Inverting the Bipolar Differential Pair for Low-Voltage Applications

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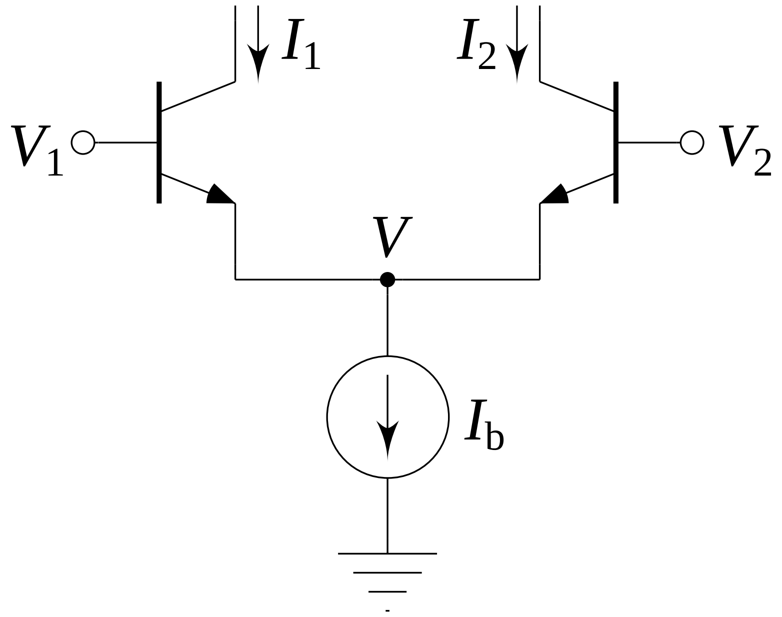
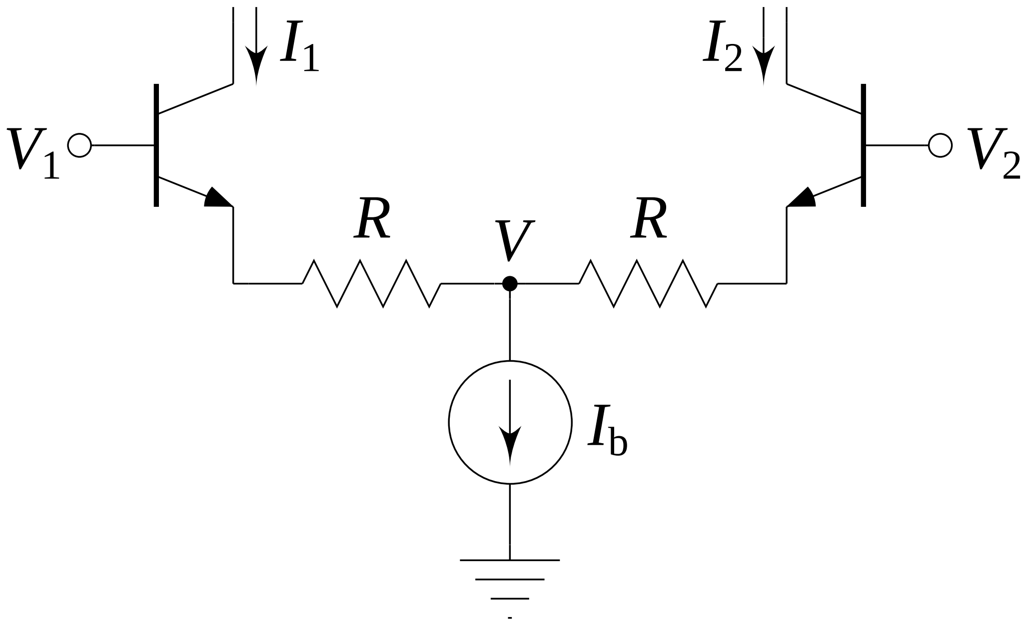
Differential Pairs

