_{\pi 6} + r_{e4} + R_{E2}} \approx \mathrm{g_{m6}}, \;\; R'_{E3} = R_{E3} \| \left(r_{\pi 6} + r_{e4} + R_{E2}\right) \approx R_{E3} \| r_{\pi 6}$$

$$g'_{m8} = g_{m8} \frac{r_{\pi 8}}{r_{\pi 8} + r_{e7} + R_{E4}} \approx \mathrm{g_{m6}}, \;\; R'_{E4} = R_{E4} \| \left(r_{\pi 8} + r_{e7} + R_{E4}\right) \approx R_{E4} \| r_{\pi 8}$$

Bipolar 3 Current Mirror OTA w/ Degenerated G_m (Lab 7)



$$R_{id} = 2(\beta + 1)(r_{e1} + R_{E1})$$

- Low-end V_{icm} set by keeping tail current source in active mode

$$V_{icm} \geq -V_{EE} + I_T R_{B3} + V_{CE,sat} + \frac{I_T}{2} R_{E1} + V_{BE,on}$$

- High-end V_{icm} set by keeping differential pair in active mode

$$V_{CE1} = V_{CC} - \frac{I_T}{2} R_{E2} - V_{BE,on} - (V_{icm} - V_{BE,on}) \geq V_{CE,sat}$$

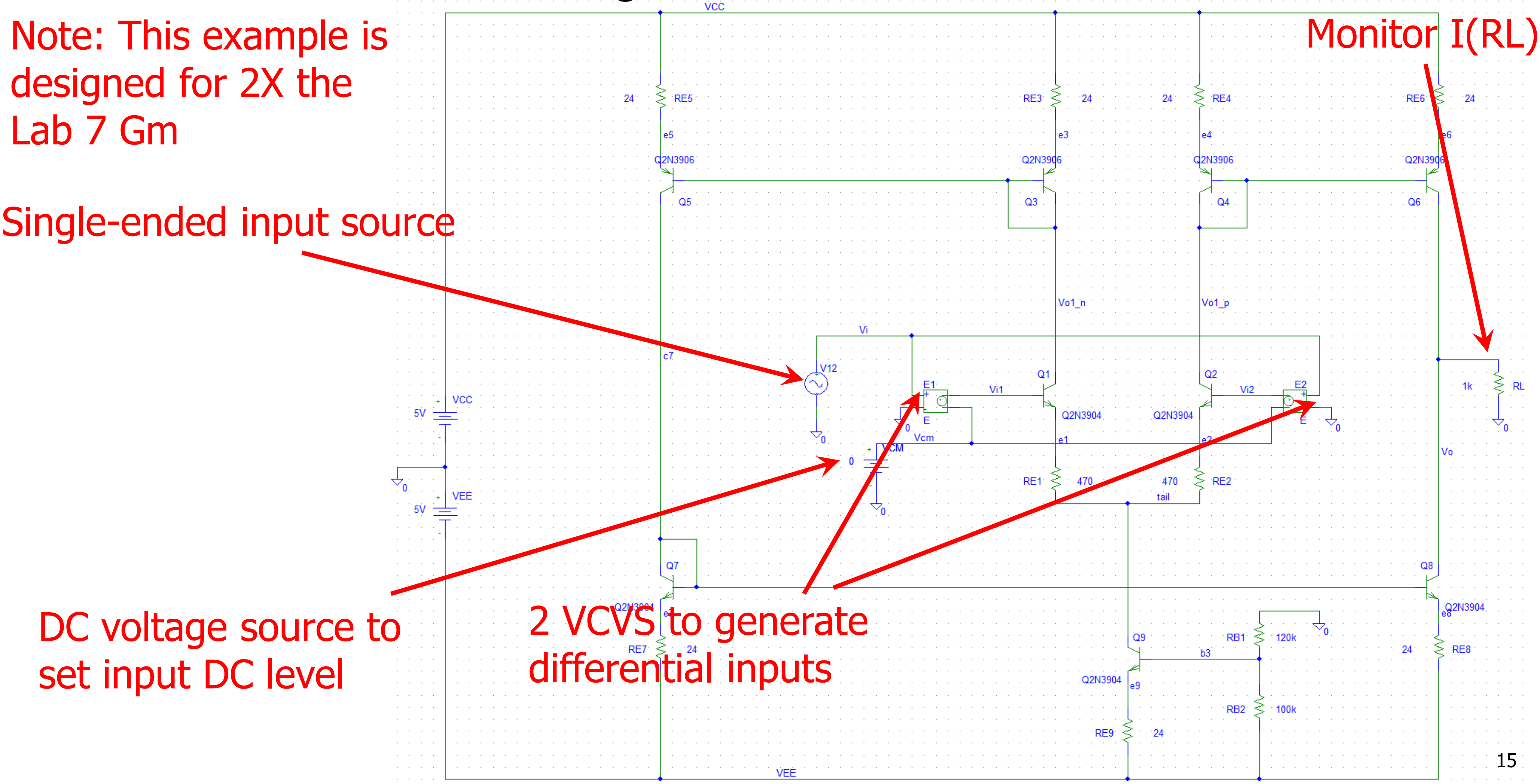
$$V_{icm} \leq V_{CC} - \frac{I_T}{2} R_{E2} - V_{CE,sat}$$

