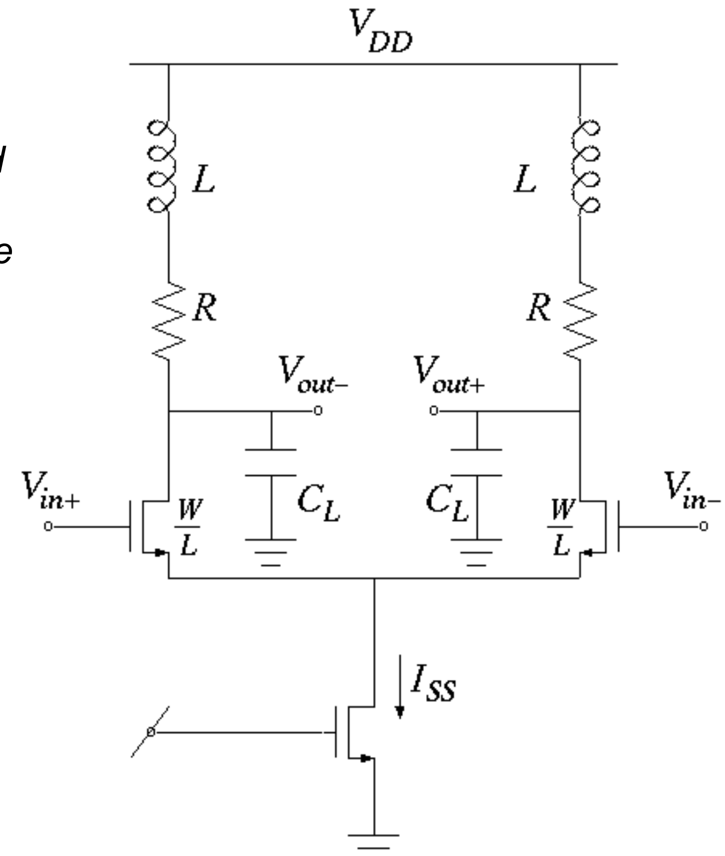
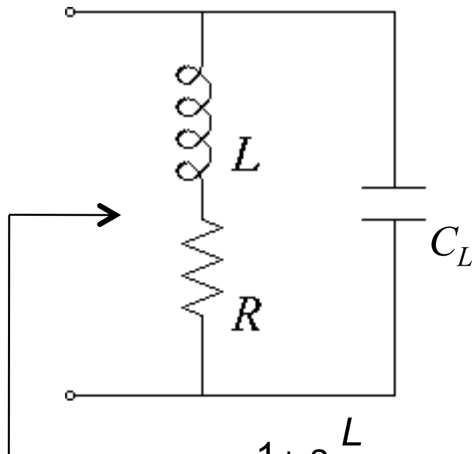
Shunt-Peaking (1)

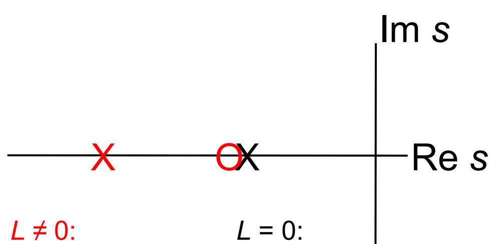
By connecting an inductor in series with the load resistor (series connection in shunt with output), more current is used, for a longer time, to charge the load capacitance.



Properties of Shunt-Peaking



$$Z(s) = R \cdot \frac{1 + s\frac{L}{R}}{1 + sC_L R + s^2 LC_L}$$



$L \neq 0$:
zero at $s = -R/L$
additional pole at
$s \approx -(1/CR + R/L)$

$L = 0$:
pole at $s = -1/RC$

Frequency response:

$$Z(j\omega) = R \cdot \frac{1 + j\omega\frac{L}{R}}{\left(1 - \omega^2 LC_L\right) + j\omega C_L R}$$

Resonant frequency:

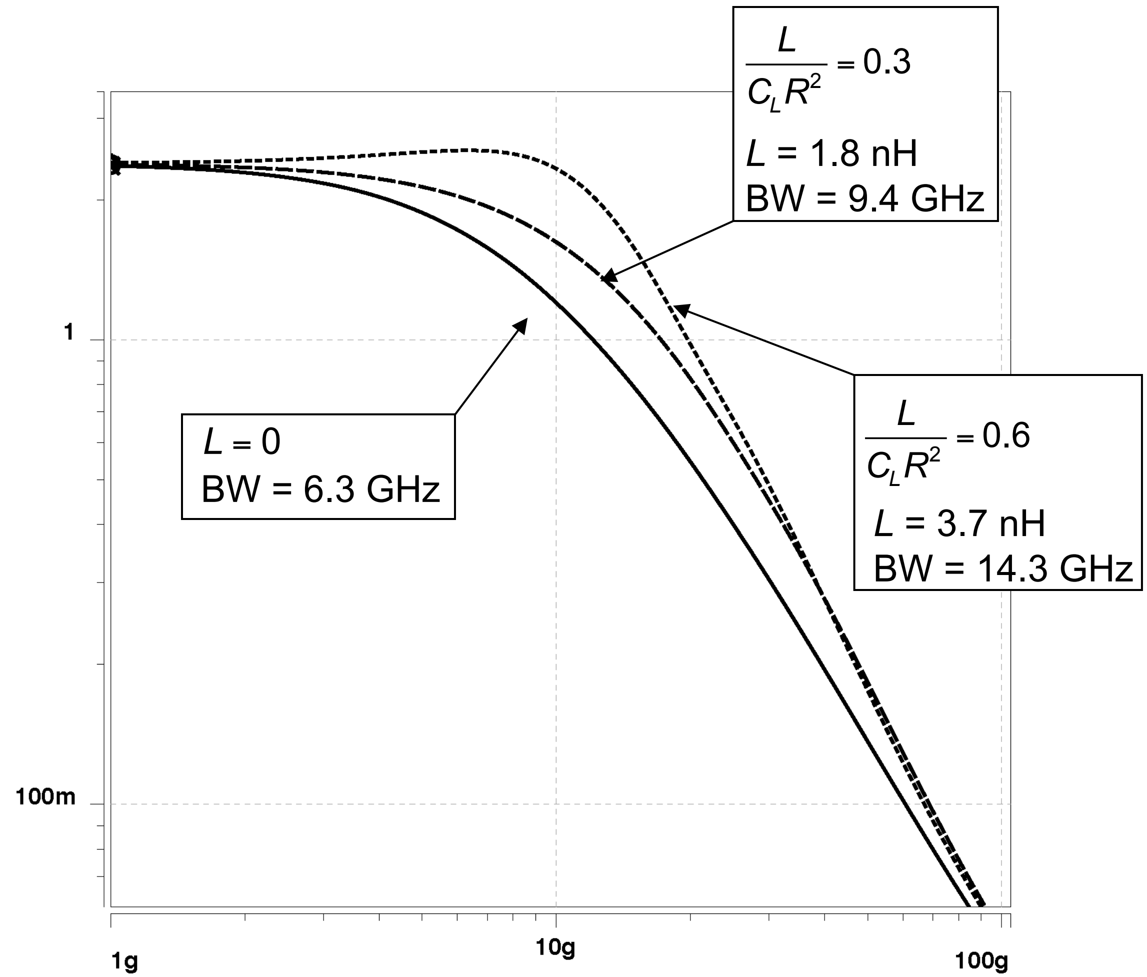
$$\omega_r^{\ 2} = \frac{1}{LC_L}\left(1 - \frac{C_L R^2}{L}\right)$$

