RF-photonics W-band Receiver for Remote Sensing Applications

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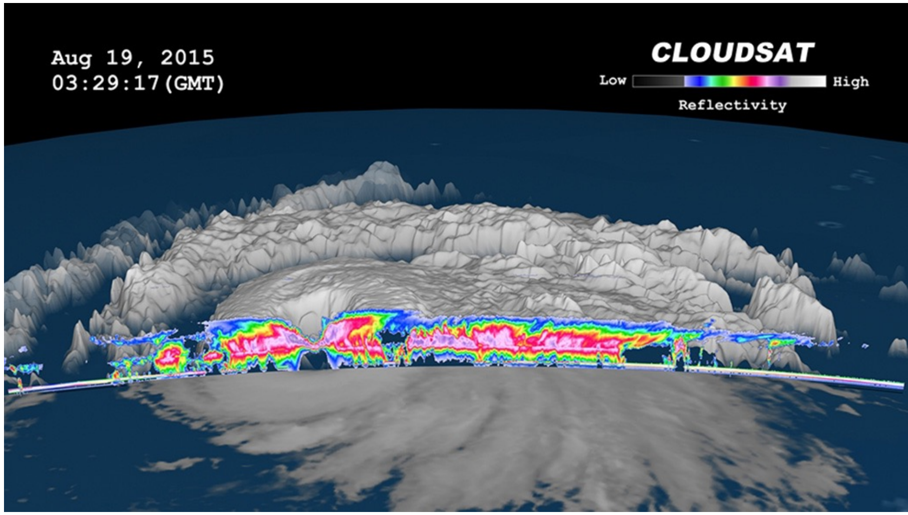
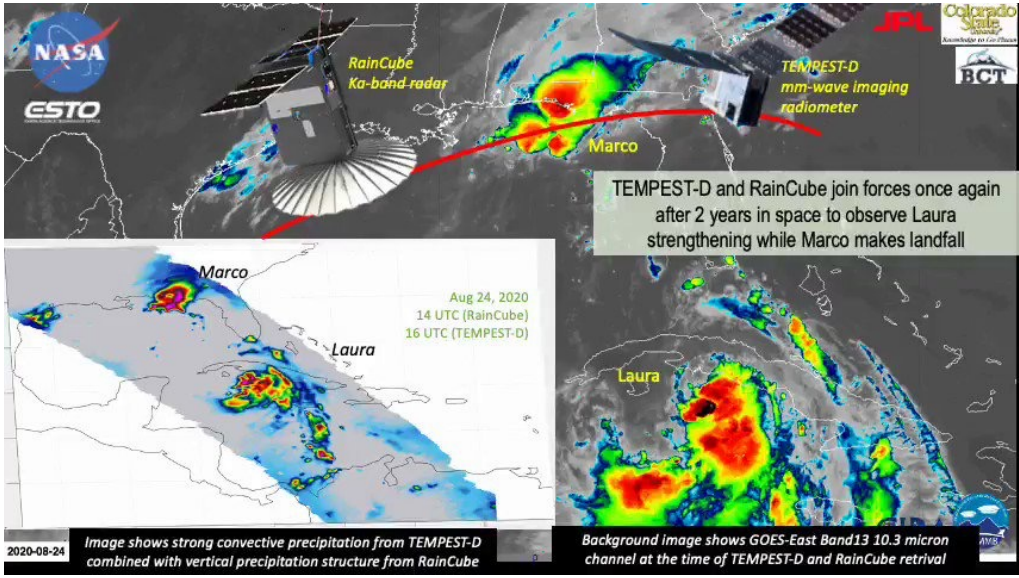
Scientific Motivation

- Climate and weather models need frequent (orders of minutes) measurements of cloud and precipitation
- TRMM, GPM, CloudSat have proven utility of spaceborne radars
- A constellation of compact radars is needed
  - TRMM/GPM/CloudSat (Volume > 10m^3, Weight > 100Kg, Power > 500W) type radars are not feasible
  - RainCube (6U, 5.5Kg, 22W) demonstrated feasibility of compact, affordable radars