- Maximum differential input amp. for good distortion

$$|v_{id,\max}| = I_T R_{E1}$$

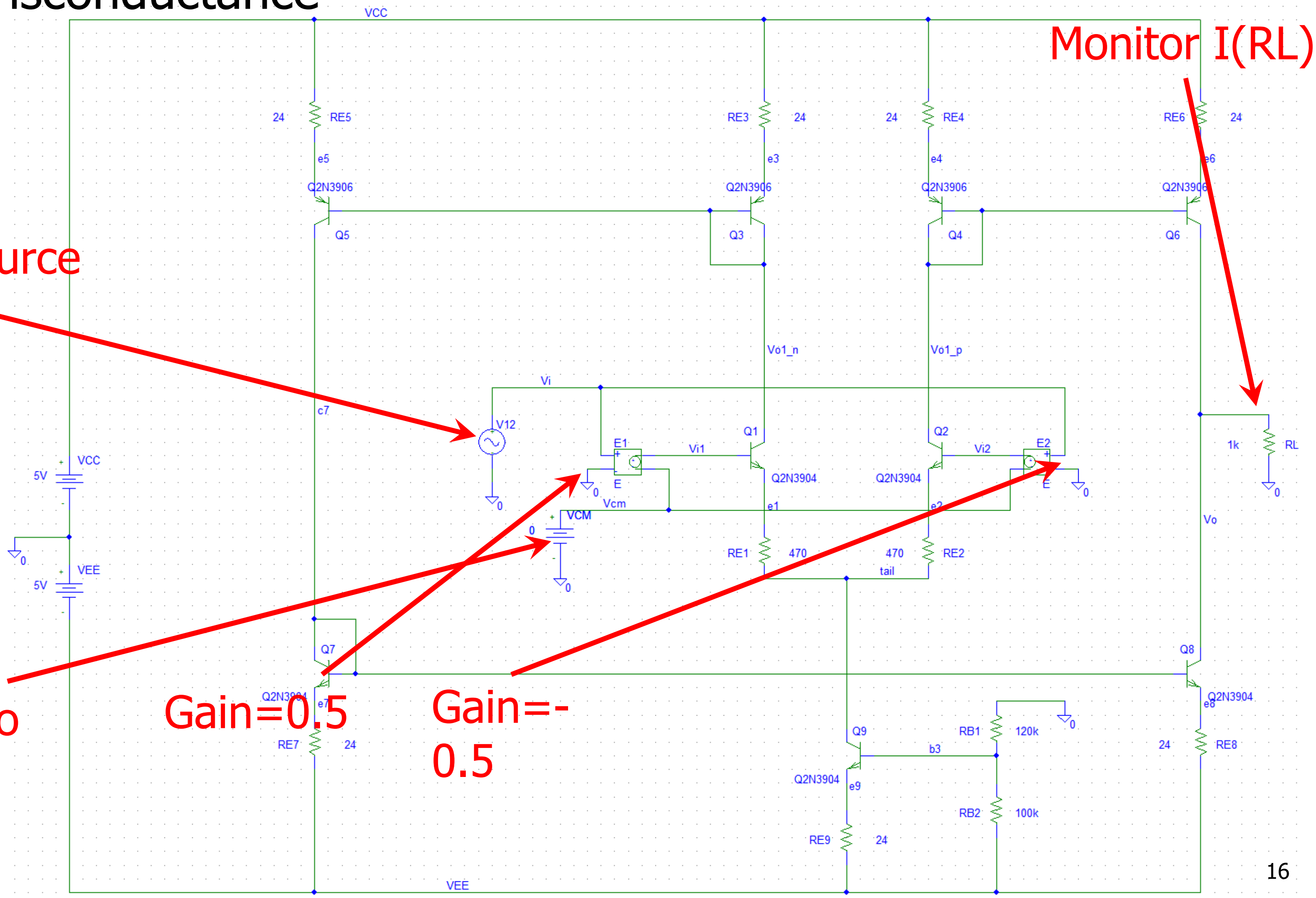
Simulating the 3 Current Mirror OTA

- To simulate differential amplifiers, use voltage-controlled voltage sources (VCVS or "E" elements) to generate the