No resonance for $\frac{L}{C_L R^2} < 1$

Shunt-Peaking -- AC Response

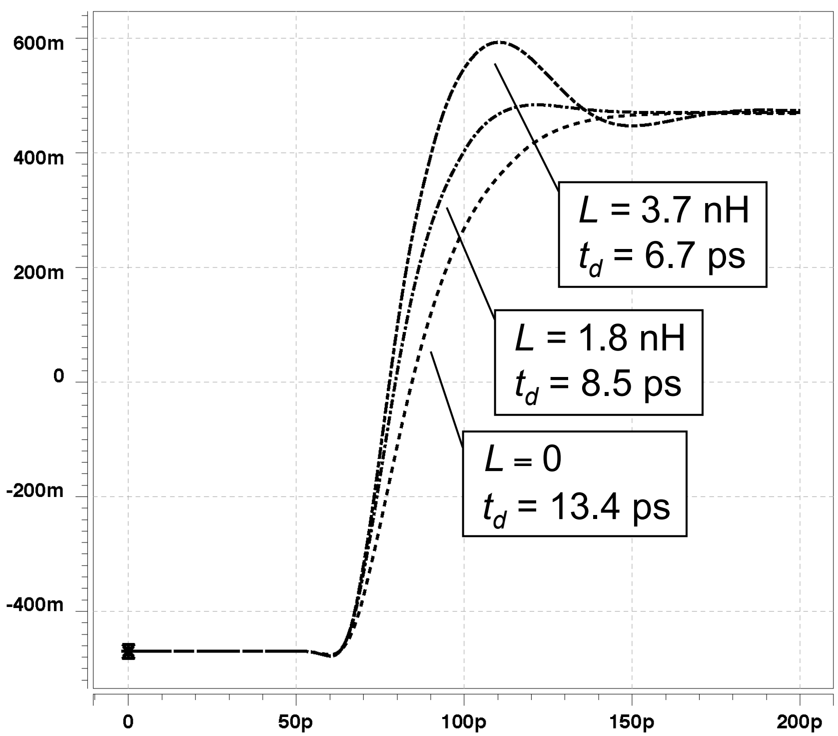
C_L = 38 fF
R = 400 Ω

Use of shunt-peaking increases small-signal bandwidth

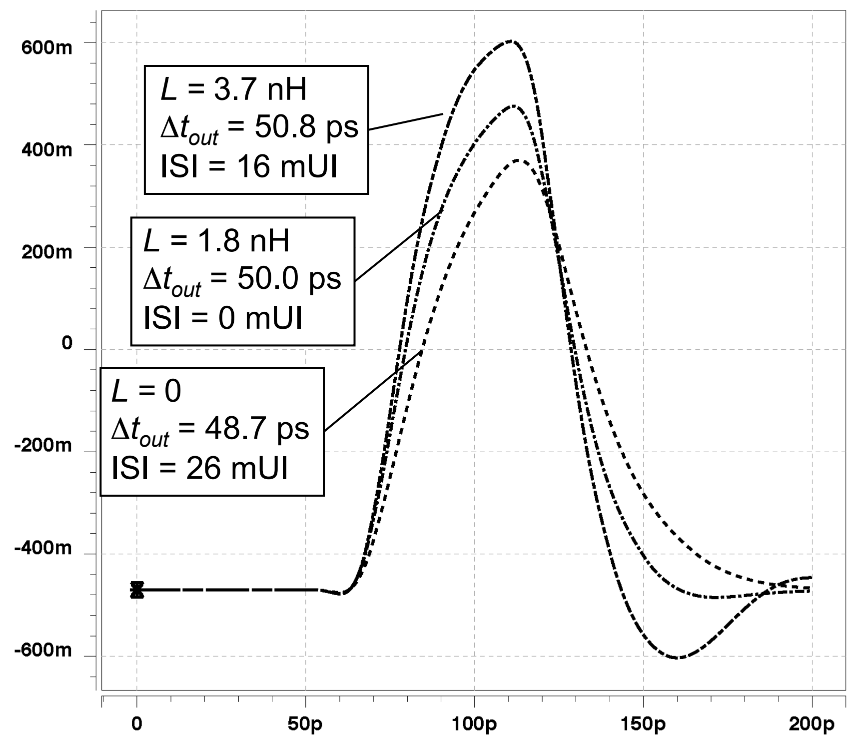


Shunt Peaking − Transient Response (1)

Step Response:



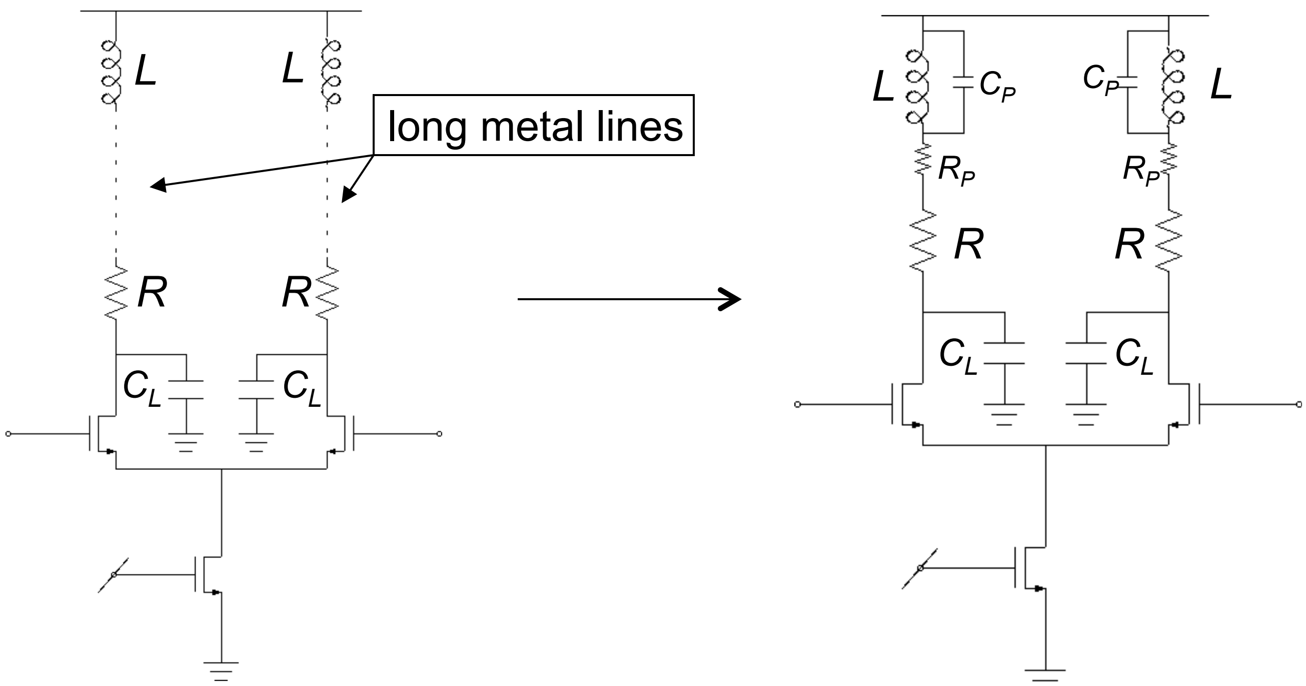
Pulse Response (Δt_{in} = 50 ps):



