Fully Electronic Generation and Detection of Broadband THz pulses and Their Applications

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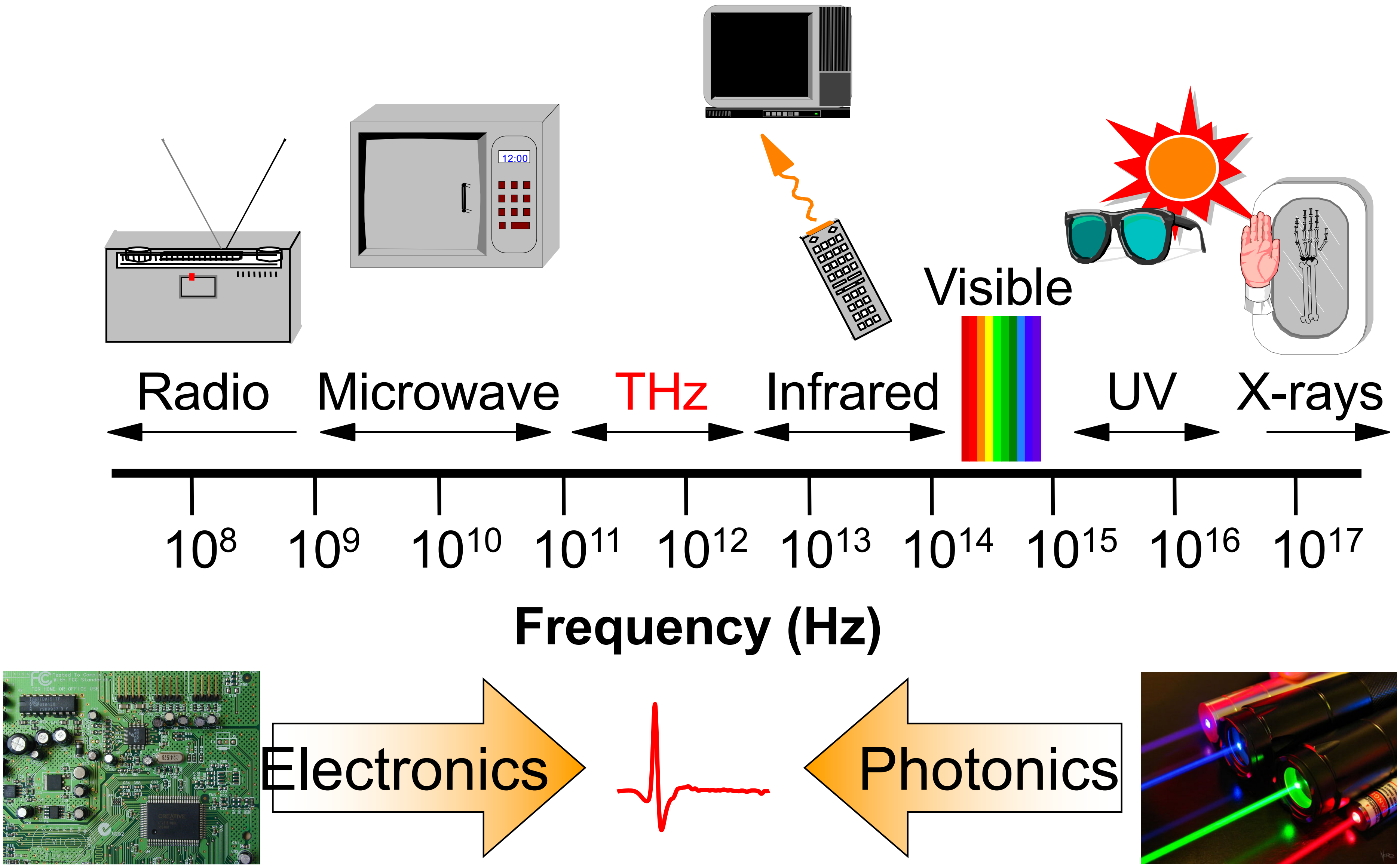
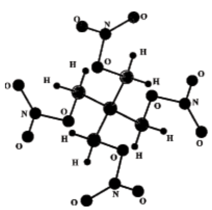
Terahertz Radiation: The Last Frontier

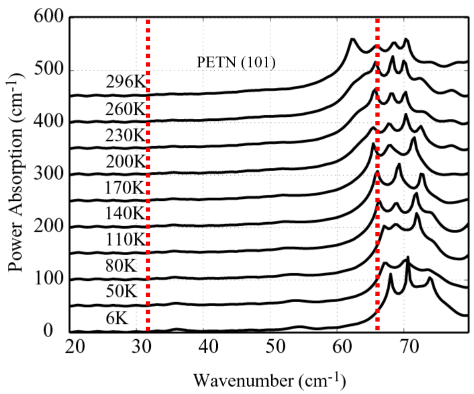


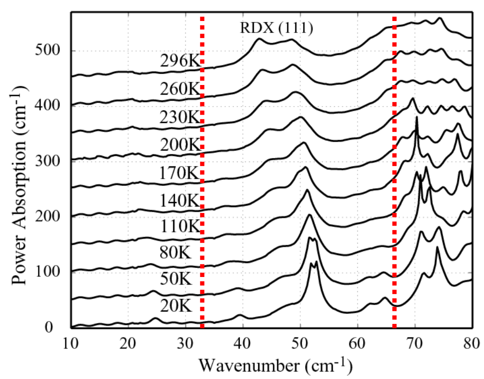
Spectroscopy Applications of Terahertz

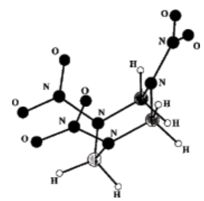
- Video-rate vibrational spectroscopy
- Detection and identification of:
  - Narcotics and pharmaceuticals
  - Explosives
  - Biological materials



PETN
$C_5H_8N_4O_{12}$

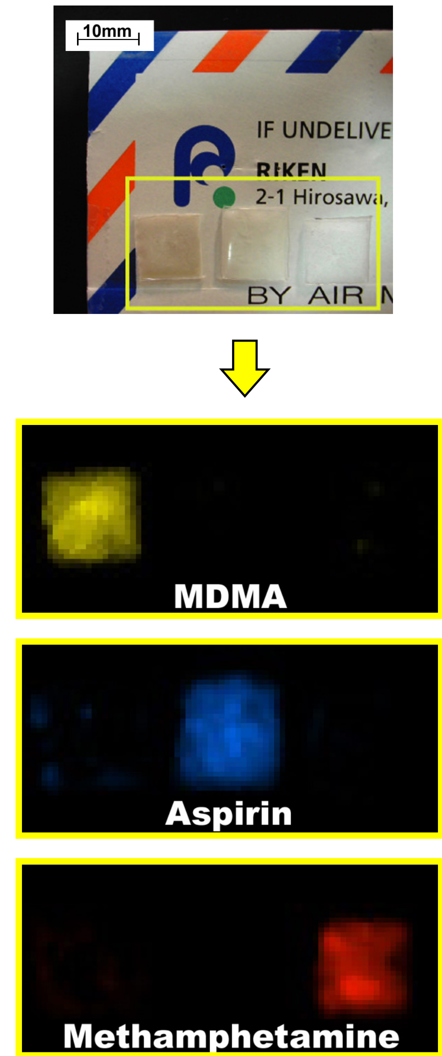






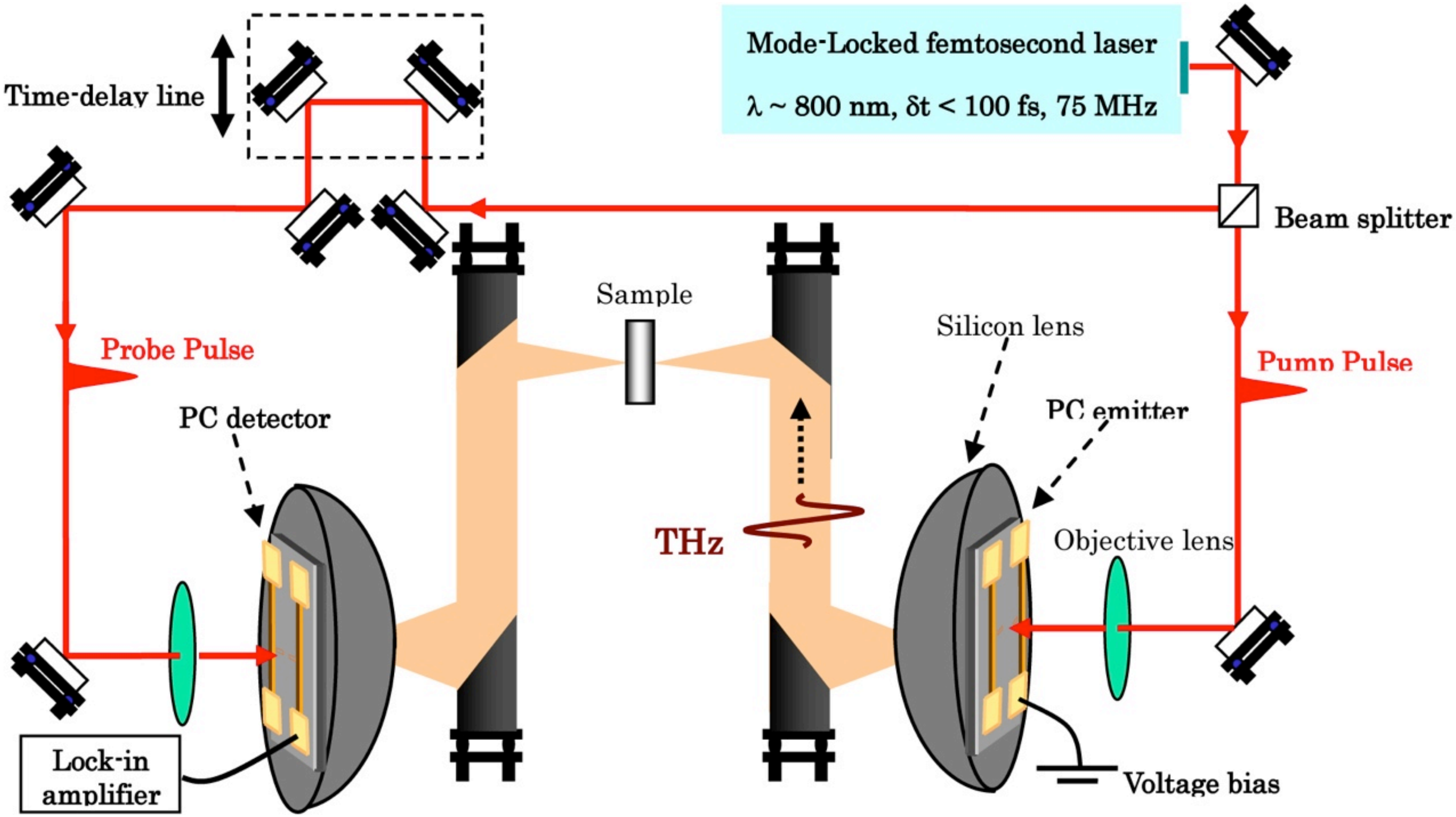
RDX
$C_3H_6N_6O_6$

"white powder" in an envelope



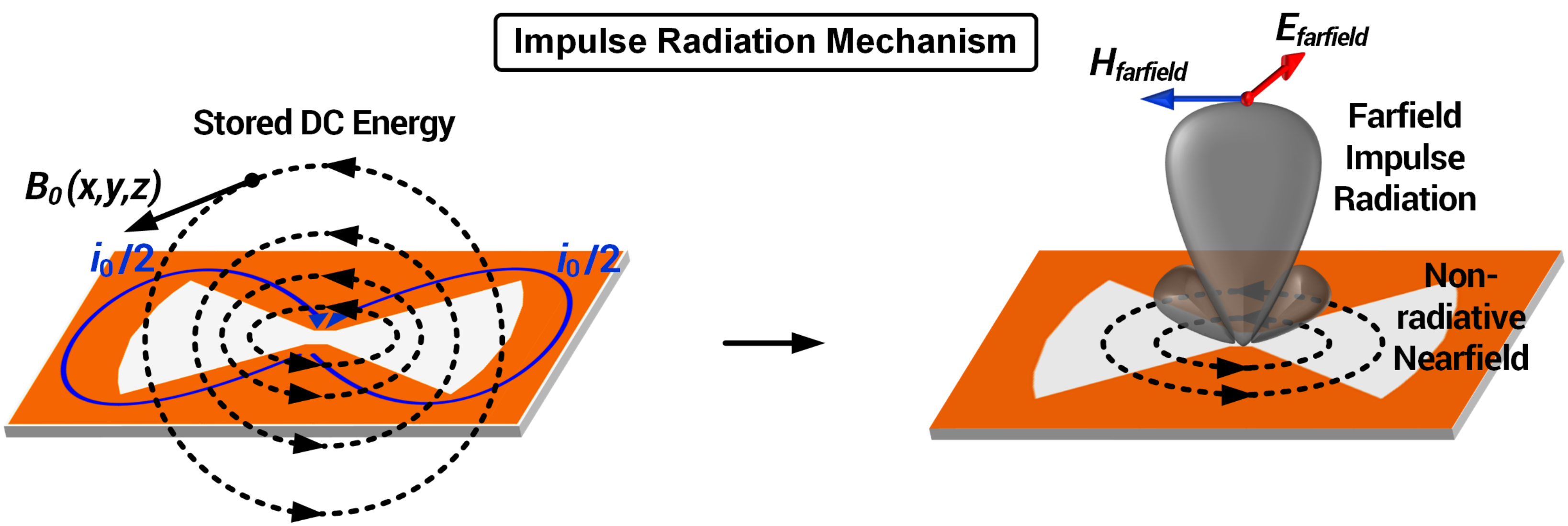
- Other Applications:
  - High-speed wireless communication
  - Security imaging
  - Skin cancer imaging

