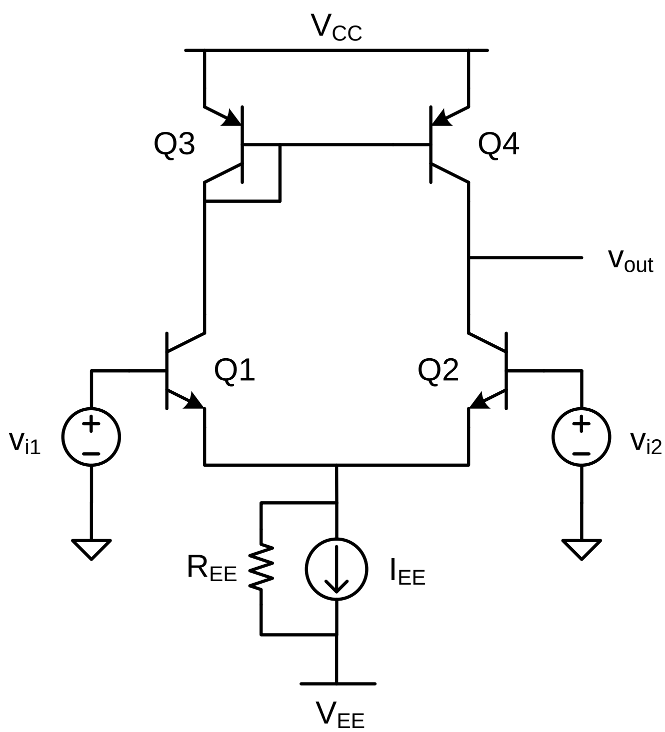
16 Differential amplifier with active load

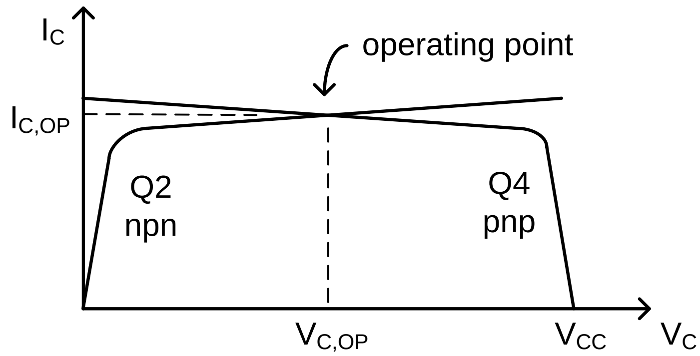
An emitter coupled pair used for a differential amplifier can be adapted to an active load in a relatively simple way. The collector resistors are replaced by a current mirror, one side of the differential amp to the input side of the current mirror and the other side of the differential amp to the output side of the current mirror. The resistor that sets the current level for the current mirror is absent since that is done by the current demanded by the left side of the differential amp. The output is single-ended.



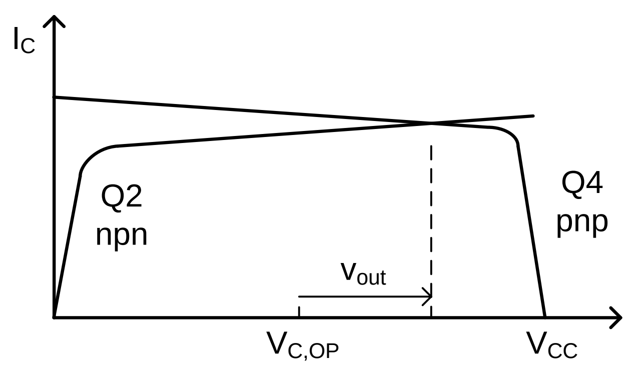
Q1 and Q2 are the differential pair and Q3 and Q4 form a pnp current source.

For zero input, $v_{i1} = v_{i2} = 0$, current I_{EE} plus additional current through R_{EE} is split equally between Q1 and Q2. Then Q3 with the base-collector short (diode connection) adjusts to supply Q1 exactly the current it demands. Q4 supplies the same current to Q2 and all transistors operate in active mode. The Q2-Q4 collector connection at the output will have a voltage somewhere between the saturation points of Q2 (on the low end) and Q4 (on the high end).

The pnp load line on the npn operating curve looks like the following. In the graph, $I_{C,OP}$ and $V_{C,OP}$ are DC operating point values for the Q2-Q4 collector connection.

