WMD:
Technologies for Terahertz Science

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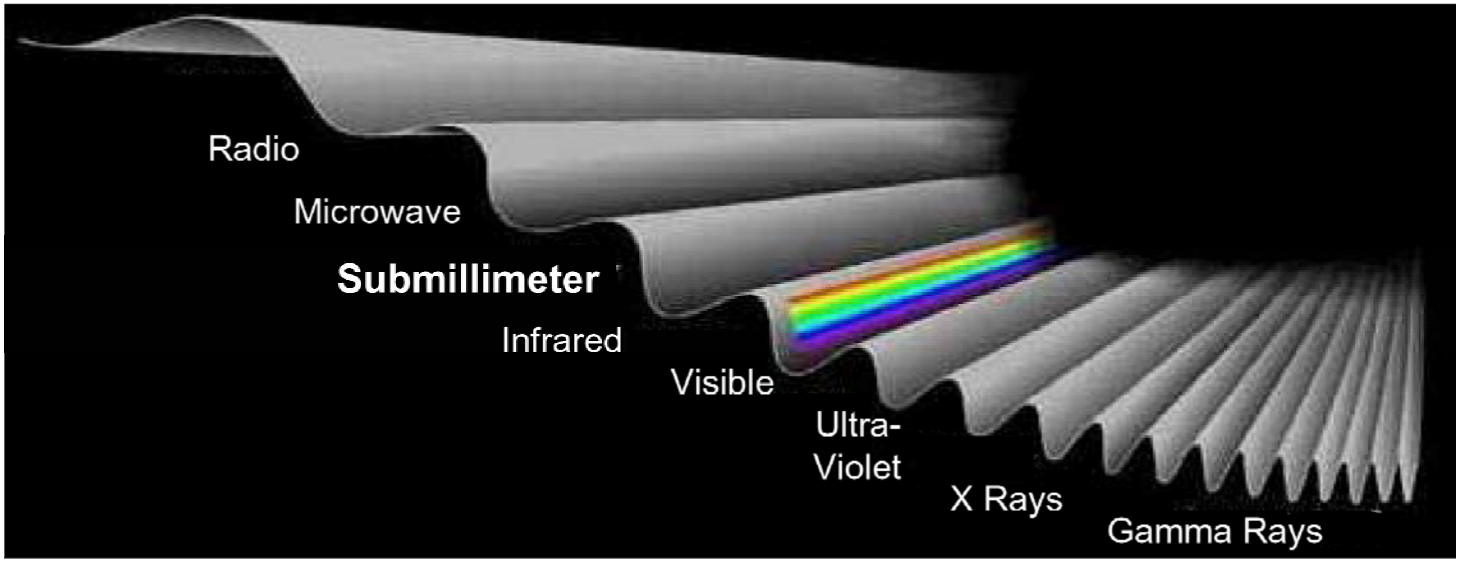
Terahertz (Submillimeter) Waves

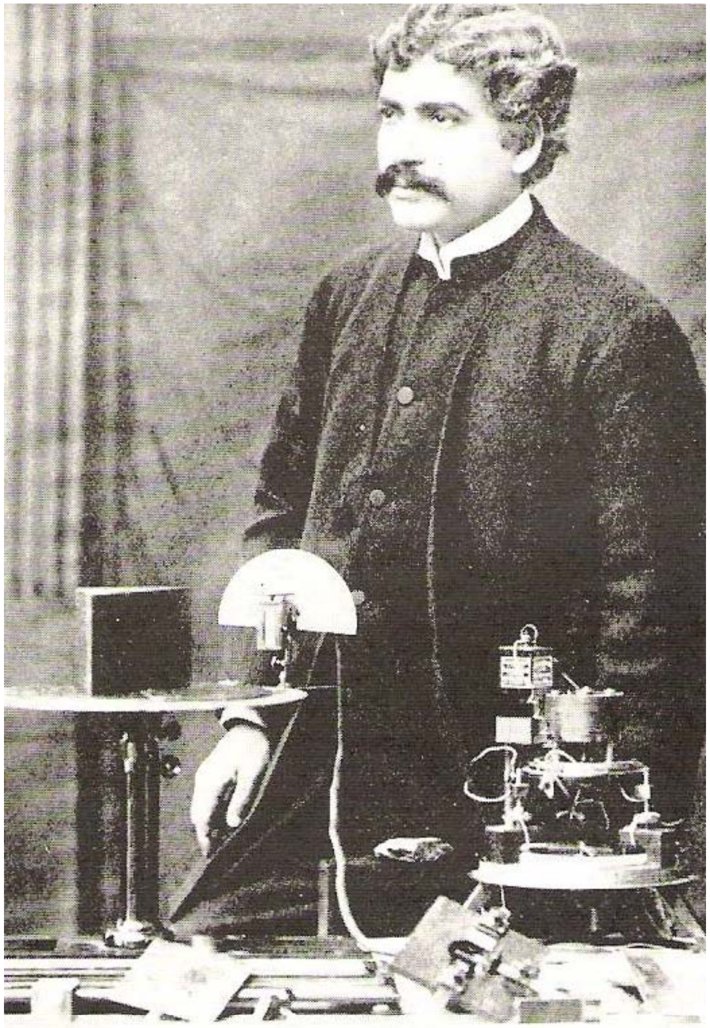


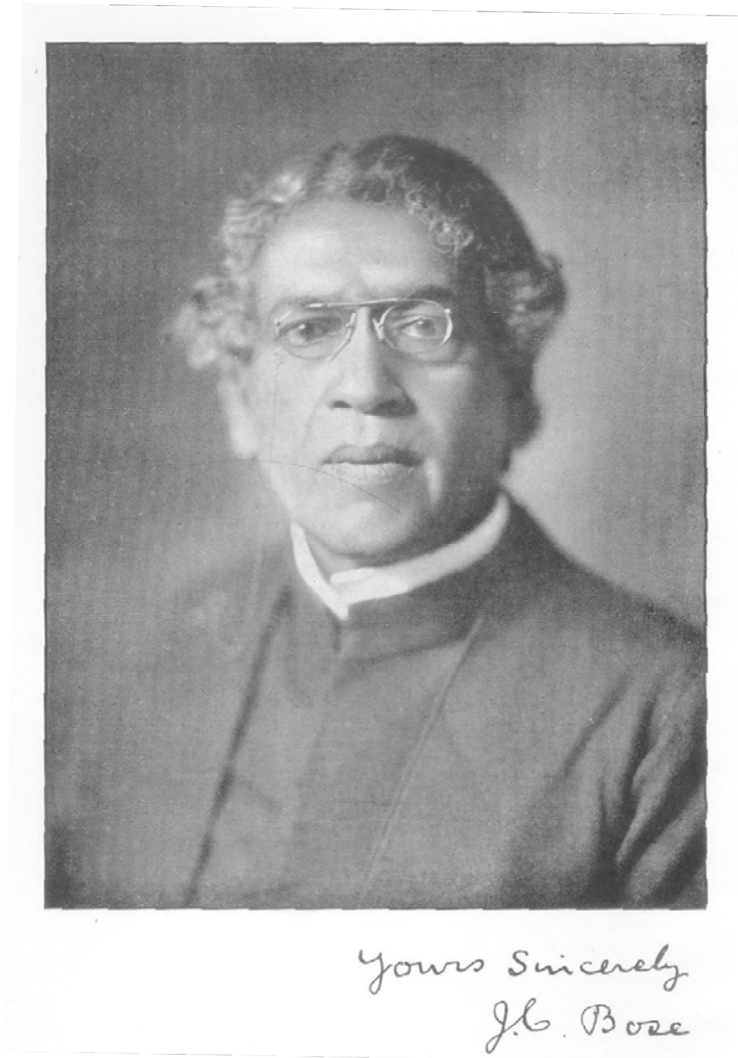
Loosely defined: 1 mm > λ > 100 μm

300 GHz < ν < 3 THz

Most of the radiation in the Universe is emitted at submillimeter-wavelengths, peaking at 3 THz (if we exclude Cosmic Microwave Background).

Prof. Bose and Terahertz



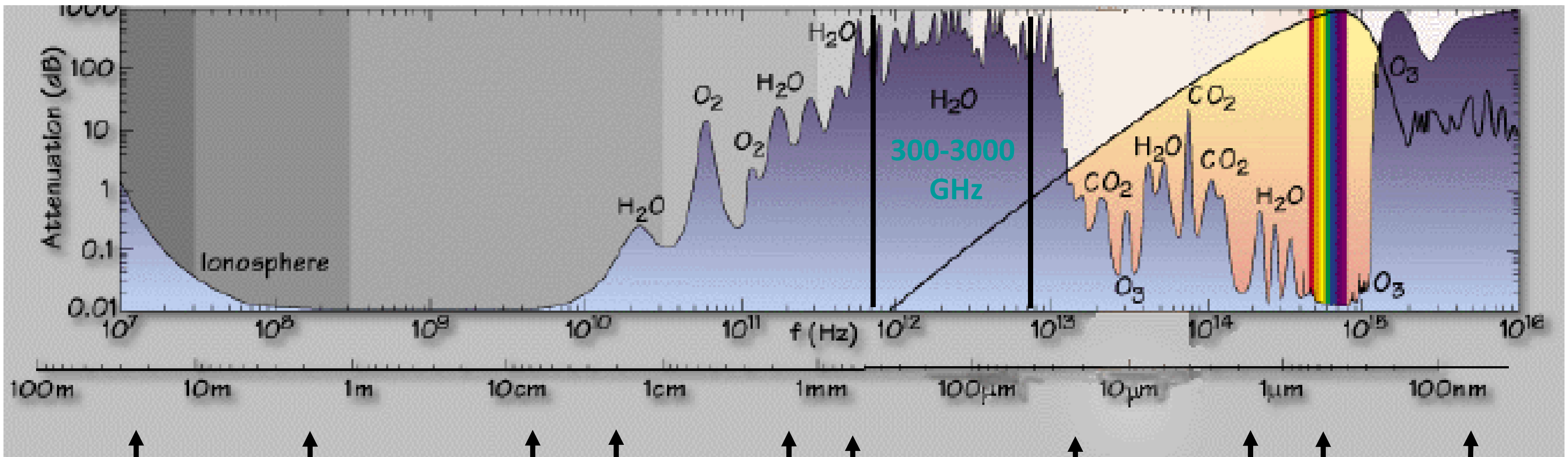


Prof. J. C. Bose laid the foundation of Terahertz Technology

Terahertz and Atmospheric Transmission

NASA is interested in the THz band. Strong water and oxygen absorption in the atmosphere make high altitude platforms essential for good seeing.

HF VHF Microwaves mm-Waves THz Infrared Vis UV



Ionosphere Opaque

Radio Window

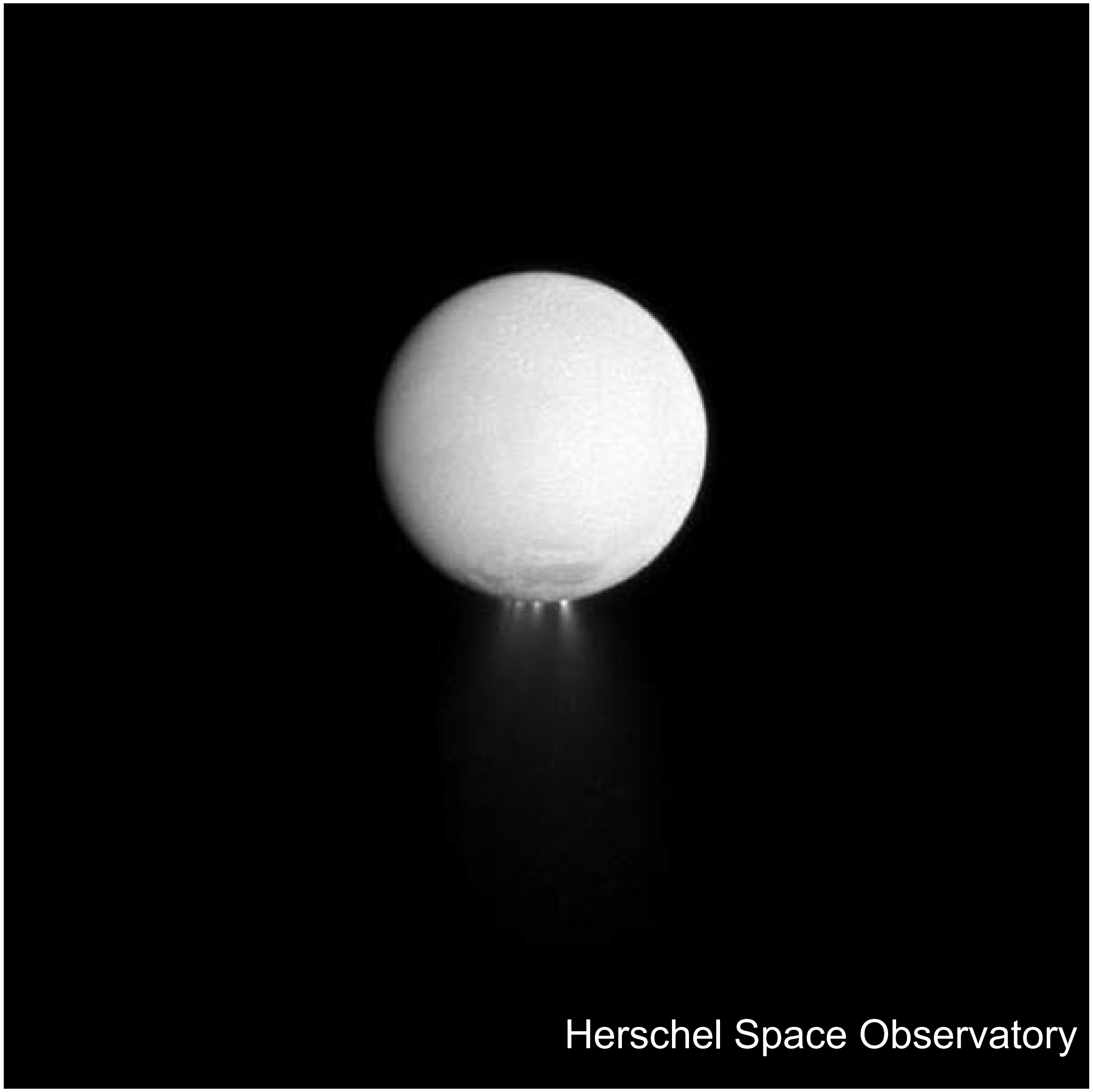
Mountain top Transmission Acceptable

Atmosphere Opaque

IR & Optical Windows

Atmosphere Opaque

Terahertz Science: Planetary Bodies



Saturn’s moon Enceladus rains down water on Saturn!

Now we know where the water vapor in Saturn’s upper atmosphere come from!

Enceladus is the only moon in the Solar System known to influence the chemical composition of its parent planet.

Terahertz Science: Oxygen Molecule

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2 August 2011 Last updated at 10:53 ET

1,171 Share

Oxygen finally spotted in space

"Hidden" oxygen may be released from dust grains and ice in star-forming regions

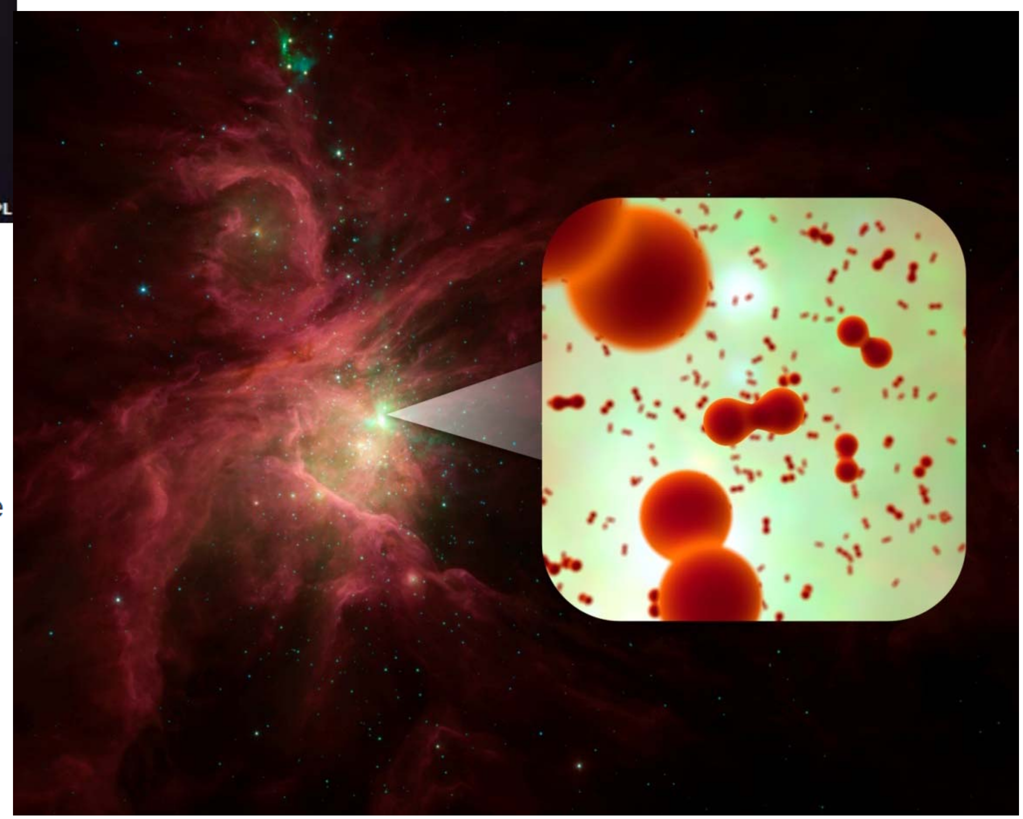
One of astronomy's longest-running "missing persons" investigations has concluded: astronomers have found molecular oxygen in space.

While single atoms of oxygen have been found alone or incorporated into other molecules, the oxygen molecule - the one we breathe - had never been seen.

The Herschel space telescope spotted the molecules in a star-forming region in the constellation of Orion.

