THz Applications

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The 6th European Microwave Integrated Circuits Conference

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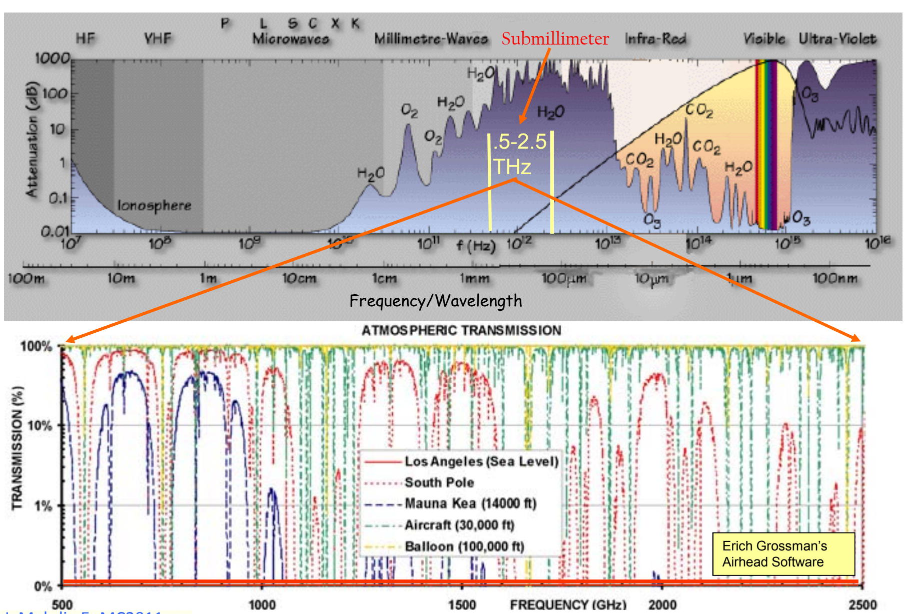
Outline

- Introduction
- What is the THz range, why is it important?
- THz Applications
- THz Technology and status
- Challenges

What is the THz range? THz Bands & Atmospheric Transmission



Introduction

- Why has there been resurgent interest in this frequency range?
  - Despite great scientific interest since at least the 1920's, the THz frequency range remains one of the least tapped regions of the electromagnetic spectrum mostly due to lack of robust technology.
- What are some of the THz applications?
  - For over 25 years the sole niche for THz technology has been in the high resolution spectroscopy and remote sensing areas where heterodyne and Fourier transform techniques have allowed astronomers, chemists, Earth, planetary and space scientists to measure, catalog and map thermal emission lines for a wide variety of lightweight molecules.
- Why should we invest in this technology?
  - As it turns out, no where else in the electromagnetic spectrum do we receive so much information about these chemical species. In fact, the universe is bathed in THz energy, most of it going unnoticed and undetected.

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THz Applications

It helps to distinguish between the customers…

Space	Defense	Commercial
Earth Science: Atmosphere and how it changes, cloud dynamics, ozone depletion etc	Imaging: Real-time detection of threats	Imaging: Contraband detection
Astrophysics: Study galaxies far away, star formation, star decay etc	Phenomenology: Detection of minute amounts of detrimental agents, i.e. poison gas, plastic explosives etc.	Structural integrity: Look for deformity, cracks in material
Planetary Science: Planetary atmospheres and the search for volcanic and life signatures, active altitude control for landers etc	Secure communications: Un-penetrable and secure links	Structural uniformity: medical pill information, ink uniformity,
Bioastrophysics: detection of bio-molecules, detection of habitability etc	Imaging: Determination of object via THz picture	Medical: detection of bio-molecules, detection of cancer, detection of tooth decay, detection of …

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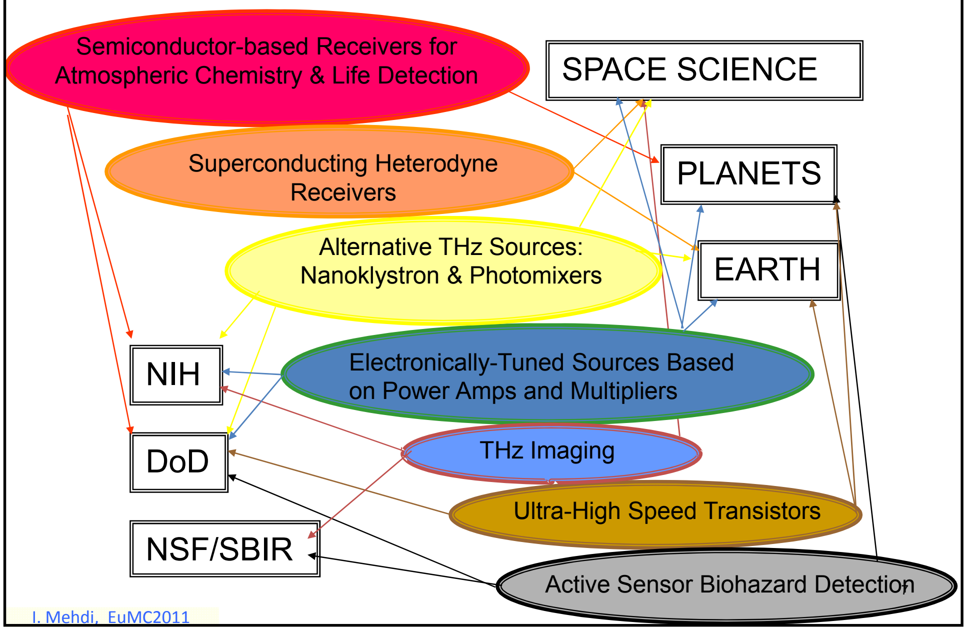
JPL THz Heterodyne Programs and Application Areas



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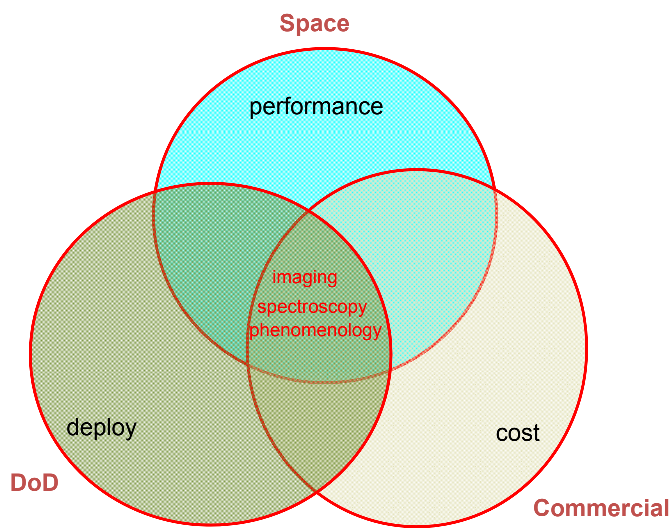
THz Technology Applications



