LOW NOISE AMPLIFIERS
HIGH IIP3
LOW COST
LOW DC POWER INPUT
GOOD INPUT and OUTPUT MATCH
HIGH GAIN and very HIGH REVERSE LOSS
STABILITY...NO oscillation, ever

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LOW NOISE AMPLIFIER - WHAT MAKES THIS SUCH A PROBLEM?

Response is sensitive to source and load impedance

LNA SPECIFICATIONS:
- Noise Figure
- Gain
- IIP3
- DC Power
- Input Match
- Output Match
- Stability

Response is sensitive to source and load impedance
All dissipative (resistive) elements generate thermal, or Johnson, noise. This noise power is expressed in Watts as

\[ P_N = KTB \]

(note: \( P_N \) is not a function of resistance)

where

\( K = \) (Boltzman constant)
\( T \) is the temperature in Kelvin
\( B \) is the bandwidth used to measure the noise power

At room temperature the thermal noise generated in a 1 Hz bandwidth:

\[ P_{NT,B_0} = \left( 1.38 \times 10^{-23} \text{ joule} / \text{K} \right)(294 \text{K})(1 \text{Hz}) \]

\[ = 4.057 \times 10^{-21} \text{W} = 4.057 \times 10^{-18} \text{mW} = \]

\[ = -174 \text{dBm} \]
The dB difference between the KTB thermal noise power and the actual noise power is called Noise Figure (NF). When it is referenced to the input port of a circuit or system, the Noise Figure

\[
NF_{dB} = 10 \log \left( \frac{P_{\text{N,actual}}}{KTB} \right) = 10 \log (P_{\text{N,actual}}) - 10 \log (KTB) = 10 \log (1 + TA/TR)
\]

The term “Noise Floor” in a linear noisy system is computed for various bandwidths as:

<table>
<thead>
<tr>
<th>Noise Bandwidth</th>
<th>Total noise power = Noise Floor, in dBm referenced to the input</th>
<th>Total noise power = Noise Floor, in dBm referenced to the output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1Hz</td>
<td>-174 + NF</td>
<td>-174 + NF + Gain(_{dB})</td>
</tr>
<tr>
<td>1KHz</td>
<td>-144 + NF</td>
<td>-144 + NF + Gain(_{dB})</td>
</tr>
<tr>
<td>1MHz</td>
<td>-114 + NF</td>
<td>-114 + NF + Gain(_{dB})</td>
</tr>
</tbody>
</table>
**NOISE FIGURE vs. FREQUENCY**

Noise Figure (dB) with a 10 °K Source

\[ \text{Noise Figure (dB)} = 10 \times \log \left( 1 + \frac{T_A}{T_R} \right) \]

\( T_A/T_R \approx 1/\sqrt{\beta} \)

S = Sky Noise Temperature

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>SiGe HBT</th>
<th>Mixed HBT</th>
<th>FET</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
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<td></td>
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<td>30</td>
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<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(parasitic losses)
LOW NOISE AMPLIFIER-WHICH DEVICE?

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Response is sensitive to source and load impedance.
A SIMPLIFIED FET NOISE MODEL

• $R_n$, the source of output noise is frequency independent.  
• The input noise comes from the loss of the gate-source R-C.  
• The high input Q of a low noise FET makes the Q of the input tuning inductor very important. Small FETs → large inductor → radiation, low Q  
• Therefore, small bipolar transistors are much easier to match.

\[
F = 1 + \frac{g_1}{G_s} + \left(\frac{R_n}{G_s}\right) \left(\frac{G_s + g_1}{g_1}\right)^2
\]

\[
\rho_{in} = \frac{1}{F_{\text{min}}}
\]

\[
G_{\text{sopt}} = g_1 \sqrt{\left(1 + \frac{1}{A}\right)} = g_1 \frac{(F_{\text{min}} + 1)}{(F_{\text{min}} - 1)}
\]
SIMPLIFIED BIPOLAR NOISE MODEL

\[ \overline{v^2_b} = 4kTBr_b \quad \text{(Thermal noise of base resistance)} \]

\[ \overline{I^2_b} = 2qI_b \quad \text{(Shot noise of base current)} \]

\[ \overline{I^2_c} = 2qI_c \quad \text{(Shot noise of collector current)} \]

\[ \overline{v^2_s} = 4kTBR_s \quad \text{(Thermal noise of source resistance)} \]

\[ F \approx 1 + \frac{r_b}{R_s} + \frac{1}{2g_mR_s} + \frac{(g_mR_s/2)(1/\beta)} {g_m} \]

\[ F_{\text{min}} \approx 1 + \frac{1}{\sqrt{\beta}} \sqrt{(1 + 2g_mr_b)} \quad \text{and} \quad R_{\text{sopt}} \approx \frac{\sqrt{\beta}}{g_m} \sqrt{(1 + 2g_mr_b)} \quad \text{(ref 6)} \]

