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

(Invited Paper)

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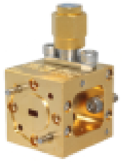
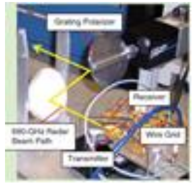
The Dawn of a New Terahertz Era

Applications (Demos)

Today

Enabling Technology





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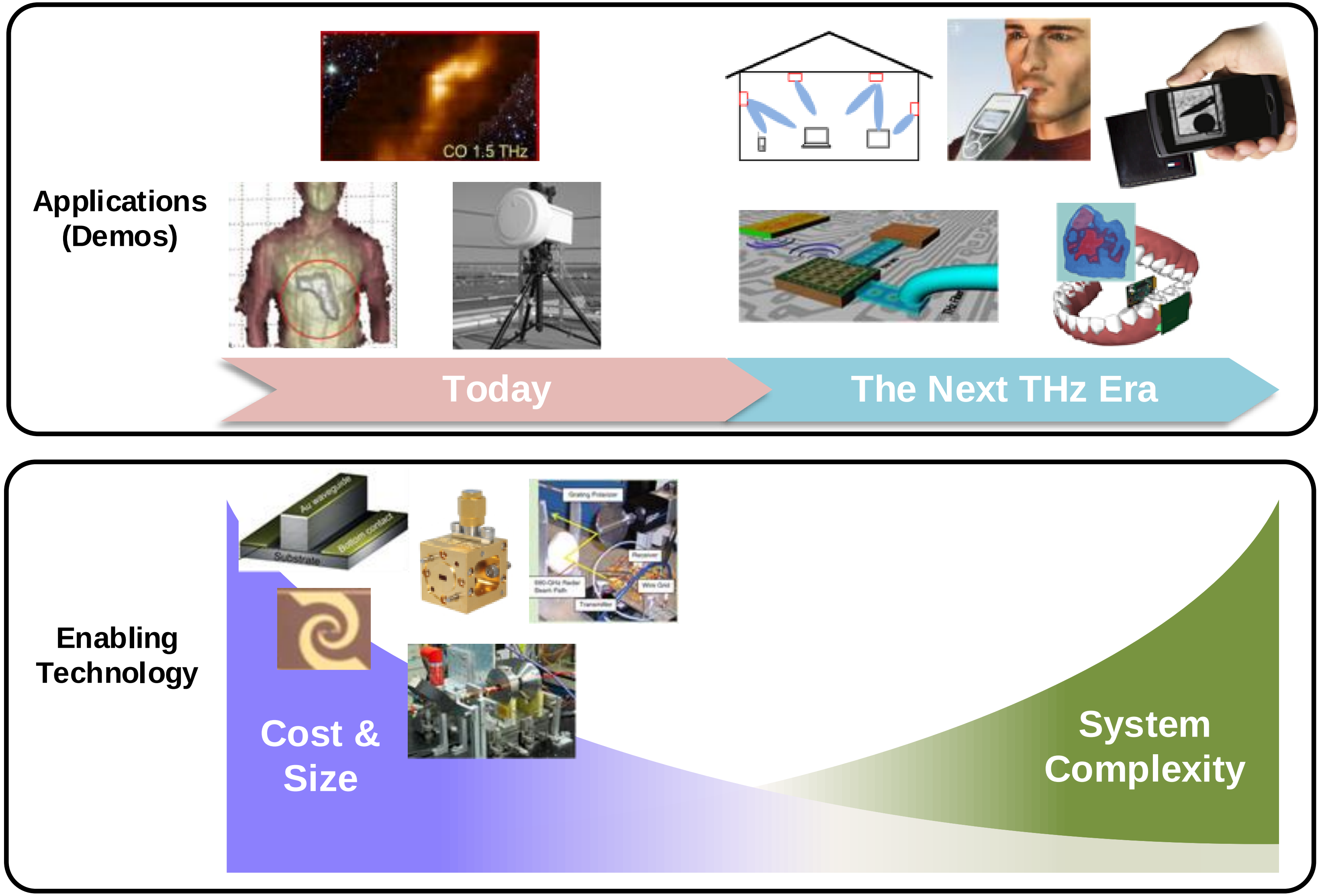

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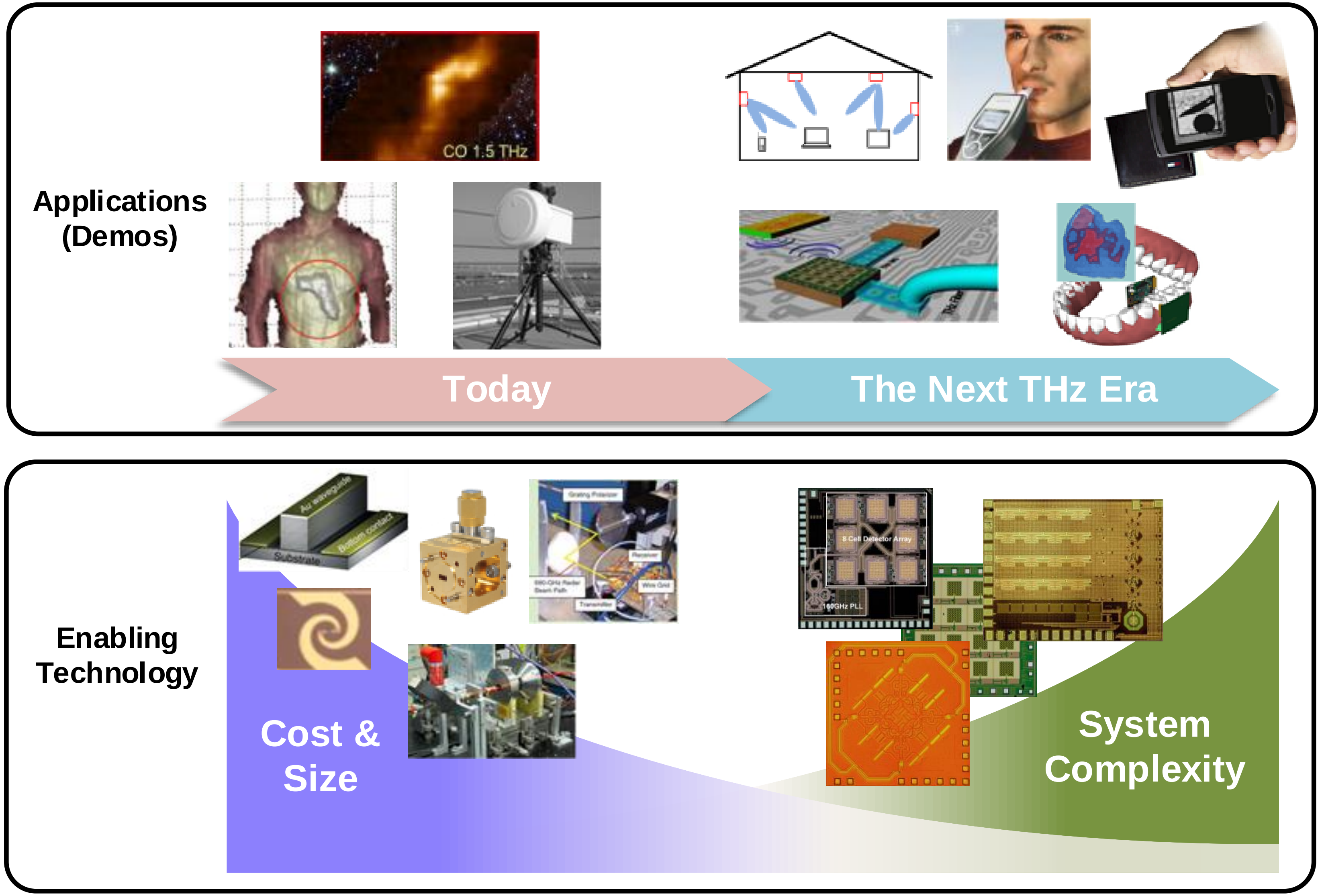
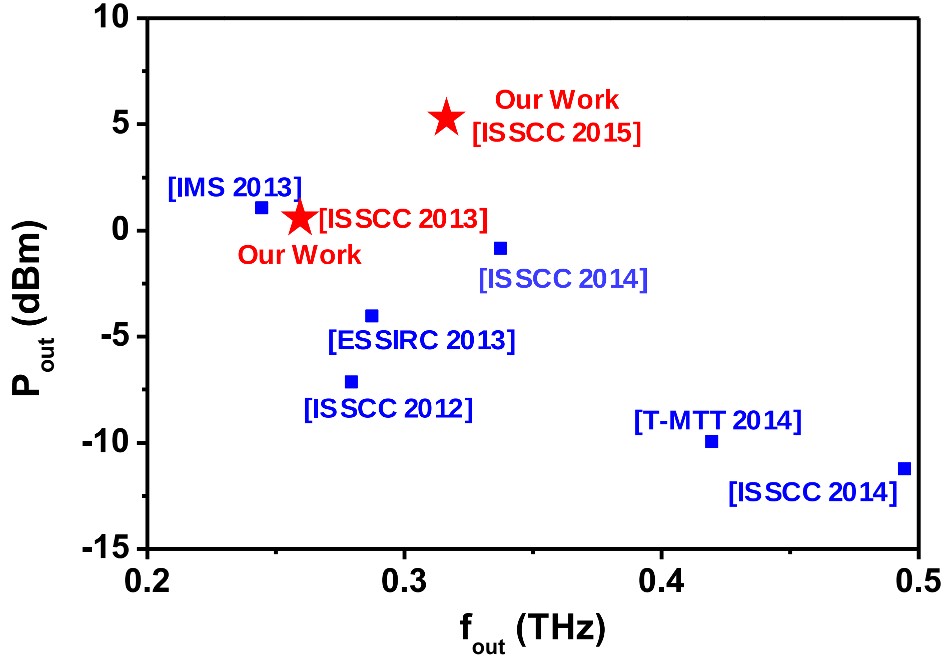
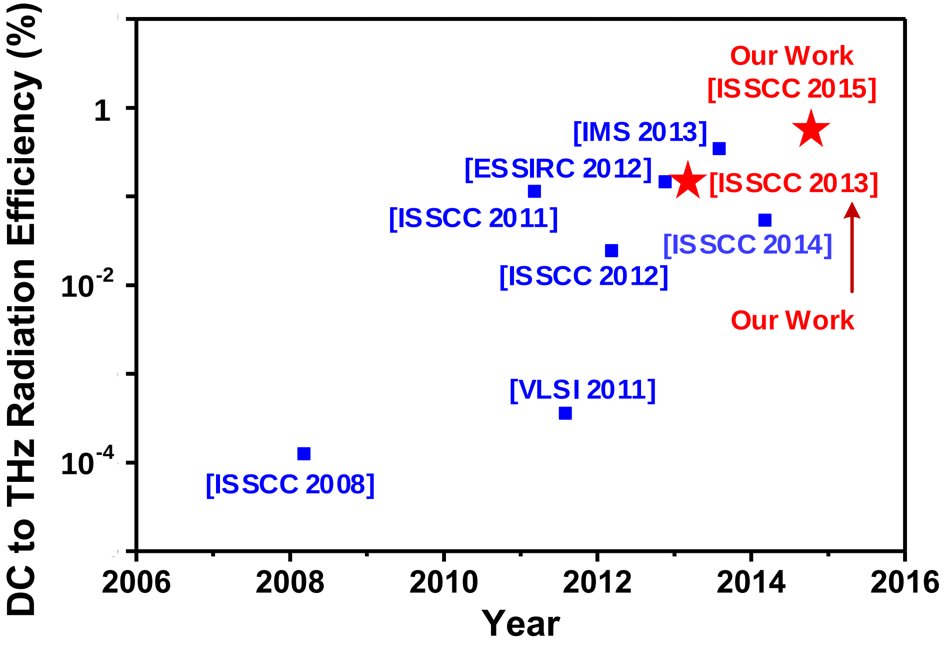


Recent Progress and New Challenges

[R. Han, etc., *IEDM* 2016]





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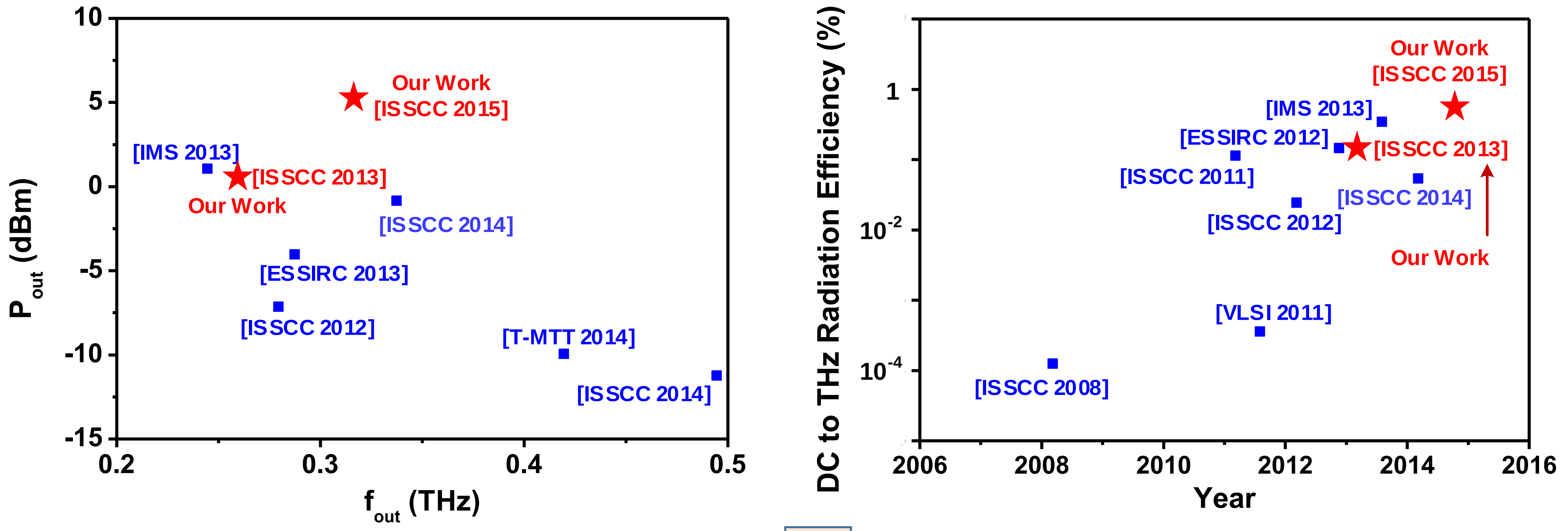
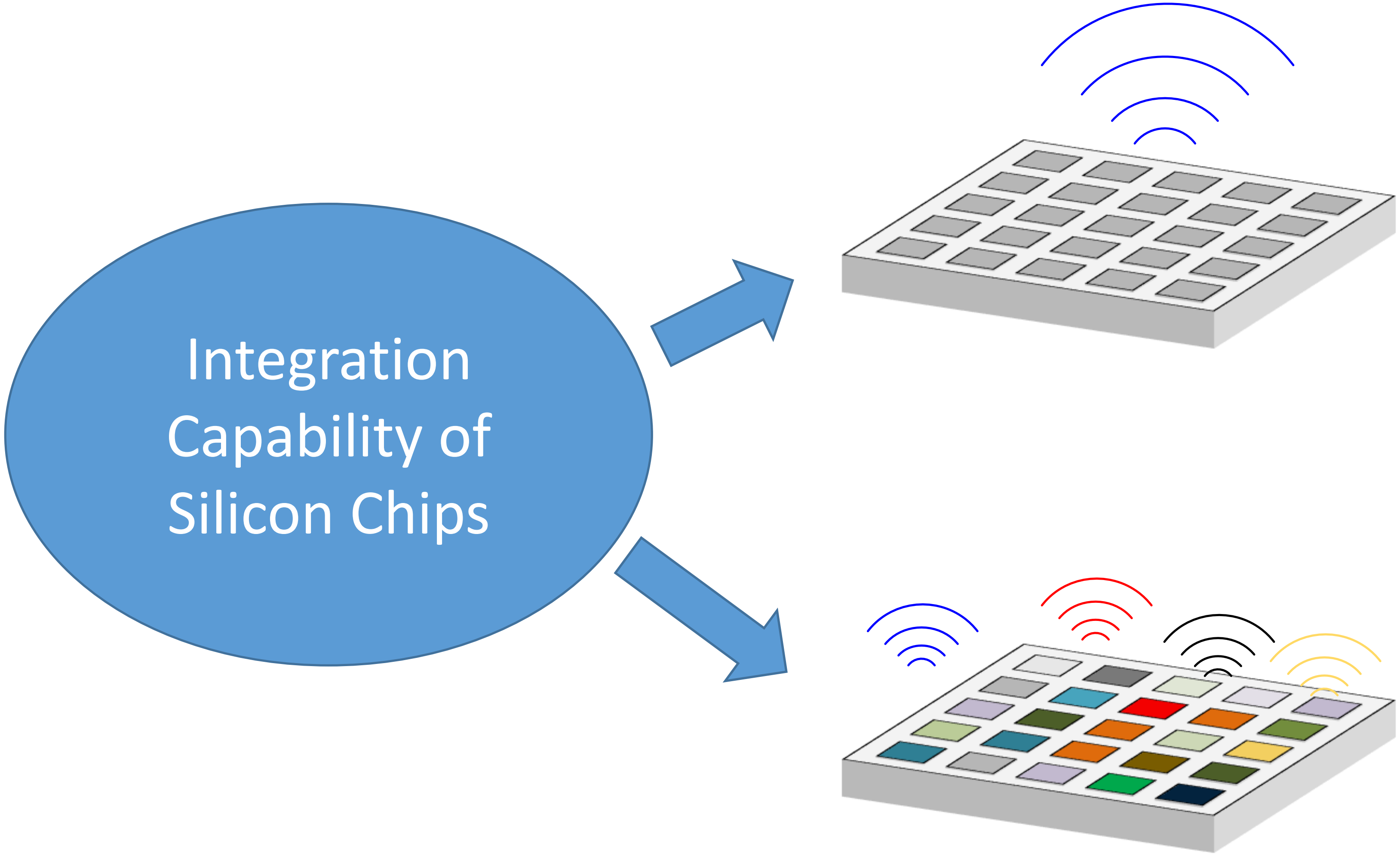