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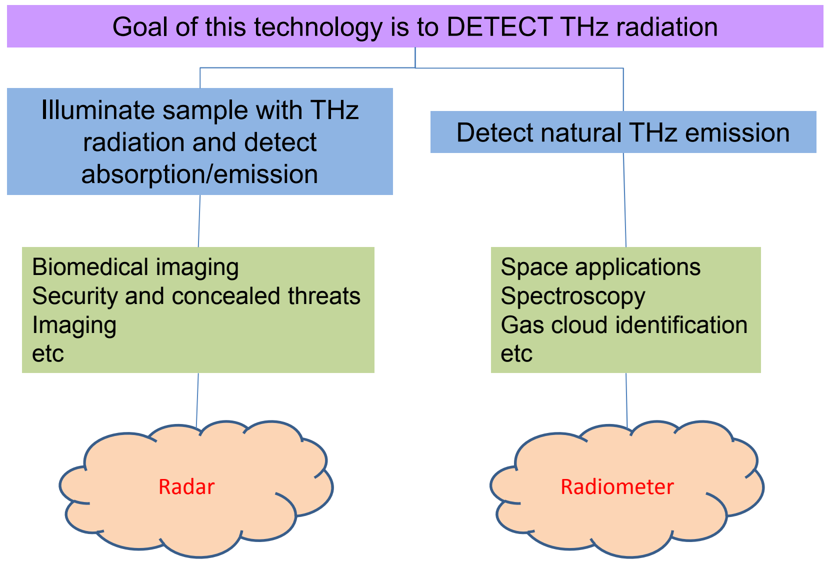
THz Technology



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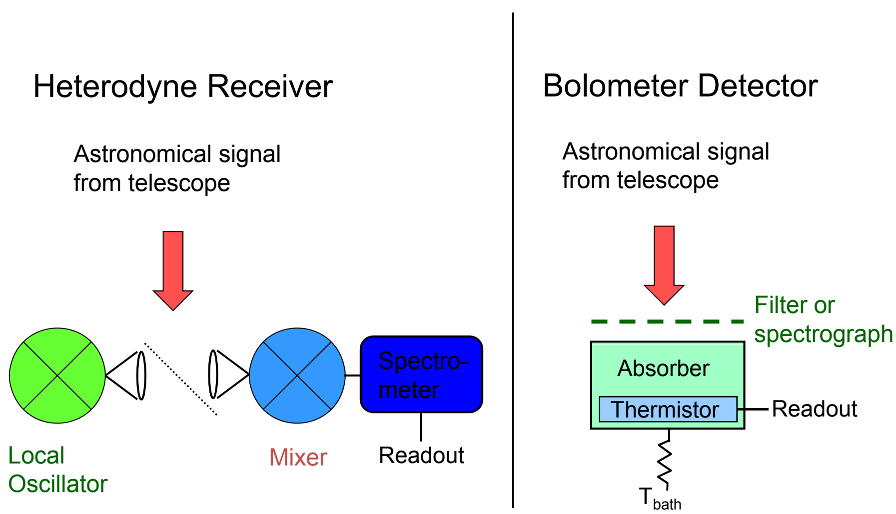
Heterodyne vs Direct Detection



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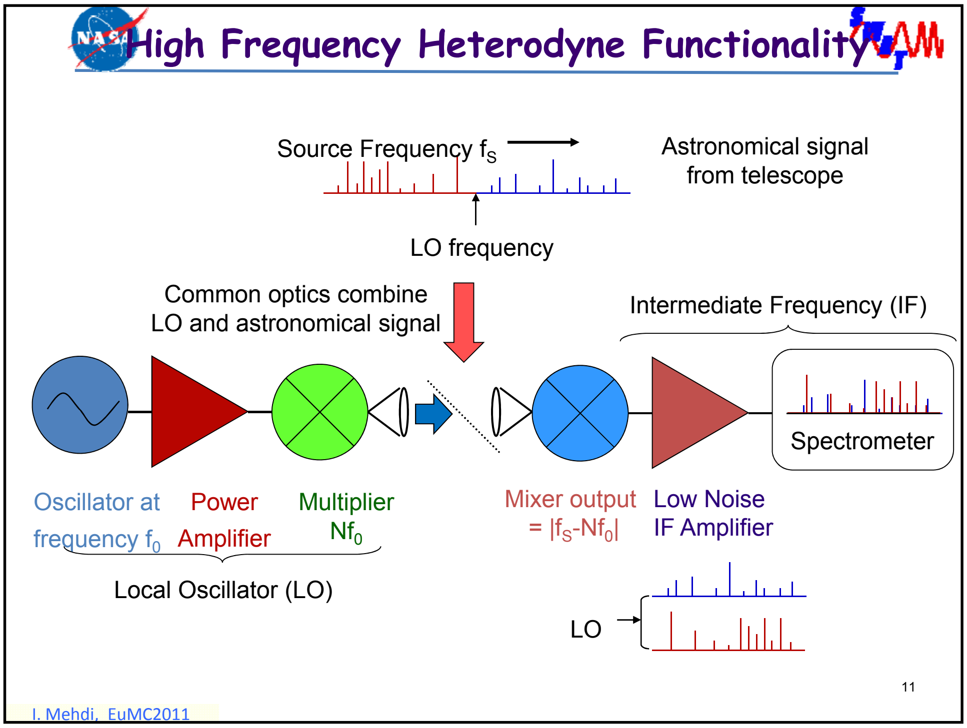
High Frequency Heterodyne Functionality
Source Frequency fS
Astronomical signal from telescope
LO frequency
Common optics combine LO and astronomical signal
Intermediate Frequency (IF)
Spectrometer
Oscillator at frequency f0
Power Amplifier
Multiplier Nf0
Mixer output = |fS-Nf0|
Low Noise IF Amplifier
Local Oscillator (LO)
LO
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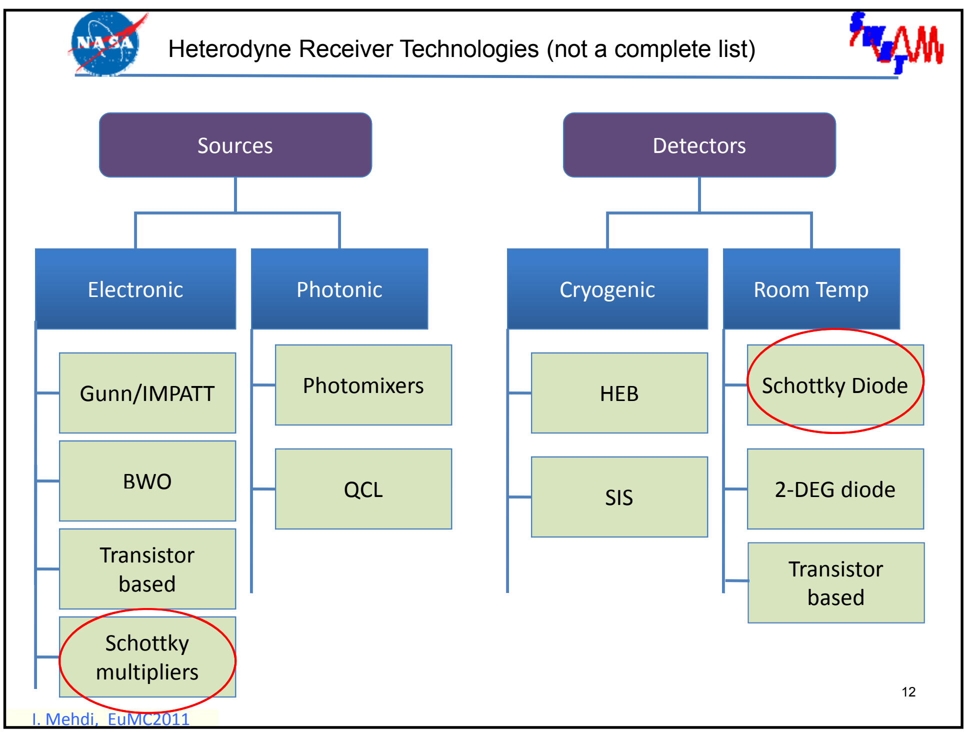
Heterodyne Receiver Technologies (not a complete list)
Sources
Detectors
Electronic
Photonic
Cryogenic
Room Temp
Gunn/IMPATT
BWO
Transistor based
Schottky multipliers
Photomixers
QCL
HEB
SIS
Schottky Diode
2-DEG diode
Transistor based
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Detector technologies

