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

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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

\[ |E| = A_0 J_l(k_t \rho) e\left(\frac{-\rho^2}{w_{BG}^2}\right) e(-jm\phi) e(-jkz) \]

Ref. [1]

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

(O: Intensity Distribution Φ: Phase Distribution)
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

Introduction

Applications and Prior Works

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Measurement Results

Conclusion
System Architecture

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

Multiplier (X4) → Doubler1
77.5\,\text{GHz}

Balun → Doubler2
155\,\text{GHz}

310\,\text{GHz}

1-to-8 Wilkinson Divider

310\,\text{GHz} Reconfigurable Pixel

Controller
Keccak
Input Seed

Key Generation

Bits-to-mode mapping

Rx Mode Search

LO Generation

IF_{OUT,i} (i=1\cdots8)
IF Combiner

\Delta \varphi

Tx/Rx Select

0°

\varphi
System Architecture (Tx Mode)

RF_IN = 19.375 GHz

Multiplier (X4) → Doubler1

Balun → Doubler2

77.5 GHz

155 GHz

310 GHz

2Δφ

3Δφ

4Δφ

5Δφ

6Δφ

7Δφ

Δφ

0°

Tx/Rx Select

Controller

Keccak

Input Seed

Key Generation

Bits-to-mode mapping

LO Generation

1-to-8 Wilkinson Divider

310 GHz Reconfigurable Pixel

Rx Mode Search

\[ \text{IF_{OUT,i}} (i=1 \ldots 8) \]

\[ \text{D_{OUT}} \]
System Architecture (Rx Mode)

- RF$_{IN}$=19.375GHz
- Multiplier (X4) → Doubler1
- Balun → Doubler2
- 155GHz
- 77.5GHz

Diagram:
- 310GHz
- IF$_{OUT,i}$ (i=1...8)
- 310GHz Reconfigurable Pixel
- 4Δφ
- 5Δφ
- 6Δφ
- 7Δφ
- 2Δφ
- 3Δφ

Controller:
- Keccak
- Input Seed

Key Generation

Bits-to-mode mapping

Rx Mode Search

LO Generation

IF$_{OUT,i}$ (i=1...8)

DO$_{UT}$
310GHz Reconfigurable Pixel
310GHz Reconfigurable Pixel (Tx Mode)
310GHz Reconfigurable Pixel (Rx Mode)
310GHz Amplifier-Multiplier Chain
310GHz Amplifier-Multiplier Chain
Controller and Key-to-OAM Mapping

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

8-Phase LO Generator (Clock Divider ÷ 4)

8-Phase LO for Each Pixel

Key-to-OAM Mapping

Φ: Phase Distribution
I: Intensity Distribution

0 0 1 0 1
1 0 1 1 1 0 1

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 Distribution $m = 0$" /></td>
<td><img src="image" alt="Intensity Distribution $m = +1$" /></td>
<td><img src="image" alt="Intensity Distribution $m = -1$" /></td>
<td><img src="image" alt="Intensity Distribution $m = \pm 1$" /></td>
</tr>
<tr>
<td><strong>Phase Distribution</strong></td>
<td><img src="image" alt="Phase Distribution $m = 0$" /></td>
<td><img src="image" alt="Phase Distribution $m = +1$" /></td>
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Chip Micrograph and Power Consumption

TSMC 65nm CMOS Process

Power Consumption Breakdown

Tx Mode → 154mW
Rx Mode → 166mW
Measurement Setups
Intensity Profiles and Tx Mode-checking

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

Tx OAM mode-checking
Measures 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
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Comparison with RF and mm-Wave OAM Prototypes based on Discrete Components

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<tbody>
<tr>
<td></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>Frequency (GHz)</td>
<td>28</td>
<td>10</td>
<td>40</td>
<td>310</td>
</tr>
<tr>
<td>OAM Modes</td>
<td>±1, ±3</td>
<td>±2, ±3</td>
<td>0, ±1, ±2, ±3</td>
<td>0, +1, -1, ±1</td>
</tr>
<tr>
<td>Data Modulation</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>Radiated Power (dBm)</td>
<td>8</td>
<td>0</td>
<td>11.5</td>
<td>-4.8 (EIRP)</td>
</tr>
<tr>
<td>Antenna Aperture Diameter (cm)</td>
<td>30</td>
<td>60</td>
<td>120</td>
<td>1.35</td>
</tr>
<tr>
<td>Application</td>
<td>Enhanced Spectral Efficiency</td>
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<td>Physical-Layer Security</td>
</tr>
<tr>
<td>DC Power (mW)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>154 (Tx), 166 (Rx)</td>
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References

Thank you!