Bandwidth Extension Techniques for CMOS Amplifiers

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Outline

• Motivations: Performance and Low Power (bandwidth $\alpha g_m \alpha [I]^{1/2}$, settling time, rise time)

• Bridged-Shunt Peaking

• Bridged-Shunt-Series Peaking

• Asymmetric T-coil Peaking

• Wideband Amplifiers

• Results

• Conclusions
Motivation

- Broad Band Amplifiers
- Ultra Wideband (UWB) Receivers
- Transimpedance Amplifiers (TIAs)
- Pre-drivers and Mux/Demux
MBOA (Multi-band OFDM Access) is supported by most of industry.
Direct Sequence Spread Spectrum (DSSS) is primarily supported
by Motorola/Freescale.
Optical Communications

Large Bandwidth Needed (~ 40Gb/s)


Common-Source Reference Amplifier

\[ A_v = \frac{V_{out}}{V_{in}} = \frac{g_m R}{1 + sRC} \]

Gain-BW Tradeoff
→ Desire BW extension for a given gain
→ Power Dissipation Fixed for Comparison
Multi-Stage Amplifier Parasitics

• CS amplifier in multi-stage cascade
• Transistor W/L depends on:
  ➢ Gain
  ➢ Voltage Swing
  ➢ Supply Current
  ➢ Noise Figure
• Define: \( k_C = \frac{C_1}{C_1 + C_2} = \frac{C_1}{C} \)
  ➔ design constraint

➔ Desire BW extension for a given \( k_C \)
Peaking Techniques

Modify Conventional Peaking Techniques:

- Obtain larger BW extension ratio (BWER), smaller settling time
- Include (and exploit) parasitic effects
- Retain simplicity and generality
- Comprehensive design for different $k_C$ values
  - Important Result: Use different techniques for different $k_C$ values

Bandwidth extension approaches:

- Resonance, capacitor splitting, magnetic coupling
**Terminology**

- BW extension ratio (BWER) = $\frac{f_{3dB, \text{peak}}}{f_{3dB, \text{ref}}}$
- Settling Time (1%) reduction ratio (STRR) = $\frac{\tau_{s, \text{ref}}}{\tau_{s, \text{peak}}}$
- Rise Time (10-90%) reduction ratio (RTRR) = $\frac{\tau_{r, \text{ref}}}{\tau_{r, \text{peak}}}$

**BWER, STRR & RTRR** hard to maximize simultaneously. Optimize for desired application.

**MST** = Minimum settling Time
Conventional Shunt Peaking

\[ Z(s) = \frac{R + sL}{1 + sRC + s^2LC} \]

\[ m = \frac{R^2C}{L} \quad \omega_0 = \frac{1}{RC} \]

\[ Z_N(s) = \frac{1 + s / m \omega_0}{1 + s / \omega_0 + s^2 / m \omega_0^2} \]
Conventional Shunt Peaking - II

\[ m = \frac{R^2 C}{L} \]

- \( m = \sqrt{2} \)  \( \rightarrow \) 1.84X & 1.5dB Peaking
Bridged-Shunt Peaking

\[ Z_N(s) = \frac{1 + \left( \frac{1}{m} \right) \frac{s}{\omega_0} + \left( \frac{k_B}{m} \right) \frac{s^2}{\omega_0^2}}{1 + \frac{s}{\omega_0} + \left( \frac{k_B + 1}{m} \right) \frac{s^2}{\omega_0^2} + \left( \frac{k_B}{m} \right) \frac{s^3}{\omega_0^3}} \]

\[ m = \frac{R^2C}{L} \quad \omega_0 = \frac{1}{RC} \quad k_B = \frac{C_B}{C} \]

Note: Inductor parasitic forms \( C_B \)

Question: Interchange \( L \) and \( R \)?
Bridged-Shunt Peaking

\[ m = 2.4, \ k_B = 0.3 \quad \text{1.83X and flat gain} \]
Bridged-Shunt Peaking - II

![Graph showing amplitude over time with different values of $K_B$ and $m$]