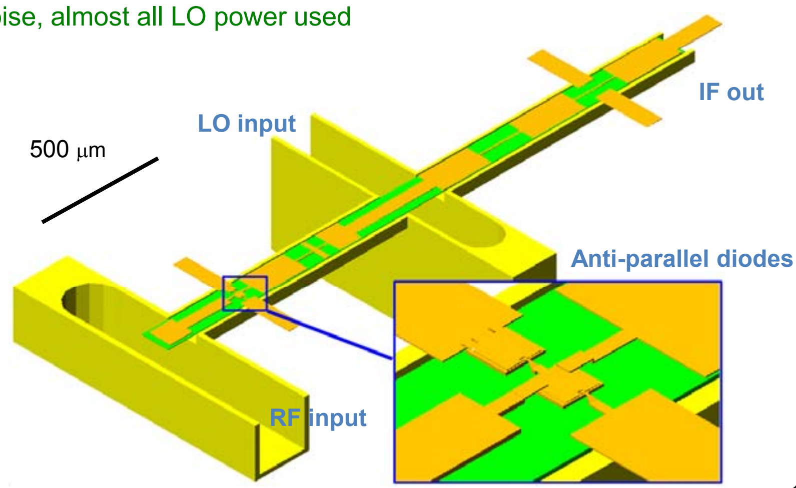
Technology	Freq Limit	Noise Temp	IF BW	Physical Temp	LO pwr	Comments
HEB	> 5 THz	low	**small**	**Very low**	**Very low**	Ideal for high freq, stability??
SIS	**To 1.5THz?**	Low-medium	large	Very low	low	Very low noise at low freq, require magnetic field to operate
Schottky	>5 THz	high	large	**Low to RT**	**large**	Space heritage
LNA	~670 GHz	Gain		**Low to RT**		

560 GHz Subharmonic Mixer

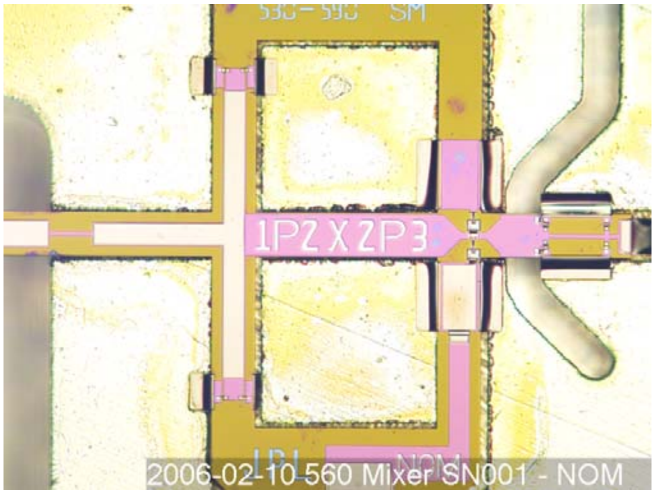
LO frequency is half of RF frequency

Anode 1 X 1.4 μm
Doping 3.5 X 10^{17} cm^{-3}
GAas Membrane 3 μm thick

Advantages: Separate RF/LO, rejects LO noise, almost all LO power used



State-of-the-art subharmonically pumped mixers



530-590 GHz Subharmonic biasable Mixer Chip

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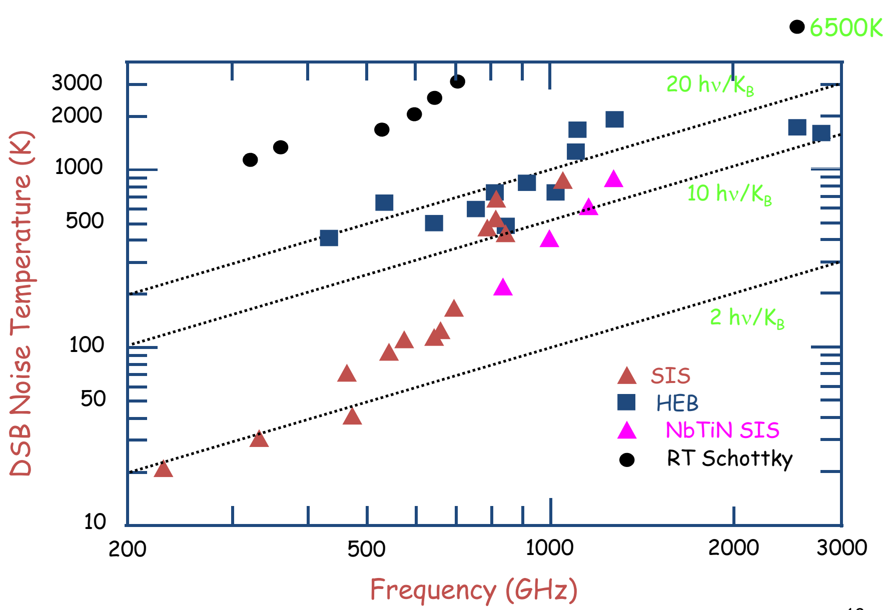
Heterodyne Mixer Technology Status



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Possibilities for THz LO Sources

For heterodyne receivers a key element that is perhaps the most challenging, especially at THz frequencies is the source

	Freq Limit (GHz)	Output power	BW (%) Instant.	Efficiency (DC pwr)	Mass	Comments
2-Terminal Oscillators	~300	~mW	**<<1**	decent	small	Tuning nec., PLL, vendors?
Amplifiers	**~670**	mW--W	~10%	decent	small	Industrial support, developing tech.
BWO	>1 THz	good	**low**	**Very low**	**large**	Multimode, vendors
FIR lasers	>> 1 THz	high	**very narrow**	**low**	**large**	Useful for lab
QCLs	>>1.5 THz	high	**narrow**	decent?	medium	**Cryogenic**, lockable?, maturing fast
Multipliers	~3 THz?	mW--nW	~10-15%	low	small	Space heritage

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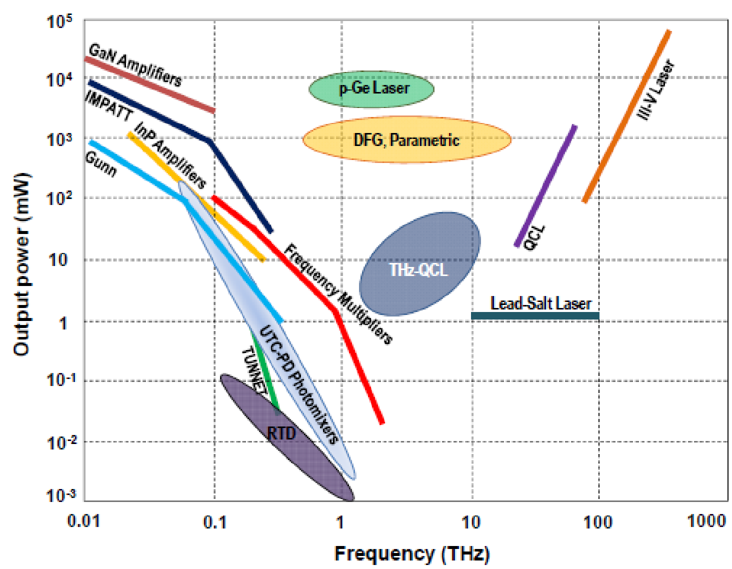

Courtsey Chattopadhyay, IEEE-TST

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What is a THz Schottky Diode ?

