
Mark Rodwell

University of California, Santa Barbara

rodwell@ece.ucsb.edu  805-893-3244, 805-893-3262 fax
Two-Port Oscillator Theory

Why?

Selection of oscillator topology seems ad-hoc.

Is there any reason to pick a particular topology?

Many standard oscillators will not oscillate at $f_{\text{max}}$!

Is "maximum frequency of oscillator" an oxymoron?

Or are we not designing our oscillators well?

Two-port theory will answer this.
Two-Port Oscillator Theory

Take an active 2 - port (transistor, etc)

..and add feedback with a passive 2 - port.

The passive 2 - port should clearly be lossless

The feedback is completely general.

We are analyzing all possible 1 - transistor oscillators
Two-Port Oscillator Theory

Passive network: $Y_{p,ij}$; this is reciprocal.
Active network: $Y_{a,ij}$; possibly not reciprocal

Note that the ground connection can be placed at nodes 1, 2, or 3.

This transforms oscillator from common - base to common - emitter, etc.
The feedback network can be represented by either $Y_{p,ij}$ or $Z_{p,ij}$.

It can be composed of either a T or a Pi network.

The Pi network is also known as a Delta network.

More complex networks can be used, but are equivalent.

Note that the feedback impedances and admittances are purely imaginary.
The feedback network

\[
[Y_{ij,p}] = \begin{bmatrix}
  Y_i + Y_f & -Y_f \\
  -Y_f & Y_o + Y_f
\end{bmatrix}
\]

\[Y_f = -Y_{p,12}\]

\[Y_i = Y_{p,11} - Y_{p,12}\]

\[Y_o = Y_{p,22} - Y_{p,12}\]

\[
[Z_{ij,p}] = \begin{bmatrix}
  Z_i + Z_f & -Z_f \\
  -Z_f & Z_o + Z_f
\end{bmatrix}
\]

\[Z_f = -Z_{p,12}\]

\[Z_i = Z_{p,11} - Z_{p,12}\]

\[Z_o = Z_{p,22} - Z_{p,12}\]

Note that the feedback impedances and admittances are purely imaginary.
Series-Line-Tuned Oscillator
Shunt-Line-Tuned Oscillator

\[ Z_{of} \]
\[ \tau_j \]

\[ Y_x \]
\[ Y_y \]

\[ Y_{ij,\text{line}} \]

\[ Y_{p,ij} \]
The Oscillator

Active device

\[
[Y_{a,ij}] = \begin{bmatrix}
G_{a,11} + jB_{a,11} & G_{a,12} + jB_{a,12} \\
G_{a,21} + jB_{a,21} & G_{a,22} + jB_{a,22}
\end{bmatrix}
\]

Oscillator

\[
[Y_{osc,ij}] = \begin{bmatrix}
G_{a,11} + jB_{a,11} + jB_i + jB_f & G_{a,12} + jB_{a,12} - jB_f \\
G_{a,21} + jB_{a,21} - jB_f & G_{a,22} + jB_{a,22} + jB_o + jB_f
\end{bmatrix} = \begin{bmatrix}
Y_{osc,11} & Y_{osc,12} \\
Y_{osc,21} & Y_{osc,22}
\end{bmatrix}
\]

Simplify: write this as

\[
[Y_{osc,ij}] = \begin{bmatrix}
G_{a,11} + jB_{11} & G_{a,12} + jB_{a,12} - jB_f \\
G_{a,21} + jB_{a,21} - jB_f & G_{a,22} + jB_{22}
\end{bmatrix}
\]

By adjusting the feedback network, we can set \( B_{11}, B_{22}, \) and \( B_f \) to any value we desire.
Oscillator Input Admittance

\[
\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix} = \begin{bmatrix}
Y_{osc,11} & Y_{osc,12} \\
Y_{osc,21} & Y_{osc,22}
\end{bmatrix}\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix}
\]

\[I_2 = 0 \rightarrow V_2 = -(Y_{osc,21}/Y_{osc,22})V_1\]

\[\rightarrow Y_{in} = Y_{osc,11} - (Y_{osc,12}Y_{osc,21}/Y_{osc,22})\]

\[
\begin{bmatrix}
Y_{osc,ij}
\end{bmatrix} = \begin{bmatrix}
G_{a,11} + jB_{11} & G_{a,12} + jB_{a,12} - jB_f \\
G_{a,21} + jB_{a,21} - jB_f & G_{a,22} + jB_{22}
\end{bmatrix}
\]

\[Y_{in} = G_{a,11} + jB_{11} - \frac{(G_{a,12} + jB_{a,12} - jB_f)(G_{a,21} + jB_{a,21} - jB_f)}{(G_{a,22} + jB_{22})} = G_{in} + jB_{in}\]

We want \(B_{in} = 0\), and to make \(G_{in}\) as negative as possible.
Input Conductance

\[ G_{in} = G_{a,11} - \left( \frac{G_{a,12}G_{a,21} - (B_{a,12} - B_f)(B_{a,21} - B_f)}{G_{a,22} + B_{22}^2} \right)G_{a,22} \]

\[- \left( \frac{G_{a,21}(B_{a,12} - B_f) + G_{a,12}(B_{a,21} - B_f)}{G_{a,22} + B_{22}^2} \right)B_{22} \]

We should pick \( B_f \) and \( B_{22} \) and to obtain a large negative \( G_{in} \).