Conventional Laser-Based Methods



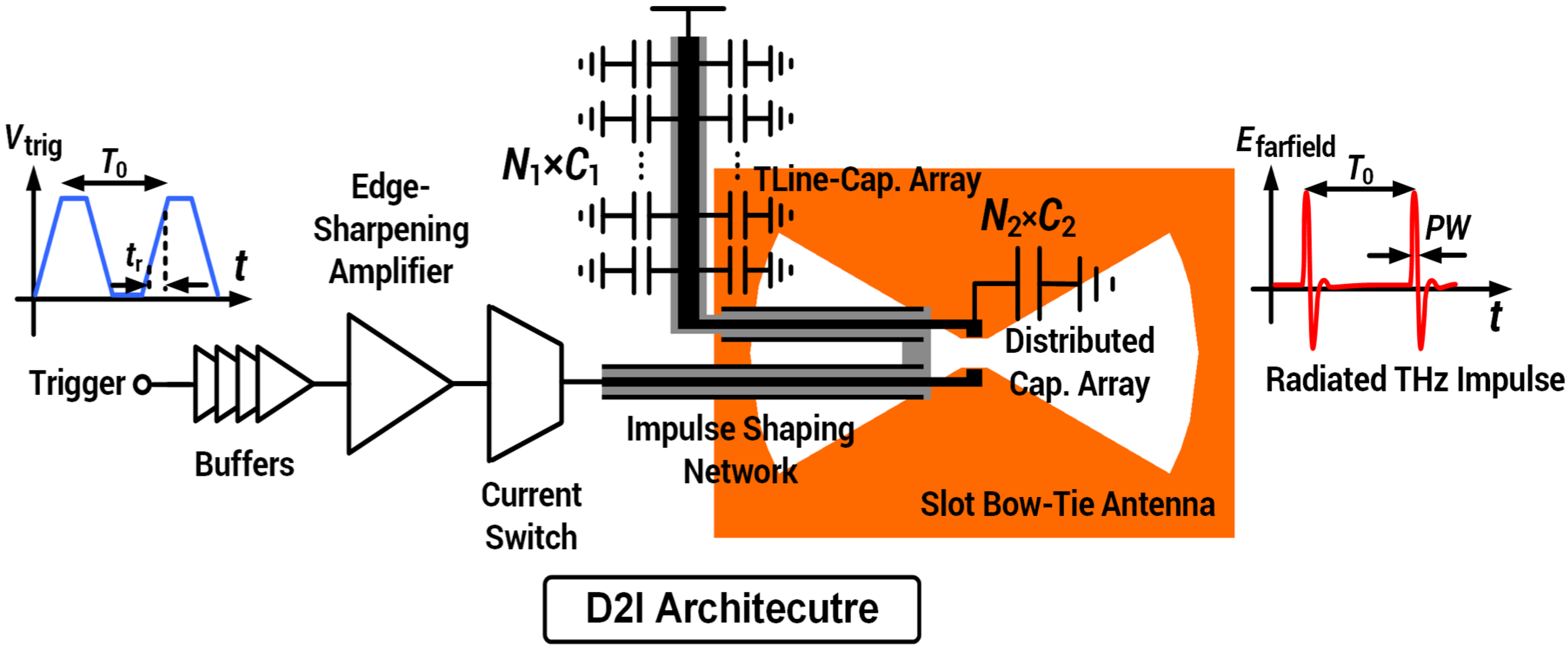
- Mechanical scanning in two dimensions, slow process
- Time consuming alignment
- Expensive >$100K

Direct Digital-to-Impulse Radiation (D2I)



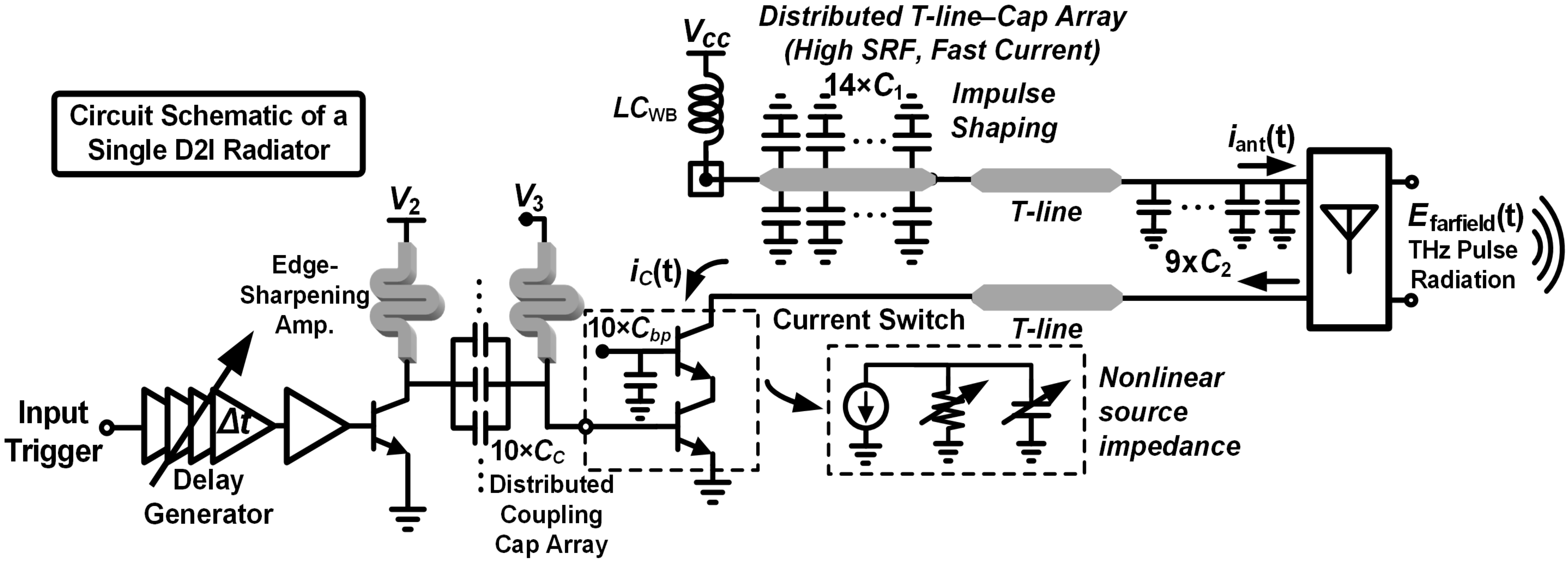
- Impulse radiation mechanism in Direct Digital-to-Impulse (**D2I**)
  - An oscillator-less design
  - Storing current in an antenna
  - Disconnecting the current by a fast switch

Circuit Architecture



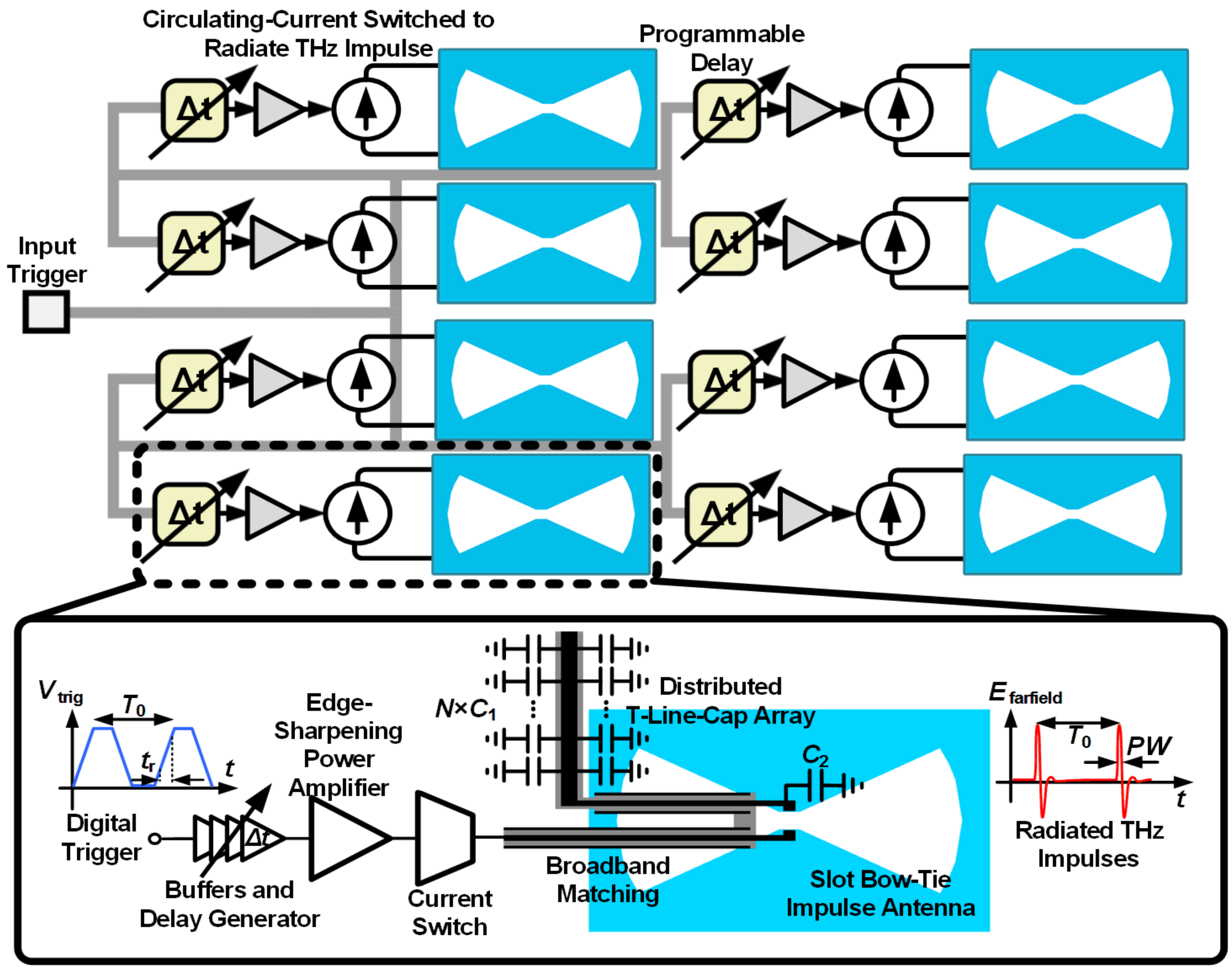
- Impulse shaping network
  - Distributed array of high SRF capacitors to deliver large current in short time (behaves like an ideal supply voltage)

Circuit Schematic



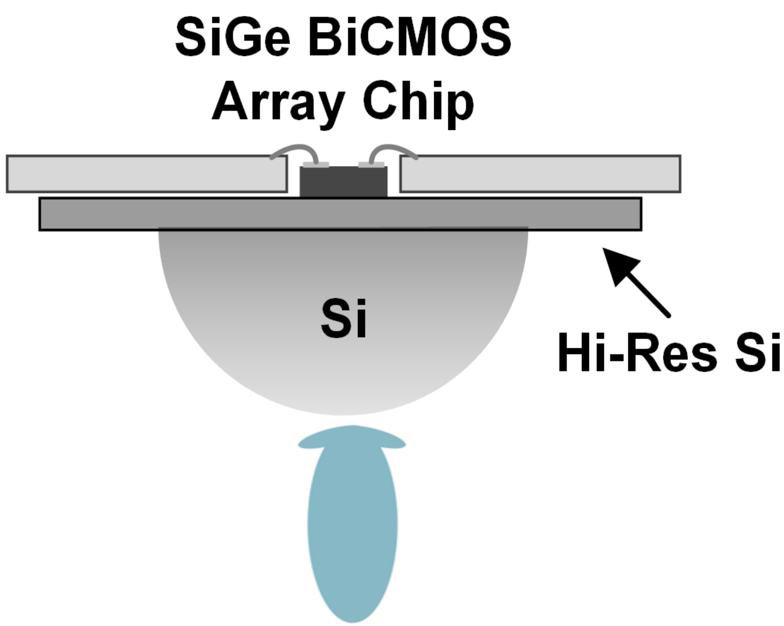
- Current is stored in a slot bow-tie antenna
- A fast switch turns off the current. The on-chip antenna releases the stored energy and radiates a short impulse
- An impulse shaping network is used to minimize the ringing

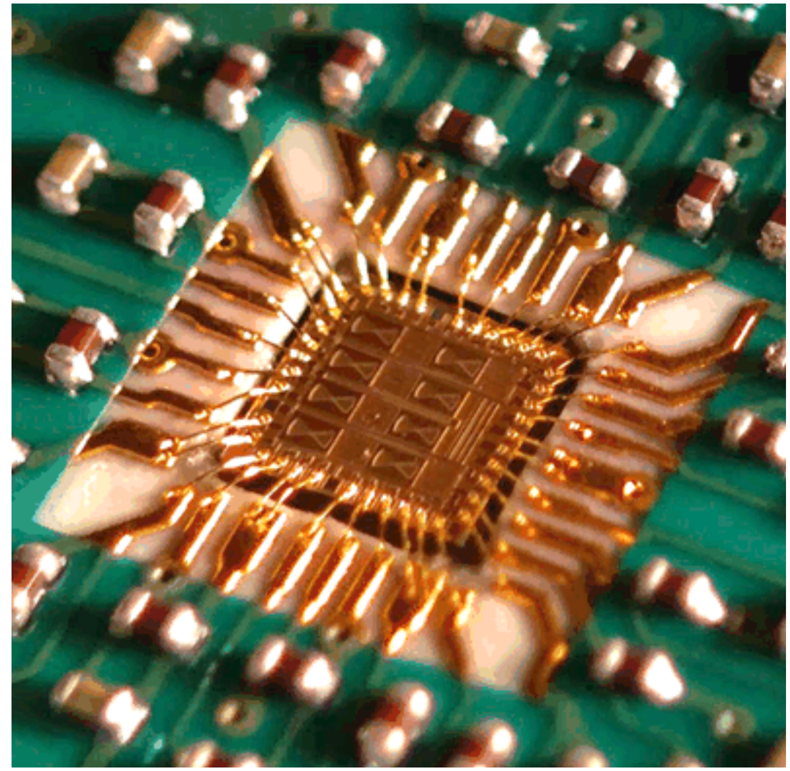
Single-Chip 4x2 D2I Array in SiGe BiCMOS



- H-tree distribution of input trigger to 8 elements
- Programmable delay generator per element

