Ultra-Broadband CMOS THz Radar Using Channel Aggregation

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Outline

• Introduction
• Comb Radar: A Broadband THz Sensing Architecture
• Circuit Implementation
• Measurement Results
• Conclusion
The Pursuit for High Resolution

Localization

Recognition

Range Resolution

\[ \Delta R = \frac{c}{2 \cdot BW} \]

Security Imaging

Fat tissue

2D Image

[Mostajeran, TMTT 2019]

3D Image

Non-Ionizing/Destructive Imaging

[humatics.com]

[atap.google.com/soli]

[Sheen, TMTT 2001]
Wideband THz FMCW Radar: Applications

• SAR 3D imaging

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

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

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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
Circuit Architecture

[Doubler1 (x2) → Slot Balun → Amplifier → Doubler2 (x2) → Matching Network → Square-Law Mixer → BPF LNA]

- 220~240GHz
- 240~260GHz
- 260~280GHz
- 280~300GHz
- 300~320GHz

- 55~60GHz
- 13.75~15GHz

- 10GHz

[Multiplier (x4) → Buffer → Divider → Up-Mixer]

-[X. Yi, ISSCC, 2020]
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 ($\tau \ll \Delta T$) is

$$S_{RX,N}(t) = \cos \left(2\pi f_{c,N} + \frac{\pi \Delta B}{\Delta T} (t - \tau) (t - \tau) + \varphi_N \right)$$

- 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.
Compared with Single Channel Radar

- Flatter frequency responses
- More linear chirp signal
- SNR is improved
- Finer velocity resolution

\[ \Delta v = \frac{\lambda}{2NT_{\text{frame}}} \]
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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><strong>Expensive Silicon Lens</strong></td>
<td>Need 😞</td>
<td>No Need 😊</td>
<td>No Need 😊</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>Wide 😊</td>
<td>Narrow 😞</td>
<td>Narrow 😞 ?</td>
</tr>
<tr>
<td><strong>Inter-Antenna Coupling</strong></td>
<td>Medium 😊</td>
<td>Large 😞</td>
<td>Small 😊</td>
</tr>
<tr>
<td><strong>Example</strong></td>
<td><img src="image" alt="Slot Antennas" /> [R. Han, ISSCC 2012]</td>
<td><img src="image" alt="Patch Antenna" /> [R. Han, JSSC 2013]</td>
<td><img src="image" alt="Substrate Integrated Waveguide" /> [S. Hu, JSSC 2012]</td>
</tr>
</tbody>
</table>
SIW Cavity with Orthogonal Slots

- Four characteristic modes at different frequencies
Antenna Simulation Results

- Wide bandwidth (~40GHz, 14.8%)
- 0dBi peak gain
- Linear polarization (axial ratio > 11.6dB)
- Low coupling (<-31dB)
- 20.5% radiation efficiency
Input Multiplier, Buffer, and SSB Mixer

- CH1 TRX → IF1
- Multiplier (x4) → OUT
- 55~60GHz
- 5GHz to 10GHz
- +2

13.75~15GHz

- IN
- OUT

Multiplier (x4)

Buffer

SSB Mixer

13.75~15GHz

IN

Multiplier (X4)

Buffer

SSB Up-Conversion Mixer

To CH1 TRX

OUT

60~65GHz

IF1

Multiplier (x4)

IN

55~60GHz

10GHz

÷2
THz Signal Generation

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

Conversion Loss (dB) vs. Output Frequency (GHz)
Output Power (dBm) vs. Output Frequency (GHz)
**Square-Law THz Mixer Receiver**

- 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 Prototype and Packaging

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

[Image: Diagram of chip prototype and packaging with labels for different components.]

[Reference: X. Yi, ISSCC, 2020]
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

Startup is calibrated by PM5

Signal Generator (83732B)  RF  VDI Extender (Transmitter)

Horn Antenna

Signal Generator (E8257D)  RF  13.75~15GHz

Signal Generator (N5173B)

PCB

Spectrum Analyzer (N9020A)

LO 10GHz

IF

RX Gain (dB)

Frequency (GHz)

RX Noise Figure (dB)
FMCW Radar Measurement Setup

Signal Generator -> DDS AD9164 -> Multipliers (x4) -> Comb Radar Chip -> BPFs VGAs -> NI PXI-5105 Digitizer -> To PC

10GHz LO

5 IFs

13.75~15GHz

Useful signals

Over-chirping

ΔB

ΔT

ΔB

ΔT
Range Accuracy Measurement

- Measured distance matches real distance
Range Resolution Measurement

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

- Three channels
- FMCW BW=60GHz
Range Resolution Measurement

- Five channels
- FMCW BW=100GHz
- The two objects are well resolved!
# Comparison Table

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<thead>
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</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>189.9~282.3</td>
<td>138~151</td>
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<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>Output EIRP (dBm)</td>
<td>0.6, 20[a]</td>
<td>18.8</td>
<td>32.8[b]</td>
<td>6, 18.4[b]</td>
<td>14[b]</td>
<td>11.5</td>
</tr>
<tr>
<td>Minimum Noise Figure (dB)</td>
<td>22.2[c]</td>
<td>22.5</td>
<td>21</td>
<td>19.7</td>
<td>NA</td>
<td>4(EINF)[c]</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>1.54</td>
</tr>
<tr>
<td>Chip Size (mm²)</td>
<td>6.0</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>

(a) With TPX focus lens; (b) with silicon lens; (c) includes antenna and baseband; (d) effective isotropic NF which includes the antenna directivity.

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

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