A Simple Class-AB Transconductor in CMOS

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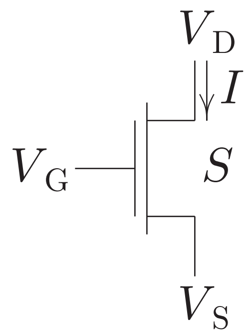
Simple EKV MOS Transistor Model

We model the channel current of an nMOS transistor as the difference between a forward current and a reverse current,



$$I = I_F - I_R,$$

whose values are given by

$$I_{F(R)} = SI_s \log^2\left(1 + e^{\left(\kappa(V_G - V_{T0}) - V_{S(D)}\right)/2U_T}\right),$$

where

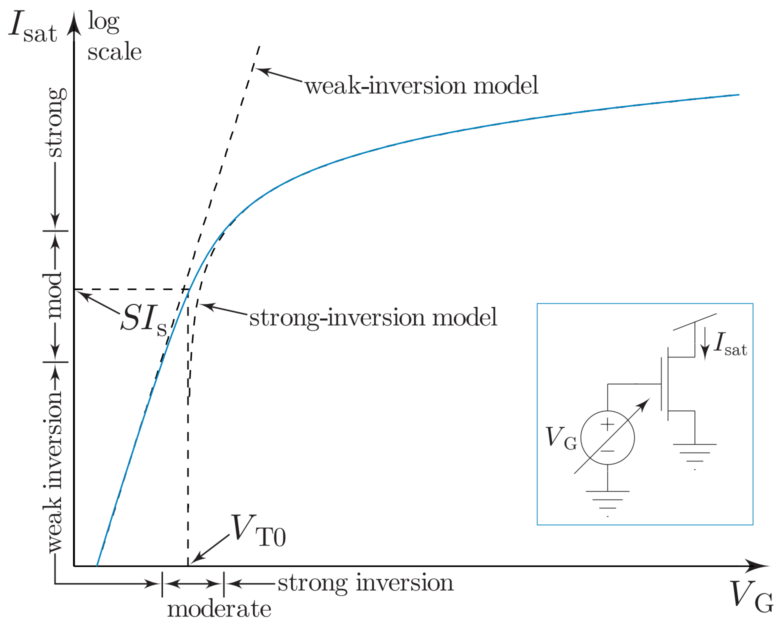
$$U_T = \frac{kT}{q}, \quad S = \frac{W}{L}, \quad I_s = \frac{2\mu C_{ox} U_T^2}{\kappa}, \quad \text{and} \quad \kappa = \frac{C_{ox}}{C_{ox} + C_{dep}}.$$

Note that SI_s is approximately twice the saturation current at threshold. This simple model covers all regions of normal MOS transistor operation.

Simple EKV MOS Transistor Model

The expressions for I_F and I_R reduce asymptotically to an exponential form in weak inversion and a quadratic form in strong inversion, given by

$$I_{\mathrm{F(R)}} \approx \begin{cases} SI_\mathrm{s} e^{\left(\kappa(V_\mathrm{G}-V_\mathrm{T0})-V_\mathrm{S(D)}\right)/U_\mathrm{T}}, \\ \qquad V_\mathrm{G} < V_\mathrm{T0} + \dfrac{V_\mathrm{S(D)}}{\kappa} \\ \dfrac{SI_\mathrm{s}}{4U_\mathrm{T}^2}\left(\kappa\left(V_\mathrm{G}-V_\mathrm{T0}\right)-V_\mathrm{S(D)}\right)^2, \\ \qquad V_\mathrm{G} > V_\mathrm{T0} + \dfrac{V_\mathrm{S(D)}}{\kappa}. \end{cases}$$



Simple EKV MOS Transistor Model

The expressions for I_{F} and I_{R} are also explicitly invertible; the inverses are given by

