Development of a Multi-band Radar on a Photonic Integrated Circuit (PIC)

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Team

- Requirements
- Waveform Design
- Breadboard Testing
- Final Testing

Team Member – Lihua Li, GSFC

- Resonator Design
- Resonator Fabrication
- Resonator Coupling
- Breadboard Testing
- Packaging Design
- Laser/PD Coupling
- PIC Radar Integration

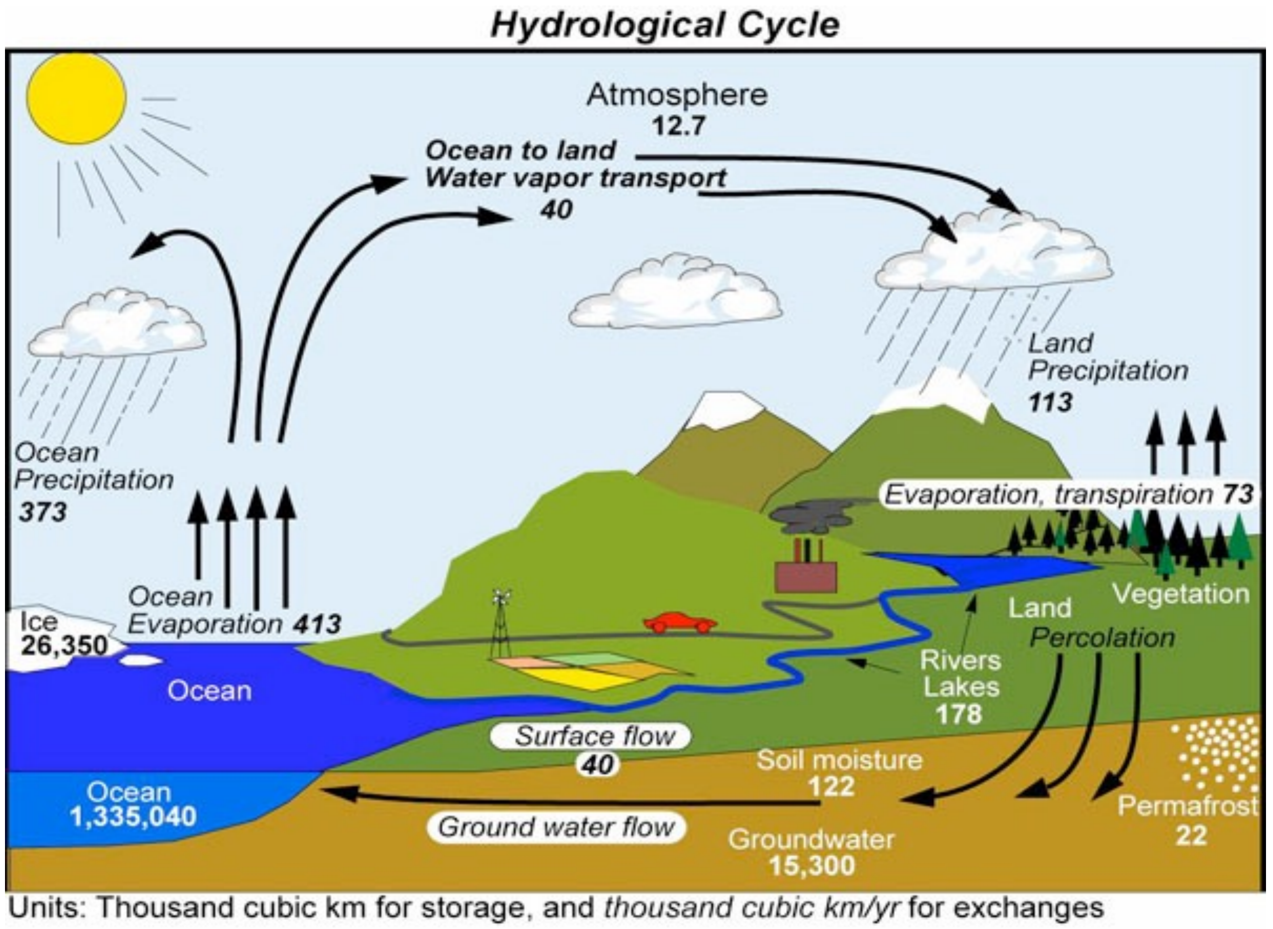
Team Members – Lute Maleki (PI), Scott Singer, Danny Eliyahu, Kayla Kulish, George Keseyan, Yu-Hung Lai, Miguel Maldonado

- Radar PIC Design
- Radar PIC Fabrication
- Lithium Niobate Integration
- PIC Characterization

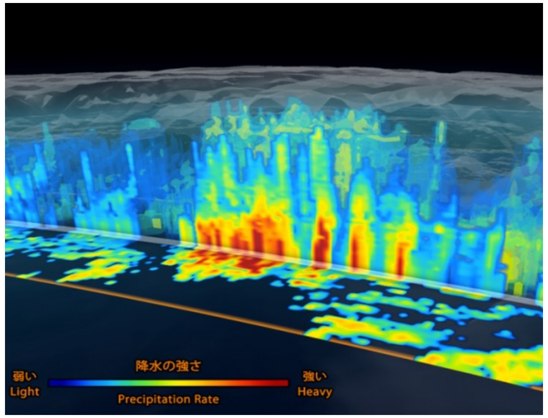
Team Members – Ben Yoo, Zhixing Li, Georgios Charalampous

Science Motivations of Radar Remote Sensing

- Clouds and precipitation are among the greatest sources of uncertainty in climate change prediction.
- Global-scale cloud and precipitation measurements are critical to understanding Earth's hydrological cycle and energy balance in response to climate change.




Convective storm seen by ER-2 pilot, 5/2014



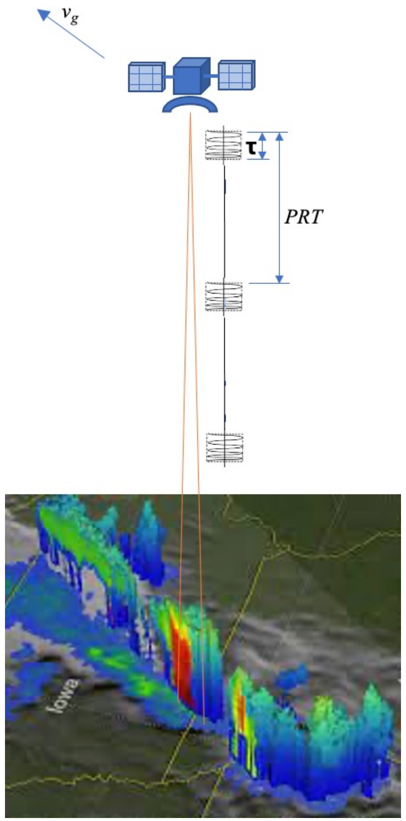
TRMM 13 GHz satellite radar image illustration of a storm system

