Nagendra Krishnapura

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7 April 2010
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_m$</td>
<td>$g_m$</td>
</tr>
<tr>
<td>$G_{out}$</td>
<td>$g_{ds1} + g_{ds3}$</td>
</tr>
<tr>
<td>$A_o$</td>
<td>$g_m/(g_{ds1} + g_{ds3})$</td>
</tr>
<tr>
<td>$A_{cm}$</td>
<td>$g_{ds0}/g_m$</td>
</tr>
<tr>
<td>$C_i$</td>
<td>$C_{gs1}/2$</td>
</tr>
<tr>
<td>$\omega_u$</td>
<td>$g_m/C_L$</td>
</tr>
<tr>
<td>$p_k, z_k$</td>
<td>$p_2 = -g_m/(C_{db1} + C_{db3} + 2C_{gs3}); z_1 = 2p_2$</td>
</tr>
<tr>
<td>$S_{vi}$</td>
<td>$16kT/3g_m(1 + g_m/g_m)$</td>
</tr>
<tr>
<td>$\sigma_{Vos}^2$</td>
<td>$\sigma_{VT1}^2 + (g_m/g_m)^2\sigma_{VT3}^2$</td>
</tr>
<tr>
<td>$V_{cm}$</td>
<td>$\geq V_{T1} + V_{DSAT1} + V_{DSAT0}$</td>
</tr>
<tr>
<td></td>
<td>$\leq V_{dd} - V_{DSAT3} - V_{T3} + V_{T1}$</td>
</tr>
<tr>
<td>$V_{out}$</td>
<td>$\geq V_{cm} - V_{T1}$</td>
</tr>
<tr>
<td></td>
<td>$\leq V_{dd} - V_{DSAT3}$</td>
</tr>
<tr>
<td>$SR$</td>
<td>$\pm I_0/C_L$</td>
</tr>
<tr>
<td>$I_{supply}$</td>
<td>$I_0 + I_{ref}$</td>
</tr>
</tbody>
</table>
Cascode output resistance

\[ R_{out} = \frac{g_{mc}}{g_{dsc}} G_s + \frac{1}{G_s} + \frac{1}{g_{dsc}} \]

\[ V_{biasc} \]\(\Rightarrow\)\( M_c \)

\[ G_s \]

\[ V_{biasc} \]\(\Rightarrow\)\( M_c \)

\[ V_{bias1} \]\(\Rightarrow\)\( G_s = g_{ds1} \)

\[ M_1 \]

\[ V_{bias1} \]\(\Rightarrow\)\( G_s = g_{m1} \)

\[ V_{dd} \]

\[ \text{differential pair: } \text{M}_c \text{ degenerated by } \text{M}_1 \text{'s source impedance (} g_{m1} \text{)} \]

- Output resistance looking into one side of the differential pair is \( 2/g_{ds1} \) (\( g_{m1} = g_{mc} \) in the figure)

\[ R_{out} = \frac{g_{mc}}{g_{dsc}g_{m1}} + \frac{1}{g_{dsc}} + \frac{1}{g_{m1}} \]

\[ \text{(negligible)} \]

\[ R_{out} = \frac{1}{g_{dsc}(1+g_{mc}/g_{m1})} \]
Opamp: dc small signal analysis

- Bias values in black
- Incremental values in red
- Impedances in blue

Total quantity = Bias + increment
Differential pair: Quiescent condition

\[ V_{cm} \]

\[ V_{bias0} \]

\[ I_0/2 \]

\[ V_{dd} \]

\[ V_{dd} - V_{GS3} \text{ (by symmetry)} \]