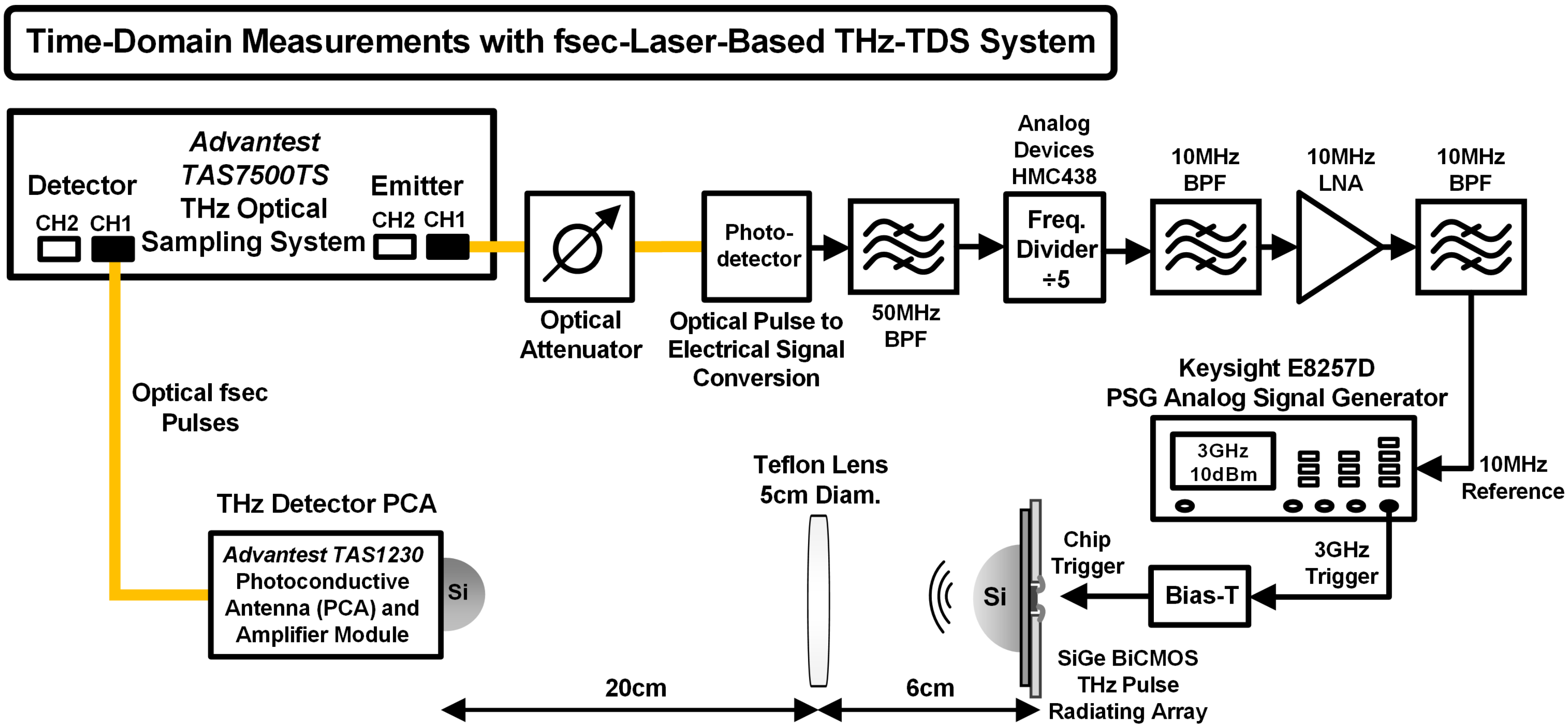
Prototype Assembly





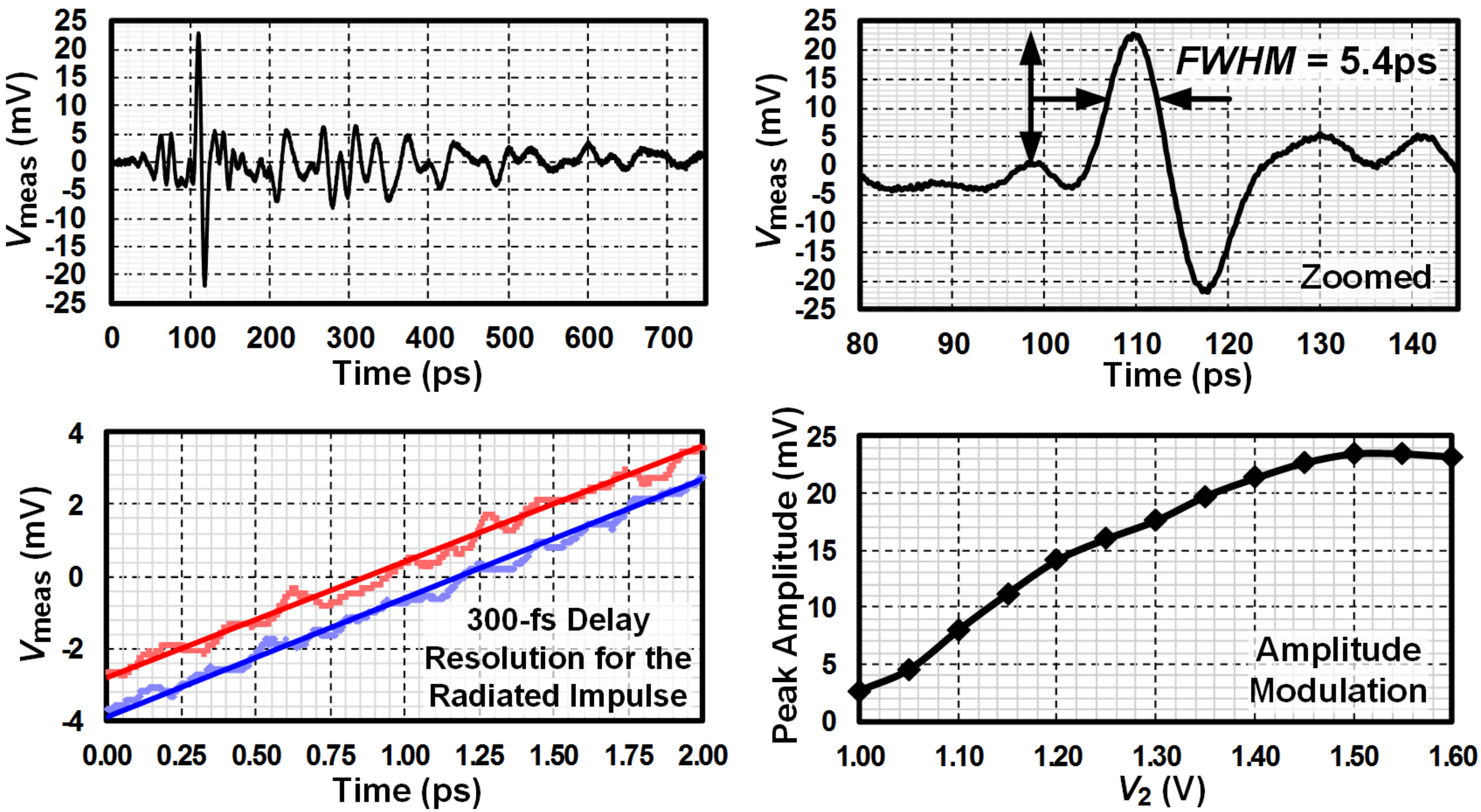
- A chip-on-board assembly with bond wires is used
- A trigger signal fed to the chip triggers radiation of a THz pulse
- Radiation is coupled to a 25mm diameter lens with 400µm extension

Time-Domain Characterization Setup



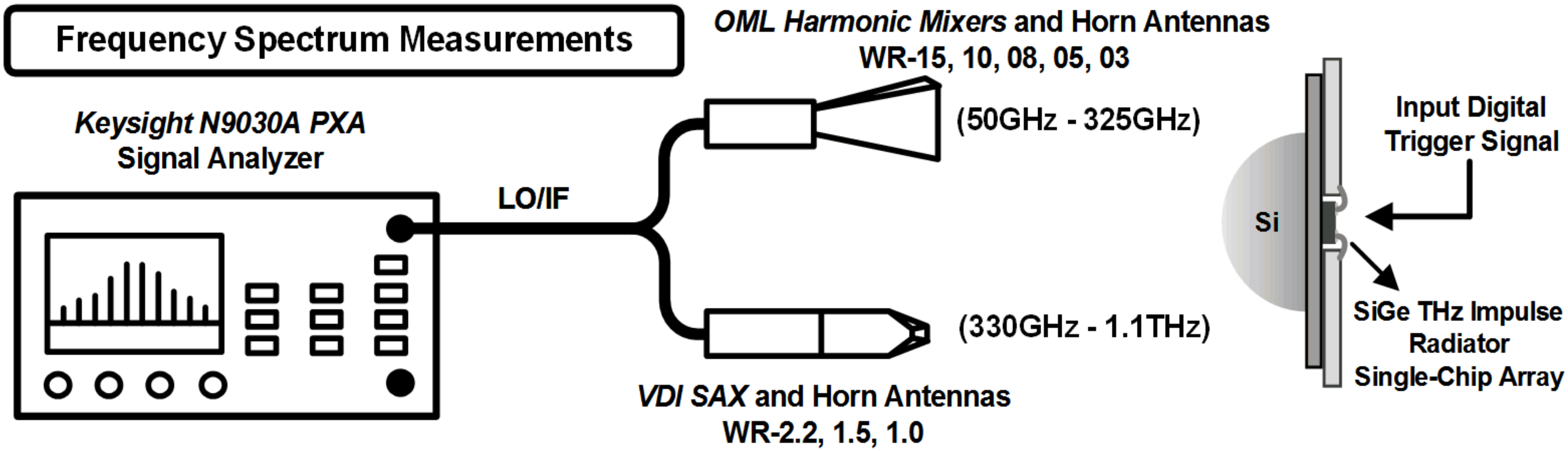
- A fsec-laser-based THz-TDS system is used to characterize the array chip
- A fully electronic chip is used as the emitter in a THz-TDS system

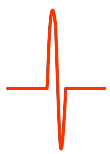
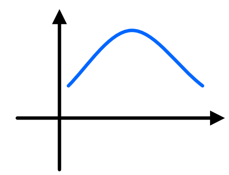
Measured Time-Domain Waveforms



- 300fs delay resolution
- Amplitude modulation capability

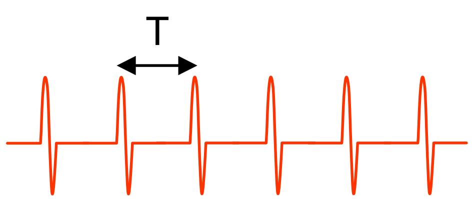
Frequency-Domain Characterization Setup

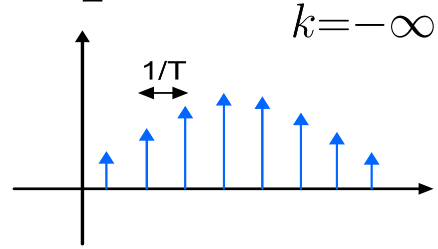


Single impulse $x(t)$  $|X(f)|$ 

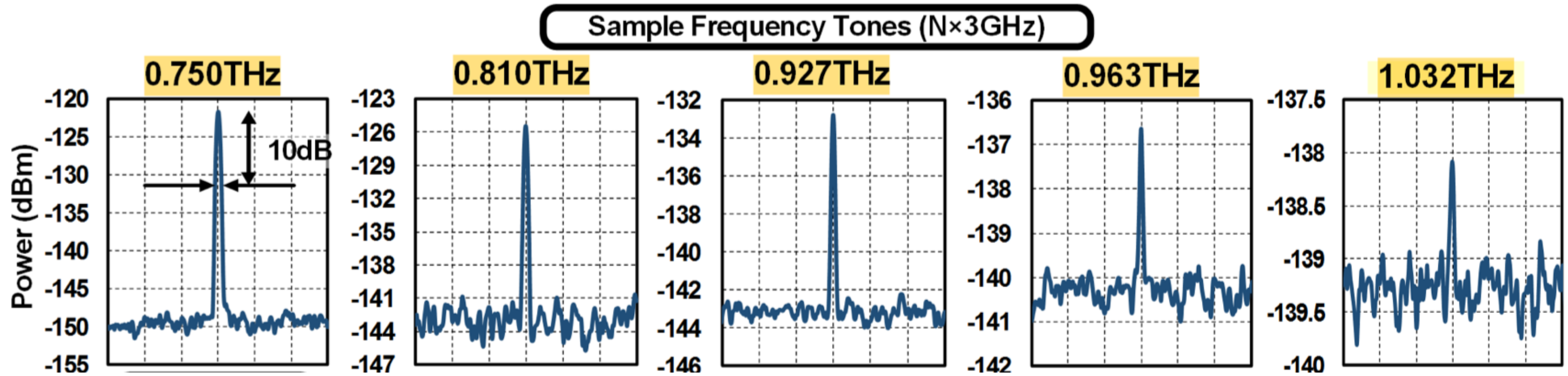
$$y(t) = \sum_{k=-\infty}^{\infty} x(t-kT) \qquad |Y(f)| = \frac{1}{T}|X(f)| \sum_{k=-\infty}^{\infty} \delta(f - k\frac{1}{T})$$

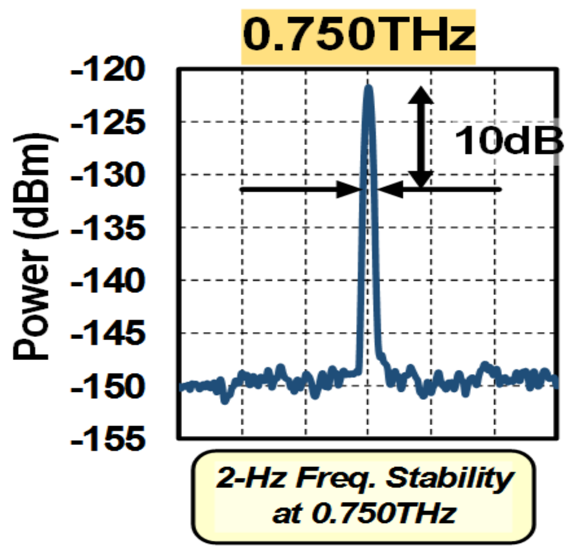
Impulse train





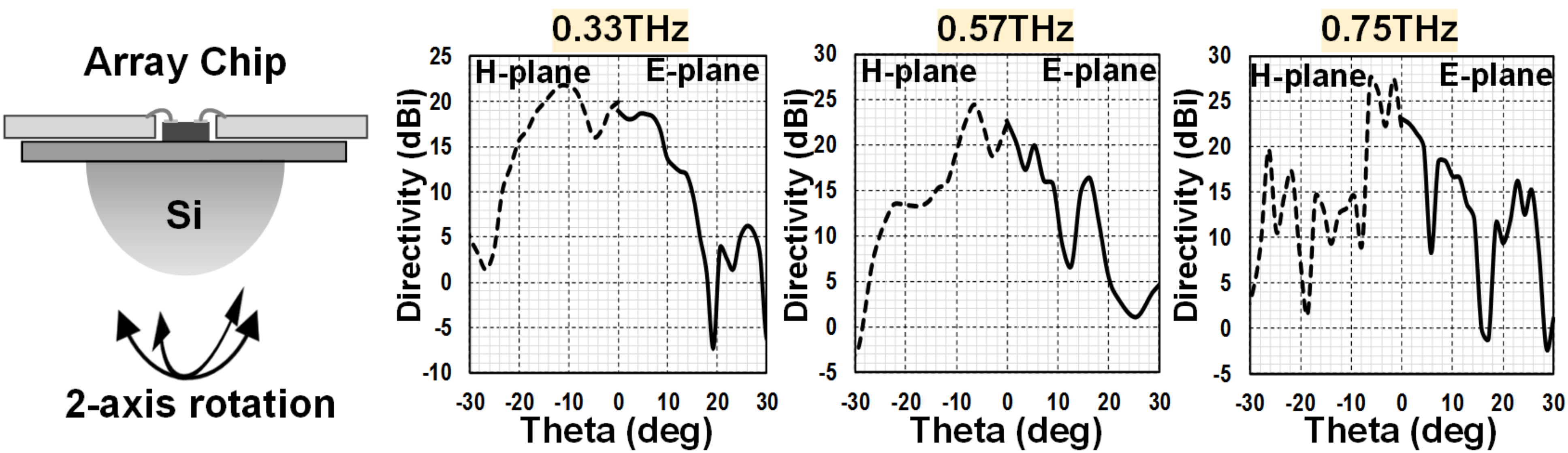
Frequency-Domain Characterization Results