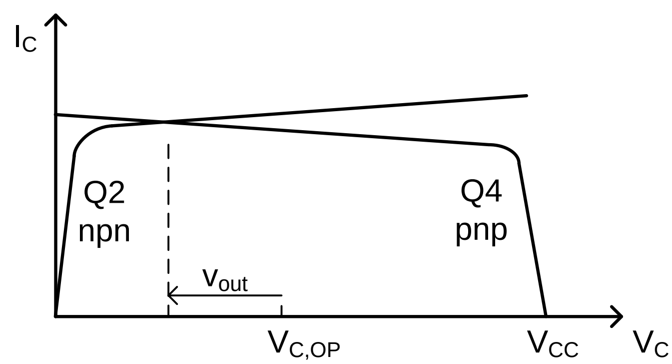


When a differential input is applied to the amplifier, current is shifted between Q1 and Q2. For example, if $v_{i1} > v_{i2}$, Q1 collector current is increased and Q2 collector current is decreased by about the same amount as some of the current from Q2 is shifted to Q1. In response to the increased current in Q1, Q3 will adjust to supply that current and Q4 will mirror that increase. But Q2 collector current has decreased due to the differential input. So we have Q4 delivering more current than Q2 demands. The result is that the voltage on the Q2-Q4 collector connection will rise to again balance the currents, turning off some of the Q4 current and turning on additional Q2 current. On the load line plot, the situation looks like this.



The Q2 characteristic curve has shifted down in the graph because Q2 has a smaller base and collector current while the Q4 characteristic curve is moved up in response to the larger current in Q4 which mirrors Q3. The intersection of the characteristic curves is the Q2-Q4 collector voltage. The small signal output, v_{out}, is the change in the collector voltage measured from the bias point, $V_{C,OP}$. v_{out} is positive in this case and Q2 has a larger collector-emitter voltage while Q4 is driven toward saturation.

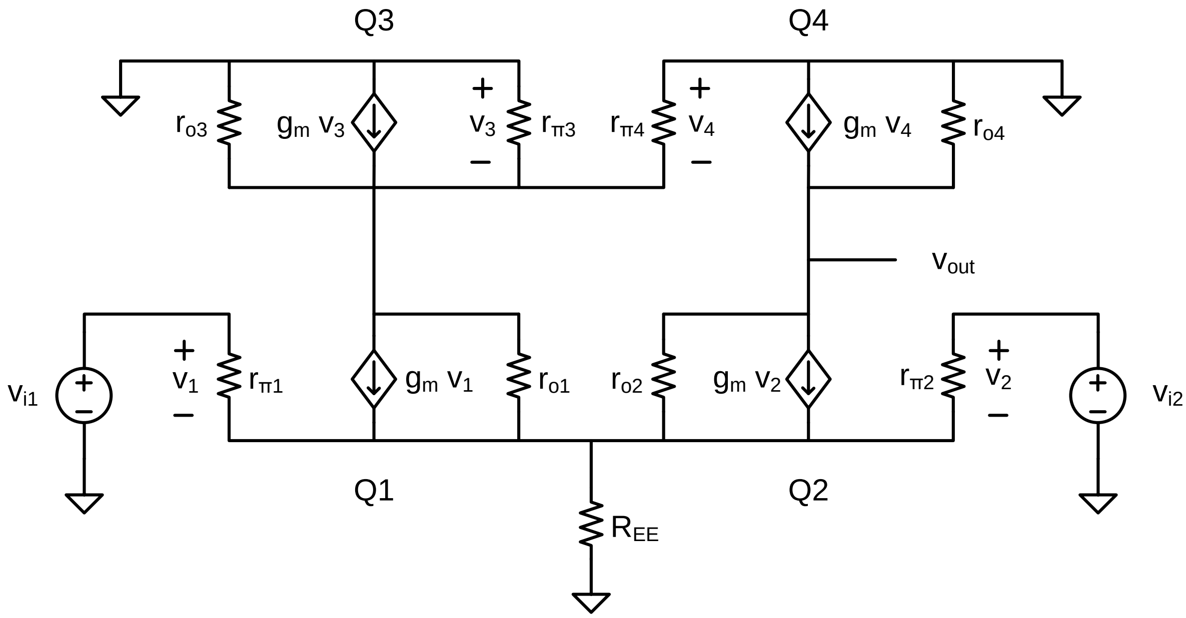
In the opposite case, $v_{i1} < v_{i2}$, Q4 delivers <u>less</u> current than Q2 demands.