M1, M2, M3, M4

\[ V_{bias0} \]

\[ V_{cm} \]

\[ - \]

\[ V_{dd} - V_{GS3} \]

zero current

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EE539: Analog Integrated Circuit Design
Differential pair: Transconductance

\[ \begin{align*}
T_{\text{ransconductance}} & = \frac{V_{cm}}{I_0/2} \\
V_{bias0} & \approx 0 \\
V_{dd} & \pm V_{GS3} \\
M_1 & \quad M_2 \\
M_3 & \quad M_4 \\
g_m v_d/2 & \quad g_m v_d/2 \\
+V_d/2 & \quad -V_d/2
\end{align*} \]
Differential pair: Output conductance

\[ V_{cm} \]

\[ I_0/2 \]

\[ V_{bias0} \]

\[ V_{dd} \]

\[ -V_{GS3} \]

\[ v_T g_{ds1}/2 + v_T g_{ds3} \]

\[ v_T g_{ds1}/2 \]

\[ v_T g_{ds1}/2 + v_T g_{ds3} \]

\[ v_T (g_{ds1} + g_{ds3}) \]

\[ v_T \]

\[ V_{dd} - V_{GS3} \]

\[ +v_T \]
Telescopic cascode: Quiescent condition

\[ V_{bias0} \]

\[ V_{biasn2} \]

\[ V_{biasp2} \]

\[ V_{cm} \]

\[ I_0/2 \]

\[ V_{dd} \]

\[ V_{dd} - V_{GS3} \]

zero current

M1, M2, M3, M4, M5, M6, M7, M8

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EE539: Analog Integrated Circuit Design
Telescopic cascode: Transconductance
Telescopic cascode: Output conductance

\[ V_{\text{bias0}} / 2 \]

\[ V_{\text{cm}} \]

\[ V_{\text{biasp2}} \]

\[ v_{T} g_{ds5} g_{ds1} / 2 g_{m5} \]

\[ I_{0} / 2 \]

\[ V_{dd} \]

\[ V_{\text{biasn2}} \]

\[ v_{T} g_{ds5} g_{ds1} / 2 g_{m5} \]

\[ g_{ds1} / 2 \]

\[ g_{ds5} g_{ds1} / 2 g_{m5} \]

\[ v_{T} (g_{ds5} g_{ds1} / g_{m5} + g_{ds7} g_{ds3} / g_{m7}) \]

\[ V_{biasn2} \]

\[ v_{T} g_{ds5} g_{ds1} / 2 g_{m5} \]

\[ V_{cm} \]

\[ V_{bias0} \]

\[ V_{V_{gs3}} \]

\[ V_{dd} - V_{gs3} + v_{T} \]
Folded cascode: Quiescent condition

$V_{cm}$

$I_0/2$ $I_0/2$

$M_1$ $M_2$

$V_{bias0}$

$V_{cm}$

$I_0/2+I_1$

$I_0/2+I_1$ $V_{bias1}$

$M_9$ $M_{10}$

$V_{dd}$

$V_{bias2}$

$V_{GS3}$

$I_1$

$I_1$

$V_{bias2}$

zero current

$M_3$ $M_4$

$M_5$ $M_6$

$M_7$ $M_8$

$M_9$ $M_{10}$

$V_{dd}$
Folded cascode: Transconductance

\[ I_0/2 + I_1 \]

\[ V_{bias0} \]

\[ V_{cm} + v_d/2 \]

\[ g_m v_d/2 \]

\[ V_{biasn2} \]

\[ V_{GS3} \]

\[ v_s \sim 0 \]

\[ g_m v_d/2 \]

\[ g_m v_d/2 \]

\[ I_0/2 \]

\[ M_1 \]

\[ M_2 \]

\[ M_3 \]

\[ M_4 \]

\[ M_5 \]

\[ M_6 \]

\[ M_7 \]

\[ M_8 \]

\[ M_9 \]

\[ M_{10} \]

\[ V_{dd} \]

\[ I_0/2 + I_1 V_{bias1} \]

\[ I_1 \]

\[ g_m v_d/2 \]

\[ g_m v_d/2 \]

\[ g_m v_d/2 \]

\[ g_m v_d/2 \]
Folded cascode: Output conductance

\[ g_{\text{ds1}} / 2g_{m5} \]

\[ V_{\text{bias0}} \]

\[ V_{\text{cm}} \]

\[ M_1 \]

\[ M_2 \]

\[ I_0 / 2 \]

\[ I_0 / 2 \]

\[ V_{\text{cm}} \]

\[ M_3 \]

\[ M_4 \]

\[ M_5 \]