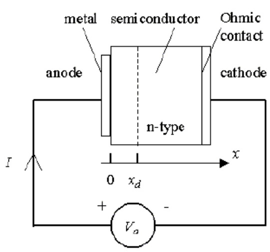


Figure 1 : Structure and sign convention of a metal-semiconductor junction

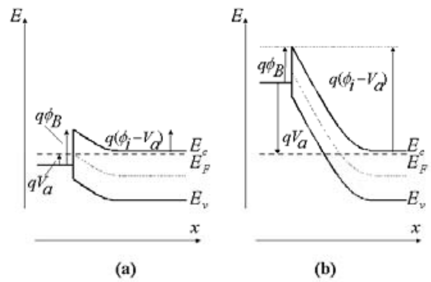
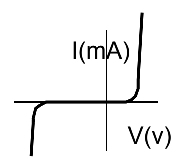
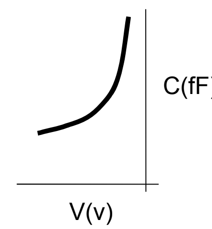


Figure 4 : Energy band diagram of a metal-semiconductor junction under (a) forward and (b) reverse bias

$$J = J_s\, [\, \exp(-qV_a/nkT) - 1]$$

$$C = \frac{\varepsilon A}{W} = \frac{\varepsilon A}{\sqrt{\dfrac{2\varepsilon (V_b - V_a)}{qN_D}}}$$





Nonlinear resistance
Nonlinear capacitance

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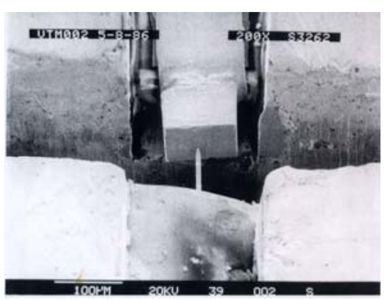
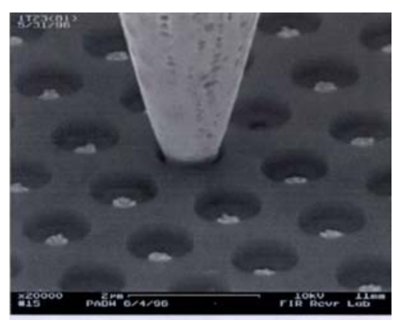
THz Diodes--Technology





Planar diodes needed for:

- Robustness
- Increased functionality
- Increased reliability
- Increased repeatability
- High power handling
- Harmonic control

But anodes must have low parasitics…

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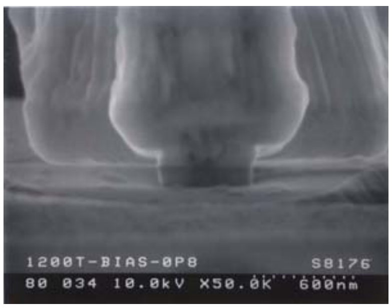
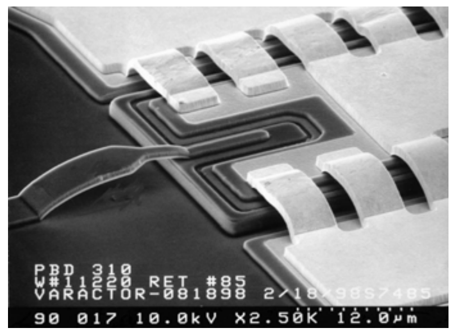
JPL planar diode process

- Based on a proprietary planarization process that allows for
  - Self aligned anode and finger
  - Dry etching
  - No use of polyimide etc
  - E-beam compatible for real small anodes
  - T-anodes





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Design of first stage doublers

6 Anodes
3 X 12 um^2
2X10^{17} cm^{-3} epi doping

150, 180, 200, doublers have been designed

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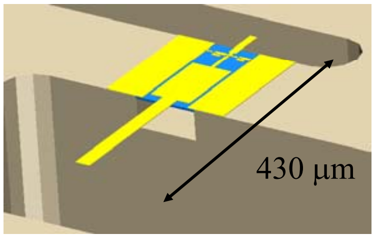
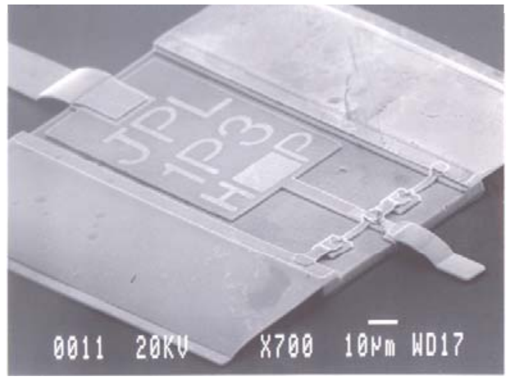
Membrane Based Devices

GaAs thickness difficult to scale

remove most of the GaAs substrate→membrane devices



1200 GHz tripler chip



- Membrane is 3 microns thick
- Extensive use of beam-leads
- Extremely simplified assembly
- Bias less design

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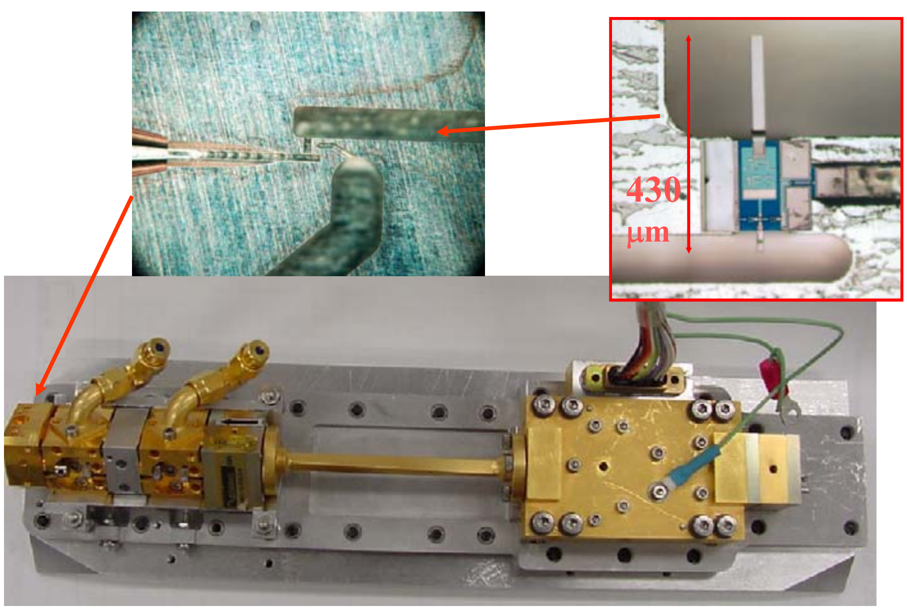
Planar LO chain at 1200 GHz



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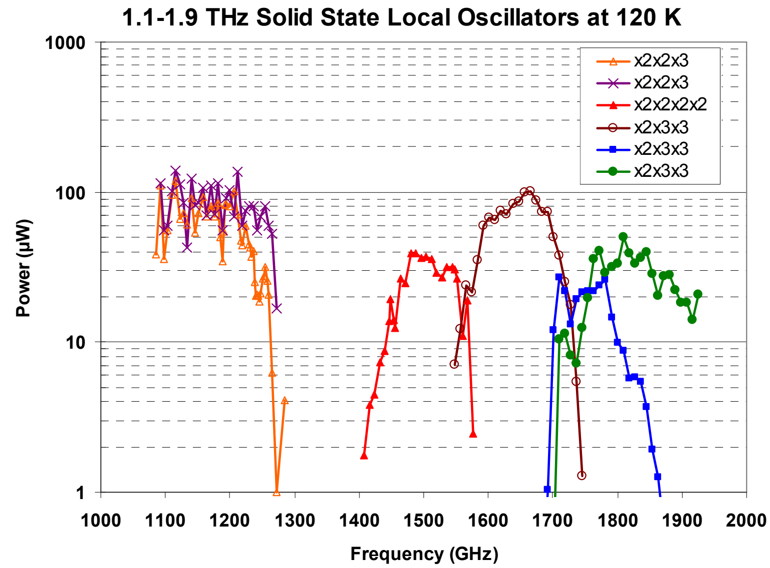
Sources developed for HIFI (2007)



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More power, higher frequencies??