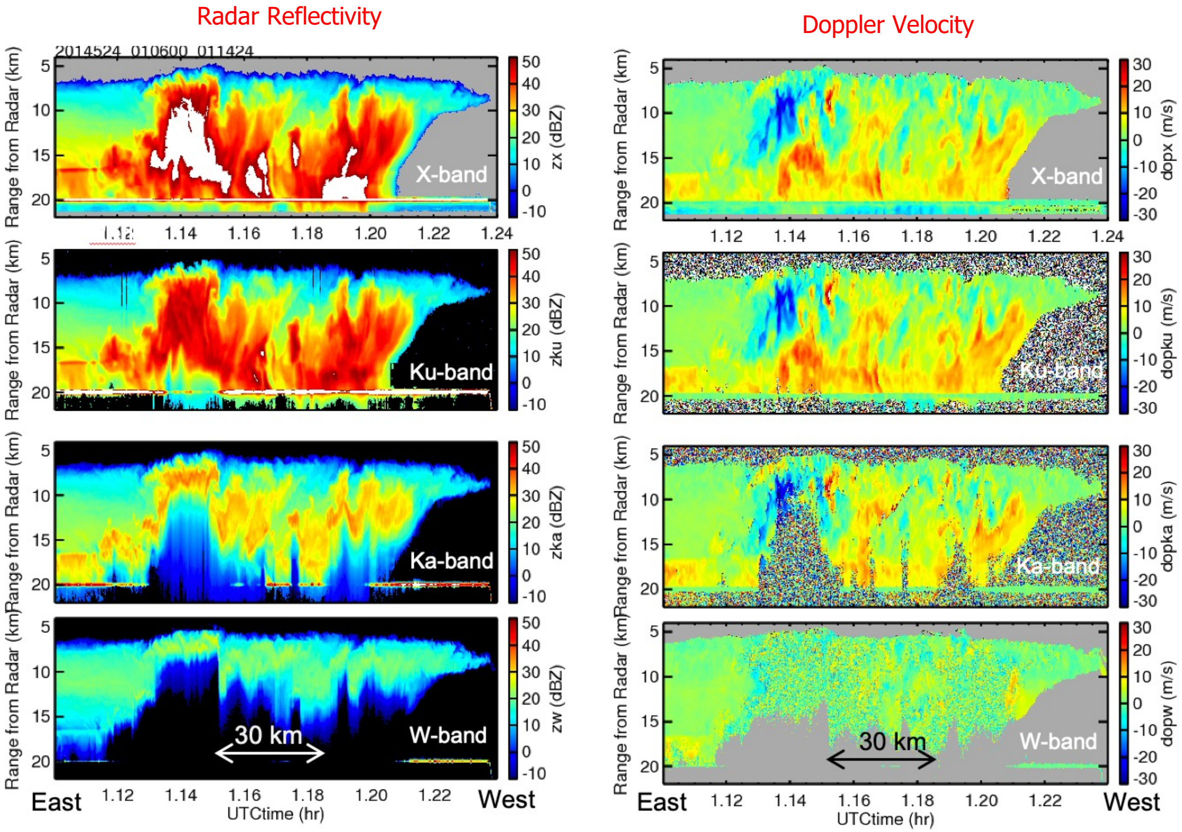
Science Motivations of Radar Remote Sensing (cont'd)

- Multi-frequency radar with high sensitivity, Doppler and imaging capability is critical for improved understanding of the characteristics of clouds, precipitation, and their interaction.
- NASA Decadal Survey (DS) Atmospheric Observation Systems (AOS) mission will include Ku, Ka and W-band Doppler radars as its key sensors.

- Multi-frequency reflectivity measurements provide quantitative estimates of <u>Ice Water Path (IWP), Liquid Water Path (LWP), particle size, and particle phase</u> with much higher accuracy than single frequency radar measurements.

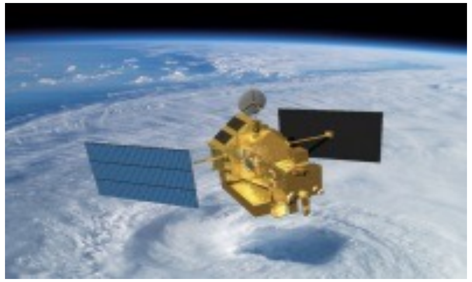
- Doppler velocity provides information on vertical air motion, convective up- and down-draft, particle size and classification (ice or water drops), and latent heat transportation.



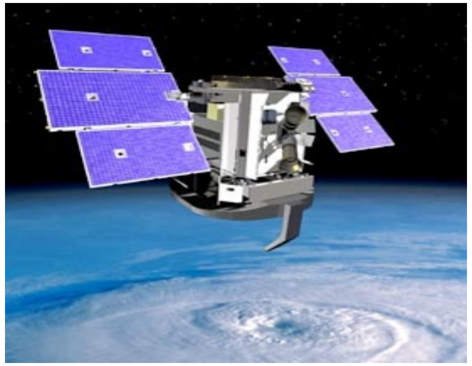


GSFC airborne radars EXRAD (X-band),HIWRAP(Ku/Ka), and CRS (W-band) measurements on ER-2 during IPHEx, 5/24/2014.

Spaceborne & GSFC Airborne Remote Sensing Radars



TRMM 13 GHz precipitation radar



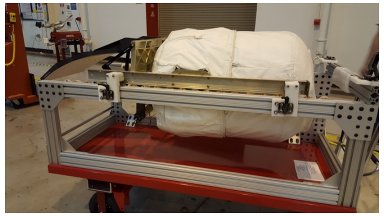
CloudSat 95 GHz cloud radar

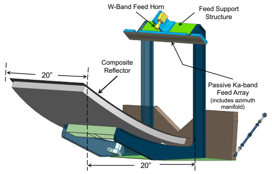
GPM 13/35 GHz Dual-frequency radar

GSFC Airborne Radars for NASA High-altitude Aircrafts

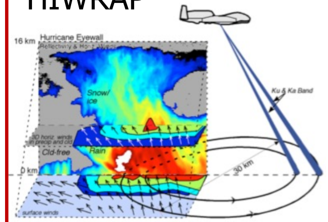
	CRS	HIWRAP	EXRAD
Frequency (GHz)	94.15 (W-band)	13.47, 13.91 (Ku-band) 33.72, 35.56 (Ka-band)	9.60 (X-band)
Transmitter Type/ Peak Power(W)	SSPA / 30 W	SSPA / 40-80 W	TWT / 9000 W
Antenna Size / Beamwidth (inches/ degree)	20 / 0.45^o	18.5 / 1.2^o Ka-band, 3.1^o Ku-band	26 / 3.4^o
IF Frequencies	160 MHz, 2.0 GHz	220 MHz (Ku), 920 MHz (Ka)	35 MHz, 65 MHz
Waveforms & Pulsewidth (μs)	2.0 (pulse), 20 (chirp)	2.0 (pulse), 20 (chirp)	0.5 (pulse)
Vertical Range Resolution (m)	37.5-150	37.5-150	75
Pulse Repetition Frequency (KHz)	4-5	4-5	4-5

