A Terahertz FMCW Comb Radar in 65nm CMOS with 100GHz Bandwidth

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Outline

• Introduction
• Comb Radar
• Circuit Implementations
• Measurement Results
• Conclusion
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Wideband FMCW Radar Applications

- High resolution detection

  ![Localization Image](humatics.com)

  ![Recognition Image](atap.google.com/soli)

- High resolution imaging

  ![Range Resolution](\Delta R = \frac{c}{2 \cdot BW})

  ![Security Imaging](Sheen, TMTT 2001)

  ![Non-Ionizing/Destructive Imaging](Fat tissue, 2D Image, 3D Image [Mostajeran, TMTT 2019])
Wideband THz FMCW Radar Example

• SAR 3D imaging

• Cross-range resolution $\Delta CR$
  – Relies on synthetic aperture $D$
  – Mm resolution is readily available (e.g. $R=3D$, $\Delta CR=1.5\text{mm}$)

• Range resolution $\Delta R$
  – Relies on bandwidth $BW$ only
  – Mm resolution: wideband (e.g. $BW=100\text{GHz}$, $\Delta R=1.5\text{mm}$)

300GHz Radar Imaging for Non-Destructive Detection of Material Defects
Integrated Radar Survey

- CMOS radar is desired
  - Low cost
  - Integration with analog and digital circuits

- Bandwidth of CMOS radars is limited

- Wideband FMCW radar issues
  - Performance fluctuation
  - Chirp signal generation

![Graph showing EIRP vs Bandwidth with markers for CMOS, SiGe, with lens, and without lens.](Image)
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Comb Radar Concept

- Divide a single wideband channel into $N$ narrowband channels
- Make these $N$ channels operate simultaneously
- Multi-tone operation looks like a comb

\[ \Delta T = \frac{T_m}{N} \]
\[ \Delta B = \frac{BW}{N} \]
Comb Radar System Diagram

Doubler1 (x2) → Slot Balun → Amplifier → Doubler2 (x2) → Matching Network → BPF LNA

Multiplier (x4) → CH1 TRX → Buffer → LO IQ (5GHz) → Up-Mixer → Divider → S_IF

220~240GHz → IF1
240~260GHz → IF2
260~280GHz → IF3
280~300GHz → IF4
300~320GHz → IF5

13.75~15GHz → External FMCW

10GHz → 75~80GHz

Target

LO IQ (5GHz) → S_SB Up-Mixer

4.8: A Terahertz FMCW Comb Radar in 65nm CMOS with 100GHz Bandwidth
Phase of IF Signals

- For Channel N, the TX signal is
  \[ S_{TX,N}(t) = \cos\left(2\pi f_{c,N} + \frac{\pi \Delta B}{\Delta T} t + \varphi_N \right) \]
  
- The echo signal (\(\tau<<\Delta T\)) is
  \[ S_{RX,N}(t) = \cos\left(2\pi f_{c,N} + \frac{\pi \Delta B}{\Delta T} (t - \tau) + \varphi_N \right) \]
  
- The band-pass-filtered IF signal is
  \[ S_{IF,N}(t) = \cos\left(\frac{2\pi \Delta B}{\Delta T} \tau t + 2\pi f_{c,N} \tau \right) = \varphi_{IF,N}(t) \]
  
- The phase of IF signal \(\varphi_{IF,N}\) has no initial RF phase \(\varphi_N\)
Phase of IF Signals

- The phases of adjacent IF signals are continuous despite of their initial phases

\[ \varphi_{IF,N}(t_0 + \Delta T) = \frac{2\pi \Delta B}{\Delta T} \tau(t_0 + \Delta T) + 2\pi f_{c,N} \tau \]

\[ \varphi_{IF,N+1}(t_0) = \frac{2\pi \Delta B}{\Delta T} \tau t_0 + 2\pi f_{c,N+1} \tau \]

\[ \varphi_{IF,N}(t_0 + \Delta T) = \varphi_{IF,N+1}(t_0) \]
Stitching Process

- IF signals are directly stitched in time domain after calibrations

\[ \Delta T = T_m / 5 \]

\[ \Delta T = T_m / 5 \]
Compared with Single Channel Radar

- Flatter frequency responses

- More linear chirp signal

- Finer velocity resolution

\[ \Delta v = \frac{\lambda}{2NT_{frame}} \]