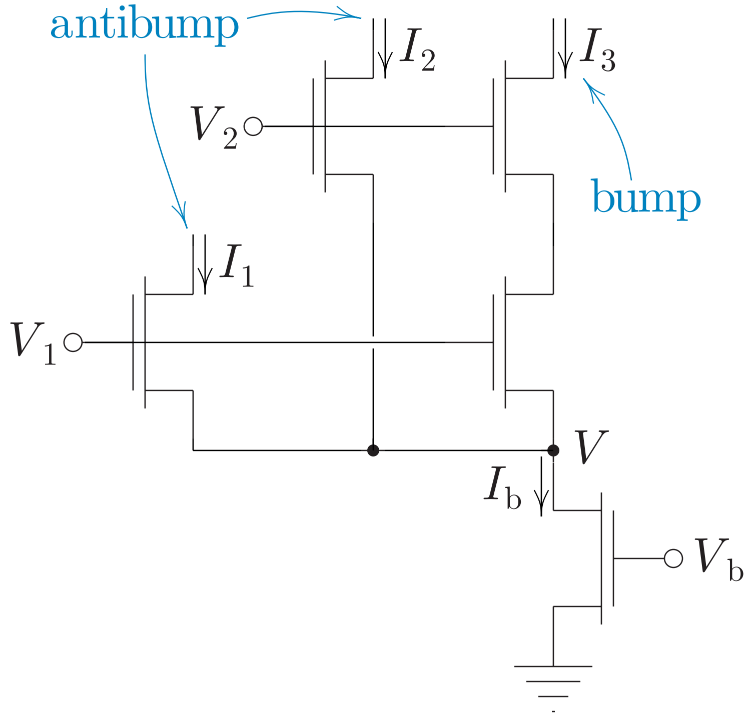
$$
\begin{aligned}
\kappa\left(V_{\mathrm{G}} - V_{\mathrm{T0}}\right) - V_{\mathrm{S(D)}} &= 2U_{\mathrm{T}} \log\left(e^{\sqrt{I_{\mathrm{F(R)}}/SI_{\mathrm{s}}}} - 1\right) \\
&\approx \begin{cases} U_{\mathrm{T}} \log\dfrac{I_{\mathrm{F(R)}}}{SI_{\mathrm{s}}}, & I_{\mathrm{F(R)}} \ll SI_{\mathrm{s}} \\ 2U_{\mathrm{T}}\sqrt{\dfrac{I_{\mathrm{F(R)}}}{SI_{\mathrm{s}}}}, & I_{\mathrm{F(R)}} \gg SI_{\mathrm{s}}. \end{cases}
\end{aligned}
$$

Delbrück's Bump/Antibump Circuit

If the bias current, I_{b}, is in weak inversion, then the bump current, I_3, is an even-symmetric, bell-shaped function of the differential-mode input voltage, $V_{\mathrm{dm}} = V_1 - V_2$, given by

$$I_3 = \frac{I_{\mathrm{b}}}{2} \operatorname{sech}^2\left(\frac{\kappa V_{\mathrm{dm}}}{2U_{\mathrm{T}}}\right).$$

Note that the three output currents sum to a constant, I_{b}, so the sum $I_1 + I_2$ is just I_{b} less the bump current, which is the antibump current.



A Variation of the Bump/Antibump Circuit

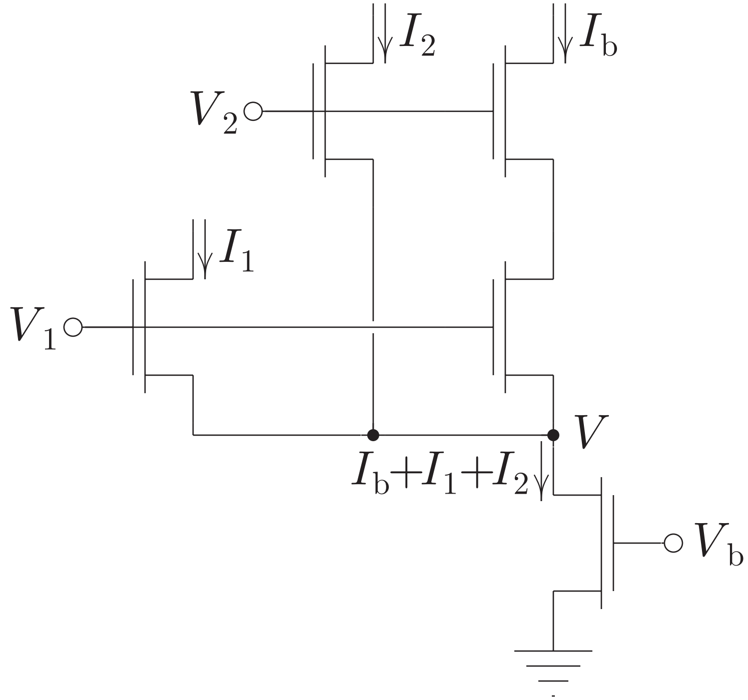
Now, suppose that we fix the bump current to be a constant, I_b. If I_1, I_2, and I_b are in weak inversion, we have that