- More anodes per chip—ultimately limited by space
- Better/optimized material system—GaN?
- Better thermal design—topology, 3-D structures
- Higher input power
- Better input power handling capability
- How about power combining?

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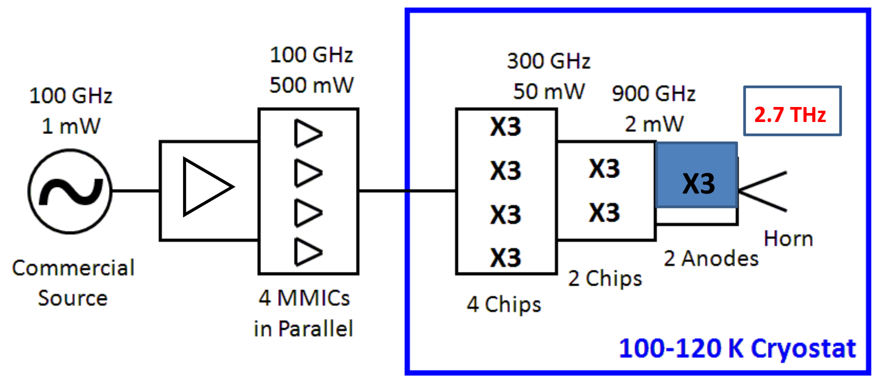
Architecture for a 2.7 THz Source



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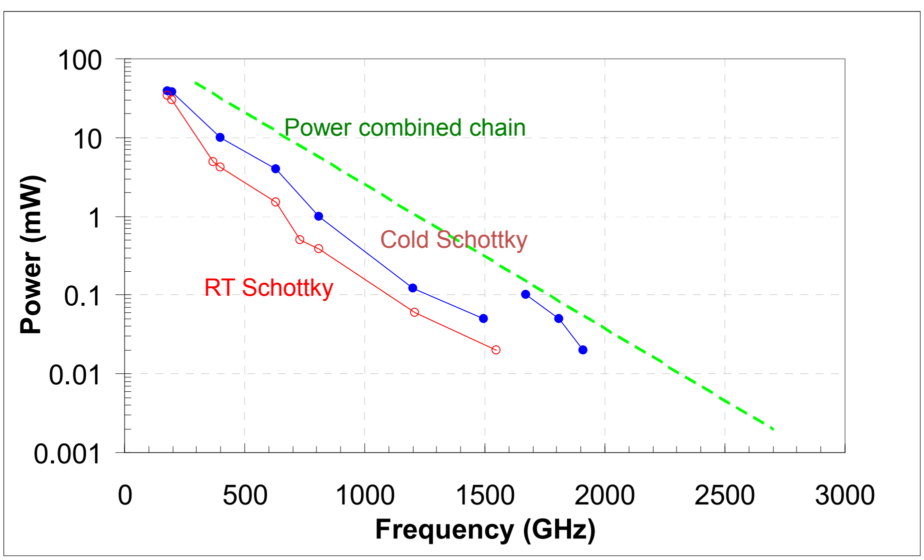
THz Sources—future expectations



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On Ground: THz Detection of Concealed Weapons

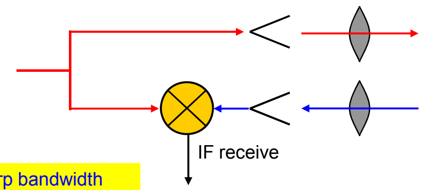
A High-Resolution Imaging Radar at 580/670 GHz (courtesy K. Cooper, JPL)

Visible, IR — high resolution, but non-penetrating

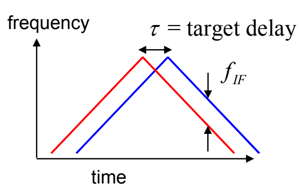
Microwaves, RF — penetrating, but low resolution

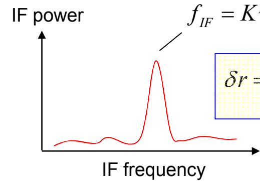
THz Gap — penetrating and high resolution

K = chirp rate (Hz/s)



Range resolution: inversely proportional to chirp bandwidth



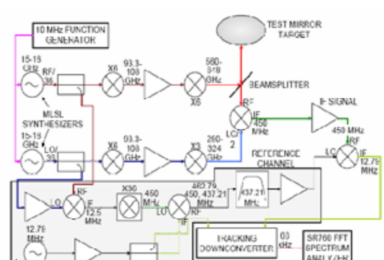


$$f_{IF} = K\tau = \frac{2KR}{c}$$

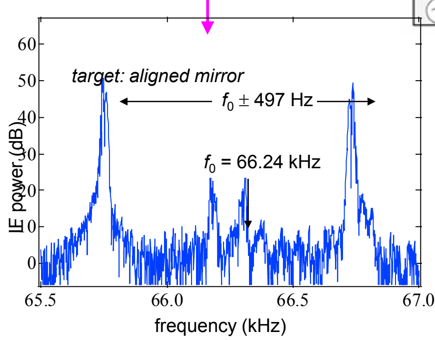
$$\delta r = \frac{c}{2\Delta F}$$

Evolution to FMCW Radar

RF and LO simultaneously chirped by slowly (1 Hz) modulating 10MHz reference!



Still, 630 GHz radar proof-of-principle achieved. First results:



$$f_{IF} = f_0 + \frac{2KR}{c} = f_0 \pm 470 \text{ Hz}$$

$f_0 =$ 66.24 kHz

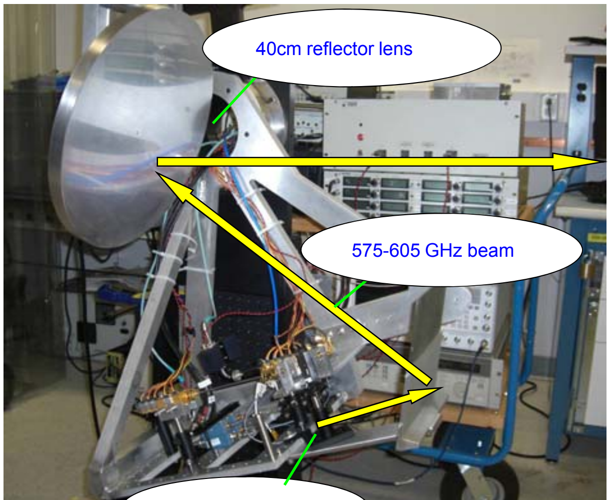
$K = \pm\frac{8 \text{ GHz}}{0.5 \text{ s}}$

$R =$ 4.4 m

$c =$ 3e8 m/s

Problems: very noisy receiver and very slow chirp speed.

