A compact 24-54 GHz CMOS band-pass DA for high fractional-bandwidth signal amplification

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(RMO-2B-1)
High bandwidth data communication

High resolution motion tracking

$\Delta \tau$ $\Delta d$

TX1

TX2

Mobile Target Object

$d$
Outline

• Distributed Amplifier Architecture
• Low-pass to Band-pass transformation
• Norton Transformation
• Physical implementation
• Measurement Results
Distributed architecture

- Divide and conquer approach
- Key challenge: Large number of inductors
Low-Pass to Band-Pass Transformation

\[ C_P \quad \Rightarrow \quad C_P \quad \Rightarrow \quad L_P \]

\[ \text{LPDA} \quad \Rightarrow \quad \text{BPDA} \]

\[ L_S \]

\[ L_S \quad C_S \]

\[ V_{\text{in}} \]

\[ V_{\text{out}} \]

\[ \pm G_m \quad \pm G_m \]

\[ N \text{ inductors in the LPDA} = (2N+1) \text{ inductors in the BPDA} \]
Challenges with the canonical BPDA

Low-pass filter

\[ \begin{array}{c}
1 \\
\text{C}_1 \\
L_2 \\
\text{C}_1 \\
1
\end{array} \]

Band-pass filter

\[ \begin{array}{c}
1 \\
\text{C}_1 \\
L_1 \\
\text{C}_2 \\
L_1 \\
\text{C}_1 \\
1
\end{array} \]

Normalized component values for a Butterworth filter response

<table>
<thead>
<tr>
<th>Component</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_2 )</td>
<td>( \frac{2}{BW} )</td>
</tr>
<tr>
<td>( C_1 )</td>
<td>( \frac{1}{BW \times 1} )</td>
</tr>
<tr>
<td>( L_1 )</td>
<td>( \frac{1 \times BW}{\omega_C^2} )</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>( \frac{BW}{2 \times \omega_C^2} )</td>
</tr>
</tbody>
</table>

Challenge-1: \( L_2 \neq f(\omega_C) \Rightarrow \omega_C \uparrow \equiv L_2 \leftarrow \)

Challenge-2: \( L_1 \propto BW \Rightarrow BW \uparrow \equiv L_1 \uparrow \)
Norton Transformations

\[ V_1 \rightarrow V_2 = \begin{array}{c}
\text{L replaced by } L_A, L_B, L_C \text{ and N:1 transformer} \\
\text{For } N>1, \text{ } L_B \text{ is negative}
\end{array} \]

\[
\begin{align*}
L_A &= \frac{L}{N} \\
L_B &= \frac{L}{1 - N} \\
L_C &= \frac{L}{N \times (N - 1)}
\end{align*}
\]
Circuit Reduction - 1

\[ \text{Diagram with components labeled } C_1, L_1, C_2, L_2 \]
Dual mirror-symmetric Norton

Start

Final

- Inductor $L_2/2$ replaced by $\{L_2/2 - L_1\}/4$
- At the very least, 75% scale-down in series inductor
## Component reduction

<table>
<thead>
<tr>
<th>Canonical</th>
<th>Norton Reduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_1 ) 180pH</td>
<td>( \frac{L_1}{2} ) 90pH</td>
</tr>
<tr>
<td>( L_2 ) 800pH</td>
<td>( \frac{L_x}{4} ) 55pH</td>
</tr>
<tr>
<td>( L_3 ) 180pH</td>
<td>( \frac{L_1}{2} ) 90pH</td>
</tr>
<tr>
<td>( C_1 ) 175fF</td>
<td>( C_1 ) 175fF</td>
</tr>
<tr>
<td>( C_2 ) 45fF</td>
<td>( 4C_2 ) 180fF</td>
</tr>
<tr>
<td>( C_1 ) 175fF</td>
<td>( \frac{C_1}{2} ) 175fF</td>
</tr>
</tbody>
</table>
Gain-cell Design

\[ C_1 - C_{oA} \]

\[ C_1 - C_{oB} \]

\[ R_iA \]

\[ C_iA \]

\[ R_{oA} \]

\[ C_{oA} \]

\[ C_1 - C_{iA} \]

\[ R_iB \]

\[ C_iB \]

\[ R_{oB} \]

\[ C_{oB} \]

\[ C_1 - C_{iB} \]