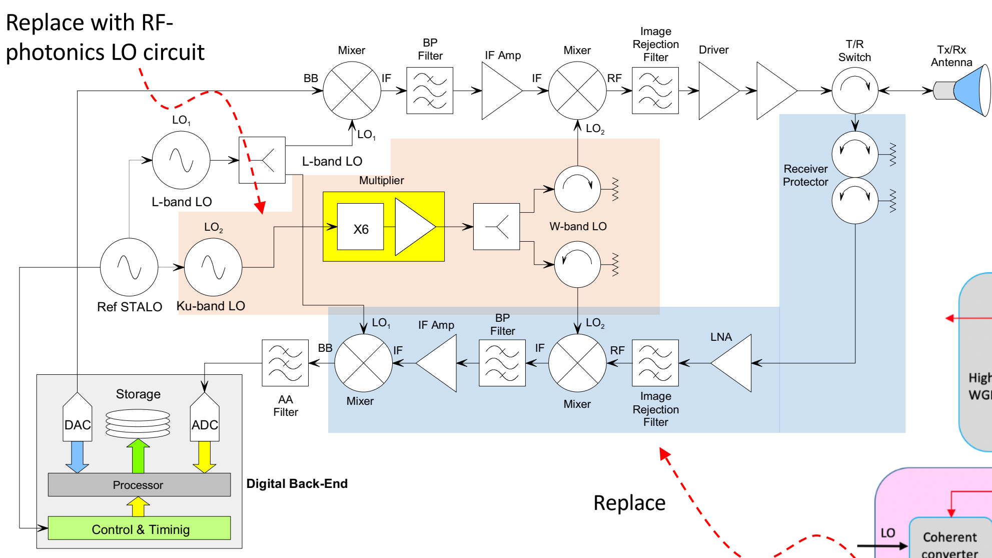
Engineering Challenge

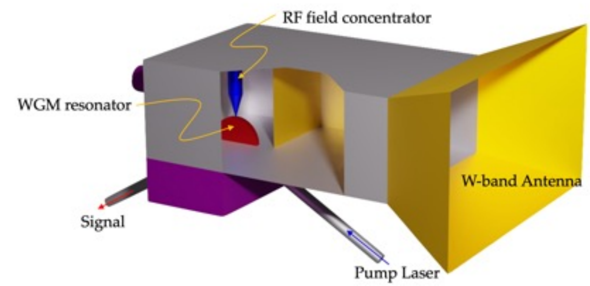
- Compact cloud radars need to be highly sensitive (40dB more than RainCube)
  - Increasing Antenna Size, Transmit power increase instrument SWaP
  - Increasing pulse widths requires extremely low phase noise LO
  - Lower bandwidth results in poorer vertical resolution
- RF-photonics offers:
  - Decrease in radar size, weight and power (>50%)
  - Low system temperature = increased sensitivity (4-6dB)
    - Can trade off for lower transmit power, smaller antenna size, more bandwidth, additional sensitivity
  - High quality 94GHz oscillator
    - Makes it possible to transmit longer pulse-widths in the presence of ground clutter

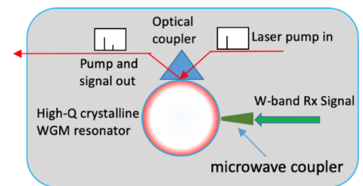
Sensitivity	Science	Missions
+15dBZ	Moderate to light rain	TRMM, GPM, RainCube
0dBZ	Most light rain, snowfall	
-15dBZ	99% of all precipitation	
-25dBZ	Most clouds associated with precipitation	ACCP, CloudCube (IIP 19)
-30dBZ	Large fraction of non-precipitating clouds	CloudSat
-35dBZ	Majority of clouds impacting radiation budget	EarthCare

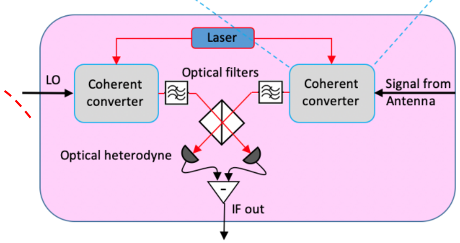
RainCube to CloudCube	Sensitivity Improvement	Consequence
Frequency (Ka to W)	9dB (scattering) + 9dB (same size antenna)	
Larger Antenna	9dB	Increase in radar size
Lower Bandwidth	7dB	Lower Resolution
Larger pulse widths	2dB	Need high quality LO
Same Transmit Power (10W)	0dB	Increase in radar size and power requirements
More Averaging	3dB	Lower spatial resolution