Ref: Paul Goldsmith et. al.,

Herschel Space Observatory's HIFI Instrument



Terahertz Science: Water

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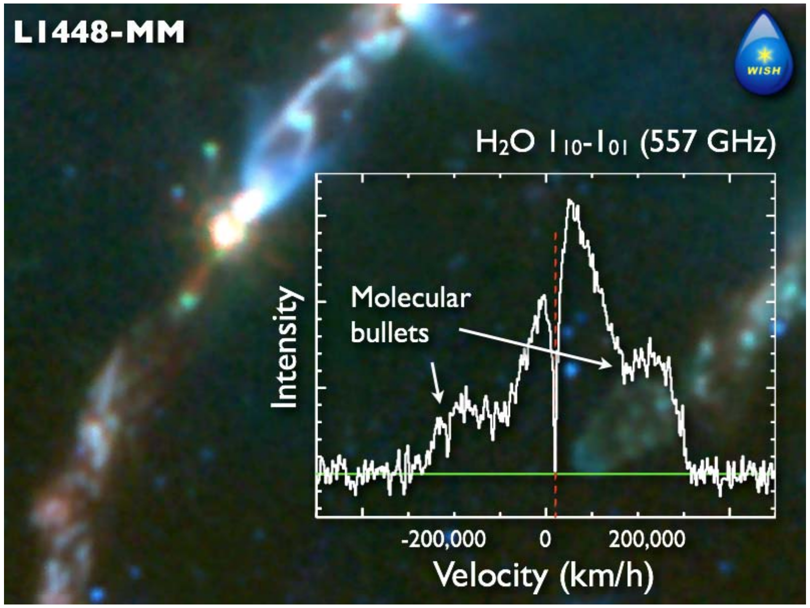
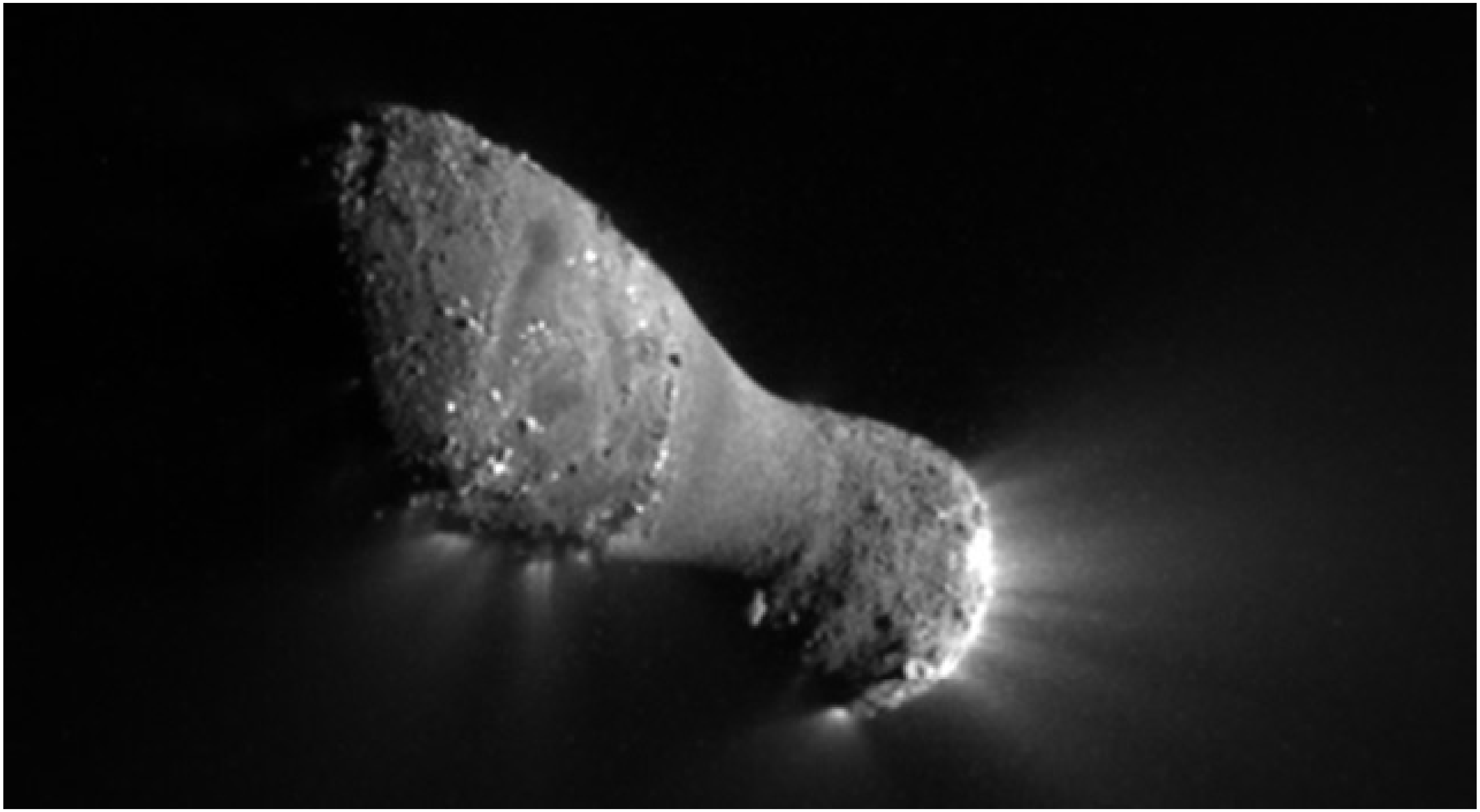


In a young Sun-like star reveal high-velocity "bullets" moving at more than 200,000 km/h from the star. Velocity of a bullet from an AK47 rifle is 2500 km/h or 80 times slower. This high velocity is surprising - they should have been destroyed in the shock where temperatures exceed 100,000 degrees.

Water very likely reforms rapidly in the hot and dense shocked gas. The conditions are so favorable that approximately 100 million times the amount of water in the Amazon river is formed, every second!

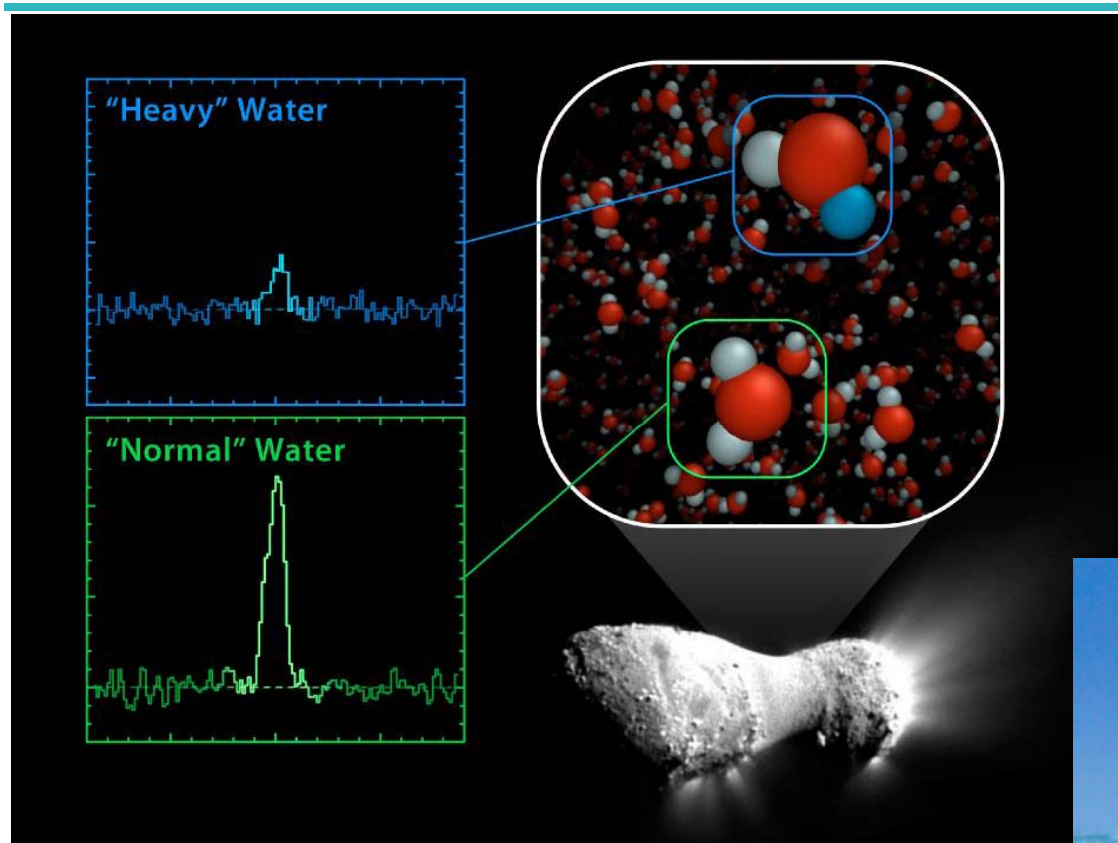
Terahertz Science: Comets



Hertley 2 Comet: EPOXI Satellite from 700 km distance, 2 km long; Nov. 4th 2010.

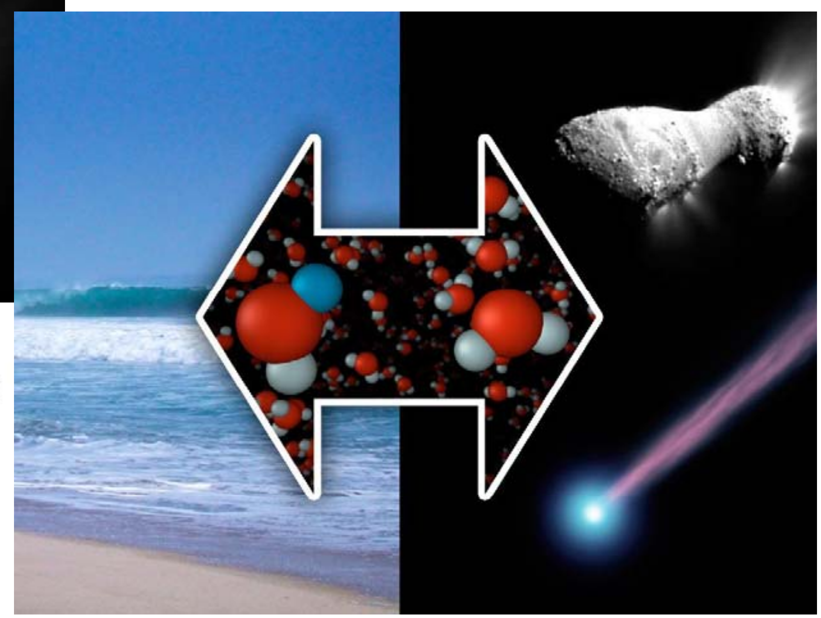
Terahertz Science: Comets

RFIC 2013



Herschel Space Observatory's HIFI Instrument (JPL).

"Earth's water may have come from comets!"



LETTER

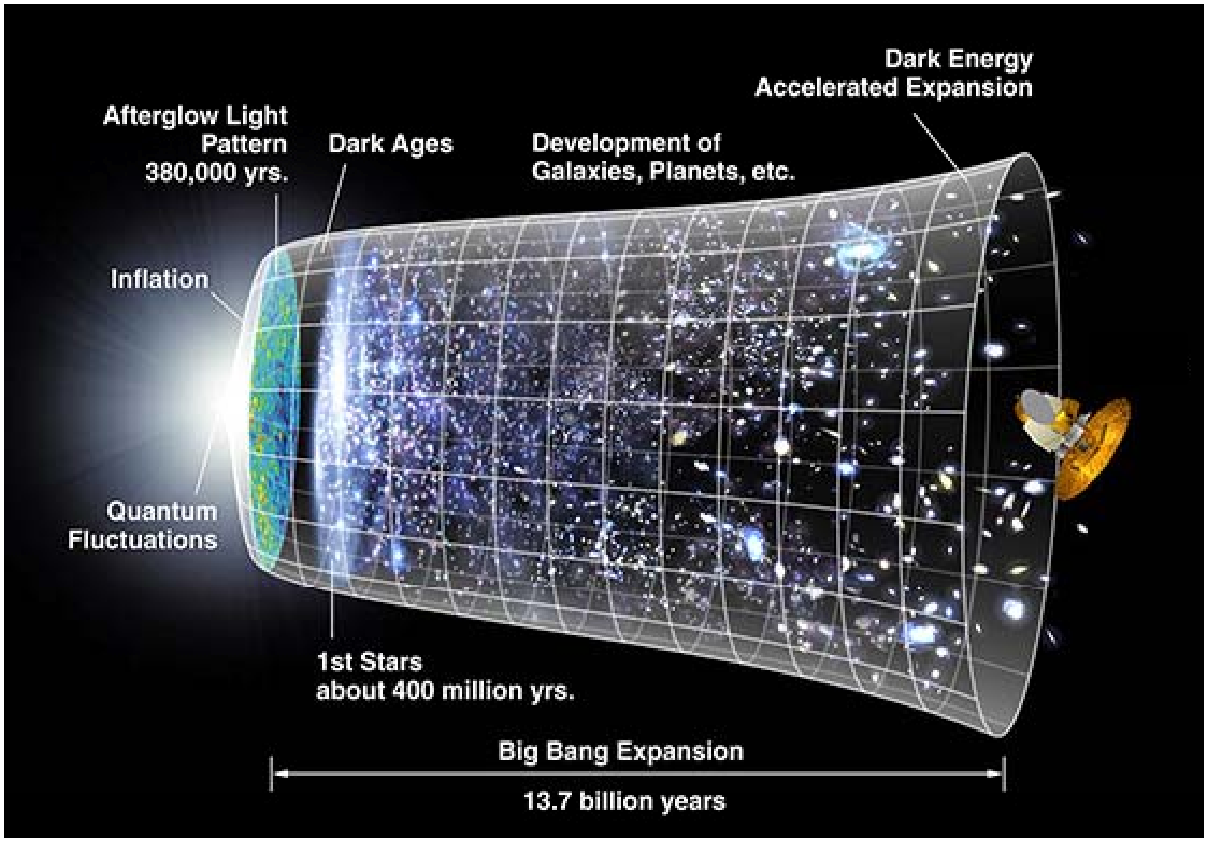
Nature, October 2011

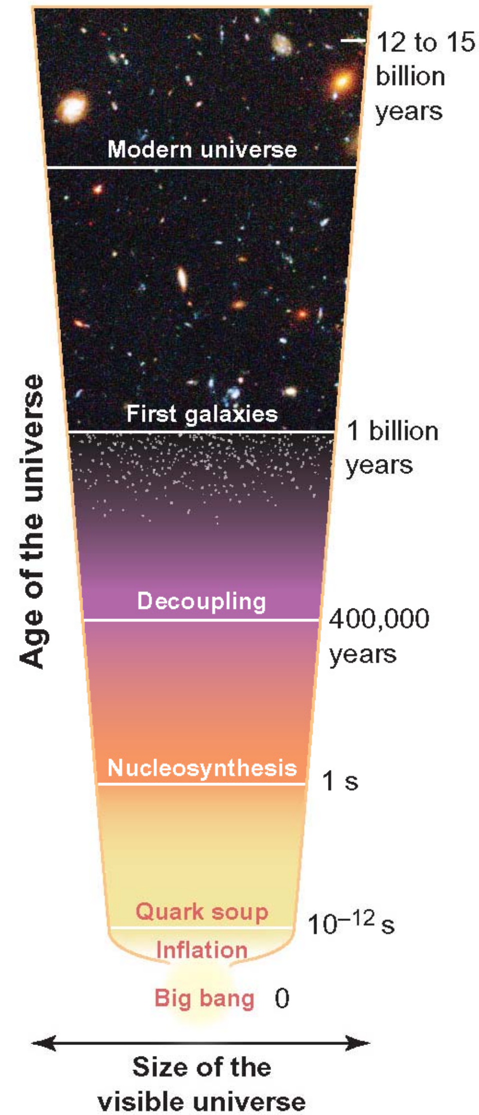
doi:10.1038/nature10519

Ocean-like water in the Jupiter-family comet 103P/Hartley 2

Paul Hartogh[1], Dariusz C. Lis[2], Dominique Bockelée-Morvan[3], Miguel de Val-Borro[1], Nicolas Biver[3], Michael Küppers[4], Martin Emprechtinger[2], Edwin A. Bergin[5], Jacques Crovisier[3], Miriam Rengel[1], Raphael Moreno[3], Slawomira Szutowicz[6] & Geoffrey A. Blake[2]

Terahertz Science: Big Bang





History of our Universe: Started with a Big Bang, and here we are, after 14 billion years!

Terahertz Science: Big Bang

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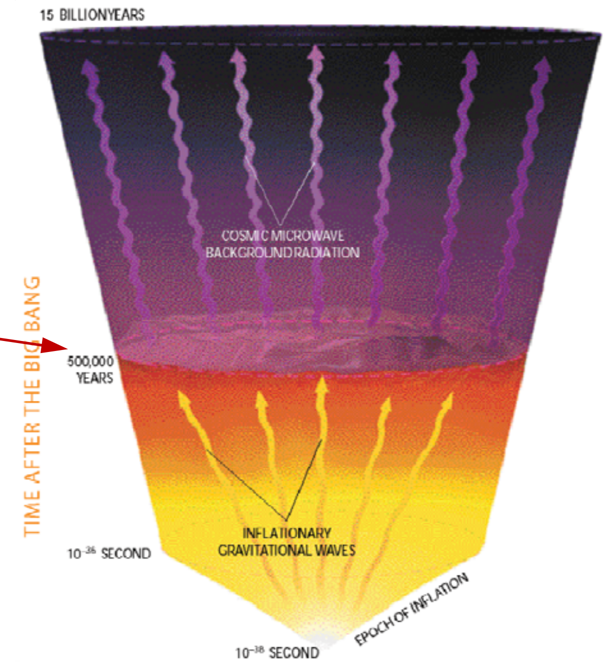
Cosmic Microwave Background (CMB):

Cooled radiation (2.7K) that permeated the Universe for 15 billion years.

CMB was emitted 400,000 years after Big Bang, when H-atoms were formed.

The most of the CMB radiation is in the 1-5 mm (peaking at 2 mm) wavelengths.

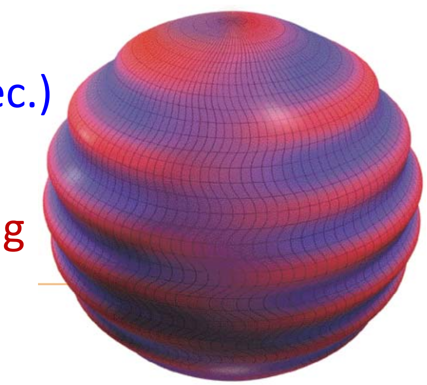
The primordial plasma was opaque to EM radiation – any emitted photons were scattered by the subatomic particles.



Traces of gravitational waves in the CMB:

Rapid expansion of the universe immediately after the Big Bang (10^{-38} sec.) should have produced gravitational waves.

They would have stretched and squeezed the primordial plasma, inducing motions in the spherical surface that emitted the CMB radiation. These motions would have caused red-shifts and blue- shifts in the **radiation temperature and polarized the CMB.**



Terahertz Science: Icy Cold Planets

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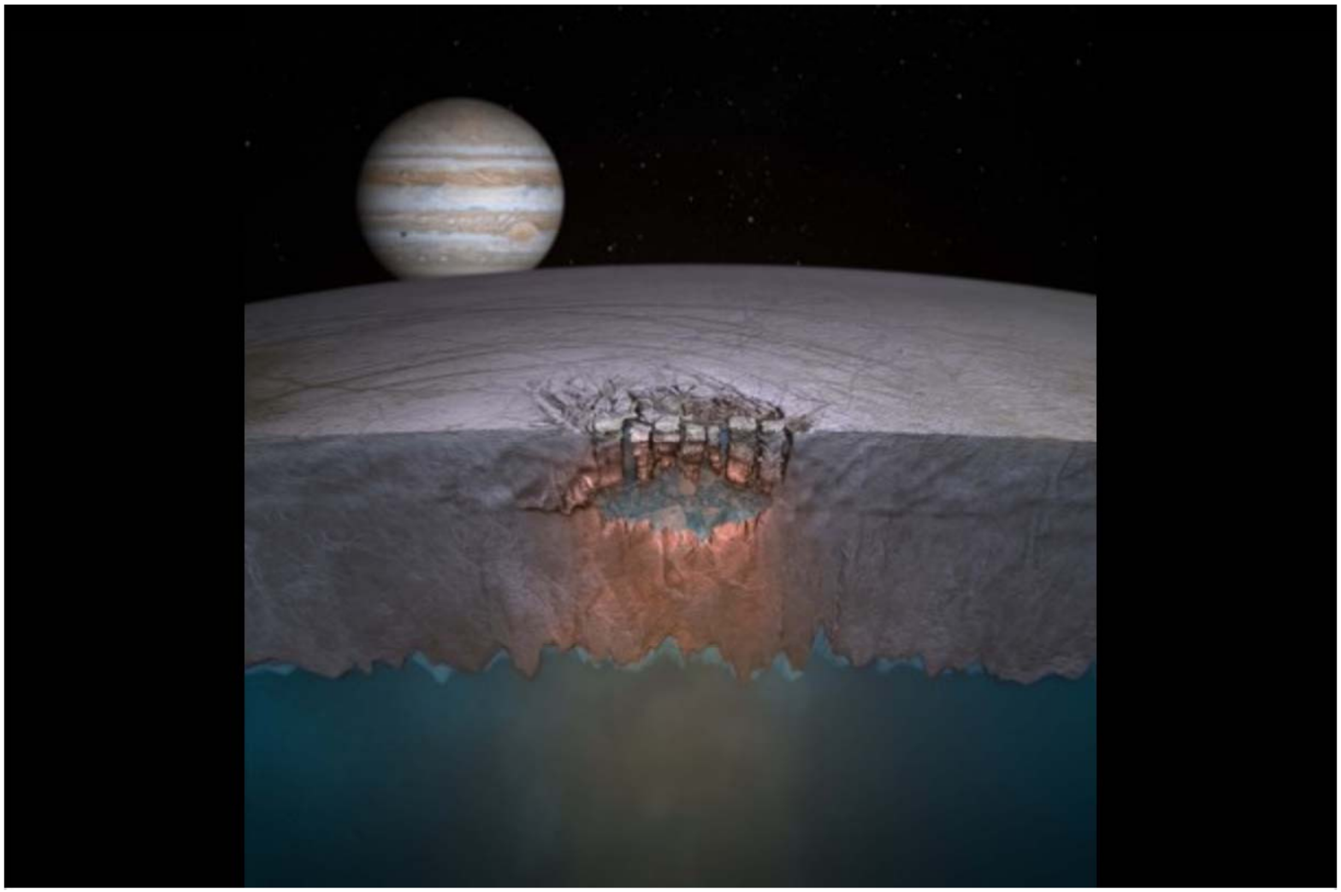
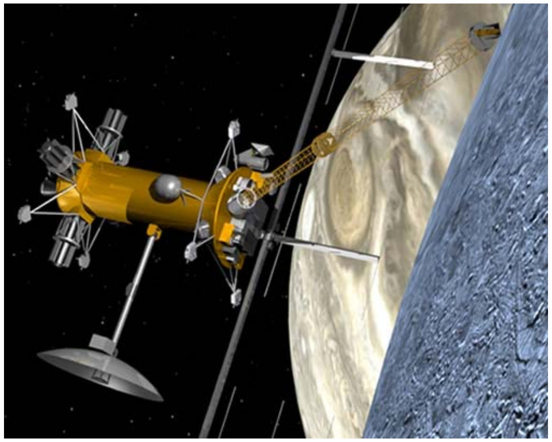
Jupiter's moon Europa: Lake theory boosts hopes for life