What are the *true* advantages of using silicon IC for THz hardware (besides low cost, baseband integration…)?

Large-Scale Terahertz Active Array



Homogeneous Array

- Power combining
- Beam collimation
- Beam steering
- …

Heterogeneous Array

- Broadband sensing
- Parallel signal processing
- Waveform generation
- …

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
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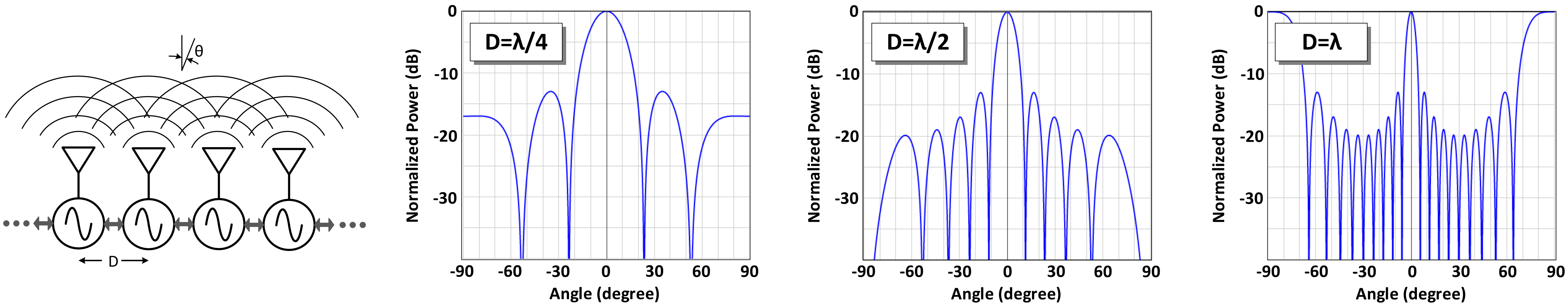
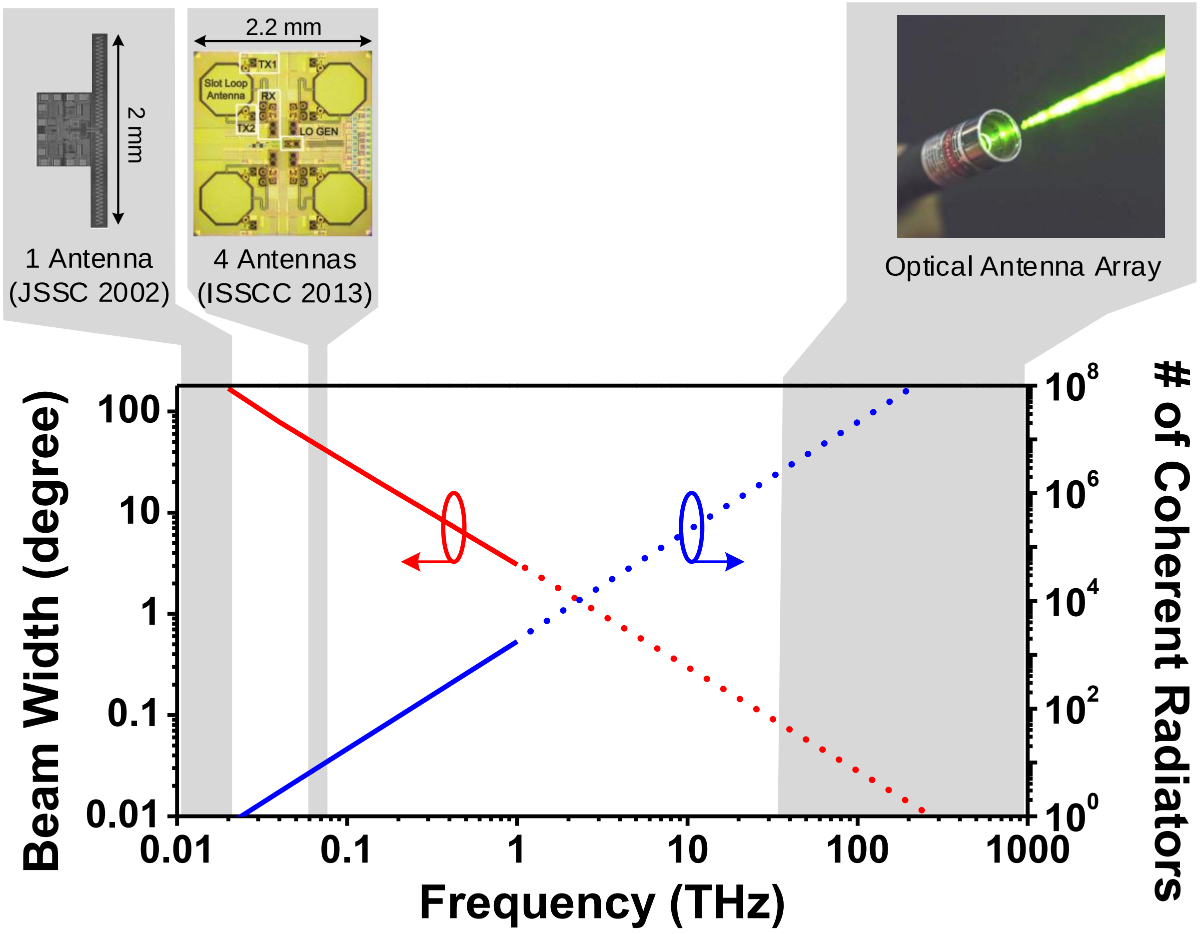
Beam Collimation in a Radiator Array



- 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: λ/2

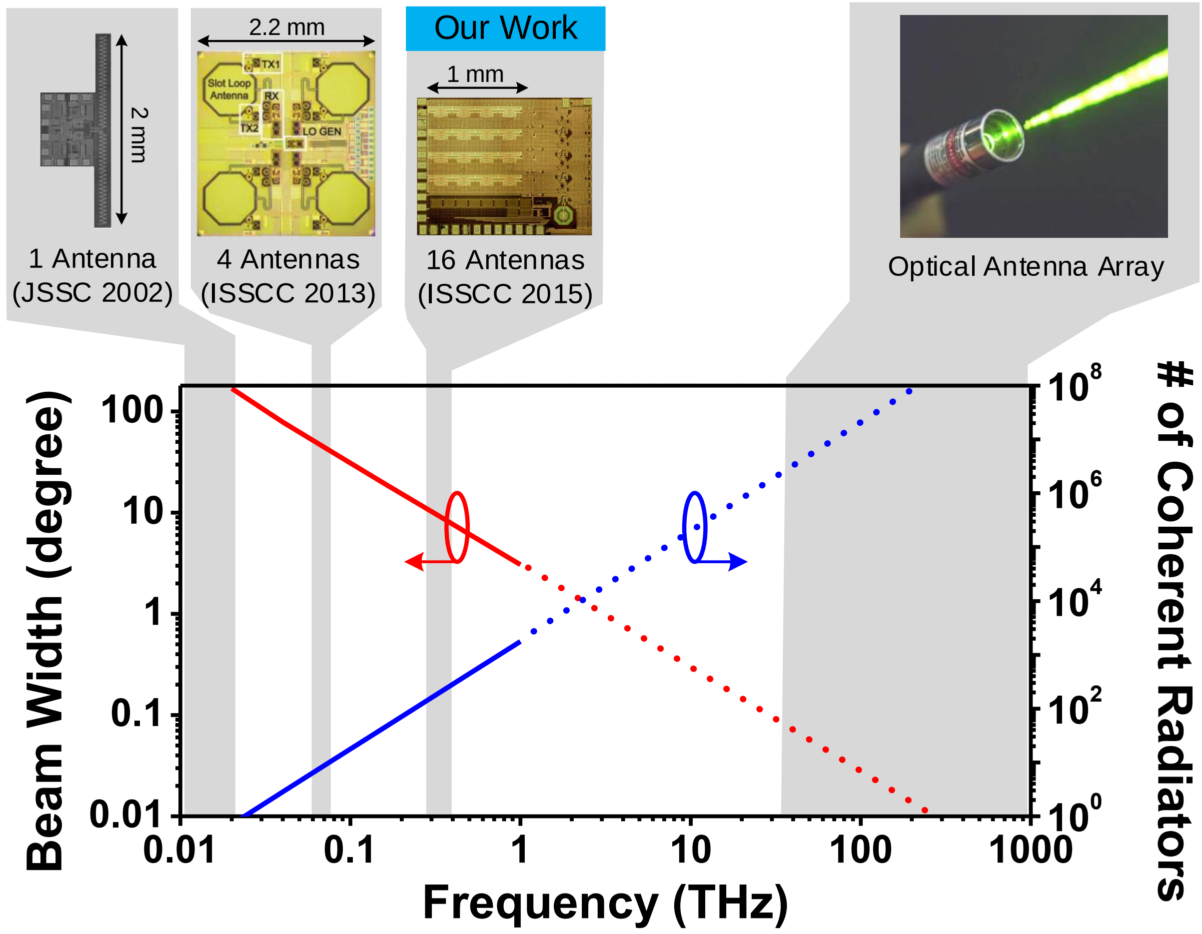
High-Density, Large-Scale Active Array on Chip



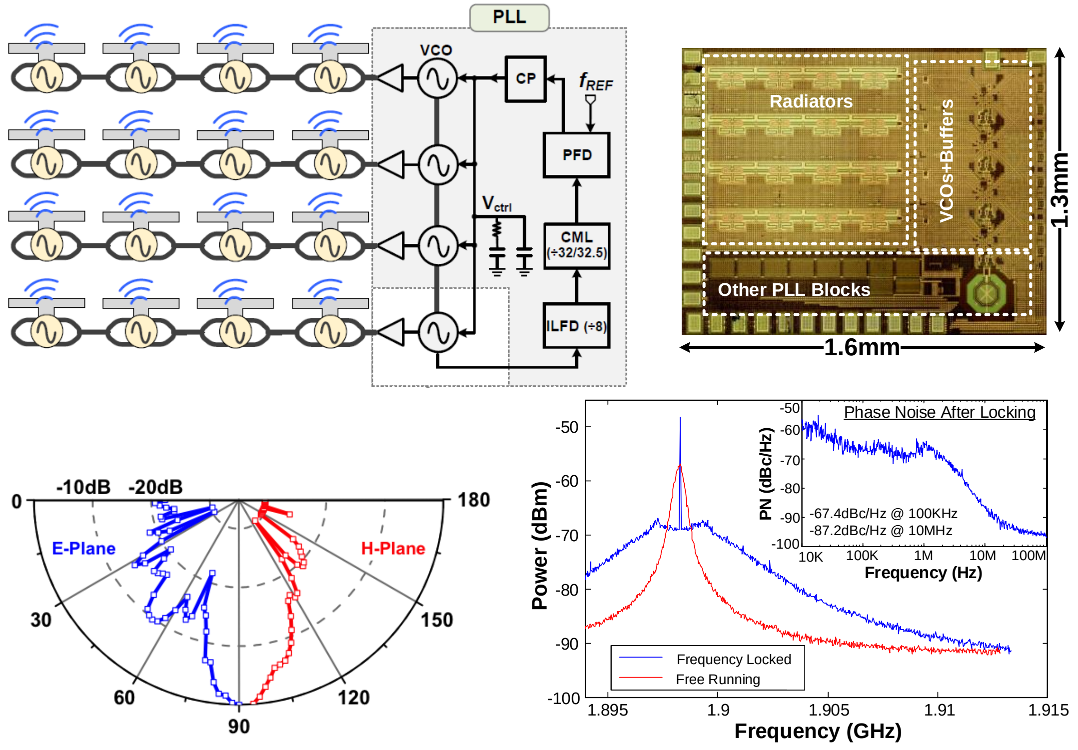
Note: Calculations Based on a $10mm^2$ Active Area

- If the λ/2 pitch is achieved:
  - >$10/mm^2$ radiators at 300 GHz can be built
  - D_{opt} is ~300μm (with $\varepsilon_{r,eff} \approx 3$)
- High effective isotropically radiated power (EIRP) may be maintained in the mid-THz range
  - Long transmission distance

