A 0.31THz CMOS Uniform Circular Antenna Array Enabling Generation/Detection of Waves with Orbital-Angular Momentum

Muhammad Ibrahim Wasiq Khan, Jongchan Woo, Xiang Yi, Mohamed I. Ibrahim, Rabia T. Yazicigil, Anantha P. Chandrakasan and Ruonan Han

May 5th, 2021

Department of Electrical Engineering and Computer Science
Massachusetts Institute of Technology

Email: ibrahimw@mit.edu  Website: https://hangroup.mit.edu/
Outline

• Introduction
• Applications and Prior Works
• 0.31THz OAM CMOS Generation/Detection
  – System architecture
  – 0.31THz Reconfigurable Pixel
  – 0.31THz Amplifier-Multiplier Chain
  – Controller and Key-to-OAM mapping
• Measurement Results
• Conclusion
**Introduction**

- **Orbital Angular Momentum (OAM)**

An OAM-based wave possesses a wavefront with a helical phase distribution around the central axis of the beam

\[
|E| = A_0 J_l(k_t \rho) e\left(\frac{-\rho^2}{w_{BG}^2}\right) e^{-j m \phi} e^{-jkz} \quad \text{Ref. [1]}
\]

\[m = 0, \pm 1, \pm 2, \ldots\] represents OAM modes

\[m = 0\]

\[m = -1\]

\[m = -2\]
Applications

• **Enhanced spectral efficiency**
  – Orthogonal modes support spatial multiplexing/demultiplexing

400Gbps using 4-OAM modes at single wavelength

100Gbps using 5-OAM modes at 28GHz
Applications

- Physical-layer security for wireless channels
  - Require multiple phase-comparing antennas or colluding eavesdroppers
Applications

- **Physical-layer security for wireless channels**
  - Require multiple phase-comparing antennas or colluding eavesdroppers

Eve with two phase-comparing antennas

Unsecure area with $L_1 = L_2$, $r_1 = r_2$, $\beta = 15^\circ$
Discrete Systems for Generation/Detection of OAM

1. Spiral Phase Plate (SPP)

2. Holographic Gratings

3. Circular Antenna Array

Outline

• Introduction
• Applications and Prior Works
• 0.31THz OAM CMOS Generation/Detection
  – System architecture
  – 0.31THz Reconfigurable Pixel
  – 0.31THz Amplifier-Multiplier Chain
  – Controller and Key-to-OAM mapping
• Measurement Results
• Conclusion
System Architecture (Tx Mode)

RF_{in}=19.375GHz

Multiplier (X4) → Doubler1

Balun → Doubler2

77.5GHz

310GHz

2Δφ, 3Δφ, 4Δφ, 5Δφ, 6Δφ, 7Δφ, Δφ

1-to-8 Wilkinson Divider

310GHz Reconfigurable Pixel

LO Generation

Keccak

Key Generation

Input Seed

Rx Mode Search

Controller

IF\textsubscript{OUT,i} (i=1\ldots8)

IF Combiner

D_{OUT}
System Architecture (Rx Mode)

RF_{in} = 19.375\,\text{GHz}

**Multiplier (X4)**

**Balun**

**Doubler1**

**Doubler2**

- 77.5\,\text{GHz}
- 155\,\text{GHz}

- 310\,\text{GHz}

- 310\,\text{GHz} Reconfigurable Pixel
- 5\Delta \phi
- 4\Delta \phi
- 3\Delta \phi
- 2\Delta \phi