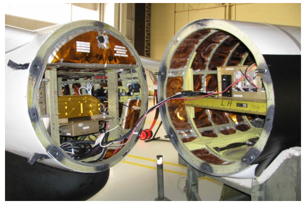
CRS

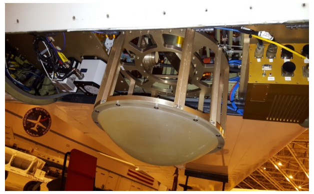


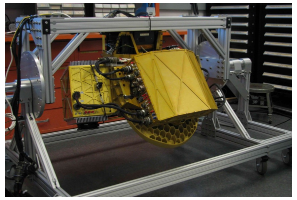


HIWRAP

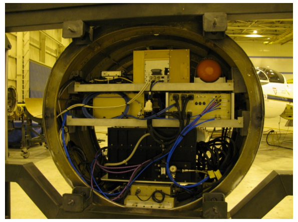




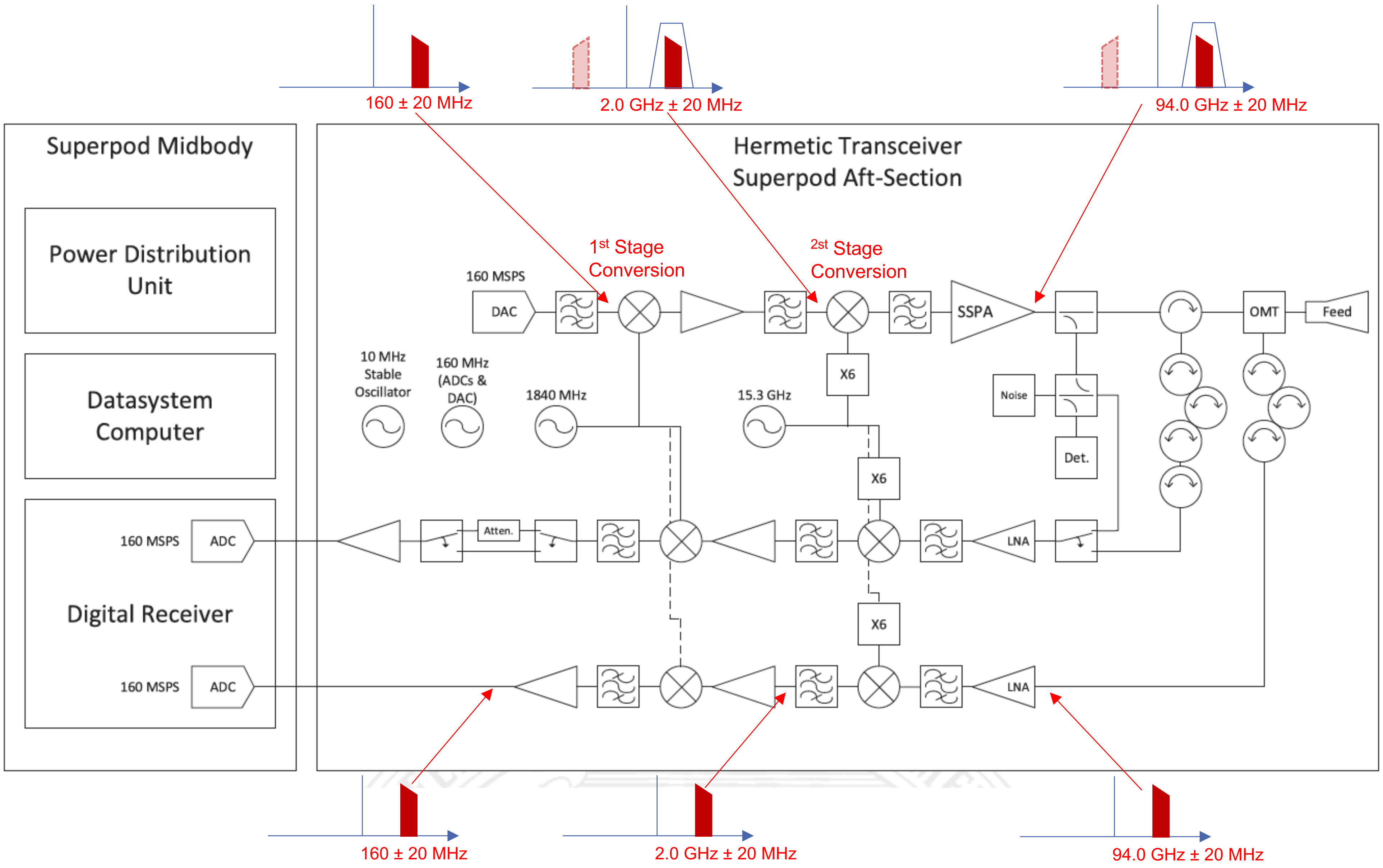




EXRAD

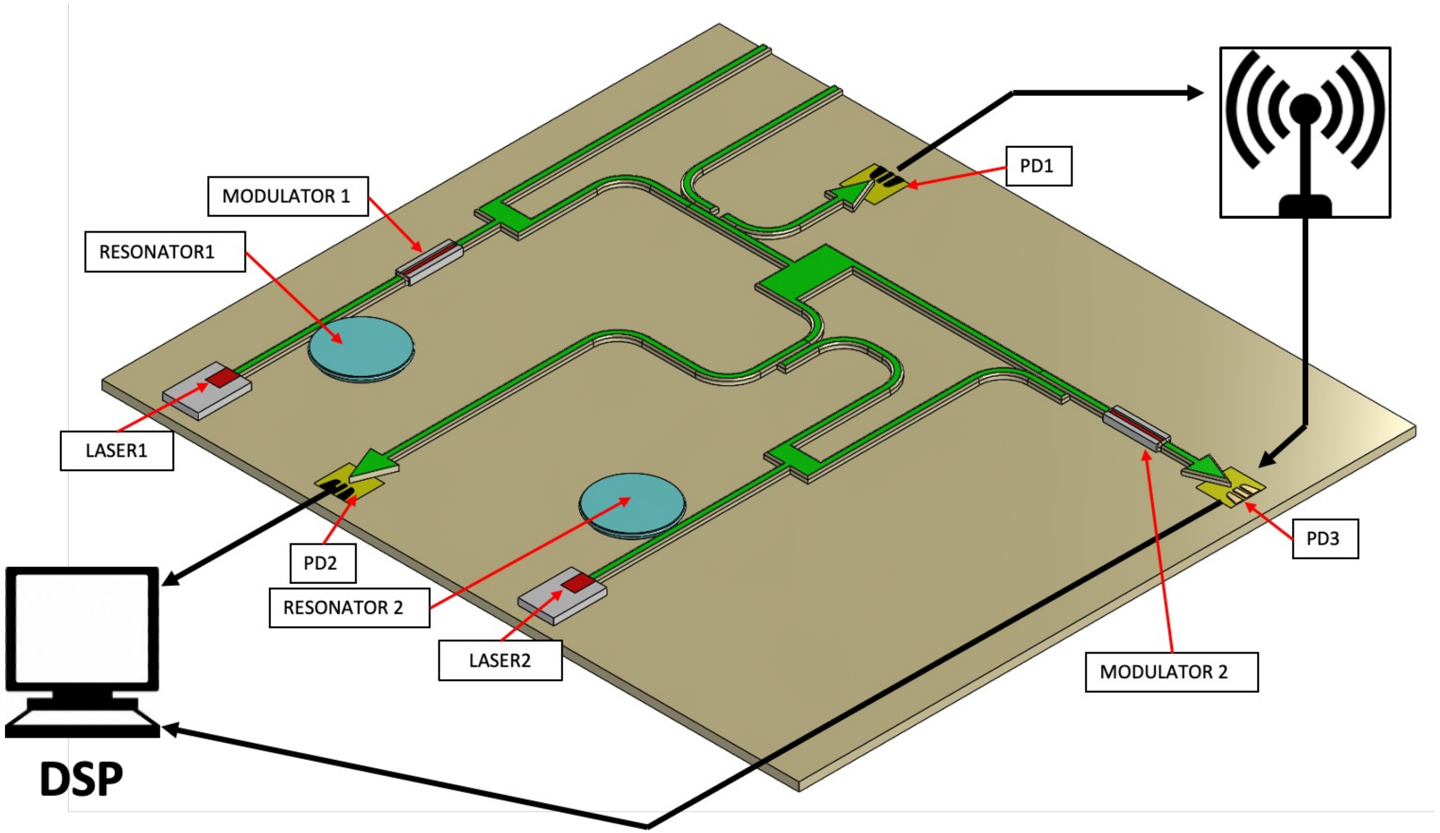


GSFC W-band (94 GHz) Cloud Radar System (CRS)



- Two stage up and down conversions
- Multiple phase locked oscillators (PLO) which requires 5-10 W each.
- Narrow band BPF to reject LO and image signals
- Fixed frequency, narrow bandwidth
- Phase noise increase as 20*log(N)
- PLO and filters are to be implemented in MMIC.