$$I_1 = SI_\mathrm{s}e^{(\kappa(V_1 - V_{\mathrm{T0}}) - V)/U_\mathrm{T}},$$

$$I_2 = SI_\mathrm{s}e^{(\kappa(V_2 - V_{\mathrm{T0}}) - V)/U_\mathrm{T}},$$

and

$$I_\mathrm{b} = \frac{I_1 I_2}{I_1 + I_2} = I_1 \| I_2.$$



A Variation of the Bump/Antibump Circuit

Now, consider the quantity

$$\begin{aligned} I_{\mathrm{b}} &= I_1 \| I_2 \\ &= SI_{\mathrm{s}}e^{(\kappa(V_1 - V_{\mathrm{T0}}) - V)/U_{\mathrm{T}}} \Big\| SI_{\mathrm{s}}e^{(\kappa(V_2 - V_{\mathrm{T0}}) - V)/U_{\mathrm{T}}} \\ &= SI_{\mathrm{s}}e^{-\kappa V_{\mathrm{T0}}/U_{\mathrm{T}}} e^{-V/U_{\mathrm{T}}} \left(e^{\kappa V_1/U_{\mathrm{T}}} \Big\| e^{\kappa V_2/U_{\mathrm{T}}} \right), \end{aligned}$$

which implies that

$$SI_{\mathrm{s}}e^{-\kappa V_{\mathrm{T0}}/U_{\mathrm{T}}} e^{-V/U_{\mathrm{T}}} = \frac{I_{\mathrm{b}}}{e^{\kappa V_1/U_{\mathrm{T}}} \| e^{\kappa V_2/U_{\mathrm{T}}}}.$$

A Variation of the Bump/Antibump Circuit

By substituting this result back into the equations for I_1 and I_2, we find that

$$I_1 = \frac{I_\mathrm{b} e^{\kappa V_1/U_\mathrm{T}}}{e^{\kappa V_1/U_\mathrm{T}} \| e^{\kappa V_2/U_\mathrm{T}}} = I_\mathrm{b}\left(1 + e^{\kappa(V_1 - V_2)/U_\mathrm{T}}\right) = I_\mathrm{b}\left(1 + e^{\kappa V_\mathrm{dm}/U_\mathrm{T}}\right),$$

