A 183 GHz Humidity Sounding Radar Transceiver

ACT-13

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Objectives

- We are developing a radar transceiver, tunable over the 183 GHz water absorption line, to enable high-resolution humidity sounding inside upper-tropospheric clouds.

- The proposed measurement will use the technique of differential absorption radar.

- The key transceiver performance targets are:
  - 1 W transmit power
  - Frequency-modulated, continuous wave (FMCW) radar operation
  - 5% tuning of center frequency
  - 500 K receiver noise temperature
  - Compact, all-solid-state semiconductor design

- Our approach builds on proven short-range radar systems JPL has developed at 340 and 680 GHz for national security applications.

Scientific Motivation

- Clouds are the single most important source of uncertainty in predictions of climate sensitivity.
- Upper-Tropospheric (UT) humidity affects cloud formation and radiative feedback, and therefore accurate measurements are needed for climate modeling.
- Conventional UT humidity measurements rely on passive radiometric sounding using the strong 183 GHz water vapor absorption line.
- Problem: passive radiometry is unreliable inside clouds because: (1) broad weighting functions are used that encompass both clouded and cloud-free regions and (2) clouds obscure the relationship between passive brightness temperatures and water vapor.
- Isolated observations show large relative humidity variability in UT cirrus clouds, spanning 50-150%. These variations are not currently quantified globally.
- Therefore, a remote sensing instrument capable of measuring humidity inside cirrus clouds on a global scale is needed.

Connections to Decadal Survey and Other Applications

- Science Focus Area: Climate Variability and Change.
  - UT humidity disproportionally affects water vapor feedback
  - Ice crystal habit, nucleation, and growth are driven by UT humidity, and they couple to earth's radiative transfer and global energy/water cycles

- A 183 GHz humidity sounding radar will be complementary to two missions: ACE (cloud/aerosol microphysics) and PATH (temperature and humidity soundings).

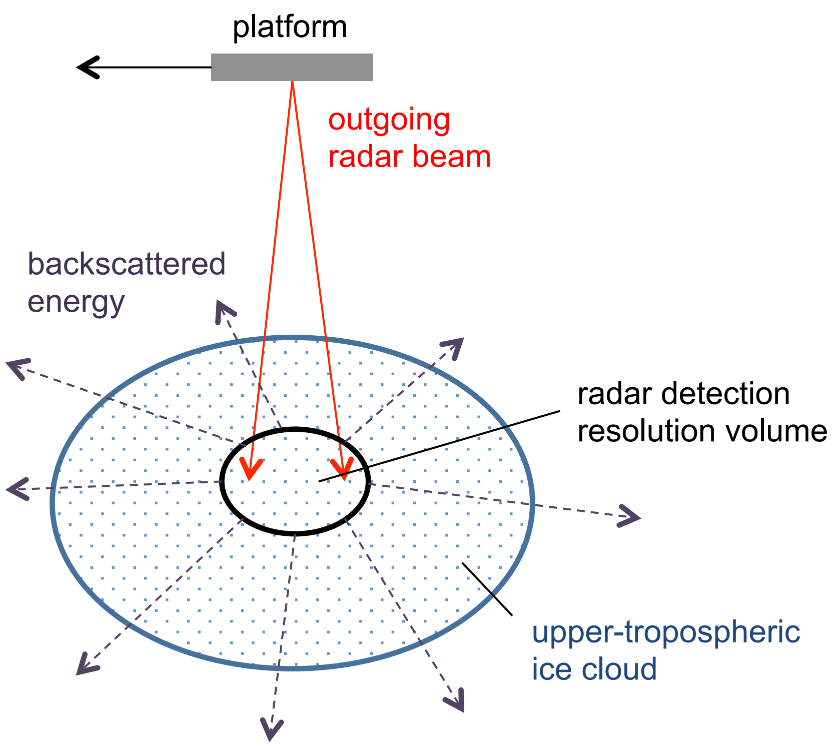
- The radar will leverage technology developed by several past ACT & IIP investments in extremely high frequency amplifiers (PIs Fung, Kangaslahti, Reising, and Lambrigsten) using state-of-the-art III-V semiconductor processes.

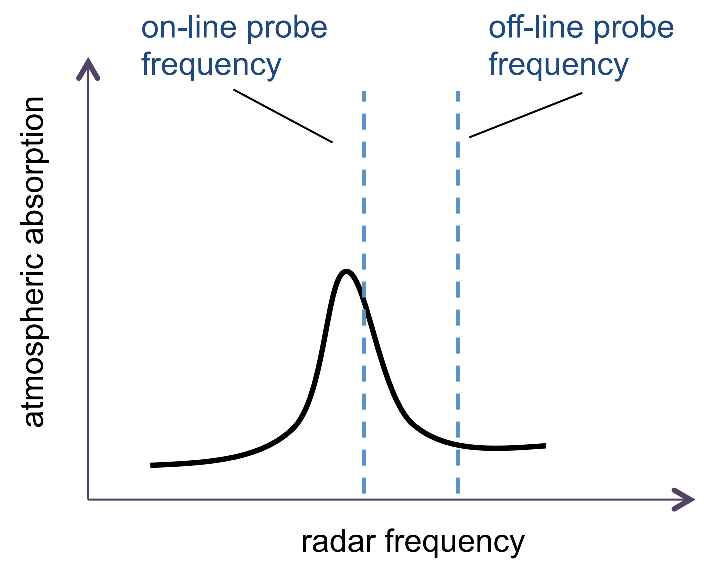
- Compact transceiver is appropriate for UAV and CubeSat platforms (e.g., no vacuum tube sources), and it has potential for measuring accurate cloud heights for moisture retrieval model accuracy.

- If re-tuned to 220 GHz atmospheric transmission window, the transceiver enables: measurements of particle size distributions, cloud-penetrating altimetry, low-altitude cloud sensing above arctic ice cracks, and national security applications.

JPL's Approach: 183 GHz Differential Absorption Radar

- *Concept*: use the scattering of ice crystals in cirrus clouds to measure range-resolved differential absorption of radar signals on and off the 183 GHz water line.
- Similar to widely used lidar techniques (DIAL) and microwave differential absorption at 60 GHz to measure integrated O_2 absorption from sea surface reflection.
- But our concept offers **range resolution** inside clouds, **wide frequency tuning** to penetrate clouds with large dynamic range of water content, and measurement capability **from above or below** clouds.

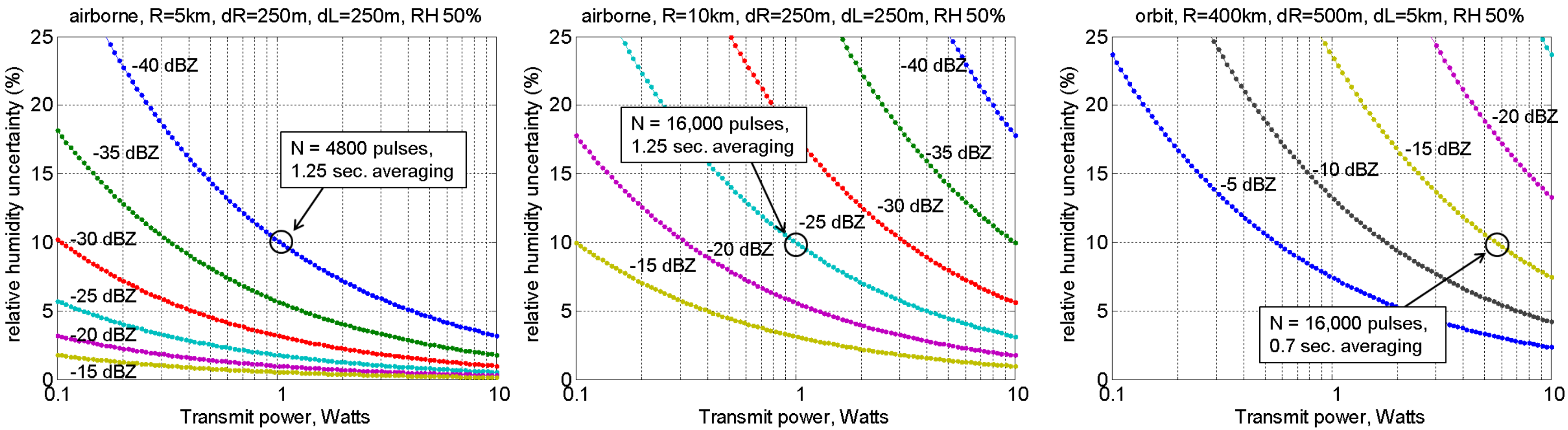




Preliminary Performance Modeling

	Airborne	Orbital
along-track resolution	250 m	5 km
range resolution	250 m	500 m
platform velocity	200 m/s	7 km/s
receiver noise temperature	500 K	500 K
antenna diameter	50 cm	250 cm
distance from clouds	5 or 10 km	400 km
UT relative humidity	50%	50%
on/off-line absorption	0.4/0.02 dB/km	0.4/0.02 dB/km
cloud reflectivity	-40 to -15 dBZ	-20 to -5 dBZ

<u>Conclusion:</u>
A 183 GHz transmit power of 1 Watt, with 50 cm diameter antenna, is sufficient for high-accuracy humidity measurements inside clouds from an airborne platform.