- SNR is improved

\[ \Delta v = \frac{\lambda}{2NT_{frame}} \]

\[ f_{error} \]

Chirp Signal

- 5 \times \]
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Comb Radar System Diagram

- Total bandwidth: $5 \times 20\,\text{GHz} = 100\,\text{GHz}$
- Scalable bandwidth extension
- Single antenna solution for each transceiver: 5 antennas, coupling?
## On-Chip Antenna Background

<table>
<thead>
<tr>
<th></th>
<th>Slot Antenna</th>
<th>Patch Antenna</th>
<th>Substrate Integrated Waveguide (SIW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expensive Silicon Lens</td>
<td>Need 😞</td>
<td>No Need 😊</td>
<td>No Need 😊</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Wide 😊</td>
<td>Narrow 😞</td>
<td>Narrow 😞 ?</td>
</tr>
<tr>
<td>Inter-Antenna Coupling</td>
<td>Medium 😊</td>
<td>Large 😞</td>
<td>Small 😊</td>
</tr>
</tbody>
</table>

### Example

- Slot Antenna: ![Slot Antennas](image)
  - [R. Han, ISSCC 2012]
- Patch Antenna: ![Patch Antenna](image)
  - [R. Han, JSSC 2013]
- Substrate Integrated Waveguide (SIW): ![SIW](image)
  - [S. Hu, JSSC 2012]
SIW Cavity and Slot

- Eigenmode simulation
SIW Cavity with Orthogonal Slots

• Four modes
SIW Orthogonal Slot Antenna

- Multiple resonant modes due to orthogonal slots in SIW cavity
- Tune size parameters to arrange mode frequencies
SIW Orthogonal Slot Antenna

- Wide bandwidth (~40GHz, 14.8%)
- 0dBi peak gain
- Linear polarization (axial ratio > 11.6dB)

- Low coupling (< -31dB)
- 20.5% efficiency
Input Multiplier, Buffer, and SSB Mixer
Doubler1 and Folded Slot Balun

![Diagram of the Doubler1 and Folded Slot Balun circuit](image-url)}
Folded Slot Balun

- Nearly perfect differential output
  - 50GHz (45%) bandwidth
  - 1.3dB insertion loss
  - 0.05dB/0.5° amplitude/phase errors
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Cascaded Neutralized Amplifier

Doubler1 (x2) → Slot Balun → Doubler2 (x2) → Matching Network

Cascaded Neutralized Amplifier
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Doubler2

Doubler1 (x2) → Slot Balun → Doubler2 (x2) → Matching Network

Conversion Loss (dB)

IN+ IN- OUT OUT

Doubler2

To MN → To RX

Graphs showing conversion loss and output power vs. output frequency.

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Multi-Stub Matching Network

Doubler1 (x2) → Slot Balun → Doubler2 (x2) → Matching Network

S-Parameters (dB)
- $S_{21}$
- $S_{11}$
- $S_{22}$

Frequency (GHz)
190 200 210 220 230 240 250 260 270

S-Parameters (dB)
- $S_{21}$
- $S_{11}$
- $S_{22}$

Layout
IN L1 L2 L3 L4 L5 L6 L7 OUT

BPF LNA
• Square-law mixer for single antenna solution, passive circuit for smaller flicker noise
• Self-biased LNA with high-pass input to suppress unwanted low frequency components
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Chip and PCB Photograph

- TSMC 65nm bulk CMOS technology
- Area: 2.5mm by 2.0mm
- Total power consumption: 840mW
Transmitter Mode Measurement

- Total EIRP without lens: 0.6dBm
- Total EIRP with lens: 20dBm
- Fluctuations: within 8.8dB
Transmitter Mode Measurement

- Friis equation is met at far-field
- Antenna radiation pattern 3dB beamwidth: 90°
- Phase noise: better than -100dBc/Hz @1MHz
Receiver Mode Measurement