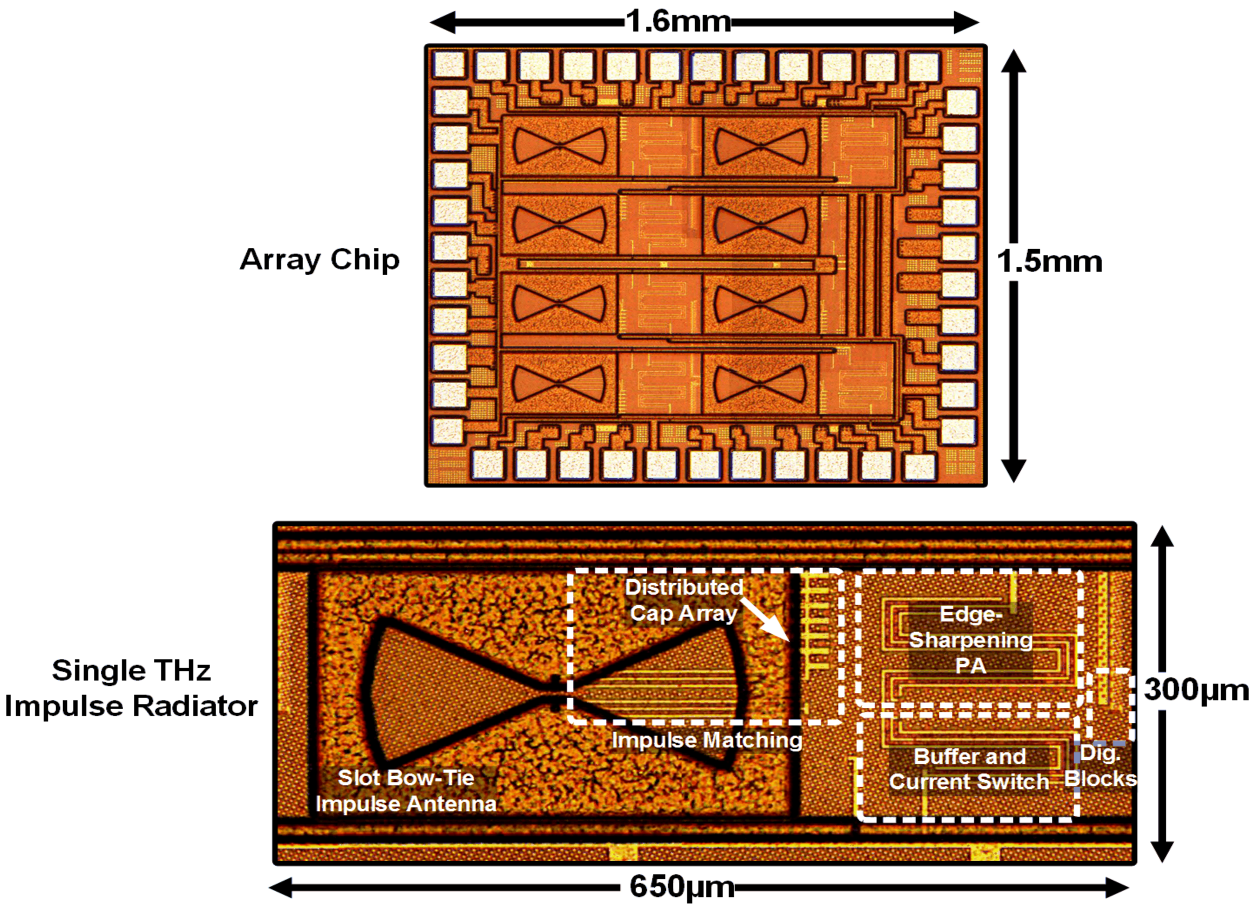
- 2-Hz spectral line-width at 0.75THz

Radiation Pattern Measurements



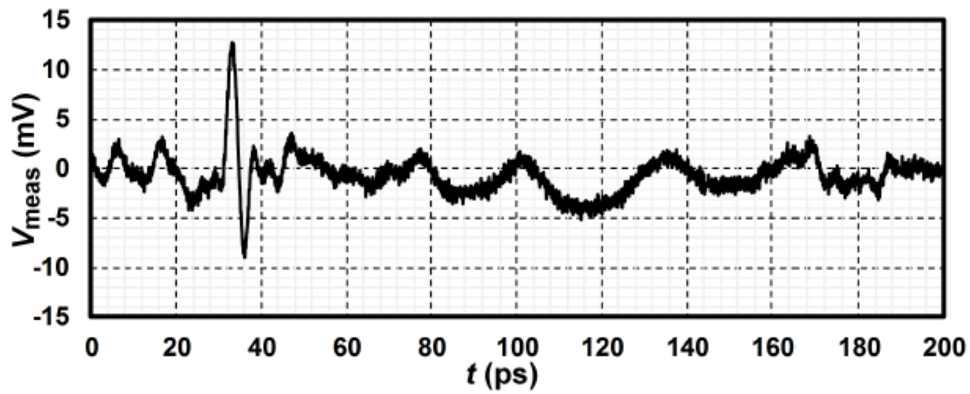
- Directivities of 22dB, 24dB and 28dB at 0.33THz, 0.57THz and 0.75THz, respectively

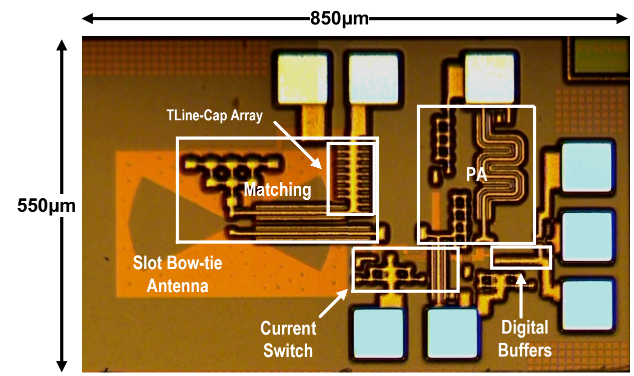
Array Chip Micrograph

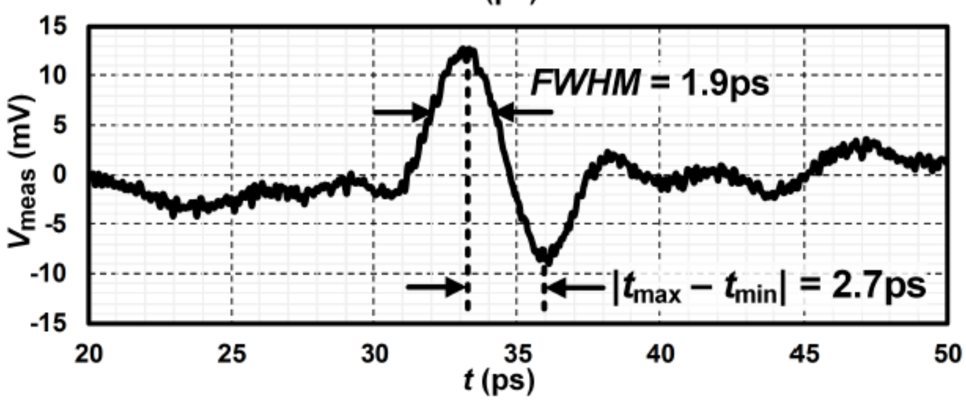


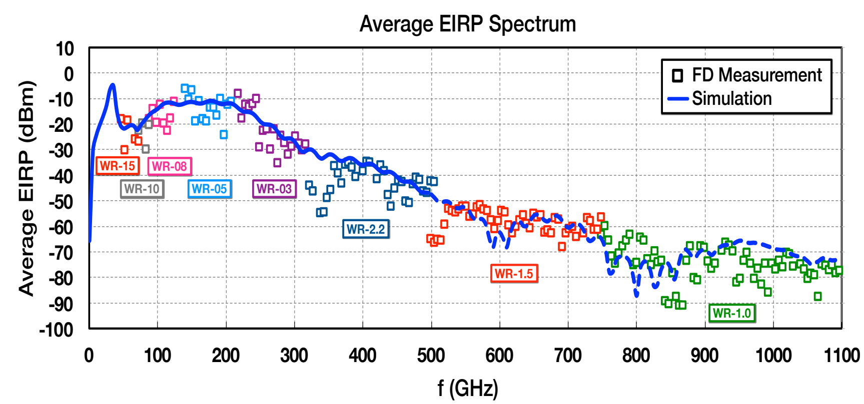
- Process technology: 90nm SiGe BiCMOS
- A single element only occupies 300µm x 650µm
- Second Best Paper Award in IEEE APS 2016

Single-Chip Direct Digital-to-Impulse Radiation



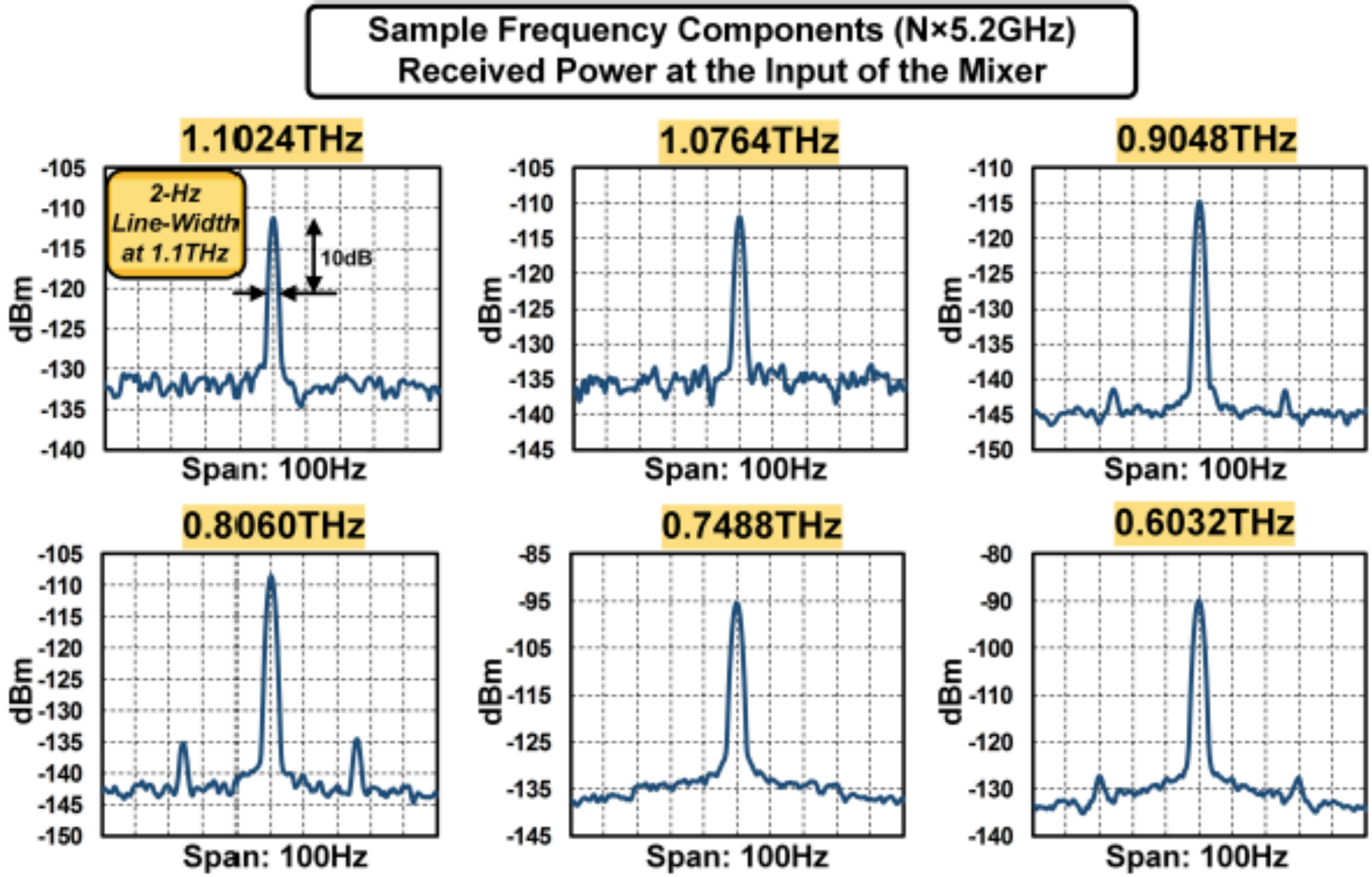




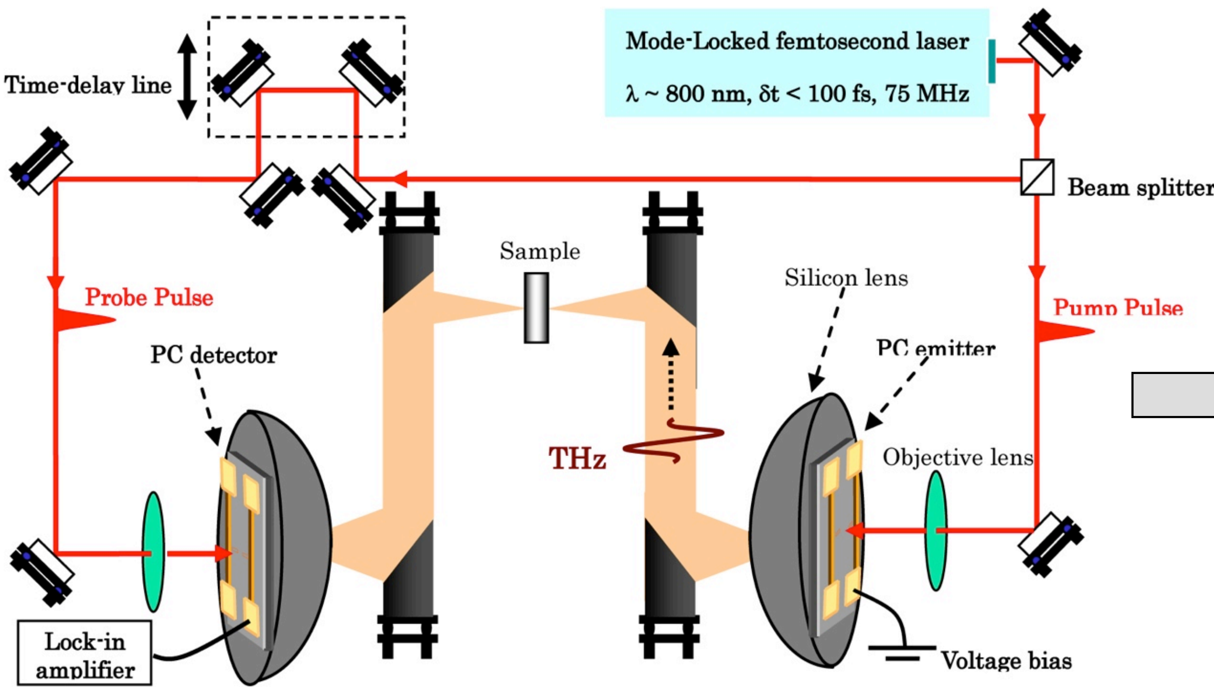


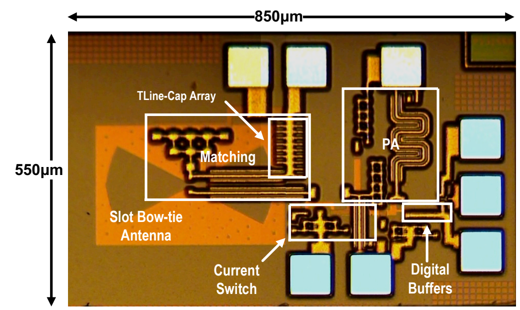
- Best Paper Award in IEEE IMS 2014
- Process technology: 130nm SiGe BiCMOS
- A single element occupies 550μm x 850μm
- Time-domain characterization is used with Advantest fsec detector setup