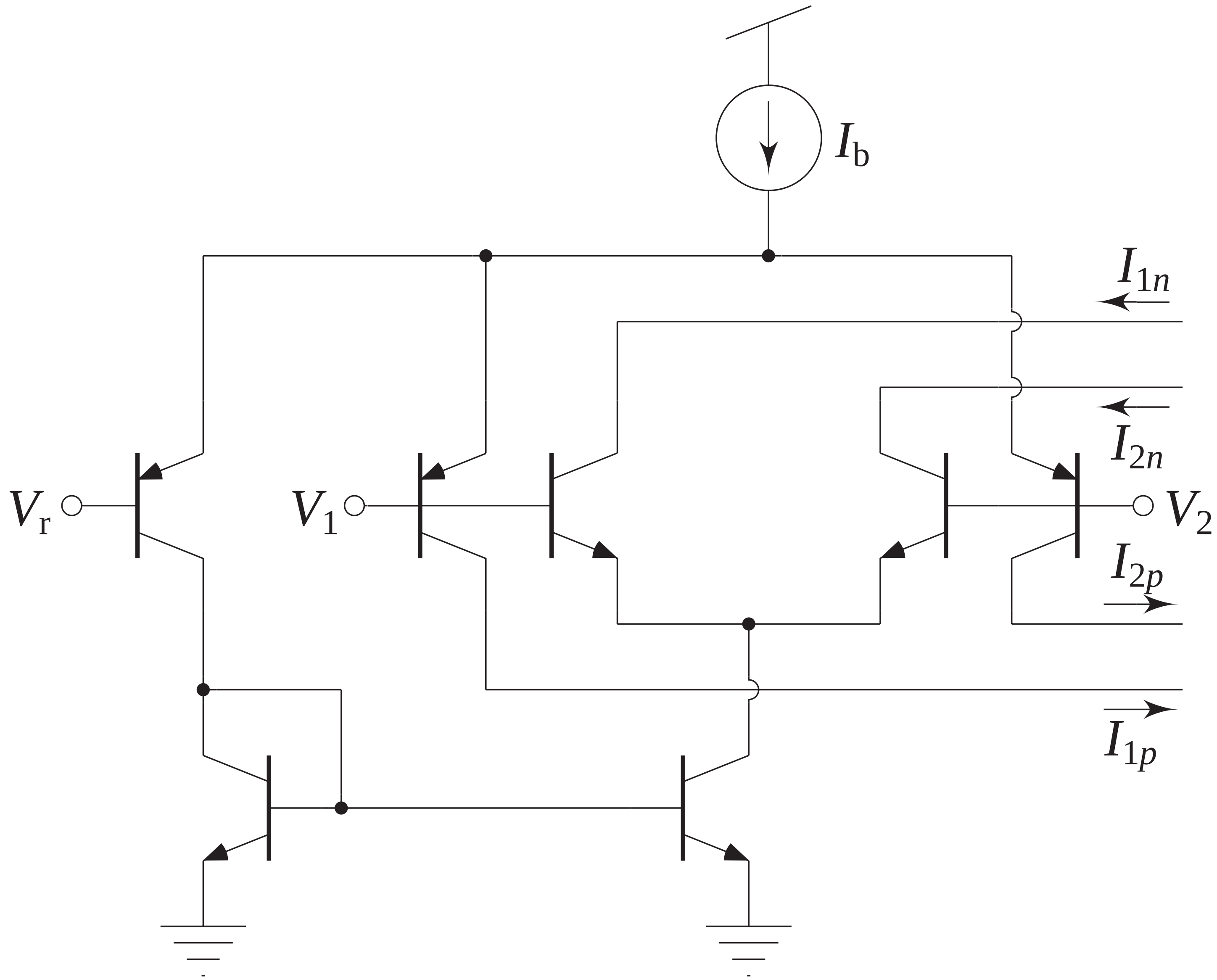
- The differential pair is used ubiquitously, but does not perform well with a low supply voltage.
- The minimum allowable V_{cm} is approximately $V_{\mathrm{diode}} + V_{\mathrm{CEsat}}$.
- To improve linearity, we introduce emitter-degeneration resistors, which increase the linear range from a few U_{T} to about $I_{\mathrm{b}}R$.
- However, the minimum allowable V_{cm} is also increased to about $V_{\mathrm{diode}} + I_{\mathrm{b}}R + V_{\mathrm{CEsat}}$.
- We present a new bipolar differential pair with comparable linearity for which this voltage is the minimum allowable supply voltage.