Where \( r_e = \frac{V_T}{I_e} \approx 26/I_e \) at 300°k, and \( \beta \) is the ac current gain
BIPOLAR INPUT MATCHING - INDUCTIVE DEGENERATION

\[
\begin{align*}
\text{Re}(Z_{\text{in}}) & \sim \omega T L_e + r_b \\
\text{Im}(Z_{\text{in}}) & \approx \omega L_e - 1/\omega C_{\text{be}}
\end{align*}
\]

- Input power match impedance can be close to the noise match.
- Inductor can be implemented with on-chip spiral, but Q is low.
- Loss in Le impacts noise figure as much as resistance in series with the base.
- Bond wire inductance is difficult to predict.
- Inductance improves linearity some without degrading noise figure.
- Degrades S12
BIPOLAR INPUT MATCHING - INDUCTIVE DEGENERATION STABILITY PROBLEMS

- Input power match good at 1.9 GHz, the design frequency.
- NF, the actual noise figure, is .05dB worse than Nfmin.
• Input power match good at 2.6 GHz, not as broad as simulated
• NF measured is slightly better than simulation.
• Stability was a bear!
LOW NOISE AMPLIFIER-WHICH DEVICE?

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LNA
SPECIFICATIONS:
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• Input Match
• Output Match
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Response is sensitive to source and load impedance
# COMPARING TECHNOLOGIES

(ON 00/00/00 AFP) 1 is best, 5 worst

<table>
<thead>
<tr>
<th>CMOS</th>
<th>CMOS</th>
<th>SOI</th>
<th>Si</th>
<th>SiGe</th>
<th>GaAs</th>
<th>GaAs</th>
<th>GaAs</th>
<th>ITEM</th>
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</thead>
<tbody>
<tr>
<td>SOS</td>
<td>SOS</td>
<td>BJT</td>
<td>HBT</td>
<td>HBT</td>
<td>FET</td>
<td>HEMT</td>
<td>HBT</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>ISOLATION</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>$F_{Max}$</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3?</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>COST</td>
</tr>
<tr>
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<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>LFNOISE</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>HFNOISE</td>
</tr>
</tbody>
</table>
LOW NOISE AMPLIFIER - IIP3

BPF

Response is sensitive to source and load impedance

LNA

SPECIFICATIONS:
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• IIP3
• DC Power
• Input Match
• Output Match
• Stability

BPF

Response is sensitive to source and load impedance

1

2

3
DISTORTION and COMPRESSION

The theoretical output level where third order distortion products \((2F_1 - F_2)\) & \((2F_2 - F_1)\) equal the desired output signal level is called the third order output intercept, OIP3. Referred to the input this level is IIP3. The 1dB compression level is about 10dB below OIP3. In exceptional devices, 20dB.

Spectrum Analyser display with a 2 signals, \((F_1 & F_2)\) input to the amplifier.
Dynamic Range = $P_{-1dB}$ - Output noise floor power

\[ = P_{-1dB} - (-174 + 10\log(B) + NF + G_A) \]

\[ = P_{-1dB} + 174 - 10\log(B) - NF - G_A \]

where $B =$ noise BW in Hz, $G_A =$ Amplifier gain in dB
**SPURIOUS FREE DYNAMIC RANGE**

The range of signal power an amplifier, mixer, or system can handle with tolerable noise or distortion is called Spurious-Free Dynamic Range. It is referenced to the power level where the third order IMD products just reach the noise floor. Expressed in dB at the output, \( SFDR = \frac{2}{3} \left[ P_{3IP} + 174 - 10 \log(B) - NF - G_A \right] \)

Example: If NF=3dB, 
\( GA = 27 \text{dB}, \) 
\( \text{OIP3} = +30 \text{dBm}, \) 
\( B = 10 \text{KHz}, \) 

\( SFDR = ? \)