High-Density, Large-Scale Active Array on Chip



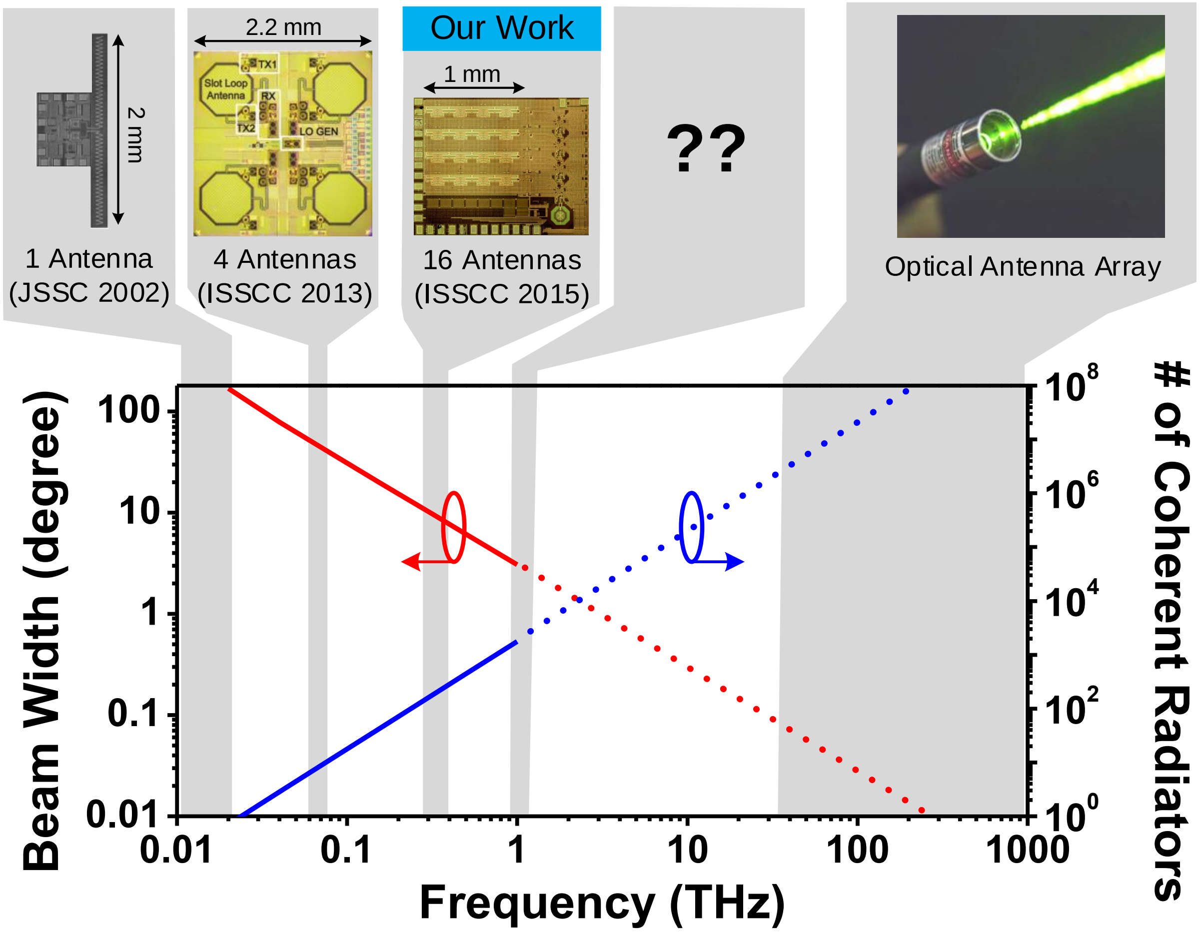
Note: Calculations Based on a 10mm² Active Area



[R. Han, *ISSCC* 2015]

- 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

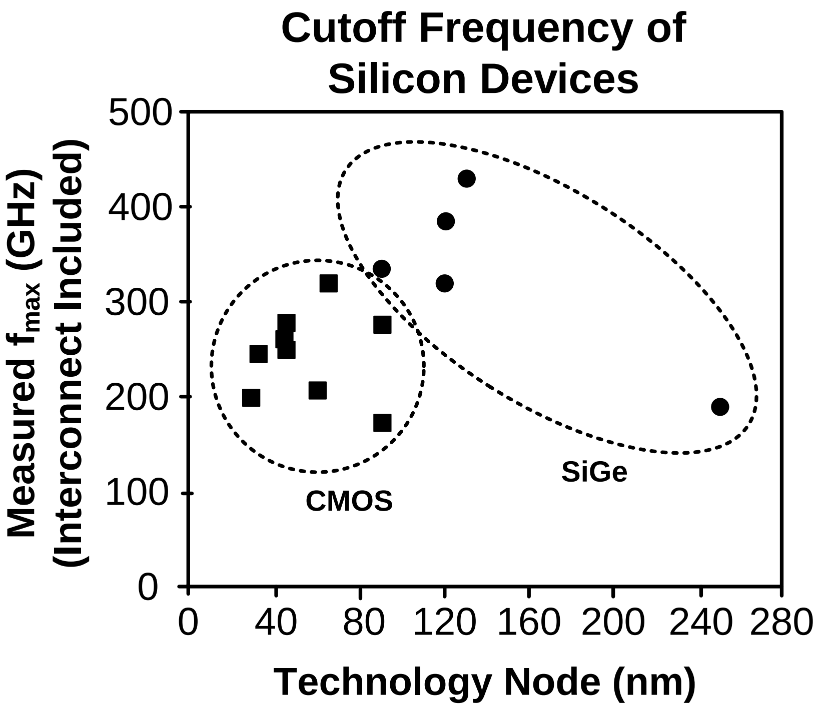


Note: Calculations Based on a $10mm^2$ Active Area

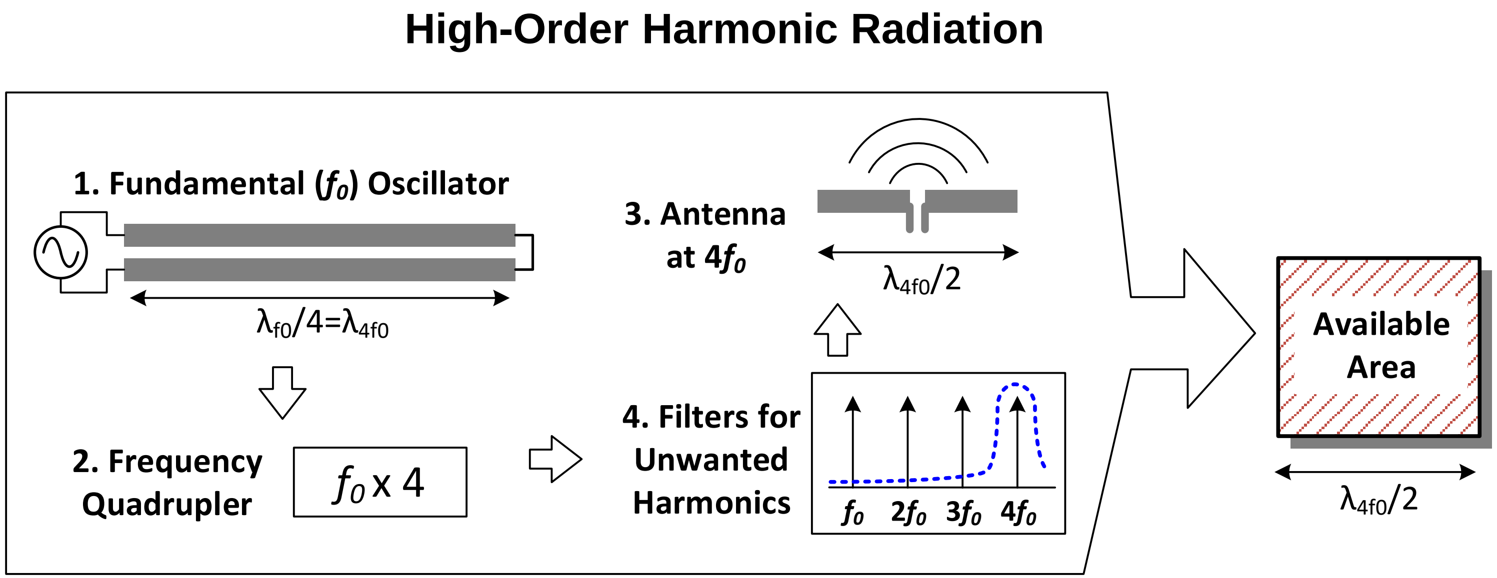
- ~100/mm² radiator density should be possible
  - Only 3° of beamwidth using 10-mm² chip area (~1000 coherent radiators)

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

Implementation Challenges



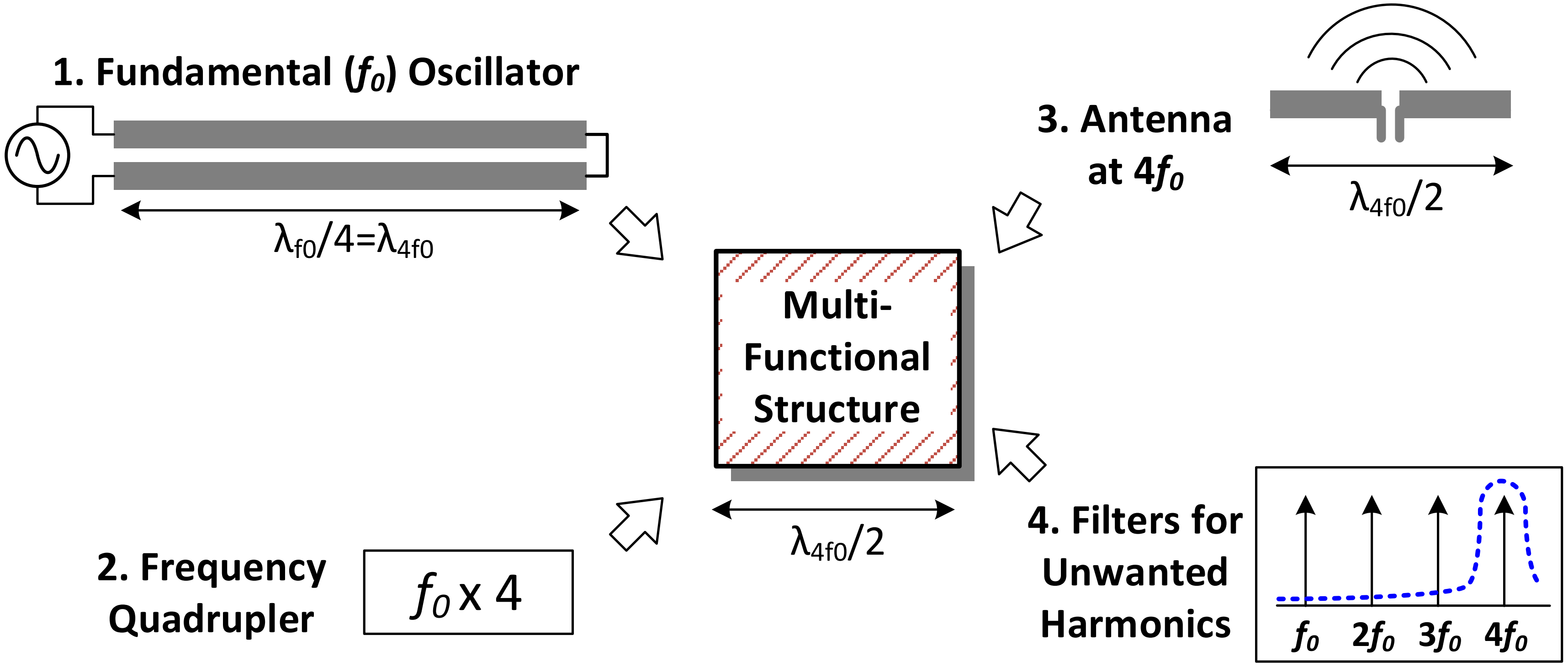
[R. Shmid, et al., IEEE Trans. Electron Devices 2015]



f_0=250GHz, f_{out}=4f_0=1THz

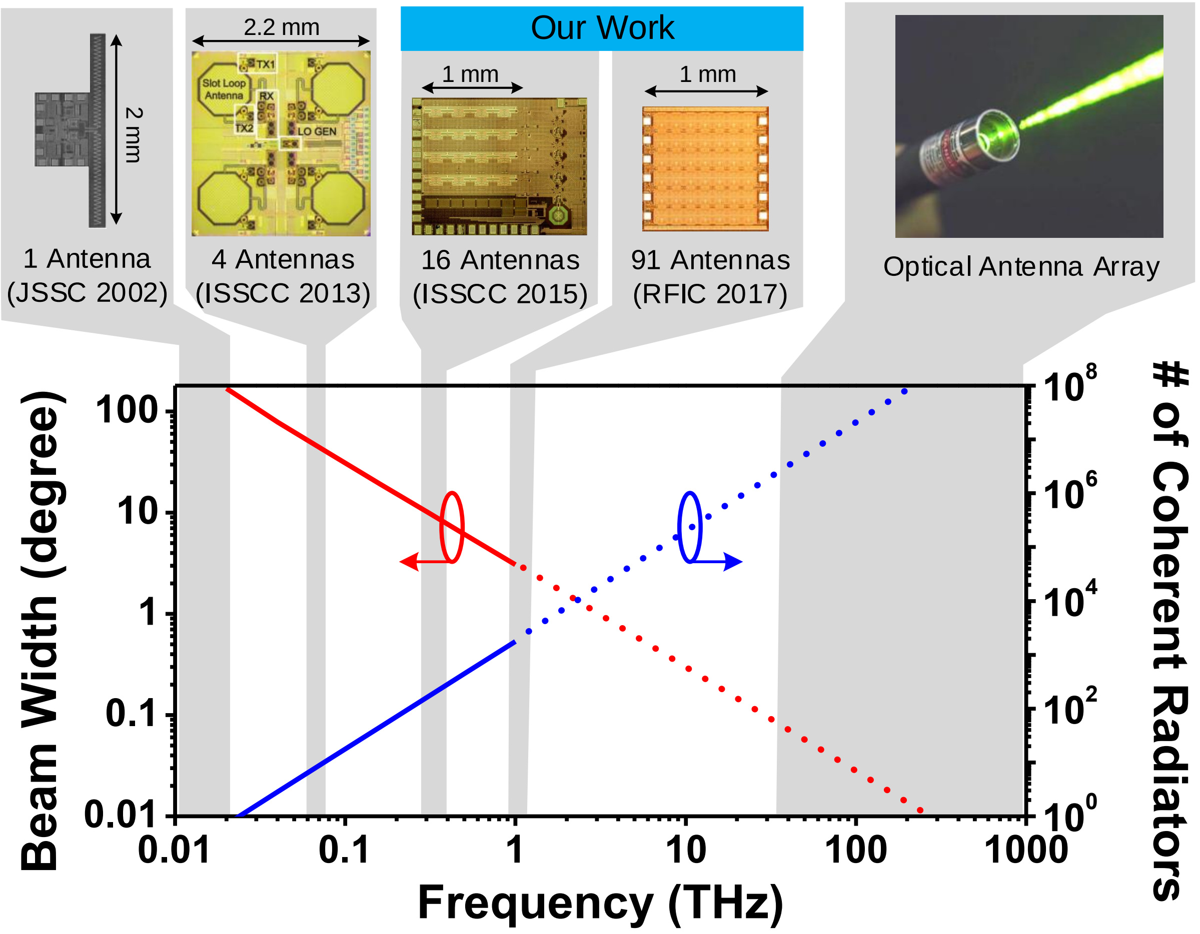
- Low device speed requires high-order harmonic generation
  - – Optimal device conditions at all harmonic frequencies should be met
- The available area is **too small** for all these necessary functions

Enabling Technology: Versatile EM Designs

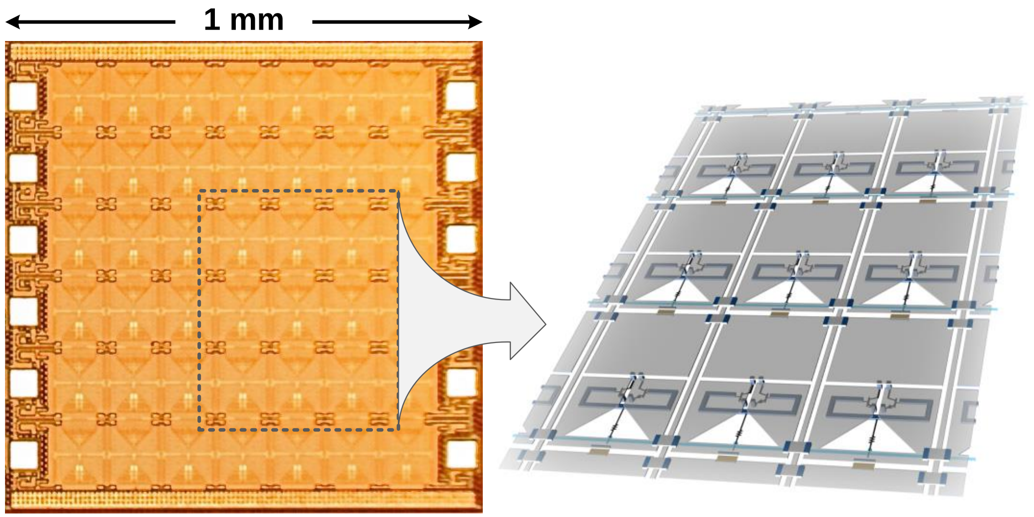


- A multi-functional electromagnetic structure around the transistors to simultaneously perform all the above tasks
  - Orthogonality of various EM wave modes
  - Multi-order standing-wave interference in the near field