The characteristic curve for Q4 is moved lower while that for Q1 moves up, pushing the intersection to the left. v_{out} is negative.

The relatively small slope to the I_C vs. V_{CE} curves for BJTs (slope = $1/r_o$ where r_o is typically 10's of kΩ) provides a large voltage gain for this amplifier. The intersection of the characteristic curves moves left and right with little differential input voltage and change in collector currents. The active load of the differential amplifier has a dynamic resistance of r_o, the pnp transistor output resistance, and we would expect a voltage gain of something like $g_m r_o$.

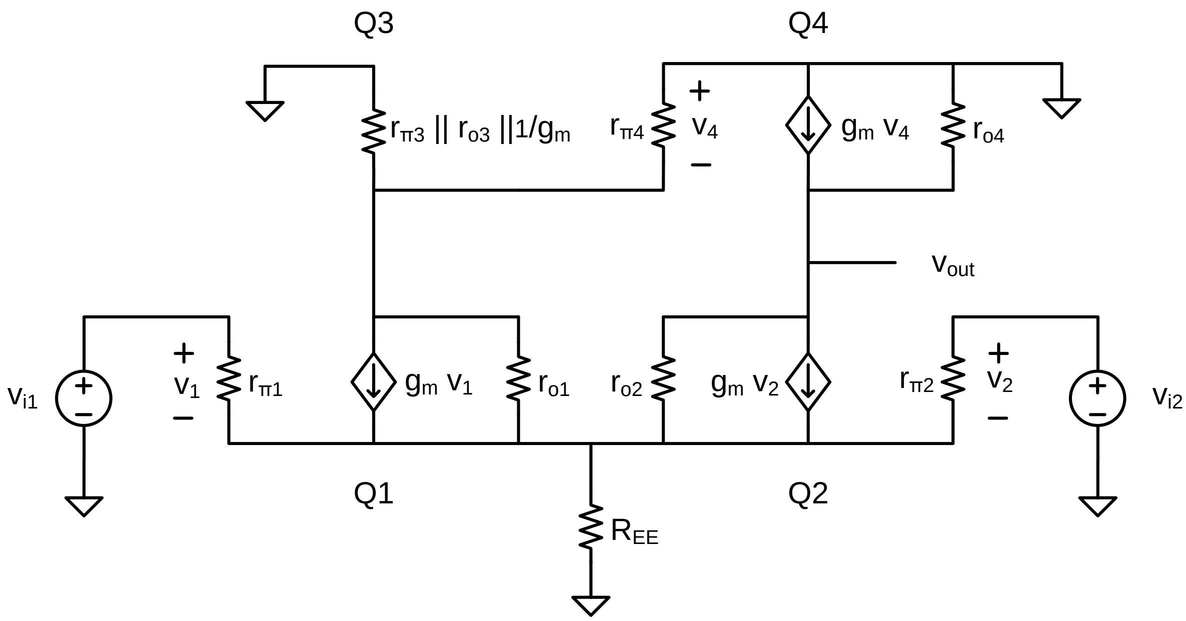
The small signal circuit is shown below. There is no differential half circuit, unlike our original differential amplifier because this circuit is <u>not</u> symmetrical. Note that all transistors have the same bias collector current making g_m the same for all transistors. It is also true that both npn transistors have the same r_π and r_o (although they are designated separately), but these are not the same as those parameters for the pnp transistors. Also note the base to collector connection of Q3.



The analysis of this circuit is somewhat complicated and we will not try to get an algebraic solution for the various amplifier parameters. But we can understand, semi-quantitatively, how the circuit functions.