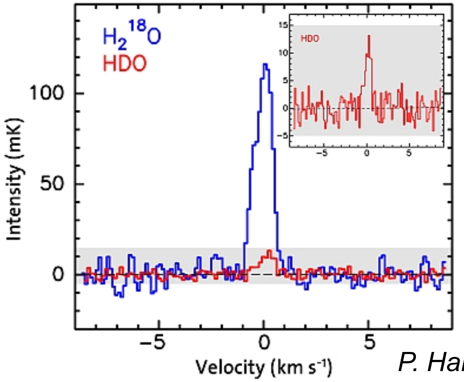


Flight Heritage for 183 GHz Radar Proposal

HIFI on Herschel Space Telescope

Launched in 2009

480-1250 GHz,
1410-1910 GHz
heterodyne spectrometers



Comet 103P/Hartley's water's isotopic ratio matches the Earth's!

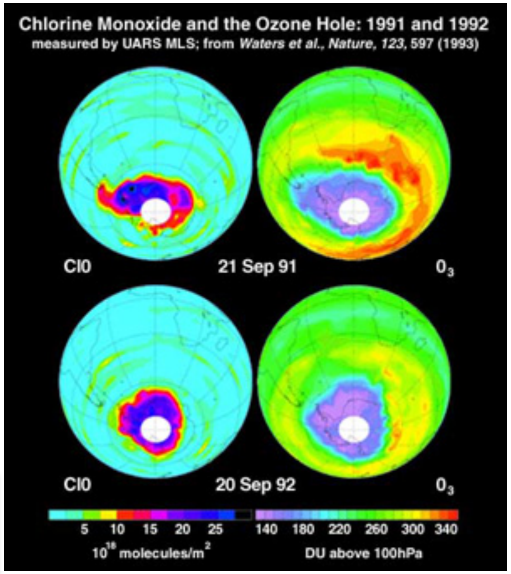
P. Hartogh et al., 2011

ozone hole monitoring:

EOS-MLS

Launched in 2004

118, 190, ... 2250 GHz radiometers

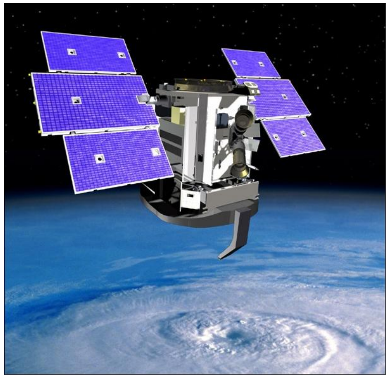


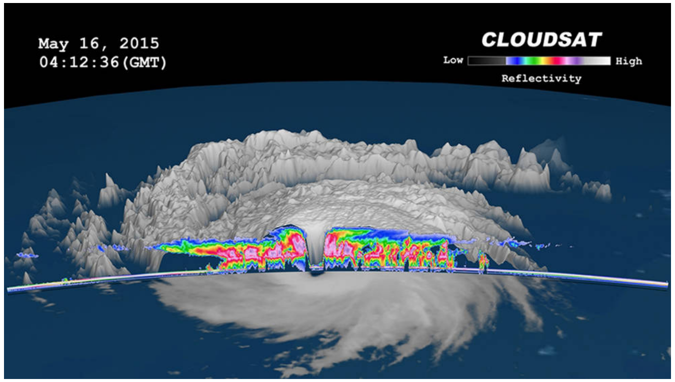
CloudSat

Launched in 2006

94 GHz radar (vacuum tube source), 1.85 m antenna, -28 dBZ sensitivity

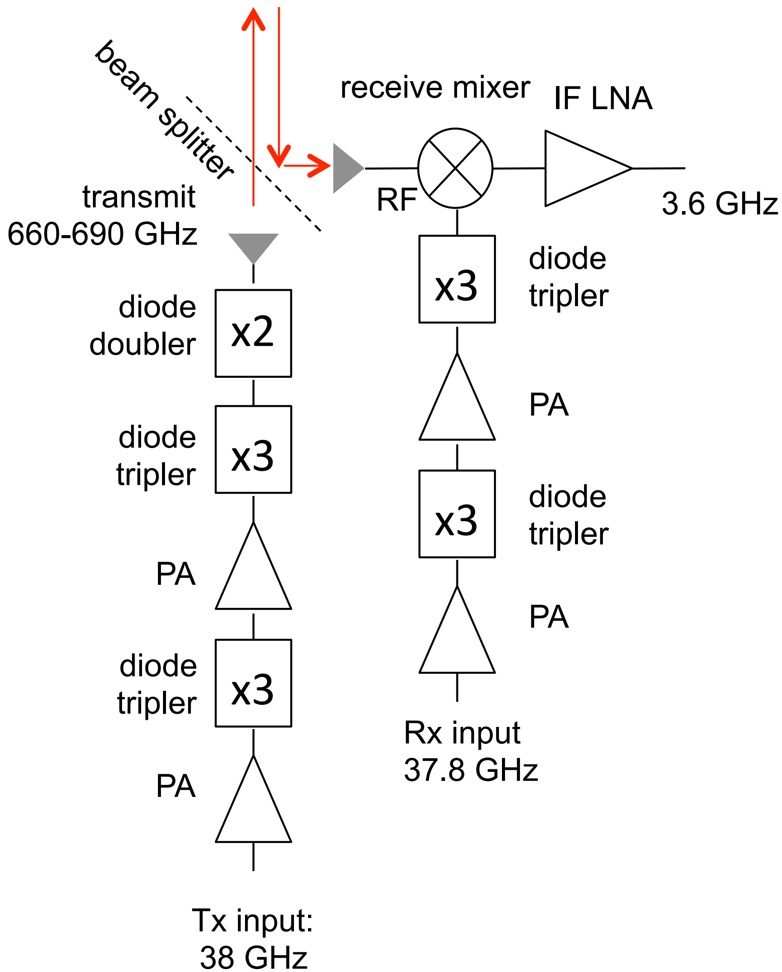
Typhoon Dolphin, 2015

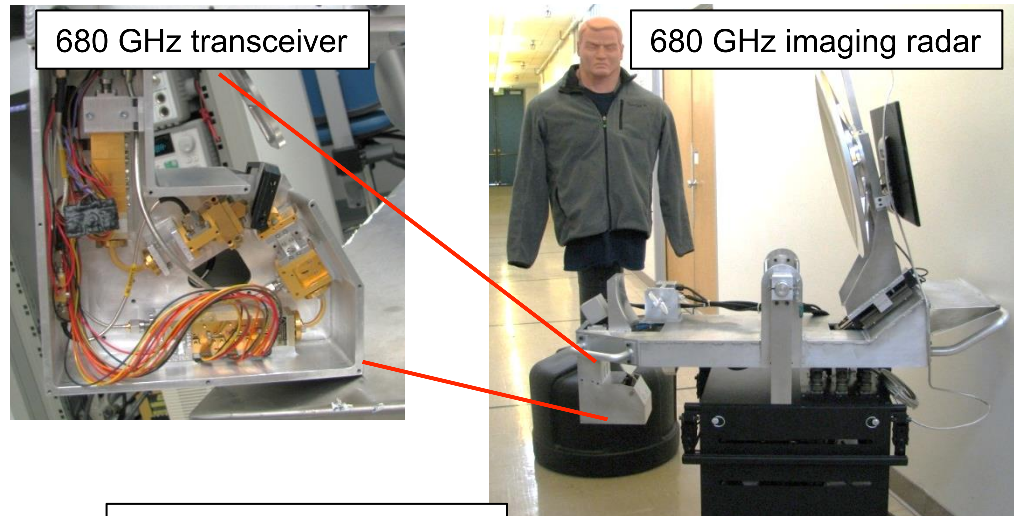


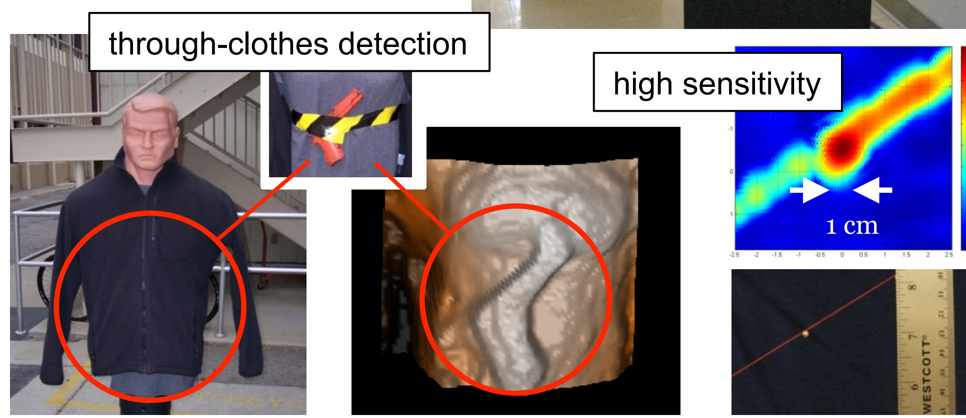


JPL's FMCW Radars Above 300 GHz

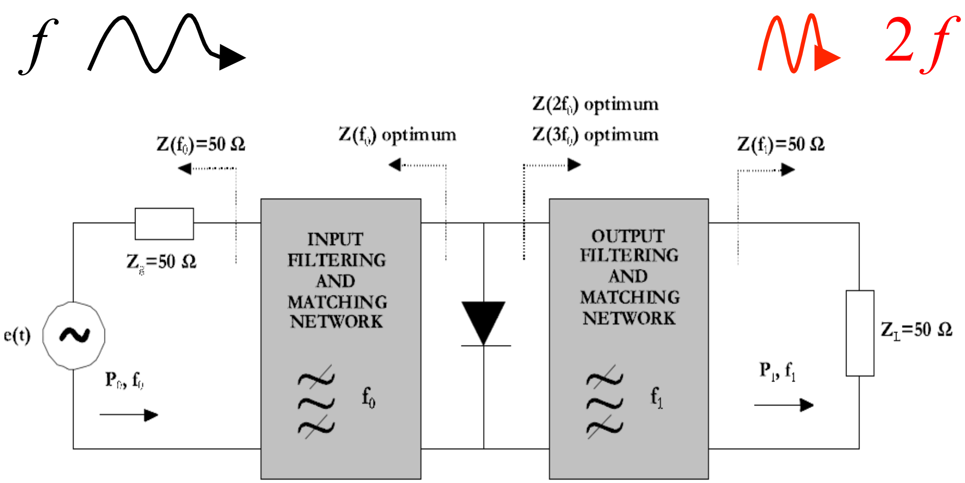
Frequency-modulated continuous wave (FMCW) radar: appropriate when available power is limited.

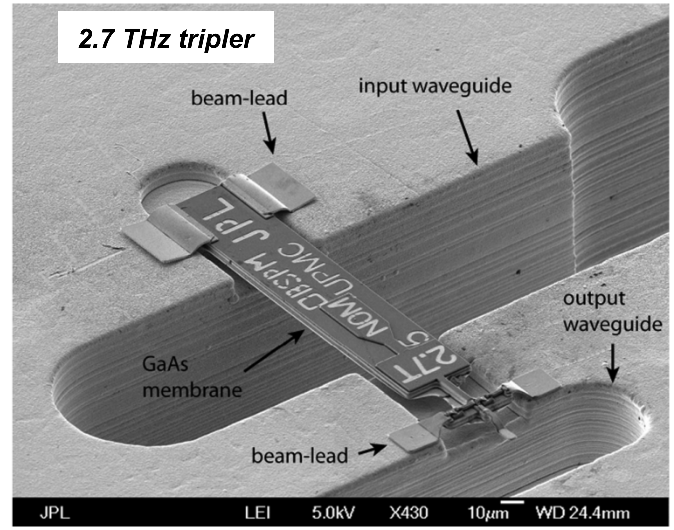






Generating Power >100 GHz at JPL

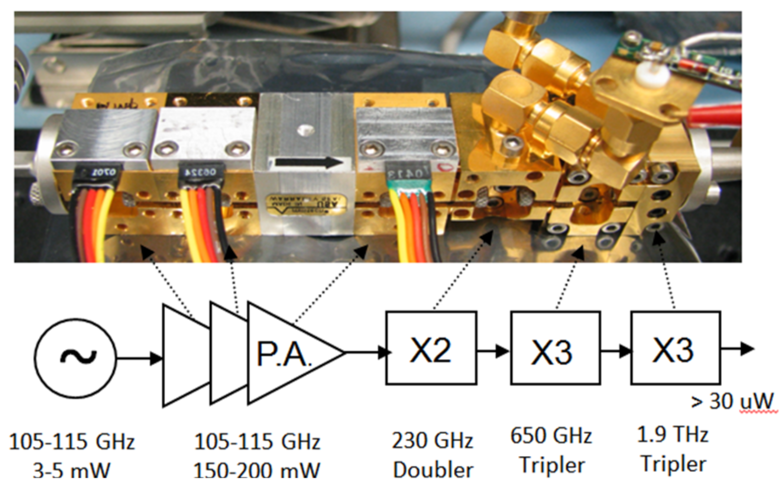




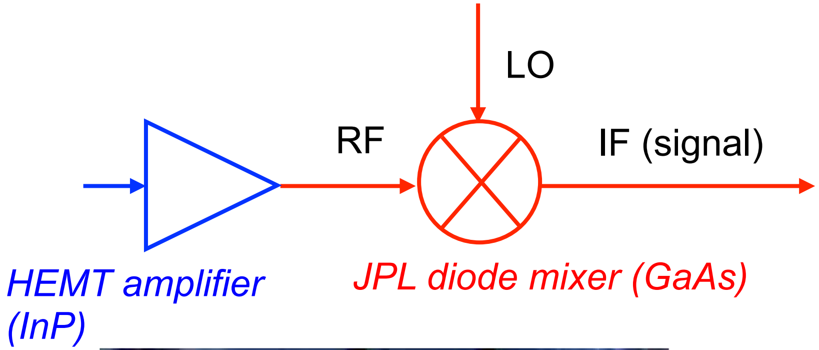
Schottky diode fabrication process:
9 masks, 135 processing

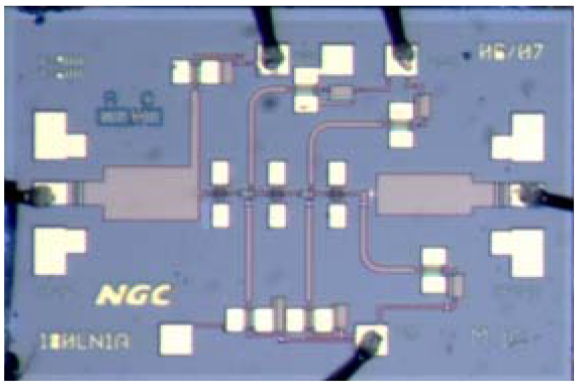
Typical Schottky diode output power:
120 mW @ 200 GHz
0.018 mW @ 2.7 THz
Typical bandwidth: 15-20%