differential input signal and monitor the current through the load resistor



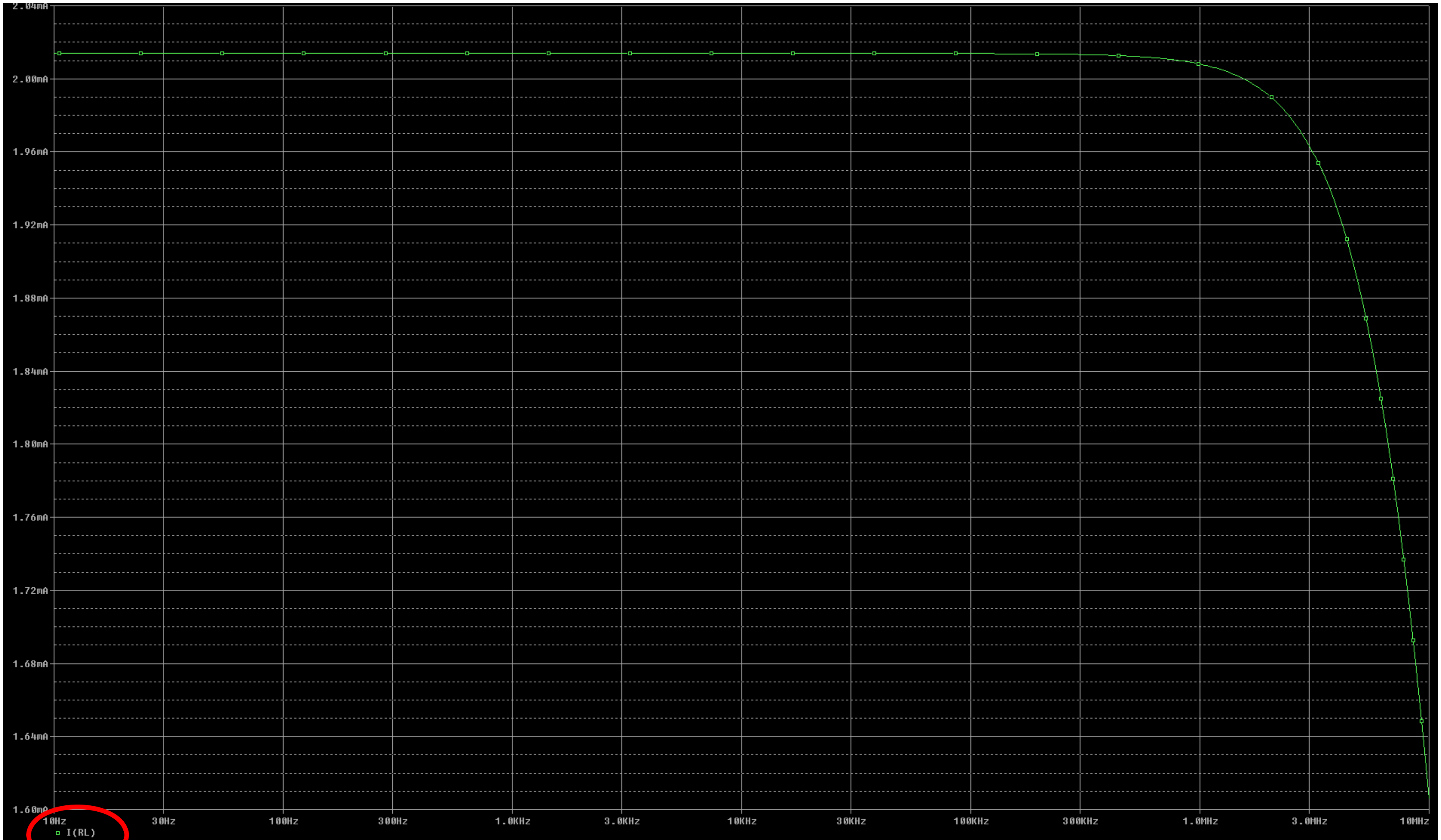
Simulating Transconductance

- Set Inputs E1 Gain=0.5 and E2 Gain=-0.5
- With input source AC=1, simply plot the load resistor current I(RL) to get the transconductance