Other Advantages of Shunt-Peaking

- CML load is passive & linear
- Can be shown to be very robust in the presence of parasitic series resistance and shunt capacitance $\Rightarrow$ inductors can be placed far away from other CML circuit elements.

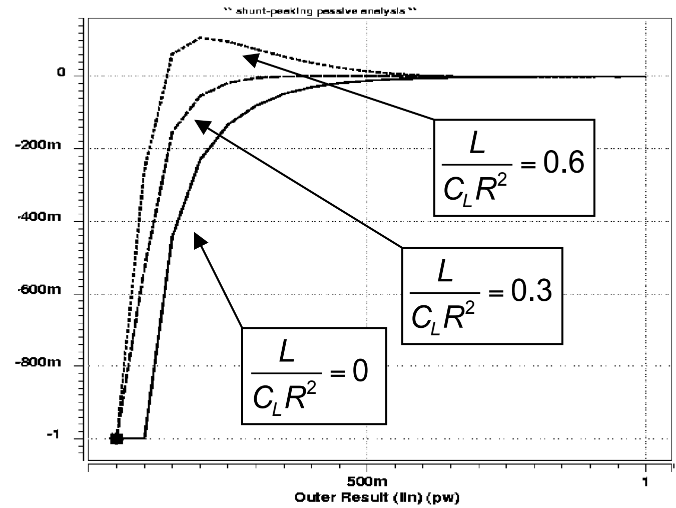
Effect of Shunt-Peaking Inductor Parasitics (1)



- Series resistance R_P simply adds to R
- Shunt capacitance C_P resonates with L …

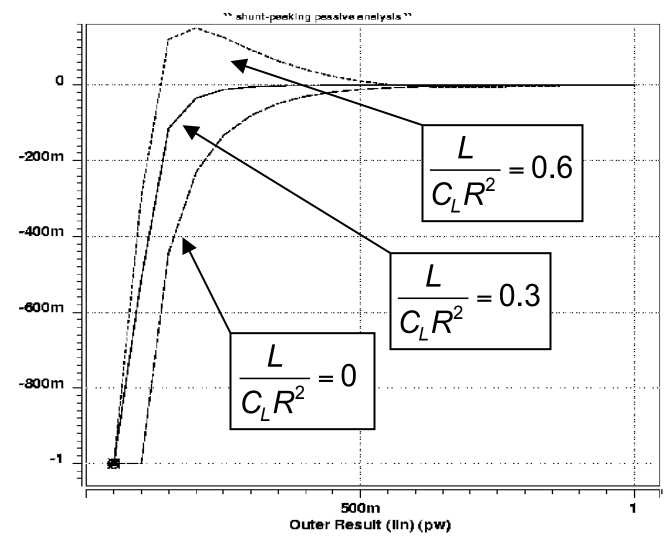
Effect of Shunt-Peaking Inductor Parasitics (2)

ISI (UI) vs. input pulse width
$C_P = 0$



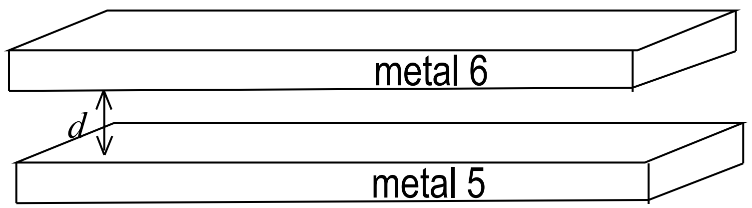
Moderate amount of parasitic capacitance has similar effect to slightly larger inductor.

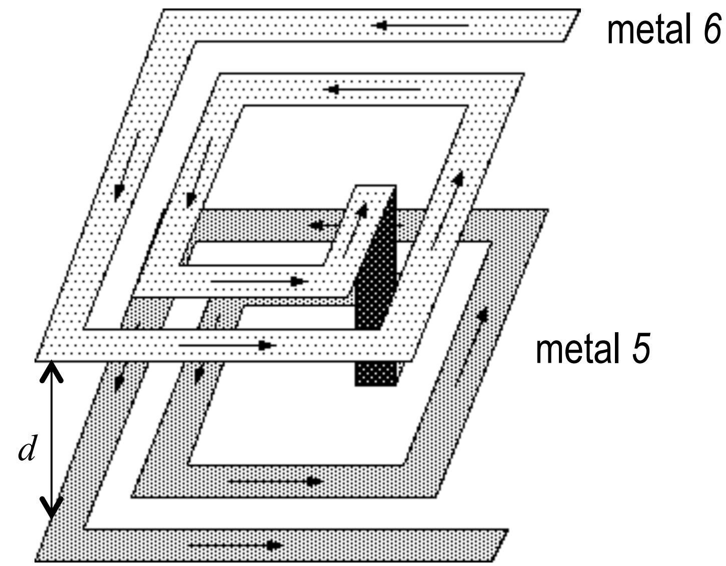
ISI (UI) vs. input pulse width
$C_P = 0.2C_L$



Disadvantages of using passive inductors:
- Consume huge die area
- Difficult to design & model

Multi-layer Inductors (1)

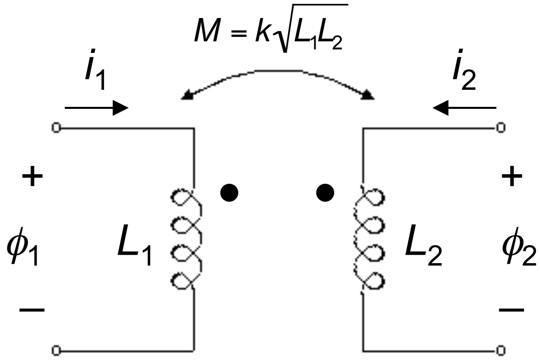




Distance *d* between two metal layers is much smaller than lateral distances (e.g., *w, l, s*)

Multi-layer Inductors (2)

<u>2-port representation of coupled inductors:</u>

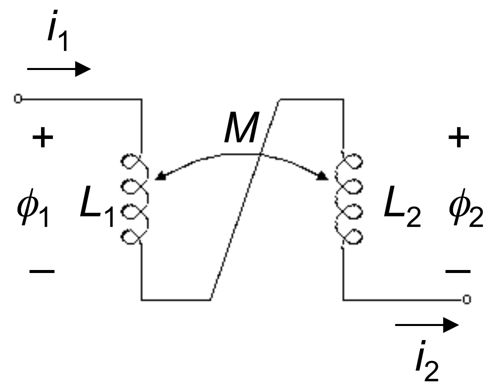


Passivity constraint: $k \le 1$

$$\begin{pmatrix}\phi_1\\ \phi_2\end{pmatrix} = \begin{bmatrix} L_1 & M \\ M & L_2 \end{bmatrix}\begin{pmatrix} i_1 \\ i_2\end{pmatrix}$$

For metal geometries close to each other, k is close to unity.