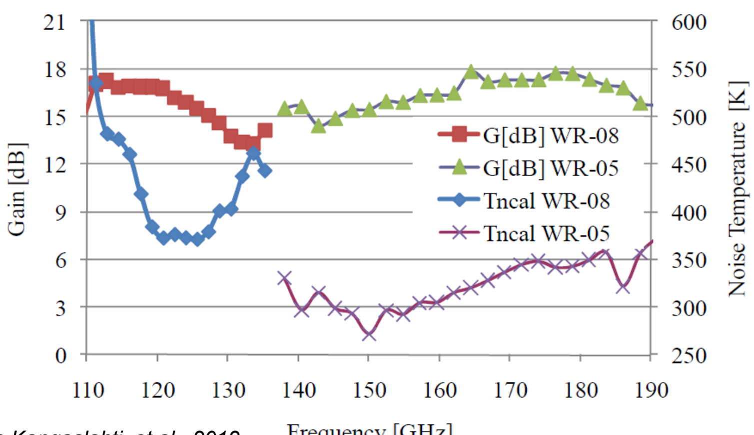
1.9 THz source



Detecting Signals >100 GHz at JPL

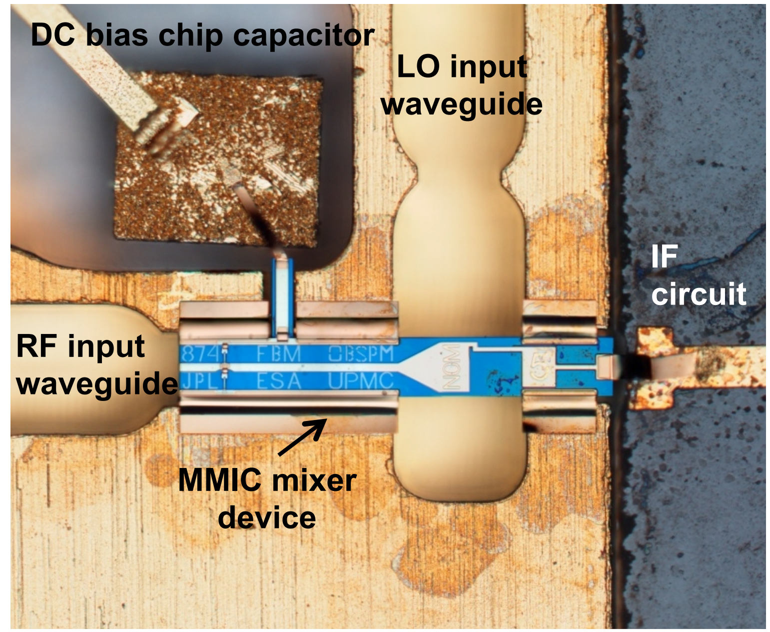


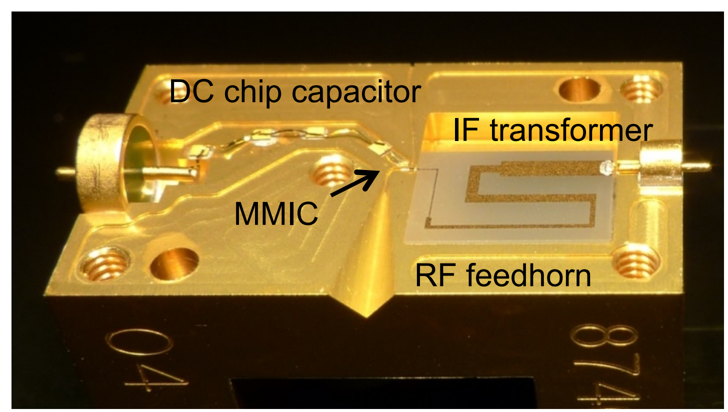




Pekka Kangaslahti, et al., 2012

850 GHz fundamental balanced mixer

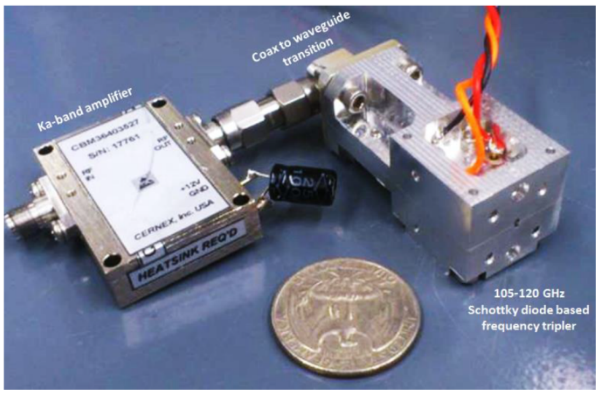


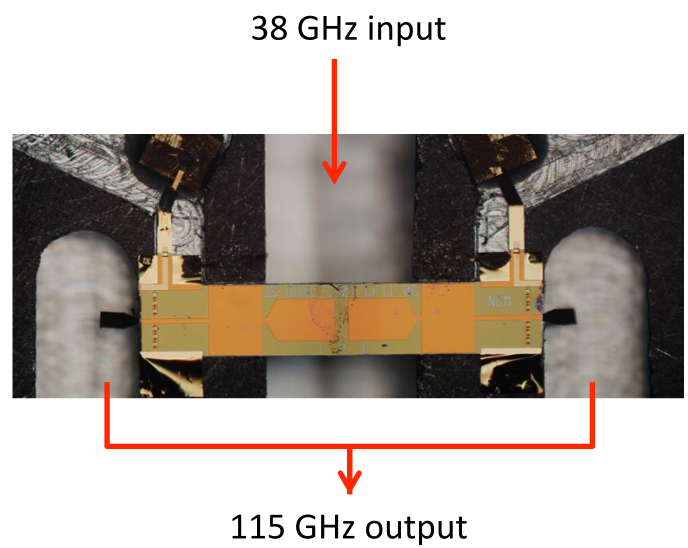


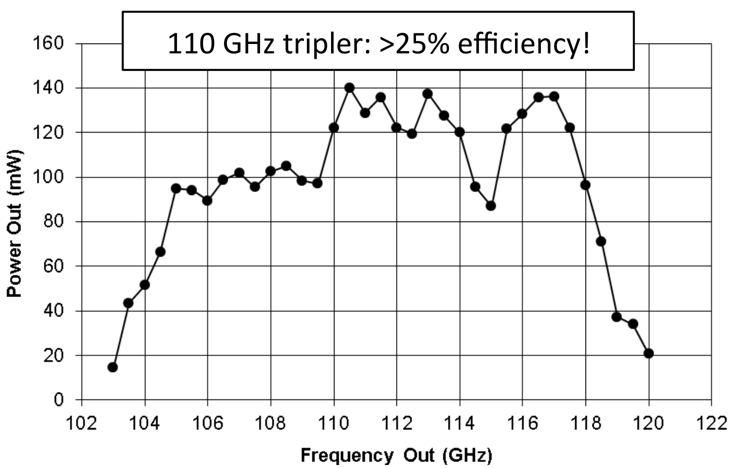
Bertrand Thomas, et al., 2010

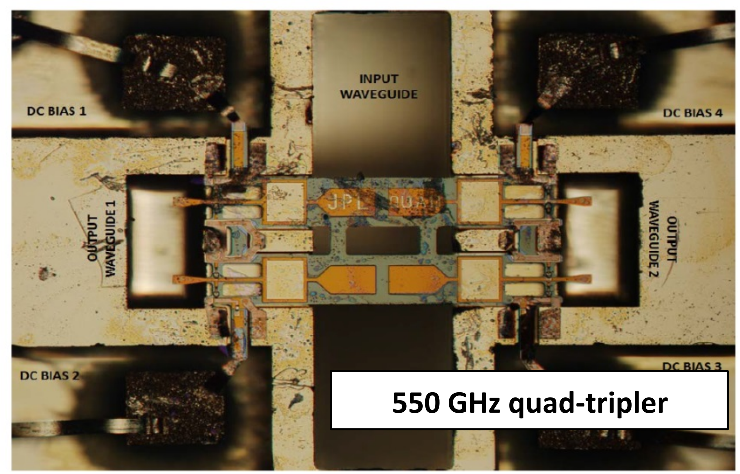
Maximizing Schottky Diode Power and Efficiency

Breakthrough power-combining technique for Schottky diode frequency multipliers.