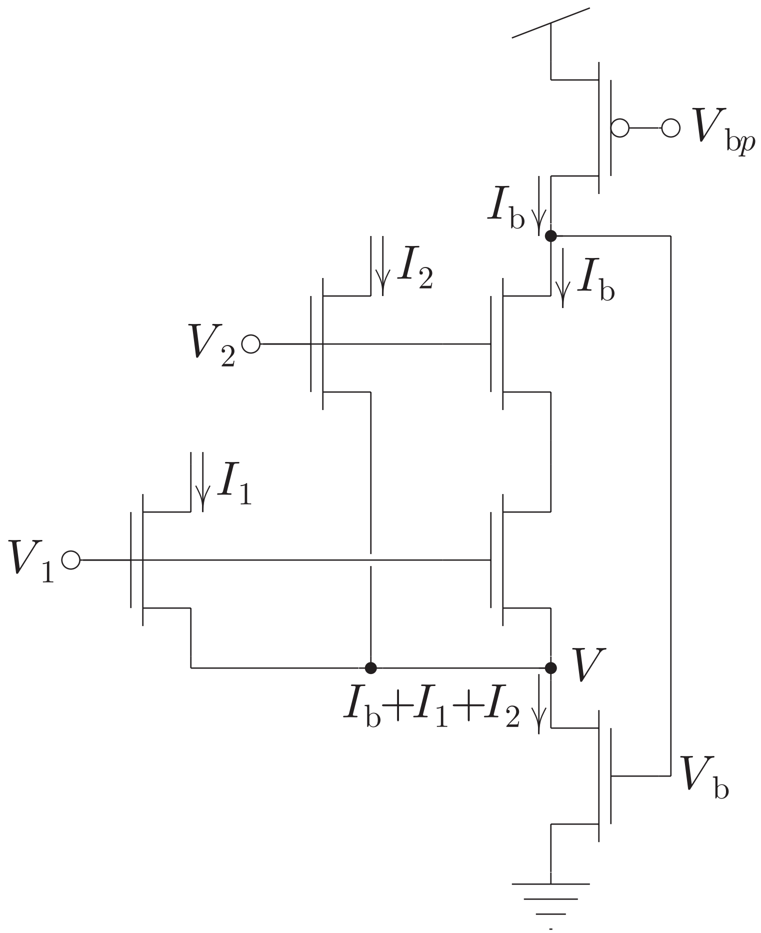
that

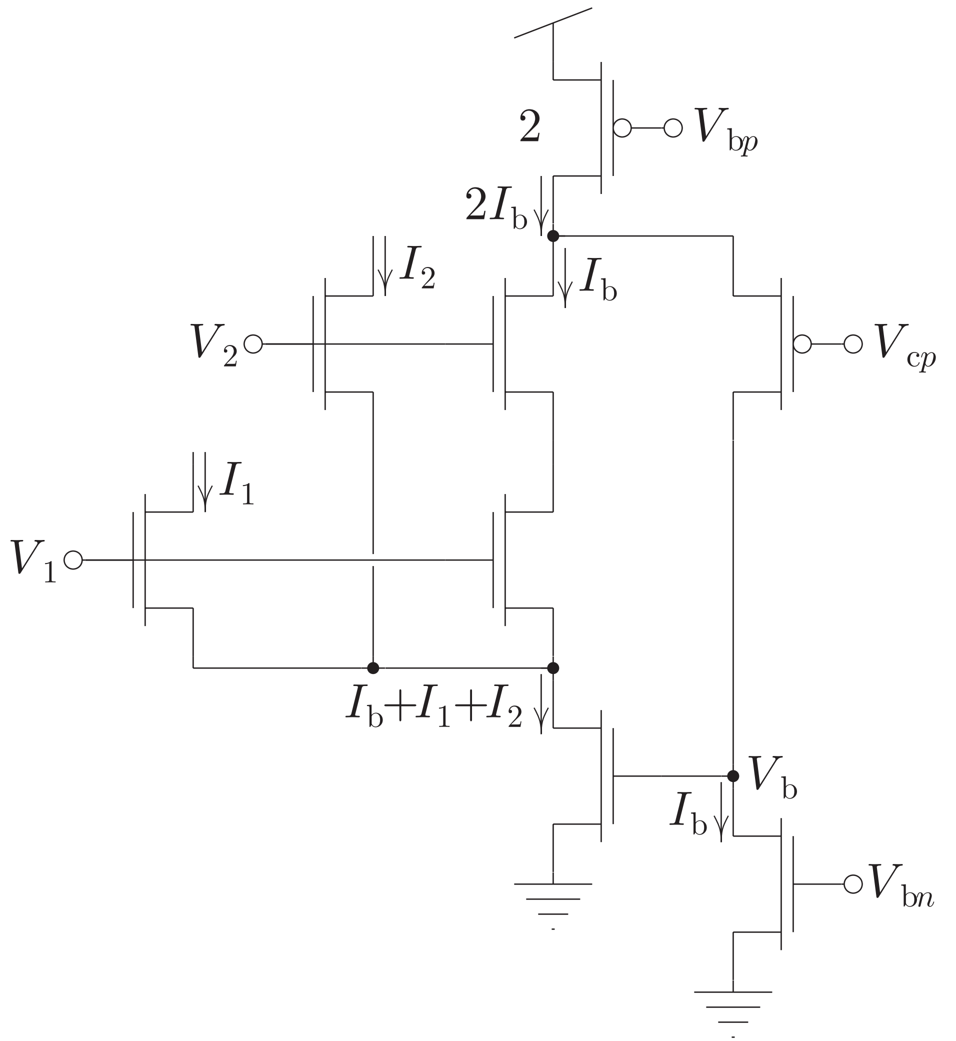
$$I_2 = \frac{I_\mathrm{b} e^{\kappa V_2/U_\mathrm{T}}}{e^{\kappa V_1/U_\mathrm{T}} \| e^{\kappa V_2/U_\mathrm{T}}} = I_\mathrm{b}\left(1 + e^{-\kappa(V_1 - V_2)/U_\mathrm{T}}\right) = I_\mathrm{b}\left(1 + e^{-\kappa V_\mathrm{dm}/U_\mathrm{T}}\right),$$