\( = 89.3 \text{dB} \)
# COMPARING TECHNOLOGIES- AGAIN

(ON 00/00/00 AFP) 1 is best, 5 worst, except OIP3-PDC is in dB

<table>
<thead>
<tr>
<th>CMOS</th>
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<th>SOI</th>
<th>Si</th>
<th>SiGe</th>
<th>GaAs</th>
<th>GaAs</th>
<th>GaAs</th>
<th>ITEM</th>
</tr>
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<tbody>
<tr>
<td>SOS</td>
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<td></td>
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<td>ISOLATION</td>
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<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>COST</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3?</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>LFNOISE</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>HFNOISE</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>OIP3-PDC</td>
</tr>
<tr>
<td>5?</td>
<td>6</td>
<td>5</td>
<td>14</td>
<td>5</td>
<td>14</td>
<td>12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
LOW CURRENT WIDEBAND FET AMP

\[ \text{gm} = \frac{RF}{Zo} \]

Fig. 2 Reduction of operation current by using 0.2μm gate MODFET
Low Current Wideband Amplifier

Third Order Output Intercept @ 2V/10mA vs. Frequency

![Graph showing the Third Order Output Intercept (OIP3) in dBm vs. Frequency (GHz). The graph includes a line for PDC (Power Due to Co) and P-1dB.](REF 2)
# LOW NOISE and HIGH INTERCEPT FETs

<table>
<thead>
<tr>
<th>Freq</th>
<th>Frequency Range</th>
<th>806</th>
<th>849 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSG</td>
<td>Small Signal Gain</td>
<td>13</td>
<td>14.5 dB</td>
</tr>
<tr>
<td>P1dB</td>
<td>P out at 1 dB Compression</td>
<td>+28.0 dBm</td>
<td>+44.0 dBm</td>
</tr>
<tr>
<td>IIP3</td>
<td>Third-order Intercept</td>
<td>+42</td>
<td>+44.0 dBm</td>
</tr>
<tr>
<td>NF</td>
<td>Noise Figure</td>
<td>1.1</td>
<td>1.5 dB</td>
</tr>
<tr>
<td>VSWR</td>
<td>Input VSWR</td>
<td>2.0:1</td>
<td>2.5:1</td>
</tr>
<tr>
<td>ΔGOF</td>
<td>Gain Variation over Freq.</td>
<td>+/-0.2</td>
<td>+/-0.5 dB</td>
</tr>
<tr>
<td>ΔGOT</td>
<td>Gain Variation over Temp.</td>
<td>-.015</td>
<td>dB/°C</td>
</tr>
<tr>
<td>Idd</td>
<td>DC Current</td>
<td>330</td>
<td>400 mA</td>
</tr>
</tbody>
</table>

![Graph showing OIP3, NF, and Power at different frequencies](image)

- 5V 100% I_dss = 150mA (DC in = 29dBm)
- 3.3V 50% I_dss (DC in = 24dBm)
LOW NOISE and HIGH INTERCEPT
HBT Amplifier

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameters: Test Conditions: $Z_0 = 50$ Ohms, $f = DC-2400$ MHz</th>
<th>Units</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{1dB}$</td>
<td>Output Power at 1dB Compression</td>
<td>$f = DC-2400$ MHz</td>
<td>dBm</td>
<td>17.0</td>
<td></td>
</tr>
<tr>
<td>$S_{21}$</td>
<td>Small Signal Gain</td>
<td>$f = DC-1000$ MHz, $f = 1000-2000$ MHz, $f = 2000-5000$ MHz</td>
<td>dB</td>
<td>17.5, 17.3, 13.5</td>
<td></td>
</tr>
<tr>
<td>$S_{12}$</td>
<td>Reverse Isolation</td>
<td>$f = DC-1000$ MHz, $f = 1000-2000$ MHz, $f = 2000-5000$ MHz</td>
<td>dB</td>
<td>22.5, 23.0, 18.0</td>
<td></td>
</tr>
<tr>
<td>$S_{11}$</td>
<td>Input VSWR</td>
<td>$f = DC-5000$ MHz</td>
<td>-</td>
<td>1.50:1</td>
<td></td>
</tr>
<tr>
<td>$S_{22}$</td>
<td>Output VSWR</td>
<td>$f = DC-5000$ MHz</td>
<td>-</td>
<td>1.50:1</td>
<td></td>
</tr>
<tr>
<td>$I_{P3}$</td>
<td>Third Order Intercept Point</td>
<td>$f = DC-2400$ MHz</td>
<td>dBm</td>
<td>31.0</td>
<td></td>
</tr>
<tr>
<td>NF</td>
<td>Noise Figure</td>
<td>$f = DC-1000$ MHz, $f = 1000-2400$ MHz</td>
<td>dB</td>
<td>3.0, 3.5</td>
<td></td>
</tr>
<tr>
<td>$T_D$</td>
<td>Group Delay</td>
<td>$f = 1000$ MHz</td>
<td>pS</td>
<td>121.0</td>
<td></td>
</tr>
<tr>
<td>$V_D$</td>
<td>Device Voltage</td>
<td></td>
<td>V</td>
<td>3.1, 3.5, 3.9</td>
<td></td>
</tr>
<tr>
<td>$I_D$</td>
<td>Device Current</td>
<td></td>
<td>mA</td>
<td>60.0</td>
<td></td>
</tr>
</tbody>
</table>
LOW NOISE AMPLIFIER- NEGATIVE FEEDBACK