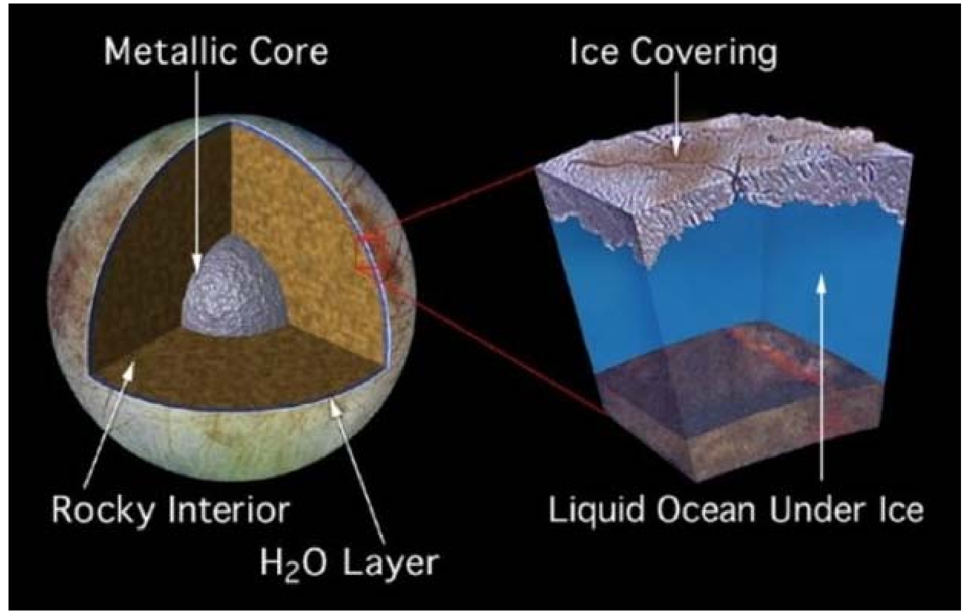


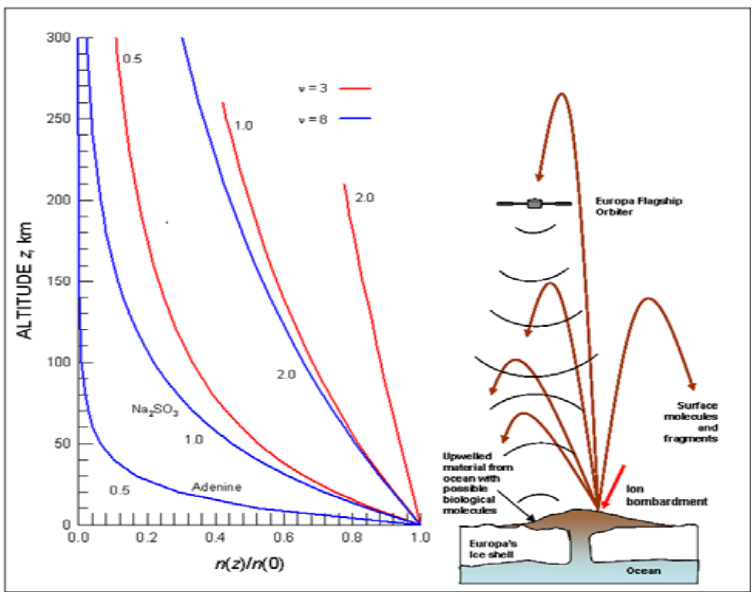
"Europa has the best chance of having life there today," said Britney Schmidt, who studies the moon at the University of Texas at Austin and led the new study appearing in the journal Nature.

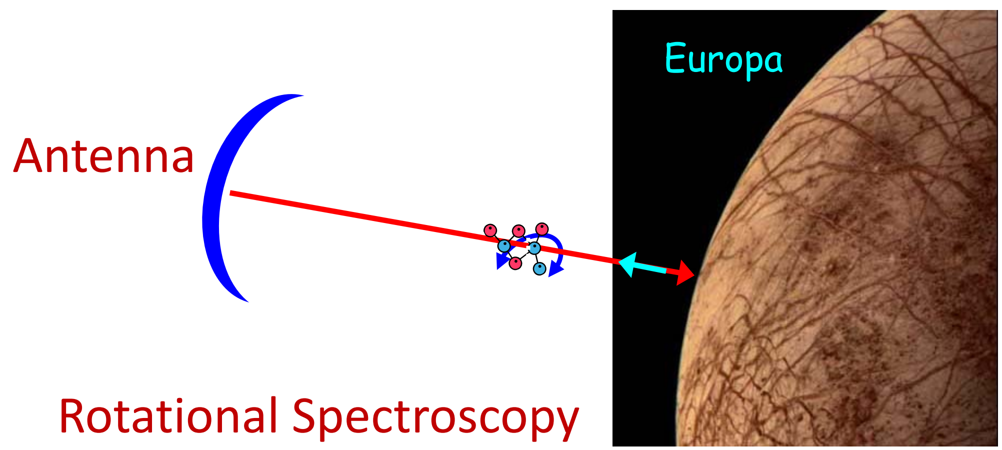
November 16, 2011, Washington Post. Paper in Nature.

Terahertz Science: Icy Cold Planets









Terahertz Science: Very Hot Planets

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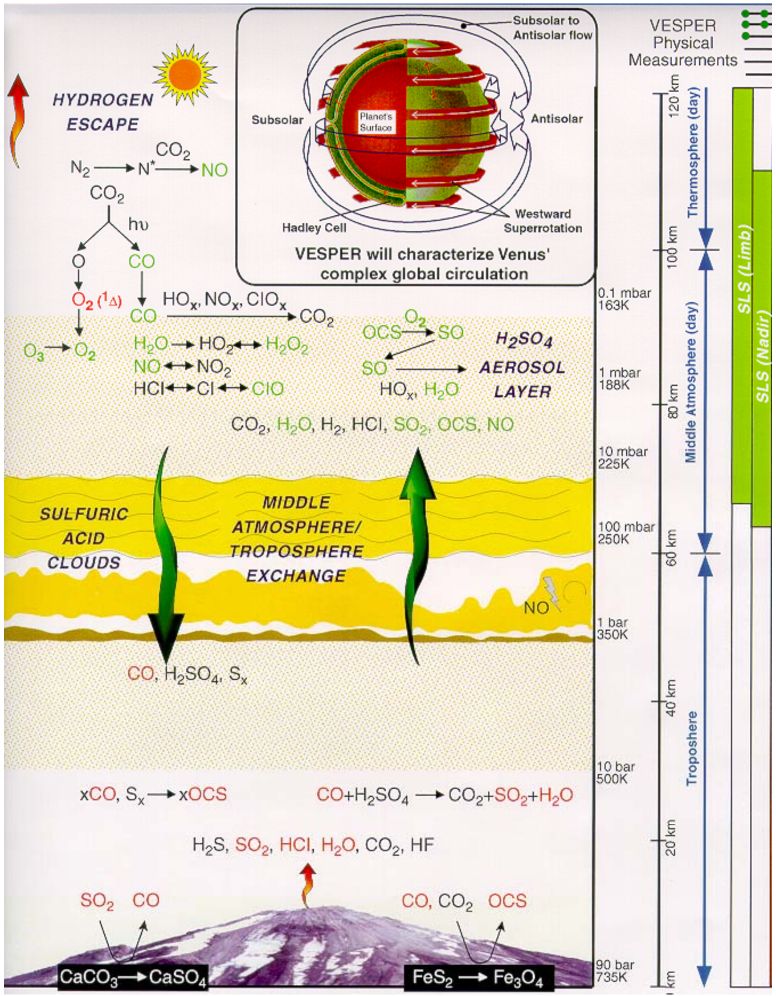
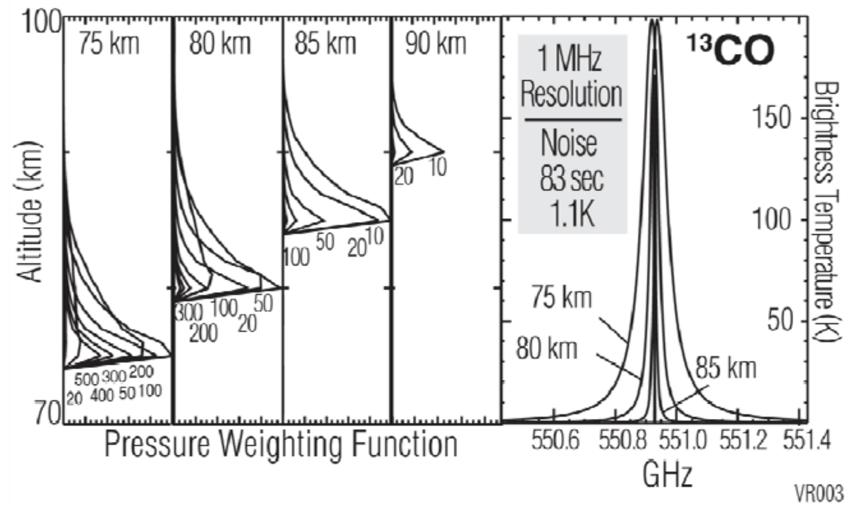


Potential Mission to Venus:
Spectroscopy on a very hot planet.



VENUS: 470° C and 97 Bars

Terahertz Science: Climate Change

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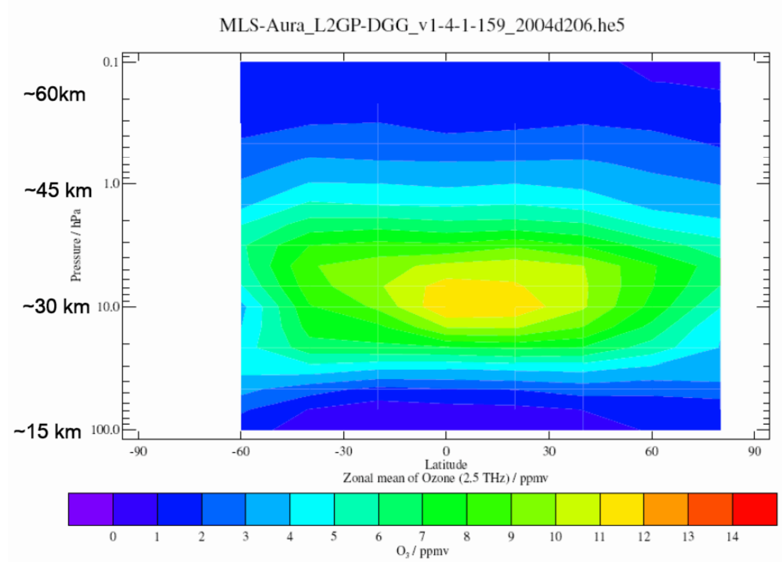
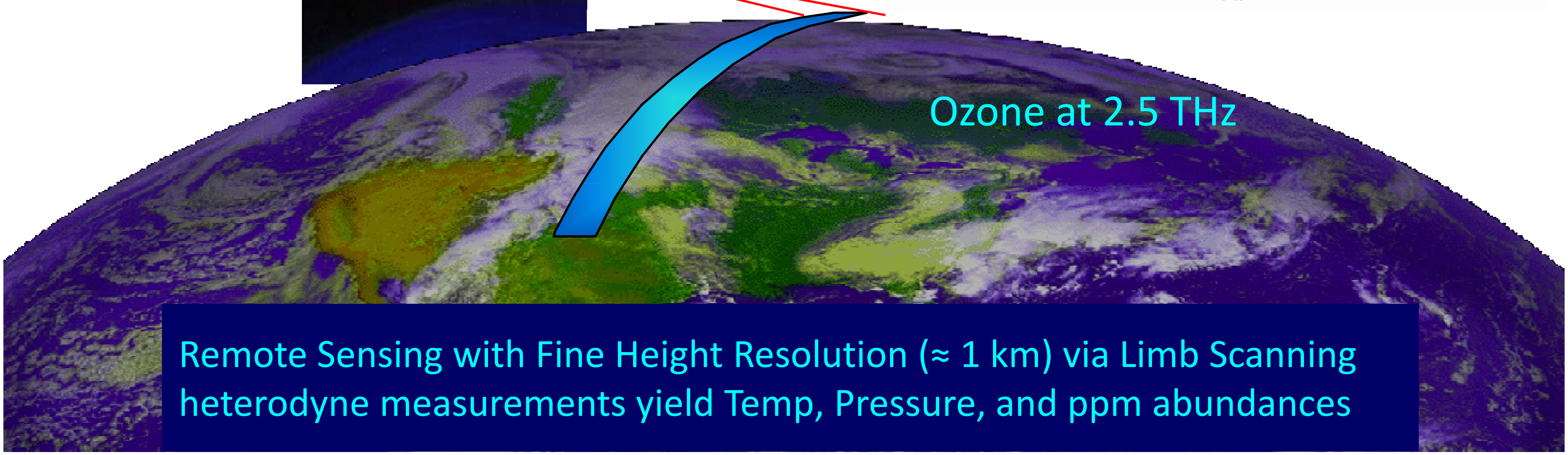
- Stratospheric and Tropospheric Chemistry
  - ozone layer modeling
  - economics vs. environment
  - water distribution/pollutants
- Clouds: Global Warming
  - ice crystal: size & distribution
- Aerosols, Volcanism, Dust

Our first 2.5 THz O_3 retrievals

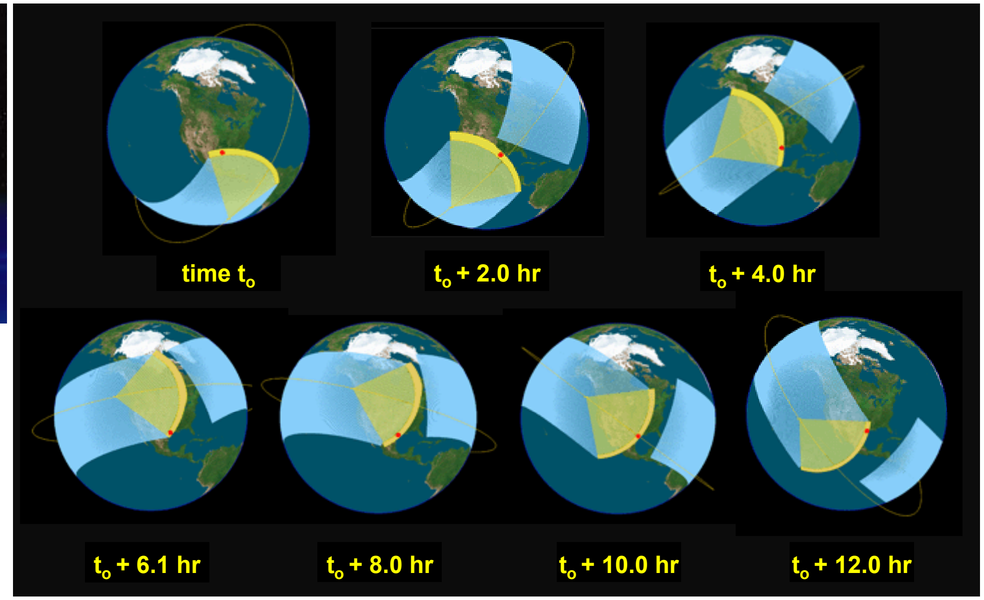




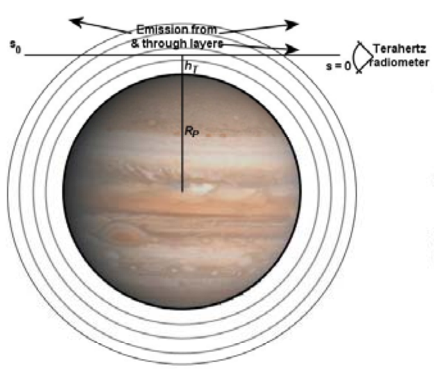
Remote Sensing with Fine Height Resolution (≈ 1 km) via Limb Scanning heterodyne measurements yield Temp, Pressure, and ppm abundances

Terahertz Science: Climate Change

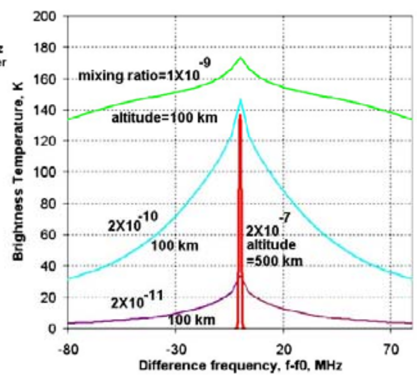
Microwave Limb Sounder (MLS):



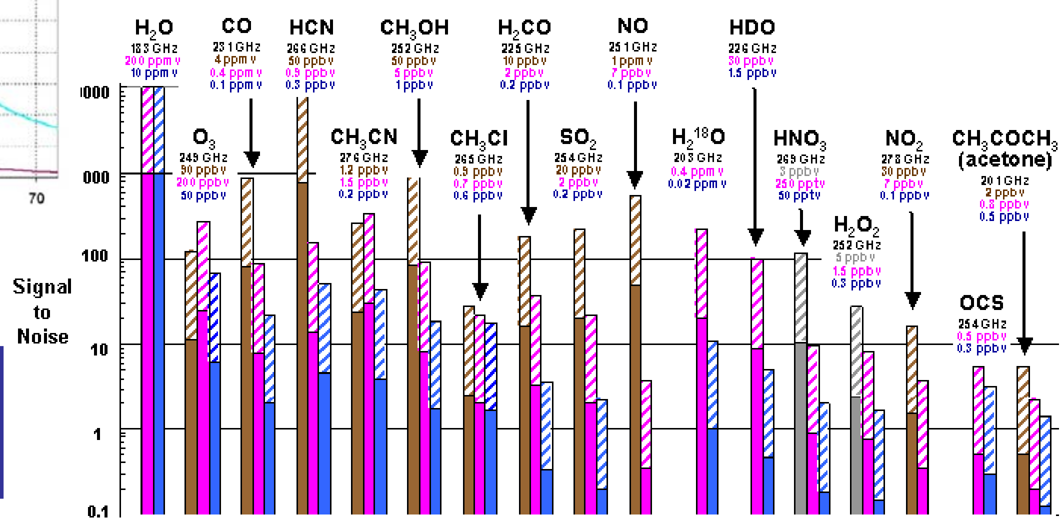
150-300 GHz,
600 GHz, 2500 GHz sensors



(a)