<table>
<thead>
<tr>
<th>$K_B$</th>
<th>$m$</th>
<th>STRR</th>
<th>RTRR</th>
<th>BWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.4</td>
<td>0.70</td>
<td>2.18</td>
<td>1.84</td>
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<tr>
<td>0.1</td>
<td>2.84</td>
<td>2.40</td>
<td>1.74</td>
<td>1.69</td>
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<tr>
<td>0.3</td>
<td>2.4</td>
<td>1.39</td>
<td>1.87</td>
<td>1.83</td>
</tr>
</tbody>
</table>

Optimum depends on application.
Bridged-Shunt Peaking

Advantages

- Incorporates inductor parasitics (Add more $C_B$ if needed)
- Maximum BW possible with flat gain (No 1.5dB peaking)
- $m \uparrow \Rightarrow L \downarrow \Rightarrow$ Smaller Area
- Area overhead for added $C_B$ minimal
Conventional Series Peaking

\[ Z_N(s) = \frac{1}{1 + \frac{s}{\omega_0} + \frac{s^2}{m\omega_0^2}} \]

- Lack of Zero
- Inferior to Shunt peaking

\[ m = 2 \rightarrow 1.41X \]
Series Peaking with Drain Parasitics

\[ Z_N(s) = \frac{1}{1 + \frac{s}{\omega_0} + \left(\frac{1-k_C}{m}\right)\frac{s^2}{\omega_0^2} + \left(\frac{k_C(1-k_C)}{m}\right)\frac{s^3}{\omega_0^3}} \]

Conventional Series Peaking
Capacitor Splitting Idea
Series Peaking vs. $k_C$
## Series Peaking with $C_1$: Summary

<table>
<thead>
<tr>
<th>$k_c = C_1/C$</th>
<th>Peaking (dB)</th>
<th>$m = R^2C/L$</th>
<th>BWER</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1.41</td>
</tr>
<tr>
<td>0.1</td>
<td>0</td>
<td>1.8</td>
<td>1.58</td>
</tr>
<tr>
<td>0.2</td>
<td>0</td>
<td>1.8</td>
<td>1.87</td>
</tr>
<tr>
<td>0.3</td>
<td>0</td>
<td>2.4</td>
<td>2.52</td>
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<tr>
<td>0.4</td>
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<td>1.9</td>
<td>2.75</td>
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<td>0.4</td>
<td>2</td>
<td>2.5</td>
<td>3.17</td>
</tr>
<tr>
<td>0.5*</td>
<td>3.3</td>
<td>1.5</td>
<td>2.65</td>
</tr>
</tbody>
</table>

Bridged-Shunt-Series Peaking

\[ Z_N(s) = \frac{1 + \left( \frac{1}{m_1} \right) \frac{s}{\omega_0} + \left( \frac{k_B}{m_1} \right) \frac{s^2}{\omega_0^2}}{1 + \frac{s}{\omega_0} + \left( \frac{1 + k_B}{m_1} + \frac{1 - k_C}{m_2} \right) \frac{s^2}{\omega_0^2} + \left( \frac{k_B}{m_1} \frac{k_C (1 - k_C)}{m_2} \right) \frac{s^3}{\omega_0^3} + \left( \frac{(k_C + k_B) (1 - k_C)}{m_1 m_2} \right) \frac{s^4}{\omega_0^4} + \left( \frac{k_B k_C (1 - k_C)}{m_1 m_2} \right) \frac{s^5}{\omega_0^5}} \]
Bridged-Shunt-Series Peaking - II

- Uncompensated
- $kC = 0.4$, $m1 = 8$, $m2 = 2.4$, $kB = 0.3$, BWER = 3.92
- $kC = 0.4$, $m1 = 6$, $m2 = 2.4$, $kB = 0.2$, BWER = 4.00
- $kC = 0.5$, $m1 = 6$, $m2 = 2.0$, $kB = 0.2$, BWER = 3.53
# Bridged-Shunt-Series Summary - I

