Noise Considerations in Microwave Operational Transconductance Amplifiers (OTAs)

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Outline

• Fundamentals: OTAs and their (mostly) baseband applications

• OTAs in Microwave Circuits and Systems

• Microwave OTA circuit design

• Conclusion
Fundamentals
The basic definition of an OTA

• voltage-in / current-out amplifiers

\[ i_{out+} - i_{out-} = g_m (v_{in+} - v_{in-}) \]

\[ g_m = f(I_{tune}, V_{DD}) \]

• infinite input resistance

• infinite output admittance

learn to exploit this!
OTA configurations

Single-ended

Differential input

Differential input & output

\[ v_i \]

\[ g_m v_i \]

\[ v_{i+} \]

\[ g_m (v_{i+} - v_{i-}) \]

\[ v_{i-} \]

\[ -g_m (v_{i+} - v_{i-}) / 2 \]
Basic OTA applications

using the simplest possible model......

\[ Z_{in} = 1/g_{m1} \]

\[ i_{in} = -i_{o} \]

\[ Z_{in} = \frac{v_{in}}{i_{in}} = \frac{v_{in}}{-i_{o}} = \frac{v_{in}}{(-(-g_{m1}v_{in}))} = 1/g_{m1} \]
Basic OTA applications

\[ H(s) = \frac{v_{out}(s)}{v_{in}(s)} = \frac{g_{m1}}{g_{m1} + sC} = \frac{1}{1 + sRC} \]

\[ \omega_p = \frac{g_{m1}}{C} \]
Basic OTA applications

\[
\frac{v_{out}}{v_{in}} = \frac{g_{m1} + sC_2}{s(C_1 + C_2) + g_{m1} + g_{m2}}
\]
Basic OTA applications

At the output,

\[ v_o = g_{m1} v_{in} Z_L \quad (1) \]

and through the feedback path,

\[ v_{in} = g_{m2} v_o Z_{in} \]

\[ v_o = v_{in} / (g_{m2} Z_{in}) \quad (2) \]

making eqn. (1) = eqn. (2),

\[ g_{m1} v_{in} Z_L = v_{in} / (g_{m2} Z_{in}) \quad (3) \]

and solving (3) for \( Z_{in} \) yields

\[ Z_{in} = 1 / (Z_L g_{m1} g_{m2}) \quad (4) \]
Basic OTA applications

\[ Z_{in} = \frac{1}{Z_L g_m1 g_m2} \]

Differential impedance inverter

See reference [1] for more baseband applications of OTAs.
OTAs in Microwave Circuits and Systems
Multi-order QAM circuit

For 4-QAM: $b_0b_1$
For 16-QAM: $b_0b_1b_2b_3$
Multi-order QAM circuit

For further details see [2].
Active quasi-circulator
Active quasi-circulator
Active Quasi-Circulator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP_{1dB}</td>
<td>-6.4 dBm</td>
</tr>
<tr>
<td>IIP3</td>
<td>+1.2 dBm</td>
</tr>
<tr>
<td>NF</td>
<td>10.4±0.2 dB</td>
</tr>
<tr>
<td>DC power</td>
<td>86 mW</td>
</tr>
<tr>
<td>Core size</td>
<td>0.25 sq. mm.</td>
</tr>
<tr>
<td>Technology</td>
<td>180 nm CMOS</td>
</tr>
</tbody>
</table>

For further details see [3].
OTAs in active mixers

 OTA

Noise in Microwave Operational Transconductance Amplifiers
Variable conversion gain mixer

\[ CG = \kappa G_m Z_L \]

\[ \kappa = \frac{2}{\pi} \left( \frac{\sin(\omega_{LO} \tau_r)}{\omega_{LO} \tau_r} \right) \]
VCG mixer