RF-photonics Based Approach





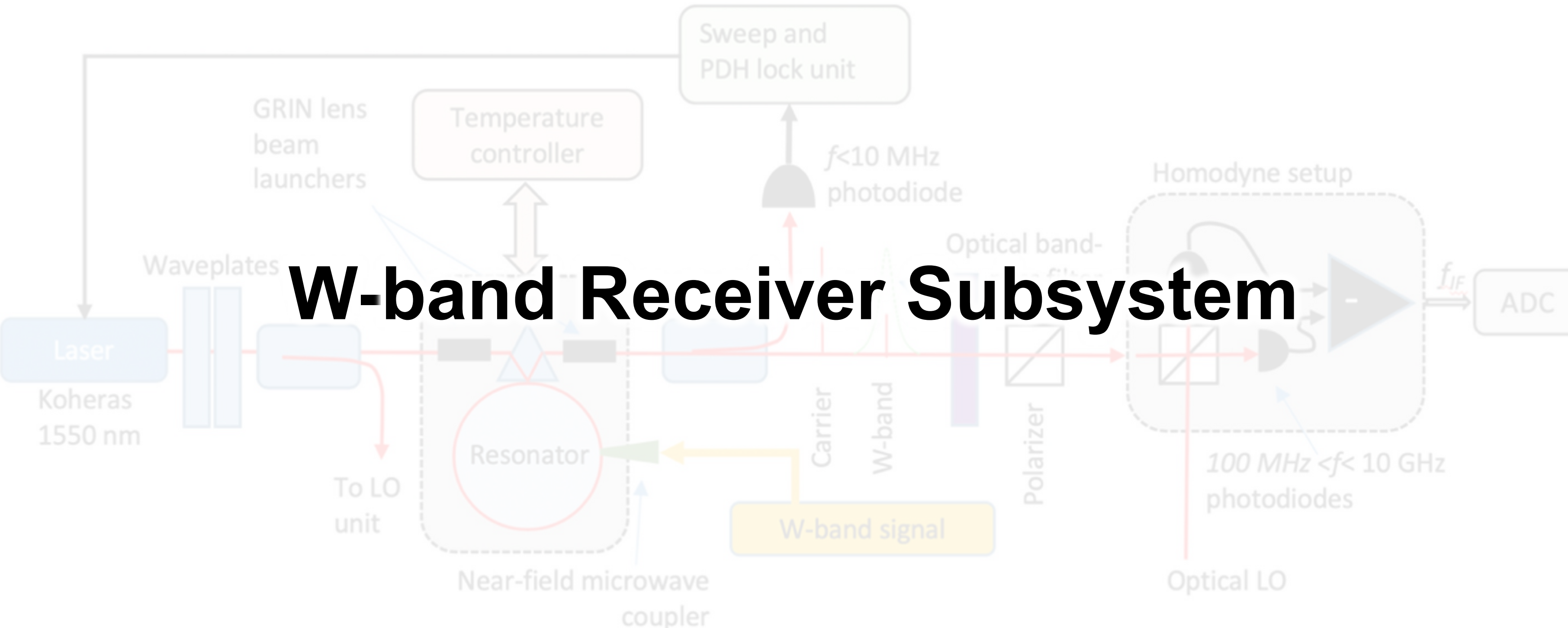




- RF-photonics device to replace radar downconverter chain and LO-generation circuit, with
  - Bandwidth of 10MHz
  - An overall system temperature <300K
  - Tolerance for large input RF-power without getting damaged
  - 94GHz RF-photonics Oscillator with -110dBc/Hz phase noise at 10kHz
- RF-photonics receiver can reduce W-band cloud radar SWaP while improving performance

Parameters	RF-electronics	RF-photonics
Volume	>100cm^3	<10cm^3
System Temp	1200K	< 300 K (below ambient)
Max input power tolerance	10-13dBm	30dBm
Phase noise	-90dBc/Hz @ 10kHz	-110dBc/Hz @ 10kHz