<table>
<thead>
<tr>
<th>$k_C = \frac{C_1}{C}$</th>
<th>Peak (dB)</th>
<th>$m_1 = \frac{R^2C}{L_1}$</th>
<th>$m_2 = \frac{R^2C}{L_2}$</th>
<th>$k_B = \frac{C_B}{C}$</th>
<th>BWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0</td>
<td>8</td>
<td>2.4</td>
<td>0.3</td>
<td><strong>3.92</strong></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6</td>
<td>2.4</td>
<td>0.2</td>
<td><strong>4</strong></td>
</tr>
<tr>
<td>0.5</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>0.2</td>
<td><strong>3.53</strong></td>
</tr>
</tbody>
</table>
Bridged-Shunt-Series Summary - II

![Graph showing amplitude vs time with different values for k_B, k_C, and BWER]

<table>
<thead>
<tr>
<th>k_C</th>
<th>k_B</th>
<th>m_1</th>
<th>m_2</th>
<th>STRR</th>
<th>RTRR</th>
<th>BWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.0</td>
<td>6.3</td>
<td>2.6</td>
<td>1.32</td>
<td>2.73</td>
<td>3.47</td>
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<tr>
<td></td>
<td>0.16</td>
<td>8</td>
<td>2.2</td>
<td>1.46</td>
<td>2.78</td>
<td>3.11</td>
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<tr>
<td></td>
<td>0.2</td>
<td>6</td>
<td>2.4</td>
<td>0.71</td>
<td>2.89</td>
<td>4.00</td>
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<tr>
<td></td>
<td>0.3</td>
<td>8</td>
<td>2.4</td>
<td>0.95</td>
<td>2.66</td>
<td>3.92</td>
</tr>
<tr>
<td>0.5</td>
<td>0.1</td>
<td>6</td>
<td>2</td>
<td>0.75</td>
<td>2.91</td>
<td>3.40</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>6</td>
<td>2</td>
<td>0.77</td>
<td>2.88</td>
<td>3.53</td>
</tr>
</tbody>
</table>
Conventional Bridged T-Coil Peaking

\[ Z_N(s) = \frac{1}{1 + \left(\frac{s}{\omega_n}\right) 2\zeta + \frac{s^2}{\omega_n^2}} \]

- \( L_1 = L_2 \)
- Butterworth response
- Double shunt-series peaking

\[ \zeta = \frac{1}{\sqrt{2}} \quad k = -\frac{1}{3} \quad 2.83X \]

Capacitor Splitting + Magnetic Coupling

Original notes from Carl Battjes. Tektronix used package lead inductors to implement T-coils circa 1970.
Conventional Bridged T-Coil Peaking-II

\[ \zeta = \frac{1}{\sqrt{2}} \quad k = -\frac{1}{3} \quad 2.83X \]
Asymmetric T-Coil Peaking - 1

\[ k_c = \frac{C_1}{C} \]

\[ k_m = \frac{M}{\sqrt{L_1 L_2}} \]

\[ Z_N(s) = \frac{1 + \left( \frac{1}{m_1} + \frac{k_m}{\sqrt{m_1 m_2}} \right) s}{1 + \frac{s}{\omega_0} + \left( \frac{1}{m_1} + \frac{k_c}{m_2} + \frac{2 k_c k_m}{\sqrt{m_1 m_2}} \right) \frac{s^2}{\omega_0^2} + \left( \frac{k_c (1 - k_C)}{m_2} \right) \frac{s^3}{\omega_0^3} + \left( \frac{k_c (1 - k_C)(1 - k_m^2)}{m_1 m_2} \right) \frac{s^4}{\omega_0^4}} \]
Asymmetric T-Coil Peaking - 2