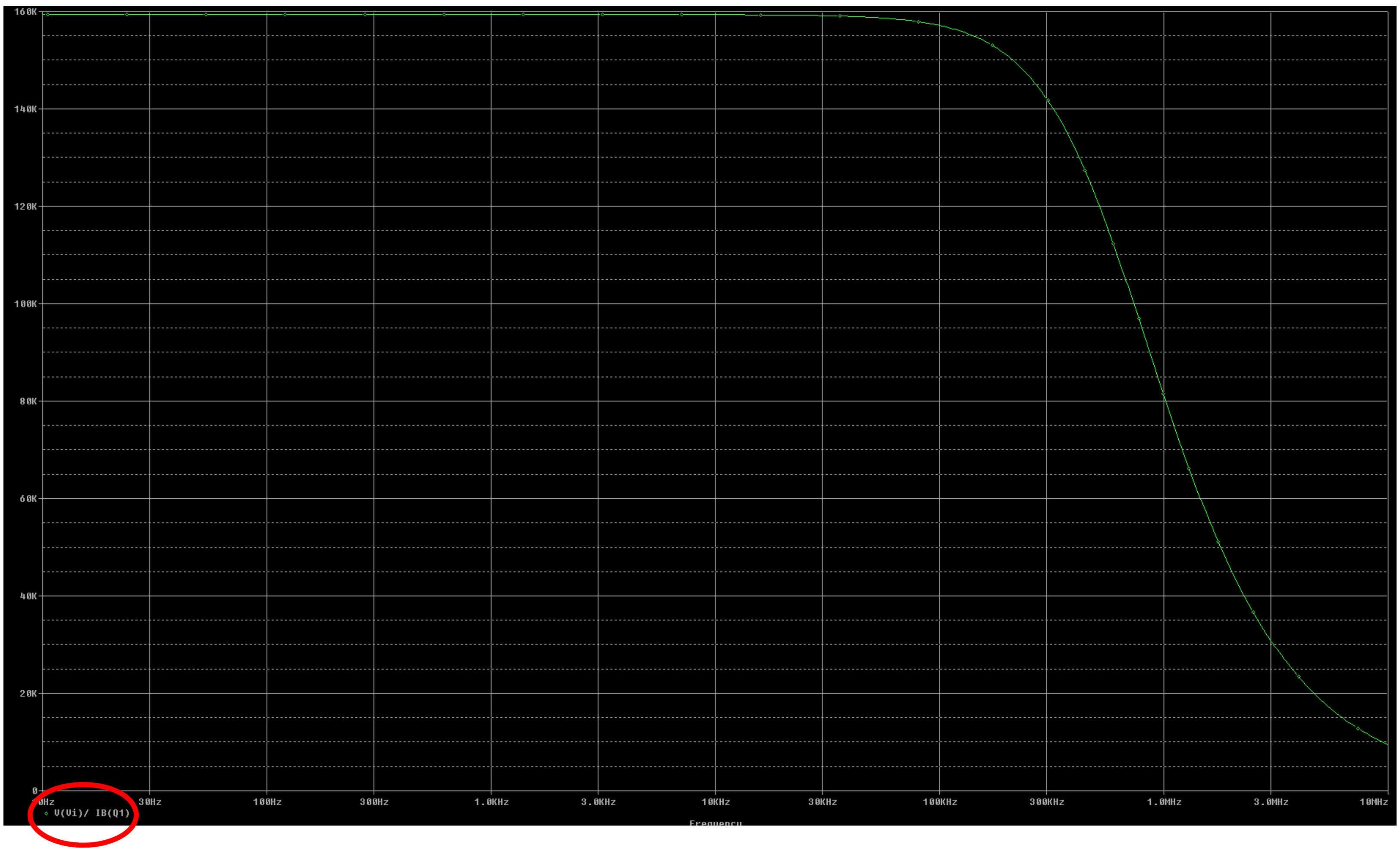
Simulating Transconductance

- G_m = 2.01mA/V



Simulating Differential R_{ind}

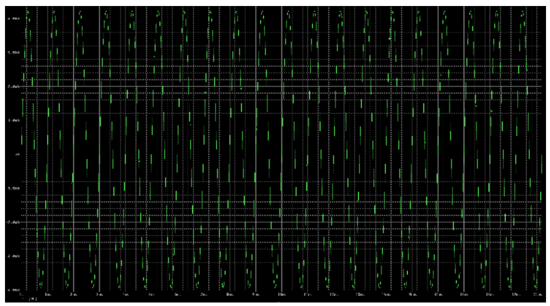
- The differential input resistance is equivalent to the differential input (Vi) divided by the input current, where I use the base current of Q1 or IB(Q1)
- R_{ind} = 159kΩ



Simulating THD

- Set input source to differential input amplitude spec
  - For Lab 7, that is 2V
- Check the THD at 3 different common-mode points
  - 0V, $V_{CM,min}$, $V_{CM,max}$

V_{CM}=0V



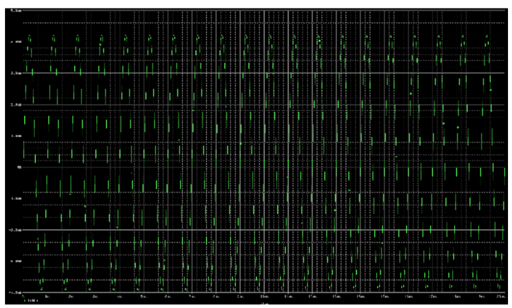
FOURIER COMPONENTS OF TRANSIENT RESPONSE I(R_RL)

DC COMPONENT = 1.399475E-04

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	1.000E+03	4.071E-03	1.000E+00	-5.660E-03	0.000E+00
2	2.000E+03	4.291E-06	1.054E-03	-8.948E+01	-8.947E+01