THz Imaging Radar, 2008



Operating Parameters

Standoff range:
4 meters

Operating frequency:
575-605 GHz

Range resolution
<1 cm

Cross-range resolution:
<1 cm

Output power:
≤0.4 mW

Time per pixel:
6-25 m s

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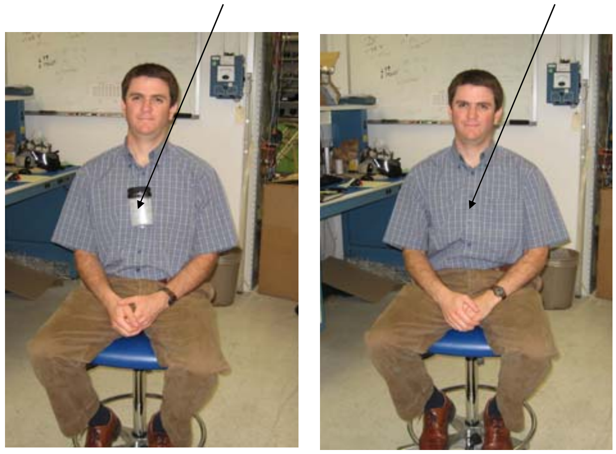
Detection of Concealed Objects on People

plastic container of BB pellets

BBs concealed by shirt



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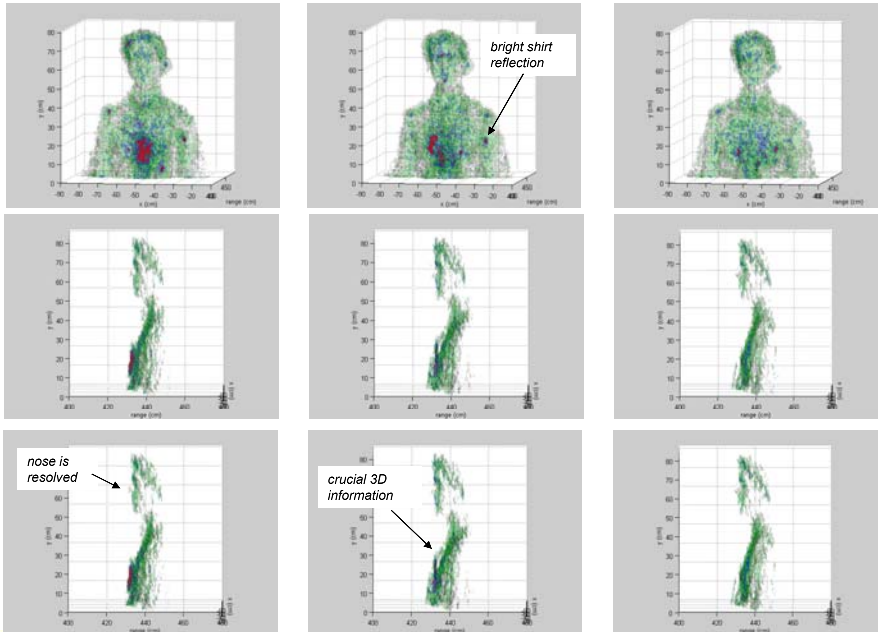
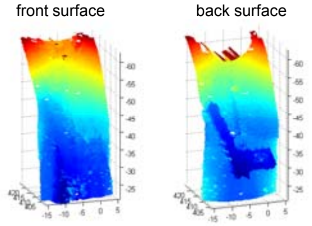
8 minute scans
100 x 110 pixels

BBs over shirt | BBs behind shirt | no BBs



Dual-Transceiver Imaging Results

front surface | back surface



(no smoothing) *660-690 GHz radar imagery*

Acquisition parameters:

- 2 x (31 x 251) = 15,562 total pixels
- 23.8 GHz chirp bandwidth (ctr. 670 GHz)
- 1.9 ms chirp duration; ≥3 ms per chirp
- 60 second acquisition time (3.9 ms/pixel)

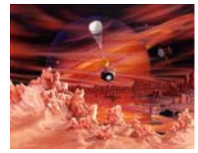
Proof of concept: multiple parallel transceivers works. Independent peak-finding from multiple channels can be integrated to generate good imagery.

Submillimeter Wave Observation Platforms

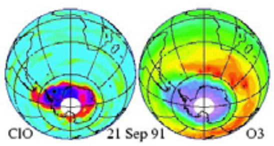
High Altitude Balloon

Airborne Platform (DC8/SOFIA)

Earth Orbiter/Sounder

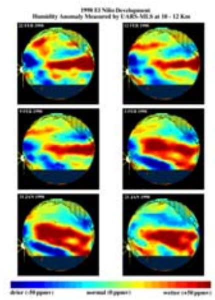


Planetary Sounder



First UARS-MLS measurement of correlation between ozone depletion and chlorine enhancement from September 1991.

NASA's Upper Atmospheric Research Satellite



Water vapor during 1997 El Nino from UARS-MLS

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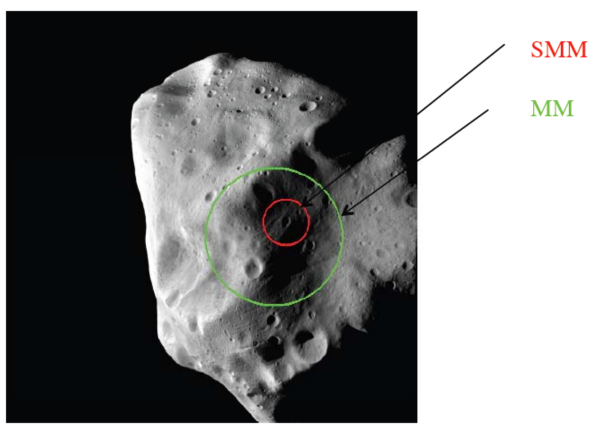
MIRO beams superimposed on Lutetia near closest approach



OSIRIS image [(c) ESA 2010 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA.]

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MIRO Instrument

STRUCTURAL THERMAL MODEL

Telescope

30 cm diameter
Boresight along z-axis of s/c

Receivers (two)

Two bands
190 GHz (1.6 mm)
563 GHz(0.5 mm)
Continuum - both bands
Spectroscopic (563 GHz only)
Single linear polarization(crossed)
Flip-mirror calibration(warm-cold-sky)

Half Power Beam Widths

Submillimeter HPBW- 7.5 arc min
Millimeter HPBW- 23.8 arc min

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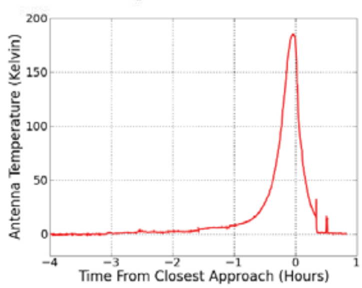
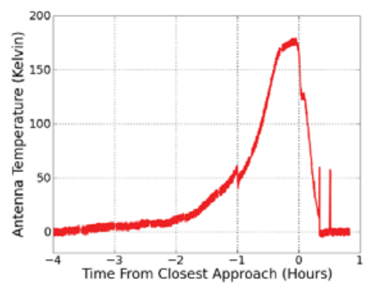
Millimeter data
Absolute accuracy
- Near CA 0.2 K
- 2nd spike after CA 0.1 K



Submillimeter data
Absolute accuracy
- Near CA 0.5 K
- 2nd spike after CA 0.9 K



Note: 1[st] spike after CA was unplanned : 2[nd] spike after CA was planned maneuver to determine the c-axis dimension