\[ M_6 \]

\[ M_7 \]

\[ M_8 \]

\[ M_9 \]

\[ M_{10} \]

\[ V_{\text{dd}} \]

\[ I_0 / 2 + I_1 \]

\[ I_0 / 2 + I_1 V_{\text{biasp1}} \]

\[ V_{\text{biasp2}} \]

\[ v_{T} g_{\text{ds5}} (g_{ds1} / 2 + g_{ds9}) / g_{m5} \]

\[ V_{\text{biasn2}} \]

\[ V_{\text{GS3}} \]

\[ V_{T} (g_{ds5} (g_{ds1} + g_{ds9}) / g_{m5} + g_{ds7} g_{ds3} / g_{m7}) \]

\[ V_{T} \]

\[ +V_{T} \]

\[ v_{T} g_{\text{ds5}} g_{\text{ds1}} / 2 g_{m5} + v_{T} g_{\text{ds7}} g_{\text{ds3}} / g_{m7} \]

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Differential pair: Noise

Carry out small signal linear analysis with one noise source at a time
Add up the results at the output (current in this case)
Add up corresponding spectral densities
Divide by gain squared to get input referred noise
Telescopic cascode opamp

The diagram shows a telescopic cascode opamp circuit with transistors M1, M2, M3, M4, M5, M6, M7, and M8. The circuit includes bias voltages V_{bias0}, V_{biasp2}, and V_{biasn2} and input and output signals labeled inp and out.
### Telescopic cascode opamp

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expression</th>
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<tbody>
<tr>
<td>$G_m$</td>
<td>$g_m$</td>
</tr>
<tr>
<td>$G_{out}$</td>
<td>$g_{ds1}g_{ds5}/g_m + g_{ds3}g_{ds7}/g_m$</td>
</tr>
<tr>
<td>$A_o$</td>
<td>$g_m/g_{ds1}g_{ds5}/g_m + g_{ds3}g_{ds7}/g_m$</td>
</tr>
<tr>
<td>$A_{cm}$</td>
<td>$g_{ds0}/g_m$</td>
</tr>
<tr>
<td>$C_i$</td>
<td>$C_{gs1}/2$</td>
</tr>
<tr>
<td>$\omega_u$</td>
<td>$g_m/C_L$</td>
</tr>
<tr>
<td>$p_k, z_k$</td>
<td>$p_2 = -g_m/(C_{db1} + C_{db3} + 2C_{gs3})$</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$p_3 = -g_m/C_{p5}$</td>
</tr>
<tr>
<td></td>
<td>$p_4 = -g_m/C_{p7}$</td>
</tr>
<tr>
<td></td>
<td>$p_{2,4}$ appear for one half and cause mirror zeros</td>
</tr>
<tr>
<td>$S_{vi}$</td>
<td>$16kT/3g_m (1 + g_m/g_m)$</td>
</tr>
<tr>
<td>$\sigma_{V os}^2$</td>
<td>$\sigma_{VT1}^2 + (g_m/g_m)^2\sigma_{VT3}^2$</td>
</tr>
<tr>
<td>$V_{out}$</td>
<td>$\geq V_{biasn1} - V_T5$</td>
</tr>
<tr>
<td></td>
<td>$\leq V_{biasp1} + V_T7$</td>
</tr>
<tr>
<td>$SR$</td>
<td>$\pm I_0/C_L$</td>
</tr>
<tr>
<td>$I_{supply}$</td>
<td>$I_0 + I_{ref}$</td>
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</table>

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EE539: Analog Integrated Circuit Design
Folded cascode opamp
### Folded cascode opamp