3	3.000E+03	1.216E-05	2.987E-03	1.798E+02	1.798E+02
4	4.000E+03	9.279E-07	2.279E-04	-9.069E+01	-9.066E+01
5	5.000E+03	2.160E-06	5.305E-04	-1.797E+02	-1.796E+02

TOTAL HARMONIC DISTORTION = 3.220127E-01 PERCENT

V_{CM}=-2V



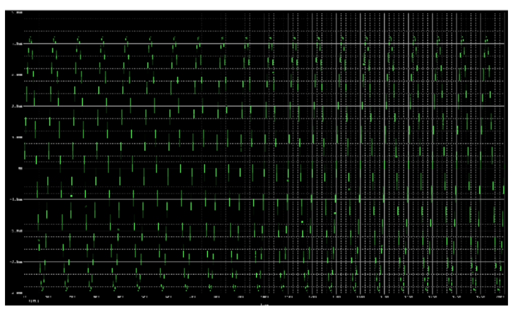
FOURIER COMPONENTS OF TRANSIENT RESPONSE I(R_RL)

DC COMPONENT = 1.386942E-04

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	1.000E+03	4.073E-03	1.000E+00	-5.699E-03	0.000E+00
2	2.000E+03	3.503E-06	8.602E-04	-8.934E+01	-8.933E+01
3	3.000E+03	9.537E-06	2.342E-03	1.797E+02	1.797E+02
4	4.000E+03	1.118E-06	2.745E-04	-9.057E+01	-9.055E+01
5	5.000E+03	4.571E-06	1.122E-03	-1.798E+02	-1.798E+02

TOTAL HARMONIC DISTORTION = 2.749084E-01 PERCENT

V_{CM}=2V



FOURIER COMPONENTS OF TRANSIENT RESPONSE I(R_RL)

