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

Frequency response:

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

Resonant frequency:

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

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

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

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

L = 0:
pole at \( s = -1/RC \)
Shunt-Peaking -- AC Response

Use of shunt-peaking increases small-signal bandwidth

- $C_L = 38 \text{ fF}$
- $R = 400 \Omega$

- $L = 1.8 \text{ nH}$
- $BW = 9.4 \text{ GHz}$

- $L = 3.7 \text{ nH}$
- $BW = 14.3 \text{ GHz}$

- $\frac{L}{C_LR^2} = 0.3$
- $L = 0$
- $BW = 6.3 \text{ GHz}$

- $\frac{L}{C_LR^2} = 0.6$
Shunt Peaking – Transient Response (1)

Step Response:

$L = 3.7 \text{ nH}$
$\tau_d = 6.7 \text{ ps}$

$L = 1.8 \text{ nH}$
$\tau_d = 8.5 \text{ ps}$

$L = 0$
$\tau_d = 13.4 \text{ ps}$

Pulse Response ($\Delta t_{in} = 50 \text{ ps}$):

$L = 3.7 \text{ nH}$
$\Delta t_{out} = 50.8 \text{ ps}$
ISI = 16 mUI

$L = 1.8 \text{ nH}$
$\Delta t_{out} = 50.0 \text{ ps}$
ISI = 0 mUI

$L = 0$
$\Delta t_{out} = 48.7 \text{ ps}$
ISI = 26 mUI
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 ⇒ 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)

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

Disadvantages of using passive inductors:
- Consume huge die area
- Difficult to design & model
Distance $d$ between two metal layers is much smaller than lateral distances (e.g., $w$, $l$, $s$)
**Multi-layer Inductors (2)**

2-port representation of coupled inductors:

\[
\begin{bmatrix}
\phi_1 \\
\phi_2
\end{bmatrix} =
\begin{bmatrix}
L_1 & M \\
M & L_2
\end{bmatrix}
\begin{bmatrix}
i_1 \\
i_2
\end{bmatrix}
\]

Passivity constraint: \( k \leq 1 \)

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

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

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

**series connection of coupled inductors:**

\[
\begin{align*}
\phi_{\text{series}} &= \phi_1 + \phi_2 = (L_1 + M)i_1 + (L_2 + M)i_2 \\
i_{\text{series}} &= i_1 = i_2
\end{align*}
\]

\[
L_{\text{series}} = \frac{\phi_{\text{series}}}{i_{\text{series}}} = L_1 + L_2 + 2M
\]

Multi-layer inductors are more appropriate for shunt-peaking than resonant structures due to additional contact resistance.
Multi-layer Inductors (3)

Effective Capacitance:

\[ L_{\text{effective}} \approx 4L \]
\[ C_{\text{effective}} \approx \frac{1}{3} C_i + \frac{1}{12} C_j \]

For more details, see:

A. Zolfaghari, A. Chan & B. Razavi, “Stacked inductors and transformers in CMOS technology,”
Multi-layer Inductors (4)

Area comparison:

metal 6 only
100\(\mu\) x 100\(\mu\)
w = 4; s = 2; n = 4
L = 2.0 nH
R = 6.9 \(\Omega\)

metal 6 over metal 4
46\(\mu\) x 46\(\mu\)
w = 4; s = 2; n = 2.5
L = 2.0 nH
R = 12.5 \(\Omega\)
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:

\[ Z_{in} = R_{gyr}^2 (sC) \]

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):**

\[
\begin{pmatrix}
  v_1 \\
  v_2 \\
\end{pmatrix} = \begin{bmatrix}
  \frac{1}{g_m} & -\left( R_G - \frac{1}{g_m} \right) \\
  \frac{1}{g_m} & \frac{1}{g_m} \\
\end{bmatrix} \begin{pmatrix}
  i_1 \\
  i_2 \\
\end{pmatrix}
\]
Active Inductors (3)

Interpretation of non-ideal matrix entries:

\[
\begin{pmatrix}
    v_1 \\
    v_2
\end{pmatrix} =
\begin{bmatrix}
    \frac{1}{g_m} & \frac{1}{g_m} - R_G \\
    \frac{1}{g_m} & \frac{1}{g_m}
\end{bmatrix}
\begin{pmatrix}
    i_1 \\
    i_2
\end{pmatrix}
\]
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) $\Rightarrow Z_{source} = R_G$

$$Z_{source} = \frac{1}{g_m \left[ 1 + s C_{gs} R_G \right]} \frac{1 + s C_{gs} / g_m}{1 + s C_{gs} / g_m}$$
Active Inductors (5)

Equivalent circuit:

\[
L_{\text{eff}} = \frac{C_{gs}R_G}{g_m} = \frac{R_G}{\omega_T}
\]

\[
g_m R_G > 1
\]

\[Z_{\text{source}}\]

\[R_G\]

\[\frac{1}{g_m}\]

\[\frac{1}{C_{gs}R_G}\]

\[\frac{g_m}{C_{gs}}\]

\[\omega\]

\[V_{\text{in}}\]
CML Buffer with Active Inductor Load

\[ \frac{W_1}{L} = \frac{4}{0.18}, \quad \frac{W_2}{L} = \frac{2.5}{0.18} \]

\[ I_{SS} = 400 \mu A \]

Low-frequency gain:

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

For shunt peaking:

\[ L \approx 0.3 C_L R^2 \]

\[ \frac{C_{gs} R_G}{g_{m2}} = 0.3 \frac{C_L}{g_{m2}^2} \]

\[ g_{m2} R_G = 0.3 \frac{C_L}{C_{gs}} \]
Active Inductor AC Response

\[ R_G = 4k \]
\[ R_G = 2k \]
\[ R_G = 0 \]
Active Inductor Transient Response (1)

Differential signals:

\[ R_G = 0 \]
\[ PW = 97\text{ps} \]

\[ R_G = 5\text{k} \]
\[ PW = 100\text{ps} \]

\[ R_G = 10\text{k} \]
\[ PW = 104\text{ps} \]
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 $V_t$ ($V_{bs} = 0$)

\[ V_{DD} \]

\[ M_1 \quad M_2 \]

$R_G$

\[ \text{differential} \]

\[ \text{single-ended} \]