Architecture



PIC Radar requires the following elements:

1. Resonator
   - Fabricated by OEwaves
   - Couple to waveguide
2. Modulator
   - Integrated $LiNbO_3$ waveguide
3. Laser Coupling
   - Butt-couple to waveguide
4. Photodiode Coupling
   - Flipchip bond diode
   - Couple to waveguide

Remote Sensing Radar Design using Traditional and Photonic-RF Technologies

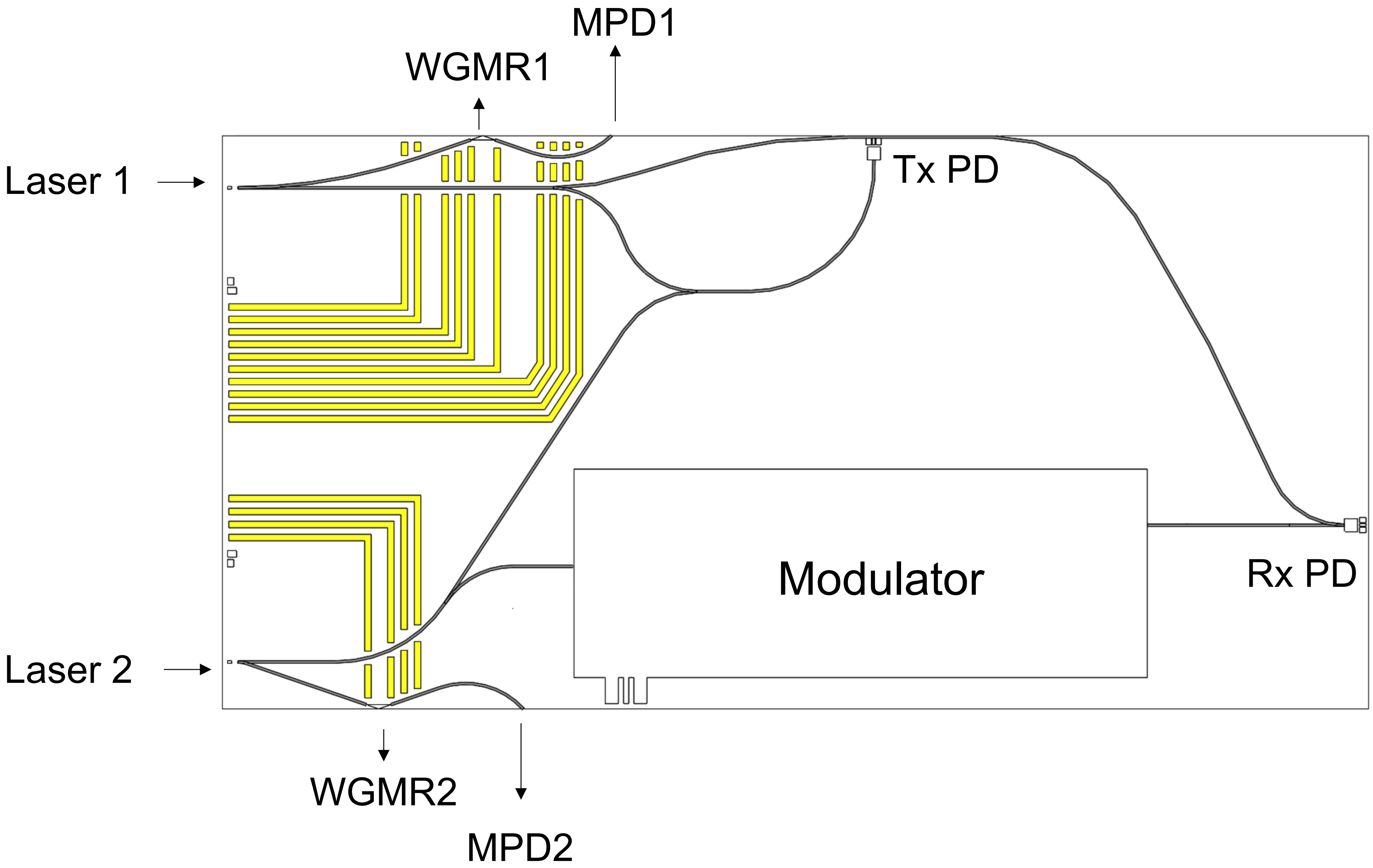
- Cloud and precipitation radar deign considerations
  - Short pulse and FM chirp versatile waveform for range sampling
  - Good frequency stability and low phase noise for pulse compression and Doppler velocity measurements
  - High Tx power and low Rx noise figure to weak backscattering signal detection
  - Low size, weight and power (SWaP) for airborne and space application
- Comparison of traditional and photonic radar technologies

	Traditional Radar	Photonic Radar
Technologies	Based on individual electronic components or Monolithic microwave integrated circuit to achieve frequency conversion between IF and RF	Utilizing modulation of laser optical signal or beat tone of two or more lasers to achieve RF signal generation and down conversion
Pros	• Well developed technology • Wide selection of parts	• Ultra wideband and tunability • No electronic phase locked oscillators • Phase noise does not increase along with RF frequency • Significant reduction of SWaP using PIC technology • Potential application for radar, radiometer and spectrometer
Cons	• Requires multiple stage up and down conversion for high frequency radars • Phase noise increase as 20*log(N) • Fixed frequency with narrow range tunability • Large SWaP of phase locked oscillators and filters, difficult to implement in MMIC	• Relative new technology. Performance needs to be verified