Raw Received Signal on the Spectrum Analyzer



A Single-Chip THz Source

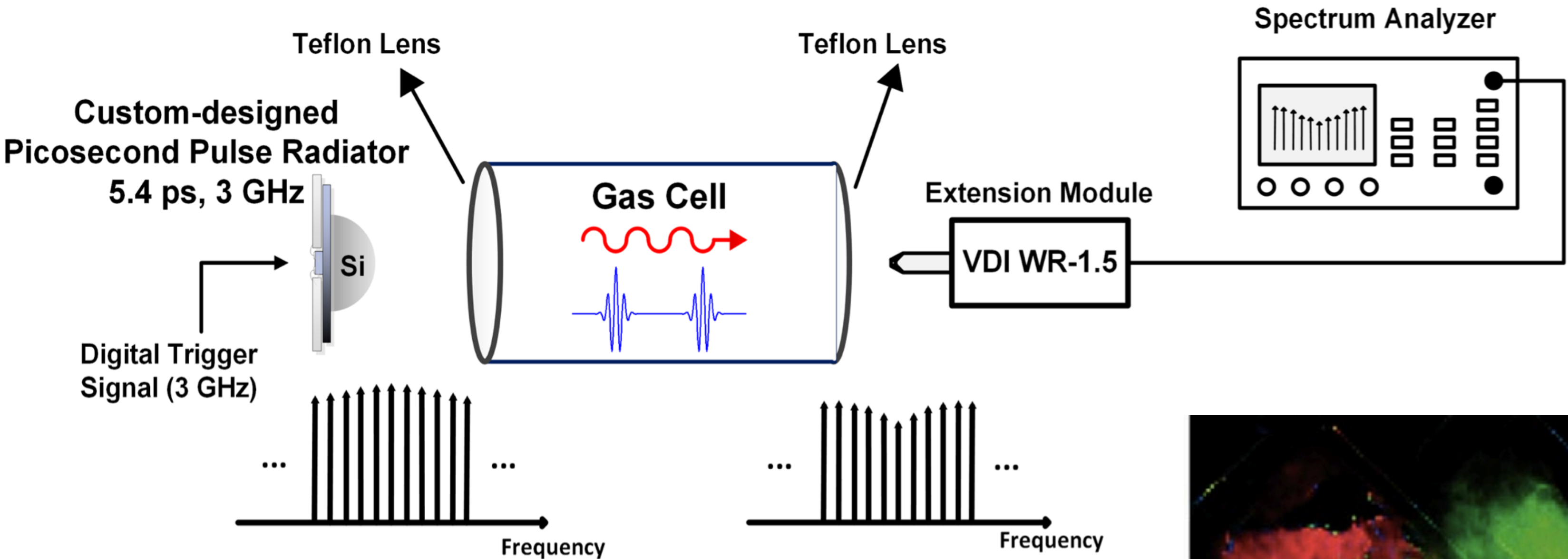


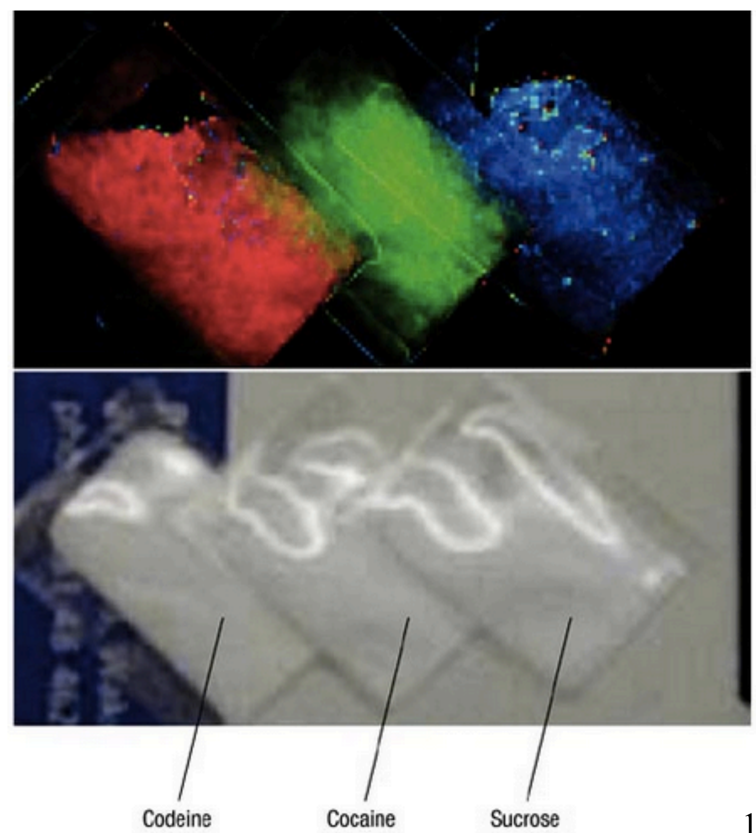


- Expensive ~$100K
- Bulky ~ 1m
- Slow ~ 100MHz rep. rate
- Not scalable to array
- Requires a fsec laser

- Low-cost ~ few $
- Small ~ 1mm
- Fast ~ 10GHz rep. rate
- Scalable
- No need for laser. Operates with a digital trigger.

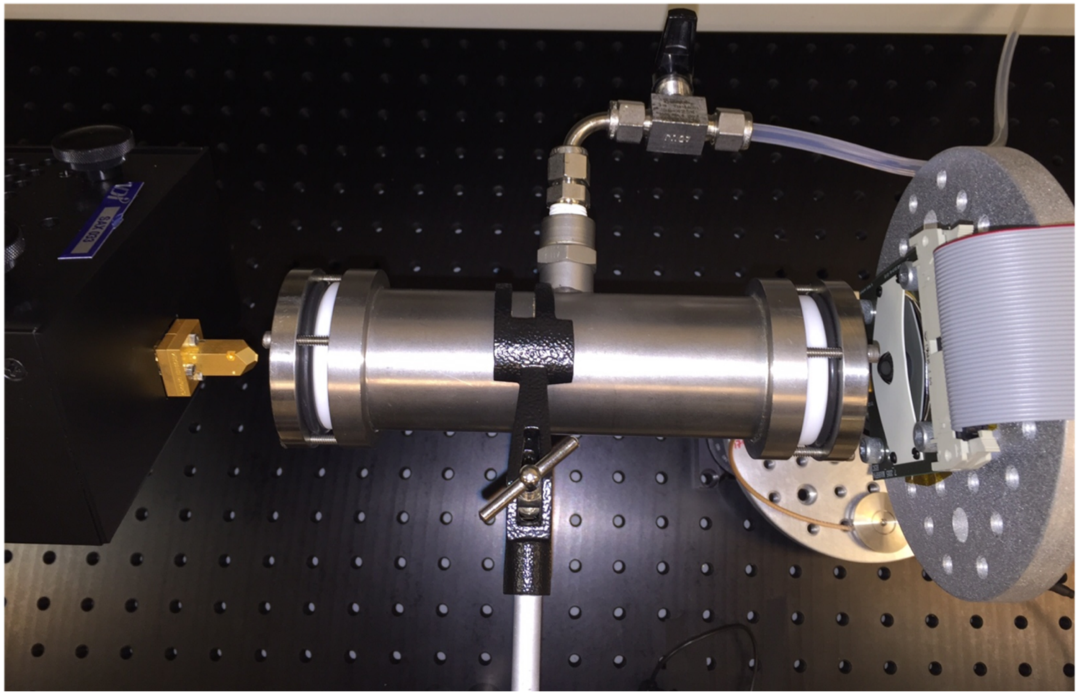
THz Rotational Spectroscopy





- Polar molecules such as H2S, CO2, H2O, NH3, …
- Explosives (e.g. RDX and HMX)
- Narcotics
- Large molecules

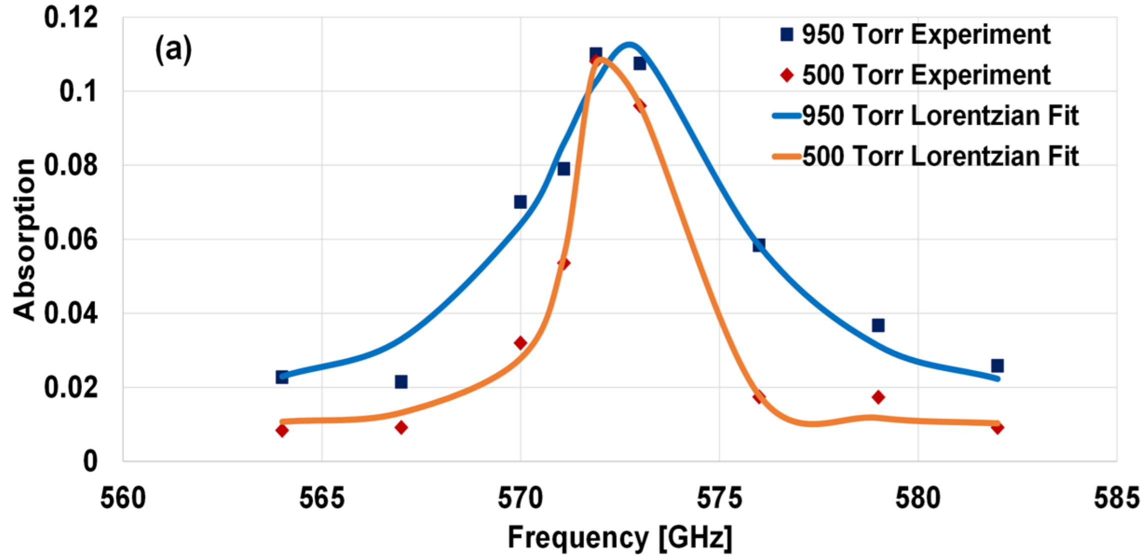
Gas Cell



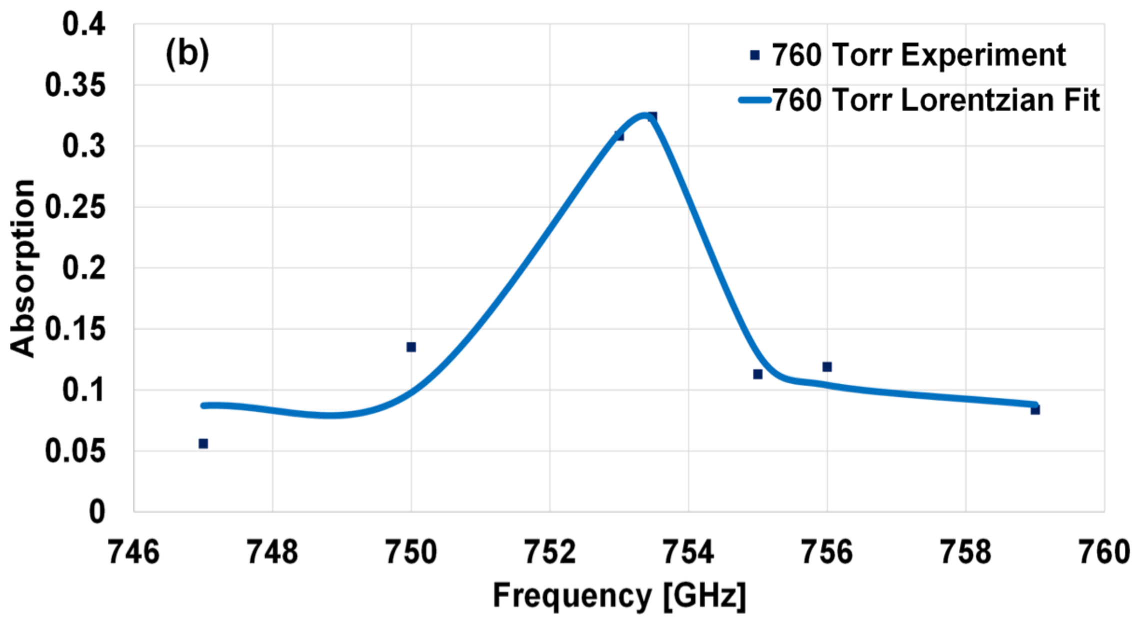
- Aluminum tube with 50mm diameter and 150mm length with Teflon lens windows on both sides
- Controlled pressure
- Received power is measured in two cases:
  - Gas cell is filled with the target gas
  - Gas cell is filled with pure nitrogen

Gas Spectroscopy Measurement Results

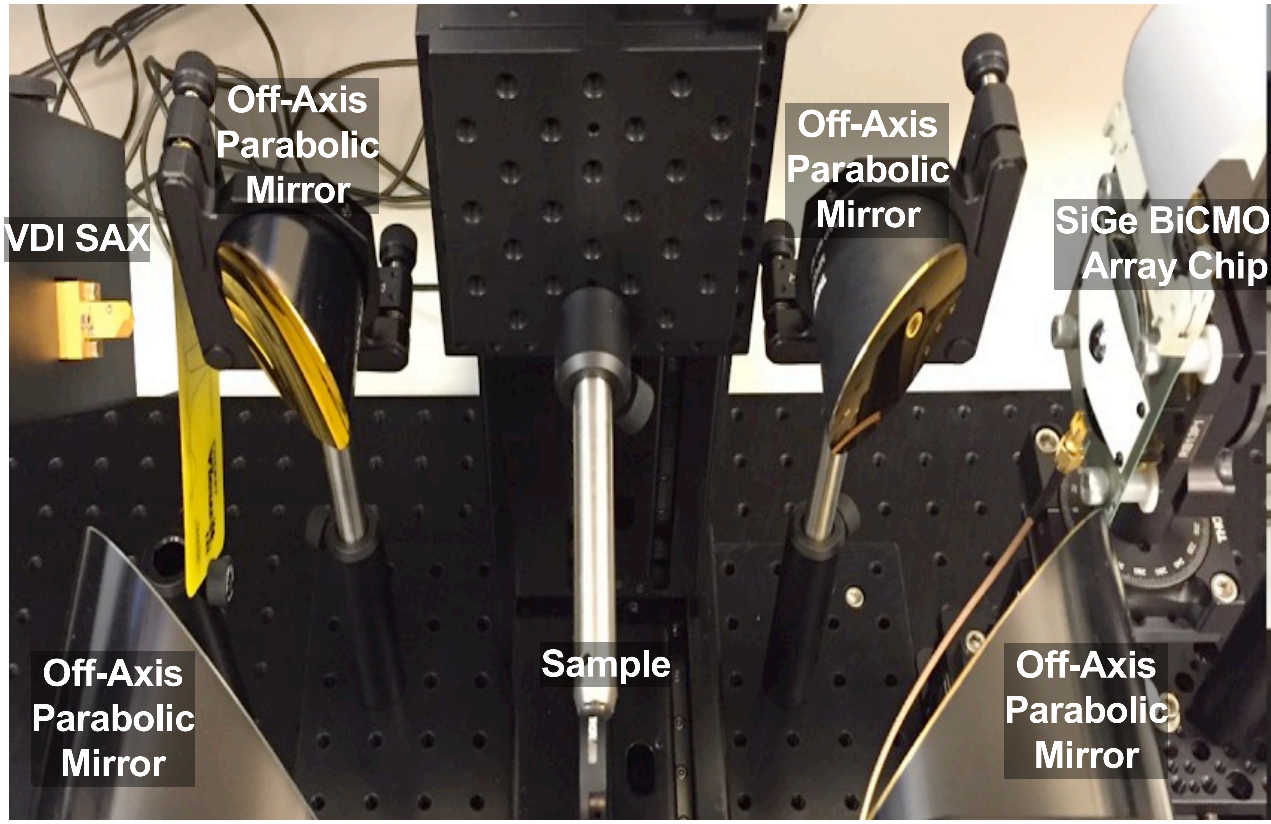
- NH_3 at 572GHz
  - 1% concentration
  - Pressure varied to demonstrate broadening effect