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_m$</td>
<td>$g_{m1}$</td>
</tr>
<tr>
<td>$G_{out}$</td>
<td>$(g_{ds1} + g_{ds9})g_{ds5}/g_{m5} + g_{ds3}g_{ds7}/g_{m7}$</td>
</tr>
<tr>
<td>$A_o$</td>
<td>$g_{m1} / ((g_{ds1} + g_{ds9})g_{ds5}/g_{m5} + g_{ds3}g_{ds7}/g_{m7})$</td>
</tr>
<tr>
<td>$A_{cm}$</td>
<td>$g_{ds0}/g_{m3}$</td>
</tr>
<tr>
<td>$C_i$</td>
<td>$C_{gs1}/2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency Domain</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_u$</td>
<td>$g_{m1}/C_L$</td>
</tr>
<tr>
<td>$p_k, z_k$</td>
<td>$p_2 = -g_{m3}/(C_{db1} + C_{db3} + 2C_{gs3})$</td>
</tr>
<tr>
<td></td>
<td>$p_3 = -g_{m5}/C_{p5}$</td>
</tr>
<tr>
<td></td>
<td>$p_4 = -g_{m7}/C_{p7}$</td>
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<tr>
<td></td>
<td>$p_{2,4}$ appear for one half and cause mirror zeros</td>
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</table>

<table>
<thead>
<tr>
<th>Noise</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{vi}$</td>
<td>$16kT/3g_{m1} (1 + g_{m3}/g_{m1} + g_{m9}/g_{m1})$</td>
</tr>
<tr>
<td>$\sigma_{Vos}^2$</td>
<td>$\sigma_{VT1}^2 + (g_{m3}/g_{m1})^2\sigma_{VT3}^2 + (g_{m9}/g_{m1})^2\sigma_{VT9}^2$</td>
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<table>
<thead>
<tr>
<th>Output Voltage</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{out}$</td>
<td>$\geq V_{biasn1} - V_T5$</td>
</tr>
<tr>
<td></td>
<td>$\leq V_{biasp1} + V_T7$</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Stability</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SR$</td>
<td>$\pm \min{I_0, I_1}/C_L$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Current</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{supply}$</td>
<td>$I_0 + I_1 + I_{ref}$</td>
</tr>
</tbody>
</table>
Body effect

- All nMOS bulk terminals to ground
- All pMOS bulk terminals to $V_{dd}$
- $A_{cm}$ has an additional factor $g_{m1}/(g_{m1} + g_{mb1})$
- $g_{m5} + g_{mb5}$ instead of $g_{m5}$ in cascode opamp results
- $g_{m7} + g_{mb7}$ instead of $g_{m7}$ in cascode opamp results
Two stage opamp

bias

stage 1

M₃  M₄

inn

M₁  M₂

inp

stage 2

V_{dd}

M₉

M₁₀

M₁₁

R_c

C_c

R_L

C_L

V_{outbias}
First stage can be Differential pair, Telescopic cascode, or Folded cascode; Ideal $g_{m1}$ assumed in the analysis

Second stage: Common source amplifier

Frequency response is the product of frequency responses of the first stage $g_m$ and a common source amplifier driven from a current source
Common source amplifier: Frequency response

\[
\frac{V_o(s)}{V_d(s)} = \left( \frac{g_m g_{m11}}{G_1 G_L} \right) \frac{sC_c (R_c - 1/g_{m11}) + 1}{a_3 s^3 + a_2 s^2 + a_1 s + 1} \tag{1}
\]

\[
a_3 = \frac{R_c C_1 C_L C_c}{G_1 G_L} \tag{2}
\]

\[
a_2 = \frac{C_1 C_c + C_c C_L + C_L C_1 + R_c C_c (G_1 C_L + C_1 G_L)}{G_1 G_L} \tag{3}
\]

\[
a_1 = \frac{C_c (g_{m11} + G_1 + G_L + G_1 G_L R_c) + C_1 G_L + G_1 C_L}{G_1 G_L} \tag{4}
\]

- \(G_1\): Total conductive load at the input
- \(G_L\): Total conductive load at the output
- \(C_1\): Total capacitive load at the input
- \(C_L\): Total capacitive load at the output
Common source amplifier: Poles and zeros

\[ p_1 \approx -\frac{G_1}{C_c\left(\frac{g_{m11}}{G_L} + 1 + \frac{G_1}{G_L} + G_1 R_c\right) + C_1\left(1 + \frac{G_1}{G_L}\right)} \]  