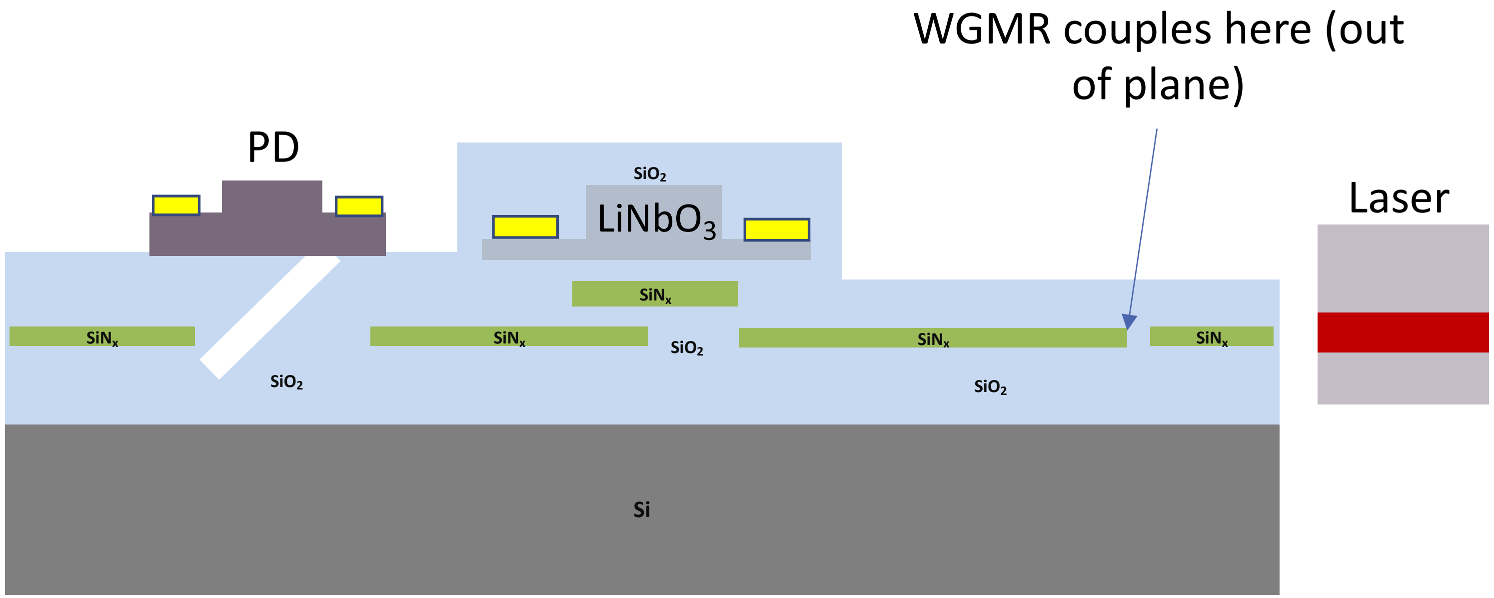
Requirements

Requirement	Units	Min	Target	Max
Operating Band (Threshold)	GHz	10		40
Operating Band (Target)	GHz	75	94	110
Output Power	dBm	-5	0	
Optical Carrier	THz		193.4	
Pulse Repetition Frequency	kHz	4		6
Pulse Width (Single Tone)	µs	0.5		2
Pulse Width (Chirp)	µs	10		100
Chirp Start Frequency	GHz	1		10
Chirp Bandwidth	MHz	2	10	100

PIC Draft Layout

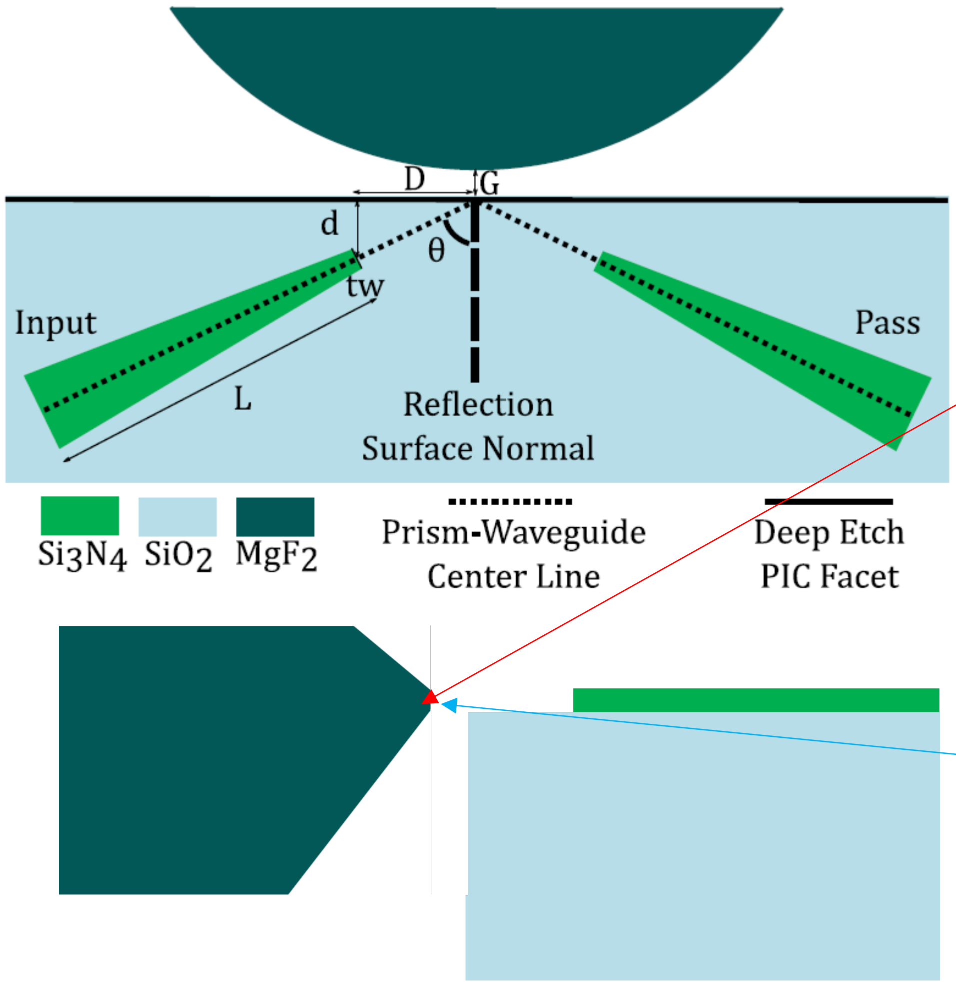


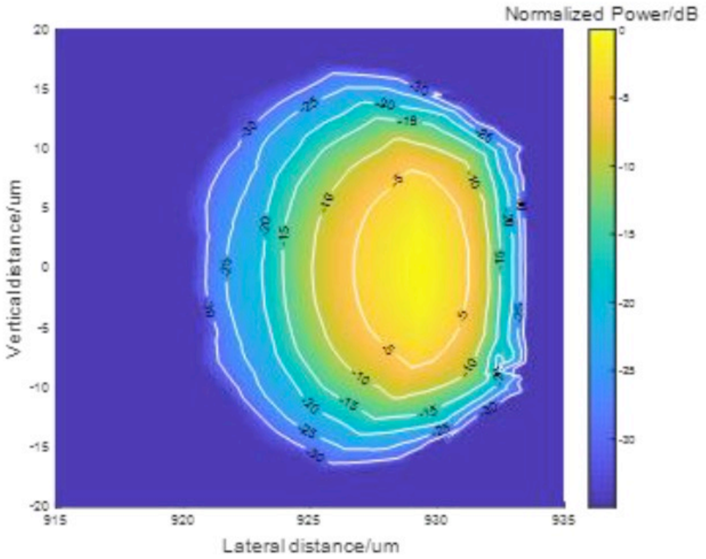
PIC Cross-Section



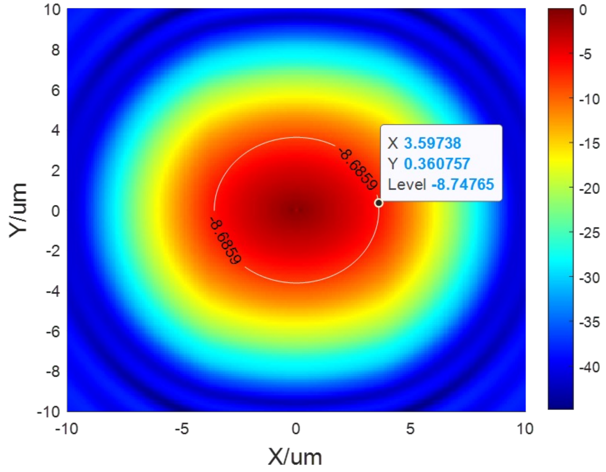
- Two-layer waveguide structure
  - Laser, PD, and resonator coupling
  - $LiNbO_3$ modulator coupling
- Laser is butt-coupled to waveguide
- Photodiode is aligned onto surface, coupled via nanofabricated mirror
- Resonator (off-chip) couples to chip edge

