4.5: Electronic THz Pencil Beam Forming and 2D Steering for High Angular-Resolution Operation: A 98×98 Unit, 265GHz CMOS Reflectarray with In-Unit Digital Beam Shaping and Squint Correction

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Speaker Bio: Nathan Monroe

- **Education**
  - S.B., MIT EE | 2013
  - M. Eng. MIT EE | 2017
  - Ph.D., MIT EE | 2021

- **Professional Experience**
  - Microsoft Xbox Sensor Development
    2013-2015

- **Research Interests**
  - THz antenna arrays
  - THz radar
Sensing in Autonomous Vehicles

- Vision is key for autonomous vehicles
- From object detection to recognition

- ✓ High angular resolution
  ✗ High cost
  ✗ Mechanical scanning
  ✗ Poor robustness to weather

- ✓ Low cost, long range
  ✓ All-weather operation
  ✗ Low 2D angular resolution
  ✗ Large size
MIMO Radar: Practicality Issues

- Low cost, long range
- All-weather operation
- Small size

- Low 2D angular resolution
- Clutter issues
- Interference concerns

[Mietzner 2017]
Imaging Radar: The Case for THz

100x100px image ➔ 1° beam
Imaging Radar: The Case for THz

100x100px image $\Rightarrow$ 1° beam

$$D = \frac{4\pi AF^2}{c^2}$$

Beam Directivity
Aperture Area
Frequency
Speed of Light
THz Array: Implementation Challenges

- 1º beam $\Rightarrow$ 100x100 antennas
- RF Power Distribution
  - High loss
  - Routing complexity/congestion
  - Phase synchronization
- Phase control issues
THz Phase Shifter Limitations

- Insertion Loss ~10dB
- Power ~ 10mW
- Size $\rightarrow \frac{\lambda}{2}$ footprint
- Phase/Amplitude errors
- Narrowband
- One-directional

Yang et al, MTT 2015  Jalili et al, JSSC 2019
Reflectarray: A Reconfigurable Mirror

- Feed antenna radiates energy onto antenna array
- Elements receive, phase shift, radiate
- Advantages over phased array
  - Reduced distribution losses
  - Phase synchronization
  - No complex RF routing
One Bit Phase Shifter Concept

- Quantize phase to 0° or 180°
  - Two passive FET switches
  - Feed opposing sides of antenna
- Tradeoffs: switch sizing
  - Insertion loss vs isolation

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Q. Yu et al, IEDM 2020
One Bit Phase Shifter Considerations

- ✔ No static DC power
- ✔ Low THz loss ~3dB
- ✔ Small area >10x10 μm²
- ✔ No phase/amplitude errors
- ✗ Phase quantization ➔ sidelobes
One Bit Reflectarray

Array Factor

\[ AF = \sum_{m=0}^{N-1} I_m e^{im\psi} \]

\[ \psi = kd \cos \theta \]

DFT

\[ X_{2\pi}(\omega) = \sum_{n=-\infty}^{\infty} x[n]e^{-j\omega n} \]

\[ \omega \]

Radiation Pattern Magnitude

- 0°
- 180°
One Bit Reflectarray: Sim. Radiation
Advantages of a Bidirectional Phase Shifter
Tiled Chips for Scalable Architecture

- Single chip with 7x7 antennas
- Tile chips on PCB for large array
  - Wirebond stitching
  - Antenna spacing maintained
- Scalable architecture
  - Arbitrary array sizes
  - Individual chip addressing
    - Robust architecture
    - Bypass defects
In-Unit Memory for Phase Control

- 80kb memory per antenna
  - Shift register
- Phases pre-computed
  - Pre-loaded at startup
- Master clock cycles array
- Addresses digital bandwidth issues
- Enables performance enhancing algorithms
265GHz Reflectarray Die Photo

Intel 22nm FinFET
98 × 98 Antenna Reflectarray

Intel 22nm FinFET
98 × 98 Antenna Reflectarray

Intel 22nm FinFET
Assembled Reflectarray

- 265GHz VDI source
- Custom CNC WR3.4 feed
  - 5.8cm feed distance
Testbench

- Motorized rotation stage
  - 0.25° steps
- Static receiver at 1.6m
  - VDI WR3.4 SHM
- E-plane/H-plane cuts
Measured Radiation Patterns

![Measured Radiation Patterns Graph](image)
Measured Radiation Patterns

H-plane

E-plane

Normalized Power (dB)

Elevation (Degree)

Azimuth (Degree)
Measured Radiation Patterns
Measured/Simulated Radiation
Beam Shaping: Squint Correction

- Required phases change during FMCW chirp
  - Beam squint reduces resolution
- Use memory to update phases during chirp
Beam Shaping: Sidelobe Reduction

- Time varying offset added before quantization\(^3\)
  - Scramble quantization error in sidelobes $\rightarrow$ average out
  - Mainlobe phase offset is de-embedded at receiver
  - Needs fast change in antenna phases $\rightarrow$ enabled by memory
Beam Shaping: Sidelobe Reduction