Response is sensitive to source and load impedance

LNA SPECIFICATIONS:
- Noise Figure
- Gain
- IIP3
- DC Power
- Input Match
- Output Match
- Stability

Response is sensitive to source and load impedance
RF TECHNIQUES

THE LOWLY RESISTOR FEEDBACK AMPLIFIER

- At a moderate current an FET does not need $R_E$, yet still has excellent IP3. This helps the NF.
- $F \equiv \frac{R_E}{R_S} + \frac{R_S}{R_F} + F(\text{transistor})$
- RAISE $R_F$ by using a load $R_L$ higher than $R_S$.....lowers NF
- Very wide bandwidth with high $F_T$ devices
- BUT the output sees the input: $S_{12} * S_{21} \approx .5$
## TRANSISTOR-EFFECT OF IMPEDANCE

Noise Figure, Intercept, and Gain vs. Source and Load Z

This approach needs a second stage to easily obtain a good output match.

<table>
<thead>
<tr>
<th>Rsource (Ω)</th>
<th>Rload (Ω)</th>
<th>Rk (Ω)</th>
<th>NF (dB)</th>
<th>Rout</th>
<th>Vgain</th>
<th>Δ OIP3</th>
<th>Rs=50</th>
<th>Rsopt</th>
<th>Nfmin (Rsopt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>50</td>
<td>0</td>
<td>1.5</td>
<td>201</td>
<td>4.59</td>
<td>0</td>
<td>280</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>20</td>
<td>2.6</td>
<td>716</td>
<td>1.63</td>
<td>5</td>
<td>307</td>
<td>0.84</td>
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</tr>
<tr>
<td>50</td>
<td>50</td>
<td>40</td>
<td>3.5</td>
<td>1250</td>
<td>1</td>
<td>7</td>
<td>350</td>
<td>1.21</td>
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</tr>
<tr>
<td>50</td>
<td>50</td>
<td>60</td>
<td>4.3</td>
<td>1810</td>
<td>0.7</td>
<td>9</td>
<td>392</td>
<td>1.51</td>
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<tr>
<td>50</td>
<td>50</td>
<td>100</td>
<td>5.6</td>
<td>2950</td>
<td>0.45</td>
<td>11</td>
<td>469</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Delta IP3=increase in OIP3 over the device with R_K=0
Transformer coupled design

- Transformer feedback linearizes circuit and sets gain
- \( V_{cc} \) can be as low as \( V_{be} (=0.9V) \)
- Very stable due to inductors, limited low frequency gain
- \( NF = 3 \text{ dB} \) \( IIP3=-3 \text{ dBm} \) (Inductor loss hurts noise figure)

(J. Long, IEEE JSSC, Dec., 95)
AGC TECHNIQUES

• Reduce gain in a large signal environment

• Raise the signal capability

• Minimize impact on noise figure

• Minimize supply power when in small signal environment

• Try to do on a stage by stage basis—detect overload> back off
The Spur Free-Dynamic Range can be extended by lowering the gain and raising the intermodulation point \textit{if} the smallest signal rises along with the largest.
MOSFET- RESISTOR EMITTER DEGENERATION

Note: Could put a resistor in series with the FETs and/or use multiple parallel paths, even switched, when practical, for the highest SFDR.
SIMPLE BALUN
YOU WILL BE NEEDING THESE IF YOU ARE BUILDING COMPLEX CIRCUITS!

THIS BALUN IS NOT A BALUN AT HARMONICS
LOW NOISE AMPLIFIER—WHAT MAKES THIS SUCH A PROBLEM? CONCLUSION

LNA SPECIFICATIONS:
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• Gain
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• Input Match
• Output Match
• Stability
• Back-to-Front

• There are many conflicting requirements.
• Noise performance is usually easy to achieve below 20 GHz.
• Large devices can give simultaneous low noise and high intercept, but at a large DC power required.
• Device technology has improved the IIP3-PDC situation.
• Stability and Back-to-Front (Isolation) are easy to forget about, but hard to fix.
• Simultaneous input and output match is difficult to obtain in a single stage with good isolation.