Initially, drain current discharges $C_1$

After delay, drain current discharges $C_2$

Negative magnetic coupling initially provides extra current to discharge $C_2$

After delay, drain current flows through $L_2$

Initially, drain current discharges $C_1$

Current step into drain terminal

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
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<tbody>
<tr>
<td>$R$</td>
<td>1</td>
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<tr>
<td>$C_1$</td>
<td>0.3</td>
</tr>
<tr>
<td>$C_2$</td>
<td>0.7</td>
</tr>
<tr>
<td>$L_1$</td>
<td>0.25</td>
</tr>
<tr>
<td>$L_2$</td>
<td>$1/2.8 = 0.357$</td>
</tr>
<tr>
<td>$K$</td>
<td>-0.4</td>
</tr>
</tbody>
</table>
Negative magnetic coupling initially provides extra current to discharge C2; it causes an increase in the voltage across R as it initially flows upward.
## Asymmetric T-Coil Summary - I

<table>
<thead>
<tr>
<th>$k_C = \frac{C_1}{C}$</th>
<th>Peak (dB)</th>
<th>$m_1 = \frac{R^2C}{L_1}$</th>
<th>$m_2 = \frac{R^2C}{L_2}$</th>
<th>$k_m = \frac{M}{\sqrt{L_1L_2}}$</th>
<th>BWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0</td>
<td>4</td>
<td>1.6</td>
<td>-0.7</td>
<td>4.63</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3.5</td>
<td>1.2</td>
<td>-0.6</td>
<td>4.92</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.5</td>
<td>1.6</td>
<td>-0.6</td>
<td>5.59</td>
</tr>
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<td>5.5</td>
<td>2.4</td>
<td>-0.6</td>
<td>4.14</td>
</tr>
<tr>
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<td>1</td>
<td>3</td>
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<td>-0.6</td>
<td>4.51</td>
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<tr>
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<td>2</td>
<td>4</td>
<td>2.8</td>
<td>-0.4</td>
<td>4.54</td>
</tr>
</tbody>
</table>
Asymmetric T-Coil Summary - II

\[ k_m = 0.6, k_c = 0.1, \text{BWER} = 5.59, \text{STRR} = 1.6 \]

\[ k_m = 0.7, k_c = 0.2, \text{BWER} = 3.34, \text{STRR} = 4.1 \]

<table>
<thead>
<tr>
<th>( k_C )</th>
<th>( k_m )</th>
<th>( m_1 )</th>
<th>( m_2 )</th>
<th>STRR</th>
<th>RTRR</th>
<th>BWER</th>
</tr>
</thead>
<tbody>
<tr>
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<td>4.0</td>
<td>1.6</td>
<td></td>
<td>1.90</td>
<td>4.20</td>
<td>4.63</td>
</tr>
<tr>
<td>0.6</td>
<td>3.5</td>
<td>1.6</td>
<td></td>
<td>1.32</td>
<td>4.50</td>
<td>4.92</td>
</tr>
<tr>
<td>0.6</td>
<td>3.5</td>
<td>1.2</td>
<td></td>
<td>1.57</td>
<td>4.43</td>
<td>5.59</td>
</tr>
<tr>
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<td>4.1</td>
<td>1.6</td>
<td></td>
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<td>4.19</td>
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</tr>
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<td>1.23</td>
<td>3.91</td>
<td>4.51</td>
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<td>4.86</td>
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<td>4.11</td>
<td>3.35</td>
<td>3.34</td>
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<td>4.0</td>
<td>2.8</td>
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<td>1.54</td>
<td>3.40</td>
<td>3.93</td>
</tr>
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<td>3.70</td>
<td>3.06</td>
<td>3.07</td>
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</table>
## Peaking Techniques: Summary

<table>
<thead>
<tr>
<th>$k_c$</th>
<th>Desired BWER</th>
<th>Desired STRR (1%)</th>
<th>Optimal Peaking Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1-0.5</td>
<td>&lt;1.83</td>
<td>&lt;2.4</td>
<td>Bridged Shunt</td>
</tr>
<tr>
<td>0.1-0.4</td>
<td>3-5.59</td>
<td>&lt;4.1</td>
<td>Asymmetric T-coil</td>
</tr>
<tr>
<td>0.4-0.5</td>
<td>3-4</td>
<td>&lt;1.5</td>
<td>Bridged-Shunt-Series</td>
</tr>
</tbody>
</table>
Prototype Amplifiers