WGM Resonator Coupling





Resonator Mode

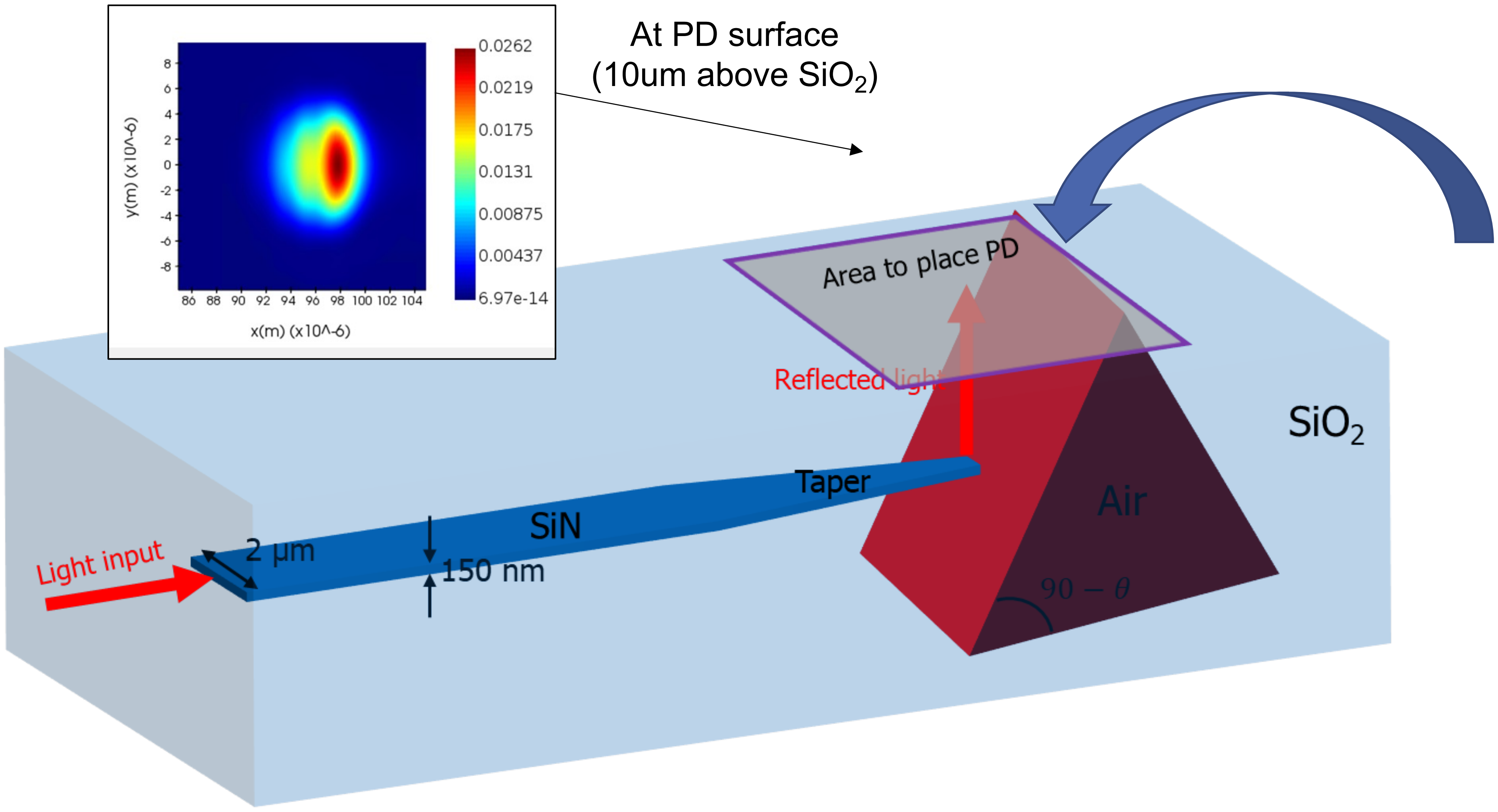


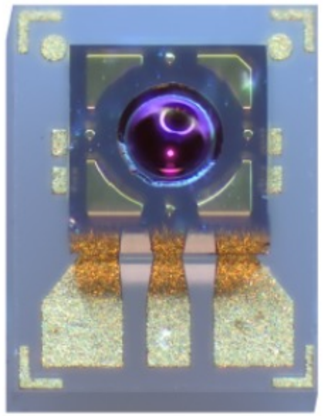
Mode size: ~7 x 7 μm

Prism Waveguide Mode

Work performed at UCD

Photodiode Coupling

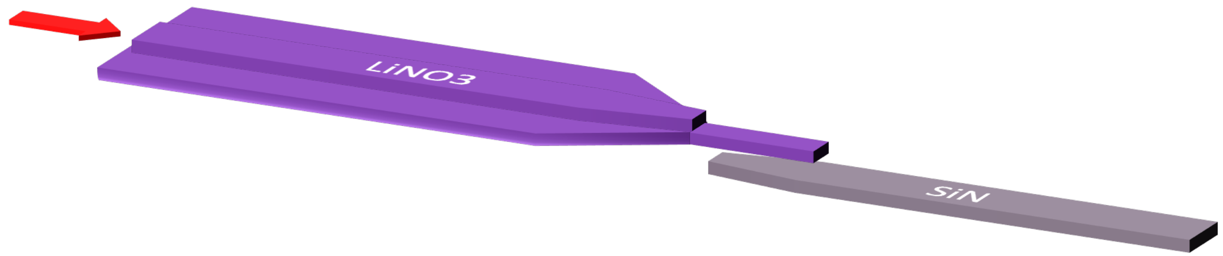




500µm× 500µm die

Couple to surface mounted photodiode via TIR off nanofabricated mirror

$LiNbO_3$ Modulator – Vertical Coupling

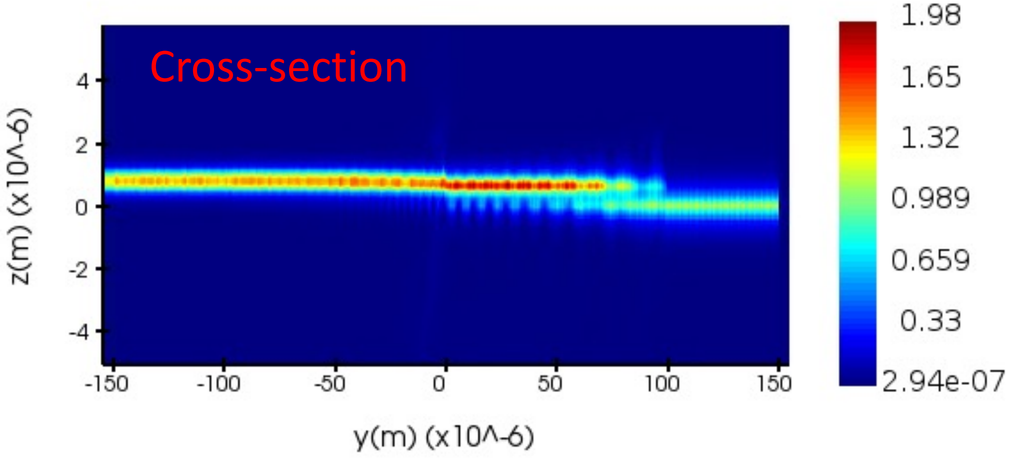


A ridge-cutting negative taper is used here to force the light into the slab

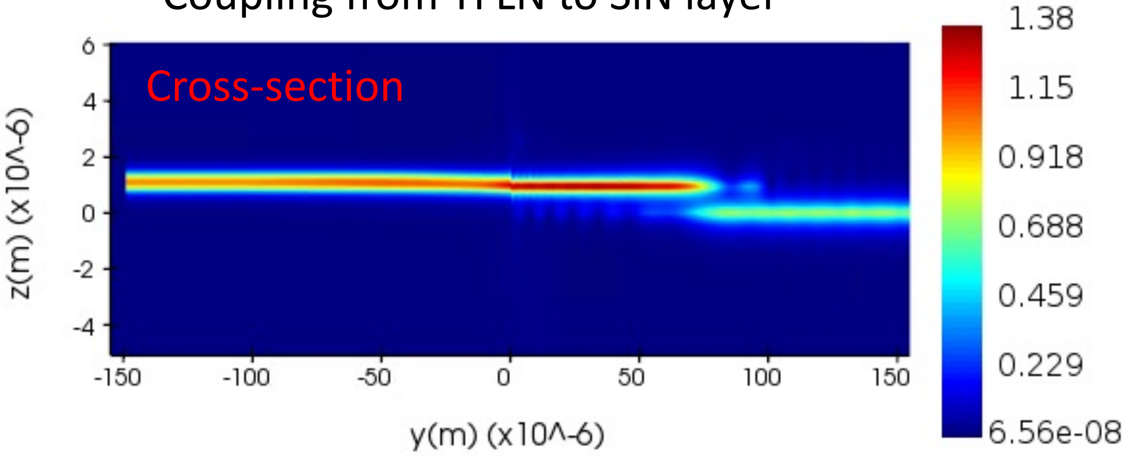
Dimension:
Slab thickness: 300 nm;
overall thickness: 600 nm;
ridge and slab taper end width: 250nm; (effective width = 360 nm);
SiN thickness: 200nm;
Interlayer thickness: 400 nm;