(b)



Atmospheric Chemistry, Air Pollution, and Global Monitoring

Terahertz Technology: Mars Landing

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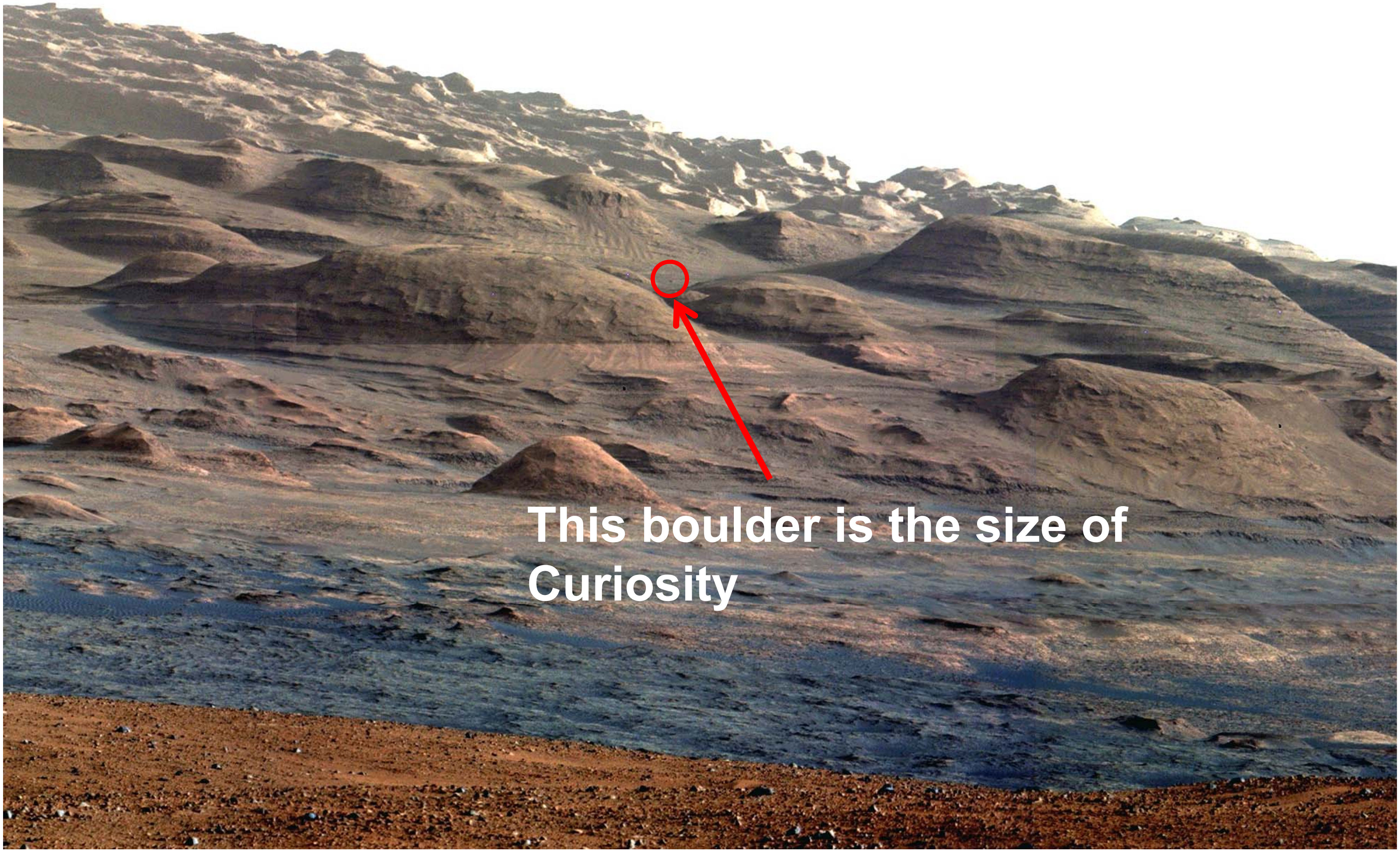
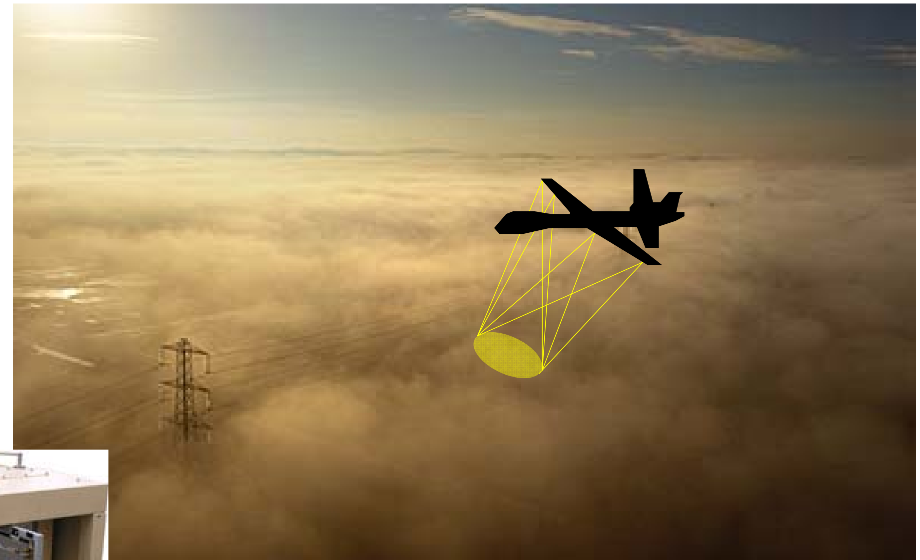
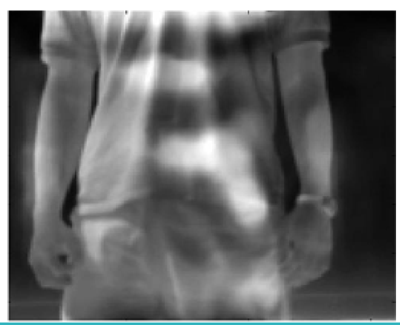
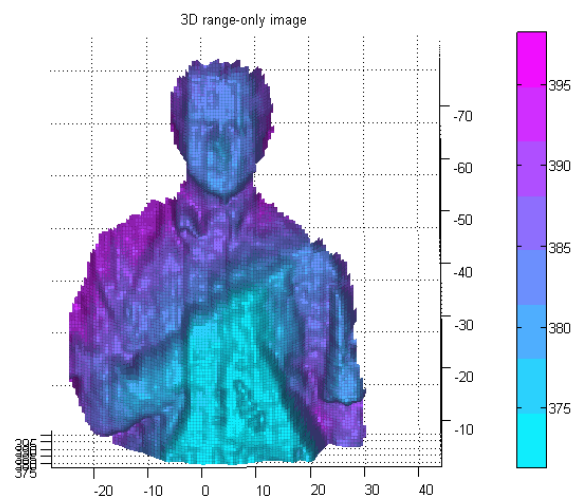


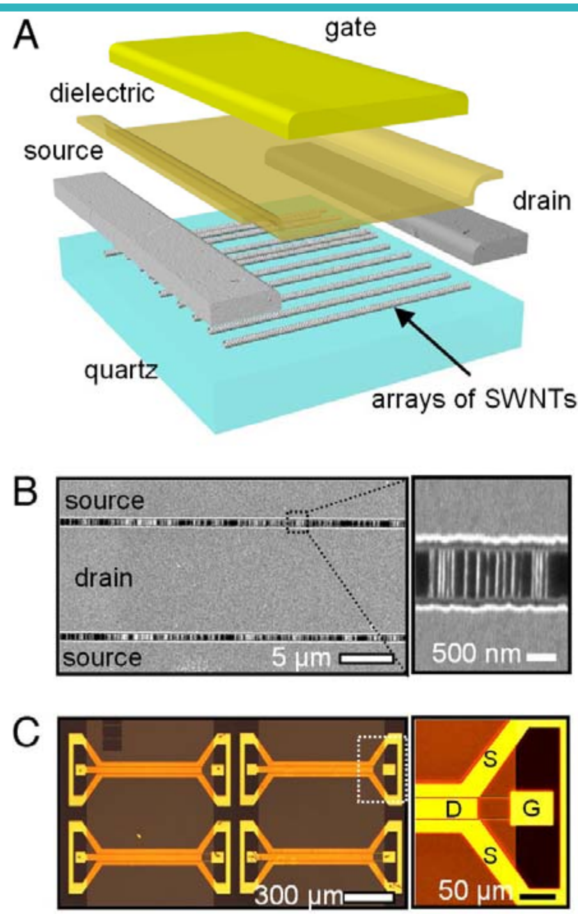
Terahertz Technology: Security

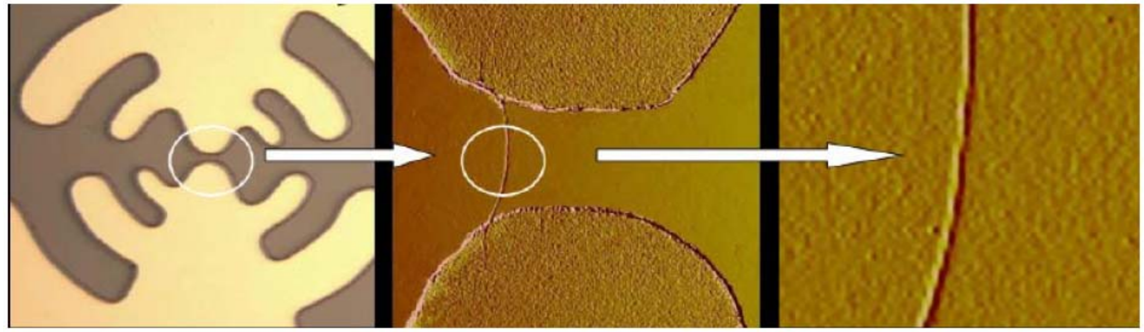


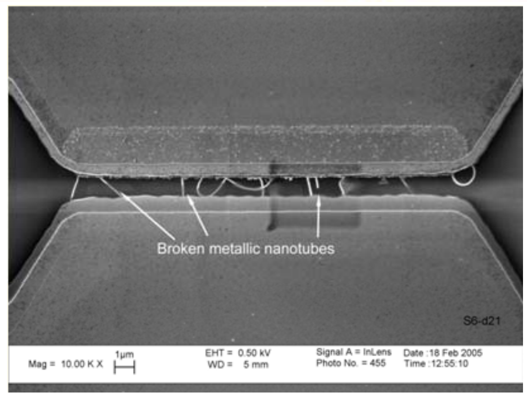


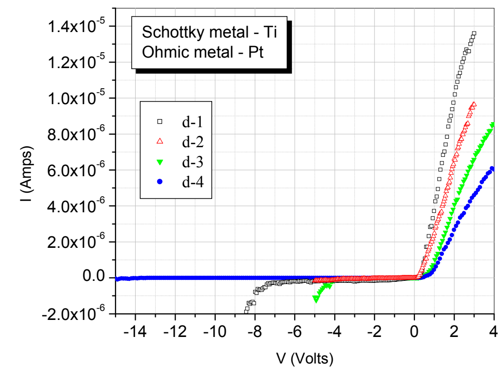


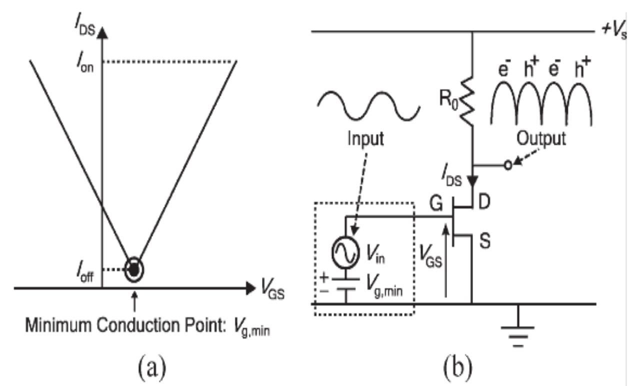
Nanotechnology and Terahertz

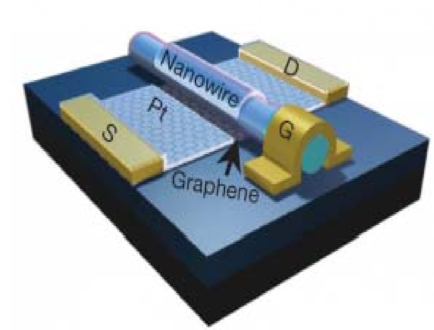








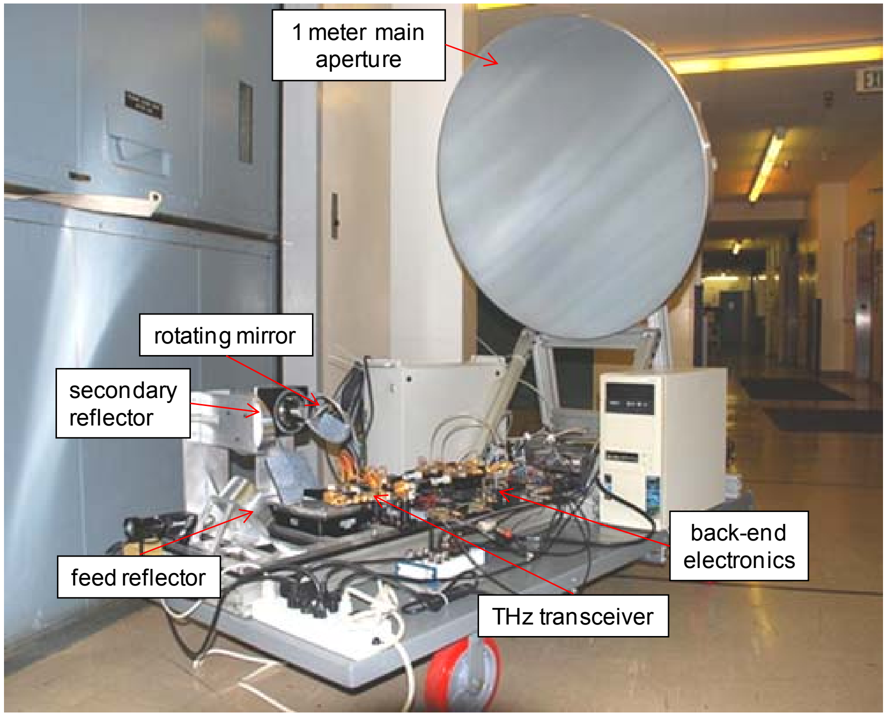




E. Cubukcu, et al.,"Aligned Carbon Nanotubes as Polarization-Sensitive, Molecular near-Field Detectors," Proceedings of the National Academy of Sciences of the United States of America, 106, 2495-2499, (2009).

K. S. Yngvesson, "Very wide bandwidth hot electron bolometer heterodyne detectors based on single-walled carbon nanotubes," Applied Physics letters 87, 043503, 2005.

Single Pixel Instruments



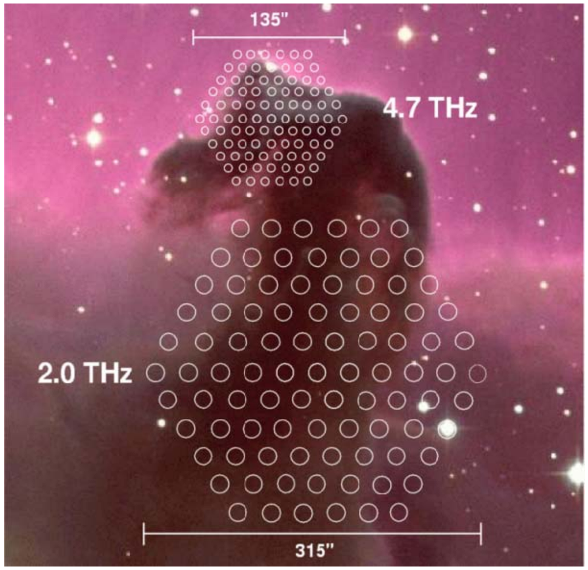
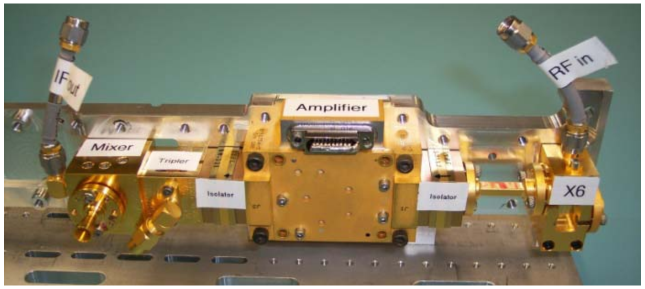


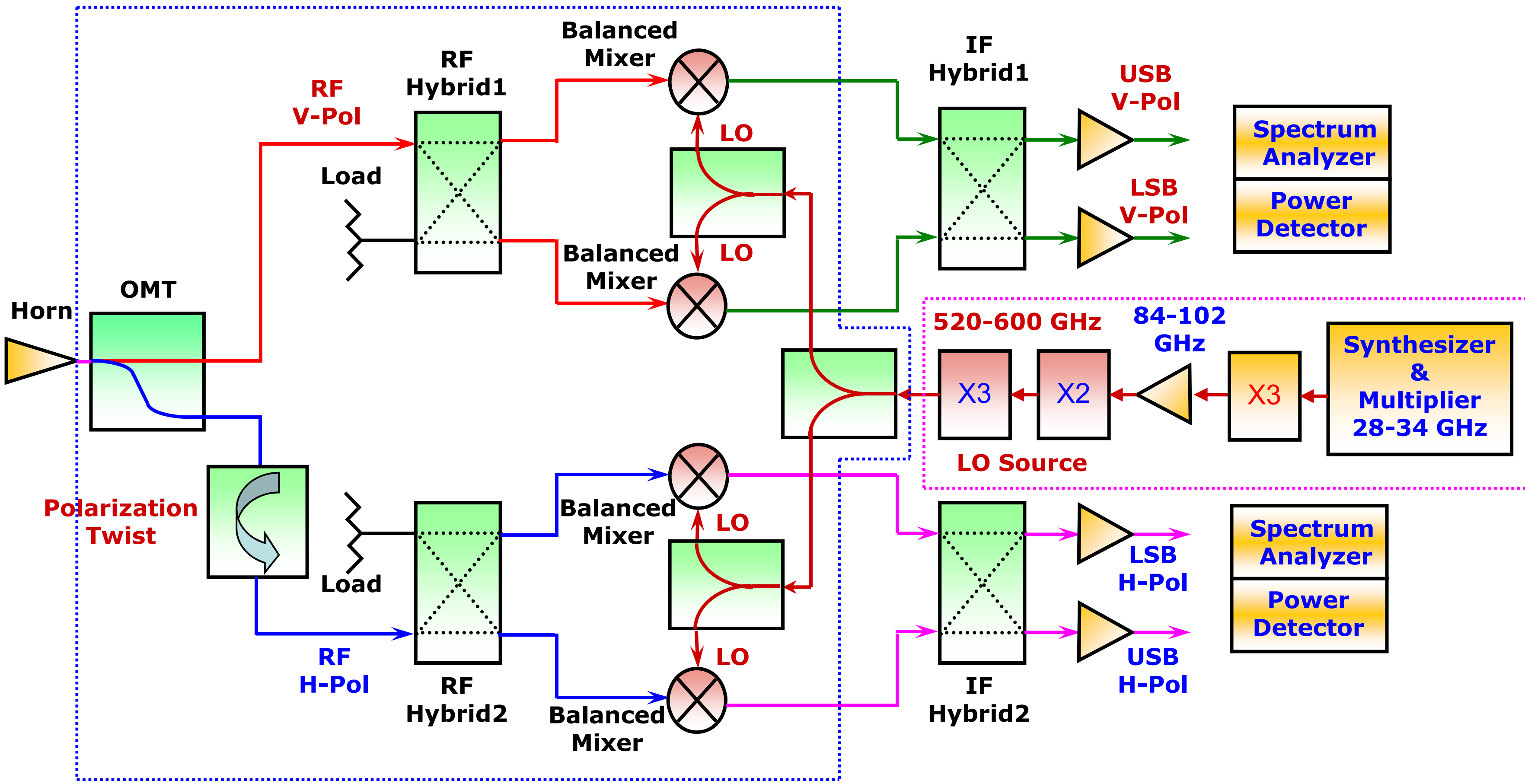
Image courtesy: Chris Walker

- Current generation heterodyne instruments are mostly single-pixel.
- Mapping of large scale areas (star forming regions) is the key for future space missions.