High-Density, Large-Scale Active Array on Chip



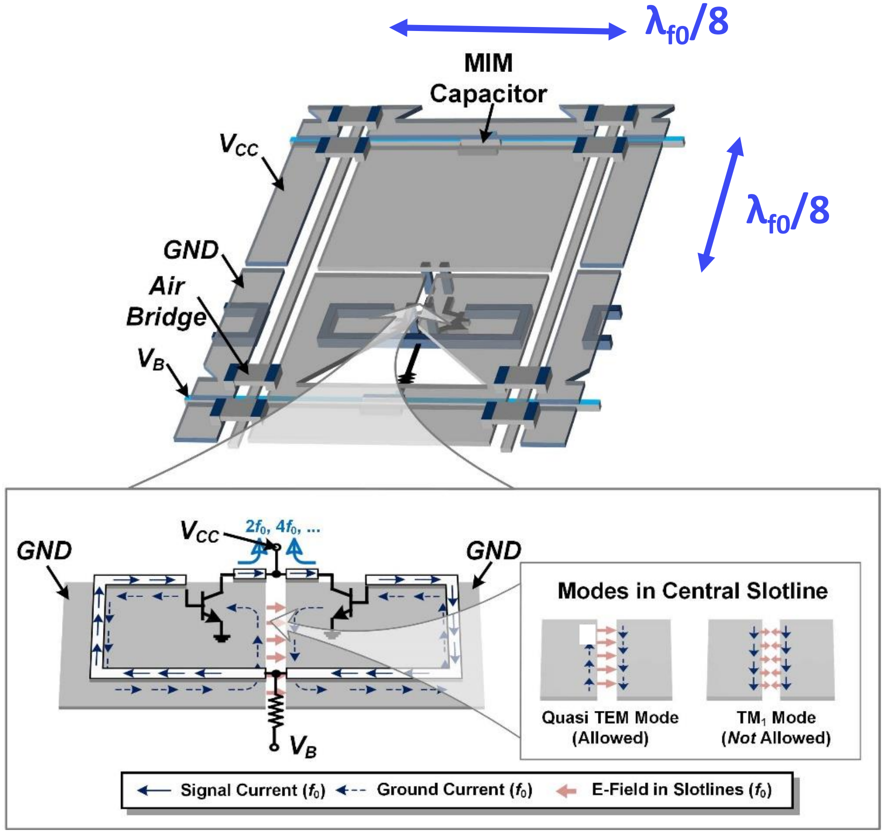
Note: Calculations Based on a 10mm^2 Active Area

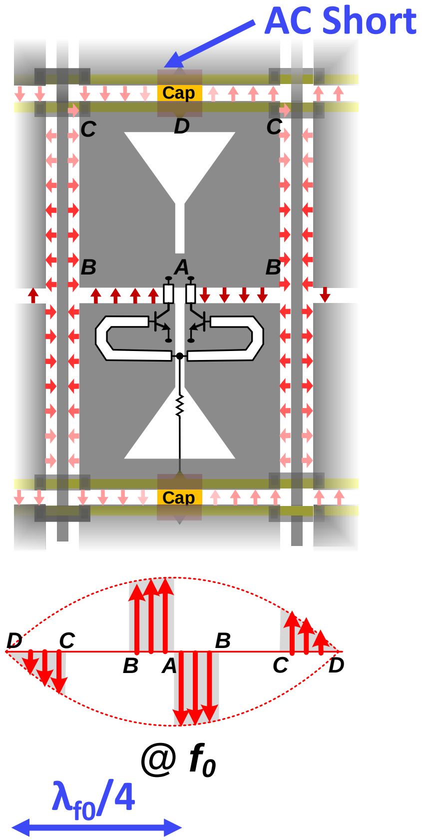


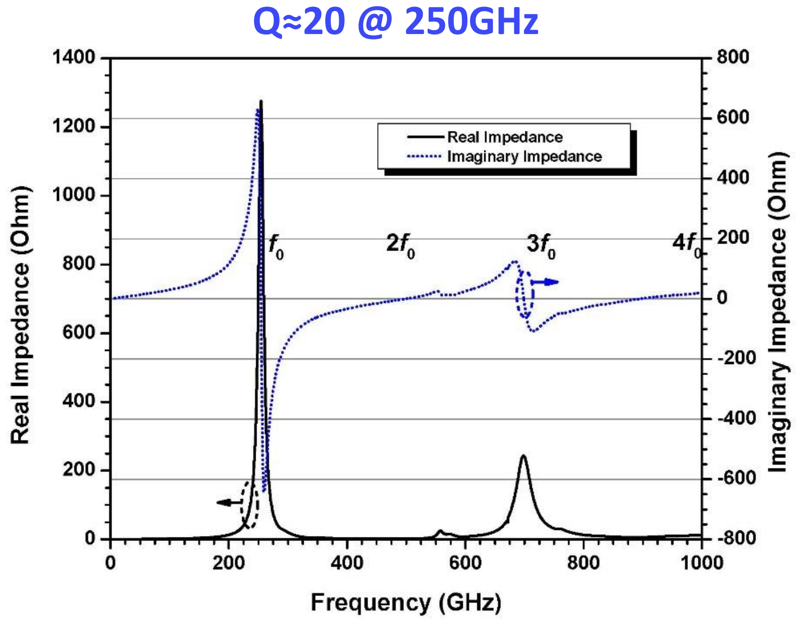
- 1-THz Array in 130-nm IHP SiGe BiCMOS
- 91 coherent radiator in 1-mm^2 area
- 0.1-mW total radiated power (EIRP: 20mW)

[Z. Hu and R. Han, *IEEE RFIC*, Jun. 2017
(Best Student Paper Award-2nd Place)]

Fundamental Oscillation at f_0=250GHz



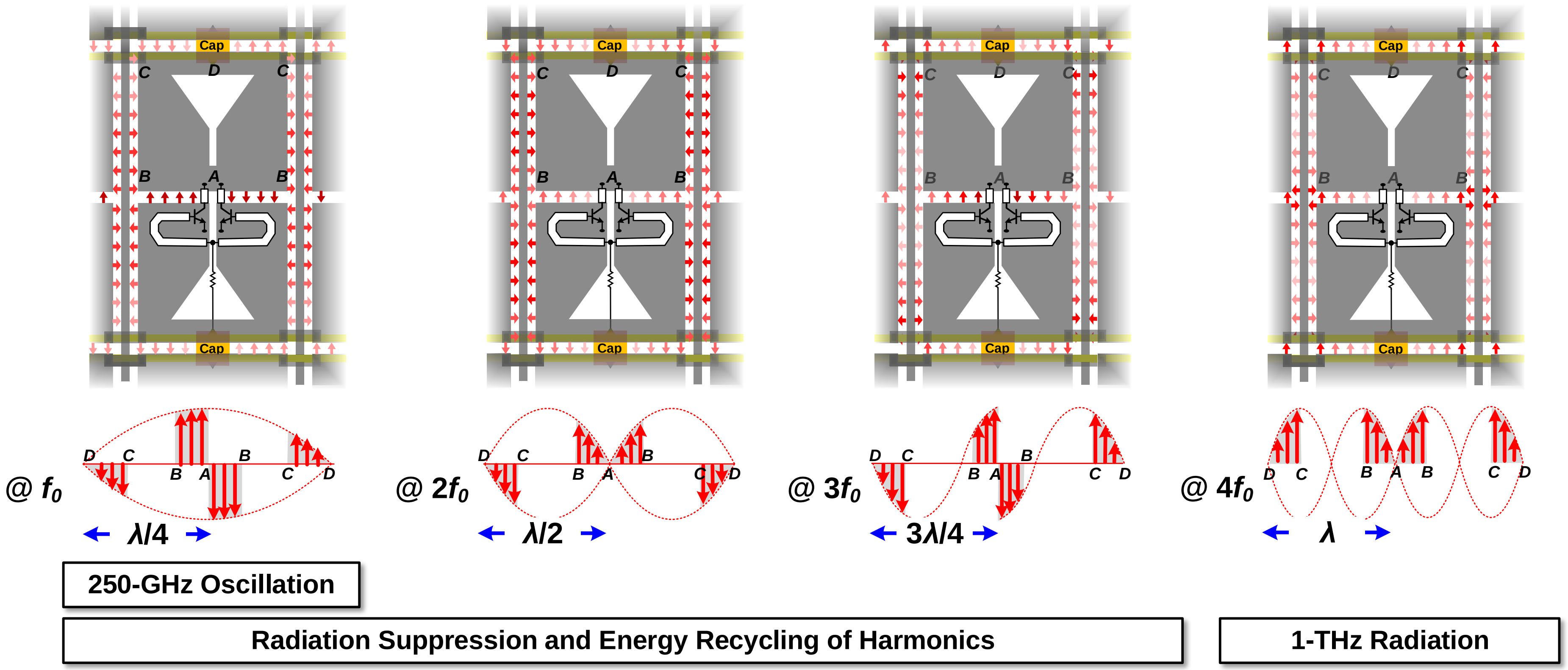




- At f_0, each square slot line behaves as a pair of $\lambda/4$ standing-wave resonators

Optimal Fundamental Oscillation

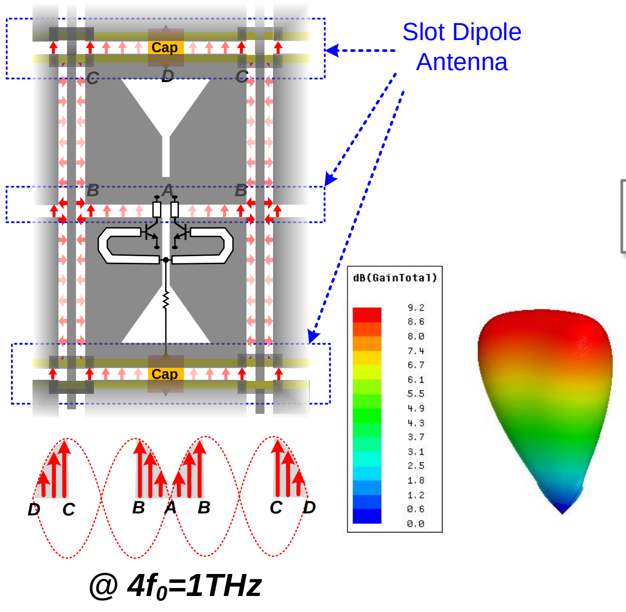
Multi-Order Standing Wave Interference

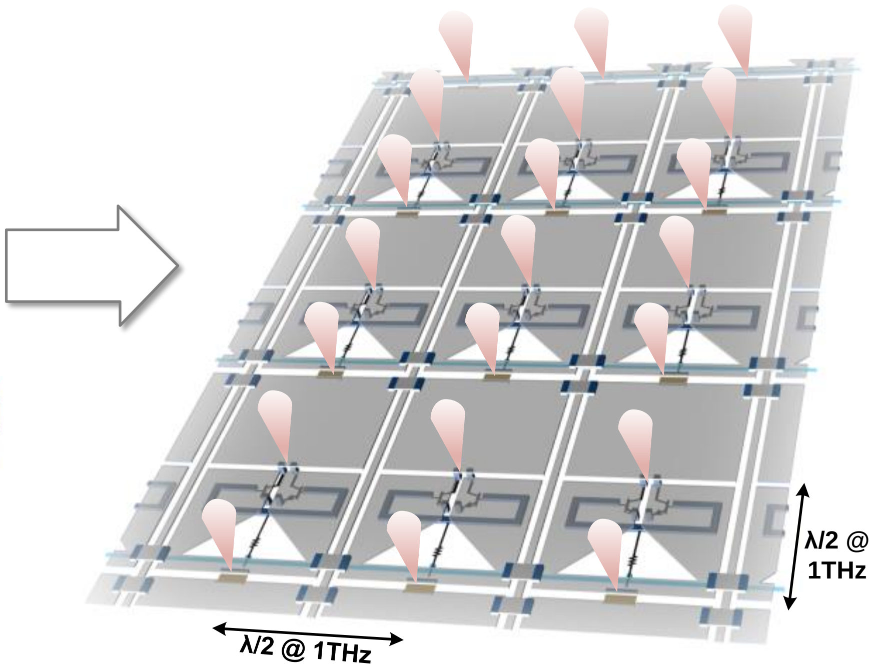


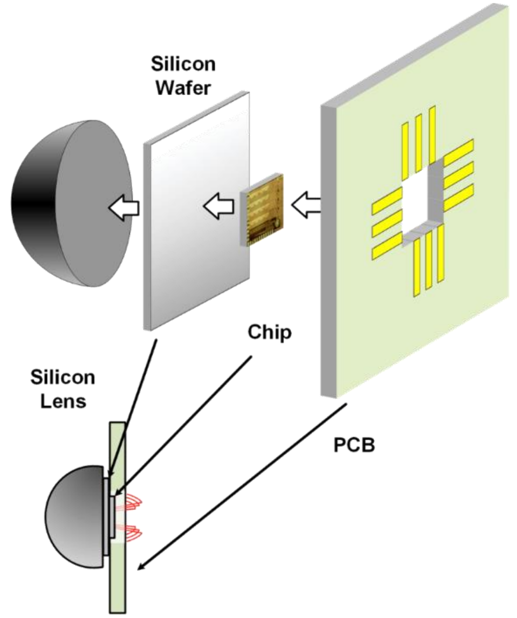
- Unwanted harmonics (@ f_0, $2f_0$, $3f_0$) are canceled by near-field interference