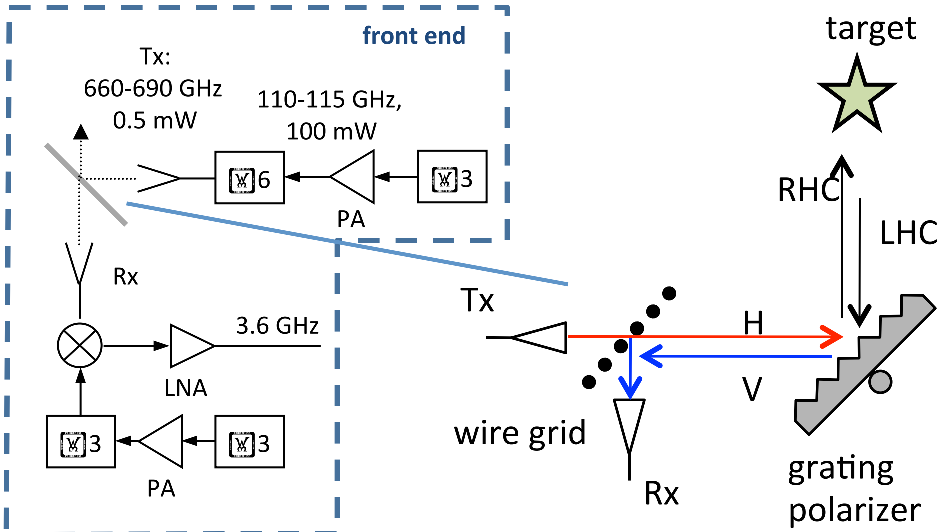


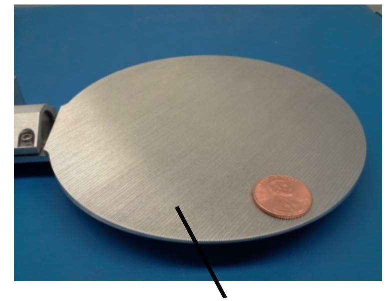


Jose Siles, et al., 2015

High-Isolation Duplexing >100 GHz

Quasioptical Duplexing:

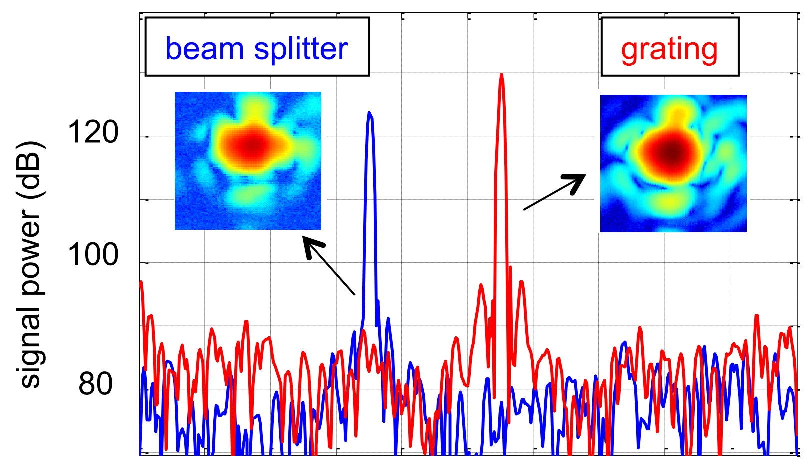




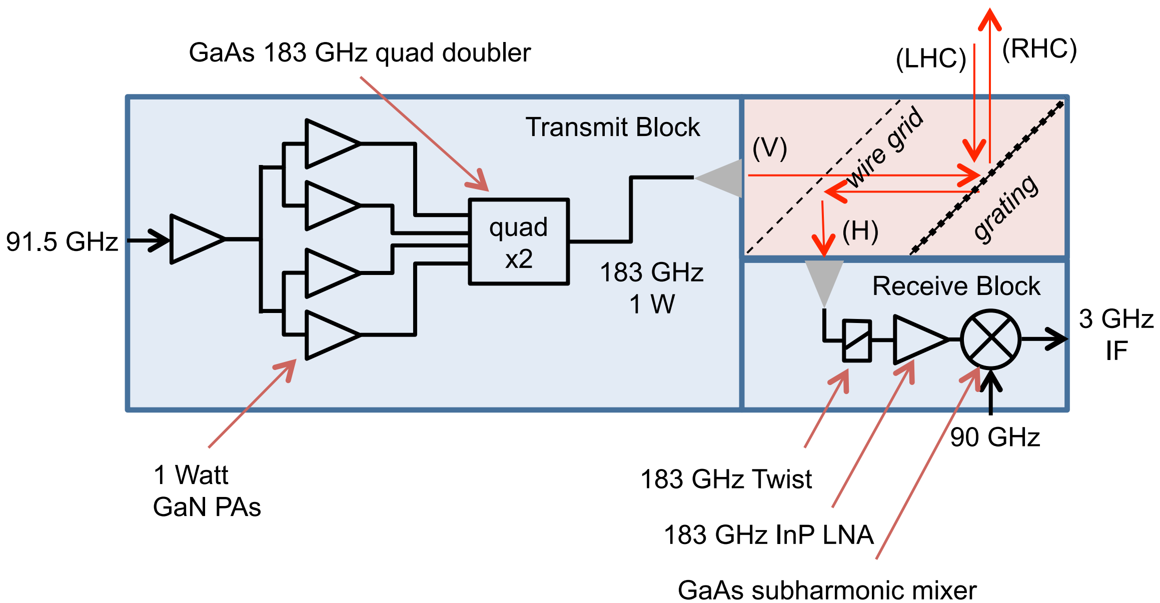
>90 dB isolation!

