WSF-1

CMOS RF for mmWave Frontends

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Outlines

- RF Applications to mmWave
- From Planar to FinFET Technology
- CMOS mmWave FoM Circuits Benchmark
- Conclusion
Basics and Benefits of mmWave

• mmWave is defined as the band of radio frequencies ranging from 30 to 300 GHz
  – Provide large bandwidths capable of delivering high data rates
  – The use of small-size passive components → Small form factor

mmWave Applications

- **28/39 GHz**: 5th Generation Mobile Network
- **60 GHz**: 802.11ad/ay Wireless HD
- **77 GHz**: Automotive Long Range Radar (LRR)
- **79 GHz**: Automotive Short range Radar (SRR)

Freq. (GHz)

- 28
- 39
- 57
- 64
- 76
- 77
- 81

- **5G mmWave**
- **WiGig**
- **LRR**

Links:
- http://www.profheath.org/analysis-of-millimeter-wave-systems-for-5g/
mmWave Sensors

- Emerging business opportunities in mmWave sensors


S. Benchikh, et al., “A novel millimeter wave radar sensor for medical signal detection,” 2018 IEEE International Microwave Biomedical Conference (IMBioC)
mmWave Phased-Array Architecture

- Multiple transceivers to enhance output power and SNR
- Power consumption of multiple transceivers and compact digital control for beamforming → toward advanced nodes

Outlines

• RF Applications to mmWave
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• CMOS mmWave FoM Circuits Benchmark
• Conclusion
16nm FinFET vs. 28nm Planar

• 16nm FinFET shows better gm and gds over 28nm planar
  – Improved gm due to 3D structure
  – Improved gds due to fully depleted transistors

Gain Efficiency

- With improved gain, 16nm FinFET shows better gain efficiency than 28nm planar
$f_T$ and $f_{\text{max}}$

- $f_T$ and $f_{\text{max}}$: key figures of merit for mmWave gain
  - $f_T$: frequency where current gain = 1
  - $f_{\text{max}}$: frequency where power gain = 1

$$f_T \sim \frac{g_m}{2\pi C_{gg}}$$

$$f_{\text{max}} \sim \frac{f_T}{2 \sqrt{R_g(g_{ds}+2\pi f TC_{gd})}}$$
16nm FinFET Enhancement ($f_T$ and $f_{max}$)

- Improved $f_T$ (300+ GHz) with innovative process and layout techniques
- Improved $f_{max}$ (400+ GHz) with innovative Rg reduction technology
Gain Efficiency (16nm vs. 28nm)

- With $f_T$ and $f_{\text{max}}$ enhancement, 16nm FinFET shows much better gain efficiency than 28nm planar
1/f Noise (16nm vs. 28nm)

- 16nm FinFET shows better 1/f noise than 28nm planar under the same dc power
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RF Design Flow

Conventional RF Design Flow

- SPEC
- Pre-Sim
- Layout
- Post-Sim
- SPEC?
- Finish

- RF Model: RF Pcell
- LPE: Interconnection between RF Pcell
- RF Model: RF Pcell
mmWave Design Flow

- Schematic Entry
- Circuit Simulation
- Layout
- Parasitic Extraction
- SPEC?
- Finish

Critical Path (EM)

- EM + RC Extraction

Non-Critical Path (RC)

- MMW RF Model/Pcell
- Critical Passive Components

- Component Options
- S-parameter
- EM Simulation
- EM Tech File
- SPEC
- Yes
- No
28GHz PA in 16nm FinFET

- Circuit structure
  - Differential cascode stage
  - MOM cap for neutralization to stabilize PA
28GHz PA in 16nm FinFET

- Input/output transformer
  - Stacked type: primary coil Mu; secondary coil AP & Mz
28GHz PA in 16nm FinFET

- For 28GHz PA, better output power and PAE in 16nm FinFET than those in 28nm planar

<table>
<thead>
<tr>
<th>Parameter</th>
<th>28GHz PA</th>
<th>28nm Planar (Si)</th>
<th>16nm FinFET (Si)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{DD}$ (V)</td>
<td>1.6</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>OP1dB (dBm)</td>
<td>17.3 [x1]</td>
<td>17.7 [x1.10]</td>
<td></td>
</tr>
<tr>
<td>PAE@OP1dB</td>
<td>34.0% [x1]</td>
<td>39.7% [x1.17]</td>
<td></td>
</tr>
<tr>
<td>Psat (dBm)</td>
<td>17.7 [x1]</td>
<td>19.3 [x1.45]</td>
<td></td>
</tr>
<tr>
<td>Peak PAE</td>
<td>34.6% [x1]</td>
<td>40.0% [x1.16]</td>
<td></td>
</tr>
</tbody>
</table>
22.4GHz LC-VCO in 16nm FinFET

- Circuit structure
  - 22.4GHz LC-VCO based on heterodyne TRx architecture
  - NMOS-PMOS balanced LC-VCO structure
22.4GHz LC-VCO in 16nm FinFET

- For 22.4GHz LC-VCO, 16nm FinFET shows better phase noise and dc power than 28nm planar

<table>
<thead>
<tr>
<th></th>
<th>22.4GHz LC-VCO</th>
<th>28nm Planar (Si)</th>
<th>16nm FinFET (Si)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{DD}$ (V)</td>
<td>0.9</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Pdc (mW)</td>
<td>4.9 [x1]</td>
<td>3.0 [x0.61]</td>
<td></td>
</tr>
<tr>
<td>PN@100kHz (dBc/Hz)</td>
<td>-68.7 [x1]</td>
<td>-72.8 [x0.39]</td>
<td></td>
</tr>
<tr>
<td>PN@1MHz (dBc/Hz)</td>
<td>-97.7 [x1]</td>
<td>-101.0 [x0.47]</td>
<td></td>
</tr>
<tr>
<td>Tuning Range (GHz)</td>
<td>3.2 [x1]</td>
<td>4.1 [x1.28]</td>
<td></td>
</tr>
</tbody>
</table>
28GHz Shunt Switch in 16nm FinFET