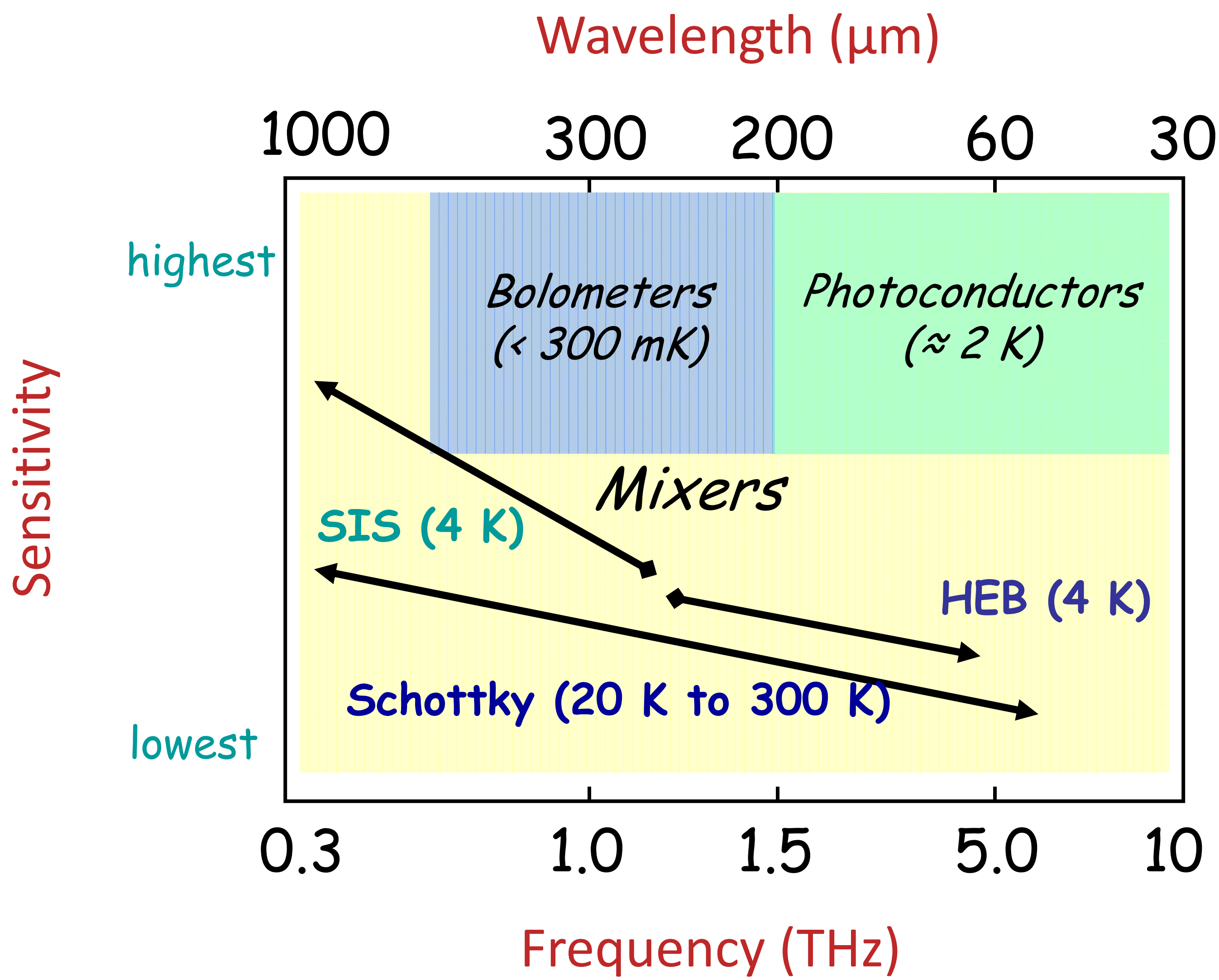


Heterodyne Receiver Front-End at 1.9 THz

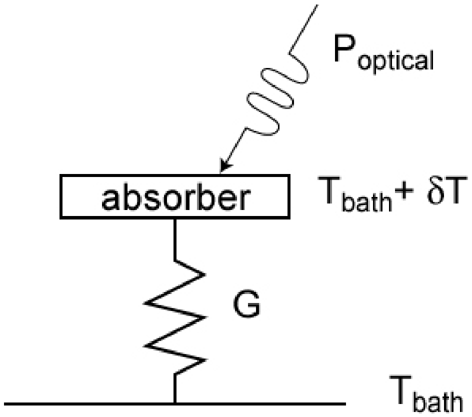
Single Pixel Heterodyne Receiver



Terahertz Sensors



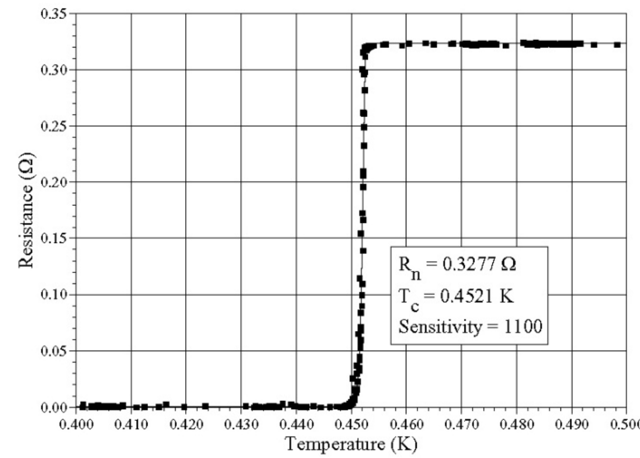
Terahertz Direct Detectors

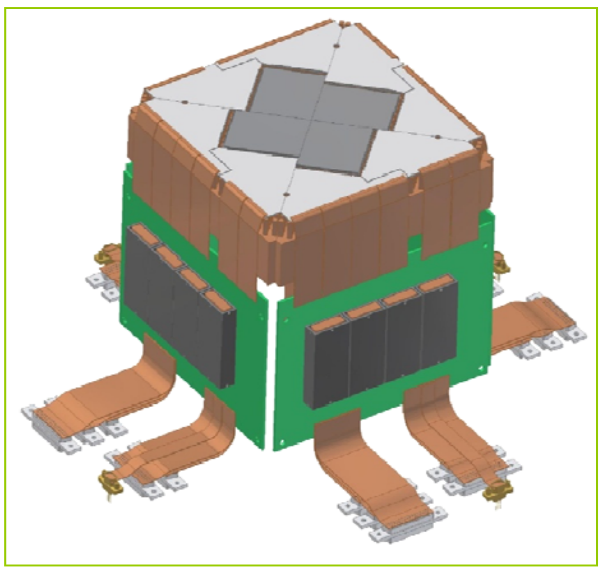


Bolometers:

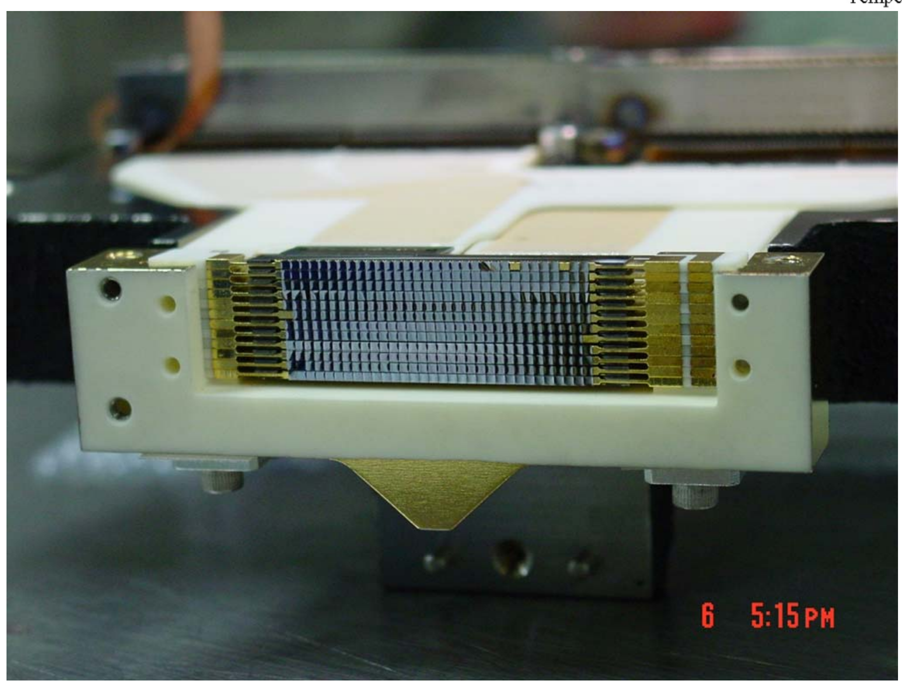
Good continuum sensitivity

- Wide optical bandwidth
- Low NEP
- Can reach photon noise limit
- Good Thermistors (TES)





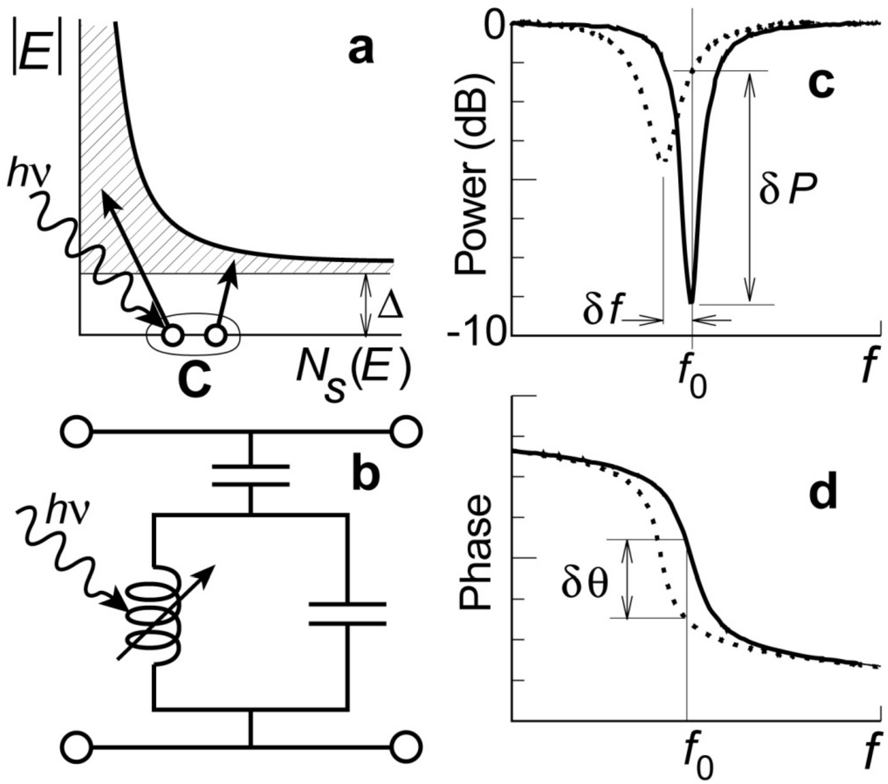
SCUBA II Multiplexed TES Bolometer Array

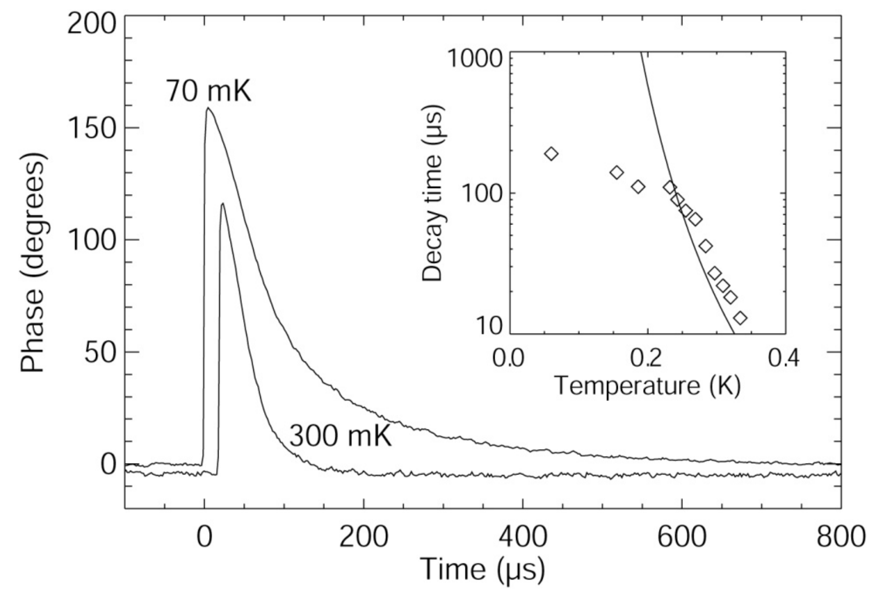


SHARC II 384 Pop-Up Pixels with Implanted Silicon Thermistors

Terahertz Direct Detectors

Microwave Kinetic Inductance Detectors (MKIDs)

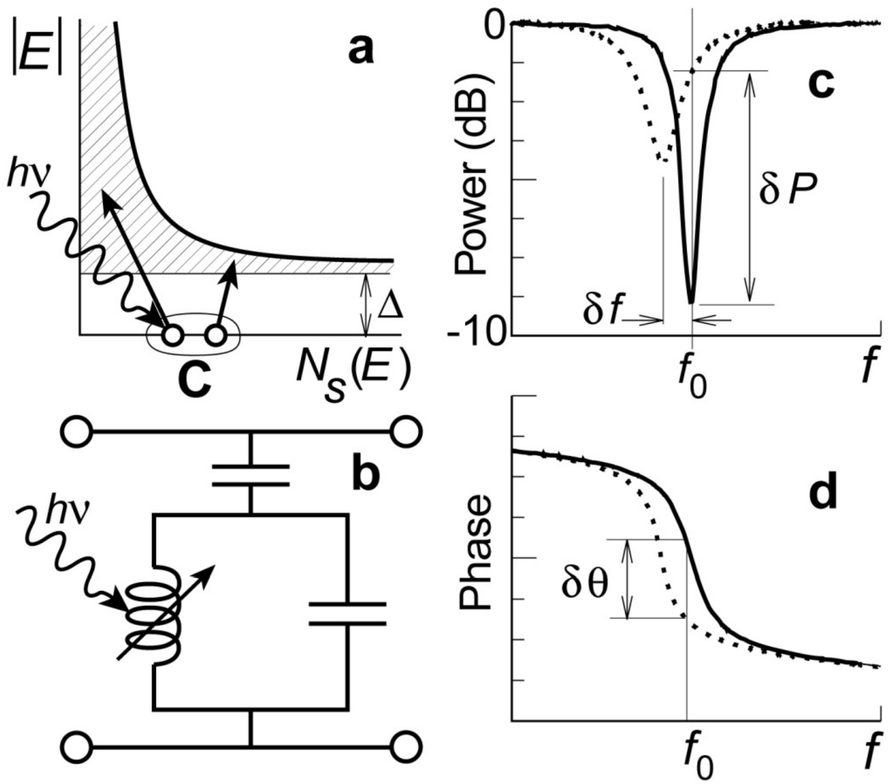


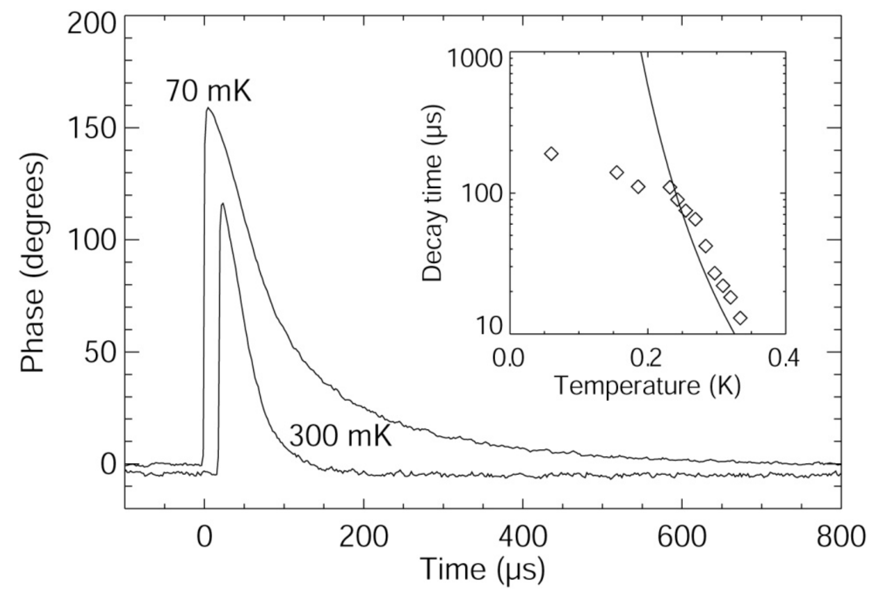


Pulses from 6 keV photons
(Day et al., Nature 425, 2004)

Terahertz Direct Detectors

Microwave Kinetic Inductance Detectors (MKIDs)





Pulses from 6 keV photons
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Terahertz Heterodyne Detectors

Schottky Diode Mixers:

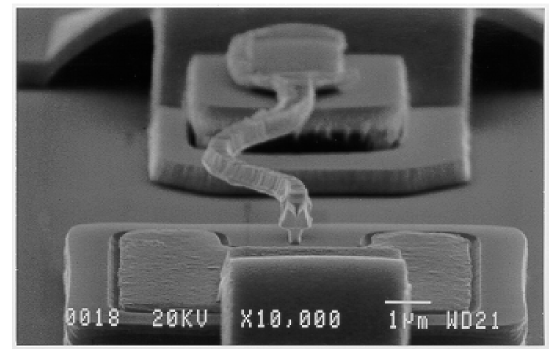
Operating frequency: Up to 5 THz and beyond.

Operating temperature: Room Temp. to 20K.

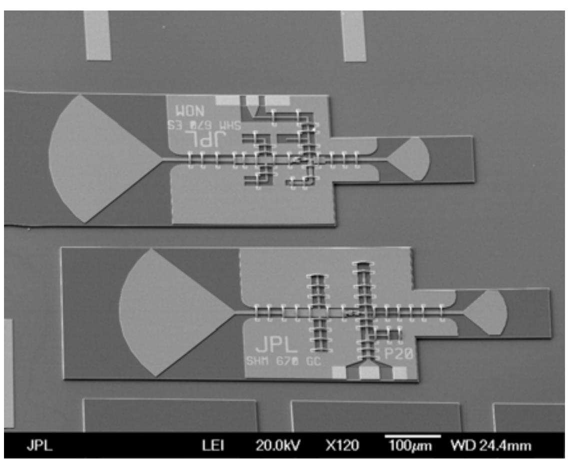
Local Oscillator Power: 0.3 – 1 mW range.

Receiver noise temperature @ 500 GHz ≈ 1800K.

Mixer conversion loss @ 500 GHz ≈ 8 dB.



2.5 THz Schottky diode mixer.
(anode size: 1 μm X 0.2 μm.)



- Planar diode technology
- IF bandwidth: Not an issue
- Robust and mature technology
- LO pump power is an issue!
- Waveguide or quasi-optical coupling

Major advantage: can operate at room temp. and at 77K.

