• FULLY CURRENT-MODE

Input Signal: Current
Output Signal: Current

Basic Building Blocks are:

Inverting Integrators
Inverting (Current Amplifiers)

Primitive Circuit Implementations:

Single Transistor Inverting Amplifier
Simple Current Mirror
Capacitor
Current-Mode Implementation using OTA's

Integrator

Self Loop Integrator

\[ R = \frac{1}{g_{mr}} \]
In order to fully obtain the benefits of current-mode techniques simpler circuits with reduced parasitics are desirable.

**Primitive CM Circuits**

**Inverting Integrator**

**Amplifier (Multiplier by a constant)**
Non-Inverting Integrator
3.3V Power supply
High frequency
Low area
Suitable for digital process
Good PSR
Poor linearity, efficiency (1% THD => $\eta < 4\%$)
Poor voltage gain

Low power supply (3.3V)
High frequency
Low area
Suitable for digital process
Very good PSR
Good Linearity (differential)
Excellent efficiency (≈ 100\%)
Poor common mode rejection
(a) Tunable CMOS class AB integrator  
(b) Transistor Implementation with Mrn and Mrp operating in triode region  
(c) Bias implementation (diffusion or poly resistors).

**Linearity sufficient**

**Very high efficiency (> 100%) => AB, low power**

**Very high frequency**

**Small area**

**Low Power Supply**

**Linearity dep. on process variations**

**PSR poor**
How to convert a Lossy Transconductance Integrator With Positive Feedback into a Current-Mode Lossy Integrator

\[
\frac{V_o}{V_{in}} = \frac{-g_{m1}Z}{1 - g_{m1}Z} = -\frac{g_{m1}}{sC_2 + (g_{m2} - g_{m1})}
\]
OTA-C Lossy Integrator With Single (Negative) Input OTA's

Current-Mode Version
Transistor Level Implementation

CM Lossy (Lossless) Integrator

\[ I_{b2} \quad I_{b1} \quad I_{b3} \quad I_{b4} \quad I_{b0} \]

\[ I_{in} \quad I_f \]

\[ g_{m2} \quad g_{m1} \quad g_{m3} \quad g_{m4} \]

\[ C \]

\[ g_{m0} = g_{m1} \]
Redrawing the CM Integrator
Fully Pseudo Differential Integrator

\[
A_{d_m} = \frac{I_+^+I_o^-}{I_{in}^+ - I_{in}^-} = \frac{-\omega_u}{s + (A_N + A_P)\omega_u}
\]

\[
A_{c_m} = \frac{I_o^+ + I_o^-}{I_{in}^+ + I_{in}^-} = \frac{-\omega_u}{s + (A_N + A_P)\omega_u}
\]

\[A_N = A_P\]

\[(g_{m_N} = g_{m_P})\]
Continuous-Time Current-Mode Integrator Based On Current-Mirrors.
\[ i_f = \frac{i_1 \frac{g_{m_2}}{g_{m_1}} - i_2}{g_{m_1}(g_{m_3} + sC) - g_{m_2}g_{m_4}} \cdot g_{m_1}g_{m_4} \]

\[ i_f = g_{m_1}g_{m_4} \frac{i_1 \frac{g_{m_2}}{g_{m_1}} - i_2}{g_{m_1}g_{m_3} - g_{m_2}g_{m_4} + g_{m_1}sC} \]

\text{a) Lossless Integrator}

\[ g_{m_1} = g_{m_2} \quad \text{and} \quad g_{m_3} = g_{m_4} \]

\[ i_f = \frac{g_{m_4}}{sC} (i_1 - i_2) \]

\[ i_{out} = K \frac{g_{m_4}}{sC} (i_1 - i_2) \]
b) Lossy Integrator

\[ g_{m1} g_{m3} > g_{m2} g_{m4} \quad , \quad g_{m1} = k g_{m2} \quad , \quad g_{m3} = k g_{m4} \]

\[ i_f = \frac{k}{k^2 - 1} \frac{ki_1 - i_2}{1 + \frac{sC}{k^2 - 1}} \frac{k}{g_{m4}} \quad , \quad k > 1 \]

i.e. \( k = 2 \)

\[ i_f = \frac{2}{3} \frac{2i_1 - i_2}{1 + \frac{3sC}{g_{m4} \frac{3}{2}}} \]

If the parasitic capacitances and the output conductances are considered, then

\[ i_f = \frac{-k_1(s - z_1)i_1}{(s + p_1)(s + p_2)} - \frac{k_2(s + z_2)}{(s + p_1)(s + p_2)} \]
Where

\[ k_1 = \frac{g_o}{C_1}, \quad k_2 = \frac{g_m}{C_2} \]
\[ p_1 = \frac{4g_o}{C_2}, \quad p_2 = \frac{g_m}{C_1} \]
\[ z_1 = \frac{g_m g_m}{C_2 g_o}, \quad z_2 = \frac{g_m + g_o}{C_1} \]

All transistors are equal, and \( C_1 \) and \( C_2 \) are the lumped nodal capacitances associated with nodes 1 and 2. Note that \( p_1 \) moves from the origin to

\[ p_1 \rightarrow \frac{\omega_o}{\alpha} = \frac{g_m}{4g_o} \]

And

\[ Q = -\frac{g_m}{C_1} \frac{C_2}{g_m} \]
Let's consider the input and output impedance,

\[ z_{\text{in}} = \left. \frac{V_1}{i_1} \right|_{i_2 = 0} = \frac{g_{m3} + g_{o2} + g_{o3} + sC_2}{-g_{m4}g_{m2} + (g_{m1} + g_{o1} + g_{o4} + sC_1)(g_{m3} + g_{o2} + g_{o3} + sC_2)} \]

\[ z_{\text{in}} = \left. \frac{V_1}{i_1} \right|_{i_2 = 0} \approx \frac{g_{m3}(1 + sC_2 / g_{m3})}{-g_{m4}g_{m2} + g_{m1}g_{m3} + s(C_2g_{m1} + C_1g_{m3}) + s^2C_1C_2} \]
a) Lossless Integrator

\[ z_{in} (0) \approx \frac{g_{m3}}{g_{m4} g_{m2} + g_{m1} g_{m3}} \bigg| \begin{array}{l}
g_{m1} = g_{m2} \\
g_{m3} = g_{m4} \end{array} \rightarrow \infty \]

b) Lossy Integrator

\[ z_{in} (0) \approx \frac{k^2}{k^2 - 1} \frac{1}{g_{m1}} , \quad k > 0 \]

\[ z_o (0) \approx \frac{1}{g_{o5}} \]