<u>series connection of coupled inductors:</u>



$$\phi_{series} = \phi_1 + \phi_2 = (L_1 + M)i_1 + (L_2 + M)i_2$$

$$i_{series} = i_1 = i_2$$

$$\Longrightarrow \quad L_{series} = \frac{\phi_{series}}{i_{series}} = L_1 + L_2 + 2M$$

For $L_1 = L_2 = L$, we have: $L_{series} = 2L + 2M = 2L(1+k) \approx 4L$

In general, for n layers we have: $L_{series} \approx n^2 L$

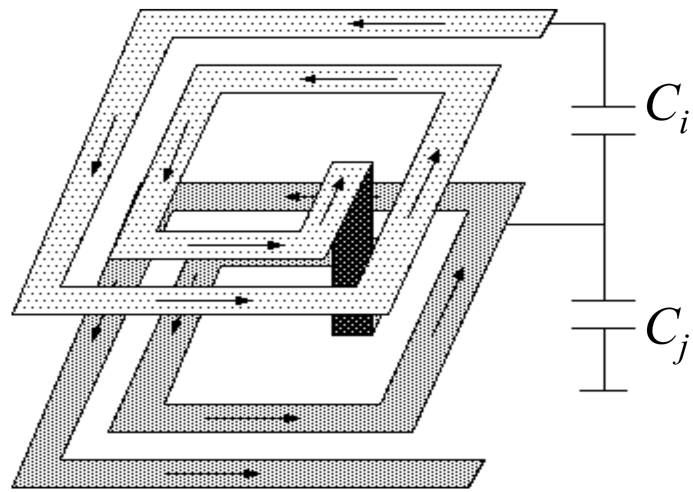
Multi-layer inductors are more appropriate for shunt-peaking than resonant structures due to additional contact resistance.

Multi-layer Inductors (3)

<u>Effective Capacitance:</u>

$$L_{effective} \approx 4L$$

$$C_{effective} \approx \frac{1}{3}C_i + \frac{1}{12}C_j$$



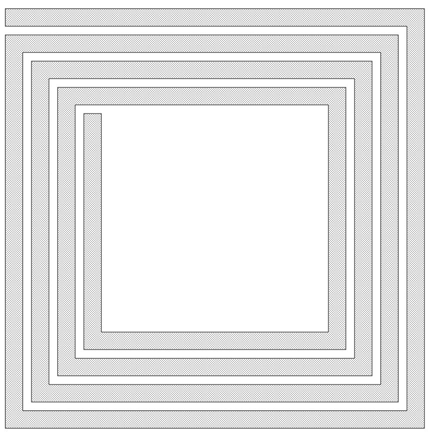
For more details, see:

A. Zolfaghari, A. Chan & B. Razavi, “Stacked inductors and transformers in CMOS technology,”
IEEE Journal of Solid-State Circuits, vol. 36, April 2001, pp. 620-628.

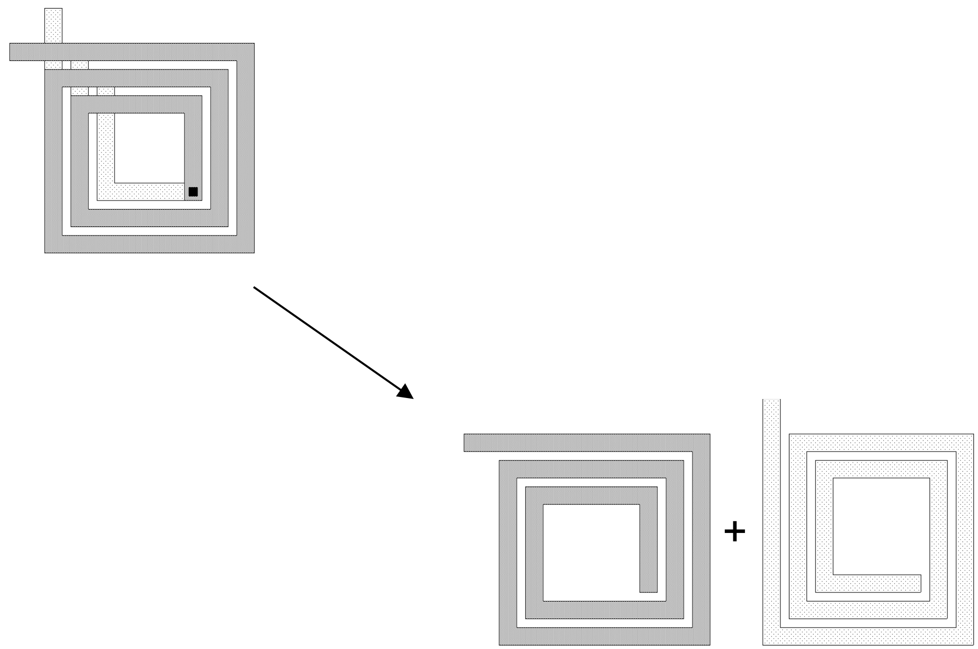
Multi-layer Inductors (4)

Area comparison:

metal 6 only
$100\mu \times 100\mu$
$w = 4$; $s = 2$; $n = 4$
L=2.0 nH
R=6.9 Ω

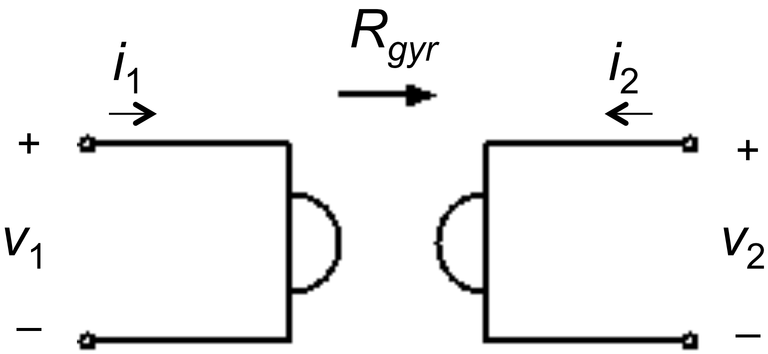


metal 6 over metal 4
$46\mu \times 46\mu$
$w = 4$; $s = 2$; $n = 2.5$
L=2.0 nH
R=12.5 Ω



Active Inductors (1)

Ideal gyrator:



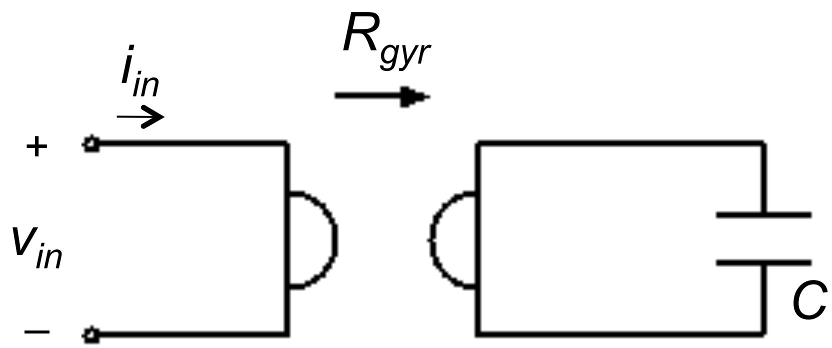
$$v_2 = R_{gyr} i_1$$

$$v_1 = -R_{gyr} i_2$$

Matrix representation (*Z*-parameters):

$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{bmatrix} 0 & -R_{gyr} \\ R_{gyr} & 0 \end{bmatrix} \begin{pmatrix} i_1 \\ i_2 \end{pmatrix}$$

Impedance inversion:

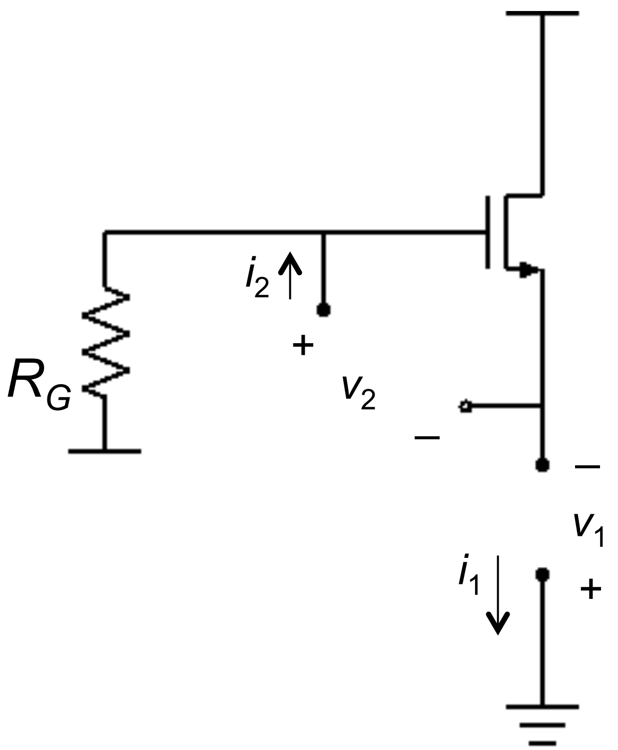


$$Z_{in} = R_{gyr}^2 \left(sC \right)$$

Port 1 exhibits inductance when port 2 is connected to a capacitance.

Active Inductors (2)

Consider common-drain configuration:



i_1 applied with port 2 open-circuited:

$$v_2 = \frac{1}{g_m} i_1$$

i_2 applied with port 1 open-circuited:

$$v_1 = -\left(R_G - \frac{1}{g_m}\right) i_2$$

(Assume $R_G\, g_m > 1$)

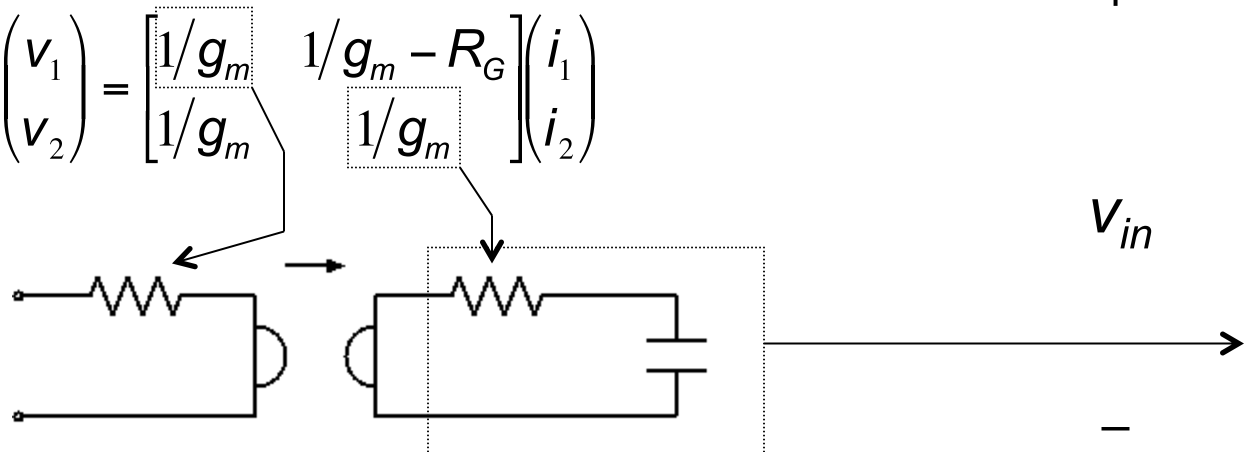
Complete Z-parameters (lossy/active gyrator):

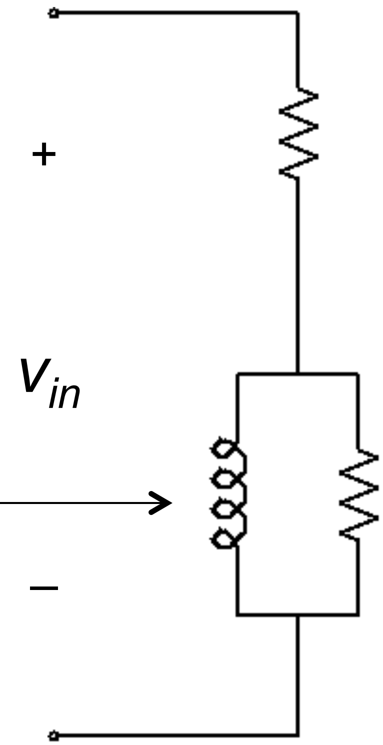
$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{bmatrix} 1/g_m & -\left(R_G - 1/g_m\right) \\ 1/g_m & 1/g_m \end{bmatrix} \begin{pmatrix} i_1 \\ i_2 \end{pmatrix}$$

Active Inductors (3)

Interpretation of non-ideal matrix entries:

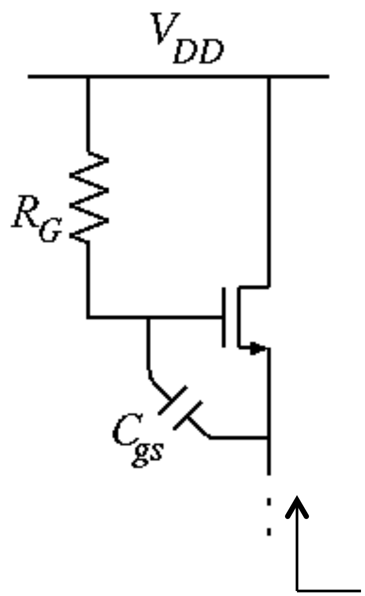
$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{bmatrix} 1/g_m & 1/g_m - R_G \\ 1/g_m & 1/g_m \end{bmatrix} \begin{pmatrix} i_1 \\ i_2 \end{pmatrix}$$





Active Inductors (4)

Impedance at port 1 with port 2 terminated with transistor C_{gs}:

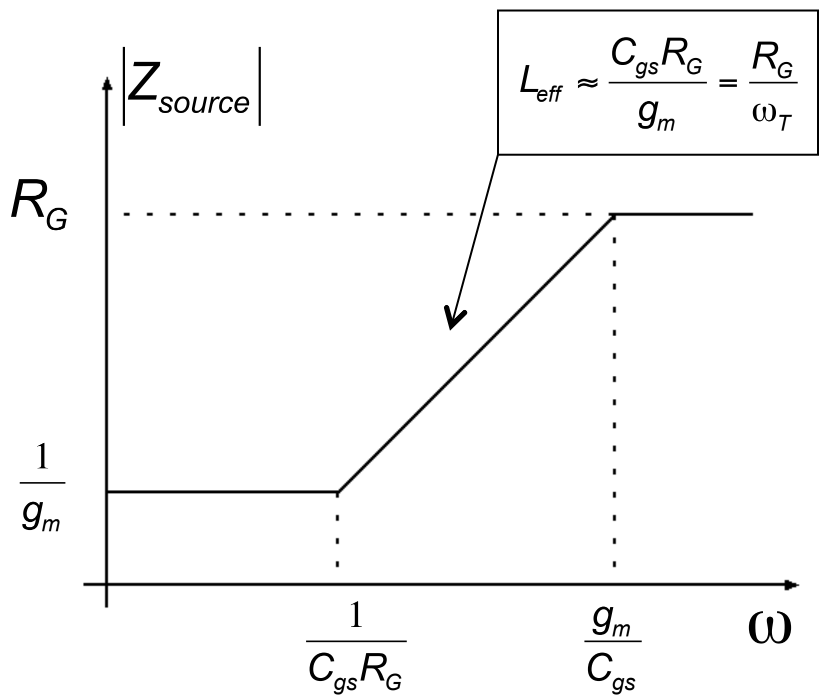


At low frequencies (C_{gs} open) $\Rightarrow$ $Z_{source} = 1/g_m$

At high frequencies (C_{gs} short) $\Rightarrow$ $Z_{source} = R_G$

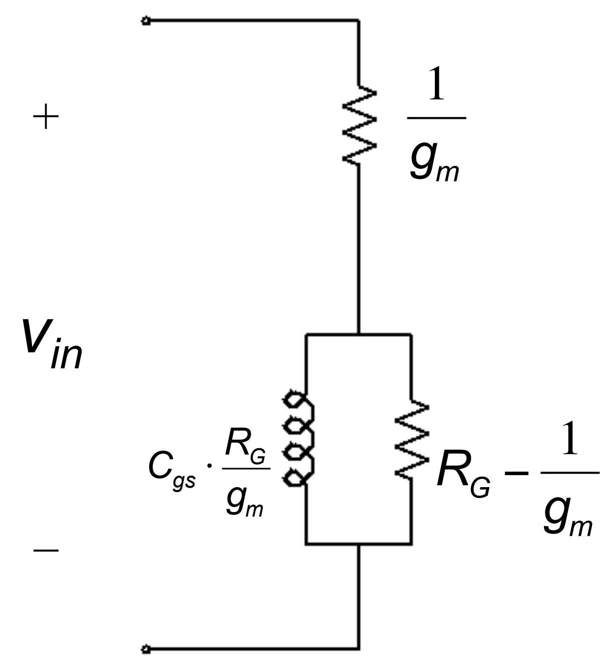
$$Z_{source} = \frac{1}{g_m}\left[\frac{1 + sC_{gs}R_G}{1 + sC_{gs}/g_m}\right]$$

Active Inductors (5)

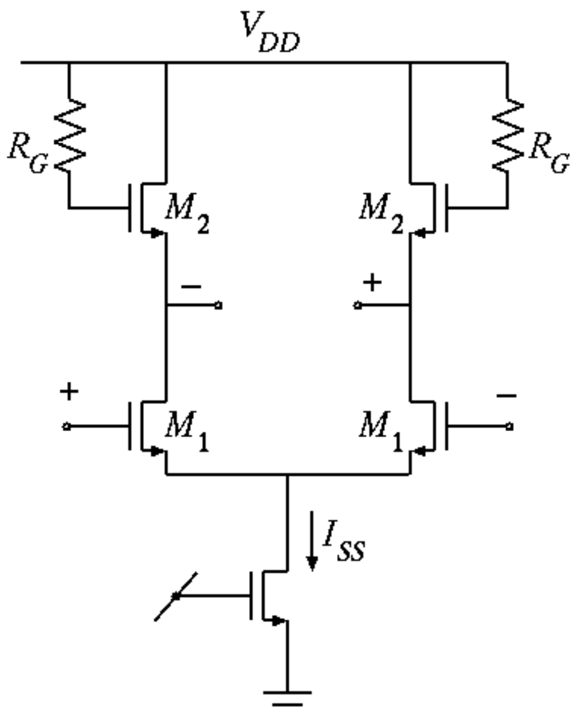


$g_m R_G > 1$

Equivalent circuit:



CML Buffer with Active Inductor Load



$$\left(\frac{W}{L}\right)_1 = \frac{4}{0.18} \quad \left(\frac{W}{L}\right)_2 = \frac{2.5}{0.18}$$

$$I_{SS} = 400\,\mu\text{A}$$

Low-frequency gain:

$$A_v = \frac{g_{m1}}{g_{m2}} = \sqrt{\frac{W_1}{W_2}}$$

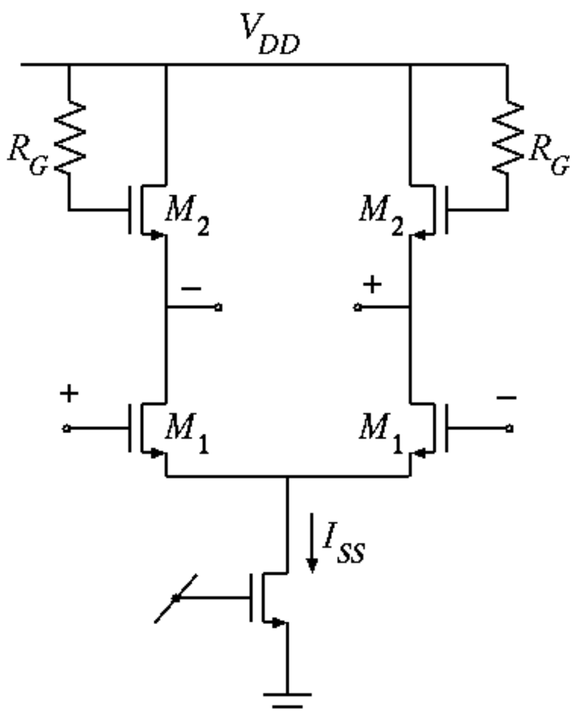
For shunt peaking:

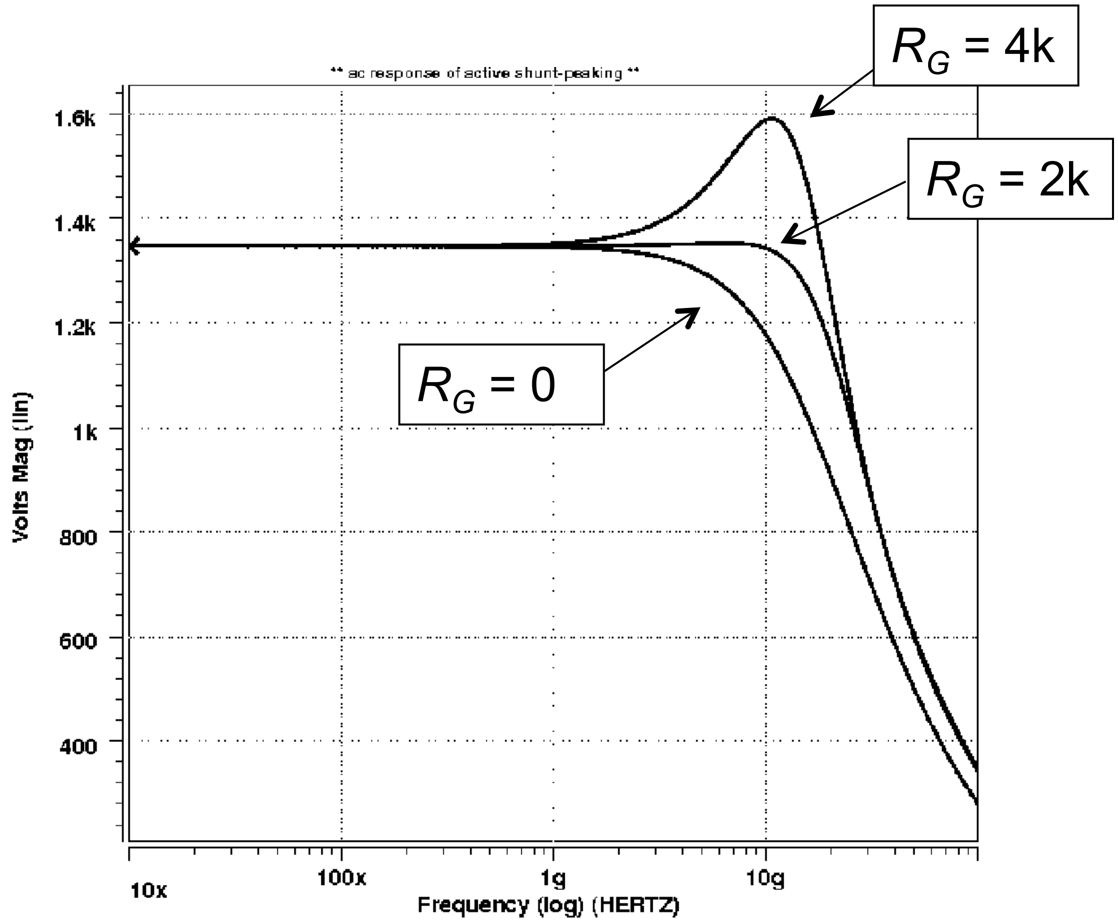
$$L \approx 0.3 C_L R^2$$

$$\downarrow$$

$$\frac{C_{gs} R_G}{g_{m2}} = 0.3 \frac{C_L}{g_{m2}^2} \longrightarrow g_{m2} R_G = 0.3 \frac{C_L}{C_{gs}}$$

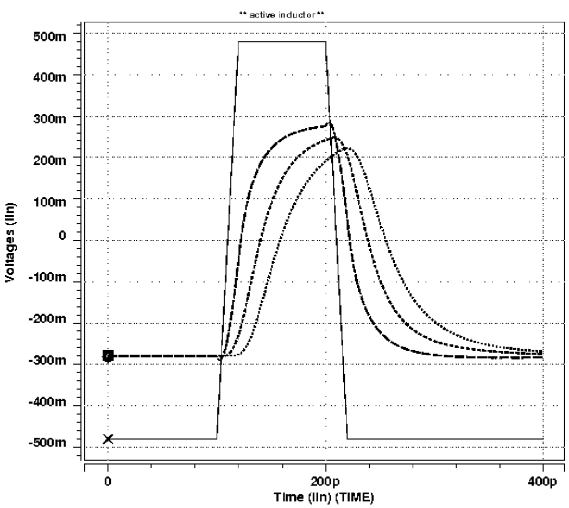
Active Inductor AC Response



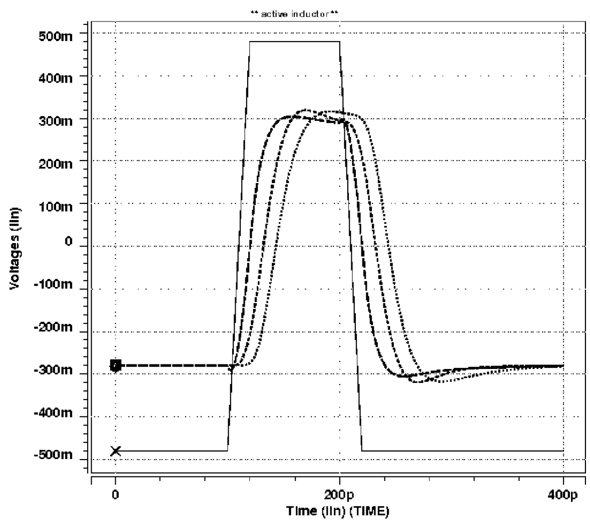


Active Inductor Transient Response (1)

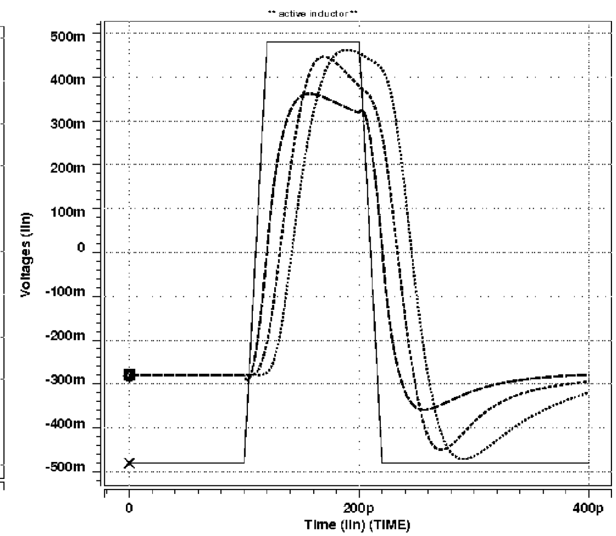
Differential signals:



$R_G = 0$
PW = 97ps



$R_G = 5k$
PW = 100 ps

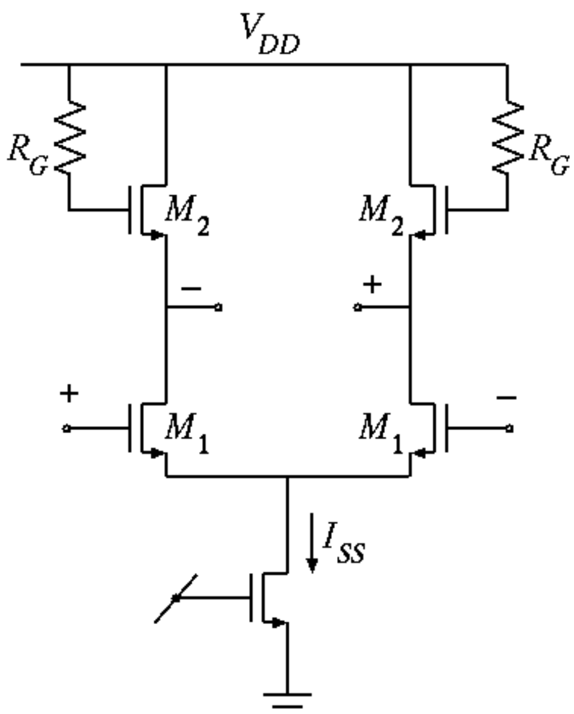


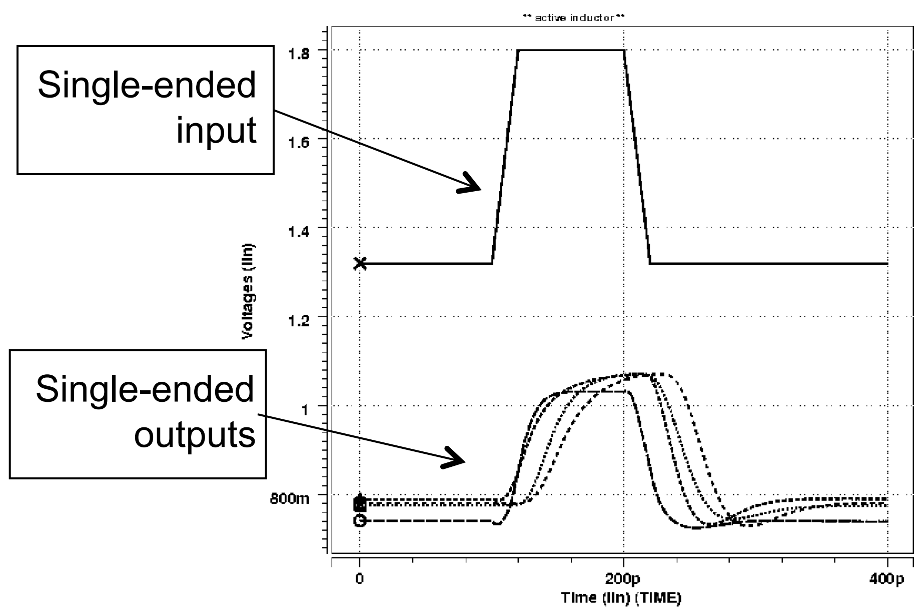
$R_G = 10k$
PW = 104 ps

Active Inductor Transient Response (2)

Single-ended signals:

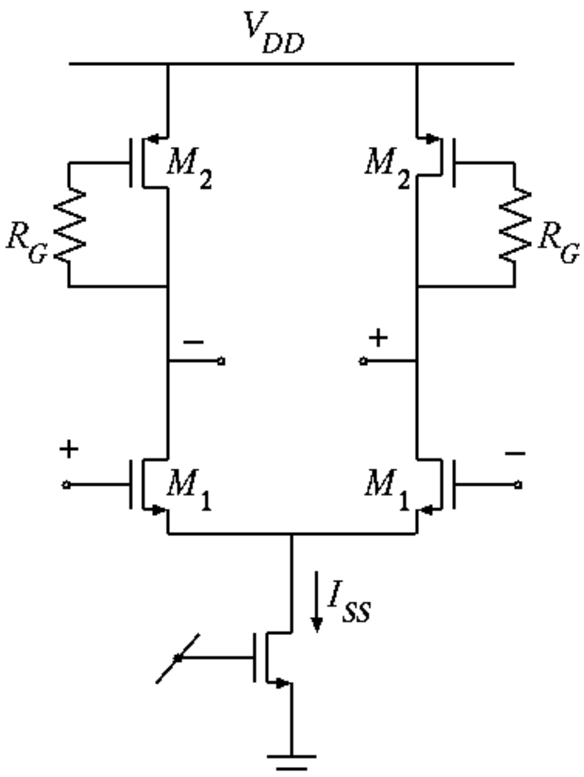
Problem: n-channel load shifts output by V_t.
V_{sb} > 0; body effects exacerbates this effect..

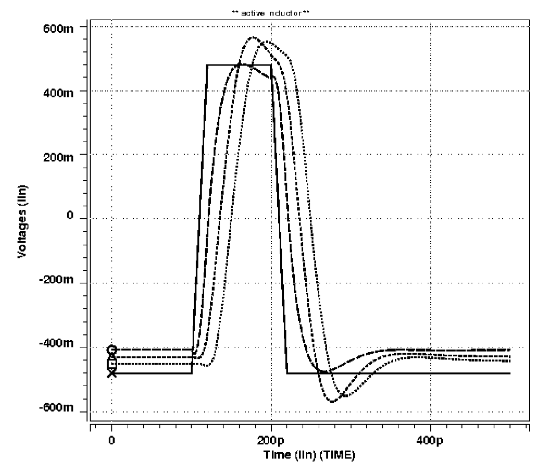




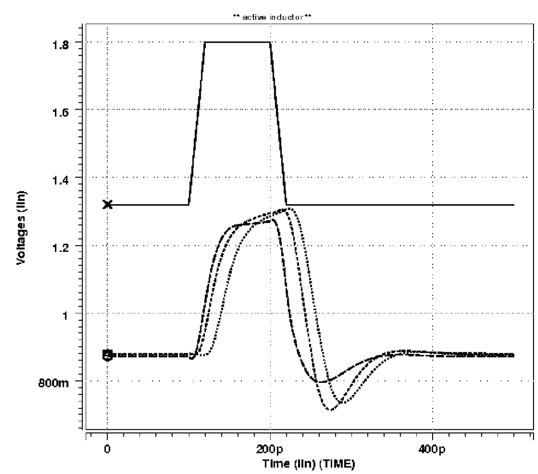
Active Inductor Alternate Topology

Alternate topology:
p-channel load exhibits lower V_t
(V_{bs} = 0)





differential



single-ended