The overall transmission between 200nm-thick SiN and LN layer is:
94.61% * 96.18% = 91.00%

Coupling from SiN to TFLN layer



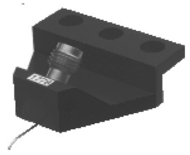
Coupling from TFLN to SiN layer

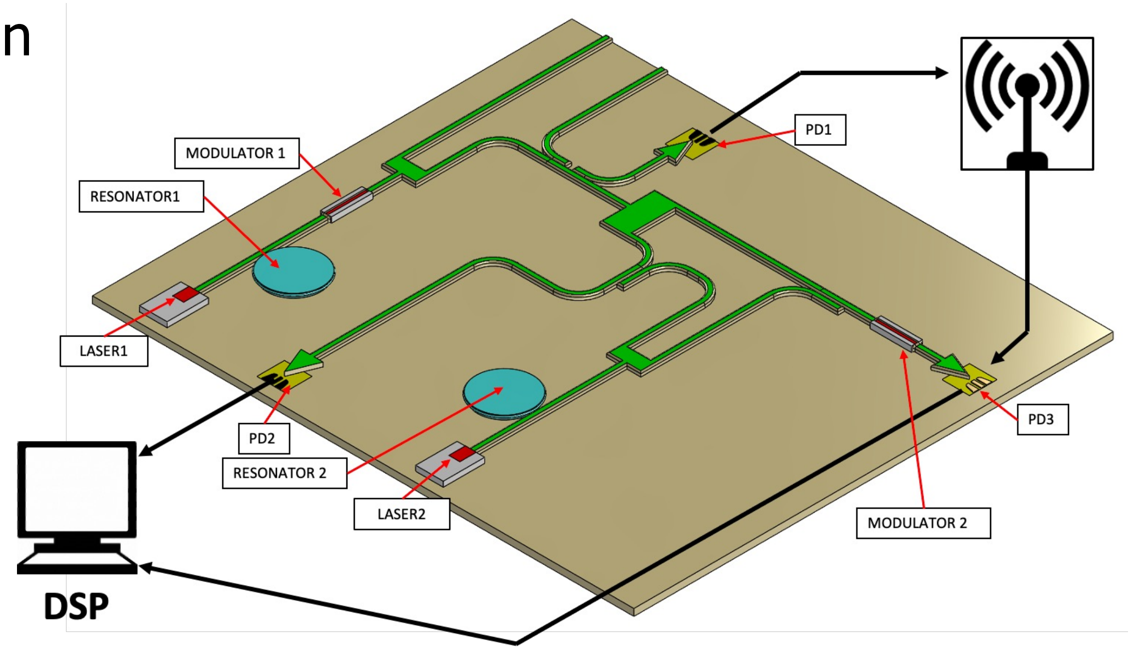


Work performed at UCD

PIC Characterization Using Test Equipment

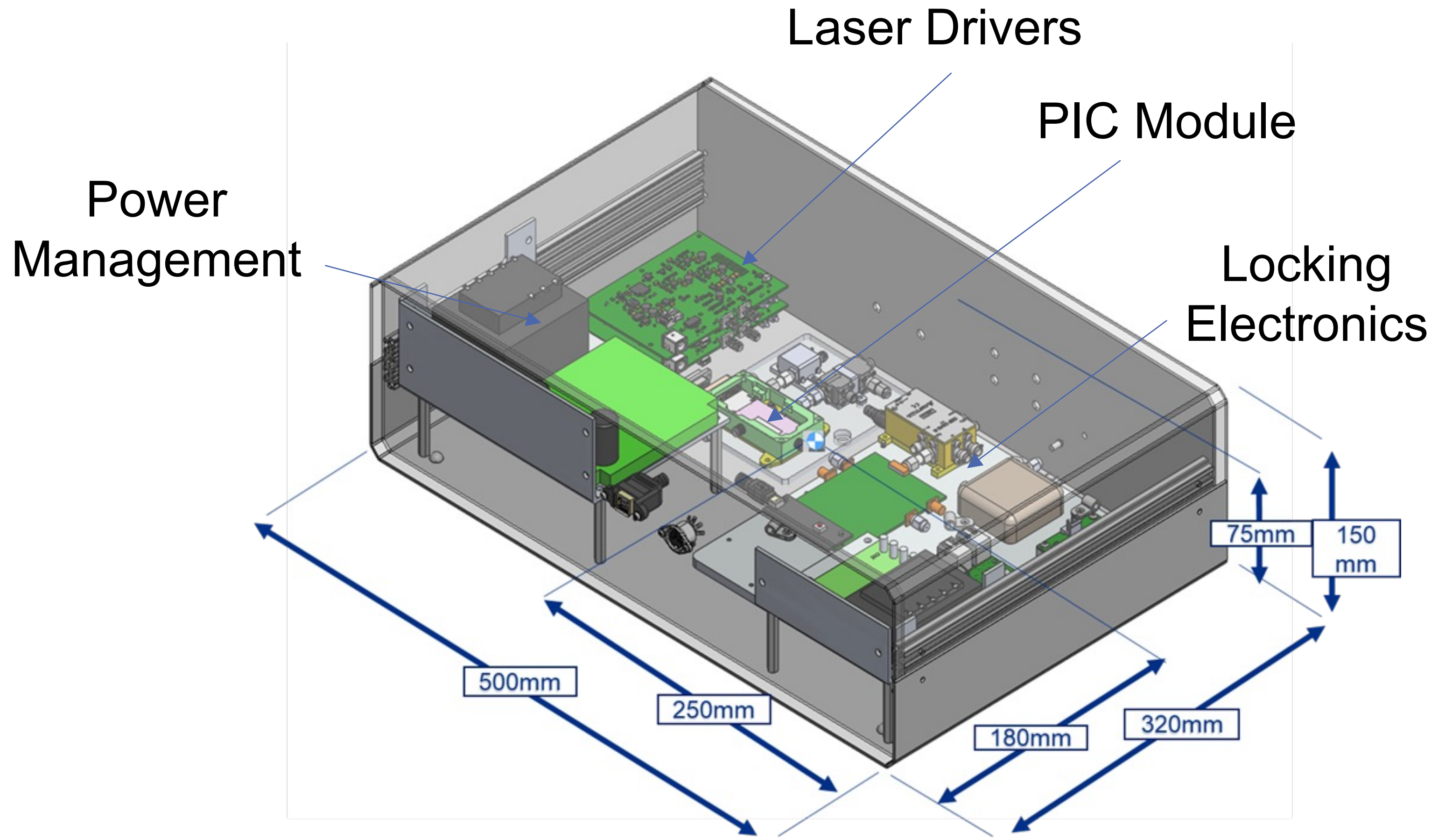
- Signal path gain/loss, output power level and modulation
- Timing jitter, frequency stability and phase noise measurements
- Frequency tunability
- Signal up- and down-conversion
- Temperature effects