Terahertz Heterodyne Detectors

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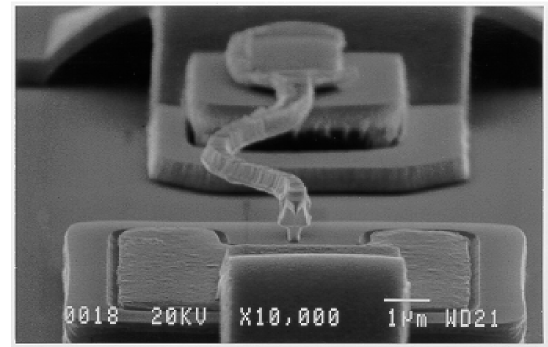

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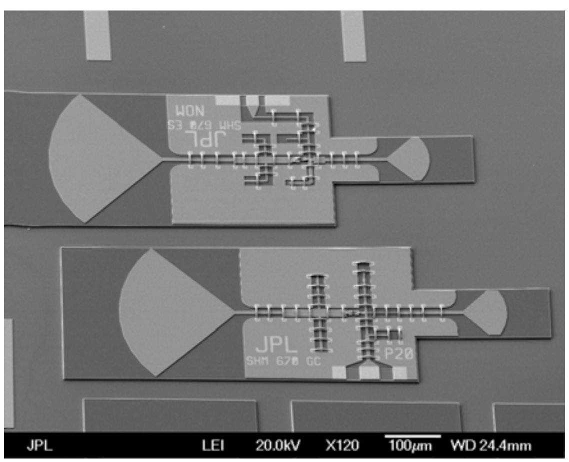

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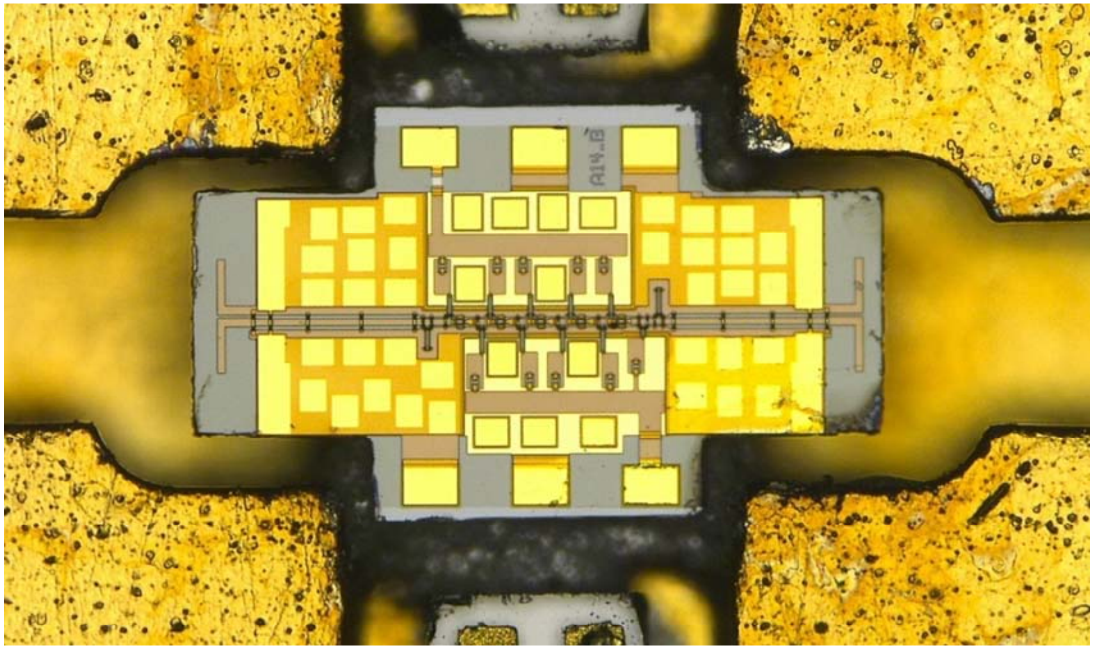
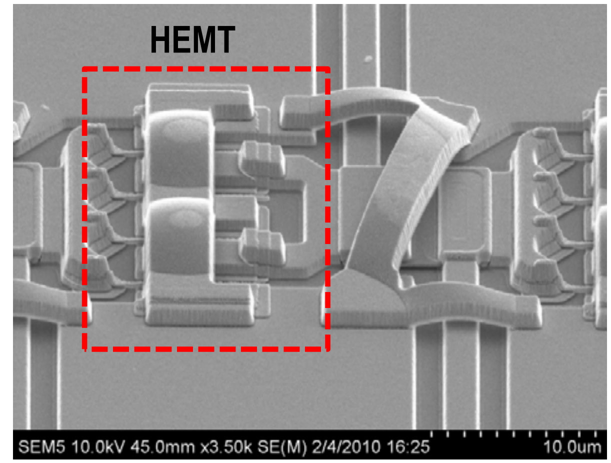
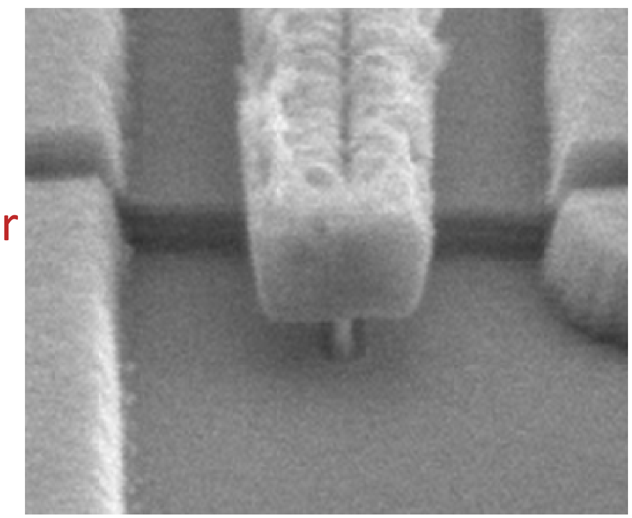
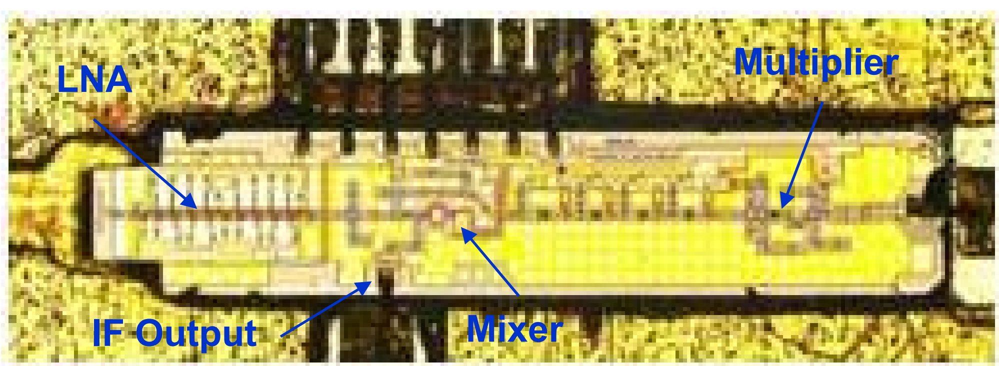
Terahertz Transistors



High Electron Mobility Transistor (HEMT) based Amplifier







Ref: W. Deal, et al., IEEE Trans. THz Sc. Tech., vol. 1, no. 1, pp. 25-32, Sept. 2011

Terahertz Transistors

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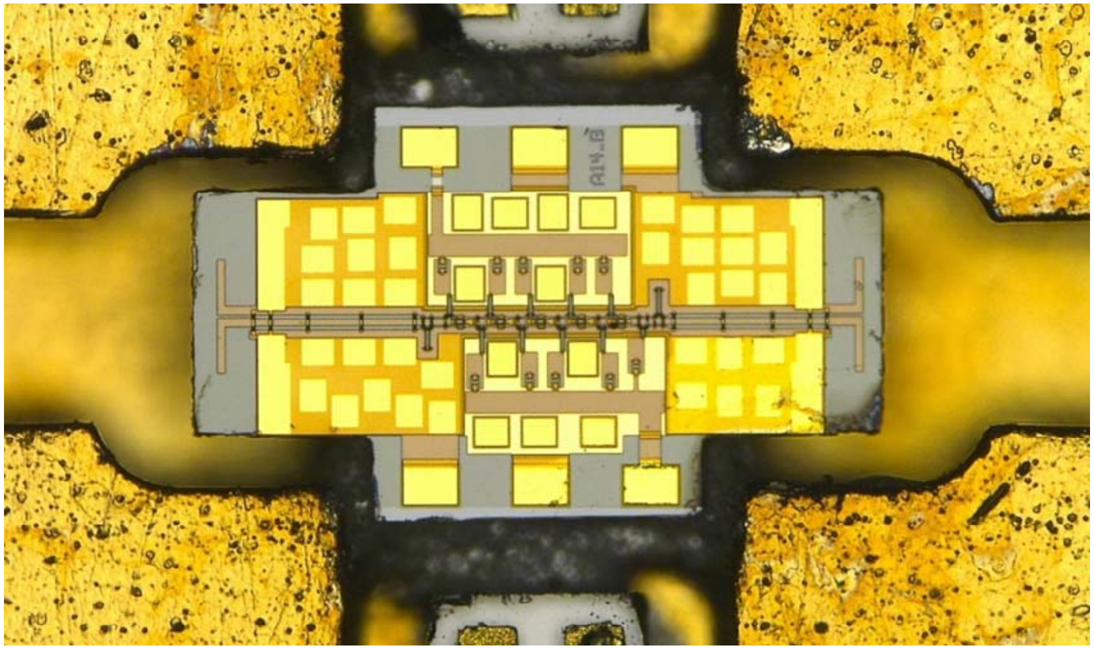
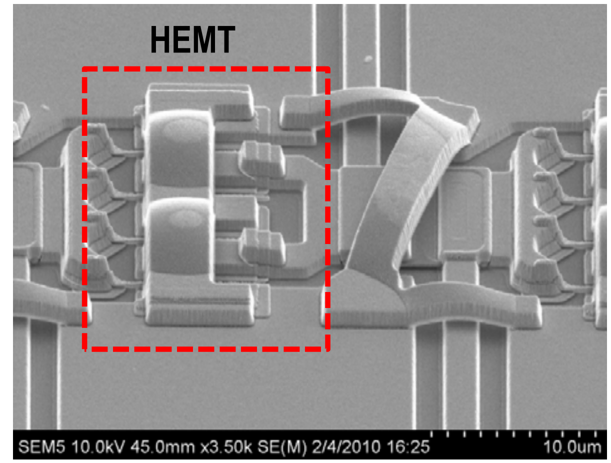
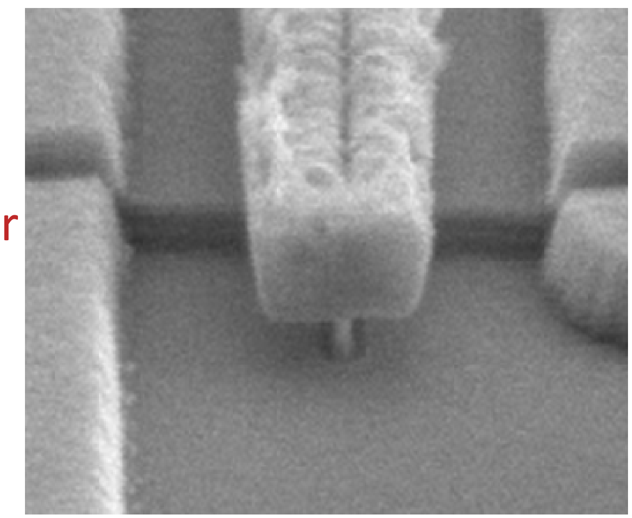
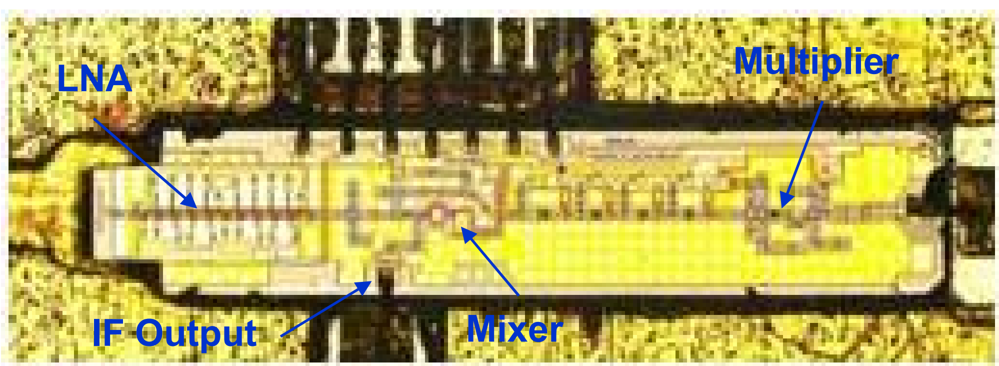


High Electron Mobility Transistor (HEMT) based Amplifier







Ref: W. Deal, et al., IEEE Trans. THz Sc. Tech., vol. 1, no. 1, pp. 25-32, Sept. 2011

Sensor Performance

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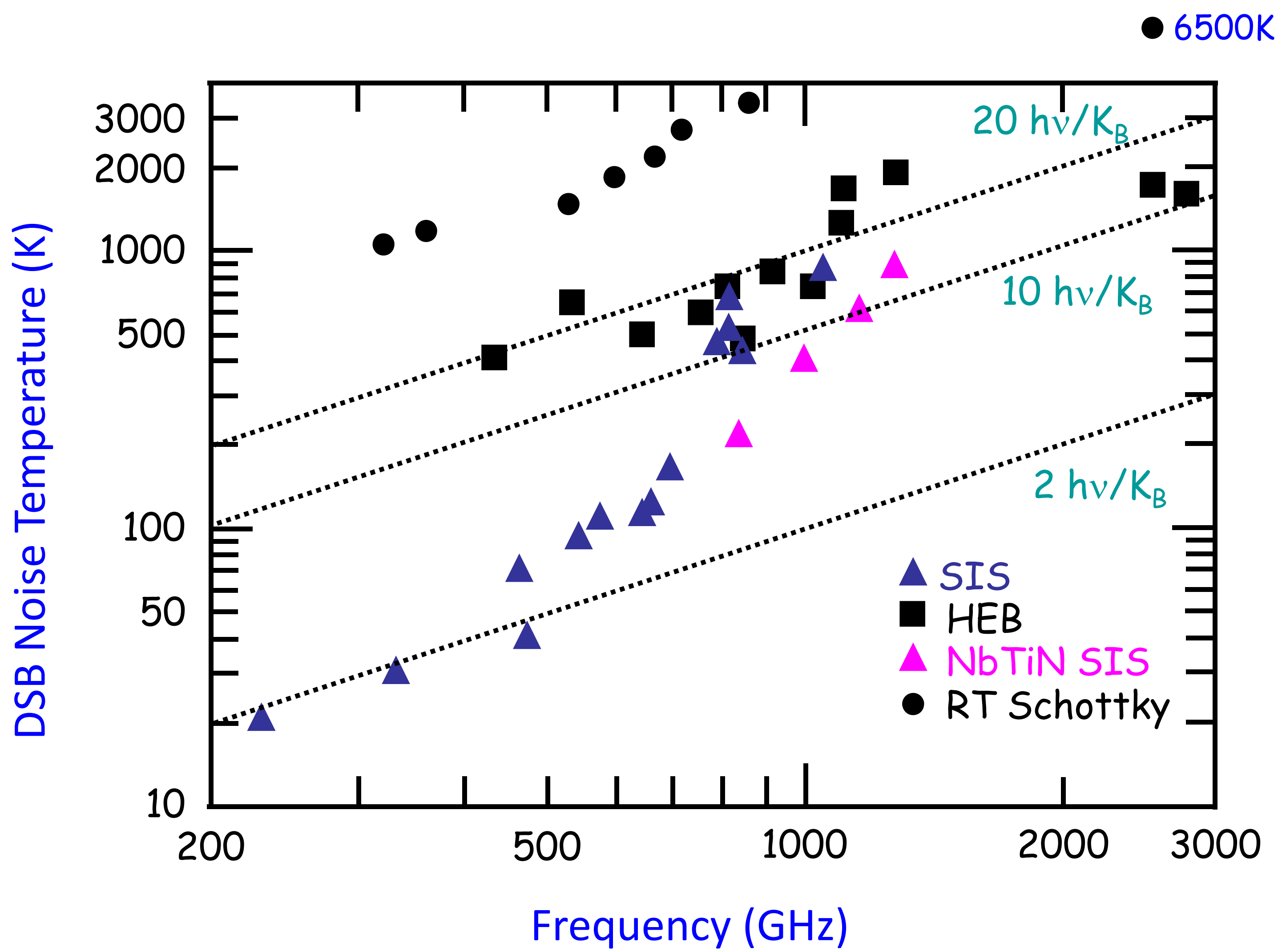
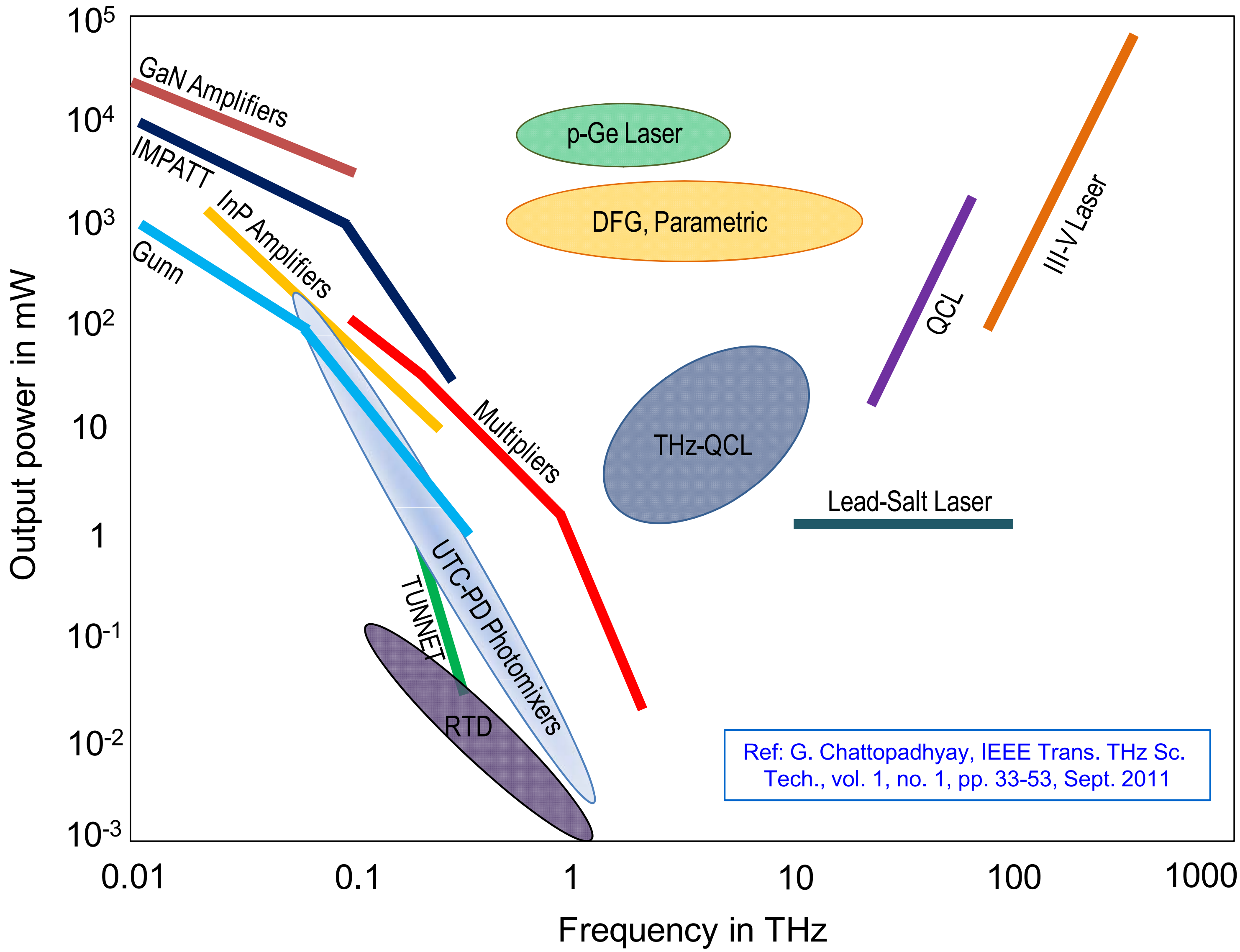