- H_2O at 753GHz
  - 50% humidity (0.75% concentration)

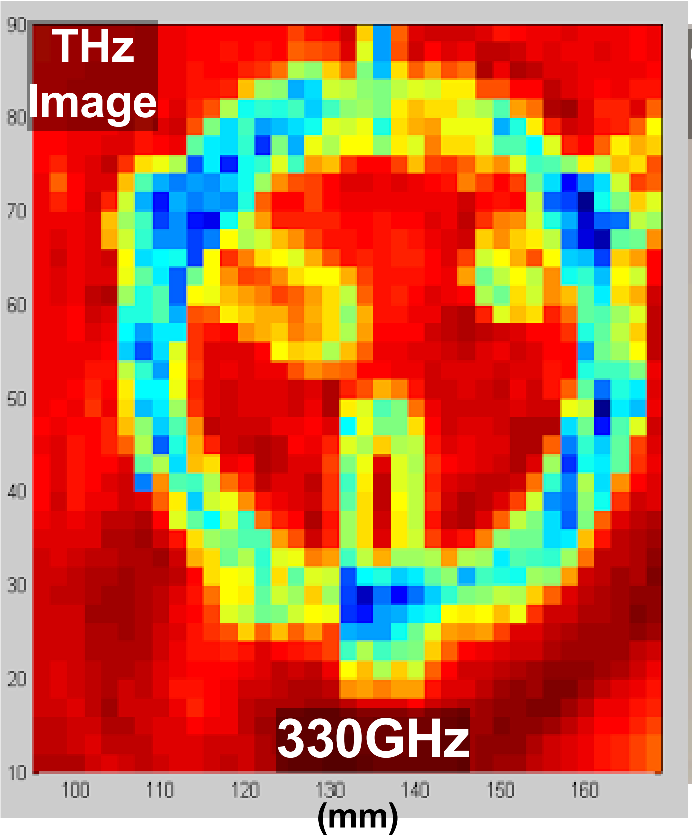


THz Hyper-Spectral Imaging Setup



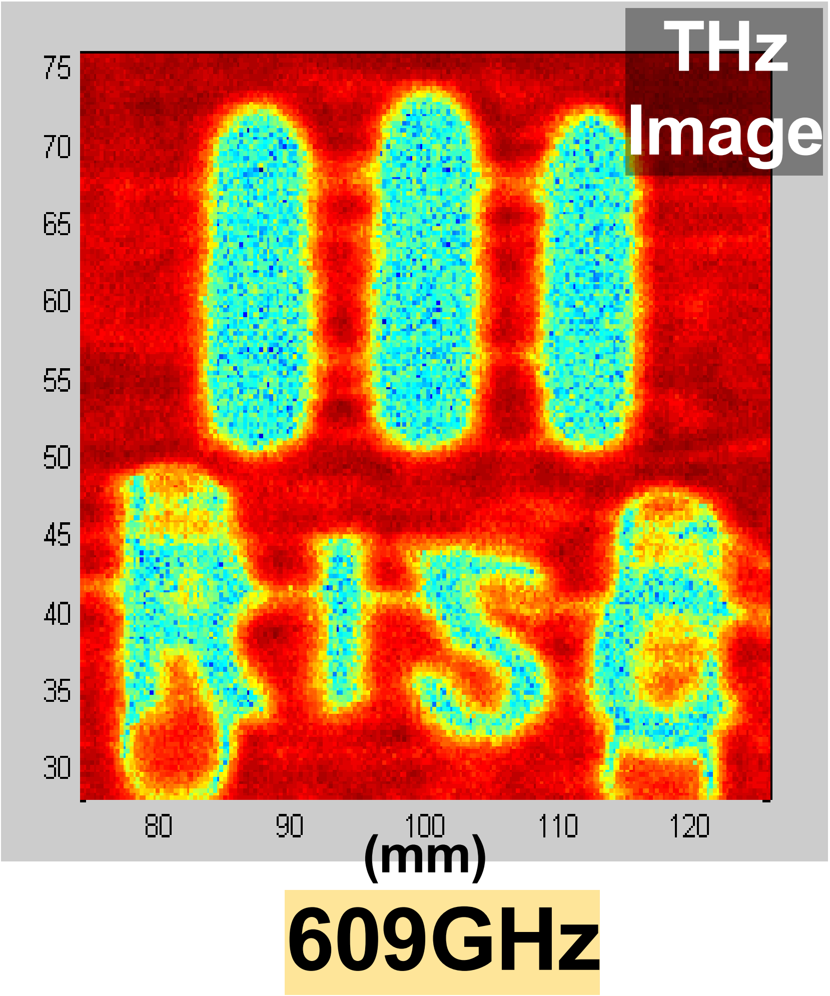
- Setup:
  - Four off-axis parabolic mirrors focus the beam on the sample
  - A 2D translation stage
- Spectral information: 0.03-1.03THz

Image at 330GHz



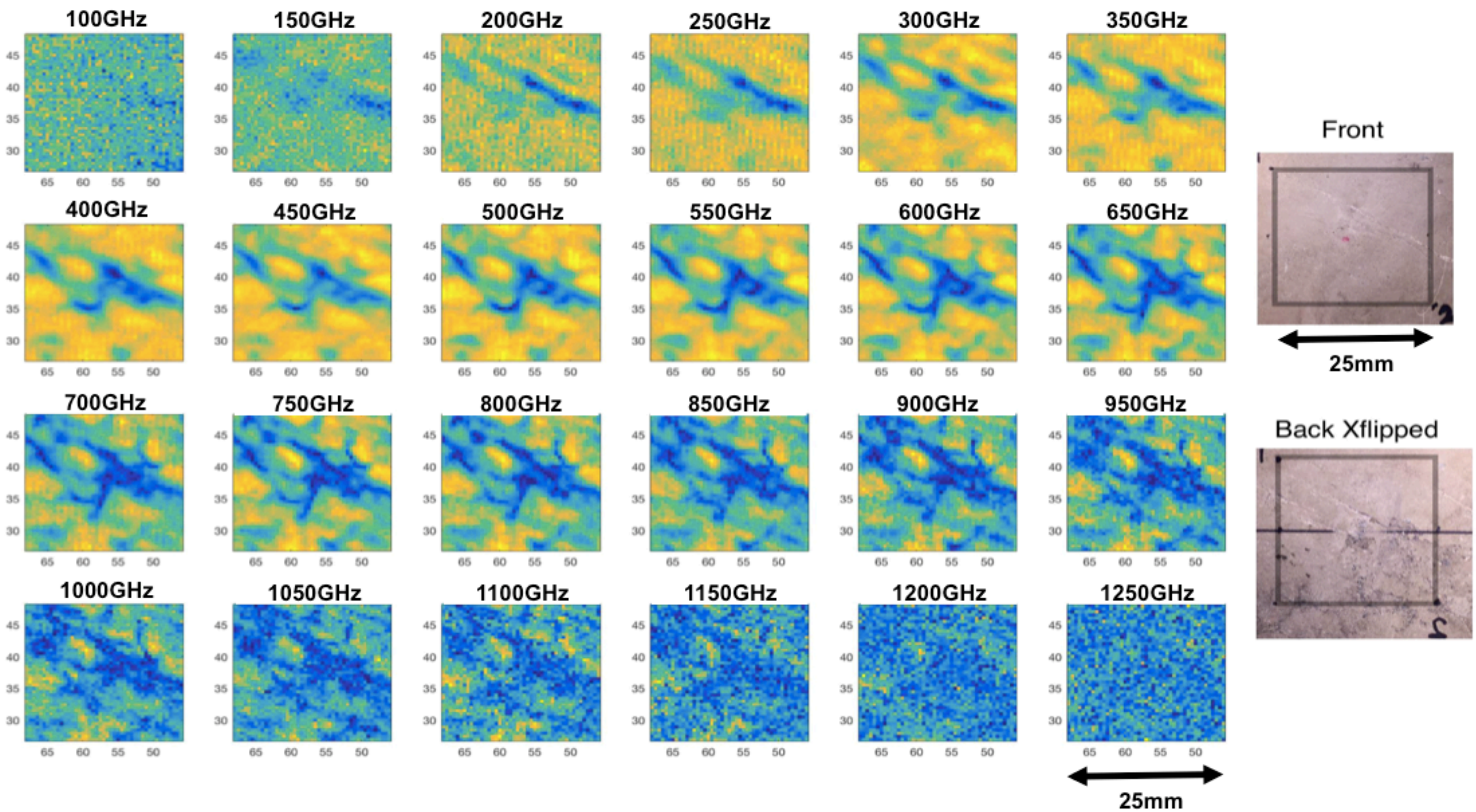
- Materials: metal and plastic

Image at 609GHz



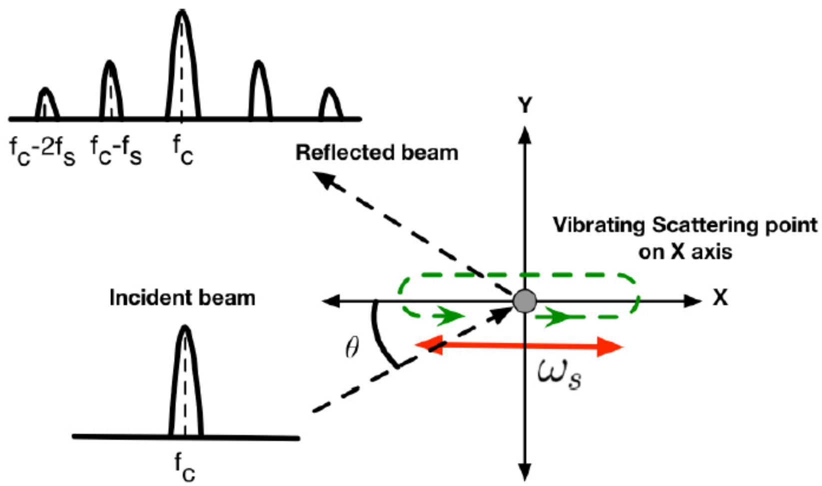
- Materials: metal, empty and filled cellulose capsules

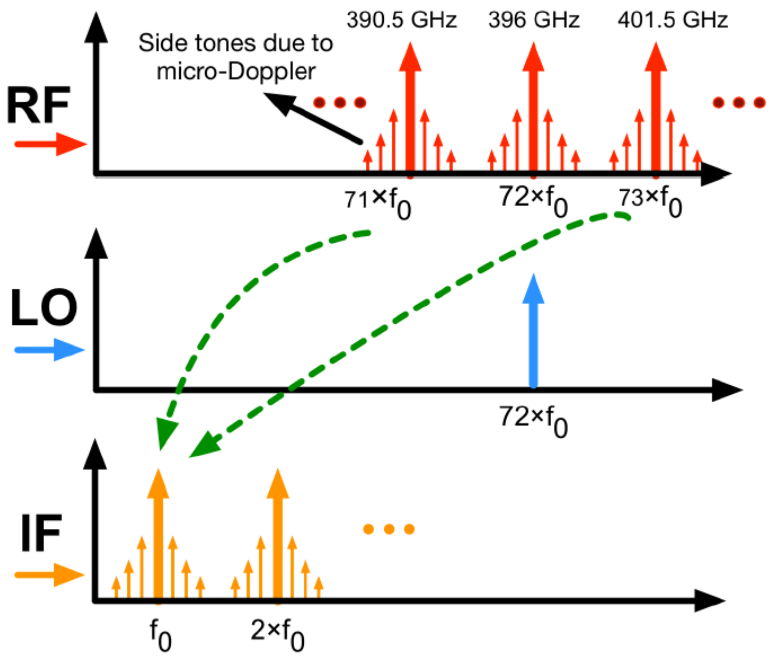
Hyper-Spectral Imaging (100GHz-1.2THz)

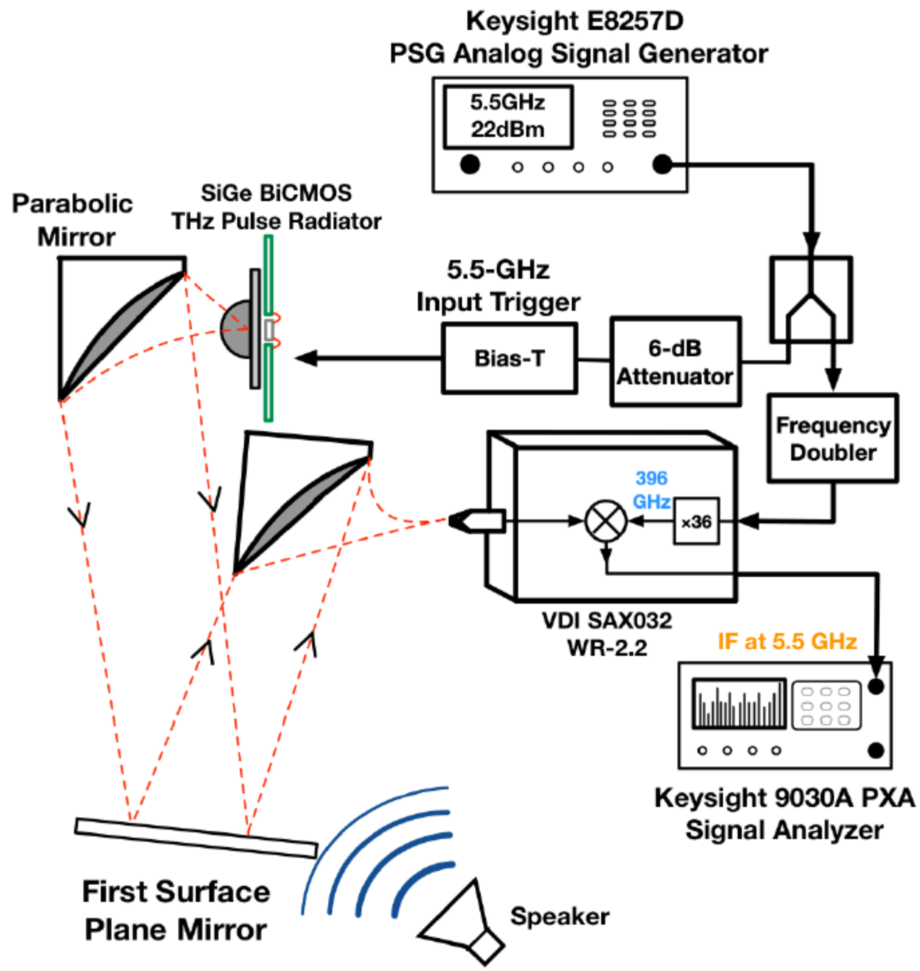


- Sample size: 25mm x 25mm, thickness: 5mm
- Transmission imaging, resolution~500µm