Unfortunately, I've been able to derive these *.

\( B_f \) and \( B_{22} \) can also be tuned manually to maximize the negative input conductance.

This is shown on the next slides.

*Optimum feedback elements given in
Design Example (1): Topology, Negative G Tuning.

620 GHz Common - Base Colpitts
with ~ 800 GHz $f_{\text{max}}$ HBT

Test port connected to transistor collectors

$C_1$ and $C_2$ are tuned to produce maximum negative conductance at the collectors:
Design Example (2): Resonator Admittance

Port admittance observed at the collectors.

$C_1$ and $C_2$ have been tuned for maximum negative $G_{11}$.

The resonator inductance has been tuned for zero $B_{11}$.
Design Example (3): Connection of Buffer

3:1 inductor step-down ratio reduces loading of buffer on oscillator core.

The feedback elements must be re-tuned.
Design Example (4): Negative $G$ given Buffer

Note that the negative conductance has been somewhat suppressed by the output loading.
Design Example (5): Transient Simulation

Transient simulation: a small (~ 10 μA) current pulse is injected into the resonator and the circuit is simulated.
Design Example (5): Transient Simulation

Build-up of oscillation is not shown here.

Note that the time axis starts at 90 ps.
2nd Example: Common-Collector Colpitts

Capacitor reduces loading of oscillator by common-base output buffer

Common-collector Colpitts with common-base output buffer.
2nd Example: Common-Collector Colpitts

Port admittance

 transient Simulation
InP HBT IC Technology for Terahertz Frequencies: Fundamental Oscillators Up to 0.57 THz

Munkyo Seo, Senior Member, IEEE, Miguel Urteaga, Member, IEEE, Jonathan Hacker, Senior Member, IEEE, Adam Young, Member, IEEE, Zach Griffith, Member, IEEE, Vibhor Jain, Richard Pierson, Petra Rowell, Anders Skalare, Member, IEEE, Alejandro Peralta, Robert Lin, David Pukala, and Mark Rodwell, Fellow, IEEE
3nd Example: The Real Design
3rd Example: The Real Design

### Oscillation Frequency

<table>
<thead>
<tr>
<th>Process Technology</th>
<th>Design Frequency</th>
<th>Measured Frequency</th>
<th>Simulation w/ revised HBT model</th>
<th>Simulation w/ revised HBT model²</th>
<th>Measured (uncorrected)</th>
<th>Measured (corrected³)</th>
<th>Phase Noise @ 10 MHz offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>THzIC1</td>
<td>292.4 GHz</td>
<td>267.4 GHz</td>
<td>261.5 GHz</td>
<td>-3.6 dBm</td>
<td>-5.1 dBm</td>
<td>-2.1 dBm</td>
<td>-102.4 dBc/Hz</td>
</tr>
<tr>
<td>THzIC1</td>
<td>315.4 GHz</td>
<td>286.8 GHz</td>
<td>280.6 GHz</td>
<td>-4.7 dBm</td>
<td>-6.9 dBm</td>
<td>-3.9 dBm</td>
<td>-99.8 dBc/Hz</td>
</tr>
<tr>
<td>THzIC1</td>
<td>336.5 GHz</td>
<td>310.2 GHz</td>
<td>303.7 GHz</td>
<td>-6.4 dBm</td>
<td>-9.2 dBm</td>
<td>-6.2 dBm</td>
<td>-95.6 dBc/Hz</td>
</tr>
<tr>
<td>THzIC1</td>
<td>387.8 GHz</td>
<td>346.2 GHz</td>
<td>346.0 GHz</td>
<td>-7.7 dBm</td>
<td>-11.0 dBm</td>
<td>-7.0 dBm</td>
<td>-88.8 dBc/Hz</td>
</tr>
<tr>
<td>THzIC2</td>
<td>397.0 GHz</td>
<td>412.9 GHz</td>
<td>394.5 GHz</td>
<td>-3.5 dBm</td>
<td>-11.1 dBm</td>
<td>-5.6 dBm</td>
<td>-</td>
</tr>
<tr>
<td>THzIC2</td>
<td>508.0 GHz</td>
<td>487.7 GHz</td>
<td>505.9 GHz</td>
<td>-5.2 dBm</td>
<td>-16.4 dBm</td>
<td>-8.9 dBm</td>
<td>-</td>
</tr>
<tr>
<td>THzIC2</td>
<td>587.9 GHz</td>
<td>573.1 GHz</td>
<td>586.3 GHz</td>
<td>-9.0 dBm</td>
<td>-36.2 dBm</td>
<td>-19.2 dBm</td>
<td>-</td>
</tr>
</tbody>
</table>