Conventional Rail-to-Rail Differential Input Stages

- The *pnp* differential pair has a complementary common-mode input-voltage range to the *npn* version.
- To build a rail-to-rail input stage, we can use a differential pair of each type, combining I_{1n} with I_{2p} and I_{2n} with I_{1p}.
- To get a constant differential transconductance, we must control the tail-currents.
- The minimum supply voltage for such a circuit is $2V_{\text{diode}} + 2V_{\text{CEsat}}$.



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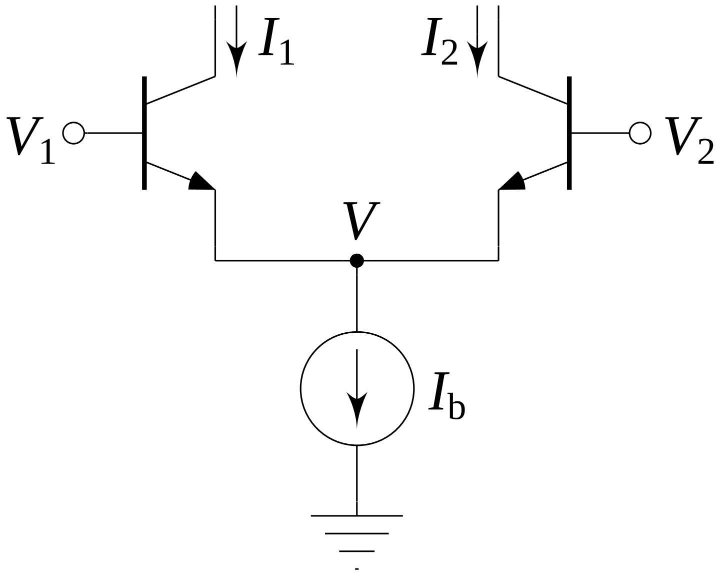
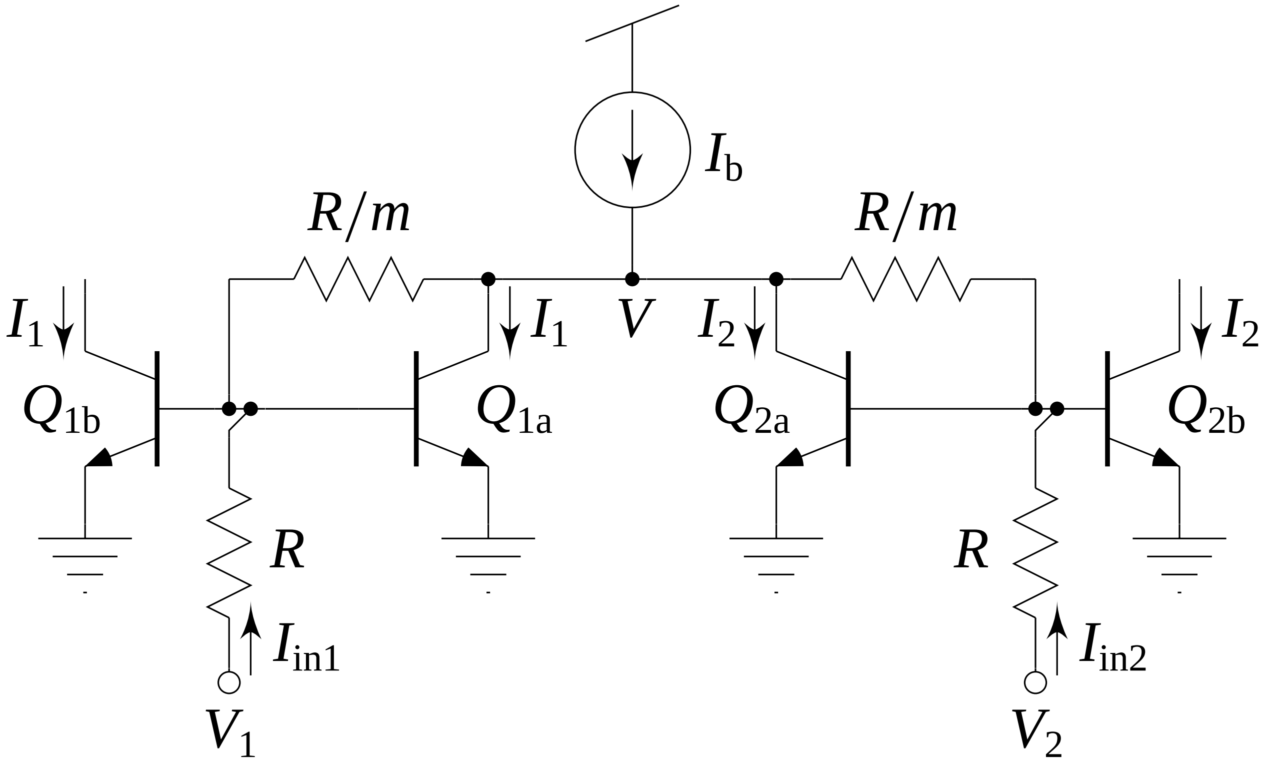
Inverted Differential Pair