and that

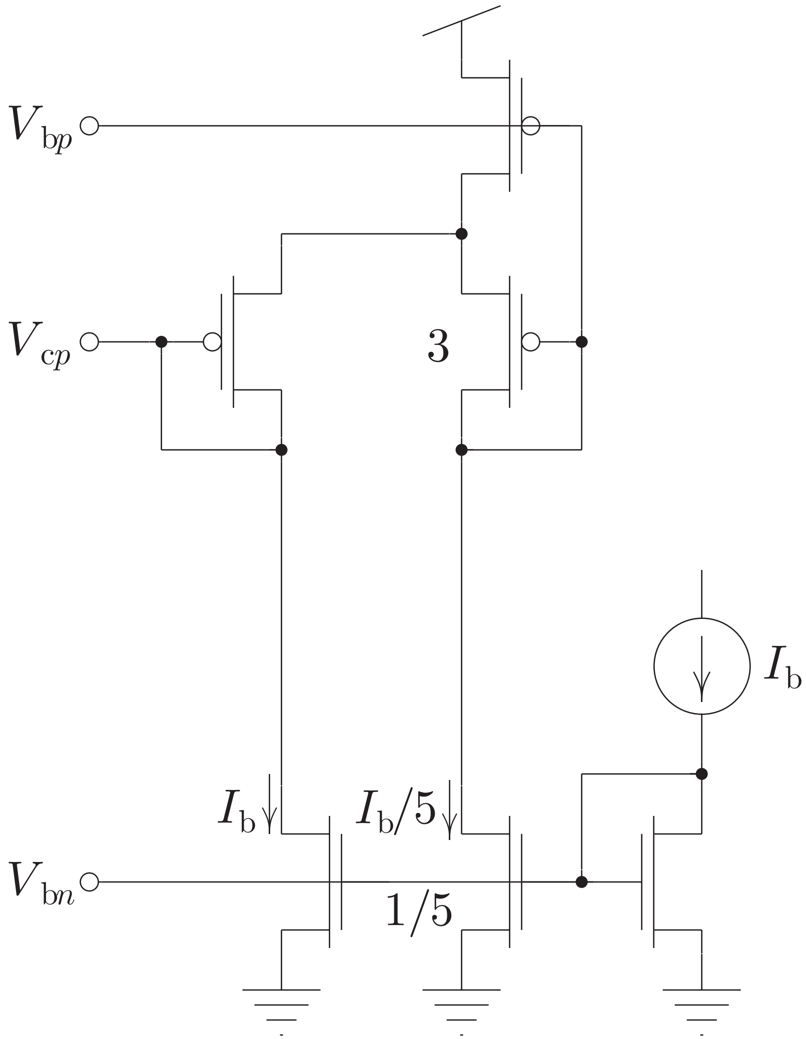
$$I_1 - I_2 = I_\mathrm{b}\left(e^{\kappa V_\mathrm{dm}/U_\mathrm{T}} - e^{-\kappa V_\mathrm{dm}/U_\mathrm{T}}\right) = 2I_\mathrm{b}\sinh\!\left(\frac{\kappa V_\mathrm{dm}}{U_\mathrm{T}}\right).$$

Fixing the Bump Current at I_b





Bias Circuit for Folded-Cascode/Flipped-Follower



Analytical Model of Output Current versus V_{dm}

By using the simplified EKV model of the MOS transistor, we can show that

$$I_1 = I_{\mathrm{b}} + SI_{\mathrm{s}} \log^2\left(1 + e^{\kappa V_{\mathrm{dm}}/2U_{\mathrm{T}}}\left(e^{\sqrt{I_{\mathrm{b}}/SI_{\mathrm{s}}}} - 1\right)\right)$$