No Separate Filter is Needed

High-Density Radiation at 1 THz



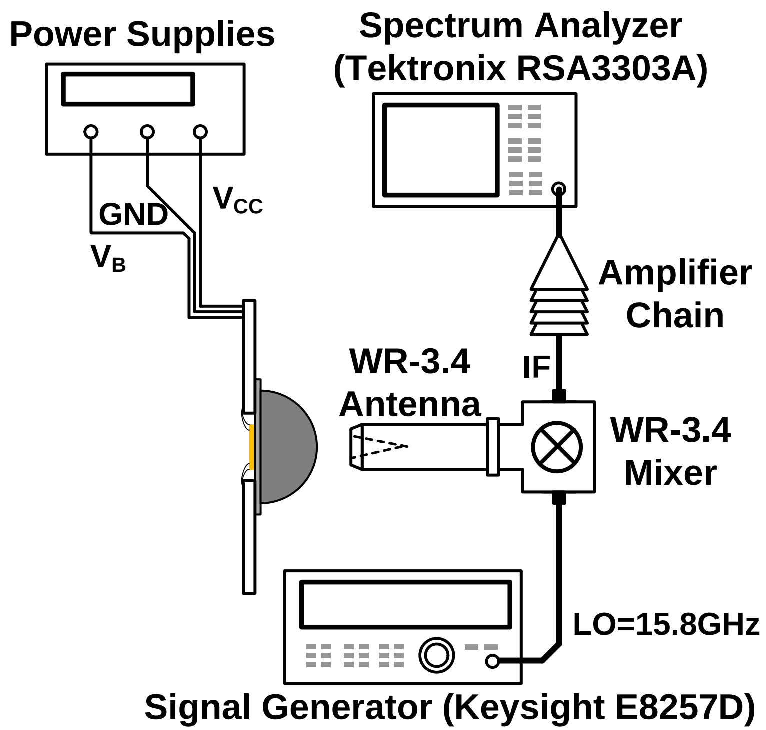


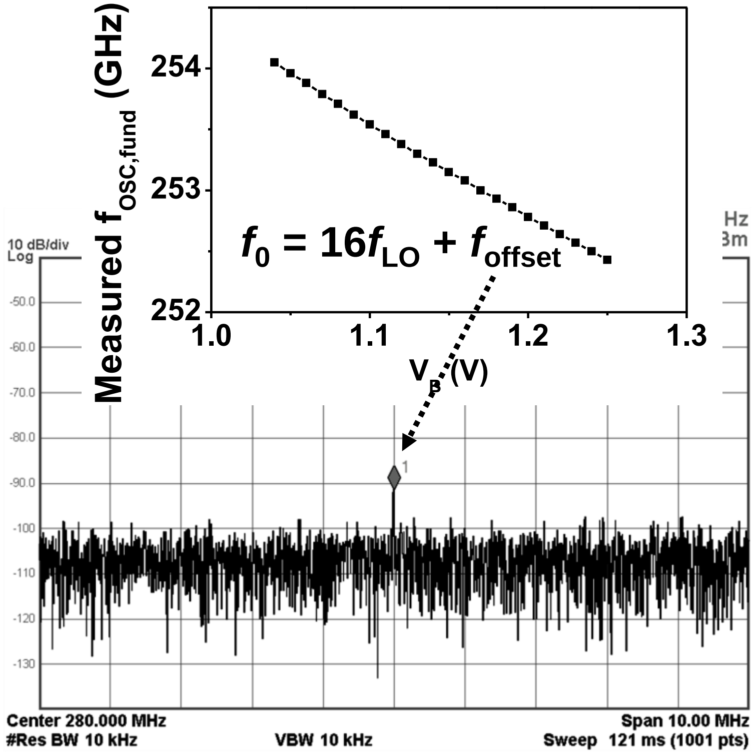


- The 1-THz standing waves in all horizontal slots are in phase
  - Effective backside radiation ($\eta_{rad,sim}$=63%)
  - On average, each oscillator (4x7 in total) drives 2 slot dipole antennas

91 Coherent Antennas (D≈λ/2)

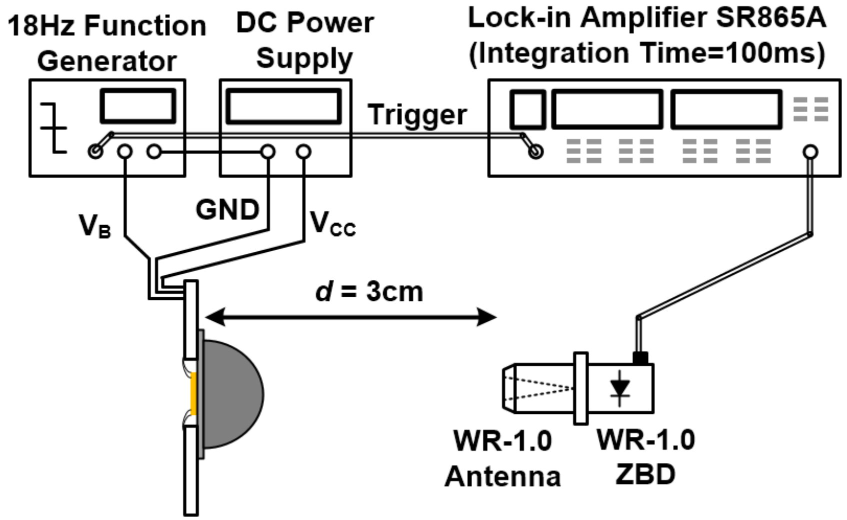
Measurement Results: Frequency and Spectrum

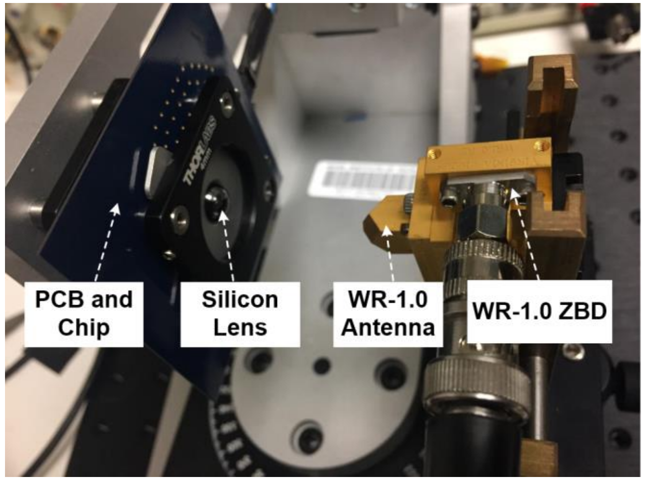


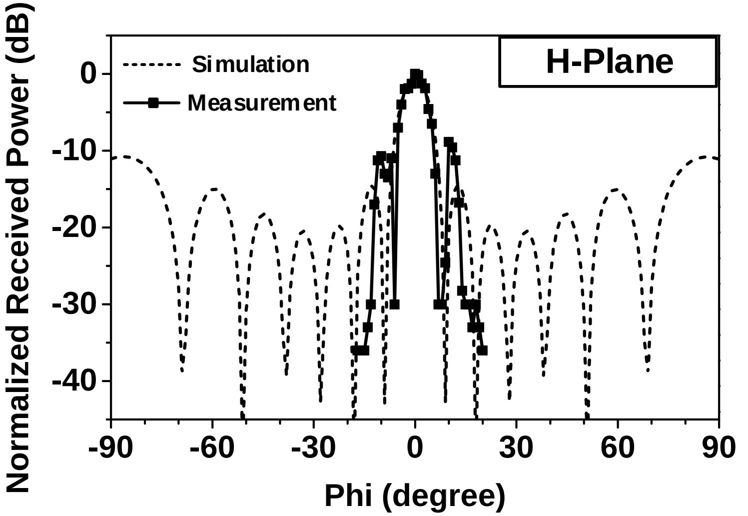


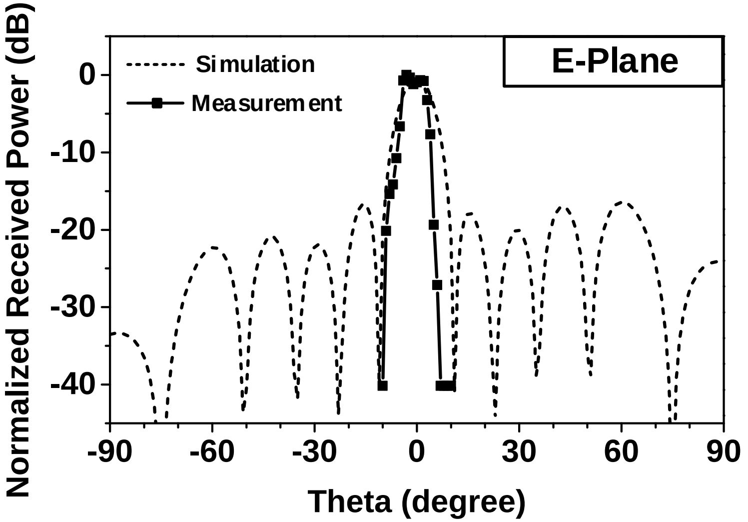
- Oscillation frequency is determined by a sub-harmonic SBD mixer
  - Weak radiation leakage at f_0
  - Measured fundamental frequency: 252.5 to 254.1 GHz
  - $4f_0$ output: 1.01 to 1.016 THz

Measurement Results: Radiated Power



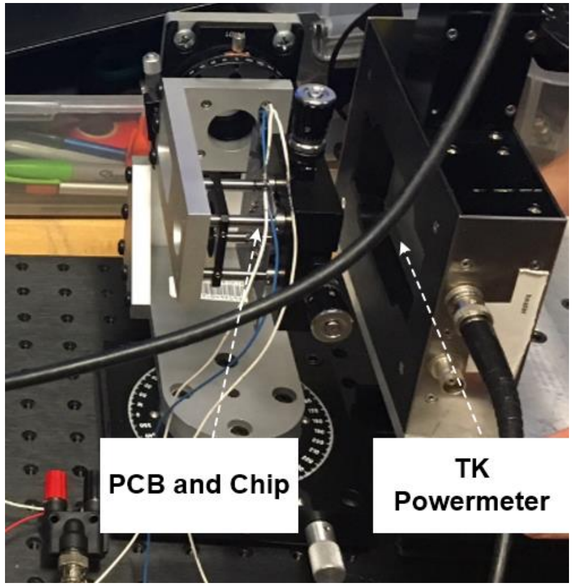


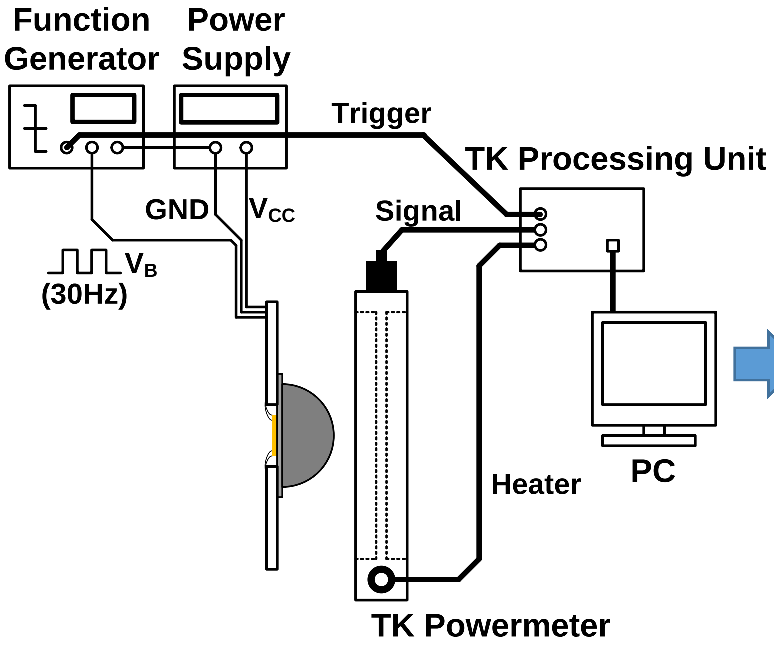




- The radiated power is measured by a calibrated WR-1.0 zero-biased diode detector
  - Measured total radiated power: 80 µW
  - Measured beam directivity: 24 dBi (θ_{-3dB}=11°)
  - Measured EIRP: 20 mW