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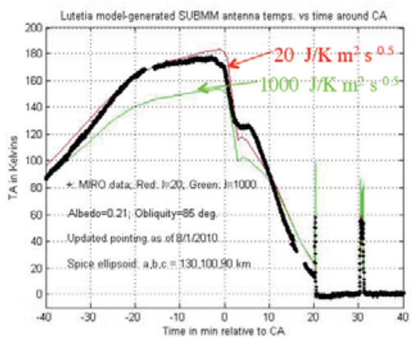

- Triaxial Ellipsoid Shape
  - {130, 100, 90}
- Thermal Inertia
  - Red 20 J/K m^2 $s^{0.5}$
  - Green 1000 J/K m^2 $s^{0.5}$
- Low thermal inertia is required to fit the data !
- Lunar Regolith (powder layer 1-2 cm thick) parameters provide a very good fit

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Biomedical application

http://news.bbc.co.uk/2/hi/science/nature/368558.stm

Sci/Tech

X-ray substitute to test teeth

The terahertz image on the right reveals enamel thickness

The spectroscopic mode shows up a tooth cavity

Toshiba Research Europe (TRE) is developing the method at the Cambridge Science Park, UK. Its managing director, Professor Michael Pepper says: "These are very early days, but it is clear that Terahertz Pulse Imaging is going to be very important, particularly in areas where X-rays are insensitive."

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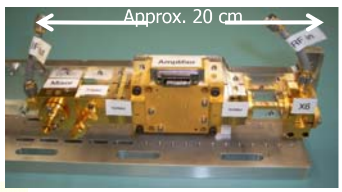
What is next?

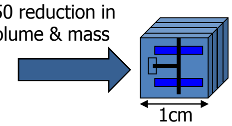
- Most receivers deployed at these frequencies have been single pixel and fairly bulky systems
- Two important considerations require a paradigm shift in terms of how we build these receivers for the future
  - This decade will witness a renewed focus on exploring planets in our solar system in the submillimeter-wave range. These missions, and especially the ones focused on the outer planets will require extremely light weight payloads.
  - Both for planetary science as well as applications on Earth, imaging arrays are now feasible (given the tremendous improvement in backend processing). Large count arrays will require that each receiver is low-mass, low-power and extremely small.

Develop an ultra-compact receiver which is compatible with array architecture

SOA 500-600 GHz Receiver Front End



x 50 reduction in volume & mass



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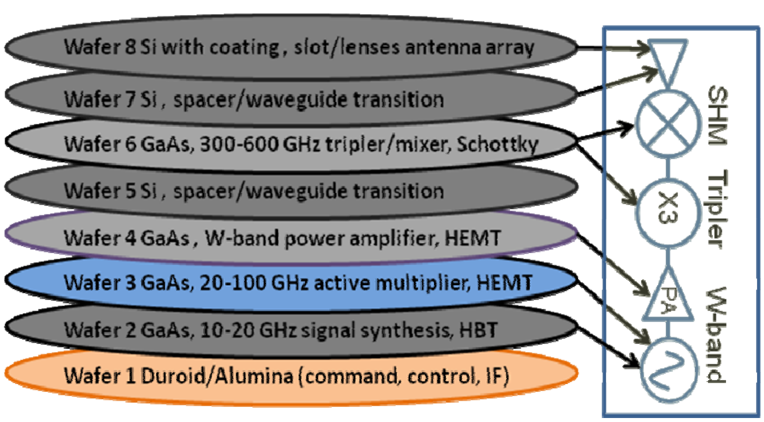
Radiometer-On-Chip (ROC) concept

- This novel architecture uses a stack of micro-machined wafers for waveguide components and interconnections, and MMIC based GaAs wafers for amplifiers, multipliers and mixers.



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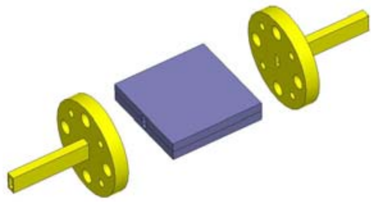
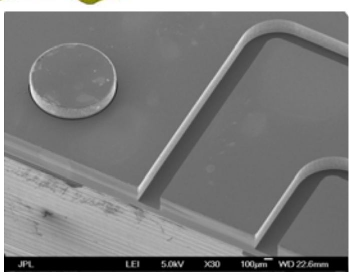
Si-metal waveguide interconnections

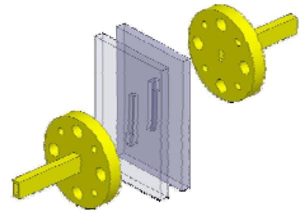
- 1st option: from the side of the Si wafer.





Commonly used approach

- 2nd option: from the flat of the Si wafer.



Our approach for interfacing

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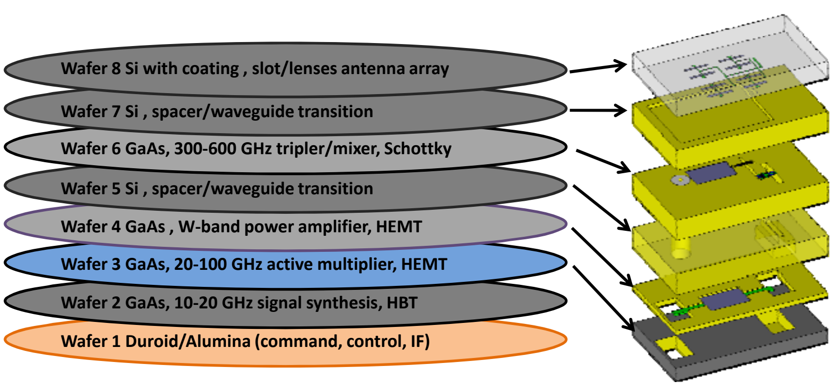
ROC modified for proof-of-concept

- Instead of more expensive GaAs wafers use Si wafers with discretely mounted GaAs based devices.



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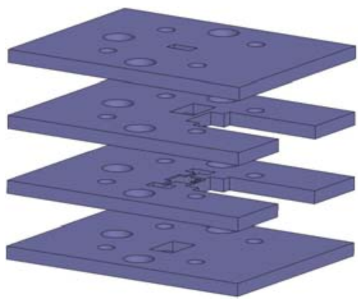
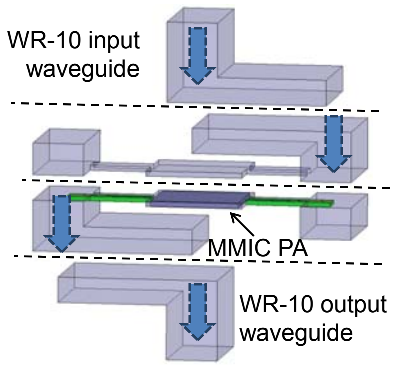
Si based W-band power amplifier

- 4 Si layers are required to package a pHEMT amplifier chip, waveguide transitions and bends.
- DC bias circuit is also included in the Si block.