For further details see [4].
## VCG mixer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF frequency input (GHz)</td>
<td>1 to 12 GHz</td>
</tr>
<tr>
<td>Conversion gain (dB)</td>
<td>+1.2 to +17 dB</td>
</tr>
<tr>
<td>Input $P_{1\text{dB}}$ (dBm)</td>
<td>-3.7 (max) -12 (min)</td>
</tr>
<tr>
<td>Input IP3 (dBm)</td>
<td>+8.6 (max) +2.5 (min)</td>
</tr>
<tr>
<td>DSB noise figure (dB)</td>
<td>11 (min) &gt;19 (max)</td>
</tr>
<tr>
<td>DC power (mW)</td>
<td>1.8 (min) 5.9 (max)</td>
</tr>
<tr>
<td>Vdd (V)</td>
<td>1.2</td>
</tr>
<tr>
<td>Chip core area (sq. mm.)</td>
<td>0.105</td>
</tr>
<tr>
<td>CMOS node (nm)</td>
<td>130</td>
</tr>
</tbody>
</table>
Microwave OTA Circuit Design
Full CMOS version

\[ Y_R = Y_0 \left( \frac{1 - S_{11}}{1 + S_{11}} \right) \]

\[ |g_{m,OTA}| \approx \text{Re}(Y_R) \]

For further details see [5].
The feedforward regulated cascode OTA

In the ideal case of a perfectly balanced circuit:

\[ G_m = \frac{i_{o+} - i_{o-}}{v_{i+} - v_{i-}} \]

\[ = g_{m3} \left[ \frac{1}{r_{o5}} + \frac{2g_{m5}}{r_{o5} + \frac{1}{r_{o5}} + 2g_{m5}} \right] \]

\[ R_o = 2r_{o3} + 2r_{o5} + 4g_{m5}r_{o3}r_{o5} \]

For further details see [6-8].
Frequency response
How to make a low-noise OTA?

Start with the noise-cancelling method [9] used in LNAs:
Low-noise OTA (LNTA)

Cross-couple the basic cells to get:

For further details see [10,11].
The CG-CS pair

Output noise voltages:

\[ v_o^+ - v_o^- = v_{ny} - v_{nz} = i_{n1}(1 - g_{m2}Z_s)Z_L \]

For cancellation:

\[ g_{m2} = 1/Z_s = g_{m1} \]
The LNTA noise circuit model
Noise Factor (thermal noise only)

Definition:

\[ F = \frac{SNR_{in}}{SNR_{out}} = 1 + \frac{|i_{n,\text{added}}|^2}{G_{m,\text{eff}}^2 |v_{ns}|^2} \]

the added noise current is:

\[ |i_{n,\text{added}}|^2 = |i_{n,G_m}|^2 + |i_{n,\text{actLoad}}|^2 \]

\[ |i_{n,G_m}|^2 = |i_{n1}|^2 (g_{m2} Z_s - 1)^2 + |i_{n2}|^2 \]

\[ = |i_{n1}|^2 (g_{m2} Z_s - 1)^2 + 4kT \gamma_n g_{m2} \]

\[ |i_{n,\text{actLoad}}|^2 = |i_{nd5}|^2 + |i_{n,R_0}|^2 = 4kT \gamma_p g_{m5} + \frac{4kT}{R_0} \]
Noise Factor

The source noise voltage is:

\[ v_{ns} = \sqrt{4kTR_s} \frac{Z_{\text{in,eff}}}{R_s + Z_{\text{in,eff}}} \]

where,

\[ Z_{\text{in,eff}} \approx \frac{r_{o1} + Z_L}{1 + (g_{m1} + g_{mb1})r_{o1}} \]

\[ G_{m,eff} \approx \frac{1 + (g_{m1} + g_{mb1})r_{o1}}{r_{o1} + Z_L} + \frac{g_m2r_{o2}}{r_{o2} + Z_L} \]

and substituting...

\[ F = 1 + \frac{|i_{n1}|^2(g_{m2}R_s - 1)^2}{4kTR_s^{-1}(R_s \parallel Z_{\text{in,eff}})^2G_{m,eff}^2} + \frac{r_ng_{m2} + r_pg_{m5} + R_0^{-1}}{R_s^{-1}(R_s \parallel Z_{\text{in,eff}})^2G_{m,eff}^2} \]

\[ F = 1 + 4 \frac{r_ng_{m2} + r_pg_{m5} + R_0^{-1}}{R_sG_{m,eff}^2} = 1 + 4 \frac{r_ng_{m2} + r_pg_{m5} + R_0^{-1}}{\left[ \frac{1+(g_{m1}+g_{mb1})r_{o1}}{Z_L+r_{o1}} + \frac{g_m2r_{o2}}{Z_L+r_{o2}} \right]^2 R_s} \]
Conclusion

• Fully differential OTAs offer the greatest versatility and system design possibilities.

• OTAs can be used to implement more complex microwave circuits while keeping chip dimensions small.

• Reducing the NF of OTAs continues to be an active area of investigation.
References