- Minimum SSB NF including antenna loss: 22.8dB
- Fluctuation of NF: 14.6dB
- Receiver gain: 22.2dB

Setup is calibrated by PM5

Signal Generator (E8257D) 13.75–15GHz
Signal Generator (N5173B)

PCB

Horn Antenna

Spectrum Analyzer (N9020A)

LO 10GHz

IF

RF

Signal Generator (83732B)

VDI Extender (Transmitter)
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FMCW Radar Measurement Setup

Signal Generator 10GHz LO Comb Radar Chip 5 IFs BPFs VGAs NI PXI-5105 Digitizer To PC

DDS AD9164 Multipliers (x4) 13.75~15GHz

Useful signals

Over-chirping

ΔB

ΔT

ΔB

ΔT

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Radar Signal Calibration

- Amplitude mismatch
  - Gain mismatch among channels
- Phase mismatch
  - Matching network delay mismatch: fixed
  - Antenna off-axis: range should be large (>20 cm)
- Calibration method [J. Grajal, TMTT 2015]
  - Reference: one single-point like target
  - One-time calibration
Range Accuracy Measurement

- Measured distance matches real distance
Range Resolution Measurement

- Two targets with 2.5mm distance
- Hamming window
- One channel
- 20GHz
Range Resolution Measurement

- Three channels
- 60GHz
Range Resolution Measurement

- Five channels
- 100GHz
Comparison Table

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<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>65nm CMOS</td>
<td>65nm CMOS</td>
<td>130nm SiGe</td>
<td>130nm SiGe</td>
<td>55nm SiGe</td>
<td>28nm CMOS</td>
</tr>
<tr>
<td>Frequency (GHz)</td>
<td>220~320</td>
<td>157.9~164.9</td>
<td>210~270</td>
<td>305~375</td>
<td>189.9~252.3</td>
<td>138~151</td>
</tr>
<tr>
<td>Bandwidth (GHz)</td>
<td>100</td>
<td>7</td>
<td>60</td>
<td>70</td>
<td>62.4</td>
<td>13</td>
</tr>
<tr>
<td>Resolution (mm)</td>
<td>1.5</td>
<td>21</td>
<td>2.5</td>
<td>2.1</td>
<td>2.4</td>
<td>11.5</td>
</tr>
<tr>
<td>Minimum Noise Figure (dB)</td>
<td>22.2[^3]</td>
<td>22.5</td>
<td>21</td>
<td>19.7</td>
<td>NA</td>
<td>4(EINF)^[^9]</td>
</tr>
<tr>
<td>Power/NF Fluctuation (dB)</td>
<td>8.8/14.6</td>
<td>3/NA</td>
<td>20/29</td>
<td>10.5/28.6</td>
<td>7.7/NA</td>
<td>1.5/4</td>
</tr>
<tr>
<td>Chip Size (mm^2)</td>
<td>5.0</td>
<td>20</td>
<td>3.2</td>
<td>2.85</td>
<td>0.51</td>
<td>6.5</td>
</tr>
<tr>
<td>DC Power (mW)</td>
<td>840</td>
<td>2200</td>
<td>1800</td>
<td>1700</td>
<td>87</td>
<td>500</td>
</tr>
</tbody>
</table>

[^3]: With TPX focus lens;[^4]: with silicon lens;[^5]: includes antenna and baseband;[^6]: effective isotropic NF which includes the antenna directivity.
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Conclusion

• Comb radar for wideband THz applications
  – Flatter frequency responses
  – More linear chirp signal
  – Finer velocity resolution
  – Improved SNR
  – Scalable bandwidth extension

• A five channel comb radar with 100GHz bandwidth was demonstrated in 65nm bulk CMOS technology
Acknowledgements

• Chip fabrication: TSMC University Shuttle Program
• Measurements: Prof. Charlie Sodini, Prof. Tomás Palacios, Qingyu Yang, Mohamed I. Ibrahim, and Nathan Monroe (MIT); Pu Wang, and Rui Ma (Mitsubishi Electric Research Labs)
• Funding: NSF CAREER award (ECCS-1653100), MIT Center of Integrated Circuits and Systems (CICS), and a gift fund from TSMC
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