- Circuit structure
  - Shunt switch (SW) with transmission line

<table>
<thead>
<tr>
<th>State</th>
<th>Operating Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ON</td>
<td>VG=0V</td>
</tr>
<tr>
<td>OFF</td>
<td>VG=Vdd</td>
</tr>
</tbody>
</table>
28GHz Shunt Switch in 16nm FinFET

• Transmission line (TL)
  – Use microstrip line for realization
  – Signal line: AP; GND plane: M1
28GHz Shunt Switch in 16nm FinFET

- For 28GHz shunt switch, 16nm FinFET shows better insertion loss than 28nm planar with the optimization of TL
60GHz PA in 16nm FinFET

• From 28GHz to 60GHz, circuit architecture changes from single stage to multiple stages
  – Sufficient gain performance and wideband operations
60GHz PA in 16nm FinFET

- Circuit structure
  - 3 differential gain stages
  - Gate resistors to stabilize PA
60GHz PA in 16nm FinFET

- Transformers
  - Stacked type: primary coil Mu; secondary coil AP
60GHz PA in 16nm FinFET

- For 60GHz PA, 16nm FinFET output power and PAE better than 28nm planar

<table>
<thead>
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<th>60GHz PA</th>
<th>28nm Planar (Si)</th>
<th>16nm FinFET (Si)</th>
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</thead>
<tbody>
<tr>
<td>$V_{DD}$ (V)</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>OP1dB (dBm)</td>
<td>5.4 [x1]</td>
<td>7.5 [x1.62]</td>
</tr>
<tr>
<td>PAE@OP1dB</td>
<td>4.5% [x1]</td>
<td>6.8% [x1.51]</td>
</tr>
<tr>
<td>Psat (dBm)</td>
<td>10.1 [x1]</td>
<td>10.8 [x1.17]</td>
</tr>
<tr>
<td>Peak PAE</td>
<td>10.9% [x1]</td>
<td>11.4% [x1.05]</td>
</tr>
<tr>
<td>Bandwidth (GHz)</td>
<td>17 [x1]</td>
<td>20 [x1.18]</td>
</tr>
</tbody>
</table>
60GHz LNA in 16nm FinFET

• Circuit structure
  – 3 gain stages (stagger tuning)
  – Transmission lines for matching purpose
60GHz LNA in 16nm FinFET

- Slow-wave transmission line (SW-TL) versus microstrip line (MS-Line)
  - SW-TL shows better Q and IND per unit length than MS-line
60GHz LNA in 16nm FinFET

• With SW-TL, the area of N16FFC 60GHz LNA reduced by ~40% compared to the one with MS-Line
60GHz LNA in 16nm FinFET

- For 60GHz LNA, under the same dc power:
  - N16FFC shows better gain and bandwidth than N28HPC
  - For N16FFC, SW-TL-based LNA shows better gain, bandwidth, and noise figure (NF) than MS-line-based LNA

<table>
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<th>28nm Planar (Si)</th>
<th>16nm FinFET (Si)</th>
<th>16nm FinFET (Si)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Line</td>
<td>MS-Line</td>
<td>MS-Line</td>
<td>SW-TL</td>
</tr>
<tr>
<td>$V_{DD}$ (V)</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Pdc (mW)</td>
<td>7.8</td>
<td>7.8</td>
<td>7.8</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>19.1 [x1]</td>
<td>20.3 [x1.32]</td>
<td>23.0 [x2.45]</td>
</tr>
<tr>
<td>Bandwidth (GHz)</td>
<td>16 [x1]</td>
<td>20 [x1.25]</td>
<td>21 [x1.05]</td>
</tr>
<tr>
<td>NF (dB)</td>
<td>6.6 [x1]</td>
<td>6.9 [x1.07]</td>
<td>6.3 [x0.93]</td>
</tr>
</tbody>
</table>
79GHz PA in 16nm FinFET

- Based on 1-stage cascode structure
  - Differential cascode stage
  - MOM cap for neutralization to stabilize PA
  - Stacked-type transformer: primary coil Mu; secondary coil Mz
79GHz PA in 16nm FinFET

• 16nm FinFET RF enhancement shows improved output power and PAE for 79GHz PA

<table>
<thead>
<tr>
<th>79GHz PA</th>
<th>16nm FinFET Baseline (Si)</th>
<th>16nm FinFET with RF Enhancement (Si)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{DD} ) (V)</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>OP1dB (dBm)</td>
<td>11.2 [x1]</td>
<td>11.3 [x1.02]</td>
</tr>
<tr>
<td>PAE@OP1dB</td>
<td>10.5% [x1]</td>
<td>10.9% [x1.04]</td>
</tr>
<tr>
<td>Psat (dBm)</td>
<td>14.8 [x1]</td>
<td>15.7 [x1.23]</td>
</tr>
<tr>
<td>Peak PAE</td>
<td>16.4% [x1]</td>
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• Emerging mmWave applications include 5G cellular, automotive radars, and mmWave sensors
• 16nm FinFET shows better gain efficiency compared to 28nm planar as a result of improved gm and gds
• Innovative device further improves gain efficiency for mmWave applications
• For mmWave FoM circuits, 16nm FinFET shows better performance than 28nm planar
Thank You!

Q & A