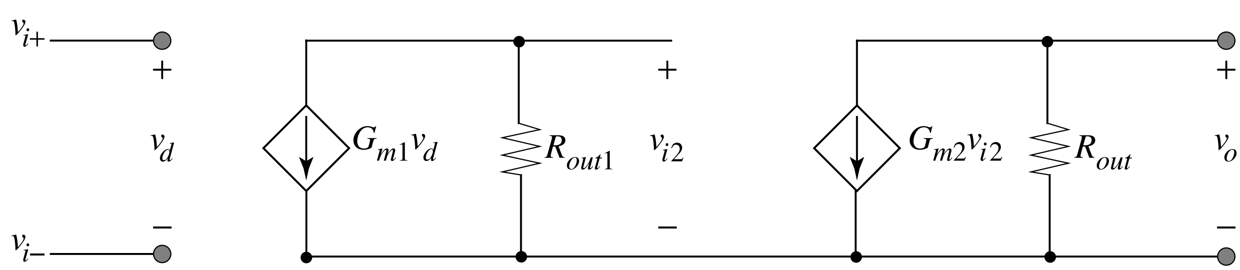
Small-Signal Analysis of CMOS Two-Stage Op Amp

- Cascade two-port models of differential amplifier with current-mirror supply (input stage) and common-source amplifier with current supply (second gain stage)



- First stage:

polarity of G_{m1} is inverted to reflect reversal of input terminals ... which is done to make the overall gain positive for $v_d > 0$

$G_{m1} = g_{m1}$

$R_{out1} = r_{o2} \parallel r_{o4}$

- Second stage:

$G_{m2} = g_{m5}$

$R_{out} = r_{o5} \parallel r_{o6}$

$$a_{vdo} = (-G_{m1}R_{out1})(-G_{m2}R_{out})$$

$$a_{vdo} = g_{m1}(r_{o2}||r_{o4})g_{m5}(r_{o5}||r_{o6})$$

Two-Stage CMOS Design Example

- Design constraints

  Typical situation for an internal op amp: area and power are both limited.

  Simplified area constraint -- set W_{max} = 150 µm

  (for minimize channel-length modulation, set L_{min} = 3 µm)

  Set DC power budget at 1.25 mW (including reference current) for case where we have symmetrical supplies: V^+ = 2.5 V and V^- = - 2.5 V.

- Initial Transistor Sizing:

  Make $(W/L)_1$ = (150 µm / 3 µm) in order to maximize G_{m1} and maximize common-mode input voltage range

  DC currents: assume I_{REF} = 50 µA

  Set DC bias current of differential amplifier = DC bias of common-source stage = 100 µA each as a first-cut --> total current drawn is 250 µA --> power spec. is just met

  Transistor dimensions: $(W/L)_5$ = (150 µm / 3 µm) to maximize g_{m5}

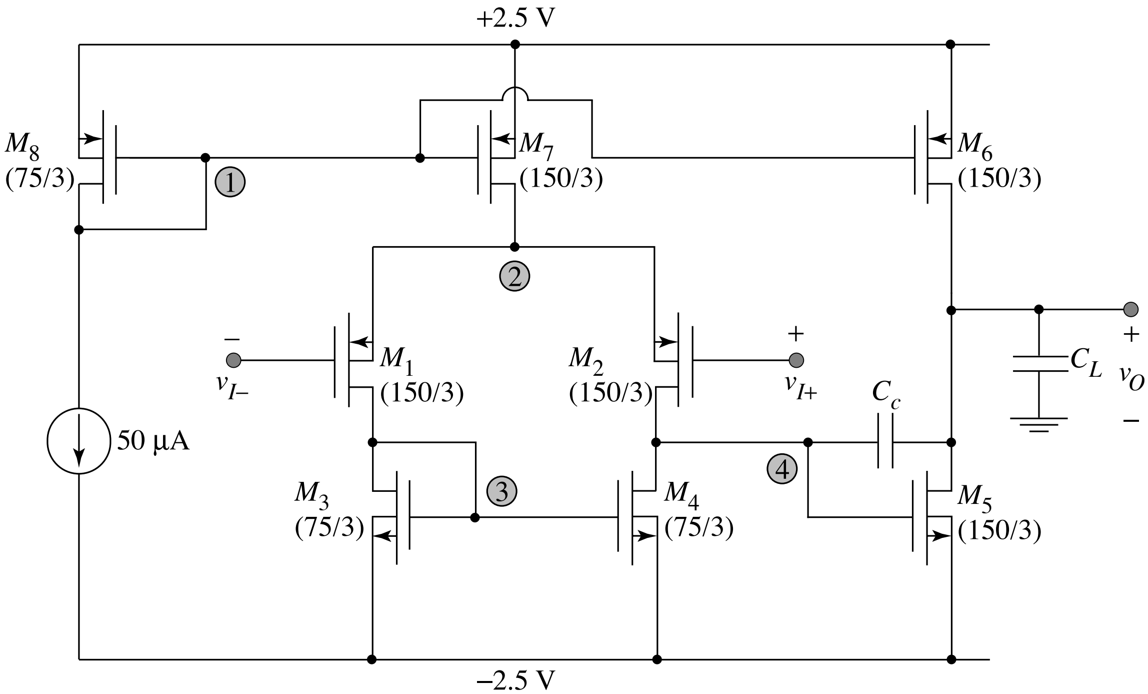
$$\frac{(W/L)_5}{2(W/L)_{3,4}} = \frac{-I_{D6}}{I_{D7}} = \frac{100\ \mu\text{A}}{100\ \mu\text{A}} = 1$$