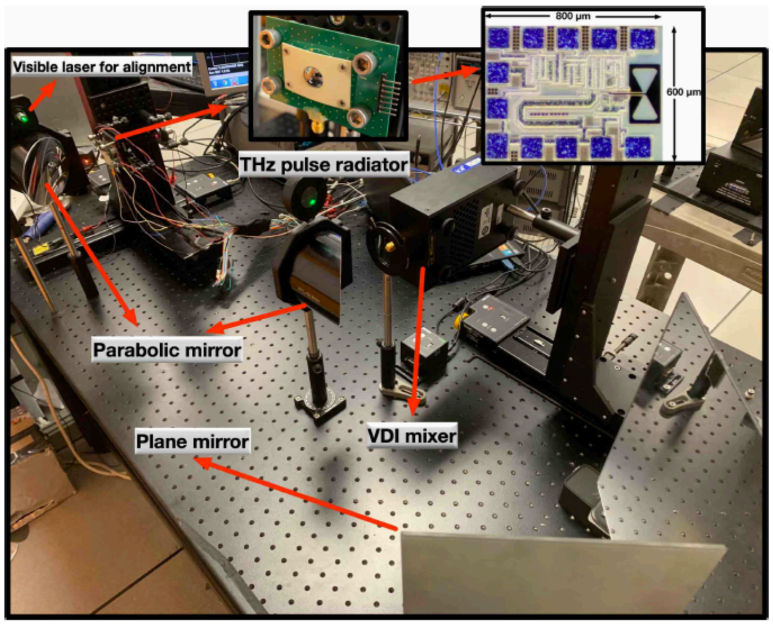
THz Micro-Doppler Radar with A Comb Source

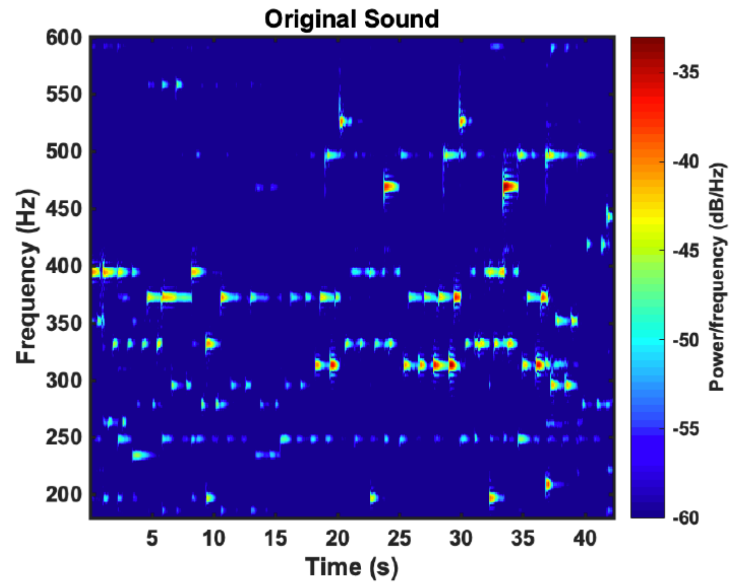






THz Micro-Doppler Measurements





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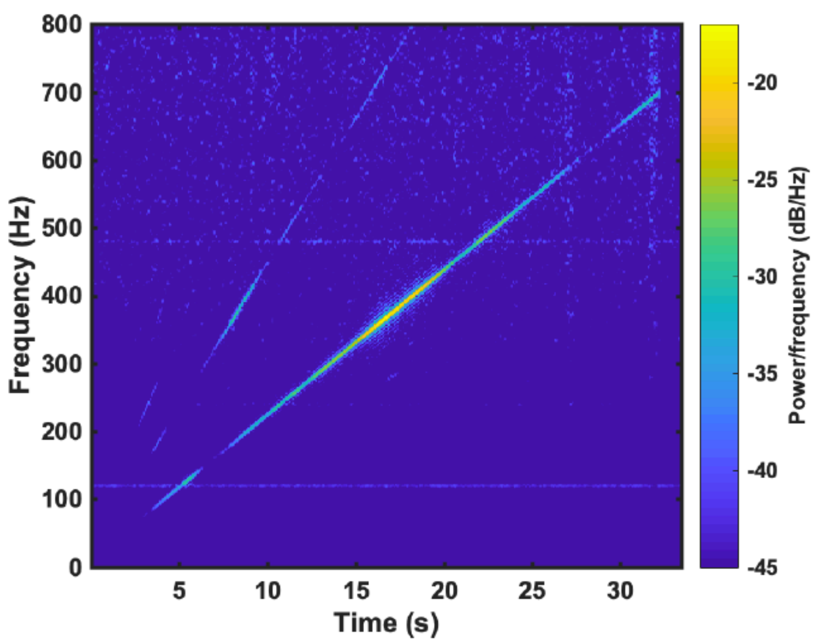
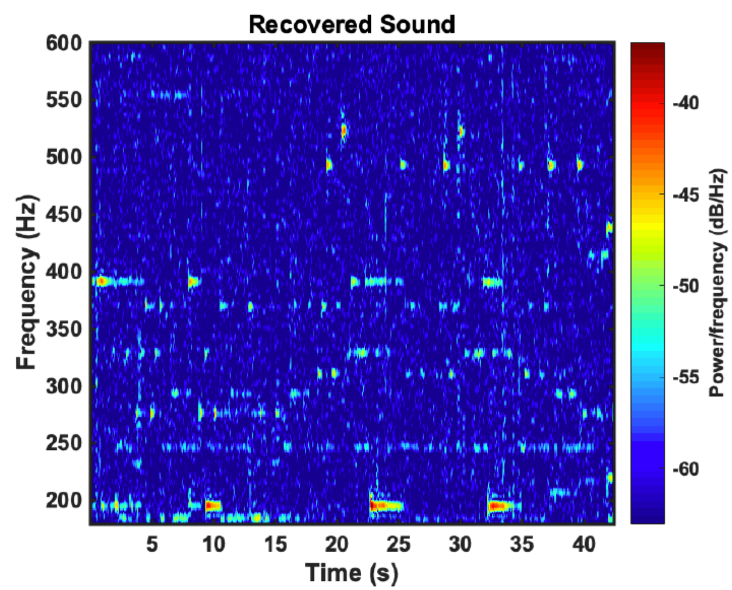
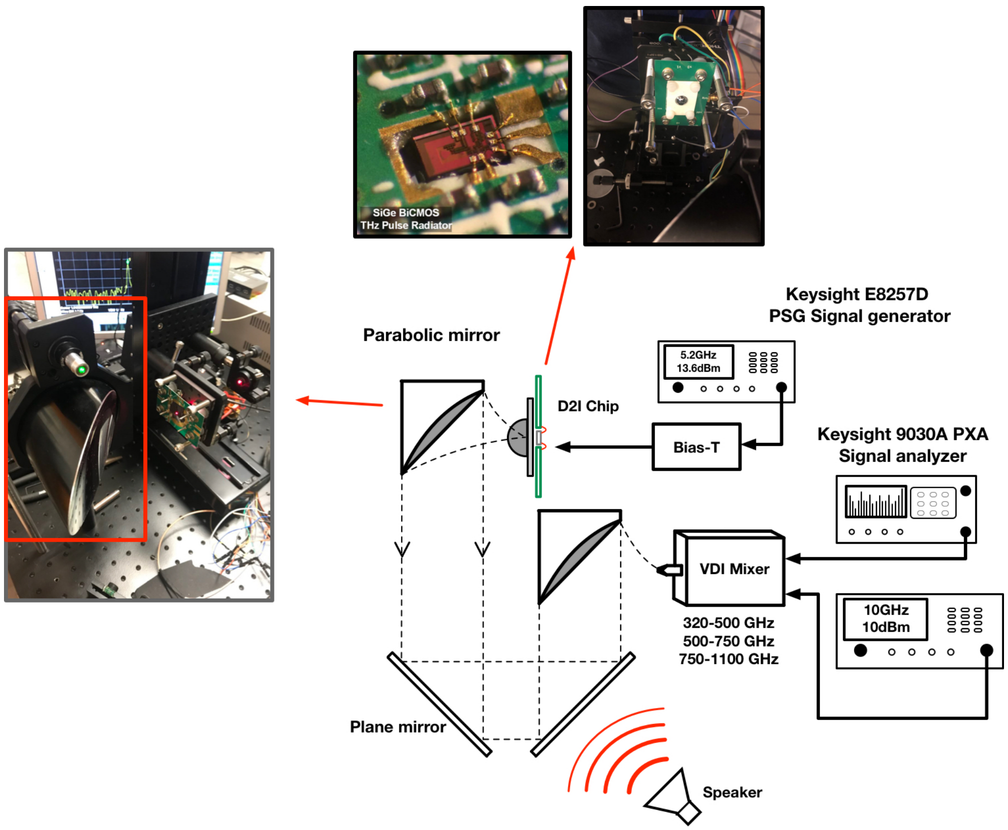




Vibration Sensing and Micro-Doppler

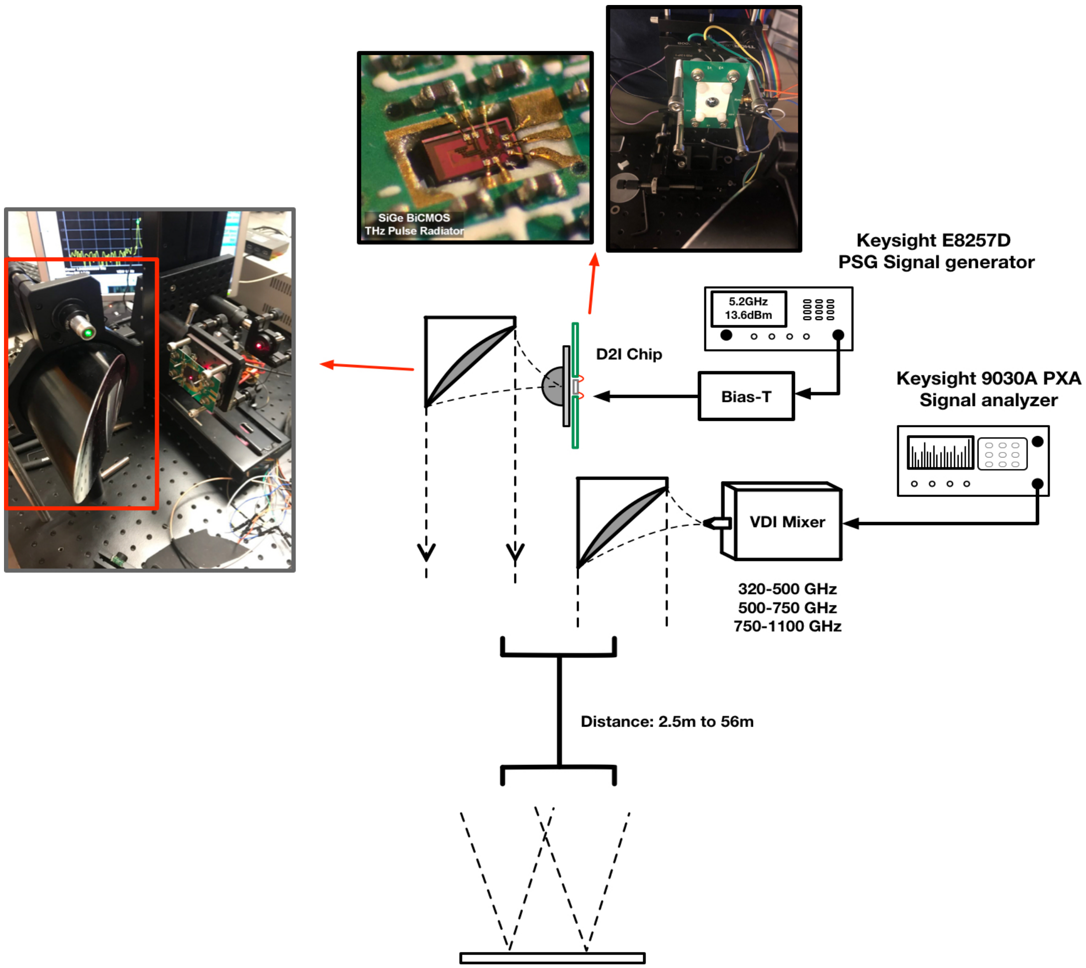


Sound wave chirp
50Hz to 700Hz

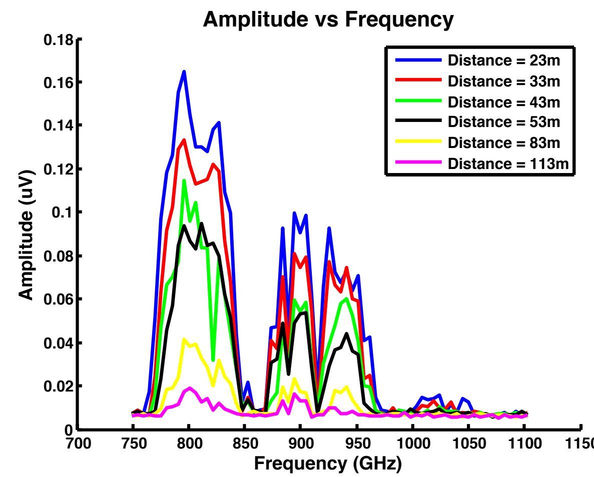
Piano notes

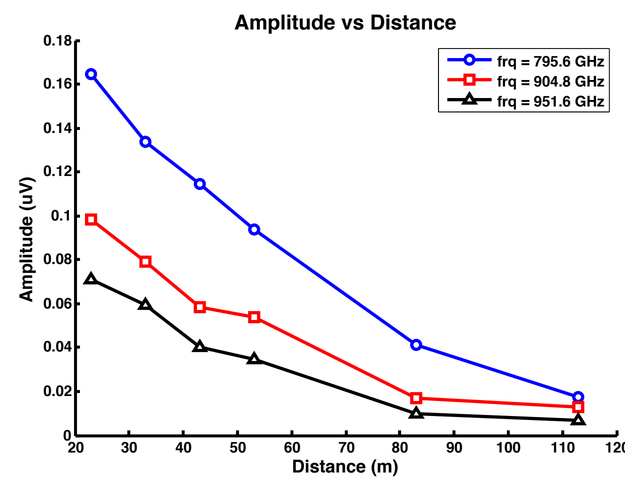
Key Enabler: Ultra-stable THz Tone Generation and Detection
2Hz line-width at 1.1THz, 2ppt!