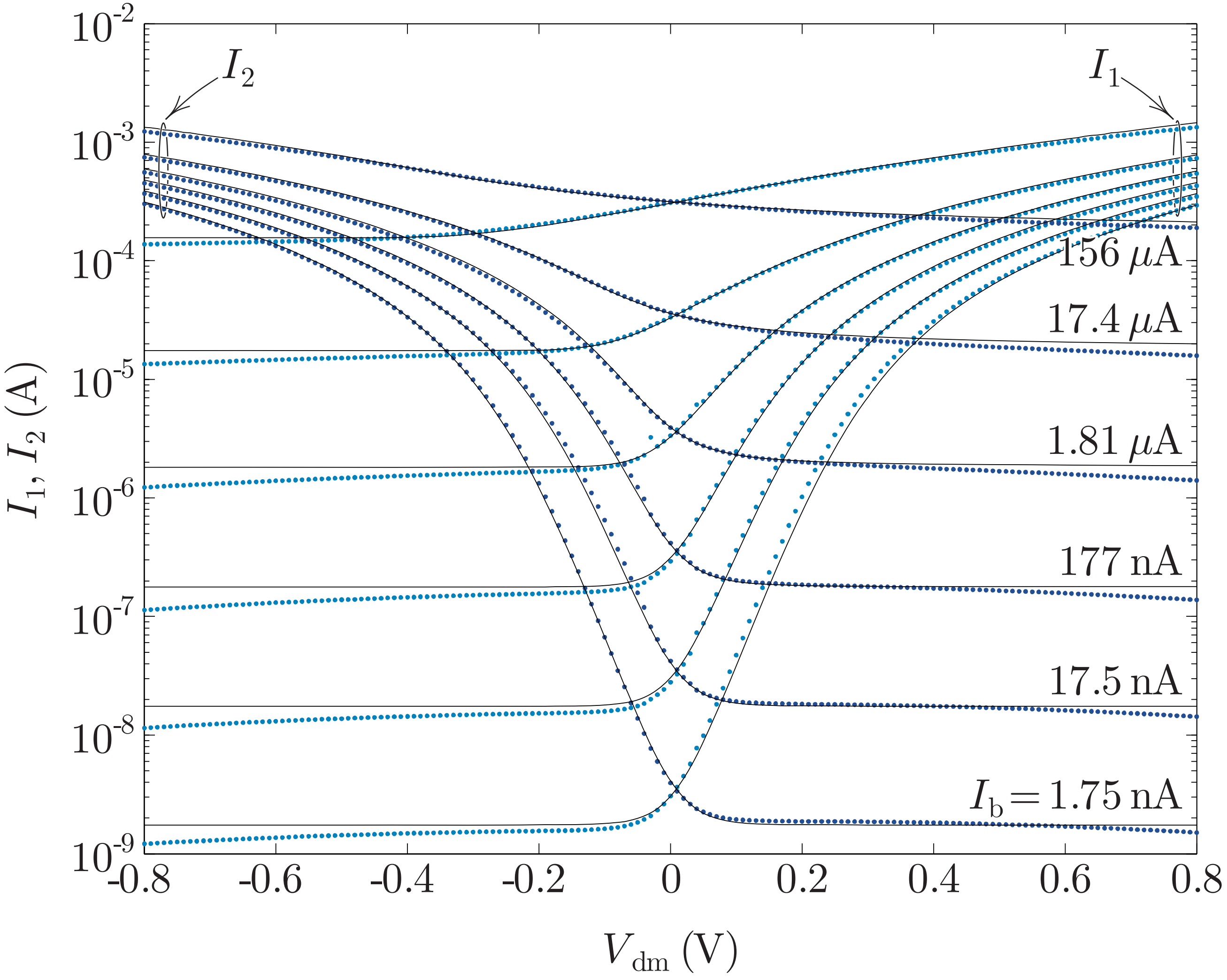
and that

$$I_2 = SI_{\mathrm{s}} \log^2\left(1 + e^{-\kappa V_{\mathrm{dm}}/2U_{\mathrm{T}}}\left(e^{\sqrt{I_1/SI_{\mathrm{s}}}} - 1\right)\right),$$

where all the symbols have their previously defined meanings.

Note that the model equation for I_2 is expressed in terms of I_1, which, in turn, is an explicit function of V_{dm}. So, we can obtain explicit expressions for I_2 and $I_1 - I_2$ in terms of V_{dm}, but it is unclear that doing so is of much value, because doing so leads to *very* cumbersome expressions.