  Therefore $(W/L)_{3,4} = (W/L)_5/2 = 25$ --> $W_{3,4}$ = 75 µm since we use L_{min} to save area.

  For symmetrical output swing, we set $(W/L)_6 = (W/L)_5$ = (150 µm / 3 µm)

  To maximize common-mode input range, we also set $(W/L)_7$ = (150 µm / 3 µm)

First-Cut CMOS Two-Stage Op Amp



n-channel MOSFET

$\mu_n C_{ox} = 50\ \frac{\mu A}{V^2}$	$t_{ox} = 15$ nm	$C_{ov} = 0.5$ fF/µm	$\phi_{Bn} = 0.95$ V
$V_{TOn} = 1.0$ V	$\lambda_n = \frac{0.1(\mu m/V)}{L}$	$C_{jno} = 0.1$ fF/µm^2	$m_{jn} = 0.5$
$\gamma_n = 0.6\ V^{1/2}$	$2\phi_p = -0.8$ V	$C_{jswno} = 0.5$ fF/µm	$m_{jswn} = 0.33$

p-channel MOSFET

$\mu_p C_{ox} = 25\ \frac{\mu A}{V^2}$	$t_{ox} = 15$ nm	$C_{ov} = 0.5$ fF/µm	$\phi_{Bp} = 0.95$ V
$V_{TOp} = -1.0$ V	$\lambda_p = \frac{0.1(\mu m/V)}{L}$	$C_{jpo} = 0.3$ fF/µm^2	$m_{jp} = 0.5$
$\gamma_p = 0.6\ V^{1/2}$	$2\phi_n = 0.8$ V	$C_{jswpo} = 0.35$ fF/µm	$m_{jswp} = 0.33$

DC Bias Solution

- Assume that the DC input voltages are $V_{I+} = V_{I-} = 0$ V and $V_O = 0$ V

- Input common-mode voltage range

$$V_{IC,max} = 2.5\text{ V} - (-1\text{ V}) - 1.28\text{ V} - 1.4\text{ V} = 0.82\text{ V}$$

$$V_{IC,min} = -2.5\text{ V} + 1.28\text{ V} + (-1\text{ V}) = -2.22\text{ V}$$

room for improvement in the upper limit -- possible at the expense of increased area (W/L) ratios must be increased.

- Output voltage swing

$$V_{O,max} = 2.5\text{ V} - 0.4\text{ V} = 2.1\text{ V}$$

$$V_{O,min} = -2.5\text{ V} + 0.28\text{ V} = -2.22\text{ V}$$

output range in nearly symmetrical and adequate

Small-Signal Performance

- Small-signal parameters:

$g_{m1} = g_{m2} = 357\ \mu S$

$g_{m5} = 2\ g_{m1} = 714\ \mu S$

$r_{o2} = r_{o4} = 600\ k\Omega$

$r_{o5} = r_{o6} = 300\ k\Omega$

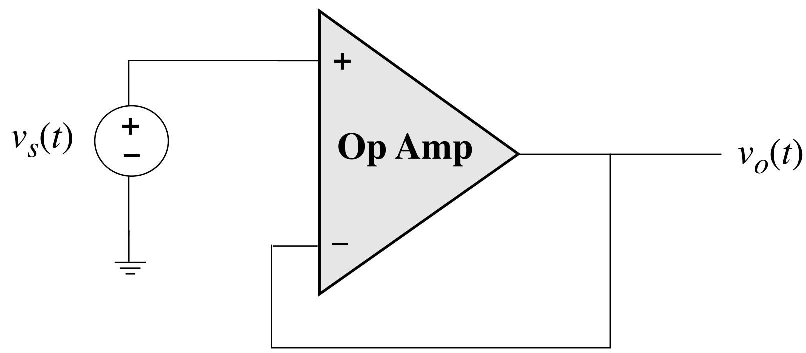
- Differential voltage gain:

$$a_{vdo} = (0.357)(600||600)(714)(300||300) = 1.15\times10^4$$

in decibels, $|a_{vdo}|_{dB} = 81$ dB.