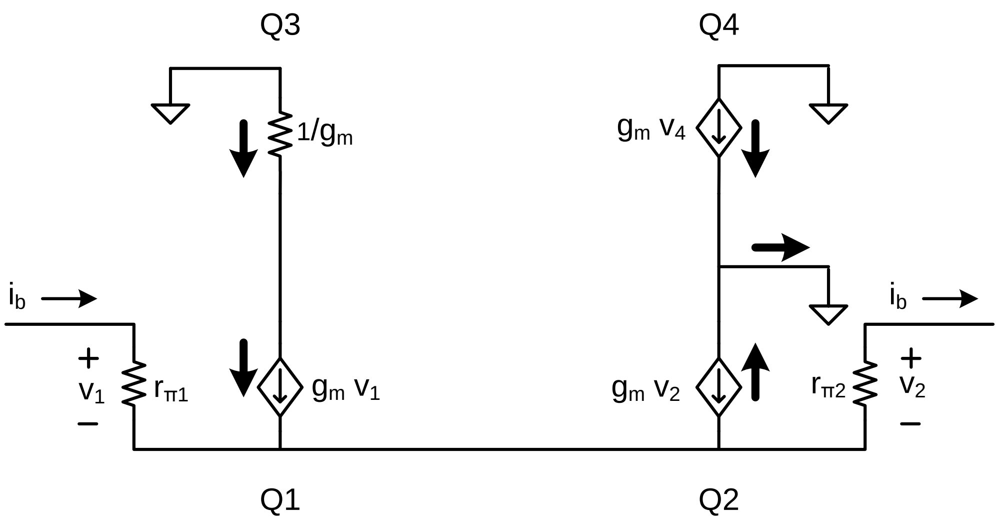
The Q3 base-collector connection is something that we previously encountered in discussing current mirrors. As we noted in that case, because the dependent source, $g_m v_3$, is controlled by the voltage across the source itself, the current source looks just like a resistor with resistance, $1/g_m$. The emitter to base-collector connection of Q3 is then a parallel combination of three resistors, $r_{\pi 3}$, r_{o3}, and $1/g_m$. It is generally true that $1/g_m$ is a much smaller resistance than r_π and r_o and dominates the parallel resistors forming a low resistance path to ground for the Q1 collector.

It is easy to see why Q3 responds to any change in the Q1 demand for current. Q3 is just a small resistor.



Also, because Q3 and Q4 form a current mirror, any change in the current in Q3 will be mirrored in Q4. The dependent current sources of Q3 and Q4 are controlled by the voltages across $r_{\pi 3}$ and $r_{\pi 4}$, respectively, which is the same voltage due to the base connection between Q3 and Q4.

Now to find the small signal behavior of the circuit for differential input, we identify the primary differential mode currents in the diagram below. We assume $v_{i1} > v_{i2}$ and ground the output.



For pure differential input, $v_{i1} = - v_{i2} = ½\, v_{i,dm}$, the coupled emitter node remains near zero, and we ignore R_{EE}.

To find the input resistance, base current, i_b, flows through $r_{\pi1}$ and $r_{\pi2}$ and we have

$$R_{in,dm} = r_{\pi1} + r_{\pi2}$$

For differential mode transconductance, we use the same small signal circuit with the output grounded. The equal base currents in $r_{\pi1}$ and $r_{\pi2}$ cause equal (but opposite) small signal collector currents in Q1 and Q2, indicated by heavy arrows. Q1 is supplied by Q3 and Q4 mirrors Q3. So we have all four current sources with equal magnitude currents. Then for the transconductance, we have, by definition,

$$G_{m,dm} = i_{out,\text{ short circuit}} / v_{i,dm}$$

The short circuit current at the output comes from Q2 and Q4.

$$\begin{aligned} i_{out,\text{ short circuit}} &= - g_m v_2 + g_m v_4 \\ &= - 2\, g_m v_2 \\ &= 2\, g_m v_1 \end{aligned}$$