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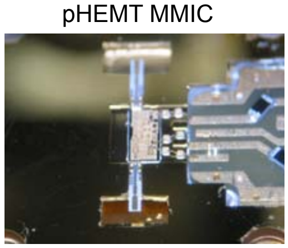
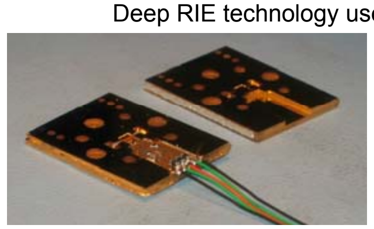
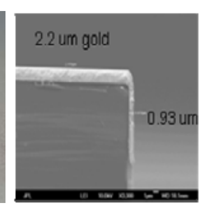
Si based W-band PA assembly

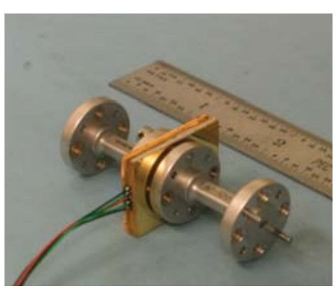
pHEMT MMIC



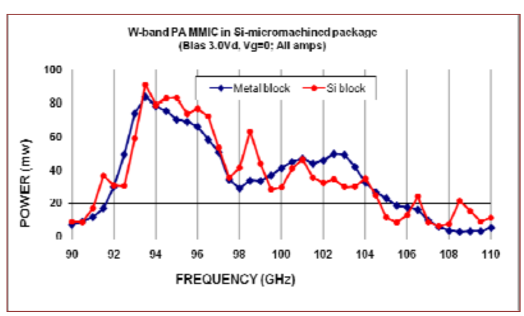
Deep RIE technology used to fab Si







Completed module is only 7 g



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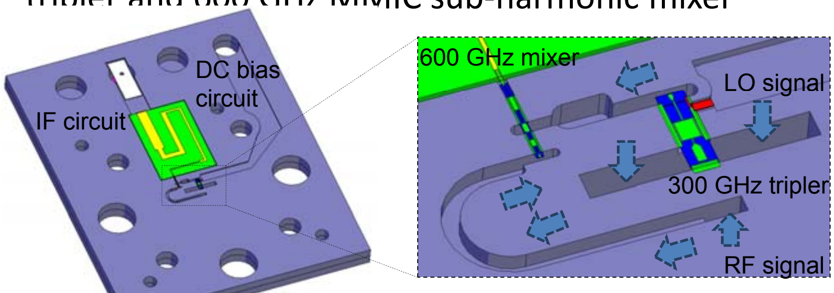
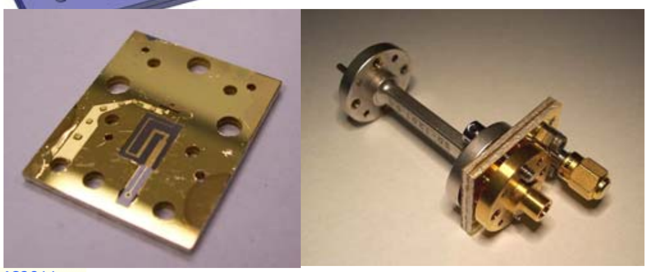
Si based 560 GHz RFE

- Integrate in a Si package (4 layers) a 300 GHz MMIC tripler and 600 GHz MMIC sub-harmonic mixer





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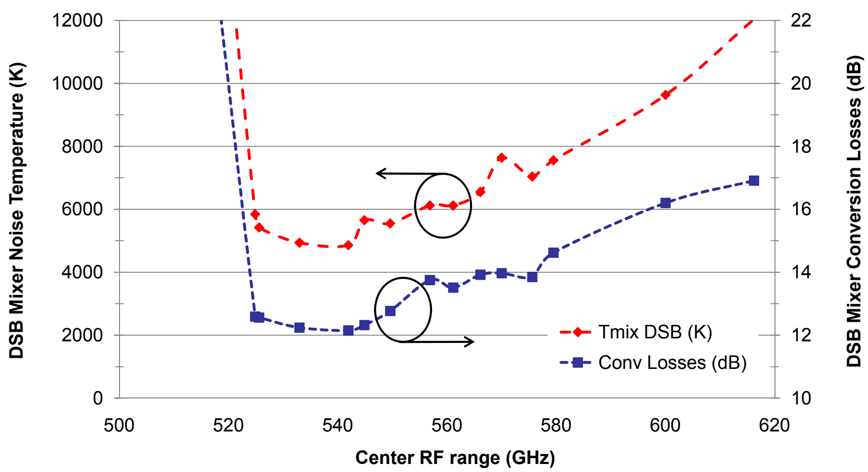
Si based 560 GHz RFE test

- IF frequency: 4 GHz. Not corrected for IF mismatch.
- Fundamental input power at W-band : 30-50 mW



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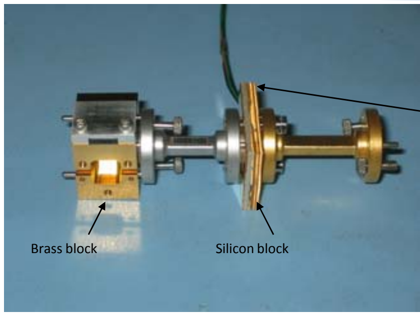
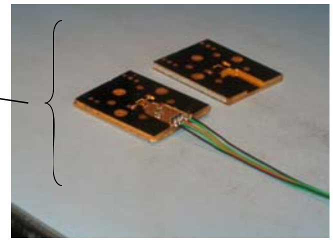
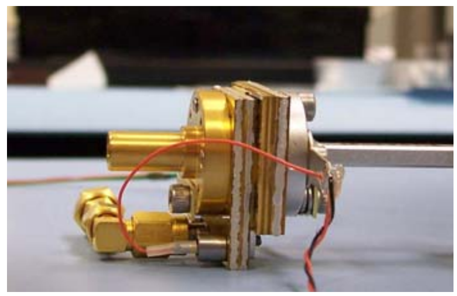
Radiometer-on-a-chip





* DRIE technology and wafer-bonding technology are combined to assemble silicon based waveguide blocks
• Demonstrated with w-band power amp
• Demonstrated with 600 GHz RFE
• Provides technology to achieve massive power combining



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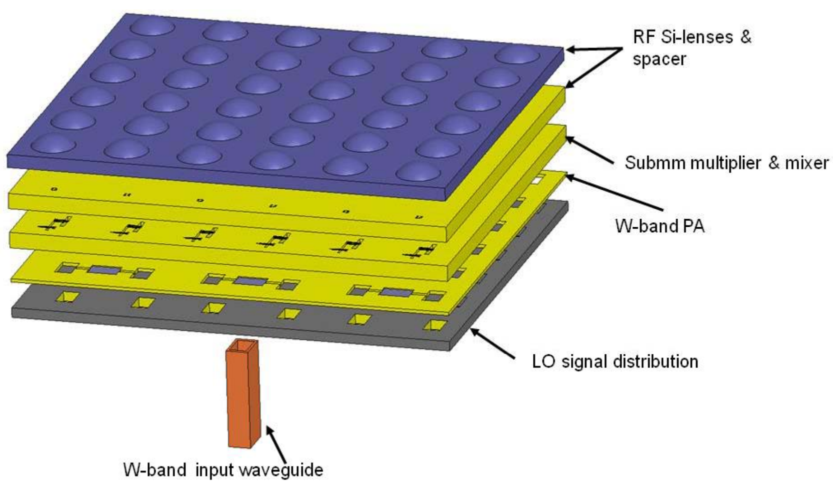
Towards a 2D array…



Work is currently underway to develop an imaging array using Si micro-lenses

Summary: Critical needs going forward

- **Smaller packages** (packaging, functionality …)
- **Better devices/circuits** (innovative circuits, higher BW)
- **Higher efficiencies** (DC and RF)
- **Multiple pixels** (Arrays, LO injection…)
- **Robust scalable back-ends** (digital…)
- **Standardized testing** (protocols, procedures, and equipment)
- All this with reduced cost.
- **A commercial THz 'killer-app' is still elusive, but I feel that improving technology will lead to new and novel applications**

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