Long Distance Propagation of THz Pulses



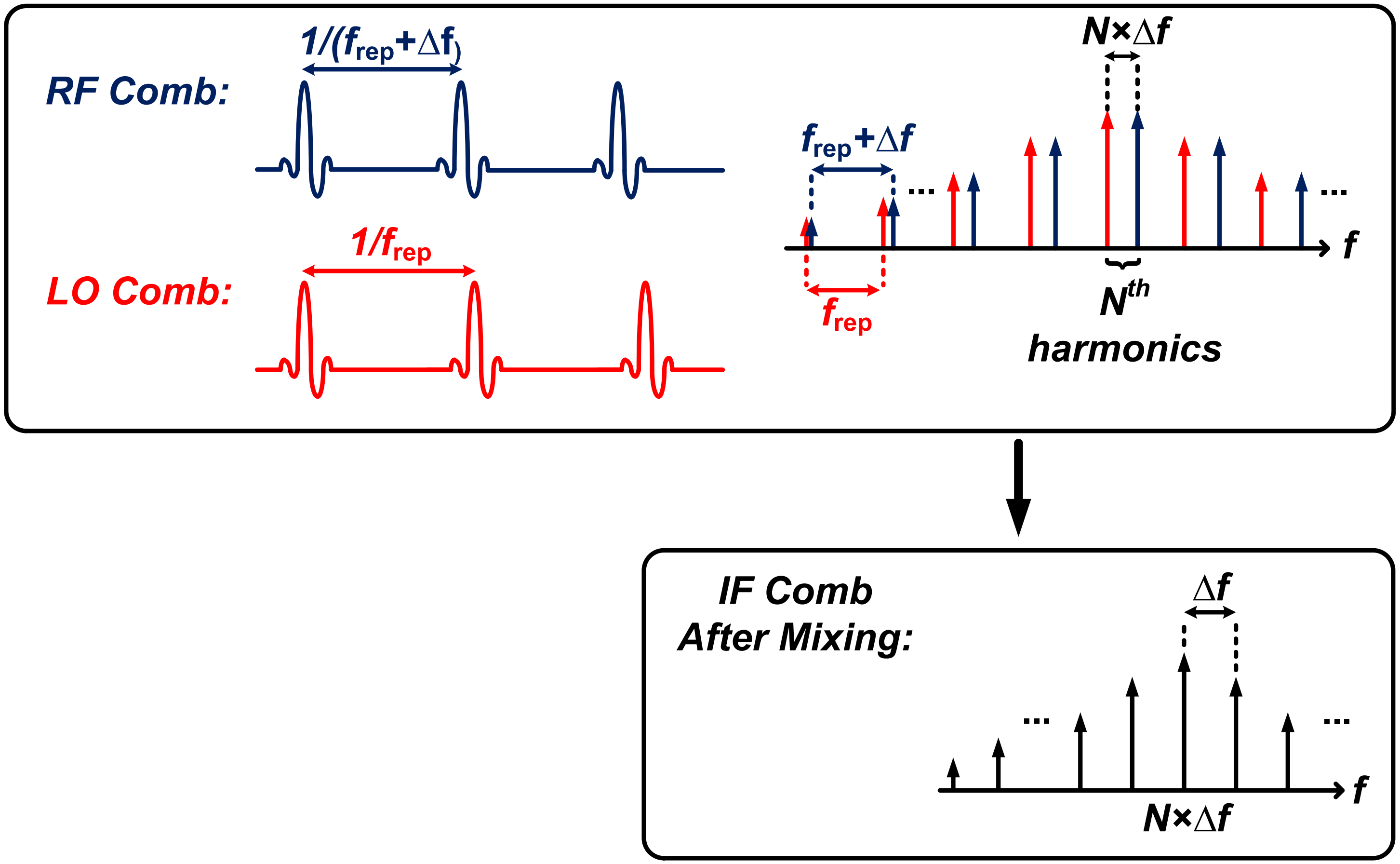
750-1100 GHz





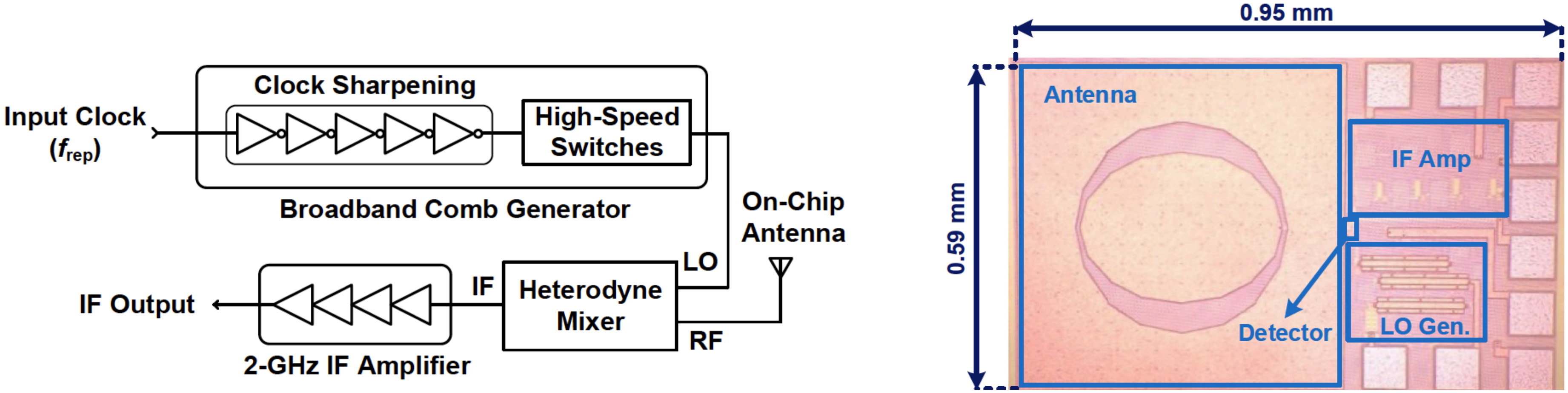
We have measured up to a distance of 112m at 1.1THz

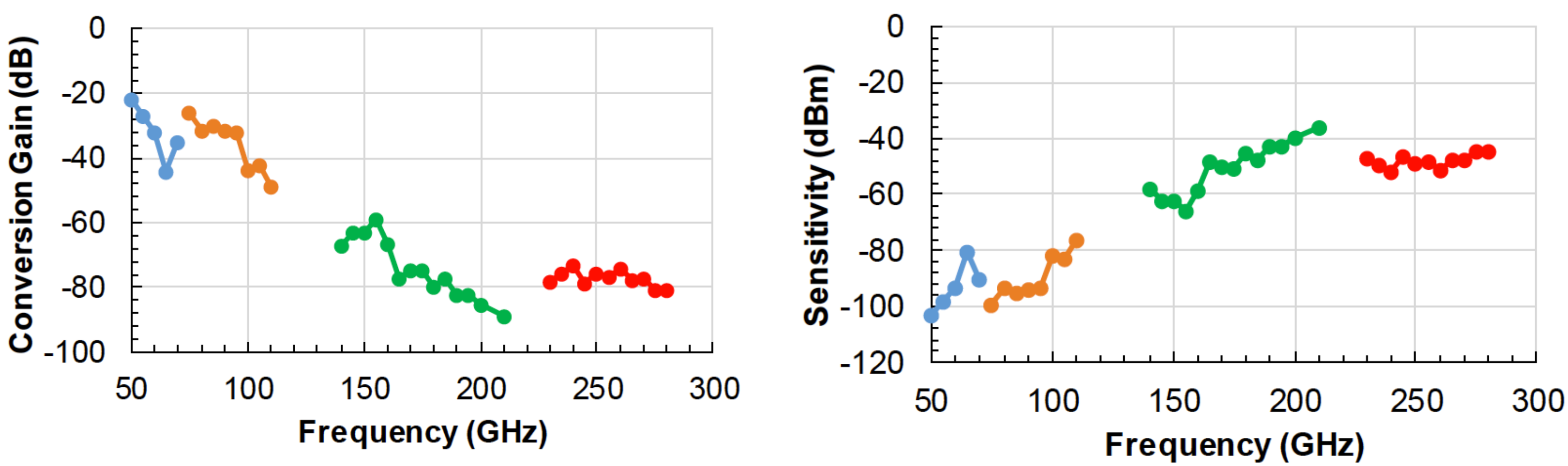
Broadband Dual-Comb Spectroscopy



- Slight difference between RF and LO repetition rates
- Compressing the signal down to low frequencies

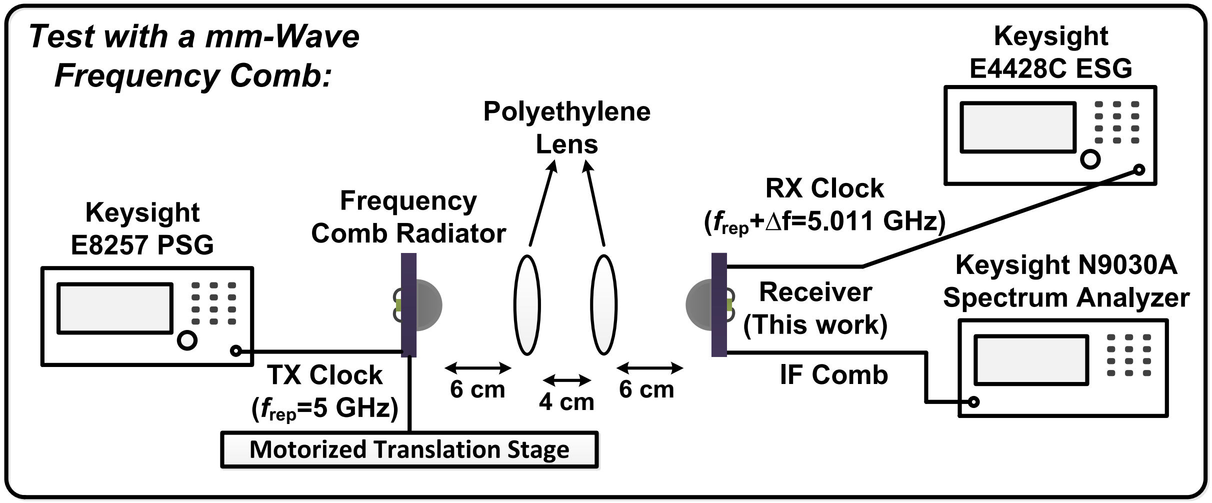
Broadband Comb Detector

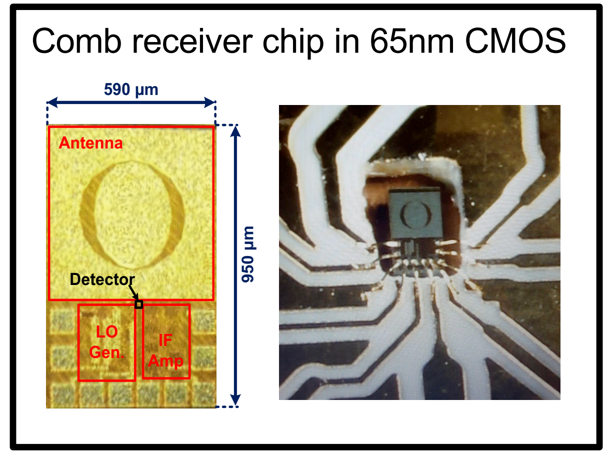


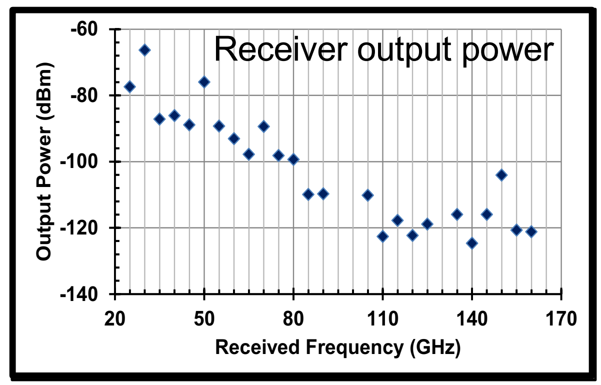


- Fabricated in TSMC 65nm CMOS process
- Die area = $0.56mm^2$, P_{dc} = 34mW

Dual Comb Experimental Setup



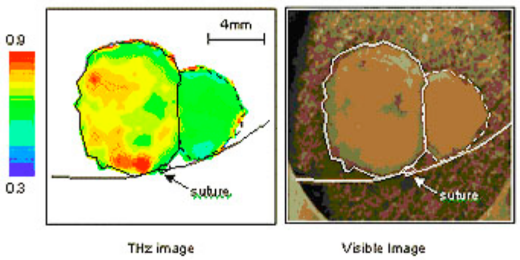


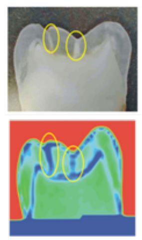


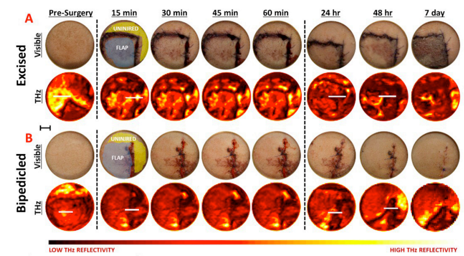
- Broadband 50-280GHz detection with 2Hz line-width is done with a low-power receiver chip (34mW)
- Combination of the TX and RX chips can be used as a broadband scalar network analyzer (imagine a sub-$1k network analyzer that covers 50-280GHz)

Future Directions

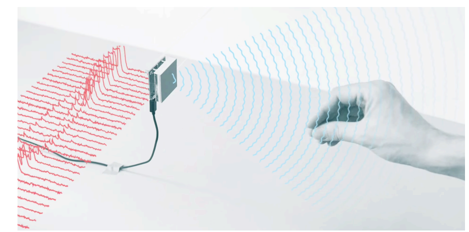
Medical Imaging and Spectroscopy



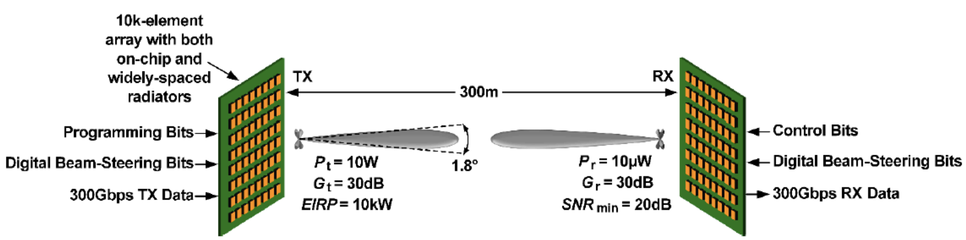




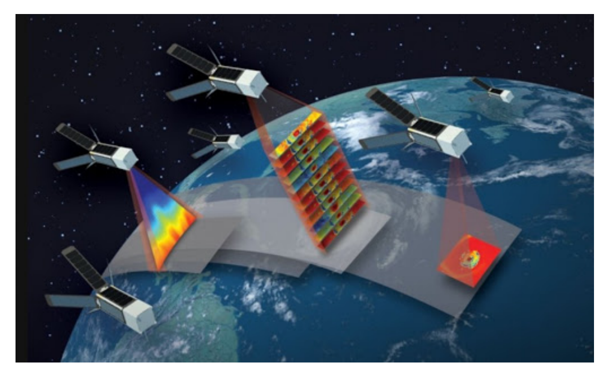
Gesture Recognition and Micro-Doppler



1Tbits/sec Wireless Communication over 100m



Broadband Remote Sensing of Materials, Objects, and Vibrations



Thank You