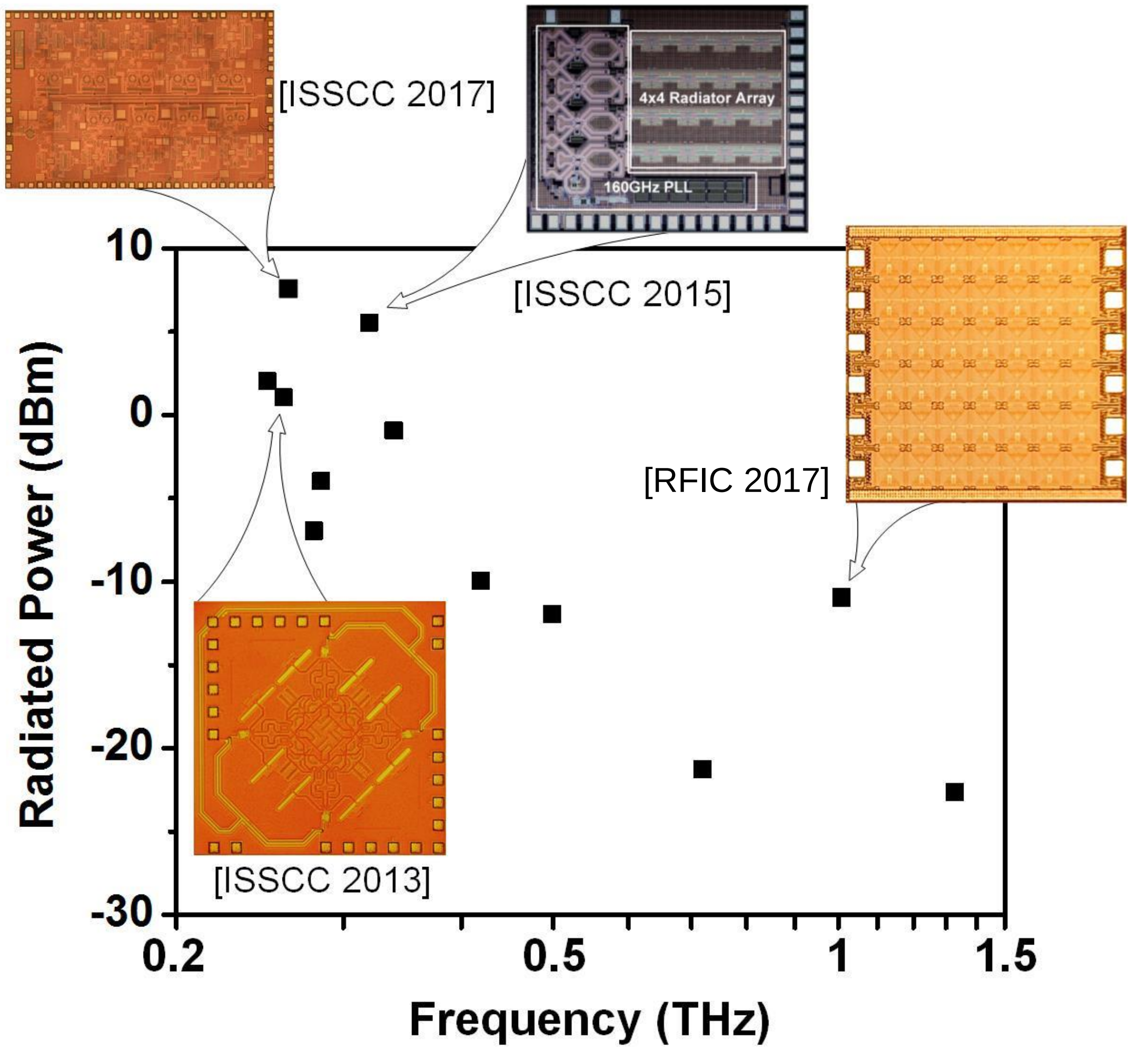
Measurement Results: Radiated Power





- 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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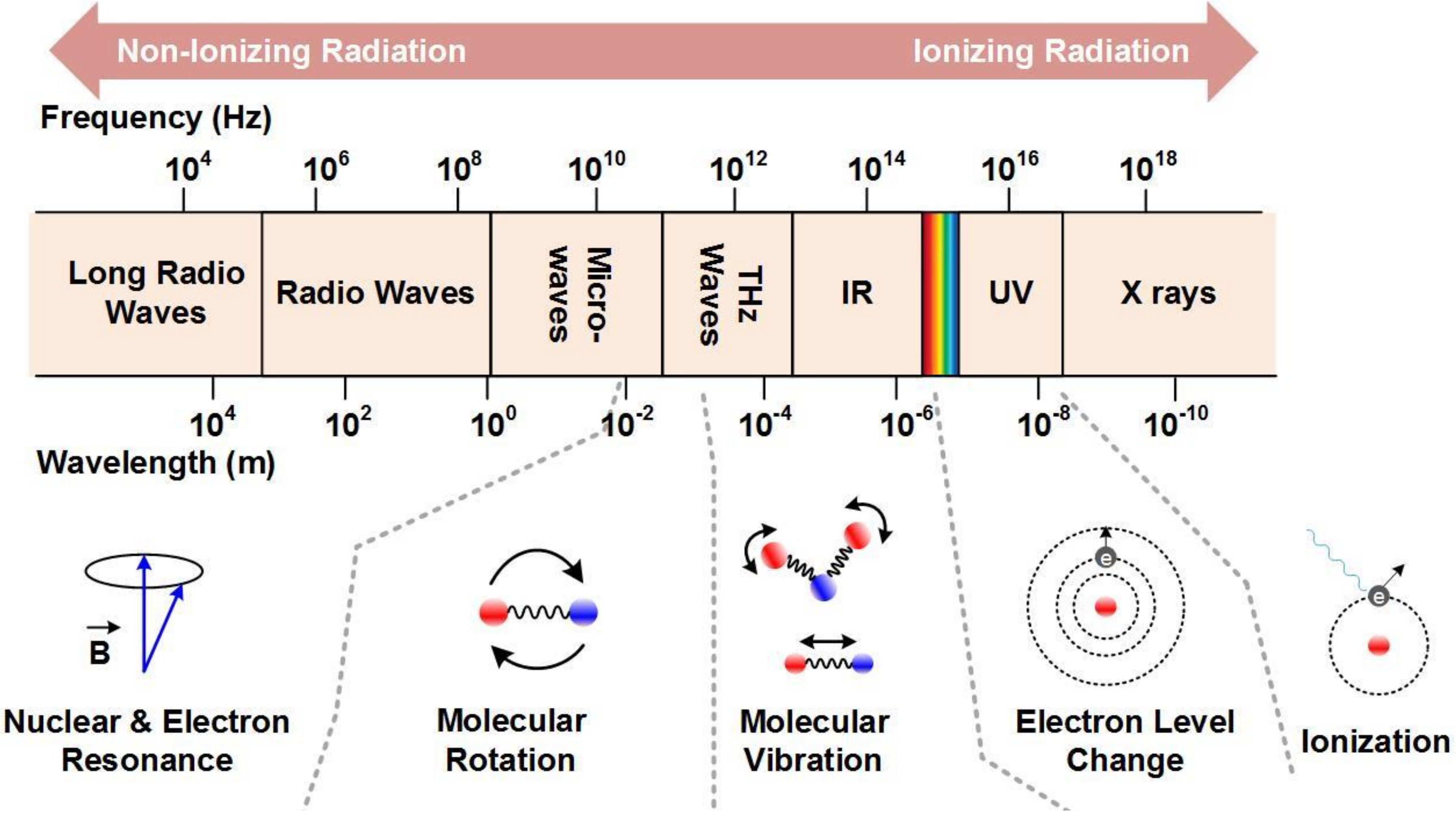
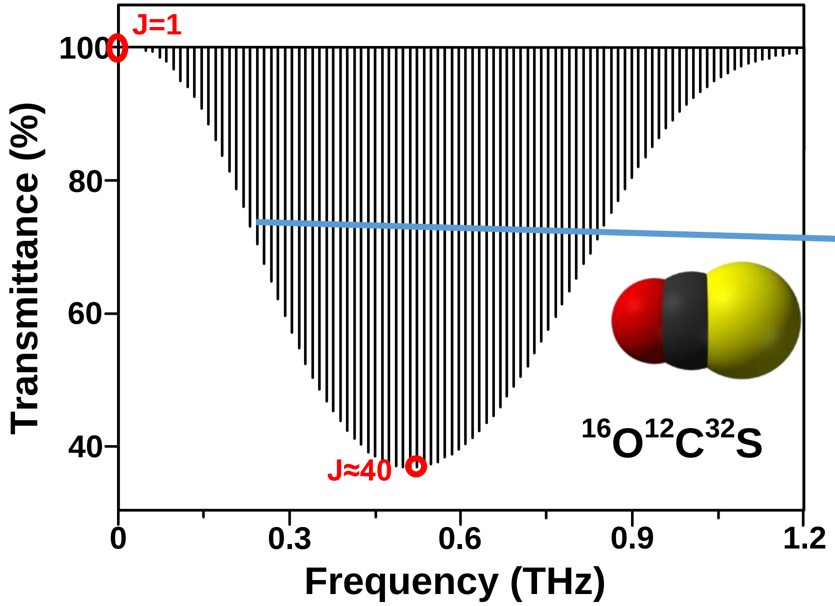
Wave-Matter Interactions for Material Sensing

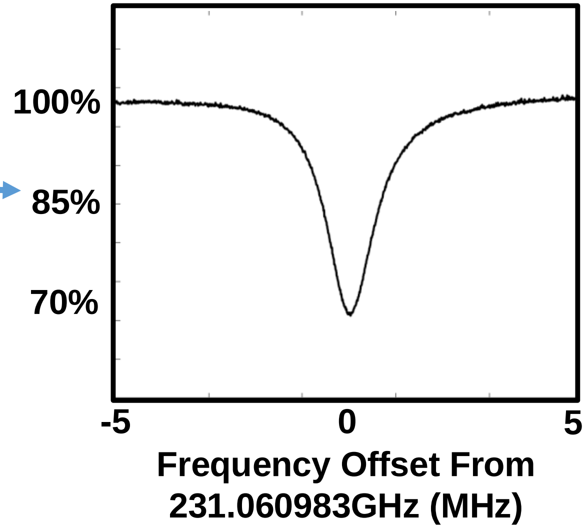


THz Spectrometer for Gas Sensing

[Source: HITRAN.org]

Molecule	Frequency (GHz)	Toxic?	Flammable?
Carbon Monoxide (CO)	230.538001	Y	Y
Sulfur Dioxide (SO_2)	251.199668		
Hydrogen Cyanide (HCN)	265.886441		Y
Hydrogen Sulfide (H_2S)	300.511959		Y
Nitric Oxide (NO)	250.436966	Y	
Nitrogen Dioxide (NO_2)	292.987169	Y	
Nitric Acid (HNO_3)	256.657731	Y	
Ammonia (NH3)	208.145904	Y	
Carbonyl Sulfide (OCS)	231.060989	Y	Y
Ethylene Oxide (C_2H_4O)	263.292515	Y	
Acrolein (C_3H_4O)	267.279359	Y	
Methyl Mercaptan (CH_3SH)	227.564672	Y	
Methyl Isocyanate (CH_3NCO)	269.788609	Y	
Methyl Chloride (CH_3Cl)	239.187523	Y	Y
Methanol (CH_3OH)	250.507156	Y	Y
Acetone (CH_3COCH_3)	259.6184	Y	Y
Acrylonitrile (C_2H_3CN)	265.935603	Y	Y





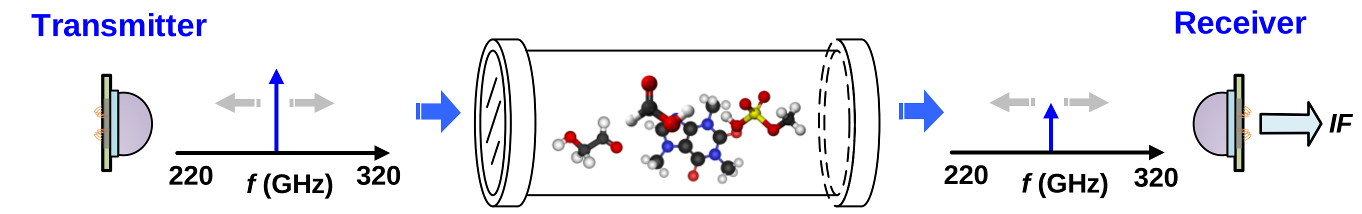
Quantum Number

Absorption Intensity: $\gamma = \frac{(2J+1)hBe^{-hBJ(J+1)/kT}}{kT}$

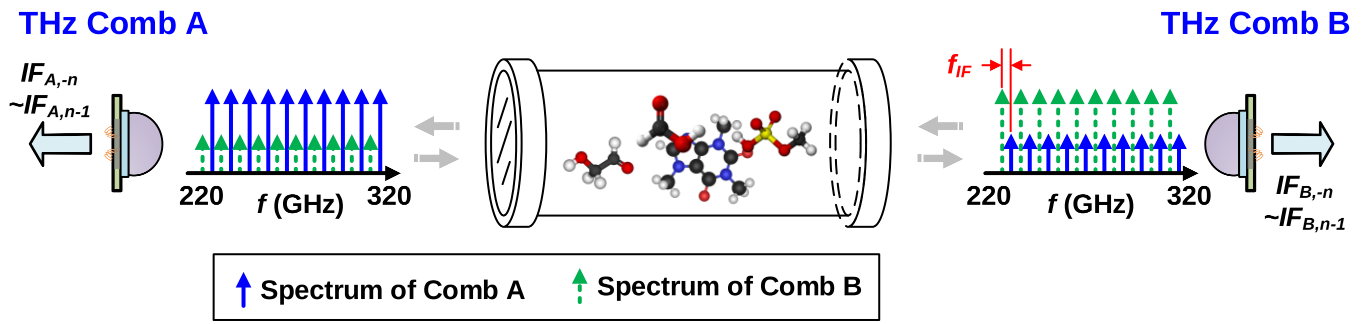
Wide Detection Range → **High Sensitivity** → **High Selectivity**

Dual-THz-Comb Spectrometer

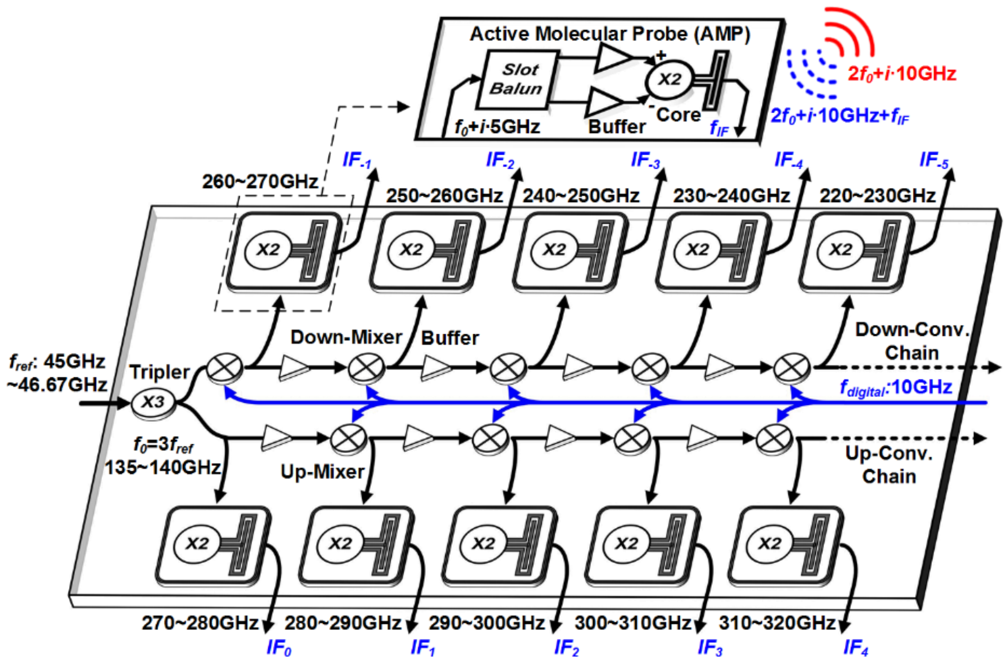
- Conventional single-tone sensing scheme
  - Bandwidth-efficiency tradeoff
  - Long scanning time (~3 hours for 100-GHz bandwidth)



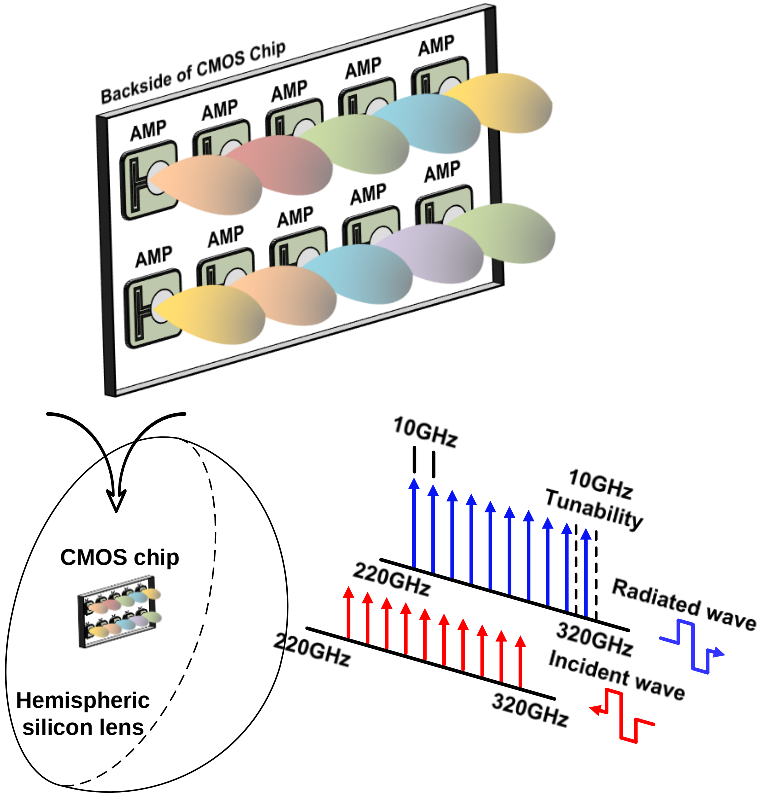
- Our scheme using bilateral THz frequency combs
  - Each circuit block maintains peak performance in a narrow band
  - Simultaneous scanning using 20 comb lines (>20x increased speed)



220-to-320GHz Comb-Based CMOS Spectrometer

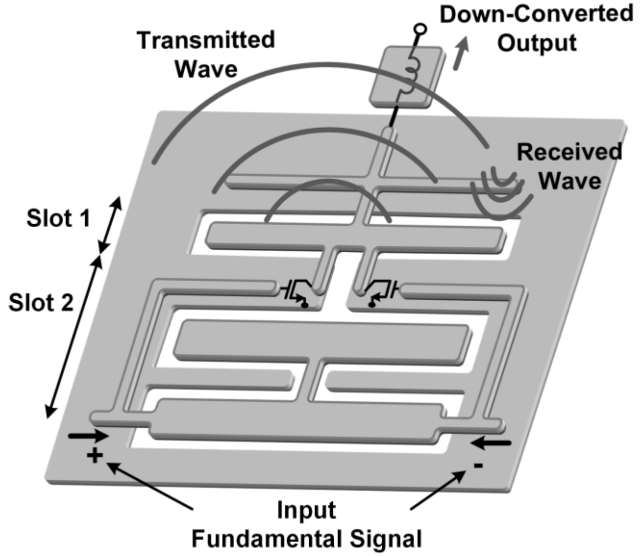


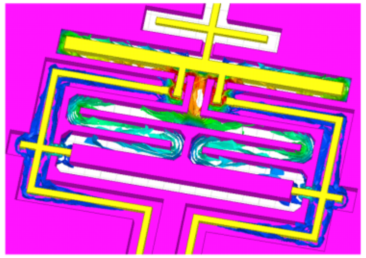
[C. Wang and R. Han, *IEEE ISSCC*, Feb. 2017]



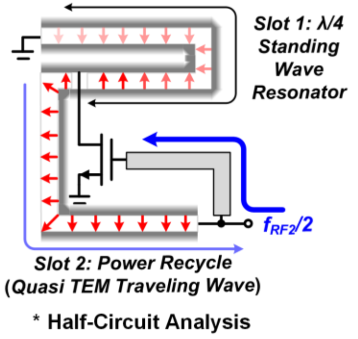
- 10 molecular-probing THz transceivers
  - Key technology: multi-function, energy-efficient electromagnetic structures
- Seamless coverage of the 220 to 320 GHz band with kHz resolution