- In the conventional differential pair, we maintain the transistors' transconductances nearly constant despite large changes in V_{cm} by keeping $I_1 + I_2 = I_{\mathrm{b}}$.
- A current comparison between $I_1 + I_2$ and I_{b} occurs implicitly at node V. V adjusts itself until $I_1 + I_2 = I_{\mathrm{b}}$.

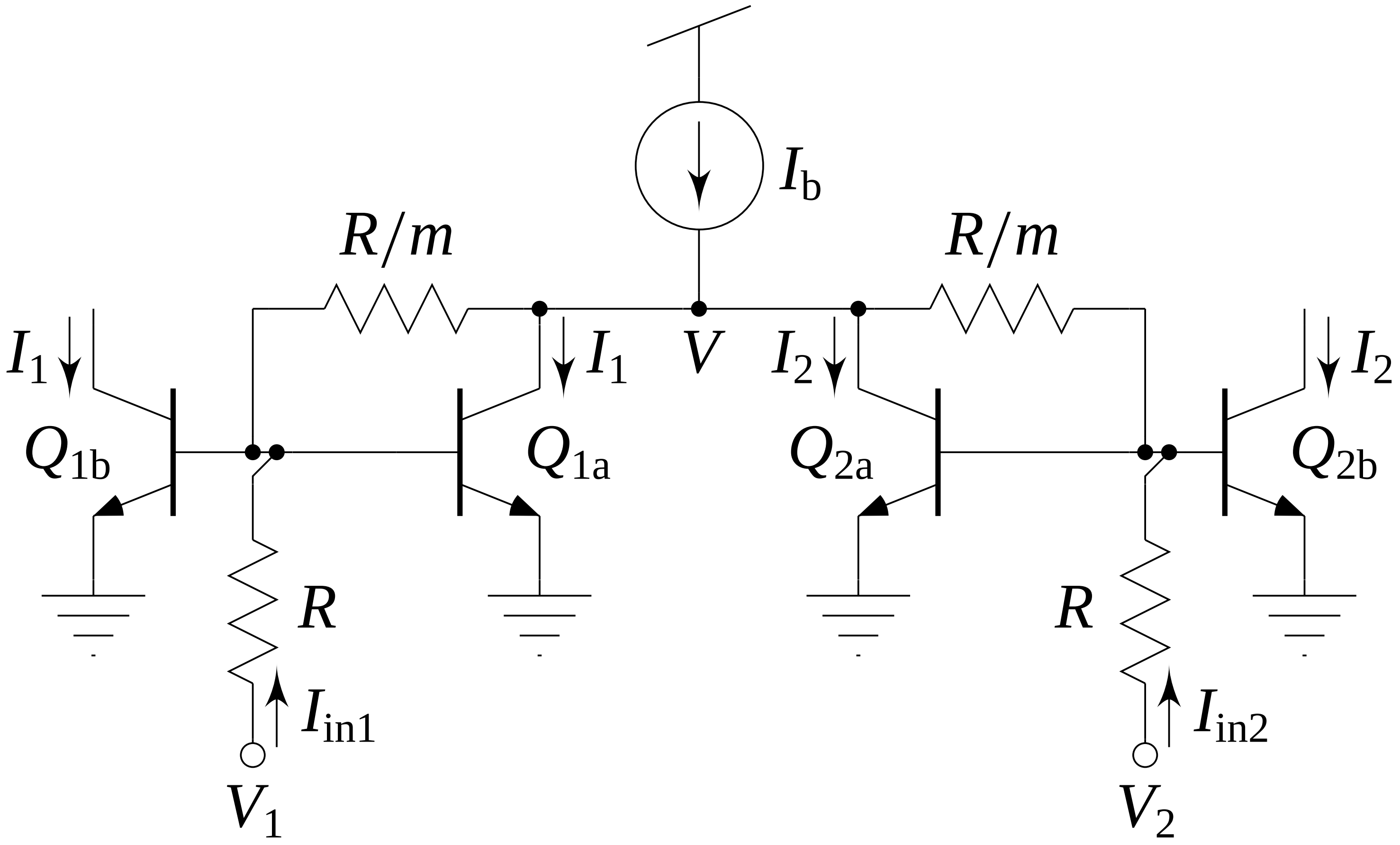


- In the *inverted differential pair*, we also maintain $I_1 + I_2 = I_{\mathrm{b}}$ using local feedback, except that we do so *indirectly* using replicas of the output currents.
- If the current flowing in the resistors is small, $I_1 + I_2 \approx I_{\mathrm{b}}$.



Inverted Differential Pair

- V attains its maximal value when V_{cm} is at its minimum.
- If V_{cm} increases, V decreases by about $1/m$ times as much to compensate the increase in $I_1 + I_2$.
- By making $m = 2$ or 3, we compress the swing on V, leaving ample headroom to keep $Q_{1\text{a}}$ and $Q_{1\text{b}}$ active.

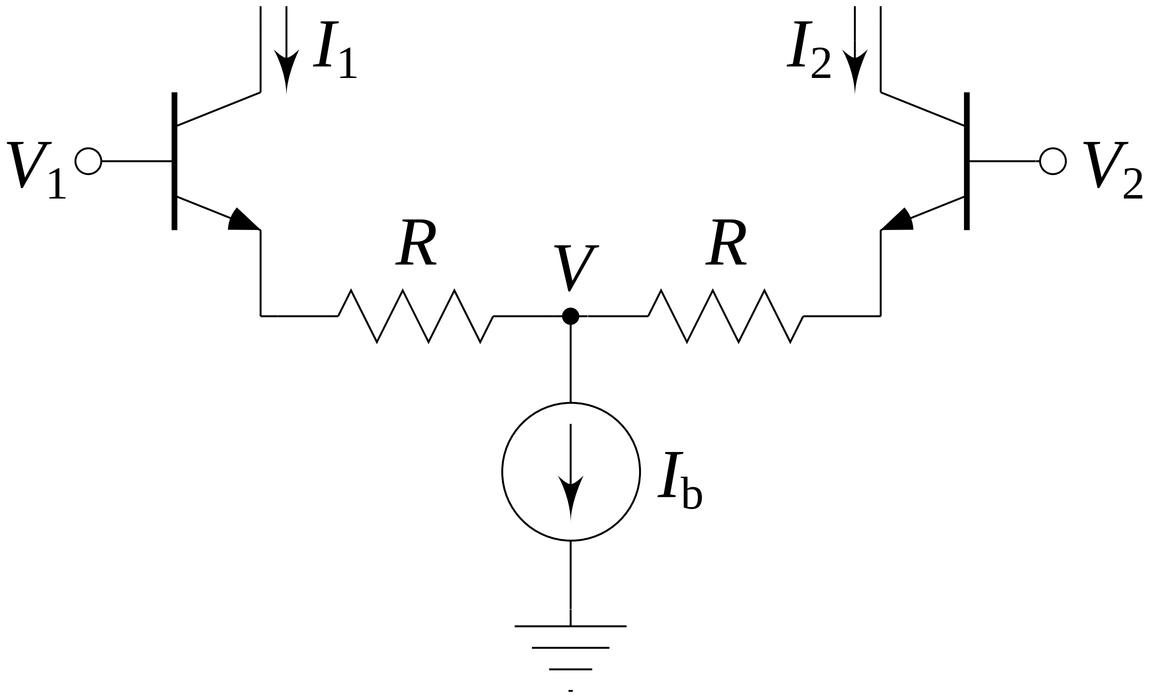


- $Q_{1\text{b}}$ and $Q_{2\text{b}}$ have their emitters at ground, permitting a wide output swing.
- The bases are fixed by feedback, making $R_{\text{in}} \approx R$. We can also use them as summing points, coupling in additional inputs.

Behaves Like an Emitter-Degenerated Differential Pair

- Emitter-degenerated differential pair

$$\begin{aligned} I_1 &= I_s e^{(V_1 - V)/U_T} e^{-\alpha I_1 R/U_T} \\ I_2 &= I_s e^{(V_2 - V)/U_T} e^{-\alpha I_2 R/U_T} \\ I_b &= \alpha \left(I_1 + I_2\right), \end{aligned}$$