Stability -- A Brief Introduction

- Non-inverting, unity gain configuration



$v_s(t) = v_s \sin(\omega_s t)$

Feedback is to negative terminal of op amp, which tends to stabilize the output voltage $v_o(t)$ to be nearly equal to $v_s(t)$

- What happens when the phase of $a_{vd}(j\omega_s) = 180^o$?

... the sign of a_{vd} is flipped! Consider + and - terminals to be reversed!

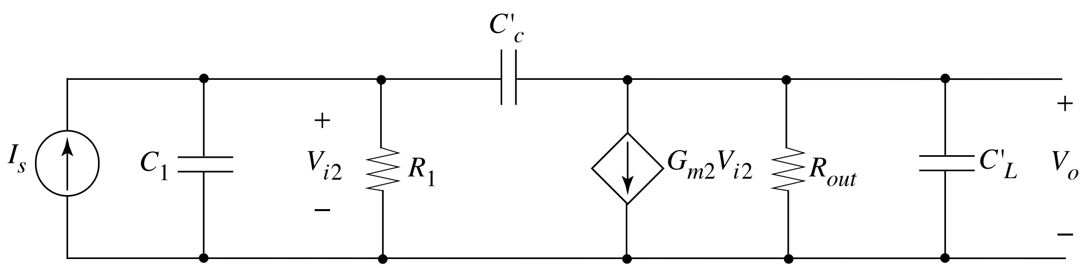
... if $|a_{vd}(j\omega_s)| > 1$, then the output is *destabilized* if the input is perturbed.

Ensuring Stability

- If the gain of the op amp is less than 1 (in magnitude) when the phase is 180^o, then the unity-gain non-inverting configuation (worst-case) will be stable
- One solution: locate the second pole of the op amp ω_2 at approximately the unity gain frequency

$$\omega_2 \approx a_{vdo} \omega_1$$

- The second gain stage is responsible for both poles



Device capacitances are lumped together in the circuit:

$$C_1 = C_{gs5} + C_{gd4} + C_{db4} + C_{gd2} + C_{db2}$$
$$C_L' = C_L + C_{db5} + C_{db6} + C_{gd6}$$
$$C_c' = C_c + C_{gd5}$$

The *compensation capacitor* C_c sets the dominant pole ω_1 by the Miller effect:

$$\omega_1^{-1} \approx R_1 C_1 + R_1 (1 + G_{m2} R_{out}) C_c'$$

where $R_1 = R_{out1}$

Second Pole Location

- Direct factoring of transfer function --> “exact” expression for ω_2

  For the case when $C_1 \ll C_c', C_L'$

$$\omega_2 \approx G_{m2}/C_L' = \frac{1}{(1/G_{m2})C_L'}$$

- Interpretation:

  At frequencies around ω_2 (>> ω_1), the impedance $Z_c = (1 / j\omega_2 C_c)$ is small enough that M_5 can be considered diode-connected

  Load capacitance sees a Thévenin resistance of $1 / g_{m5}$ -->

  ω_2 is set by the load capacitance in parallel with $1 / g_{m5}$

- Adjusting compensation and load capacitors to satisfy $\omega_2 \approx a_{vdo}\omega_1$

$$\omega_2 \approx \frac{G_{m2}}{C_L'} \approx \frac{(G_{m1}R_{out1})(G_{m2}R_{out})}{R_1C_1 + R_1(1 + G_{m2}R_{out})C_c'} \approx \frac{(G_{m1}R_{out1})(G_{m2}R_{out})}{G_{m2}R_1R_{out}C_c'}$$

since $G_{m2}R_{out} >> 1$

$$C_c' \approx C_L'\left(\frac{G_{m1}}{G_{m2}}\right)$$

Capacitor Sizing

- The load capacitor is set by system specifications: $C_L = 7.5$ pF

  with parasitic capacitances --> $C_L{}' = C_L + 350 \text{ fF} = 7.85 \text{ pF}$

- The compensation capacitor is approximately

$$C_c{}' \approx \left(\frac{357\ \mu\text{S}}{714\ \mu\text{S}}\right) C_L{}' = 3.9 \text{ pF}$$

  the "exact" result is significantly higher ... $C_c{}' = 5.3 \text{ pF}$

- Area requirement with a 500 Å thick oxide is less than 100 x 100 μm^2 --> not a significant addition to the op amp area

- Pole locations:

  $\omega_1 = 5.8 \text{ krad/s}$ $\omega_2 = 67.2 \text{ Mrad/s}$

- SPICE: must increase C_c to 20 pF in order to have $\omega_2 \approx a_{vdo}\omega_1$

  $\omega_1 = 1.3 \text{ krad/s}$ $\omega_2 = 10.4 \text{ Mrad/s}$