- \( C_{iA}, C_{oA}, C_iB, C_{oB} < C_1 \)
- \( R_iA, R_{oB} \gg 50, R_{oA}, R_iB \approx 50 \)
\[ \frac{1}{re(Y_{i1})} = 350\Omega \]

\[ \frac{1}{re(Y_{o1})} = 50\Omega \]

\[ \frac{1}{re(Y_{i2})} = 140\Omega \]

\[ \frac{1}{re(Y_{o2})} = 300\Omega \]
Chip Details

- TSMC 40nm
- 6 Metal Stack
- 1 UTM Layer
- Total Area : 0.45mm²
- Core Area : 0.15mm²
Measured S-Parameters
Noise-Figure Measurement Test Set-Up

Analog Signal Generator

N5183A

18-40 GHz

M9-0950LNV

+10dBm

HD30055

6-18 GHz

346CK01

28V

0V

Die

GSG

25-55 GHz

GSG

25-55 GHz

Chuck

N8975A

DC

RF

Noise Figure Analyzer

25-55 GHz

6-18 GHz
Measured Noise and Linearity

- $O_{P_{1dB}}$ (dBm)
  - Frequency (GHz)

- $IIP_3$ (dBm)
  - Frequency (GHz)

- Group Delay (ps)
  - Frequency (GHz)

- NF (dB)
  - Frequency (GHz)
## Comparison with state-of-the-art

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Technique</td>
<td>High-pass DA</td>
<td>Coupled resonator</td>
<td>T-type matching</td>
<td>BPDA</td>
</tr>
<tr>
<td>Bandwidth (GHz)</td>
<td>21-42.5</td>
<td>23-32</td>
<td>47-77</td>
<td>24-54</td>
</tr>
<tr>
<td>$\omega_C$ (GHz)</td>
<td>31.75</td>
<td>9</td>
<td>30</td>
<td>39</td>
</tr>
<tr>
<td>fBW</td>
<td>67.7%</td>
<td>32%</td>
<td>48%</td>
<td>77%</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>8.3, Power gain</td>
<td>12, Voltage gain</td>
<td>22.5, Power gain</td>
<td>7dB, Power gain</td>
</tr>
<tr>
<td>Power (mW)</td>
<td>28</td>
<td>13</td>
<td>52</td>
<td>34</td>
</tr>
<tr>
<td>IIP3 (dBm)</td>
<td>-x-</td>
<td>-6.3 to -4.5</td>
<td>-x-</td>
<td>10 to 13</td>
</tr>
<tr>
<td>$\text{OP}_{1\text{dB}}$ (dBm)</td>
<td>0</td>
<td>-x-</td>
<td>4.5 (simulated)</td>
<td>-0.5 to 2</td>
</tr>
<tr>
<td>NF (dB)</td>
<td>6.9-8</td>
<td>4.5-6.3</td>
<td>5-7.2</td>
<td>3.9-6.2</td>
</tr>
<tr>
<td>Area (mm$^2$)</td>
<td>0.28</td>
<td>0.25</td>
<td>0.55</td>
<td>0.15</td>
</tr>
<tr>
<td>Technology</td>
<td>120nm SiGe-BiCMOS</td>
<td>180nm BiCMOS</td>
<td>250nm BiCMOS</td>
<td>40nm CMOS</td>
</tr>
</tbody>
</table>
Conclusions

• Compact band pass distributed amplifier using Norton transforms
• Design and layout principles discussed.
• Implemented in a 40nm CMOS technology
• Core area of 0.15mm^2 and a pass-band of 24-to-54 GHz
Acknowledgments

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Thank You