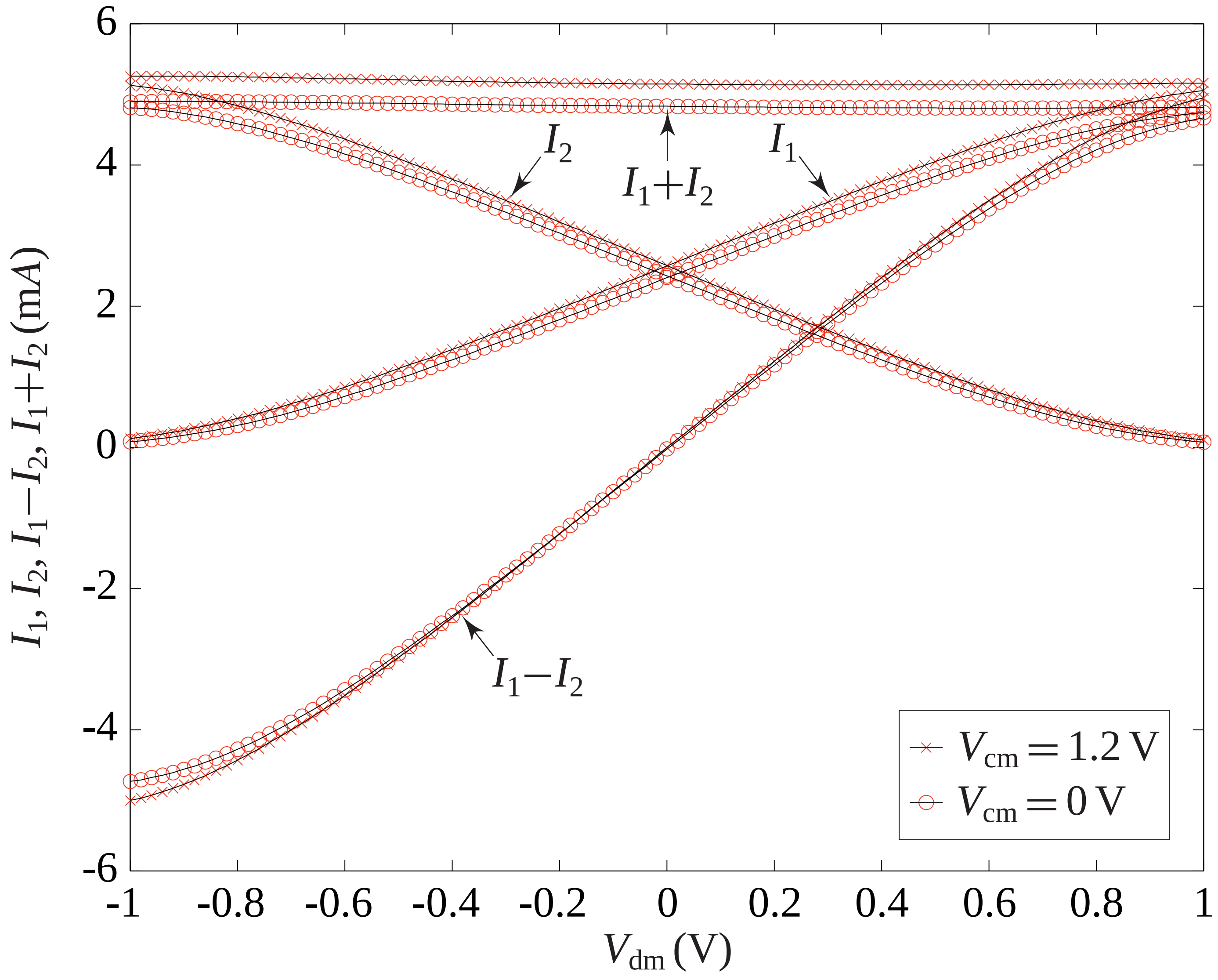


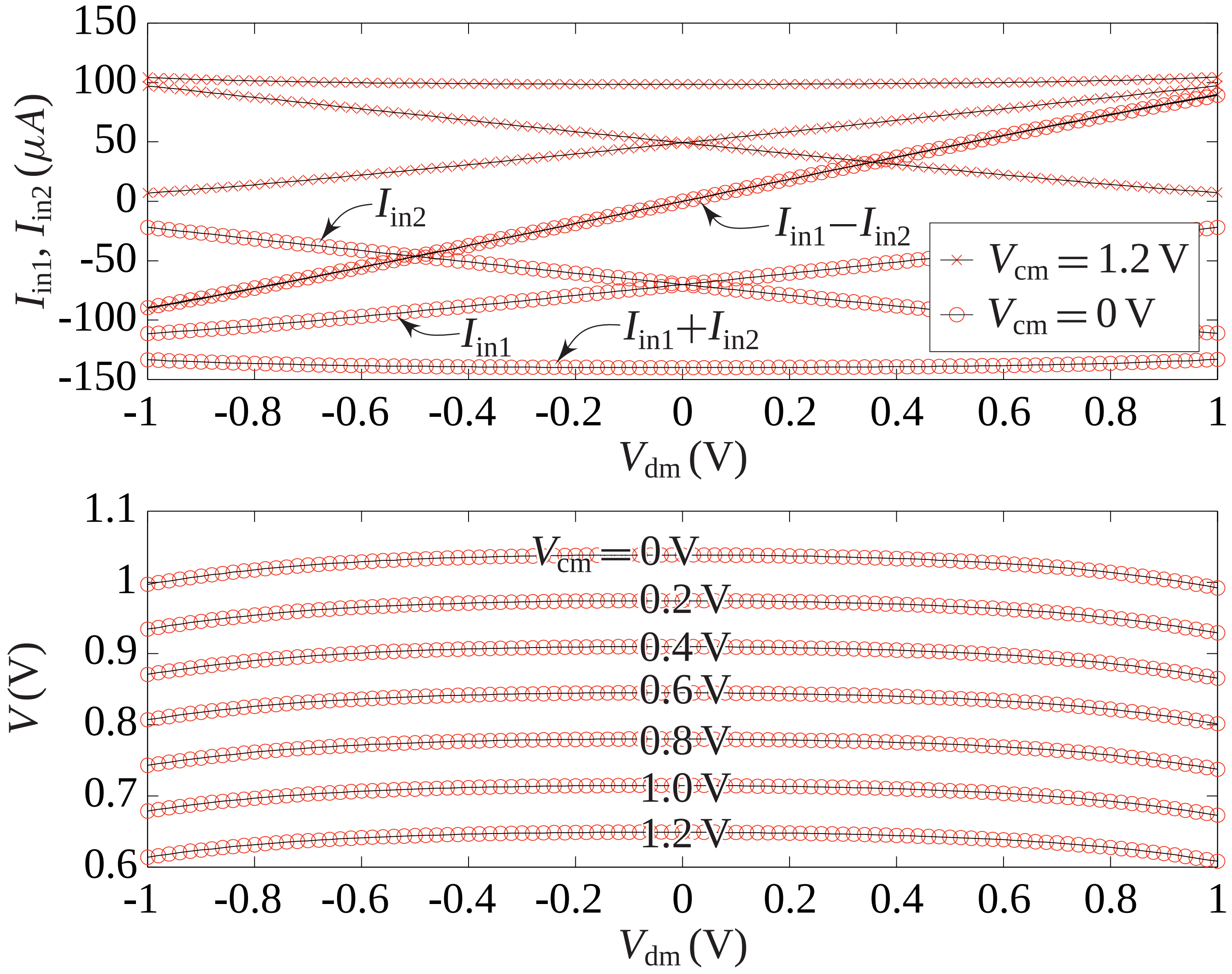
- Inverted differential pair

$$\begin{aligned} I_1 &= I_s e^{(V_1 + V)/(1+m)U_T} e^{-2 I_1 R/\beta(1+m)U_T} \\ I_2 &= I_s e^{(V_2 + V)/(1+m)U_T} e^{-2 I_2 R/\beta(1+m)U_T} \\ I_b &= \left(1 + \frac{2}{\beta}\right)\left(I_1 + I_2\right) - \left(I_{in1} + I_{in2}\right), \end{aligned}$$

- If $I_{in1,2} \ll I_b$, these systems are isomorphic with $-V \rightarrow V$, $U_T \rightarrow (1+m)\,U_T$, and $\alpha R \rightarrow 2R/\beta$.

Measured DC Characteristics with $I_b = 5\,\mathrm{mA}$ and $R = 10\,\mathrm{k\Omega}$