Bridged-Shunt-Series
\( k_C = 0.4, 0.5 \)
Gain = 14dB
BW = 8GHz

Asymmetric T-Coil
\( k_C = 0.3 \)
Gain = 12dB
BW = 10.4GHz
Asymmetric T-coil

- T-coil needs weak-coupling
  \[ k_m \sim 0.4 \]
- Simplicity, weak-coupling
  \[ \text{concentric-windings} \]
- Two-pronged design method
  \[ \text{reduced design cycle} \]
  1. Grover Calculations
  2. EM Simulation

Asymmetric T-coil - II

- T-coil EM simulation
  → freq. domain representation
- Transient simulation needs circuit model
- Proposed equivalent wideband circuit model
  → incorporates skin-effect, bulk-eddy currents
- Good to first self-resonance
Measurement Results

Bridge Shunt-Series
Gain = 14dB
BW = 8GHz
BWER = 3.0

Asymmetric T-Coil
Gain = 12dB
BW = 10.4GHz
BWER = 4.1
# Comparison

<table>
<thead>
<tr>
<th>Reference</th>
<th>Bandwidth Extension Technique</th>
<th>CMOS Tech. (nm)</th>
<th>Single-stage</th>
<th>Multi-stage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Peaking (dB)</td>
<td># Stages</td>
</tr>
<tr>
<td>This work</td>
<td>Bridged-Shunt-Series</td>
<td>180</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Asymmetric T-coil with Negative Mutual Inductance</td>
<td>180</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Galal, JSSC’04</td>
<td>Shunt-Series</td>
<td>180</td>
<td>1.8</td>
<td>5</td>
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<tr>
<td>Kim, ISSCC’05</td>
<td>Asymmetric T-coil with Positive Mutual Inductance</td>
<td>130</td>
<td>0</td>
<td>-</td>
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<td>Kanda, ISSCC’05</td>
<td>Shunt-Series</td>
<td>90</td>
<td>2.4</td>
<td>2</td>
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<tr>
<td>Analui, ESSCIRC’02</td>
<td>Series Peaking</td>
<td>180</td>
<td>1.84-3</td>
<td>3</td>
</tr>
</tbody>
</table>

* Simulated
Die Micrographs in 0.18μm CMOS

(a)

(b)

(c)

(d)
Conclusions

- Peaking techniques for larger BW extension
- Applicable to different $k_C$ constraints
- Trade-off gain flatness for BW
- Amplifiers show large gain (>12dB) with largest BWER (4.1) reported.
- Wide bandwidth, high gain $\rightarrow$ fewer stages $\rightarrow$ power, area savings
Modified-Series Peaking

\[ Z_N(s) = \frac{1}{1 + \frac{s}{\omega_0} + \left( \frac{k}{m} \right) \frac{s^2}{\omega_0^2} + \left( \frac{k(1-k)}{m} \right) \frac{s^3}{\omega_0^3}} \]

- \( C_1 \equiv \text{Drain parasitics, etc.} \)
- \( C = C_1 + C_2 \)
- \( C_1 = k_c C = kC \)
- \( m = R^2C/L \)
- Note: \( R \) and \( L \) interchanged

Assuming \( k \ll 1 \), \( Z_N(\omega) \approx \frac{1}{\left( 1 - \omega^2 LC_1 \right) \left( 1 + j\omega RC_2 \right)} \)
Peaking Response

Simulated normalized responses of (b) with (c) $L_1$, ideal, and (d) $L_1$ with typical parasitics in a CMOS implementation ($\pi$-model)

• Low Q Desired!
Anti-Staggered Series Peaking

- Similar to Pre-emphasis Idea
- Actually Tuning $S_{11}$ (zero) and $S_{21}$ (pole)
- Common-gate Amplifier!
\[ F \approx 1 + \frac{\gamma}{\alpha} \]

\[ F \approx 1 + \frac{\gamma}{\alpha} \cdot \frac{1}{1+A} \]