Quantized Phases

- ■ = 0°
- □ = 180°

Radiation Pattern Magnitude

Normalized Power (dB)

Azimuth Angle (degree)

Radiation Pattern Phase

Phase (degree)

Azimuth Angle (degree)

\( d\phi = 100^\circ \)
Beam Shaping: Sidelobe Reduction

Simulated 2d pattern

1-bit, No Mitigation

1-bit, 2x Mitigation

1-bit, 4x Mitigation

Ideal Phase Shifter

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Beam Shaping: Sidelobe Reduction

Simulated 2d pattern

Measured cut

Integrated Sidelobe Power ↓ 4.6dB
Imaging Radar Demo

- Raster FMCW beam across scene
- Depth samples at each point
- Process IF into radar image

### Imaging Radar Demo

Raster FMCW beam across scene
- Depth samples at each point
- Process IF into radar image

### Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chirp rate (MHz/μs)</td>
<td>62.5</td>
</tr>
<tr>
<td>Transmit Power (dBm)</td>
<td>20</td>
</tr>
<tr>
<td>Transmit Bandwidth (GHz)</td>
<td>1.92</td>
</tr>
<tr>
<td>Frequency (GHz)</td>
<td>263~265</td>
</tr>
<tr>
<td>Range Resolution (cm)</td>
<td>7.8</td>
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<tr>
<td>Pixel Integration Time (ms)</td>
<td>15</td>
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2D Radar Imaging
2D Radar Imaging

*1 degree step per dot
3D Radar Imaging
3D Radar Imaging
## Performance Comparison

<table>
<thead>
<tr>
<th></th>
<th>Freq. (GHz)</th>
<th>Beam Forming Approach</th>
<th>Array Size</th>
<th>3dB Beam-width</th>
<th>Steering Range</th>
<th>Automatic Beam Profile Correction?</th>
<th>Technology</th>
<th>Area</th>
<th>Power Consumption</th>
<th>3D Sensing Demo?</th>
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<tbody>
<tr>
<td>ISSCC 2021 [1]</td>
<td>380</td>
<td>Active-Driven Beam Squint Antenna</td>
<td>2x1</td>
<td>~15° (1)</td>
<td>±40°</td>
<td>No</td>
<td>65nm CMOS</td>
<td>3mm²</td>
<td>0.14W (TX) 0.16 (RX)</td>
<td>NA</td>
</tr>
<tr>
<td>ISSCC 2021 [2]</td>
<td>450</td>
<td>Active Reconfigurable Array+Si Lens</td>
<td>3x7</td>
<td>~7° (2)</td>
<td>±28° &amp; ±8°</td>
<td>No</td>
<td>65nm CMOS</td>
<td>4mm²</td>
<td>0.051~0.095W</td>
<td>NA</td>
</tr>
<tr>
<td>SPIE 2019 [3]</td>
<td>235</td>
<td>Reflect Array (Tiled GaN Chips)</td>
<td>32x32 (3)</td>
<td>~3°</td>
<td>&gt; ±40°</td>
<td>No</td>
<td>GaN + Silicon Micromachining</td>
<td>31mm² (Chip) 500mm² (Array)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Nat. E. 2020 [4]</td>
<td>300</td>
<td>Transmit Array (Tiled CMOS Chips)</td>
<td>24x24</td>
<td>~10° (4)</td>
<td>±30°</td>
<td>No</td>
<td>65nm CMOS</td>
<td>4mm² (Chip) 16mm² (Array)</td>
<td>0.025W (5) (f_{ck}=5GHz)</td>
<td>NA</td>
</tr>
<tr>
<td>This Work</td>
<td>260</td>
<td>Reflect Array (Tiled CMOS Chips)</td>
<td>98x98</td>
<td>1°</td>
<td>&gt; ±60°</td>
<td>Yes</td>
<td>22nm CMOS</td>
<td>16mm² (Chip) 3100mm² (Array)</td>
<td>0.85W (7) (f_{ck}=100kHz)</td>
<td>Yes</td>
</tr>
</tbody>
</table>

(1) Achieved only in one dimension.  
(2) Achieved through a Si lens (R=5mm).  
(3) ~50% of array units not functioning.  
(4) Estimated from the simulated value.  
(5) Dynamic power driving phase shifter switches.  
(6) The only all-inclusive solution requiring no external data control during beam scanning.  
(7) Dynamic power driving 98x98x2 phase shifter switches and 780Mb built-in cyclic memory.
Conclusion

- Towards high angular resolution THz antenna arrays
  - Reflectarray architecture
  - 1 bit passive phase shifter design
  - Scalable architecture
  - Local memory

- Demonstrated electronically steered 1° beam over 120° window in 2D
- Digital Beam Shaping via local memory
- Solid state 3D THz radar imaging
Acknowledgements

- **Intel Corporation**
  - University Shuttle, SRS Program

- **MIT**
  - Greg Wornell, Jeffrey Lang, Xiang Yi, Zhi Hu, Mohamed Ibrahim, Muhammad Ibrahim Khan

- **Thomas Keating**
  - THz absorbing materials
Thank You