Output Currents versus V_{dm}



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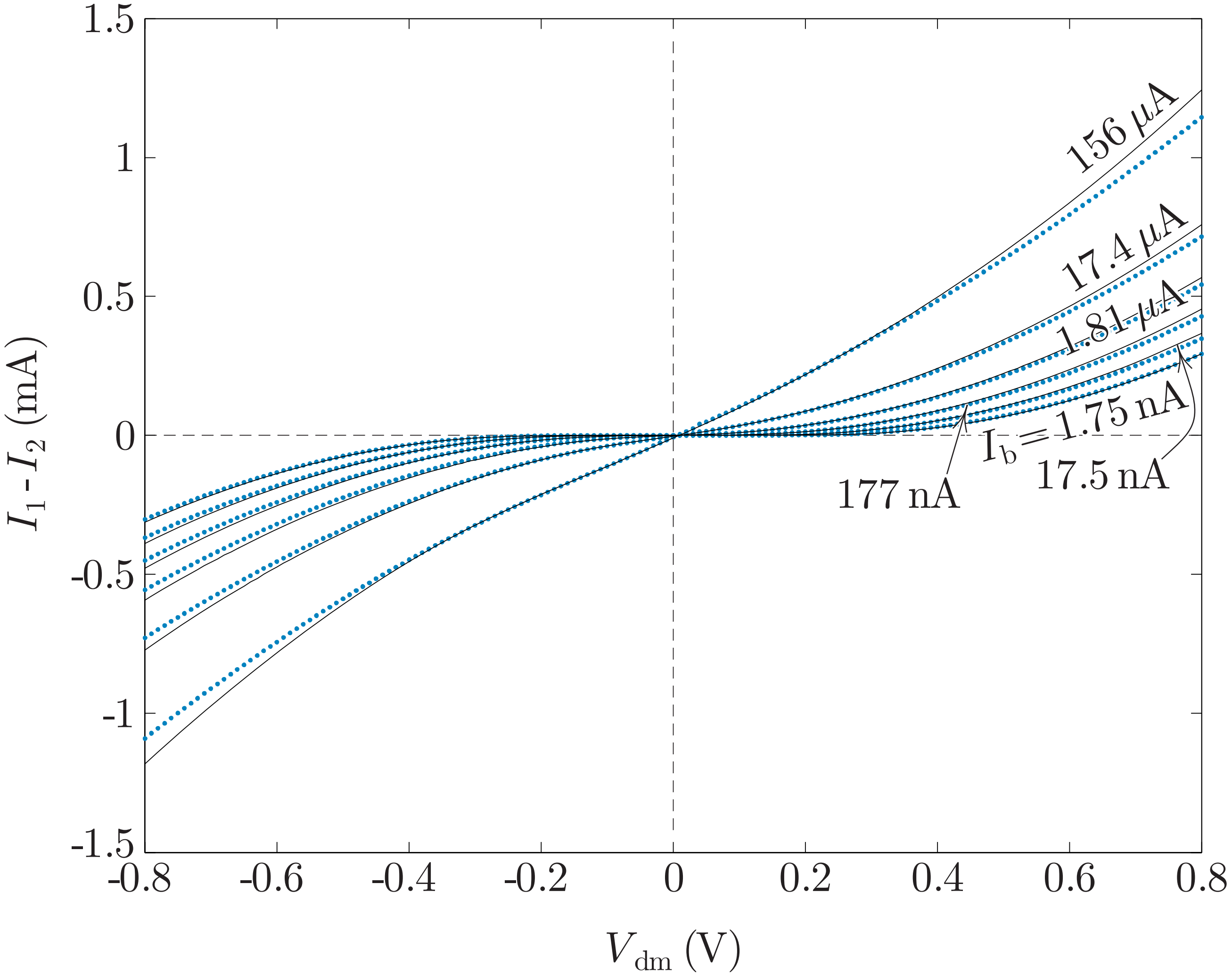
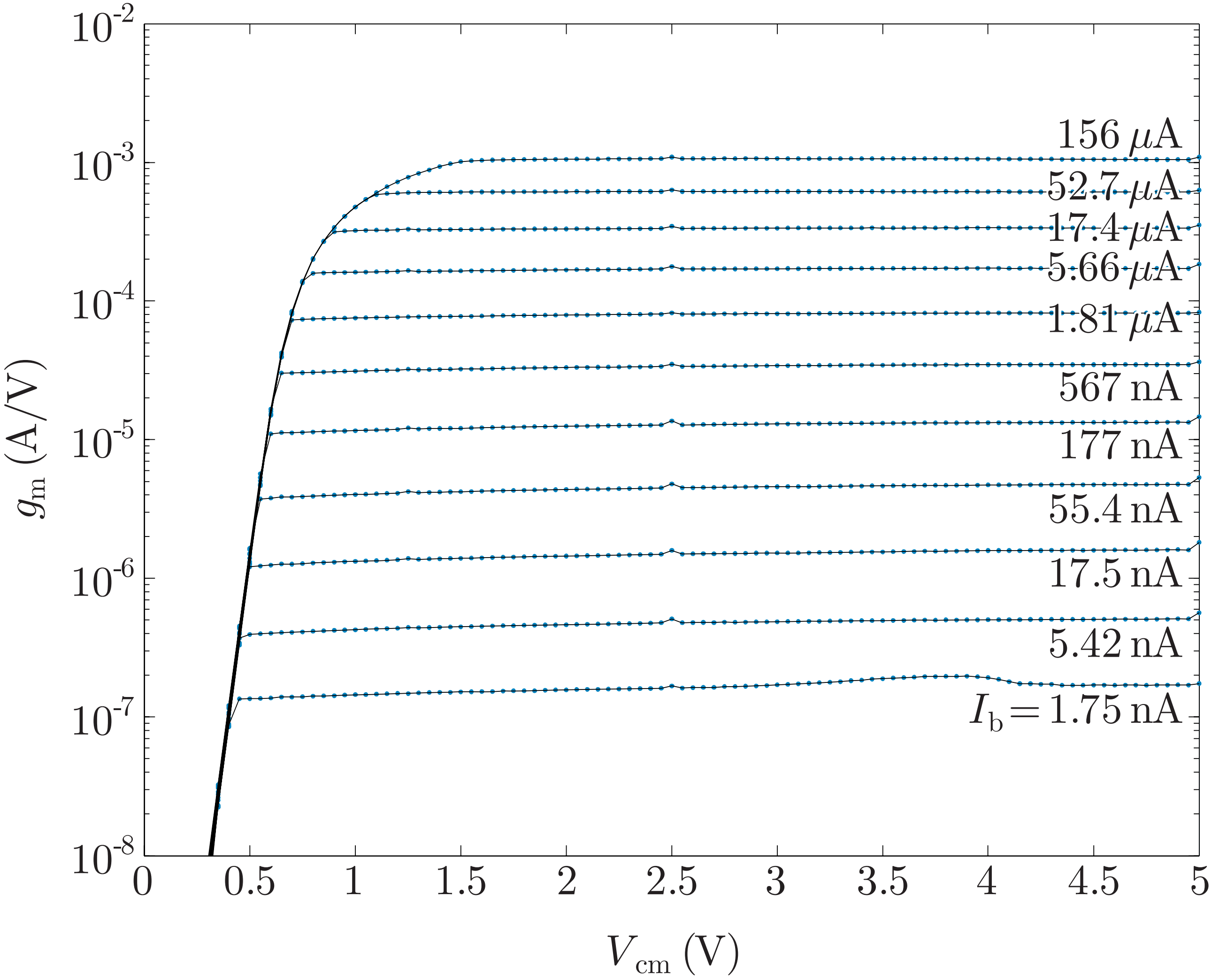
Differential Output Current versus V_{dm}



