Heterodyne Sensing CMOS Array with High Density and Large Scale: A 240-GHz, 32-Unit Receiver Using a De-Centralized Architecture

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Outline

- Introduction
- Array Architecture
- Multi-functional Heterodyne Pixels
- Phase Locking Circuitry
- Measurement Results
- Conclusion
Terahertz Radar as an Important Sensing Mode

• Multiple sensing modes are needed in navigation applications where safety is a priority
  – Examples: self-driving cars, unmanned aerial vehicles, etc.
Terahertz Radar as an Important Sensing Mode

- Multiple sensing modes are needed in navigation applications where safety is a priority
  - Examples: self-driving cars, unmanned aerial vehicles, etc.
- Terahertz sensing is an important complement to light-based sensing (e.g. LiDAR)
  - Sub-THz waves have much lower propagation loss than light waves under various conditions (fog, dust etc.)
Review of Previous On-Chip THz Sensing Arrays

- Direct (Square-Law) Detector Arrays (large scale)

- Techniques of building large-scale direct detector arrays have been well-tested and become mature
- Limitations of direct detection
  - Low responsivity and high NEP, due to limited received RF power \( P_{IF} \propto P_{RF}^2 \)
  - Coherence of RF signals is lost, thus unable to perform beam-forming (electrical scanning)
Review of Previous On-Chip THz Sensing Arrays

• **Heterodyne Detector Arrays (small scale)**

  - **2 x 2 array** [K. Statnikov, et al., TMTT, 2015]
  - **8-unit array** [C. Jiang, et al., JSSC, 2016]

  - **One 164GHz x9 multiplier with a harmonic generator**
  - **18GHz RF input**
  - **Harmonic generator**
  - **DC-pads**

  - **Strengths of heterodyne detection**
    - High responsivity and low NEP, by leveraging high LO power ($P_{IF} \propto P_{LO} \cdot P_{RF}$)
    - Coherence of RF signals is preserved, thus inherently capable of beam-forming

• **There are still challenges of designing large-scale heterodyne detector arrays to form sharp beam**
Our Vision of the Path Towards Sharp THz Beam

- Heterodyne array is desired, and its scale should be pushed up to the extreme
- How large the scale needs to be, to get an angular resolution comparable to that of LiDAR?
  - Using a single array, at 240 GHz, to obtain 1° beam width, an area of 6cm x 6cm (~ 10,000 units) is needed
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Our vision is based on the two-way array pattern
- On-board sparse TX array generates sharp beams
- On-chip dense RX array synthesizes single beam to filter out TX sidelobes – with relaxed, but still high, scale requirement
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RX Chip: Centralized vs. De-Centralized Arrays

- Centralized array relies on a single LO source, however,
  - Generating sufficient power shared by tens of units is difficult
  - Long LO feed lines are lossy and hard to route
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  – Generating sufficient power shared by tens of units is difficult
  – Long LO feed lines are lossy and hard to route

• De-Centralized array ensures every unit having an LO source
  – LO sources are coherently coupled; corporate feed is thus eliminated
  – Oscillator power requirement is relaxed
  – Bonus: LO phase noise improves as more units are coupled
Challenges of Scaling and How We Address them

- **Scalability challenge:**
  - Strong coupling mechanism between units is needed

- **Density challenge**
  - Within $\lambda/2 \cdot \lambda/2$ area, antenna, oscillator, mixer, coupler etc. needs to be incorporated
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• Self-Oscillating harmonic mixer (SOHM) employed
  – Oscillator and mixer condensed into one component

• Slotline-resonator-based oscillator coupling employed

• Two interleaved 4x4 array integrated ($A_{unit} = \lambda/2 \cdot \lambda/2$)
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EM Structure of a Single Pixel Unit

- The array consists of 16 cells, each cell contains 2 units.
- The boundaries of each unit is well-defined, as a result of LO coupler design.
- The unit is structurally and electrically symmetric; a PEC boundary (AB) can be drawn in the middle at $f_0$. 