**Wilkinson Divider**

**1-to-8**

**Δφ**

**Δφ**

**Δφ**

**Δφ**

**Δφ**

**Δφ**

**Δφ**

**Δφ**

- 0°

**Tx/Rx Select**

**Keccak**

**Input Seed**

**Key Generation**

**Bits-to-mode mapping**

**Rx Mode Search**

**LO Generation**

**IF_{OUT,i} (i=1\ldots8)**

**IF Combiner**

**D_{OUT}**
310GHz Reconfigurable Pixel

- **Tx Chain**: LO1, LO2, Matching Network, Coupler, SSB Mixer
- **Patch Antenna**: TX Mode (Single-Ended Port)
- **RX Mode (Differential Port)**: LO1, LO2, Balun, Wilkinson Combiner, Mixer, Amplifier, Buffer, RC-poly phase shifter, SSB Mixer
- **Coupled Line SPDT**: Keccak & Digital Control, EN, EN
- **1 to 8 Wilkinson Divider**: To Other Pixels, From 310GHz Chain
310GHz Reconfigurable Pixel (Tx Mode)
310GHz Reconfigurable Pixel (Rx Mode)
310GHz Amplifier-Multiplier Chain

Multiplier (X4) → Doubler1 → Balun → Doubler2 → 1 to 8 Wilkinson Divider → Pixels

19.375 GHz → Multiplier (X4) → Buffer → Doubler1 → Balun → To Amp
310GHz Amplifier-Multiplier Chain
Controller and Key-to-OAM Mapping

- SPI
  - 32 Byte Secret Seed
  - CLK

Keccak-f[400] Pseudo-Random Number Generation

OAM Mode Selection
- 0, +1, -1 or (+1)+(-1)

OAM Initial Phase Selection
- 0° to 315° with 45° Steps

LO Pattern
- CLK

8-Phase LO Generator
- (Clock Divider ÷ 4)

8-Phase LO for Each Pixel

Key-to-OAM Mapping

Φ: Phase Distribution
I: Intensity Distribution

m=0, m=1, m=-1, m=(+1)+(-1)
EM Simulation of OAM Modes

<table>
<thead>
<tr>
<th>OAM Modes</th>
<th>$m = 0$</th>
<th>$m = +1$</th>
<th>$m = -1$</th>
<th>$m = \pm 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intensity Distribution</strong></td>
<td><img src="image" alt="Intensity $m = 0$" /></td>
<td><img src="image" alt="Intensity $m = +1$" /></td>
<td><img src="image" alt="Intensity $m = -1$" /></td>
<td><img src="image" alt="Intensity $m = \pm 1$" /></td>
</tr>
<tr>
<td><strong>Phase Distribution</strong></td>
<td><img src="image" alt="Phase $m = 0$" /></td>
<td><img src="image" alt="Phase $m = +1$" /></td>
<td><img src="image" alt="Phase $m = -1$" /></td>
<td><img src="image" alt="Phase $m = \pm 1$" /></td>
</tr>
</tbody>
</table>
Outline

• Introduction
• Applications and Prior Works
• 0.31THz OAM CMOS Generation/Detection
  – System architecture
  – 0.31THz Reconfigurable Pixel
  – 0.31THz Amplifier-Multiplier Chain
  – Controller and Key-to-OAM mapping
• Measurement Results
• Conclusion
Chip Micrograph and Power Consumption

TSMC 65nm CMOS Process

Power Consumption Breakdown

- Controller: <1 mW
- Input Multiplier (x4): 7.7 mW
- 77.5GHz Buffer/Amplifier: 11.2 mW
- Doubler1: 21 mW
- Doubler2: 24.8 mW
- 155GHz Amplifier: 57 mW
- Rx Down Mixer: 1.3 mW
- Rx LNA: 1.4 mW
- Rx SSB Mixer: 1.4 mW
- Tx Mode → 154mW
- Rx Mode → 166mW
Measurement Setups

Chip Package

Teflon Lens Removed

19.4GHz Source

1" Teflon Lens

Spiral Phase Plate

FPGA (XEM 7001)

VDI Down-Mixer (WR3.4MixAMC-1)

12.9GHz Source

Spectrum Analyzer

Oscilloscope

BPF

1MHz Amplifier (54dB)

Spectrum Analyzer

Combined IF

FPGA (XEM 7001)