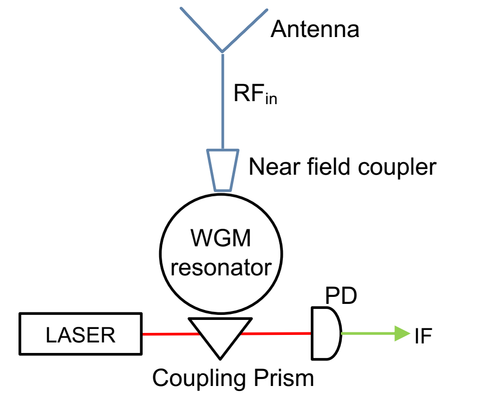
W-band Receiver Subsystem

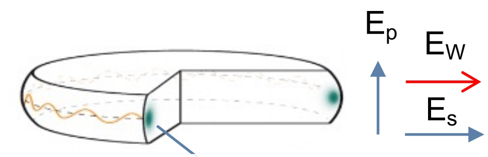


Receiver Concept

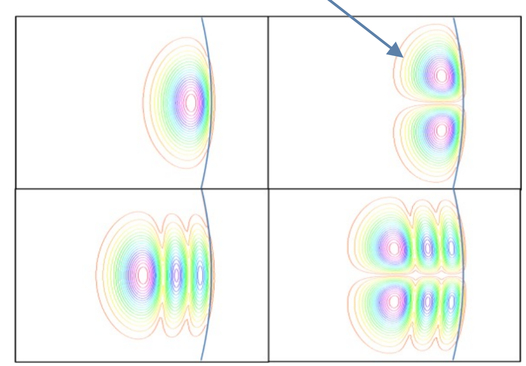
- **Principle of Operation**
  - Incident 94GHz RF-field from antenna is directed to the crystal resonator via a near-field coupler
  - 1550nm laser is coupled to the resonator exciting optical WGM modes
  - RF electric field generates an optical harmonic detuned from the optical carrier utilizing the electro-optic effect
  - This harmonic is coupled out and detected via a homodyne detector

- **Performance Critical elements**
  - Near-Field Coupler
    - Enhanced interaction between optical and RF-fields makes receiver much more efficient than typical electro-optic modulators
  - WGM Resonator
    - $LiTaO_3$ material with high electro-optic coefficient
    - Fabricated resonator with high Quality factor ($Q_0 > 10^7$)
  - Optomechanical Assembly
    - Tunable, rigid, thermally stable optomechanical assembly with tight temperature control