Terahertz Sources



Ref: G. Chattopadhyay, IEEE Trans. THz Sc. Tech., vol. 1, no. 1, pp. 33-53, Sept. 2011

Terahertz Sources

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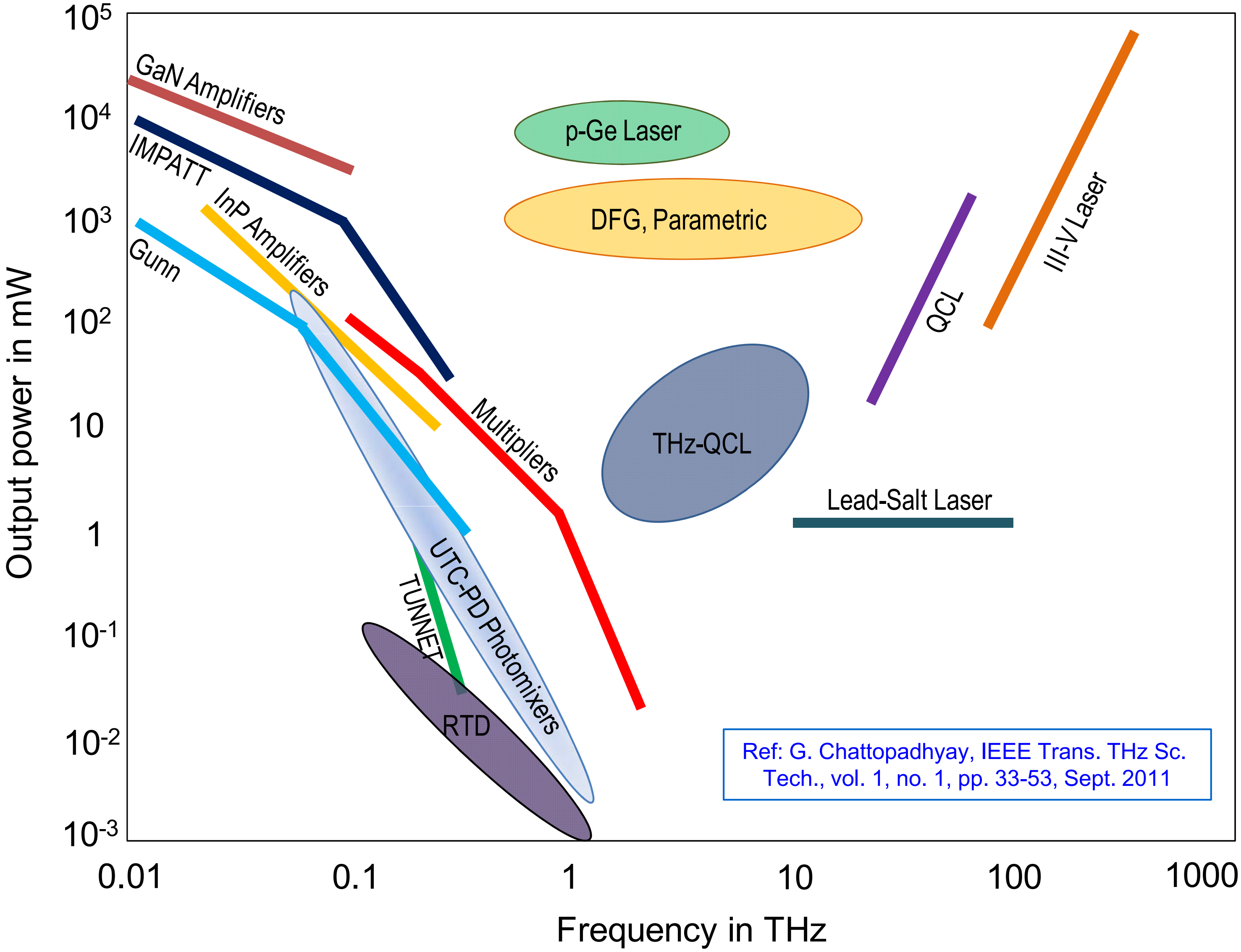
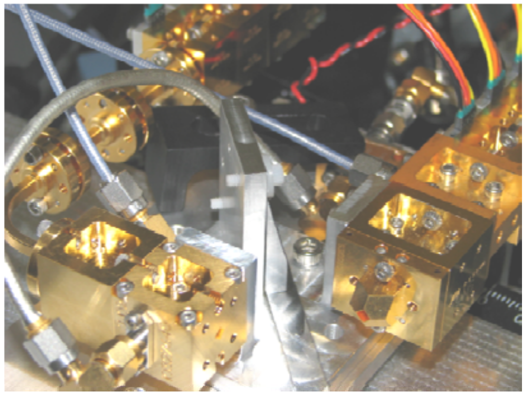
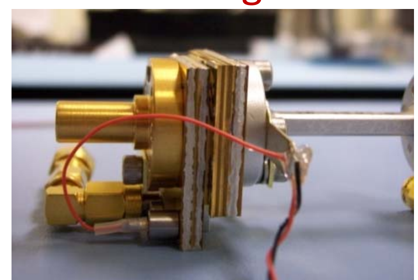


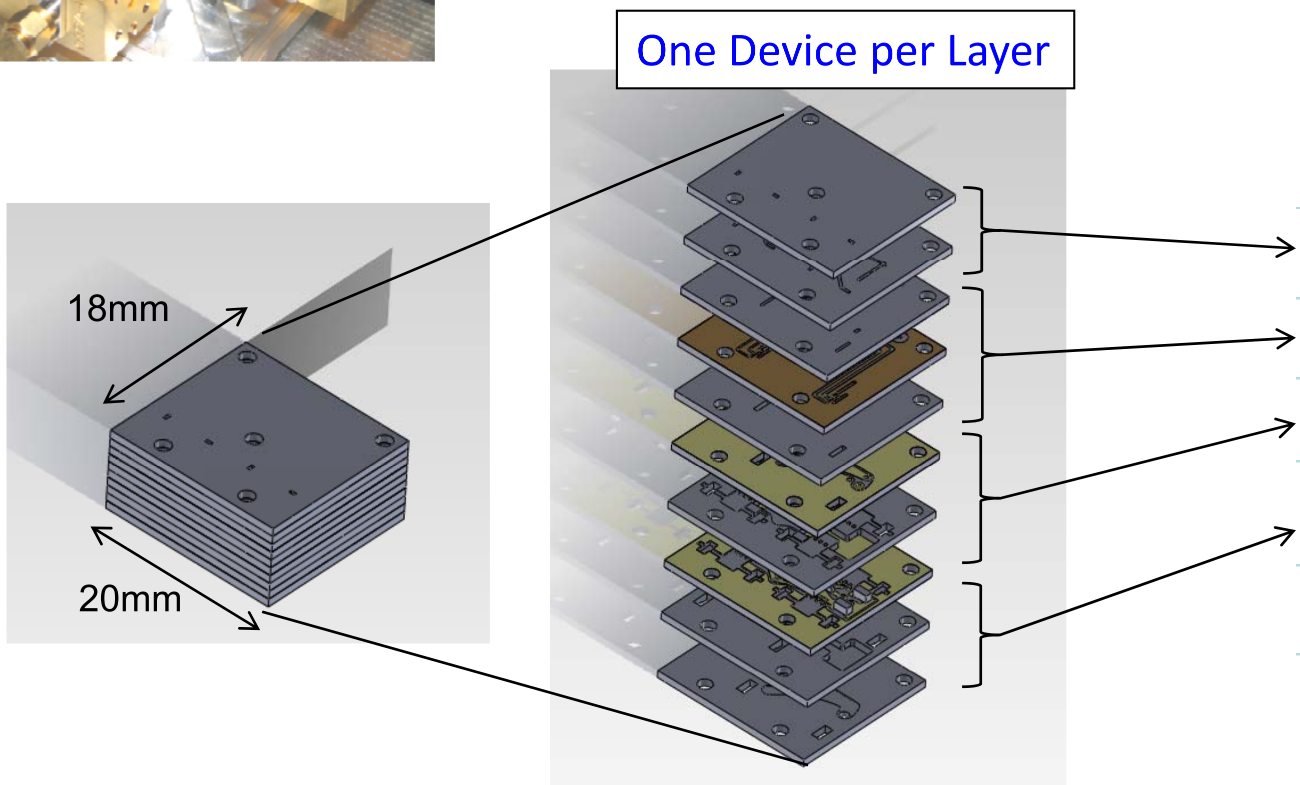
Terahertz Array Designs

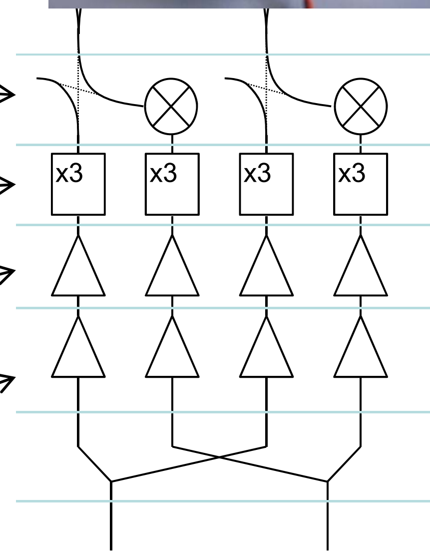


System-on-a-chip achieved by 3-D integration:

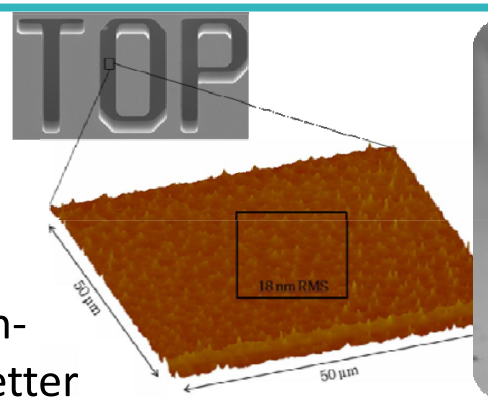
- Stacking each functional component reduces each layer's complexity
- Enables a highly integrated package while still remaining modular
- Vertical routing of bias and IF connections

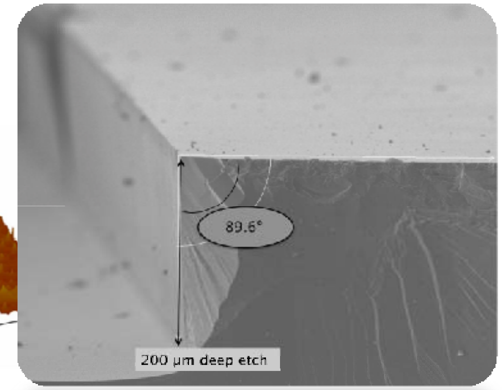






Silicon Micromachining





Silicon Micromachining

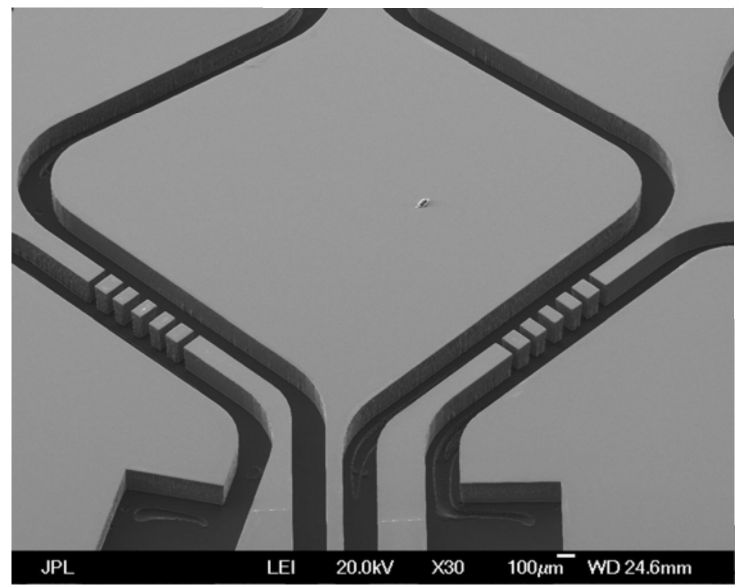
- Etch silicon wafer with plasma using a photolithographic pattern

Advantages:

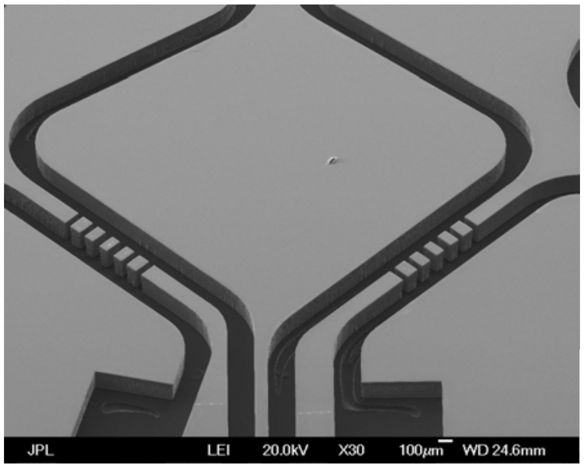
- Potential for lower cost because of batch-processed device fabrication, yielding better uniformity too.
- Lithographically precise feature definitions
- Integration of bias & IF lines on silicon itself. Future potential for integrated CMOS silicon devices.
- Potential for higher density 2D transceiver arrays.

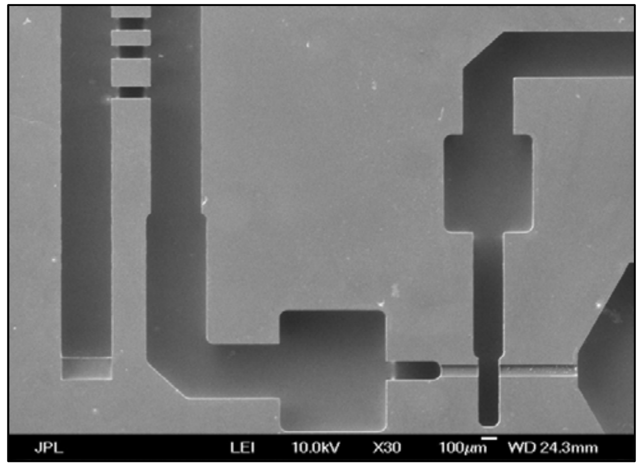
Disadvantages:

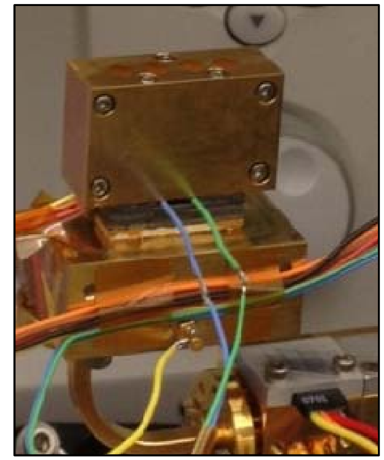
- Immature technology: need for process development.
- Challenge of wafer alignment.

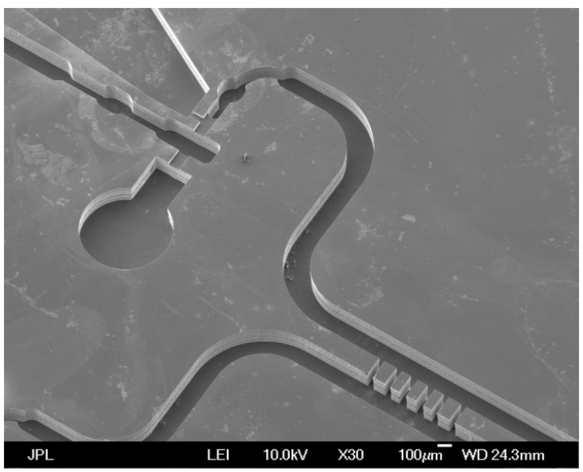


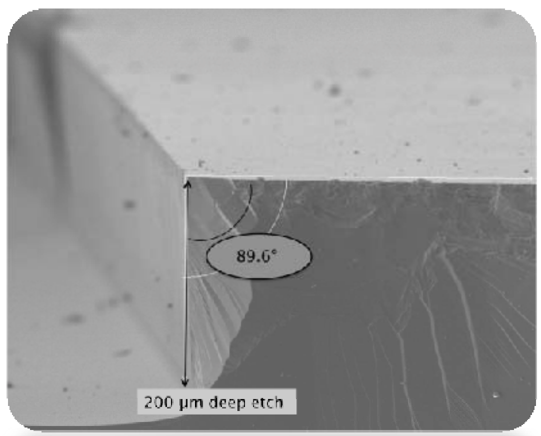
Silicon Micromachining

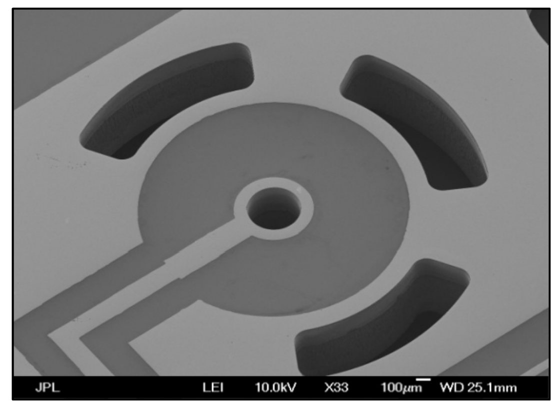












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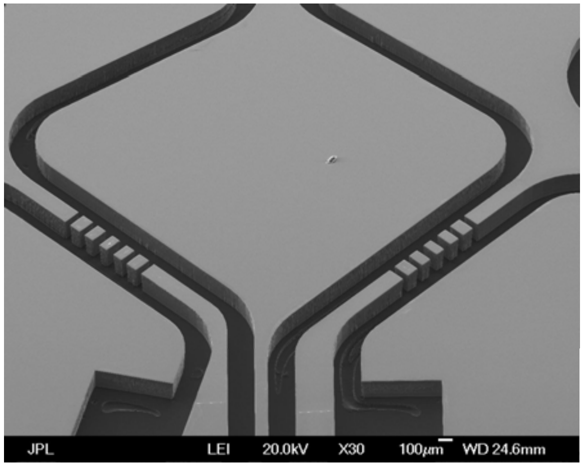
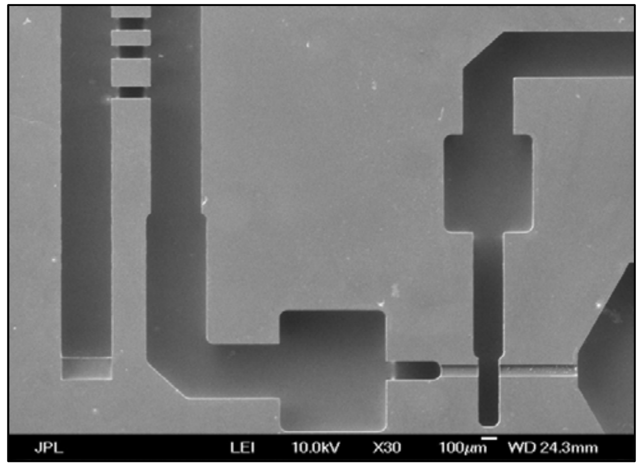
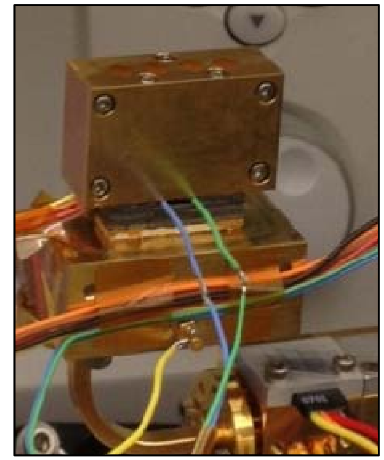
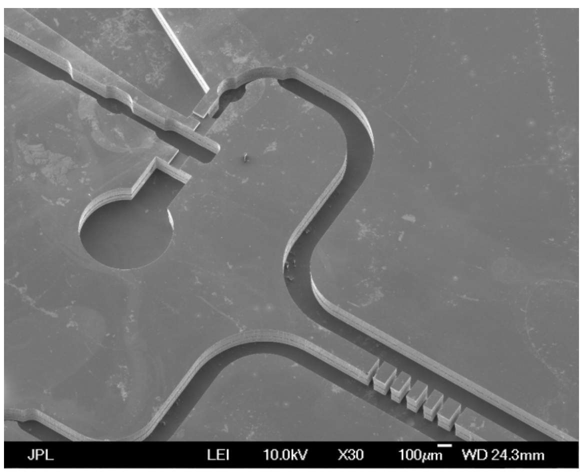
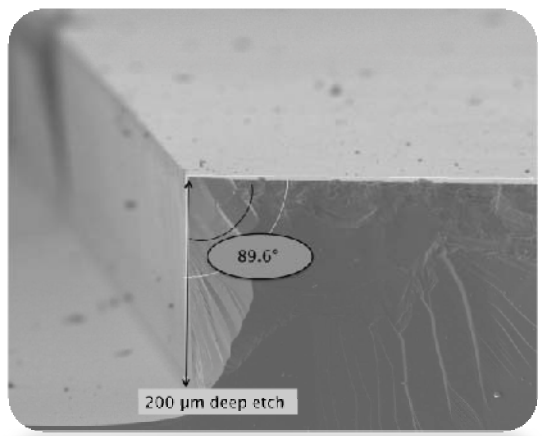
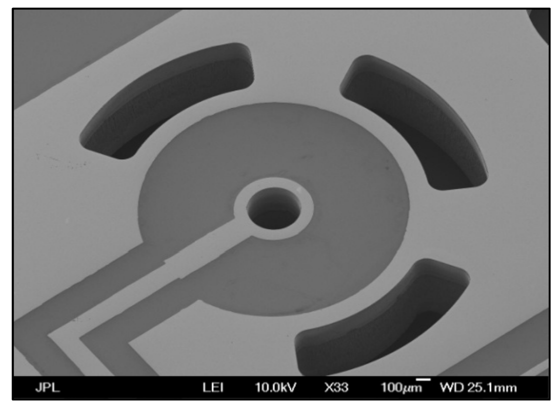