The differential mode input is given by

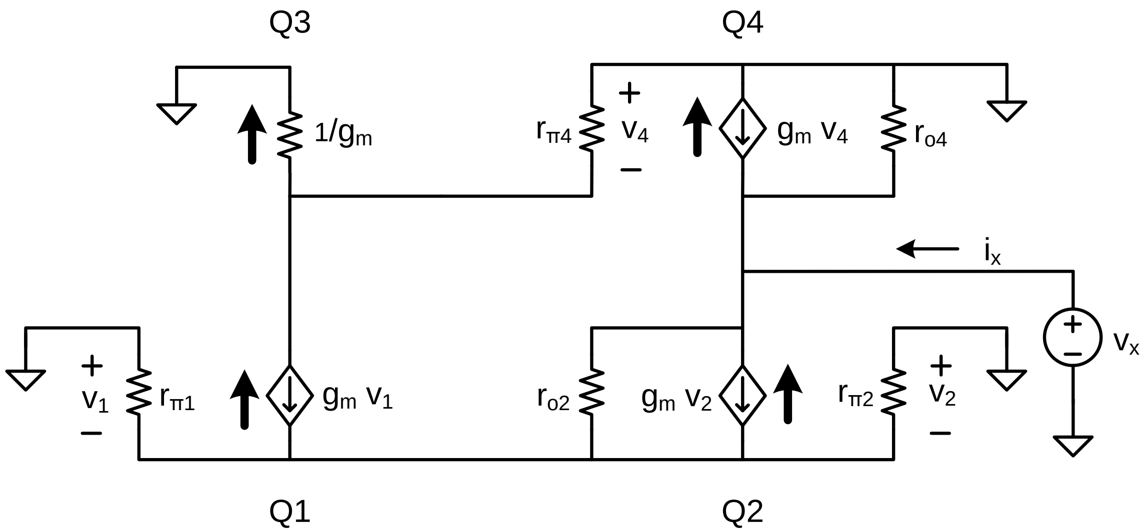
$$\begin{aligned} v_{i,dm} &= v_{i1} - v_{i2} \\ &= 2\, v_{i1} = 2\, v_1 \end{aligned}$$

Finally, we get

$$\begin{aligned} G_{m,dm} &= i_{out,\text{ short circuit}} / v_{i,dm} \\ &= 2\, g_m v_1 / 2\, v_{i1} = g_m \end{aligned}$$

The transconductance of the amplifier in differential mode is just g_m.

The output resistance is found from the following circuit.



The test voltage, v_x, is applied to the output with inputs grounded. Current, i_x, flows both toward Q2 and Q4. Current flowing from v_x toward Q2 finds a path to ground through r_{o2} and then $r_{\pi1}$ and $r_{\pi2}$ in parallel. Since r_{o2} is typically much larger than the base resistor parallel combination, $r_{\pi1} \| r_{\pi2}$, the coupled emitter node of Q1 and Q2 remains near ground and we can ignore R_{EE}. Also, r_{o1} is much larger than $r_{\pi1} \| r_{\pi2}$ and we ignore that resistance, as well. The currents in the four dependent current sources are again equal. The total current supplied by the test voltage is what passes through r_{o2} and r_{o4} to ground. Then the output resistance is very nearly just

$$R_{out,dm} = r_{o2} \| r_{o4}$$

Finally, the differential voltage gain is

$$\begin{aligned} A_{v,dm} &= G_{m,dm} \cdot R_{out,dm} \\ &= g_m\, r_{o2} \| r_{o4} \end{aligned}$$

For common mode input, the coupled emitter node is raised nearly by the amount of the input voltage and all four current sources conduct small but equal currents. The effect at the output is very small.

Example 16-1

Find the differential mode input and output resistance and the open circuit voltage gain for an npn differential amplifier with pnp active load where $I_C = 1$ mA, $\beta_{npn} = 220$, $V_{A,npn} = 104$ V, and $V_{A,pnp} = 114$ V. Simulate this circuit with B2spice using 2N2222 npn's and 2N4402 pnp's and compare to calculated results.

Solution:

Calculated results.

$$r_{\pi,npn} = \beta_{npn} V_t / I_C$$
$$= 220 \bullet .026 \text{ V} / 1 \text{ mA} = 5.7 \text{ k}\Omega$$
$$R_{in,dm} = 2\, r_{\pi,npn}$$
$$= 11.4 \text{ k}\Omega$$

$$r_{o,npn} = V_{A,npn} / I_C$$
$$= 104 \text{ V} / 1 \text{ mA} = 104 \text{ k}\Omega$$
$$r_{o,pnp} = V_{A,pnp} / I_C$$
$$= 114 \text{ V} / 1 \text{ mA} = 114 \text{ k}\Omega$$
$$R_{out,dm} = r_{o,npn} \,||\, r_{o,pnp}$$
$$= 54 \text{ k}\Omega$$

