65-nm CMOS, W-band Receivers for Imaging Applications

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Motivation

• Investigation of W-band receivers in 65-nm GP CMOS

• CMOS might provide alternatives to III-V and SiGe technology in imaging arrays:
  • Broadband (multi-GHz)
  • Low power
  • Low noise
  • Small area

• Comparison of two LNA feedback topologies
  • Series-series feedback with inductor
  • Shunt-series feedback with transformer
Receiver Block Diagram
• Inductive (series-series) feedback LNA
• Input matched by \( L_G \) and \( L_S \)
• Noise impedance matched by transistor sizing and biasing

\[ \mathcal{R}\{Z_{IN}\} = 2\pi f T L_S + R_G + R_S \]
LNA – Schematic (2)

- Transformer (shunt-series) feedback LNA
- Input matched by $L_P$, $L_S$ and $M$
  \[ R\{Z_{IN}\} \approx \frac{L_P}{g_m \cdot M}, \quad M = k \sqrt{L_P L_S} \]
- Noise impedance matched by transistor sizing and biasing
- $S_{11}$, $\Gamma_{\text{opt}} < -10$ dB from 74-100 GHz for both designs
Mixer – Schematic

- Gilbert cell mixer with inductive broad-banding
Fabrication

- 65-nm GP/LP digital CMOS process
- 7 metal layers
- GP n-MOSFETs (80×60nm×1μm) with gate contacted on one side: \( f_T / f_{\text{MAX}} = 170 \, \text{GHz} / 200 \, \text{GHz} \) at \( V_{\text{DS}} = 0.7 \, \text{V} \)
- GP MOSFETs 30% faster than LP MOSFETs and require lower \( V_{\text{GS}} \) and \( V_{\text{DS}} \) → lower power
- Gate leakage does not affect mm-wave performance
LNA breakouts – Die Photos

IND-feedback
490 um x 300 um (pad) → 120 um x 170 um (core)

XFMR-feedback
Mixer breakout – Die Photo

470 um x 560 um (pad) → 190 um x 160 um (core)
Receiver – Die Photos

IND-feedback Receiver

460 um x 500 um (pad) \rightarrow 160 um x 370 um (core)

XFMR-feedback Receiver
Meas. LNA – 1st Spin

- Requires 2.2 V $V_{DD}$ for 8 – 9 dB gain
- 4 – 5 dB below simulation
Measurements for 2\textsuperscript{nd} Spin with Modified Layout

Series resistance in ground metallization of LNA was found in the first spin.

A second spin of the design was fabricated with:

- Wider metal lines in ground mesh at top level
- Increased number of vias (even between M5 and M6)
- LNA inductance values adjusted to match @ 80 GHz
Meas. LNA – 2\textsuperscript{nd} Spin

- Measured gain @ 1.5 V $V_{DD} = 13$ dB
2\textsuperscript{nd} Spin LNA – meas. vs sims.

- Meas. gain @ V_{DD} = 1.5 V is 1 – 2 dB below sims.
- S_{11} < -20 dB from 80 – 90 GHz (xfmr-feedback)
Meas. Transformer S-params.

- \( \text{MAG} \) (loss) < -2 dB between 75 – 95 GHz
Meas. Mixer – Conversion Gain

- 1 – 2 dB below simulation
Meas. Mixer – $N_{DSB}$

- Includes ~2 dB transformer loss
- Lowest $N_{DSB}$ mixer at 80 – 90 GHz in silicon
Meas. Rx Gain, $\text{NF}_{\text{DSB}}$ vs IF

XFMR-feedback RCVR

- $\text{NF}_{\text{DSB}} \sim 7 - 8 \text{ dB, LO @ 89 GHz}$
Meas. Rx Gain, \(NF_{DSB}\) vs RF

- 3dB-bandwidth: 75 – 91 GHz
• LO @ 75 GHz due to equipment limitation

LO = 75GHz
RF = 80GHz
$P_{1dB} = -16.2$ dBm
Estimated LNA NF

\[ G_{LNA} = G_{RCVR} - G_{MIXER} \]

\[ F_{LNA} = F_{RCVR} \frac{F_{MIXER} - 1}{G_{LNA}} \]

- LNA gain peaks at frequency higher than measured (output pad capacitance removed)
- LNA NF\(_{50} \approx 6 – 7 \) dB

XFMR-feedback LNA
### Summary of Results

<table>
<thead>
<tr>
<th>Spin</th>
<th>$V_{DD}$ [V]</th>
<th>LNA</th>
<th>IF Buffer</th>
<th>Receiver</th>
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<tbody>
<tr>
<td>1st</td>
<td>1.8</td>
<td>38</td>
<td>5.8</td>
<td>47</td>
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<tr>
<td></td>
<td>2.2</td>
<td>57</td>
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<td>34</td>
<td>13.4</td>
<td>30</td>
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<tr>
<td></td>
<td>1.8</td>
<td>48</td>
<td>14.9</td>
<td>45</td>
</tr>
</tbody>
</table>

- Dramatic increase in performance just with better top-level ground mesh and vias
- $\sim \frac{1}{2}$ of $P_{diss}$ used in IF buffer to drive $50\Omega$ off-chip
Conclusion

• 74 – 94 GHz receiver with 8 dB NF and 13 dB gain demonstrated in 65 nm GP CMOS technology.
• Inductive-feedback and transformer-feedback LNA topologies presented:
  • Similar performance achieved by different matching procedures
  • Layout style significantly affects circuit performance.
• Post-layout simulation at top-level, with ground mesh must be carried out.
Acknowledgement

- Katya Laskin for measurements on the second-spin
- Alex Tomkins for inductor and transformer measurements
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- CITO for funding
- ECTI, NSERC, CFI and OIF for equipment
\textbf{2nd spin LNA – Meas. Gain}

- \textbf{IND-feedback LNA}
  - \( S_{11} \) matched at 93 GHz for inductive-feedback LNA (increase \( L_G \))

- \textbf{XFMR-feedback LNA}

\begin{itemize}
  \item \( V_{DD} = 1.2 \text{V} \)
  \item \( V_{DD} = 1.5 \text{V} \)
  \item \( V_{DD} = 1.8 \text{V} \)
\end{itemize}
Receiver – vs LO Power

- Requires 2 – 3 dBm (1\textsuperscript{st} spin) and > 5 dBm (2\textsuperscript{nd} spin) LO power
Receiver – $P_{1\text{dB}}$

**LO=77GHz, RF=75GHz**

IND-feedback Receiver

- **RF at 75 GHz due to equipment limitation**

XFMR-feedback Receiver