VDI VNA (WR3.4)

Frequency Extender

17.2GHz Source

Spectrum Analyzer

Combined IF

FPGA (XEM 7001)

Buffer
Intensity Profiles and Tx Mode-checking

Measured intensity distribution for m=+1 and m=(+1)+(-1) OAM modes

Tx OAM mode-checking
Measured spectrums when Tx chip is m=+1 and Rx SPP is m=+1 and -1
Time-domain Tx OAM Mode-checking

Time-domain OAM mode-checking setup with 1m Tx-Rx distance

Time-domain output of the Rx configured to respond to different OAM modes, when it is illuminated by the same OAM sequence (1Mbps) generated by on-chip Keccak
Rx Mode-checking and Tx-Rx Characterization

Measured spectrum of combined IF when OAM modes are matched and unmatched

Measured Tx EIRP ($m = 0$)  Measured Rx pixel conversion loss
CMOS Tx-Rx OAM Link

Full-silicon OAM link and sensitivity to co-axial alignment
Outline

• Introduction
• Applications and Prior Works
• 0.31THz OAM CMOS Generation/Detection
  – System architecture
  – 0.31THz Reconfigurable Pixel
  – 0.31THz Amplifier-Multiplier Chain
  – Controller and Key-to-OAM mapping
• Measurement Results
• Conclusion
# Comparison with RF and mm-Wave OAM Prototypes

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Implementation</strong></td>
<td>Discrete Transceivers + SPP + Quasi-Optical Beam Combiner</td>
<td>Active-Driven Antenna Arrays + Parabolic Reflectors</td>
<td>Active-Driven Antenna Arrays</td>
<td>Active-Driven Antenna Array on a 65nm CMOS Chip + Teflon Lens</td>
</tr>
<tr>
<td><strong>Frequency (GHz)</strong></td>
<td>28</td>
<td>10</td>
<td>40</td>
<td>310</td>
</tr>
<tr>
<td><strong>OAM Modes</strong></td>
<td>±1, ±3</td>
<td>±2, ±3</td>
<td>0, ±1, ±2, ±3</td>
<td>0, +1, -1, ±1</td>
</tr>
<tr>
<td><strong>Data Modulation</strong></td>
<td>16QAM/Mode Dual Polarization</td>
<td>32QAM on each mode, Full Duplex</td>
<td>256QAM/Mode Dual Polarization</td>
<td>Bit-to-Mode OAM Hopping</td>
</tr>
<tr>
<td><strong>Radiated Power (dBm)</strong></td>
<td>8</td>
<td>0</td>
<td>11.5</td>
<td>-4.8 (EIRP)</td>
</tr>
<tr>
<td><strong>Antenna Aperture Diameter (cm)</strong></td>
<td>30</td>
<td>60</td>
<td>120</td>
<td>1.35</td>
</tr>
<tr>
<td><strong>Application</strong></td>
<td>Enhanced Spectral Efficiency</td>
<td>Enhanced Spectral Efficiency</td>
<td>Enhanced Spectral Efficiency</td>
<td>Physical-Layer Security</td>
</tr>
<tr>
<td><strong>DC Power (mW)</strong></td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>154 (Tx), 166 (Rx)</td>
</tr>
</tbody>
</table>
Acknowledgement

• This work is supported by National Science Foundation EAGER SARE award

• Prof. Yang Yang at University of Technology, Sydney for the spiral phase plates

This work will be presented at RFIC 2021
M. I. W. Khan, J. Woo, X. Yi, M. I. Ibrahim, R. T. Yazicigil, A. P. Chandrakasan and R. Han, “A 0.31THz CMOS Uniform Circular Antenna Array Enabling Generation/Detection of Waves with Orbital-Angular Momentum,” 2021 IEEE Radio Frequency Integrated Circuits Symposium (RFIC), Atlanta, GA, USA, 2021 (Best Student Paper Award)
References

Thank you!