`PMC`
Equivalent Circuit of a Single Pixel Unit

- TL4 and TL4’ are slot antennas
- TL3 and TL3’ are resonator and coupler of oscillators
- TL1, TL1’, TL2, and TL5 are integral components of oscillators
Analysis of SOHM with Further Simplifications
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Virtual Ground

Self-Feeding Oscillator

Enhance instability

Antenna (Resonator II)

Coupler (Resonator I)
Analysis of SOHM with Further Simplifications

Virtual Ground

C1
C2
C3

TL1
TL2
TL3
TL4
TL5

Self-Feeding Oscillator

Enhance instability

TL1
M1
C1

Antenna (Resonator I)

Coupler

TL3
TL4

V2f0

Vf,RF

Short @ f0

Vf,IF

from oscillator

from antenna

from antenna

TL1

TL3

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Analysis of SOHM with Further Simplifications

- Self-oscillating harmonic mixer (SOHM) can be regarded as an oscillator that
  - Oscillates at \( f_0 = 120 \) GHz and simultaneously generates LO signal \( f_{LO} = 2f_0 = 240 \) GHz
  - Receives RF power from resonator (\( TL_4 \), Resonator II)
  - Down-converts RF to IF, i.e. \( f_{IF} = f_{RF} - 2f_0 \) (using the non-linearity of the transistor)
- Oscillator is optimized to the optimal phase condition [6] by choosing proper \( Z_{TL1} \) and \( \phi_{TL1} \)
E-Field Distributions at $f_0$, $2f_0$ ($f_{LO}$), and $f_{RF}$

- Resonator I and II are for coupling and radiation cancelling
- For explanation, E-field distributions are needed
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At $f_0$, waves in TL3 induce coupling between oscillators
- E-Field polarizations in TL3 and TL4 of adjacent units ensure radiation cancellation at $f_0$
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- At $f_{RF}$, waves are received by antennas since they are from a far-field source with the same polarization
Full-Wave Simulation Results of a Pixel Unit

• E-Field Distribution at $f_0$ (ports at drains are driven)

• E-Field Distribution at $2f_0$ (ports at drains are driven)

• E-Field Distribution at $f_{RF}$ (ports at antennas are driven)

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Schematic as reference
Simulation Results of SOHM Performance

- DC Power per unit: 43.2 mW
- Conversion loss (CL): 16 dB (with 50-Ω output load)
- Noise figure (NF): 46.5 dB at $f_{IF} = 5$ MHz; 19.3 dB at $f_{IF} = 100$ MHz
- Antenna peak directivity: 4.8 dB; antenna efficiency: 40 %
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Overview of the Phase Locking Circuitry
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- Bottom two pixel units inject a small amount of waves at $f_0 = 120$ GHz into the divider
- PLL components generate the VCO control voltage for the entire array
- Due to array-wide coupling, all units are locked
Design of the 120-GHz Divide-by-16 Divider

- **1st stage**: div-by-4 ILFD, based on $f_{\text{inj}} = 4f_{\text{osc}}$ mixing with $3f_{\text{osc}}$
- **2nd stage**: div-by-4 ILFD, based on injected signals modulating the current sources of the ring oscillator
- Total DC power consumption: 10.5 mW
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Die Photo and Chip Packaging Details

- Technology: 65nm CMOS; chip area 2.8 mm² (1.21 mm² for the array)
- Silicon lens is attached to the backside of the chip (backside radiation)
- Off-Chip multiplexer is used to select the desired IF signal from 32 outputs
Overview of the Chip Measurement

- VDI WR-3.4 extender is used as the RF source
- Frequency reference of the chip and the VDI source are synchronized
- Locking range of the array (obtained from divider output): 232.96 GHz – 234.88 GHz

- Center: 73.2 MHz
- Span: 200 kHz
- RBW: 10 Hz
Measured IF Spectra at Low/High Frequencies

- Flicker noise dominates until ~ 450 MHz (IF amp BW = 500 MHz)
Measured IF Spectra at Low/High Frequencies