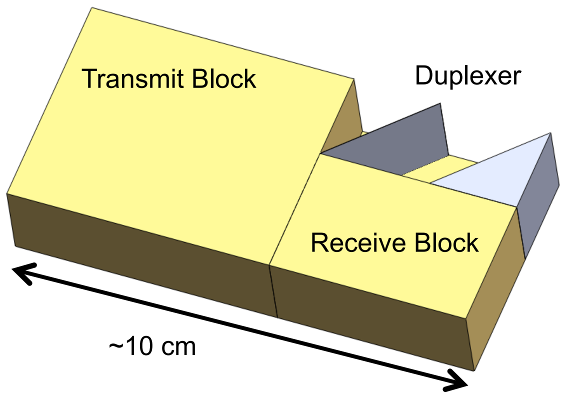
grating polarizer:
0.285 mm period

6 dB grating advantage



183 GHz Transceiver Plan

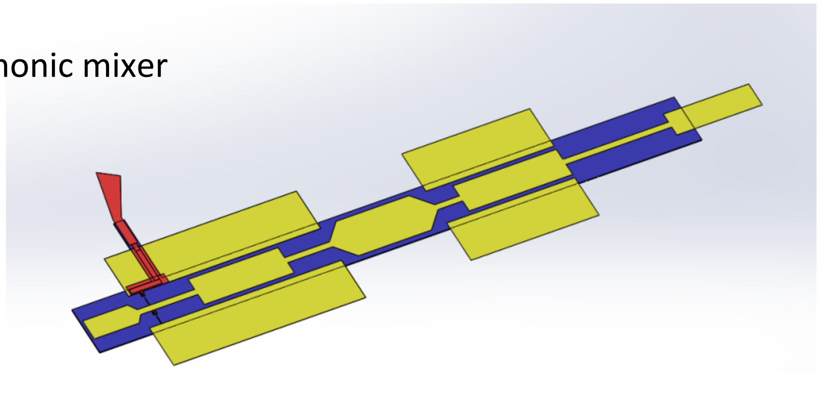


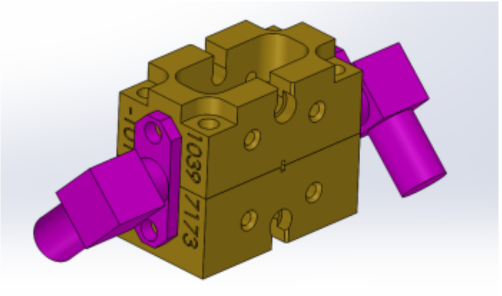


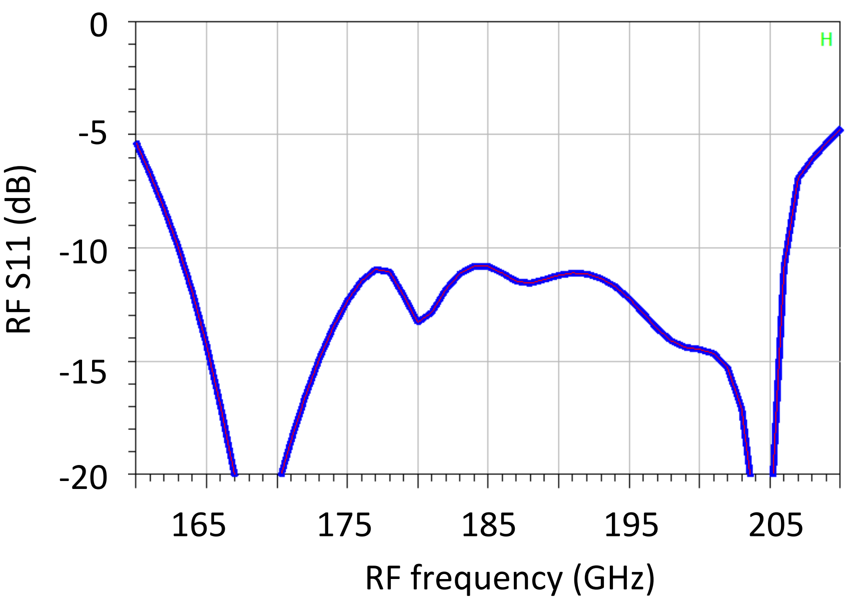
- All-solid-state, room-temperature 183 GHz transmitter & receiver to achieve smallest SWAP.
- Highest transmit power practical & most sensitive receiver possible, to measure backscattered signals from the weakest clouds.
- Ultra-high transmit/receive isolation for continuous-wave measurements.
- Wide tunability over the 183 GHz water line for probing a variety of cloud densities and depths.
- First develop transceiver as piecewise-component assembly, then integrate multiple devices into single block(s).

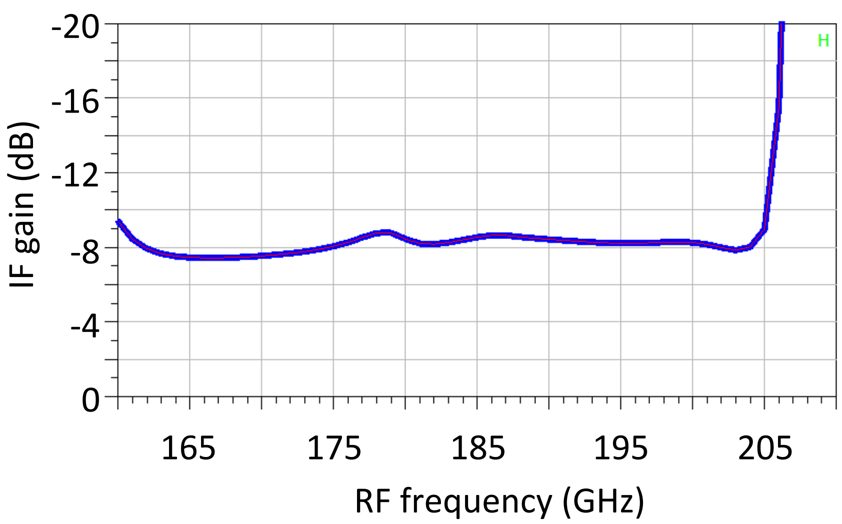
Schottky Diode Designs

183 GHz subharmonic mixer



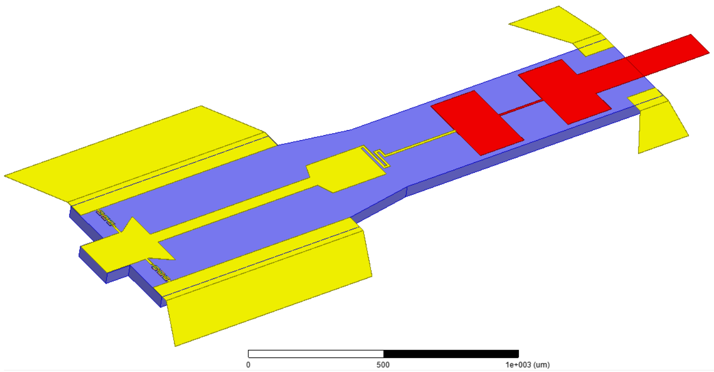




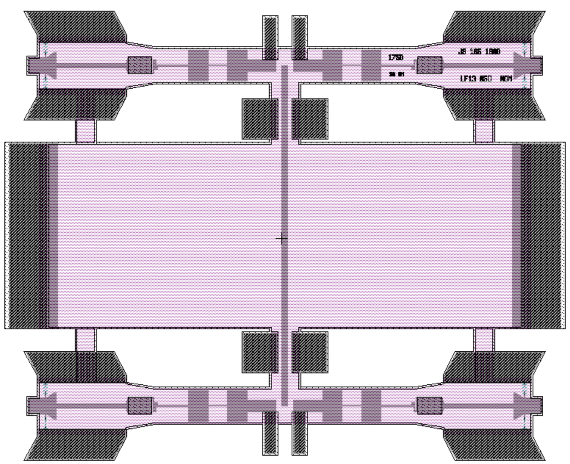


Schottky Diode Designs

183 GHz high-power frequency doubler



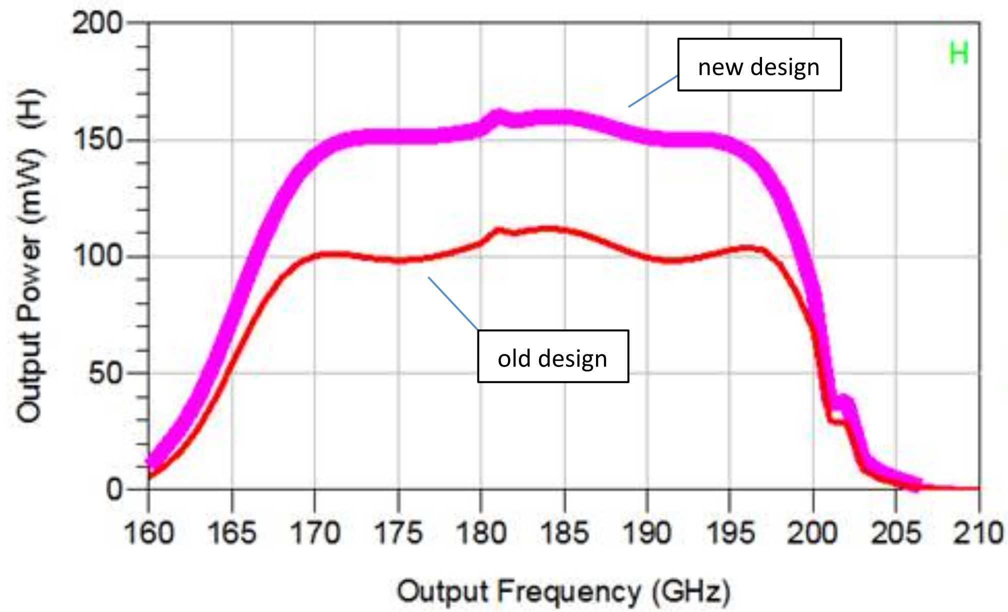
quad version: on-chip power combining



	junction capacitance	optimized input power
old design	54 fF	250 mW (per diode set)
new design	69 fF	500 mW (per diode set)