(5)

\[ p_2 \approx -\frac{g_{m11} \frac{C_c}{C_1+C_c} + G_L + G_1 \frac{C_c+C_L}{C_1+C_c} + G_1 G_L R_c \frac{C_c}{C_1+C_c}}{\frac{C_1C_c}{C_1+C_c} + C_L + \frac{R_c C_c (G_1 C_L + G_L C_1)}{C_c+C_L}} \]  

(6)

\[ p_3 \approx -\left(\frac{1}{R_c} \left(\frac{1}{C_L} + \frac{1}{C_c} + \frac{1}{C_1}\right) + \frac{G_1}{C_1} + \frac{G_L}{C_L}\right) \]  

(7)

\[ z_1 = \frac{1}{(1/g_{m11} - R_c) C_c} \]  

(8)

Unity gain frequency

\[ \omega_u \approx \frac{g_{m1}}{C_c \left(1 + \frac{G_L}{g_{m11}} + \frac{G_1}{g_{m11}} + \frac{G_1 G_L R_c}{g_{m11}}\right) + C_1 \left(\frac{G_L}{g_{m11}} + \frac{G_1}{g_{m11}}\right)} \]  

(9)
Pole splitting using compensation capacitor $C_c$
- $p_1$ moves to a lower frequency
- $p_2$ moves to a higher frequency (For large $C_c$, $p_2 = g_{m11}/C_L$)

Zero cancelling resistor $R_c$ moves $z_1$ towards the left half $s$ plane and results in a third pole $p_3$
- $z_1$ can be moved to $\infty$ with $R_c = 1/g_{m11}$
- $z_1$ can be moved to cancel $p_2$ with $R_c > 1/g_{m11}$ (needs to be verified against process variations)
- Third pole $p_3$ at a high frequency

Poles and zeros from the first stage will appear in the frequency response—$Y_{m1}(s)$ instead of $g_{m1}$ in $V_o/V_i$ above
- Mirror pole and zero
- Poles due to cascode amplifiers
Compensation cap sizing

\[ p_2 \approx -\frac{g_{m11}}{C_1 + C_c} \frac{C_c}{C_1 C_c + C_L} \]  

(10)

\[ \omega_u \approx \frac{g_{m1}}{C_c} \]  

(11)

Phase margin (Ignoring \( p_3, z_1, \ldots \))

\[ \phi_M = \tan^{-1} \frac{|p_2|}{\omega_u} \]  

(12)

\[ \frac{|p_2|}{\omega_u} = \tan \phi_M \]  

(13)

\[ \frac{g_{m11}}{g_{m1}} \left( \frac{C_c}{C_L} \right)^2 = \frac{C_c}{C_L} \left( 1 + \frac{C_1}{C_L} \right) \tan \phi_M + \frac{C_1}{C_L} \tan \phi_M \]  

(14)

- For a given \( \phi_M \), solve the quadratic to obtain \( C_c / C_L \)
- If \( C_1 \) is very small, \( p_2 \approx -g_{m2}/C_L \); further simplifies calculations.
Two stage opamp

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<td>$g_{m1}g_{m11}/(g_{ds1} + g_{ds3})(g_{ds11} + g_{ds12})$</td>
</tr>
<tr>
<td>$A_{cm}$</td>
<td>$g_{ds0}g_{m11}/g_{m3}(g_{ds11} + g_{ds12})$</td>
</tr>
<tr>
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<tr>
<td>$S_{vi}$</td>
<td>$\sigma^2_{V_{os}} \approx \sigma^2_{VT1} + (g_{m3}/g_{m1})^2\sigma^2_{VT3}$</td>
</tr>
<tr>
<td>$V_{cm}$</td>
<td>$\geq V_T1 + V_{DSAT1} + V_{DSAT0}$</td>
</tr>
<tr>
<td></td>
<td>$\leq V_{dd} - V_{DSAT3} - V_T3 + V_T1$</td>
</tr>
<tr>
<td>$V_{out}$</td>
<td>$\geq V_{DSAT12}$</td>
</tr>
<tr>
<td></td>
<td>$\leq V_{dd} - V_{DSAT11}$</td>
</tr>
<tr>
<td>$SR+$</td>
<td>$I_0/C_c$</td>
</tr>
<tr>
<td>$SR-$</td>
<td>$\min{I_0/C_c, I_1/(C_L + C_c)}$</td>
</tr>
<tr>
<td>$I_{supply}$</td>
<td>$I_0 + I_1 + I_{ref}$</td>
</tr>
</tbody>
</table>
## Opamp comparison