- Flicker noise dominates until ~ 450 MHz (IF amp BW = 500 MHz)
- At 4.6 MHz (below corner frequency), SNR = 63 dB (RBW = 1 Hz)
- At 475 MHz (beyond corner frequency), SNR = 87 dB (RBW = 1 Hz)
- Other pixels are also locked; they have similar responses, and their $f_{IF}$ all shifts simultaneously as $f_{ref}$ shifts

### IF noise spectrum (from spectrum analyzer)

- Start: 1.0 MHz
- Stop: 500.0 MHz
- RBW: 100 kHz

### IF noise spectrum (referred to chip output)

- Start: 1.0 MHz
- Stop: 500.0 MHz
- RBW: 100 kHz
Antenna Pattern and Performance Evaluation

- **Conversion gain (dB)**
  \[
  CG = P_{IF} - P_{RF}, \text{ where} \\
  P_{IF} = P_{IF, \text{ analyzer}} - G_{amp}, \text{ and} \\
  P_{RF} = P_{RF, \text{ TX}} + D_{TX} + G_{RX} - 20 \log_{10}(\lambda/(4\pi d))
  \]

- **Noise Figure (dB)**
  \[
  NF = P_{\text{noise}} - (-174 \text{ dBm}) - CG, \text{ where} \\
  P_{\text{noise}} = 10 \log_{10}(10^{(P_{\text{noise, analyzer}} - G_{amp})/10} - 10^{-17.4})
  \]
  (considering \( NF_{amp} = 3 \text{ dB} \))
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  (considering \( NF_{\text{amp}} = 3 \text{dB} \))

- Here, we have \( G_{\text{amp}} = 49 \text{ dB}, P_{RF, \text{TX}} = -7.1 \text{ dBm}, D_{TX} = 24 \text{ dBi}, D_{RX} = 6.0 \text{ dB}, n_{RX} = 40 \% \text{ (simulated)}, \lambda = 1.28 \text{ mm}, d = 0.1 \text{ m} \)

- For \( f_{IF} = 475 \text{ MHz} \text{ (beyond corner frequency)}, CG = 42.4 \text{ dB}, NF = 42.4 \text{ dB} \)

- Define \textbf{Sensitivity} = \( NEP \cdot \sqrt{1000Hz} = -174 \text{ dBm} + NF + 30\text{dB}; \) for \( f_{IF} = 475 \text{ MHz}, \text{Sensitivity} = 0.105 \text{ pW} \)
Measured Phase Noise of the LO Signal

- VDI extender is placed very close to the chip to capture the leaked near-field radiation at $2f_0$
- Measured $2f_0$ phase noise at 1 MHz offset is -84 dBC/Hz
## Performance Comparison

<table>
<thead>
<tr>
<th>References</th>
<th>This Work</th>
<th>[5]</th>
<th>[1]</th>
<th>[2]</th>
<th>[3]</th>
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</thead>
<tbody>
<tr>
<td>Detection Method</td>
<td>Heterodyne Detection</td>
<td>Square-Law (Direct) Detection</td>
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<tr>
<td>Array Size</td>
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<td>130nm SiGe</td>
<td>130nm CMOS</td>
<td>180nm SiGe</td>
<td>130nm SiGe</td>
</tr>
</tbody>
</table>

**Notes:**

* Received $P_{RF}$ to get unity SNR for IF output at 1-kHz detection bandwidth
# Calculated based on $P_{IF}$ and $P_{noise}$ at $f_{IF} = 4.6$ MHz
† Calculated based on $P_{IF}$ and $P_{noise}$ at $f_{IF} = 475$ MHz
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• For the first time, heterodyne receiver array has achieved the scale and density that are comparable to those of square-law detector arrays

• Our array improves the sensitivity by ~680x compared with the 8-unit heterodyne receiver array in [5], and by ~2400x compared with the best square-law detector arrays

• Scalability and sensitivity improvements make sub-THz array technology a more promising candidate for the implementation of high-resolution beam-forming imagers in the future
References


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