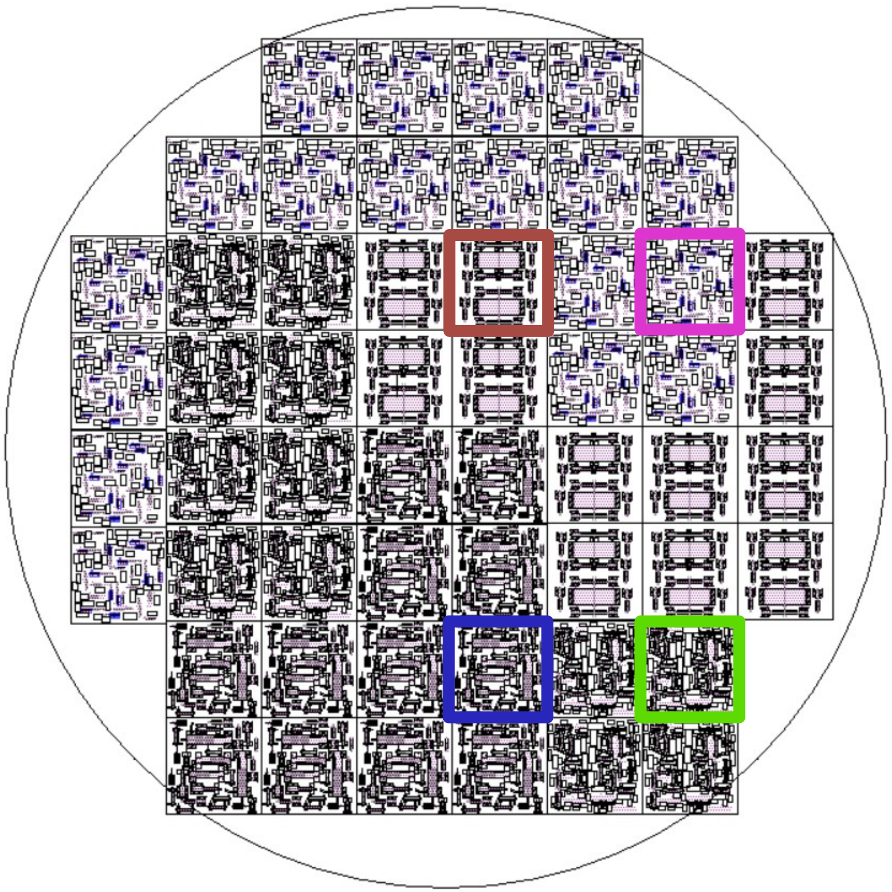
Enabling design innovations:

- bigger anode for power handling
- substrate for heat conduction



Diode Microfabrication

Wafer Map



Devices fabricated for seven projects.
4 GaAs wafers processed simultaneously.

183 GHz doubler (single & quad)

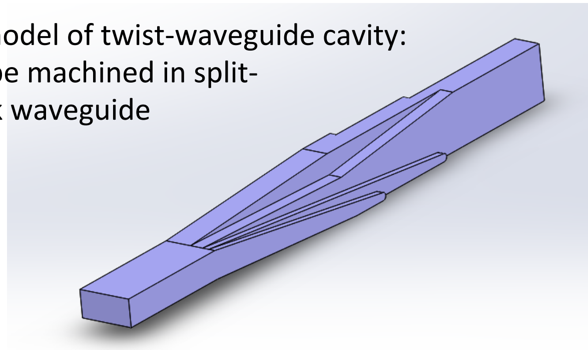
devices for other projects

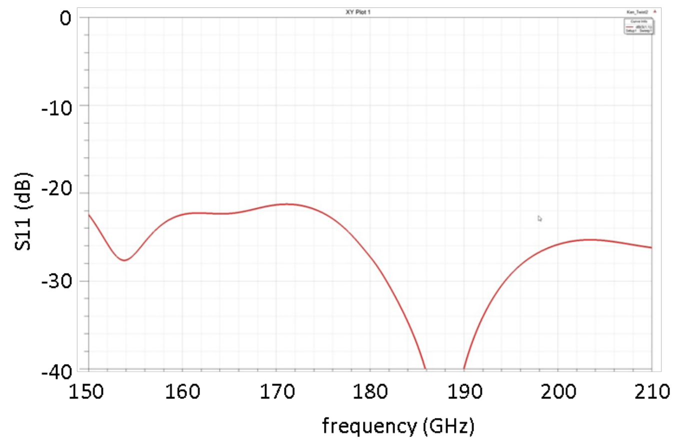
183 GHz mixer + devices for other projects

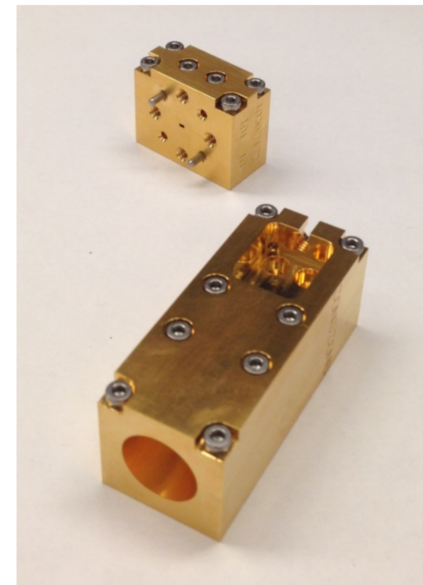
devices for other projects

Horn & Twist Designs

3D model of twist-waveguide cavity: can be machined in split-block waveguide

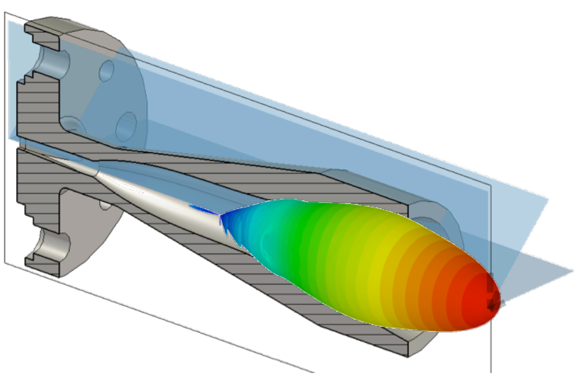


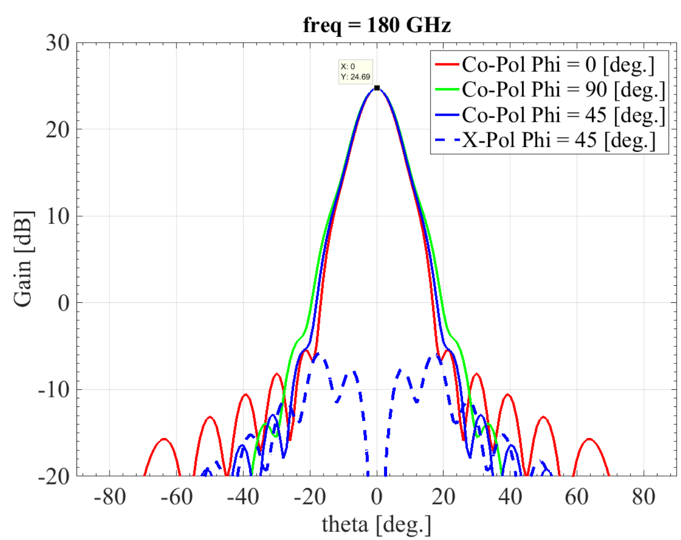




Smooth-walled spline 183 GHz horns:

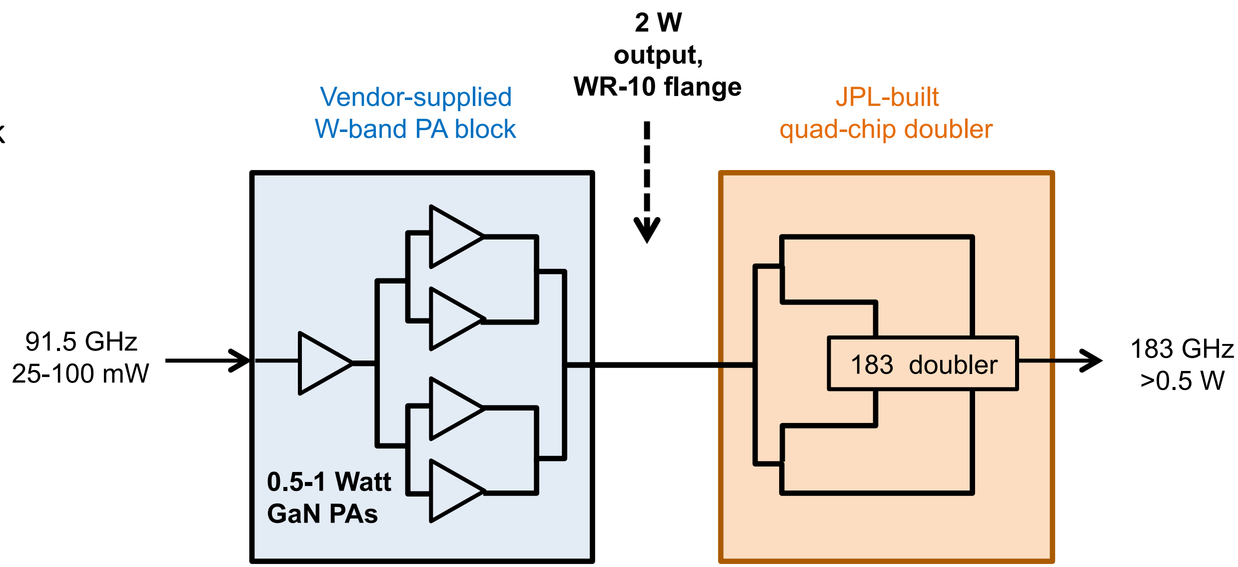
- Highly Gaussian beams
- Very low sidelobes and low cross-pol
- Ensures maximum duplexer isolation
- Easily machined (compared to corrugated)