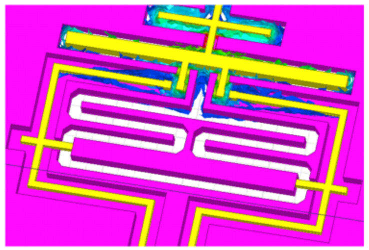
Operation of the Transceiver Unit Core

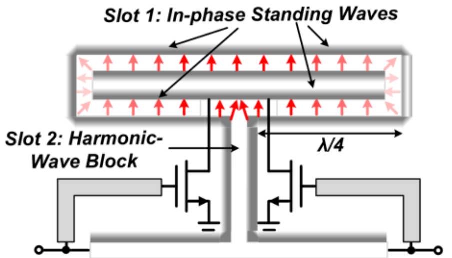




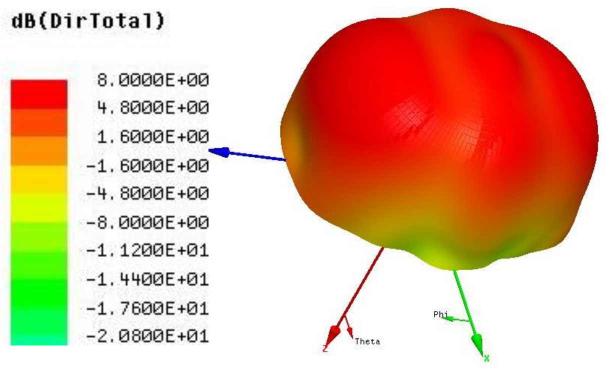
Electrical Wave Distribution at $f_{TX}/2$







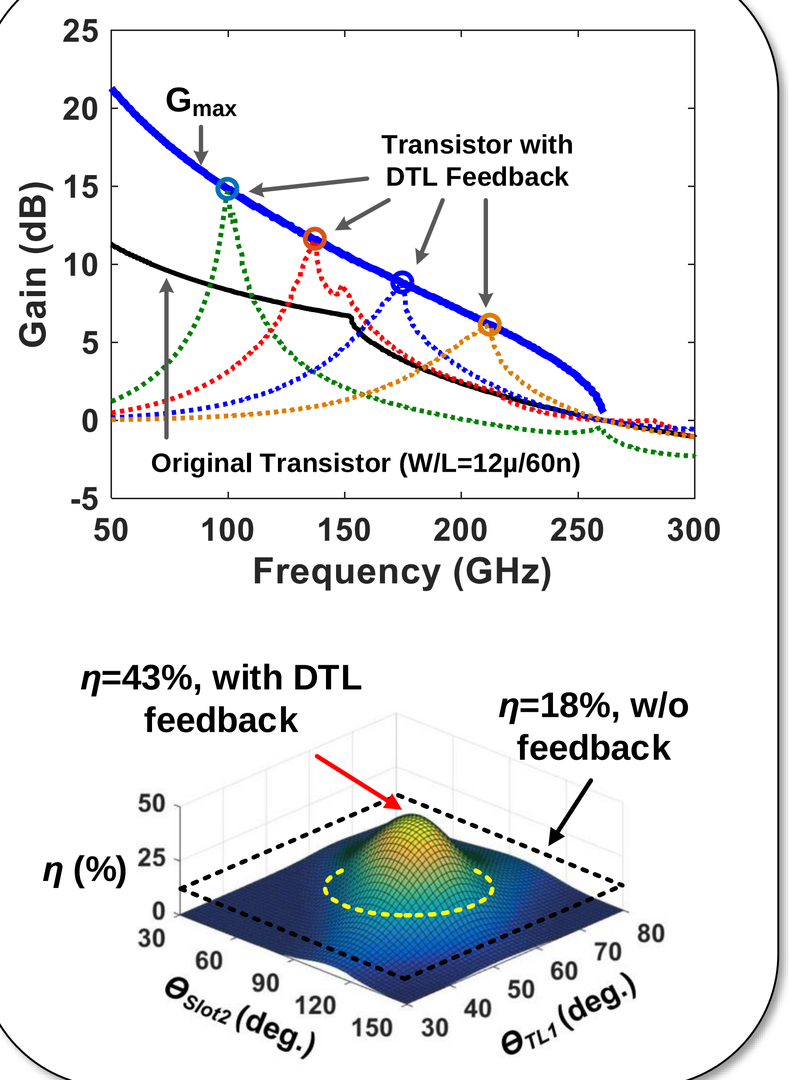
Electrical Wave Distribution at f_{TX} *(transmit mode)* and f_{RX} *(receive mode)*

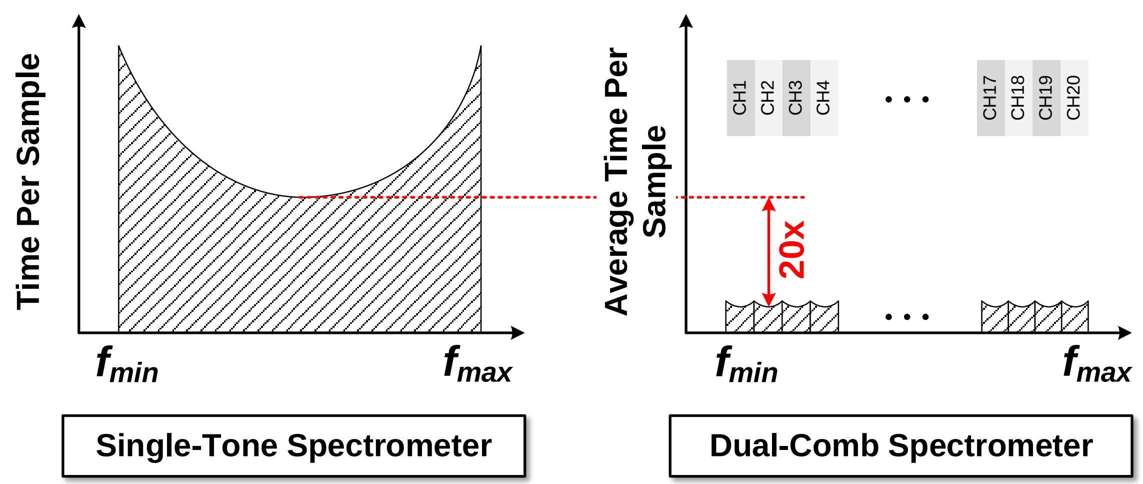


[C. Wang and R. Han, *IEEE JSSC*, Dec. 2017]

- 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

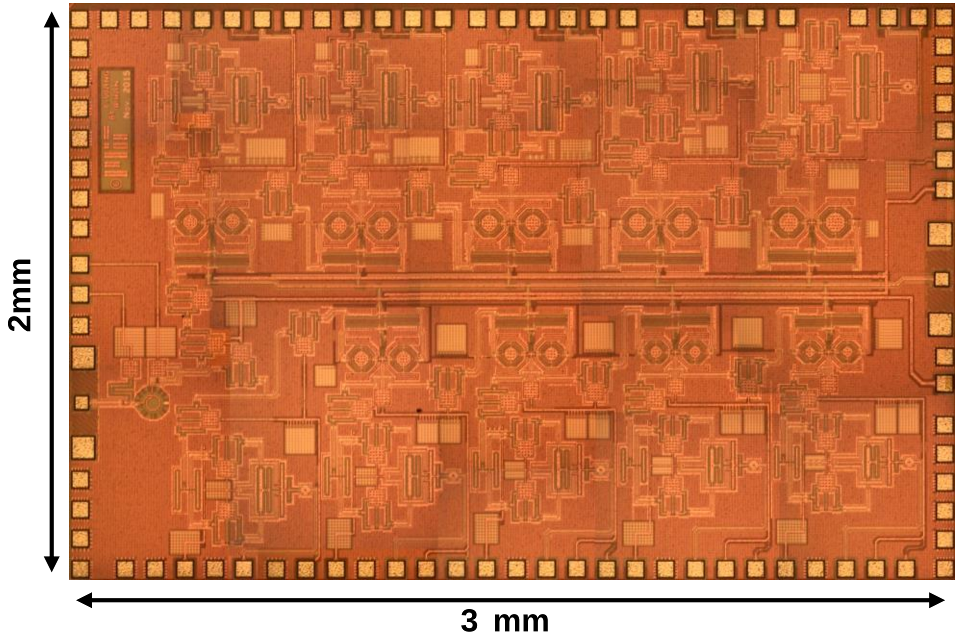
High-Parallelism Broadband Architecture

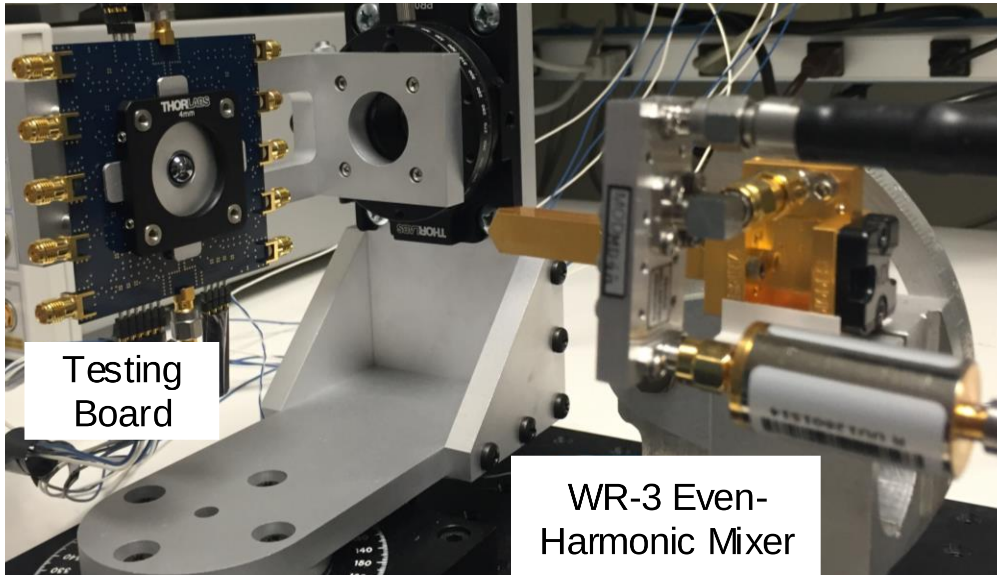




- The relaxed tunability requirement allows the introduction of device positive feedback and higher device gain
  - 43% simulated doubler conversion efficiency
- The total spectral scanning time is reduced by more than 20x, leading to high energy efficiency

CMOS Chip Prototype

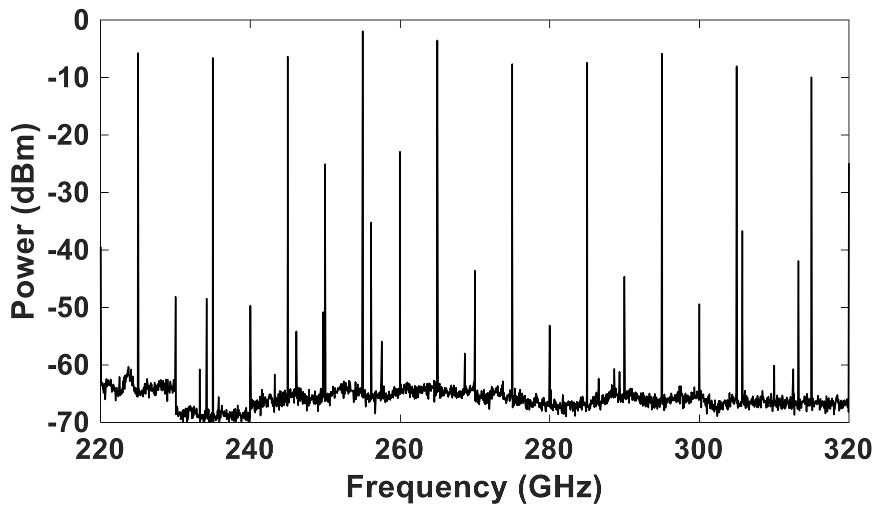




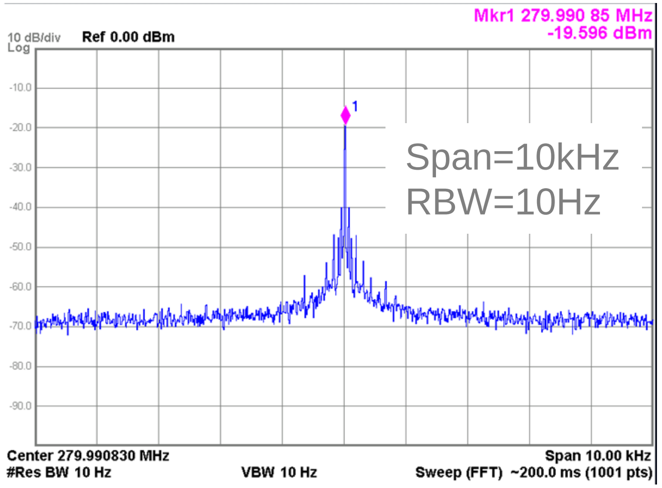
Setup for Radiation Spectrum and Pattern Testing

- TSMC 65nm bulk CMOS process (f_{max}=250GHz)
  - 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

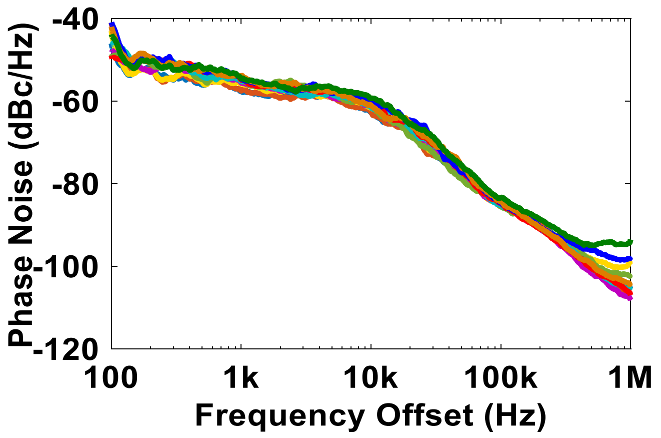
Experimental Results



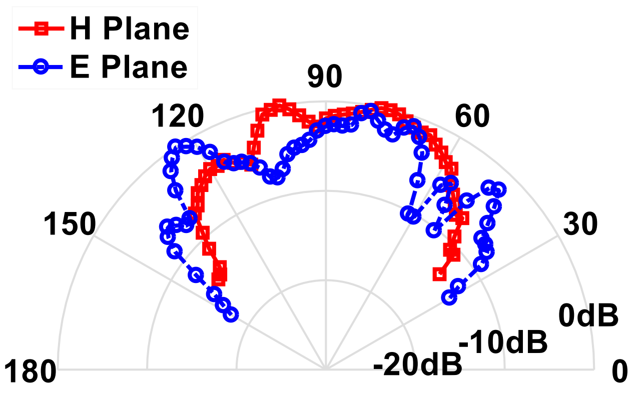
Measured Down-converted IF Spectra of all Comb Lines