Capacitor Cross-Coupled-CGLNA

- Lower Noise Figure
- Lower DC Current

\[ A = \frac{1}{1 + \frac{C_{gs}}{C_c}} \]

For \( C_c \gg C_{gs} \)

- \( G_m = 2g_m \)
- \( C_{in} = 4C_{gs} \)
- \[ F \approx 1 + \frac{\gamma}{2\alpha} \]

UWB CCCLNA

Test Buffer

Series-Peaked Response

Staggered Response

Overall Compensated Response

UWB LNA employing anti-stagger-compensated series peaking
Measurement Results

**4.1X with 2.4dB Passband Ripple**

**4.9X with 3.0dB Passband Ripple**

Measured S-parameters of two versions of the UWB LNA
Measurement Results

Measured (a) $NF$, and (b) $IIP3$ values of two versions of the UWB LNA
# Performance Comparison

<table>
<thead>
<tr>
<th>Ref.</th>
<th>CMOS Tech. (nm)</th>
<th>-3dB BW (GHz)</th>
<th>Power (mW)</th>
<th>NF (dB)</th>
<th>Max. S21 (dB)</th>
<th>IIP3 (dBm)</th>
<th>Area (mm²)</th>
<th>FOM</th>
<th>Gain_{abs} \cdot BW_{GHz}</th>
<th>Gain_{abs} \cdot IIP3_{mW} \cdot BW_{GHz}</th>
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<tbody>
<tr>
<td>LNA #1</td>
<td>180</td>
<td>1.3 - 10.7</td>
<td>4.5</td>
<td>4.4 - 5.3</td>
<td>8.5</td>
<td>7.4 to 8.3</td>
<td>1.0</td>
<td>2.33 to 3.17</td>
<td>12.8 to 21.4</td>
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<tr>
<td>LNA #2</td>
<td>180</td>
<td>1.3 - 12.3</td>
<td>4.5</td>
<td>4.6 - 5.5</td>
<td>8.2</td>
<td>7.6 to 9.1</td>
<td>1.0</td>
<td>2.69 to 3.64</td>
<td>15.5 to 29.6</td>
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<tr>
<td>[1]</td>
<td>180</td>
<td>2.3 - 9.2</td>
<td>9</td>
<td>4.0 - 9.0</td>
<td>9.3</td>
<td>-8.2 to -5.6</td>
<td>1.1</td>
<td>0.32 to 1.48</td>
<td>0.05 to 0.41</td>
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<tr>
<td>[2]</td>
<td>180</td>
<td>0.5 - 14</td>
<td>52</td>
<td>3.4 - 5.4</td>
<td>10.6</td>
<td>9.4</td>
<td>1.6</td>
<td>0.36 to 0.74</td>
<td>3.11 to 6.45</td>
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<td>[2]</td>
<td>180</td>
<td>0.6 - 22</td>
<td>52</td>
<td>4.3 - 6.1</td>
<td>7.3</td>
<td>8.7</td>
<td>1.35</td>
<td>0.31 to 0.56</td>
<td>2.3 to 4.18</td>
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<tr>
<td>Heydari, RFIC05</td>
<td>180*</td>
<td>0 - 12.6</td>
<td>19.8</td>
<td>2.9</td>
<td>9.6</td>
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<td>Yazdi, Isscc05</td>
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<td>54</td>
<td>4.8 - 7</td>
<td>9.1</td>
<td>4.7</td>
<td>1.32</td>
<td>0.33 to 0.65</td>
<td>0.97 to 1.93</td>
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</tr>
</tbody>
</table>

**Wideband LNA Measured Performance Comparison**
Chip Microphotographs

Conclusions

• **Pros ☺**
  - Large Bandwidth Extension
  - Low Power
  - Simple Input Match
  - Low Inductor Count
  - Flat Noise Figure

• **Cons ☹**
  - Low Gain
  - Bandwidth Extension Requires Two Stages/Nodes
  - 3dB Ripple Too Large for Some Applications
  - Sensitive Tuning