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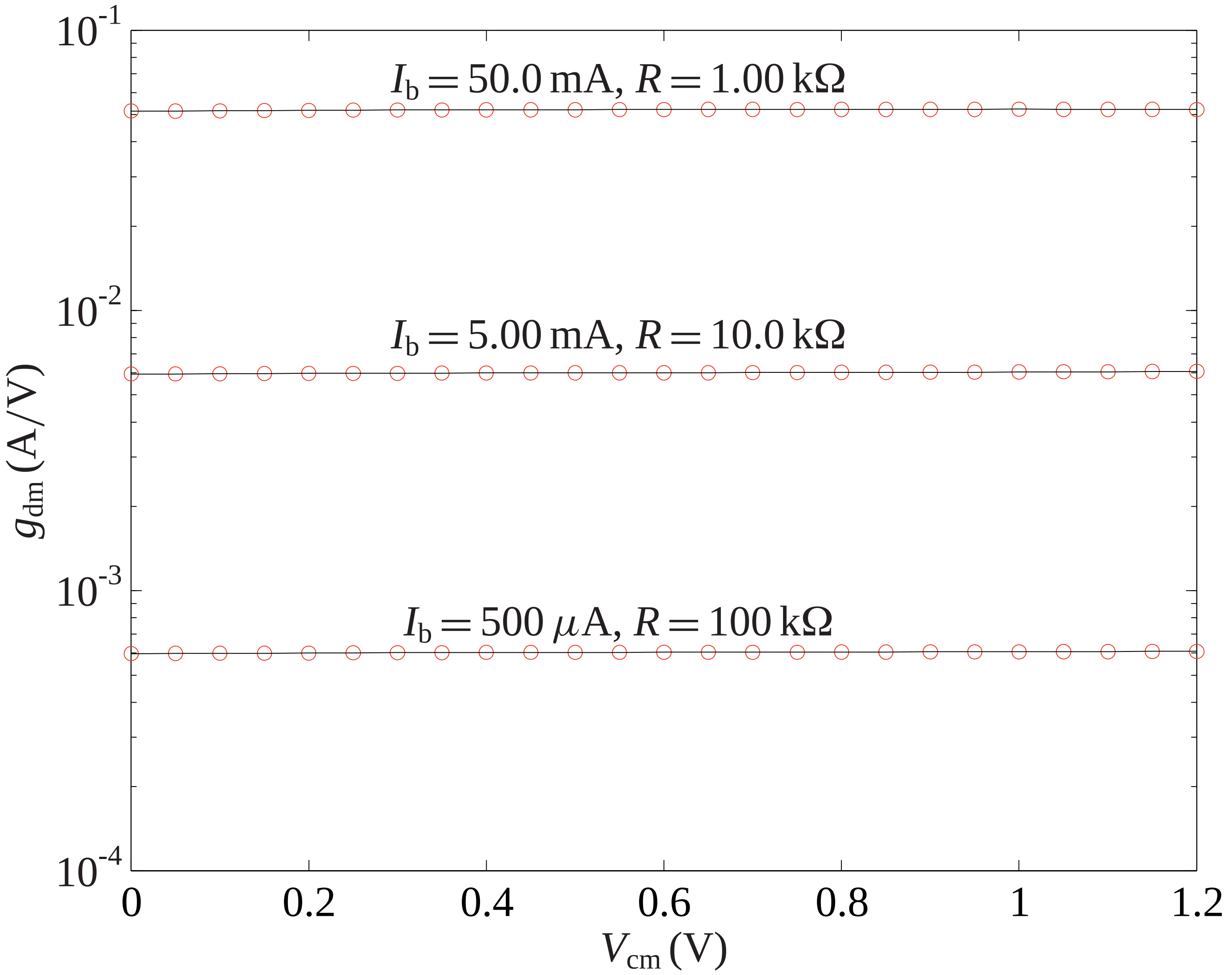
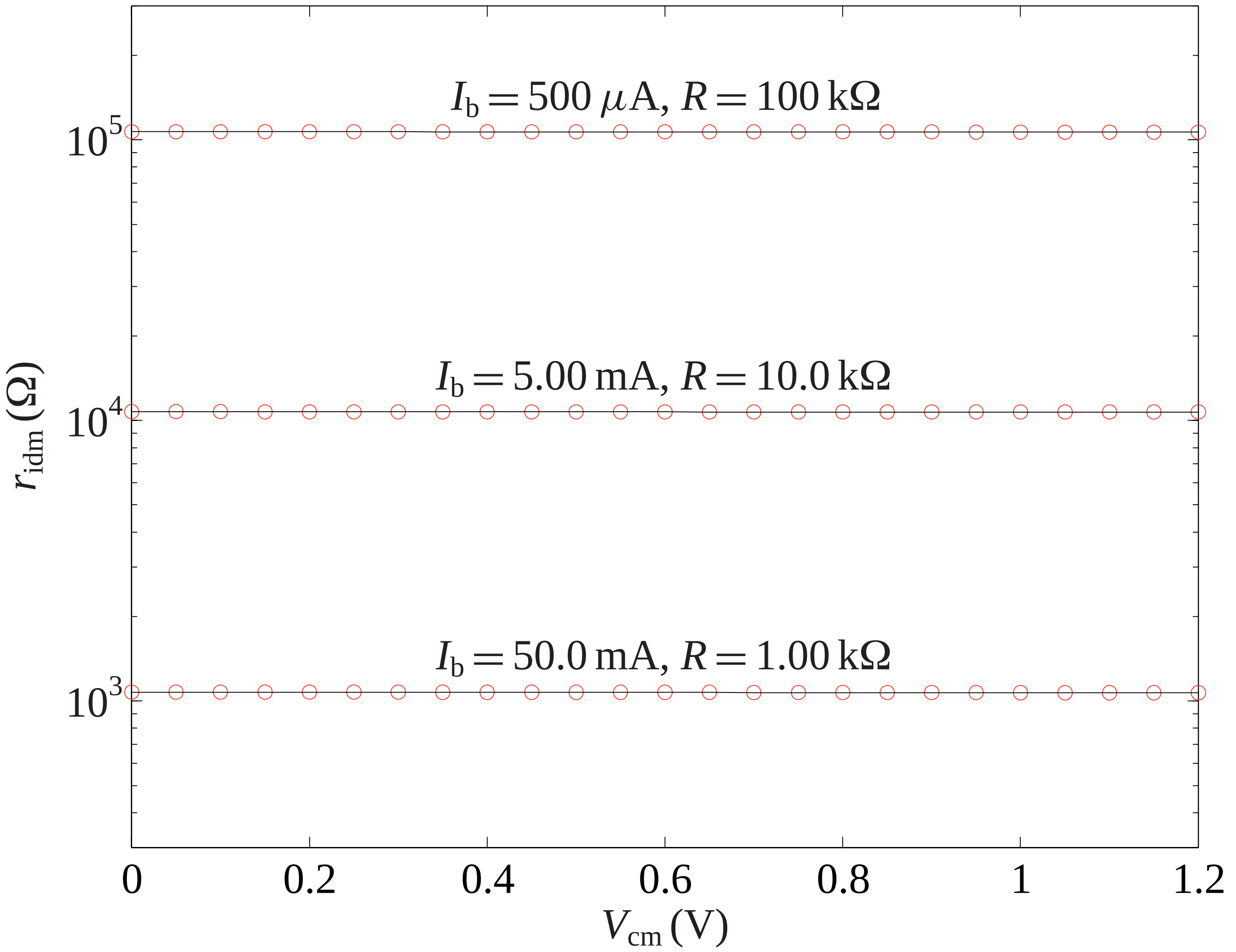
Measured Differential Transconductance Gain and Input Resistance





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Summary

We have presented a new bipolar differential transconductor that functions just like an emitter-degenerated differential pair except that it

- can operate on a low power supply voltage,
- has a rail-to-rail common-mode input-voltage range,
- permits a wide output-voltage swing,
- has a differential transconductance gain that is nearly independent of V_{cm}, and
- requires only *npn* transistors in the signal path.

We provided DC measurements from a prototype circuit, breadboarded from a quad TPQ3904 and a thick-film resistor array, demonstrating operation on a single-ended 1.2-V power supply.

