Large-Scale Terahertz Active Arrays in Silicon Using Highly-Versatile Electromagnetic Structures

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The Dawn of a New Terahertz Era

Applications (Demos)

Enabling Technology

Today
The Dawn of a New Terahertz Era

Applications (Demos)

Enabling Technology

System Complexity

Cost & Size

Today

The Next THz Era
The Dawn of a New Terahertz Era

Applications (Demos)  

Today  The Next THz Era

Enabling Technology

Cost & Size  System Complexity
Recent Progress and New Challenges

Our Work

Our Work

Our Work

Our Work

Our Work

[IMS 2013]

[ISSCC 2013]

[ESSIRC 2013]

[ISSCC 2012]

[T-MTT 2014]

[ISSCC 2014]

[ISSCC 2014]

[ISSCC 2010]

[ISSCC 2012]

[ESSIRC 2012]

[ISSCC 2011]

[VLSI 2011]

[ISSCC 2013]

[ISSCC 2014]

[ISSCC 2015]

[ISSCC 2015]

[IMD 2016]

[R. Han, etc., IEDM 2016]
Recent Progress and New Challenges

What are the true advantages of using silicon IC for THz hardware (besides low cost, baseband integration...?)?
Large-Scale Terahertz Active Array

Integration Capability of Silicon Chips

Homogeneous Array
- Power combining
- Beam collimation
- Beam steering
- ...

Heterogeneous Array
- Broadband sensing
- Parallel signal processing
- Waveform generation
- ...

[Diagram showing homogeneous and heterogeneous arrays with corresponding features listed]
Outline

- Background
  - Homogeneous Array: 1-THz Radiation Source
    - Multi-Functional Mesh Structure
    - Chip Prototype in SiGe and Measurement Results
  - Heterogeneous Array: 220-to-320GHz Frequency-Comb Spectrometer
    - High-Parallelism Architecture and THz Molecular Probing Module
    - Chip Prototype in CMOS and Measurement Results
    - Gas-Sensing Demonstration
- Conclusion
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Beam Collimation in a Radiator Array

- Array of $N$ coherent radiation sources enables:
  - Power combining from a large number of solid-state devices
  - Beam collimation through wave interference
  - The far-field radiation intensity increases by $N^2$

Optimum Element Pitch: $\lambda/2$
High-Density, Large-Scale Active Array on Chip

- If the $\lambda/2$ pitch is achieved:
  - $>10$/mm$^2$ radiators at 300 GHz can be built
  - $D_{\text{opt}}$ is $\sim300\mu$m
    (with $\varepsilon_{r,\text{eff}}\approx3$)

- High effective isotropically radiated power (EIRP) may be maintained in the mid-THz range
  - Long transmission distance

Note: Calculations Based on a 10mm$^2$ Active Area
High-Density, Large-Scale Active Array on Chip

Note: Calculations Based on a 10mm² Active Area

- 320-GHz Array w/ PLL in SiGe BiCMOS
- 4x4 elements in 1-mm² area
- 3.3mW total radiated power (EIRP: 24mW)
High-Density, Large-Scale Active Array on Chip

• ~100/mm² radiator density should be possible
  – Only 3° of beamwidth using 10-mm² chip area
    (~1000 coherent radiators)

• Large challenges
  – Signal generation at 1 THz
  – Available radiator area: 100×100μm²
  – Highly scalable array architecture

Note: Calculations Based on a 10mm² Active Area
Implementation Challenges

Cutoff Frequency of Silicon Devices

High-Order Harmonic Radiation

- Low device speed requires high-order harmonic generation
  - Optimal device conditions at all harmonic frequencies should be met
- The available area is too small for all these necessary functions

Enabling Technology: Versatile EM Designs

- A multi-functional electromagnetic structure around the transistors to simultaneously perform all the above tasks
  - Orthogonality of various EM wave modes
  - Multi-order standing-wave interference in the near field
High-Density, Large-Scale Active Array on Chip

- 1-THz Array in 130-nm IHP SiGe BiCMOS
- 91 coherent radiator in 1-mm² area
- 0.1-mW total radiated power (EIRP: 20mW)

[Z. Hu and R. Han, IEEE RFIC, Jun. 2017 (Best Student Paper Award-2nd Place)]
Fundamental Oscillation at $f_0=250\text{GHz}$

- At $f_0$, each square slot line behaves as a pair of $\lambda/4$ standing-wave resonators

**Optimal Fundamental Oscillation**
Multi-Order Standing Wave Interference

Unwanted harmonics ($@ f_0$, $2f_0$, $3f_0$) are canceled by near-field interference

No Separate Filter is Needed
High-Density Radiation at 1 THz

- The 1-THz standing waves in all horizontal slots are in phase
  - Effective backside radiation ($\eta_{rad,sim} = 63\%$)
  - On average, each oscillator (4x7 in total) drives 2 slot dipole antennas

91 Coherent Antennas ($D = \lambda/2$)
Measurement Results: Frequency and Spectrum

- Oscillation frequency is determined by a sub-harmonic SBD mixer
  - Weak radiation leakage at $f_0$
  - Measured fundamental frequency: 252.5 to 254.1 GHz
  - $4f_0$ output: 1.01 to 1.016 THz

\[ f_0 = 16f_{LO} + f_{offset} \]
Measurement Results: Radiated Power

- The radiated power is measured by a calibrated WR-1.0 zero-biased diode detector
  - Measured total radiated power: 80 μW
  - Measured beam directivity: 24 dBi (θ_{3dB}=11°)
  - Measured EIRP: 20 mW
Measurement Results: Radiated Power