Spectrum of a Comb Line at 265GHz



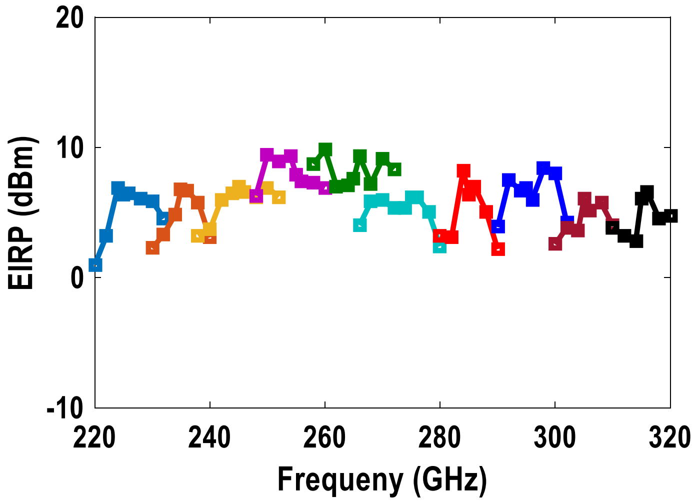
Average Phase Noise: -102dBc/Hz @ 1MHz



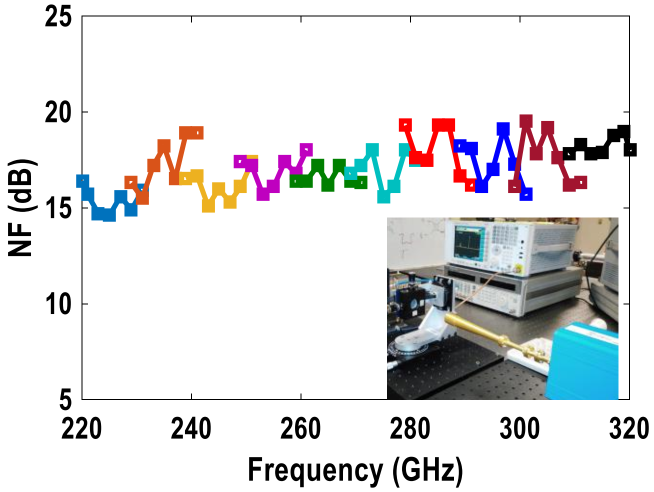
Antenna Pattern of One Line (265GHz)

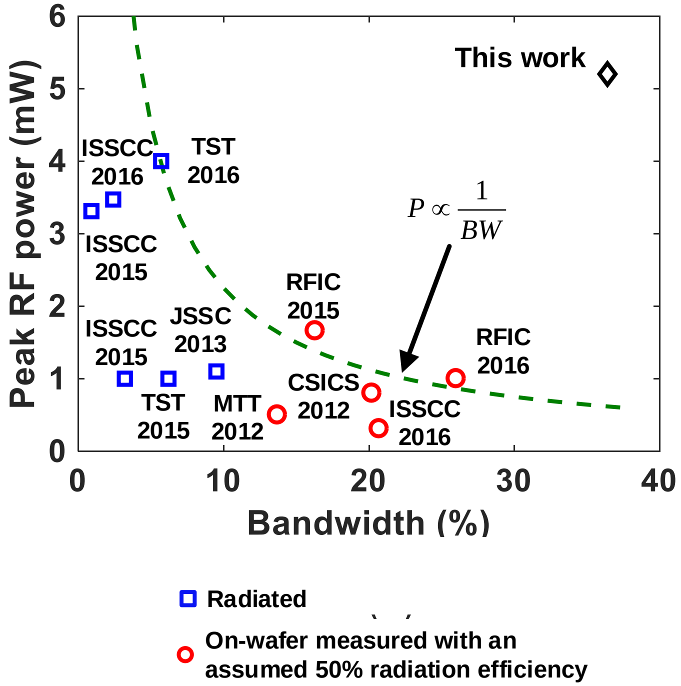
Experimental Results

Effective Isotopically-Radiated Power



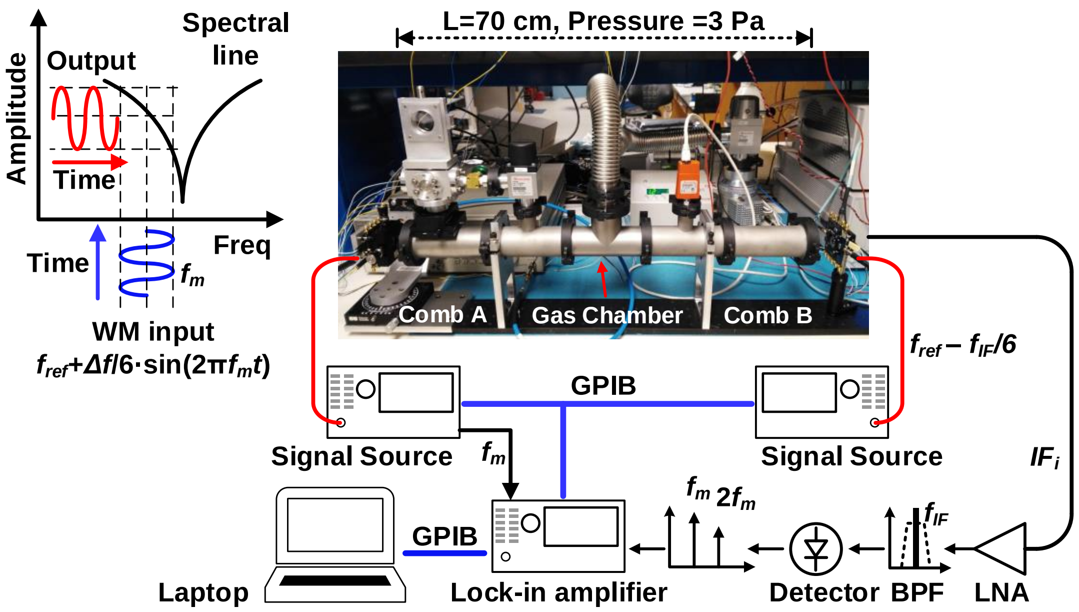
Noise Figure of Each Channel (SSB, Antenna Loss Included)

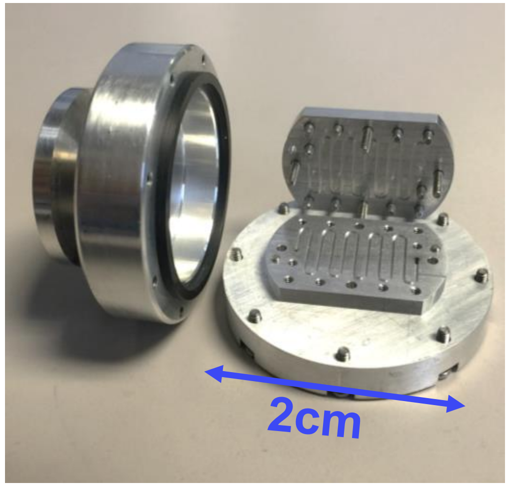


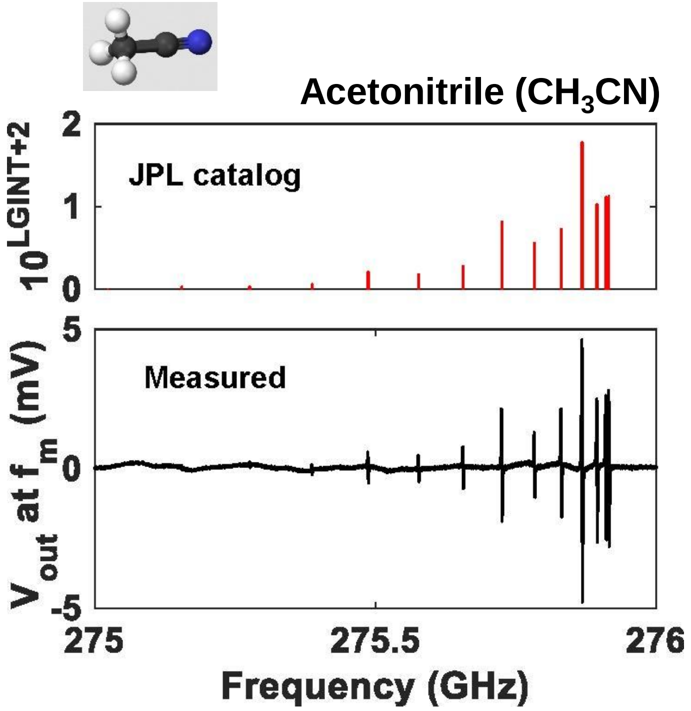


- Total radiated power of the 10 comb lines: 5.2 mW
  - Highest in silicon
- Minimum detectable signal: 0.1 fW (-130 dBm) @ τ=1 ms

Spectroscopy Demonstration

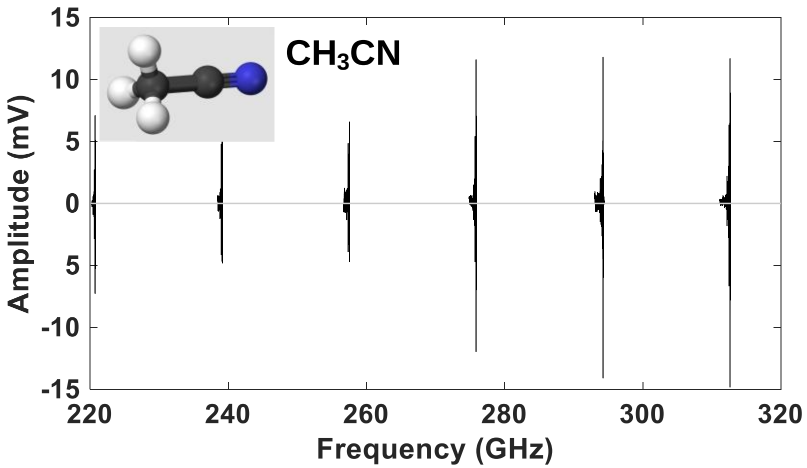


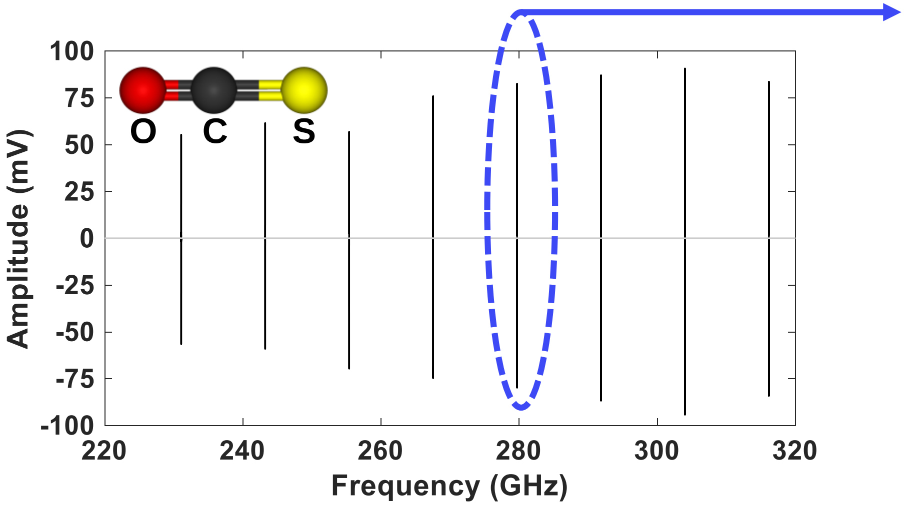


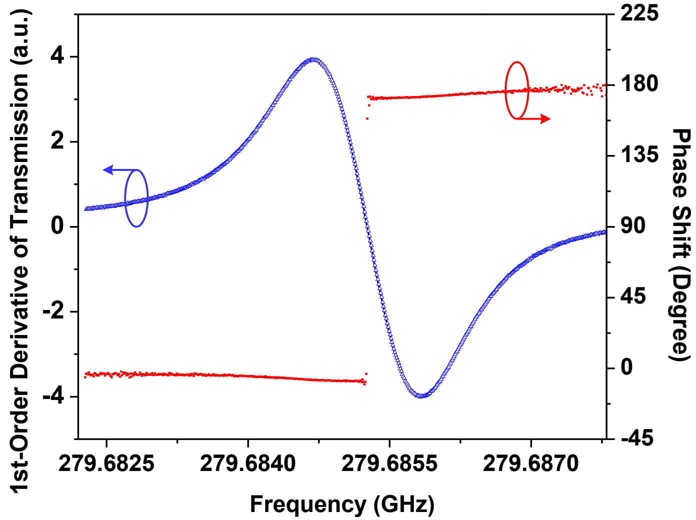


- Low pressure is applied to eliminate the spectral broadening due to the inter-molecular collisions
- Wavelength modulation is used to reduce the impacts of the standing wave inside the gas chamber

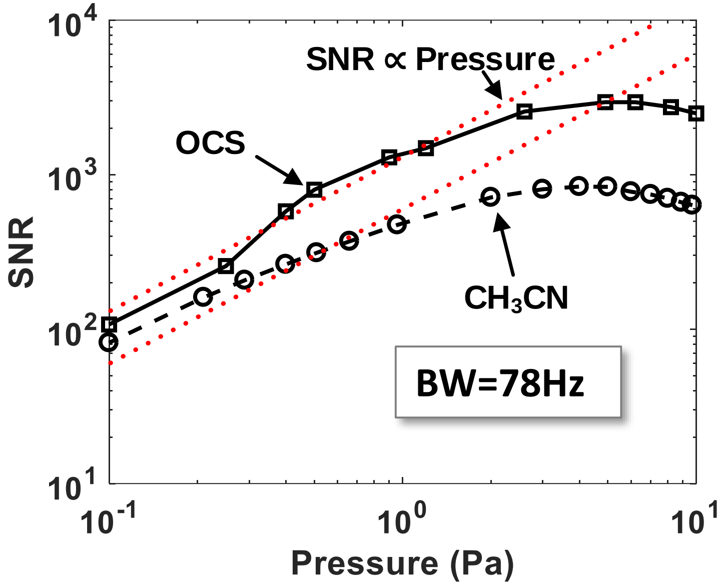
Spectroscopy Results







- Sensitivity: 11 ppm for OCS, 14 ppm for CH_3CN, 3 ppm for HCN…
  - 10-100 ppt with standard gas pre-concentration
- Any polar molecule heavier than HCN can be detected
- Spectral linewidth is ~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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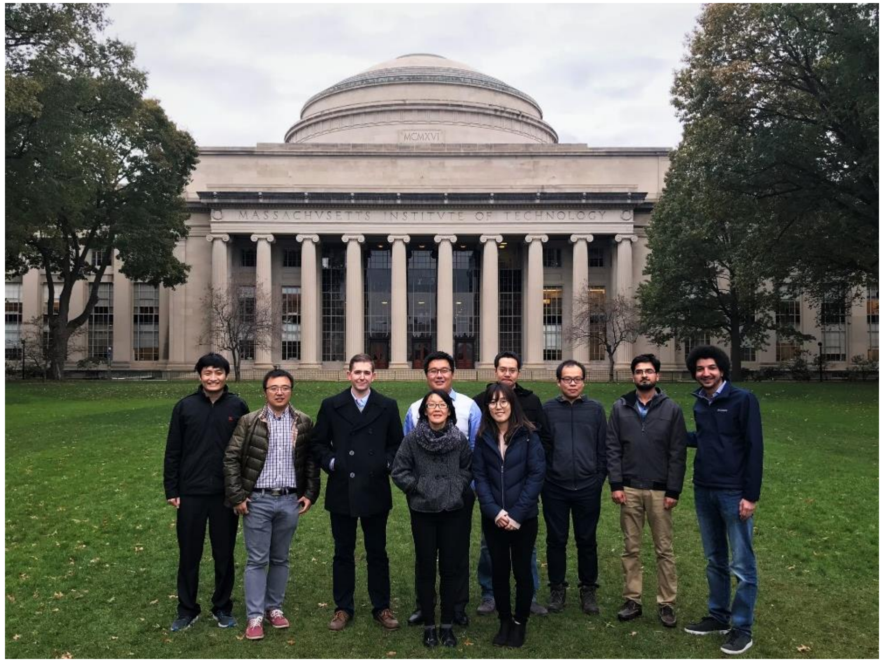
  Q. Hu (MIT), M. Kaynak (IHP)



- **Sponsors:**

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

Cheng Wang, Zhi Hu, Guo Zhang,
Jack Holloway and Ruonan Han

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