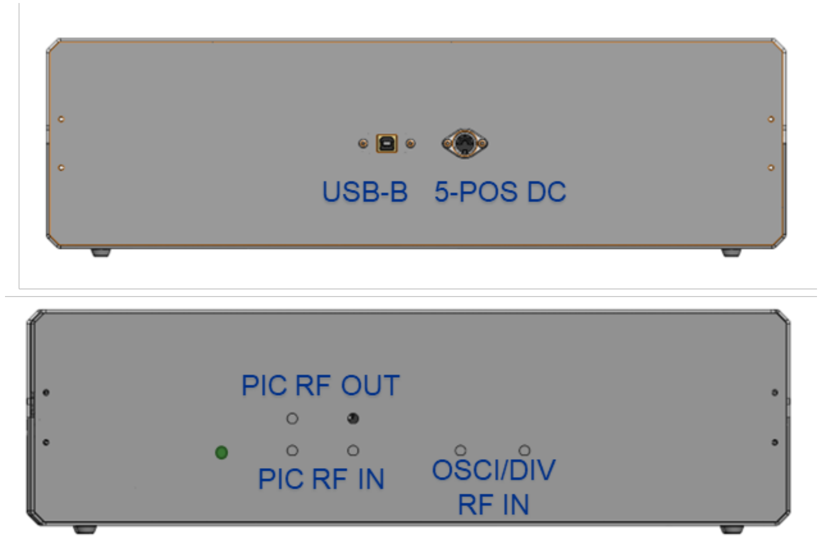




Work performed at NASA GSFC

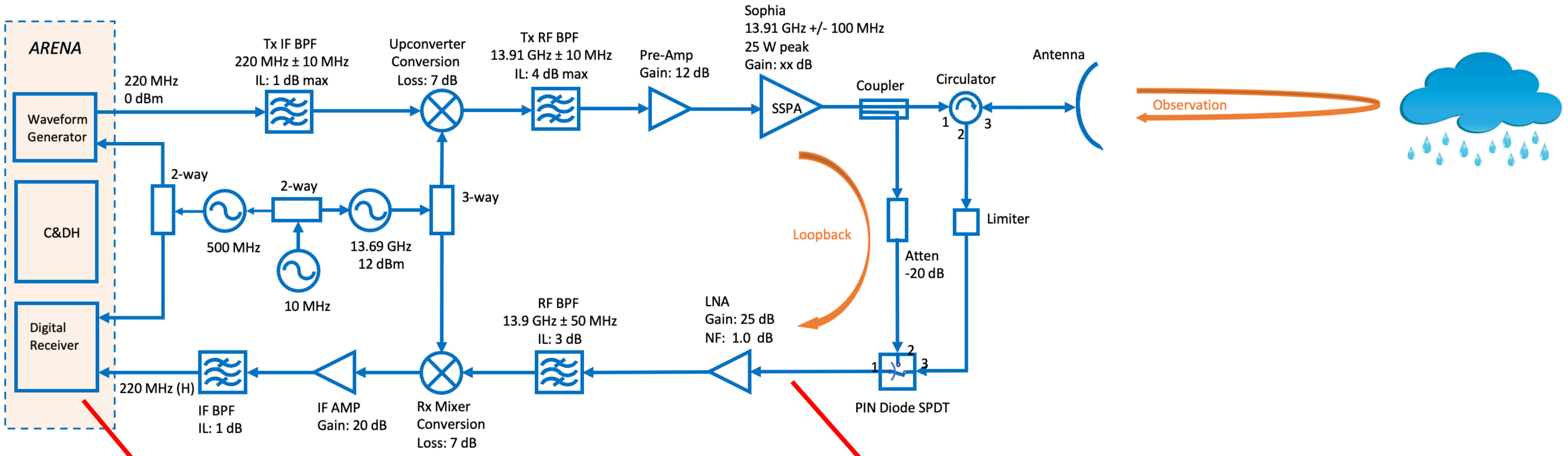
Radar Design

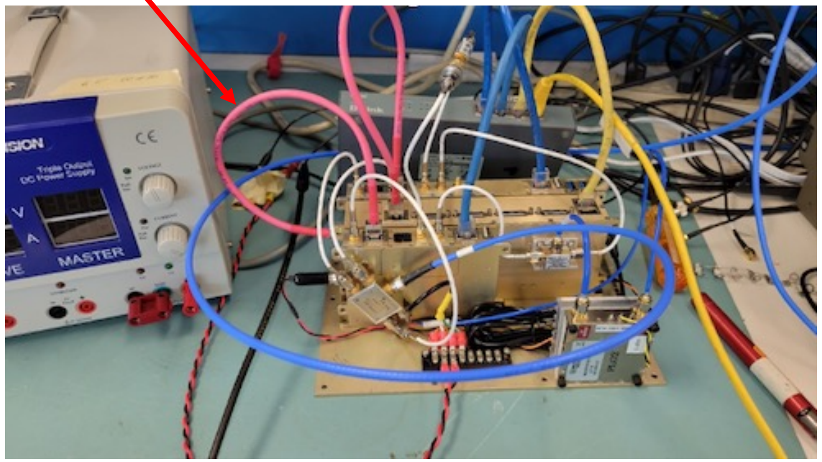




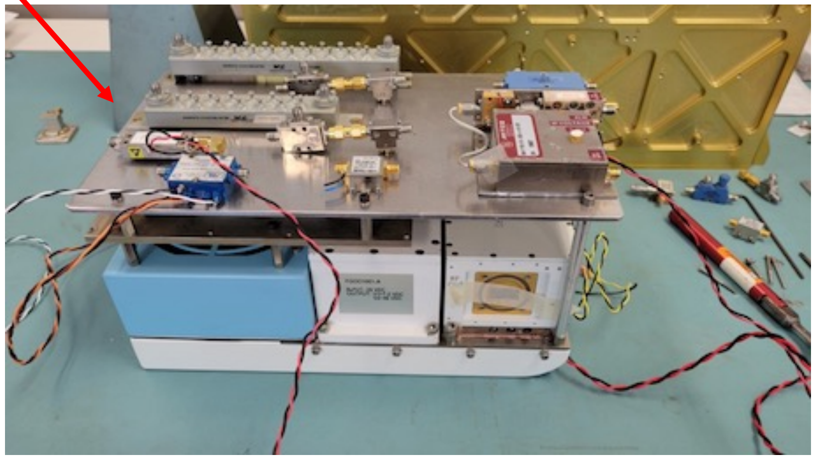
Radar system contains all electronics necessary to drive PIC in portable breadboard housing

Ku-Band Radar Transceiver Test Setup

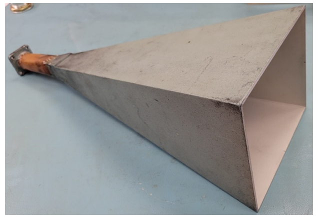




FPGA based ARENA modules for radar waveform generation, digital receiver/processor and system control/data handling



Conventional Ku-band radar transceiver using a phase-locked local oscillator and a solid state power amplifier



Ku-band horn antenna

Work performed at NASA GSFC

Current Status

- Completed mechanical/electrical design of system housing
- Completed opto-mechanical design of PIC module assembly
- Completed component design/fab
- Tested laser and resonator waveguides
- First modulator and PD waveguides currently under test at OEwaves
- UCD finishing process development necessary for integrated PIC
- Schedule delays due to tool downtime
- Derisking schedule by transferring laser/PD integration to OEwaves
- Integrated PIC on track to be fabricated next quarter