- The measured radiated power is further verified by a photo-acoustic (TK) power meter with large aperture.
Comparison with the State-of-the-Arts in Silicon

• The achieved radiated power is 10x higher than prior silicon-based radiation sources in the mid-THz range
  – 100x higher EIRP than prior arts

• Even larger scale with higher power should be possible
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Wave-Matter Interactions for Material Sensing

Non-Ionizing Radiation

Ionizing Radiation

Frequency (Hz)

Long Radio Waves

Radio Waves

Microwave Waves

THz Waves

IR

UV

X rays

Wavelength (m)

Nuclear & Electron Resonance

Molecular Rotation

Molecular Vibration

Electron Level Change

Ionization
## THz Spectrometer for Gas Sensing

[Source: HiTRAN.org]

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Frequency (GHz)</th>
<th>Toxic?</th>
<th>Flammable?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>230.538001</td>
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<td>Y</td>
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<tr>
<td>Sulfur Dioxide (SO₂)</td>
<td>251.199668</td>
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<td>Hydrogen Cyanide (HCN)</td>
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<td>Hydrogen Sulfide (H₂S)</td>
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<tr>
<td>Nitric Oxide (NO)</td>
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<td></td>
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<tr>
<td>Nitrogen Dioxide (NO₂)</td>
<td>292.987169</td>
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<td></td>
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<tr>
<td>Nitric Acid (HNO₃)</td>
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<td></td>
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<tr>
<td>Ammonia (NH₃)</td>
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<tr>
<td>Carbonyl Sulfide (OCS)</td>
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<td>Ethylene Oxide (C₂H₄O)</td>
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<tr>
<td>Acrolein (C₃H₅O)</td>
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<td>Methyl Mercaptan (CH₃SH)</td>
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<td>Acetone (CH₃COCH₃)</td>
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<td>Y</td>
<td>Y</td>
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<tr>
<td>Acrylonitrile (C₃H₃CN)</td>
<td>265.935603</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

**Absorption Intensity:**

\[
\gamma = \frac{(2J + 1)hB e^{-hBJ(J+1)/kT}}{kT}
\]

**Quantum Number:**

\[J \approx 40\]

**Wide Detection Range**

**High Sensitivity**

**High Selectivity**
Dual-THz-Comb Spectrometer

- Conventional single-tone sensing scheme
  - Bandwidth-efficiency tradeoff
  - Long scanning time
    (~3 hours for 100-GHz bandwidth)

- Our scheme using bilateral THz frequency combs
  - Each circuit block maintains peak performance in a narrow band
  - Simultaneous scanning using 20 comb lines
    (>20x increased speed)
220-to-320GHz Comb-Based CMOS Spectrometer

[C. Wang and R. Han, IEEE ISSCC, Feb. 2017]

• 10 molecular-probing THz transceivers
  – Key technology: multi-function, energy-efficient electromagnetic structures
• Seamless coverage of the 220 to 320 GHz band with kHz resolution
Operation of the Transceiver Unit Core

- Optimum device conditions created via a multi-functional EM structure
  - Slot 1: resonator at $f_0$ and antenna at $2f_0$
  - Slot 2: power recycle path at $f_0$ and leakage blocker at $2f_0$
- Simultaneous transmit/receive function

High-Parallelism Broadband Architecture

- The relaxed tunability requirement allows the introduction of device positive feedback and higher device gain
  - 43% simulated doubler conversion efficiency
- The total spectral scanning time is reduced by more than 20x, leading to high energy efficiency
CMOS Chip Prototype

- TSMC 65nm bulk CMOS process \( f_{\text{max}} = 250\text{GHz} \)
  - Chip area: 2×3mm\(^2\)
- 10 transceivers (doubler+receiver+antenna), 9 mixers, 40 amplifiers, operating at 0.1~0.3 THz
  - DC power: 1.7 W
Experimental Results

Measured Down-converted IF Spectra of all Comb Lines

Average Phase Noise: -102dBc/Hz @ 1MHz

Spectrum of a Comb Line at 265GHz

Antenna Pattern of One Line (265GHz)
Experimental Results

- Total radiated power of the 10 comb lines: 5.2 mW
  - Highest in silicon
- Minimum detectable signal: 0.1 fW (-130 dBm) @ τ=1 ms
Spectroscopy Demonstration

- Low pressure is applied to eliminate the spectral broadening due to the inter-molecular collisions
- Wavelength modulation is used to reduce the impacts of the standing wave inside the gas chamber
Spectroscopy Results

- Sensitivity: 11 ppm for OCS, 14 ppm for CH$_3$CN, 3 ppm for HCN...
  - 10-100 ppt with standard gas pre-concentration
- Any polar molecule heavier than HCN can be detected
- Spectral linewidth is $\sim$1MHz, leading to absolute specificity
Conclusions

• Using CMOS/BiCMOS device technologies not only enables “THz frontend + analog/digital baseband” integration, but may also directly enhance the THz-circuit performance
  – Homogeneous arrays: high-density coherent wave interference
    → Large total radiated power
    Ultra-narrow beam generation
  – Heterogeneous arrays: high-parallelism EM spectral sensing
    → Broadband coverage
    Optimal energy efficiency

• Key technology: versatile THz circuits with multi-functional structures

A unified design framework:
device, circuit, electromagnetism and architecture, all rolled into one
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• Sponsors:

[Logos and images of sponsors]
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