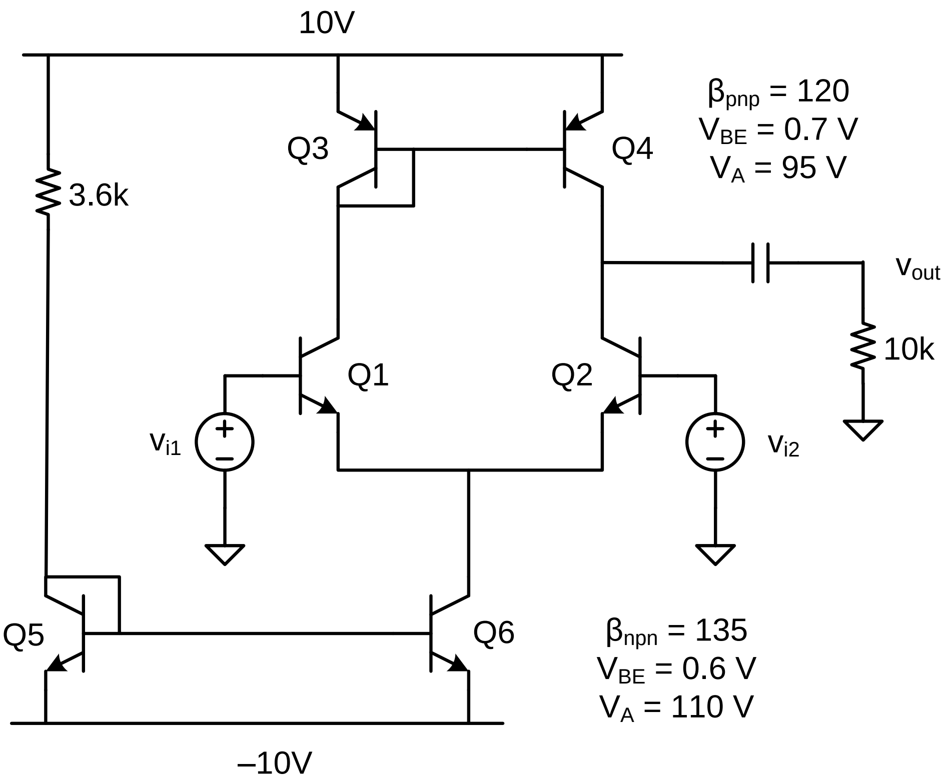
$$G_{m,dm} = g_m = I_C / V_t$$
$$= 1 \text{ mA} / .026 \text{ V} = 38 \text{ mA/V}$$

$$A_{v,dm} = G_{m,dm} R_{out,dm} = 38 \text{ mA/V } 54 \text{ k}\Omega = 2050$$

A B2spice simulation gives the results, $R_{in,dm} = 11.8$ kΩ, $R_{out,dm} = 57$ kΩ and $A_{V,dm} = 2150$. Also by simulation, common mode gain is much less than one. The CMRR of this amplifier is, consequently, very high.

Example 16-2

Find the differential mode open circuit gain and the overall gain for this differential amplifier.



Solution:

The Q5 and Q6 current mirror provides emitter current to the differential amplifier.

$$I_{EE} = (20\ \text{V} - 0.6\ \text{V}) / 3.6\ \text{k}\Omega = 5.4\ \text{mA}$$

The Q1 and Q2 collector current is then

$$I_C = \tfrac{1}{2} \bullet 5.4\ \text{mA} = 2.7\ \text{mA}$$

For Q1 and Q2

$$g_{m,npn} = 2.7 \text{ mA} / .026 \text{ V} = 104 \text{ mA/V}$$

$$r_{\pi.npn} = 135 / 104 \text{ mA/V} = 1.3 \text{ k}\Omega$$

$$r_{o,npn} = 110 / 2.7 \text{ mA} = 41 \text{ k}\Omega$$

For Q3 and Q4

$$g_{m,pnp} = 2.7 \text{ mA} / .026 \text{ V} = 104 \text{ mA/V}$$

$$r_{o,pnp} = 95 / 2.7 \text{ mA} = 35 \text{ k}\Omega$$

Then we have

$$R_{in,dm} = 2\, r_{\pi,npn} = 2 \bullet 1.3 \text{ k}\Omega = 2.6 \text{ k}\Omega$$

$$R_{out,dm} = r_{o,npn} \,||\, r_{o,pnp} = 41 \text{ k}\Omega \,||\, 35 \text{ k}\Omega = 19 \text{ k}\Omega$$

$$G_{m,dm} = g_m = 104 \text{ mA/V}$$

$$A_{V,dm} = G_{m,dm}\, R_{out,dm} = 1980$$

$$A_{overall} = A_{V,dm}\, R_L / (R_{out,dm} + R_L)$$

$$= 1980 \bullet 10 \text{ k}\Omega / 29 \text{ k}\Omega = 680$$