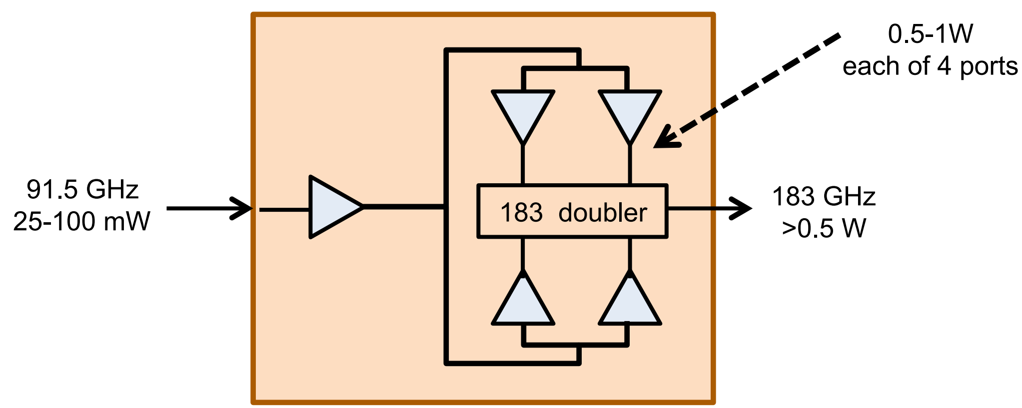


W-Band Power Amplifier Plan

<u>Year 1 Plan:</u>
"standard" vendor PA block driving JPL quad-input doubler. The doubler block includes power dividing.

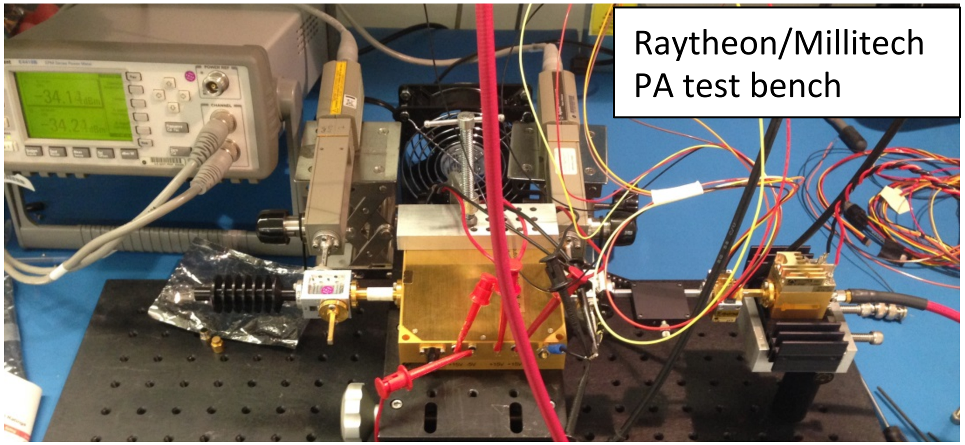


<u>Year 2 Plan:</u>
Custom block combining waveguide routing and MMIC pockets to hold both JPL's 183 doubler and the vendor PAs in a compact module.

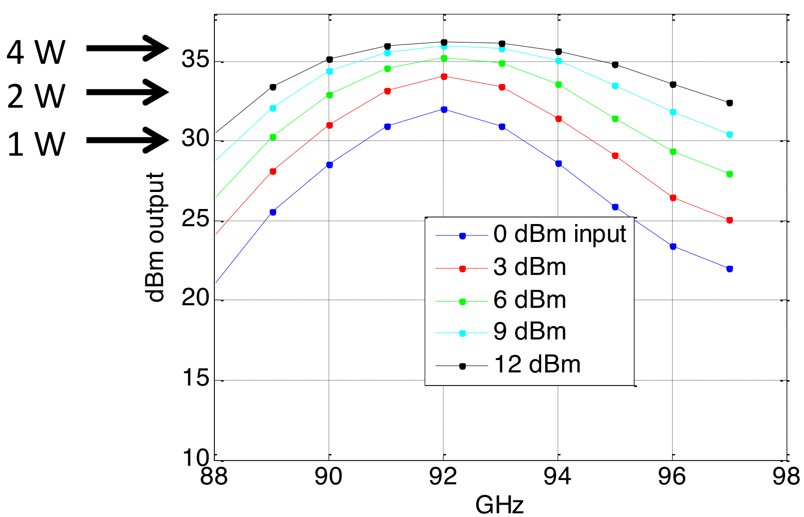


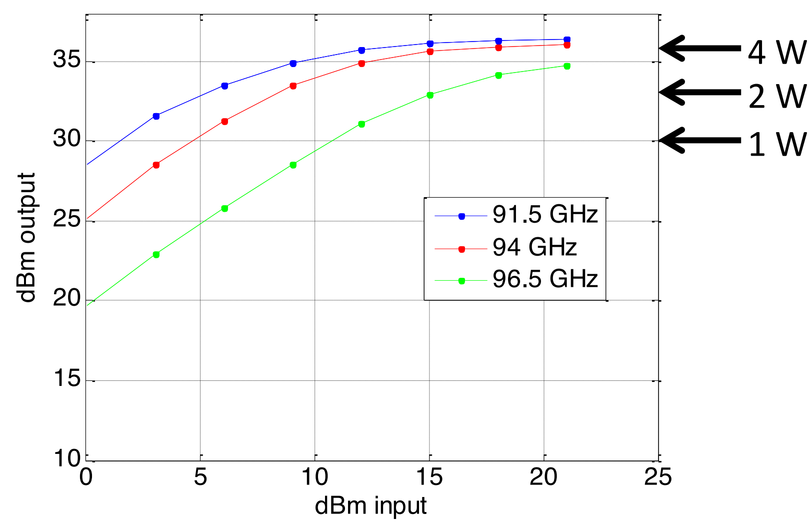
(<u>Year 2/3 Plan:</u> two power-combined quad doublers)

W-Band Power Amplifier Testing



- Achieves >2 W goal over 91.5-96.5 GHz
- Easily exceeds 4 W at 92 GHz!
- Must make choice between operating on lower or upper flank of 183 GHz line. These devices are appropriate for upper flank (183-193 GHz -> 91.5-96.5 GHz).
- Lower-flank of water line offers somewhat smaller background absorption, but W-band PAs are optimized for 94 GHz atmospheric transmission window (e.g. Raytheon's Active Denial System).
- Ready to test high-power quad-doubler with this module





Conclusions

- 183 GHz differential absorption is a promising technique for measuring range-resolved humidity inside upper-tropospheric clouds.

- FMCW-based radar approach is proposed, relying on:
  - all-solid-state semiconductor devices for compact size, wide frequency tuning
  - high efficiency, high power Schottky diode frequency multiplication
  - state-of-the-art W-band power amplifiers
  - high isolation transmit/receive duplexing

- Highlights of progress to date:
  - New diode designs for 183 GHz doubler, 183 GHz mixer
  - Block designs for waveguide twist, spline-profile horn, power splitting/combining structures, low-noise amplifier, and W-band tripler
  - Demonstrated >2 W GaN amplifier module to pump new quad-183 GHz doubler diodes