Differential-Mode Transconductance versus V_{cm}



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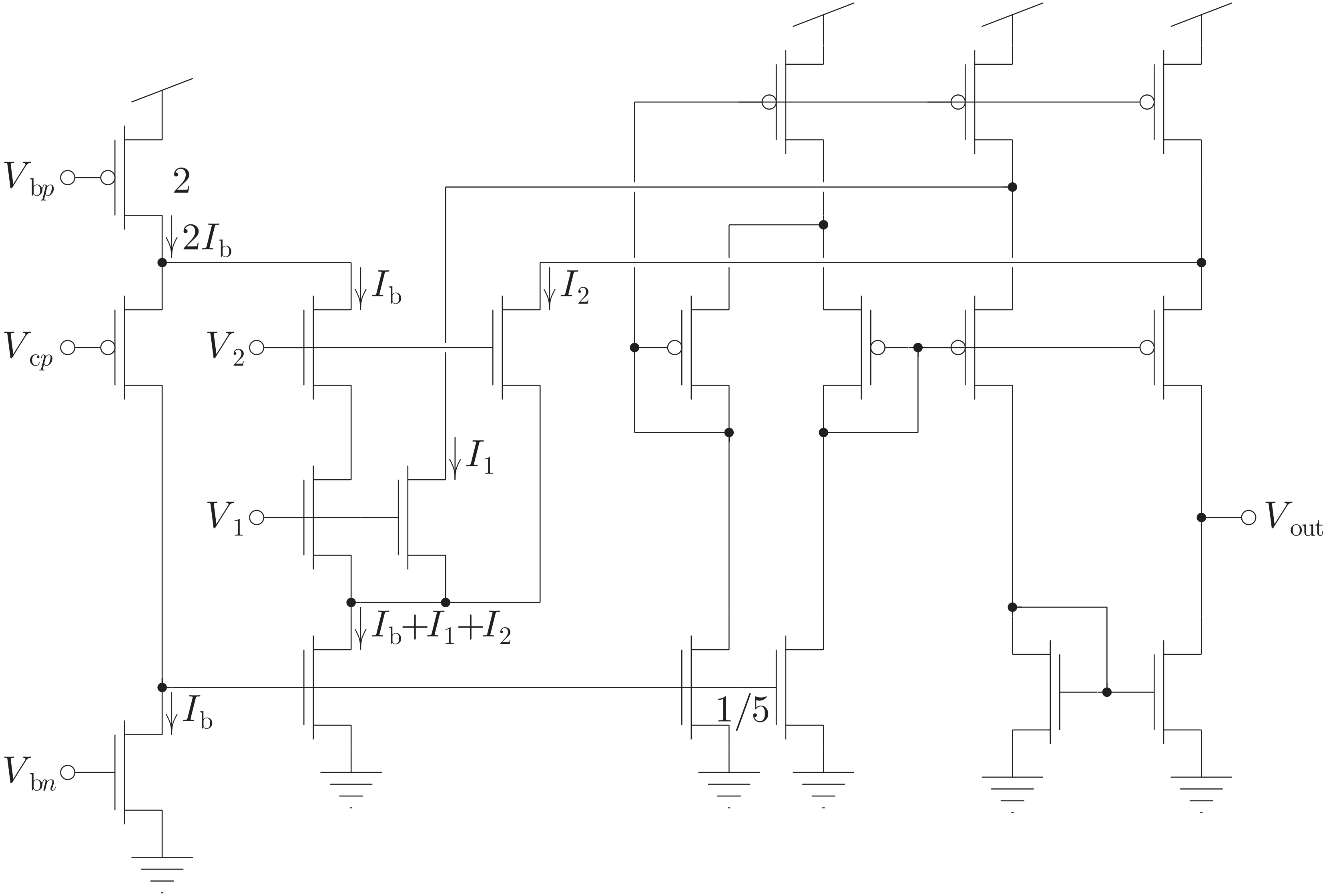
Enhanced-Slew-Rate Folded-Cascode Amplifier



Enhanced-Slew-Rate Folded-Cascode Amplifier Step Response