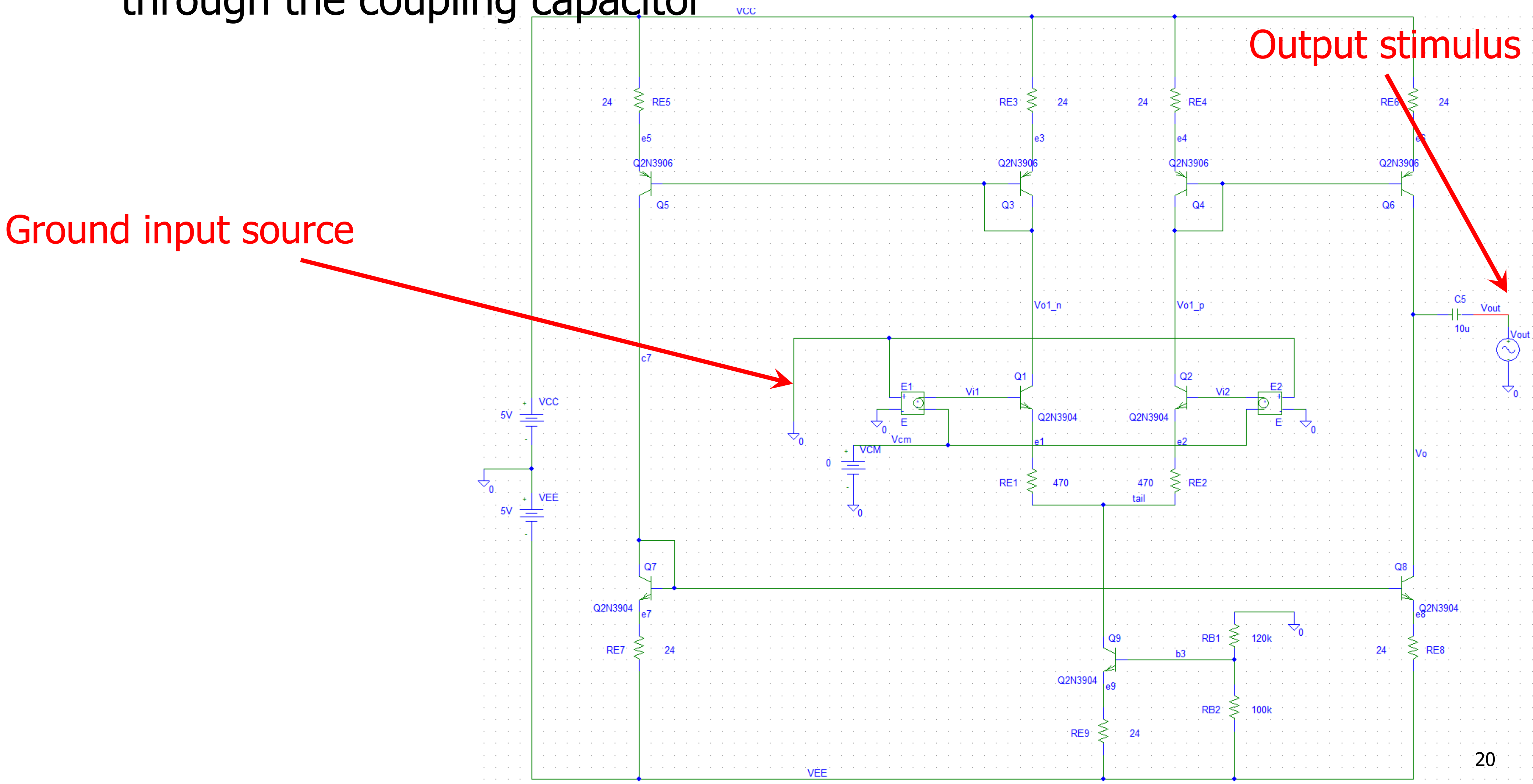
DC COMPONENT = 1.410955E-04

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	1.000E+03	4.067E-03	1.000E+00	-5.759E-03	0.000E+00
2	2.000E+03	4.976E-06	1.223E-03	-8.956E+01	-8.954E+01
3	3.000E+03	1.330E-05	3.270E-03	1.798E+02	1.798E+02
4	4.000E+03	7.584E-07	1.865E-04	-9.070E+01	-9.067E+01
5	5.000E+03	8.260E-07	2.031E-04	-1.791E+02	-1.791E+02

TOTAL HARMONIC DISTORTION = 3.502601E-01 PERCENT

Simulating Output Resistance

- Ground input source and apply an AC-coupled voltage stimulus at output
- With output source AC=1, plot the ratio of V(Vout) over the current through the coupling capacitor



Simulating R_o

- The output resistance is equivalent to the output stimulus V(Vout) divided by the output current, which is equal to the current through the output capacitor I(C5)
- $R_o = 25.4k\Omega$