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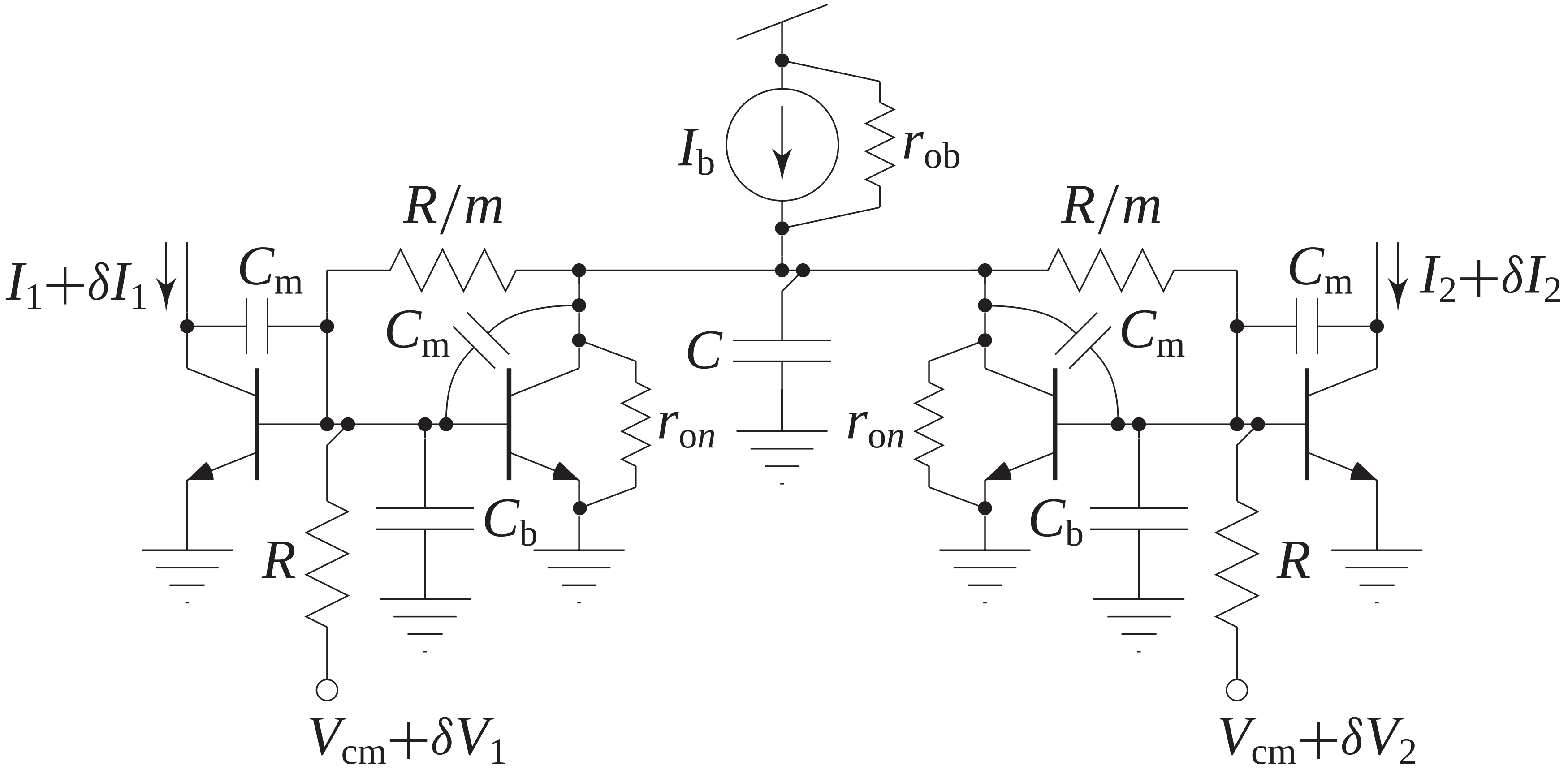
Inverted Differential Pair Frequency Response

- We use the circuit shown to the right to compute the frequency response of the inverted differential pair.
- Assuming that $C \gg C_\mathrm{m}$, $C_\mathrm{b} \gg C_\mathrm{m}$, $\beta \gg 1$, $g_\mathrm{m} R \gg 1$, and $g_\mathrm{m}\left(r_\mathrm{on} \| 2r_\mathrm{ob}\right) \gg 1$, we can show that



$$G_\mathrm{dm} \equiv \frac{\delta I_{1,2}}{\delta V_\mathrm{dm}} = \pm\frac{1}{2}\cdot\frac{g_\mathrm{m}}{1+m+2g_\mathrm{m}R/\beta}\cdot\frac{1-\tau_3 s}{1+\tau_1 s},$$

Inverted Differential Pair Frequency Response

$$G_{\mathrm{cm}} \equiv \frac{\delta I_{1,2}}{\delta V_{\mathrm{cm}}} = \frac{1}{m} \cdot \frac{1}{(R/m \| r_{\mathrm{on}} \| 2r_{\mathrm{ob}})} \cdot \frac{(1-\tau_3 s)(1+\tau_2 s)}{1+\left(\tau_4^2/(\tau_1 \| \tau_2)\right) s + \tau_4^2 s^2},$$

and

$$\mathrm{CMRR} \equiv \frac{G_{\mathrm{dm}}}{G_{\mathrm{cm}}} = \frac{m}{2} \cdot \frac{g_{\mathrm{m}}(R/m \| r_{\mathrm{on}} \| 2r_{\mathrm{ob}})}{1+m+2g_{\mathrm{m}}R/\beta} \cdot \frac{1+\left(\tau_4^2/(\tau_1 \| \tau_2)\right) s + \tau_4^2 s^2}{(1+\tau_1 s)(1+\tau_2 s)},$$

where

$$\begin{array}{lcllcl}
\tau_1 & \equiv & (R/(1+m) \| \beta/2g_{\mathrm{m}}) C_{\mathrm{b}} & \qquad \tau_3 & \equiv & C_{\mathrm{m}}/g_{\mathrm{m}} \\
\tau_2 & \equiv & (R/m \| r_{\mathrm{on}} \| r_{\mathrm{ob}}) C/2 & \qquad \tau_4 & \equiv & \sqrt{(C_{\mathrm{b}}/g_{\mathrm{m}})(RC/2m)}.
\end{array}$$

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