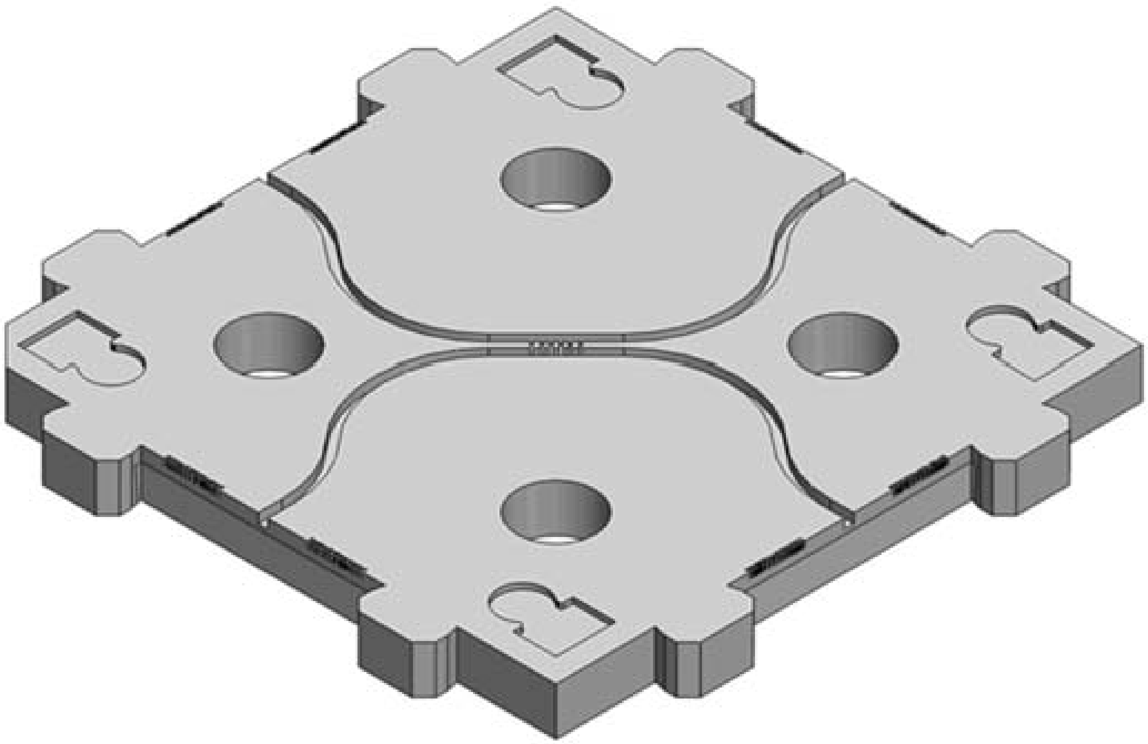


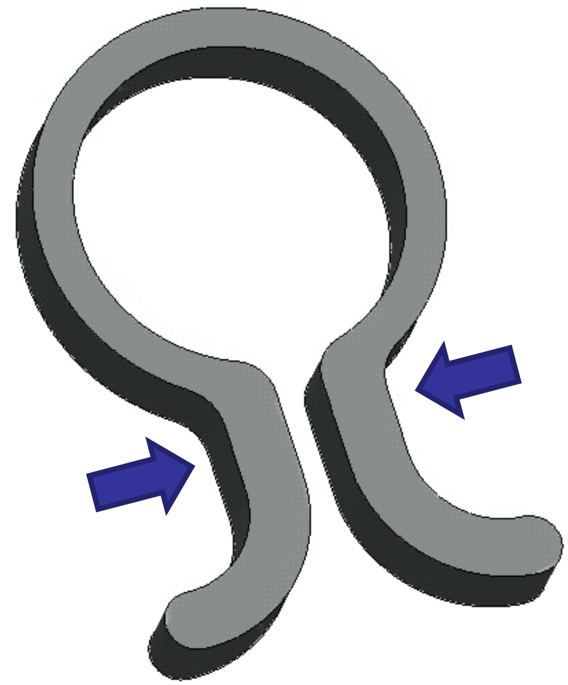




Silicon Micromachining and Alignment

- How do we align individual silicon wafers?





Silicon Micromachining and Alignment

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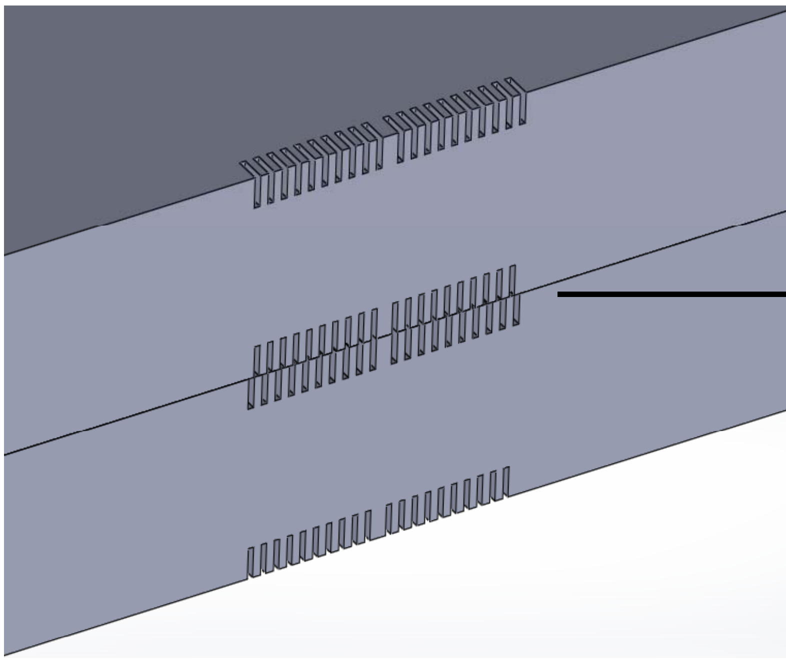
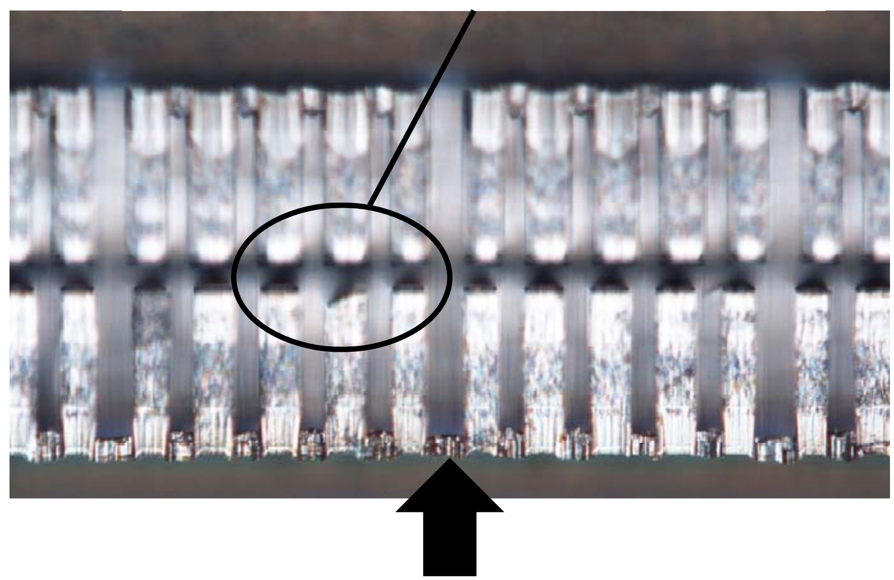
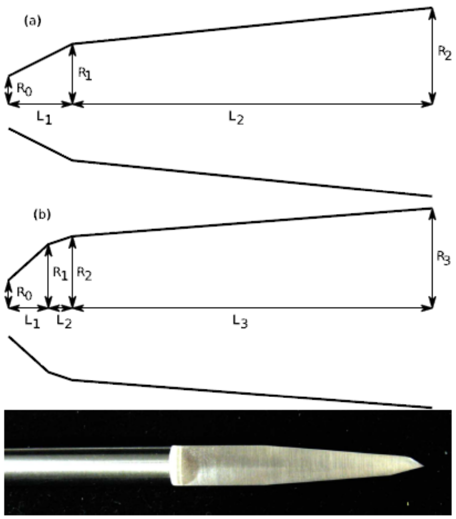
- How do we align individual silicon wafers?

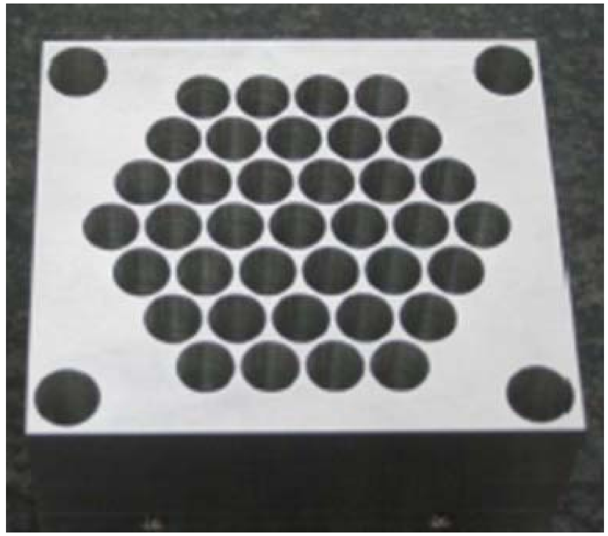


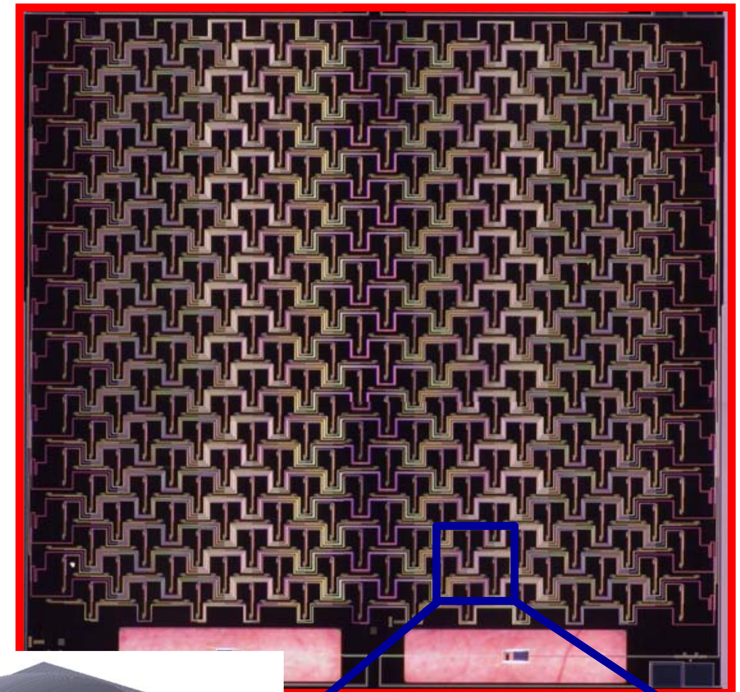


- Enables characterization of alignment schemes
- Improves hand alignment

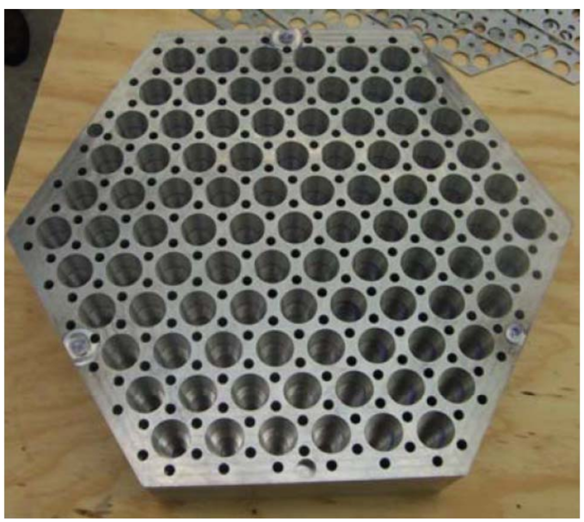
Terahertz Antenna Arrays

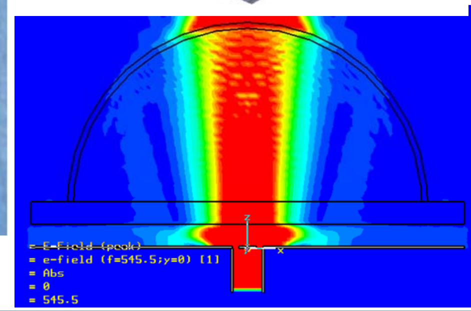


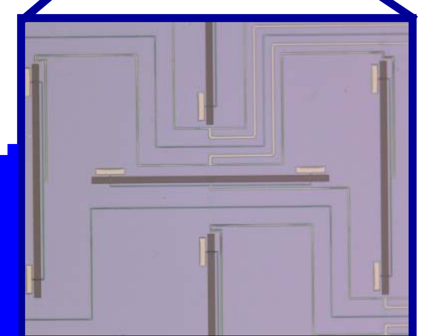




Ref: J. Leech et al., “Experimental investigation of a low-cost, high performance focal –plane horn array,” IEEE Trans. Terahertz Sc. Tech., vol. 1, no. 2, Jan. 2012.







Summary

- Very exciting time for terahertz Scientists and Technologists.
- Traditional areas such as astrophysics, planetary, and Earth science applications are still driving the technology developments.
- New and emerging areas such as security and wireless power transfer is going to be the key drivers in future developments.
- People have recently started looking into designing multi-pixel heterodyne arrays at terahertz frequencies.
- Vertical integration of subsystems will play a critical role in future terahertz array instruments.

IMS 2013

Acknowledgement

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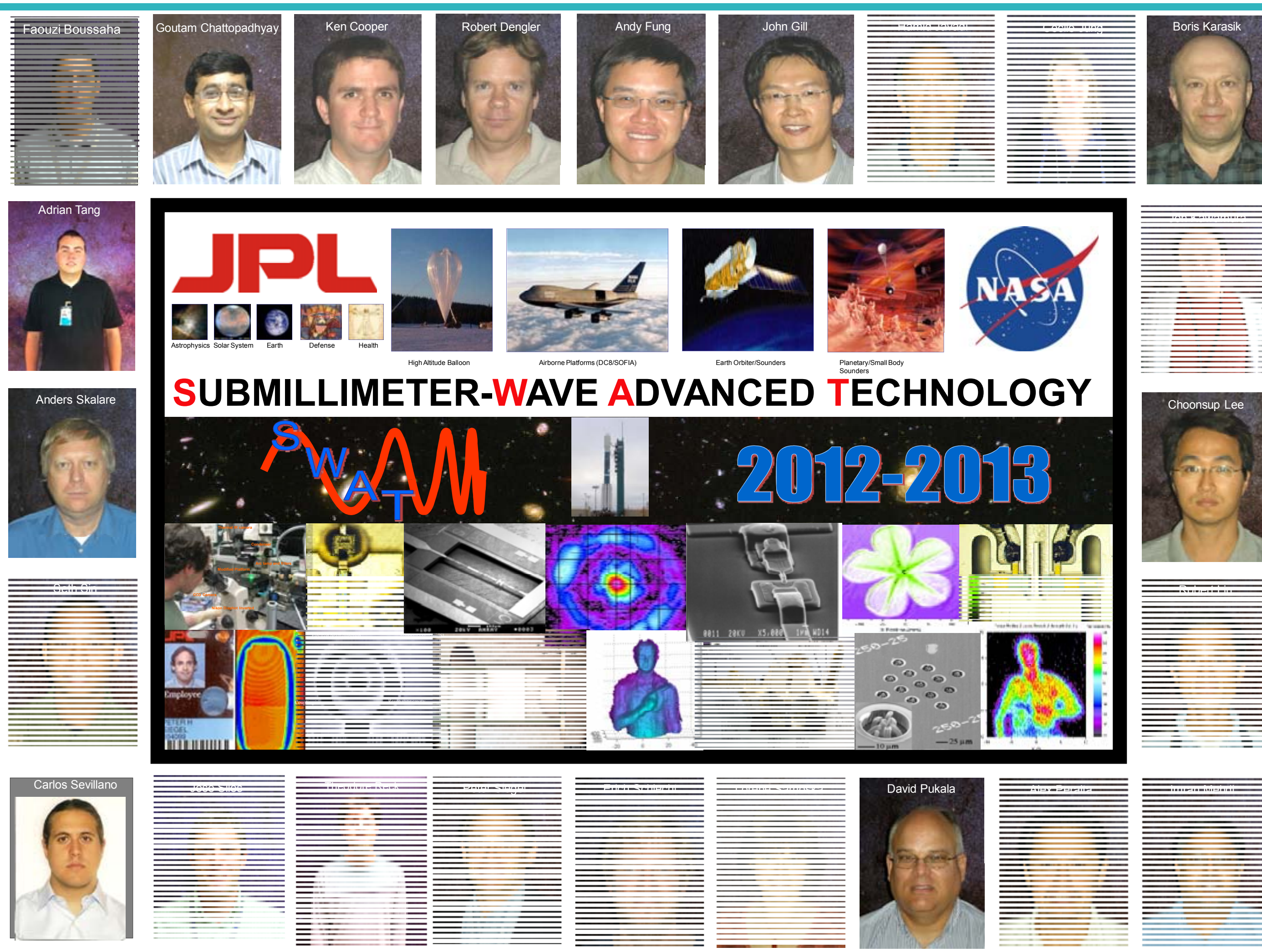

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