<table>
<thead>
<tr>
<th></th>
<th>Differential</th>
<th>Telescopic</th>
<th>Folded</th>
<th>Two</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pair</td>
<td>cascode</td>
<td>cascode</td>
<td>stage</td>
</tr>
<tr>
<td>Gain</td>
<td>−</td>
<td>++</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Noise</td>
<td>=</td>
<td>=</td>
<td>high</td>
<td>=</td>
</tr>
<tr>
<td>Offset</td>
<td>=</td>
<td>=</td>
<td>high</td>
<td>=</td>
</tr>
<tr>
<td>Swing</td>
<td>−</td>
<td>−</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Speed</td>
<td>++</td>
<td>+</td>
<td>−</td>
<td>+</td>
</tr>
</tbody>
</table>
Low accuracy (low gain) applications
Voltage follower (capacitive load)
Voltage follower with source follower (resistive load)
In bias stabilization loops (effectively two stages in feedback)
Telescopic cascode

- Low swing circuits
- Switched capacitor circuits
  - Capacitive load
  - Different input and output common mode voltages
- First stage of a two stage opamp
  - Only way to get high gain in fine line processes
- Higher swing circuits
- Higher noise and offset
- Lower speed than telescopic cascode
  - Low frequency pole at the drain of the input pair
- Switched capacitor circuits (Capacitive load)
- First stage of a two stage class AB opamp
Two stage opamp

- Highest possible swing
- Resistive loads
- Capacitive loads at high speed
- “Standard” opamp: Miller compensated two stage opamp
- Class AB opamp: Always two (or more) stages
Opamps: pMOS versus nMOS input stage

- nMOS input stage
  - Higher $g_m$ for the same current
  - Suitable for large bandwidths
  - Higher flicker noise (usually)

- pMOS input stage
  - Lower $g_m$ for the same current
  - Lower flicker noise (usually)
  - Suitable for low noise low frequency applications
Fully differential circuits

- Two identical half circuits with some common nodes
- Two arms of the differential input applied to each half
- Two arms of the differential output taken from each half
Differential half circuit

Line of symmetry

Differential half circuit
Symmetrical

linear (or small signal linear) circuit under fully differential (antisymmetric) excitation

- Nodes along the line of symmetry at 0 V (symmetry, linearity)
- Analyze only the half circuit to find the transfer function
Common mode half circuit

Symmetrical circuit (maybe nonlinear) under common mode (symmetric) excitation

- Nodes in each half at identical voltages (symmetry)
- Fold over the circuit and analyze the half circuit
Common mode feedback circuit for setting the bias
Detect the output common mode and force it to be \( V_{o,cm} \) via feedback
Common mode feedback loop has to be stable

- Analyze it by breaking the loop and computing the loop gain with appropriate loading at the broken point
- Apply a common mode step/pulse in closed loop and ensure stability
Fully differential circuits: Noise

- Calculate noise spectral density of the half circuit
- Multiply by 2

\[ S_{n,\text{full}} = 2S_{n,\text{half}} \]
Fully differential circuits: Offset

\[ v_{off,full} = 2v_{off,half} + \Delta V_T \]

\[ v_{off,full}^2 = 2v_{off,half}^2 \]

- Calculate mean squared offset of the half circuit
- Multiply by 2 if mismatch (e.g. \( \Delta V_T \)) wrt ideal device is used
Fully differential circuits: Offset

\[ v_{\text{off,full}} = v_{\text{off,half}} + \Delta V_{T12} + \Delta V_{T34} \]

\[ v_{\text{off,full}} = v_{\text{off,half}} + \Delta V_{T12} - \Delta V_{T34} \]

- Calculate mean squared offset of the half circuit
- Multiply by \( 1 \times \) if mismatch between two real devices is used