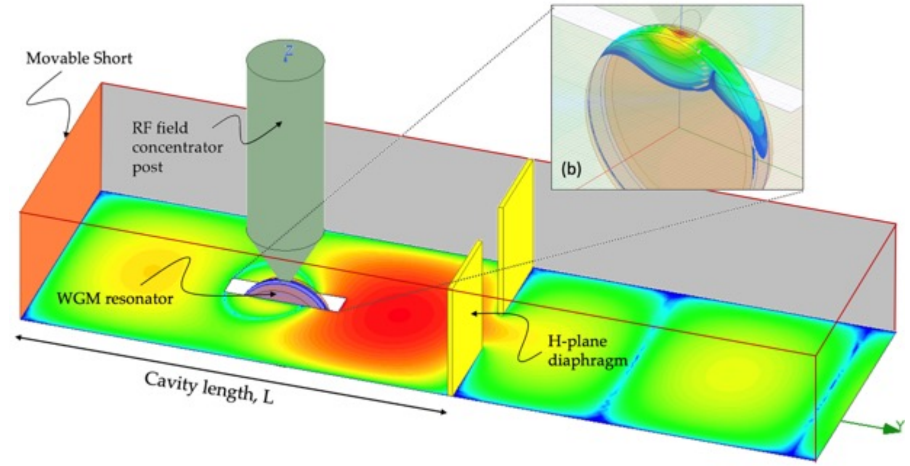
TE-TM Optical conversion scheme

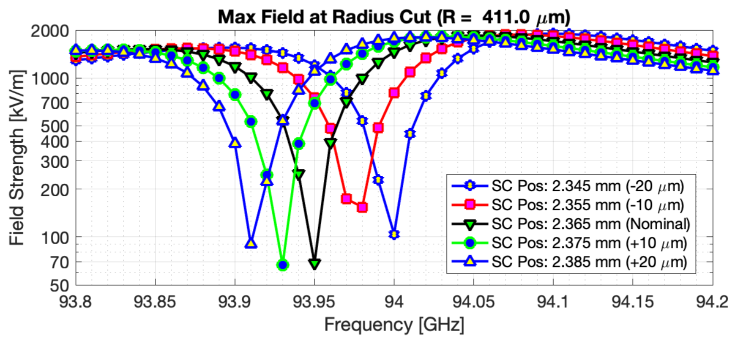

WGM modes near resonator rim

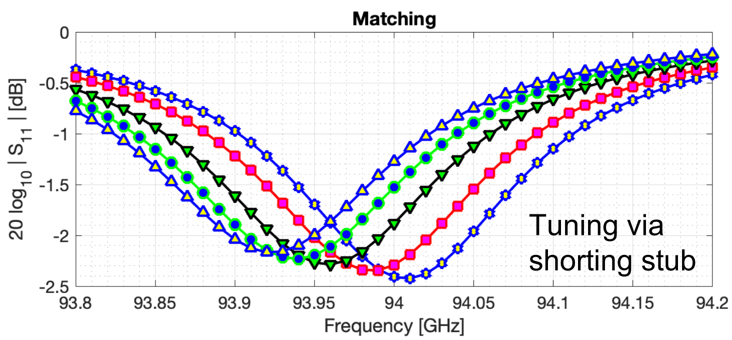
Near Field RF-Coupler Design

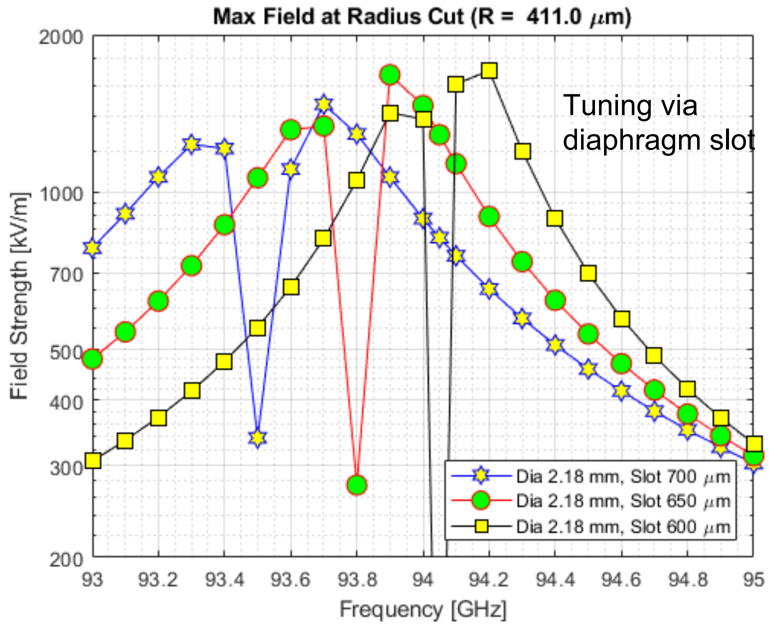
- Metal post tip as field concentrator
- H-plane inductive diaphragm, creating a RF cavity resonator to enhance field strength
- Tunability via movable short and varied diaphragms

- Designed for significant increase (~2 OM) in field concentration relative to nominal peak field strength in WG









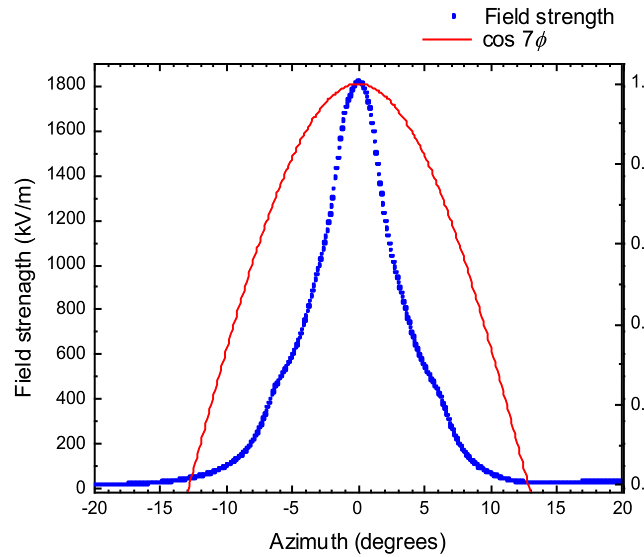
Performance Modeling and Prediction

- Performance model to predict receiver gain, SNR and noise figure
  - Uses HFSS simulated fields in the resonator
  - Analytical approximations for WGM eigenfunctions

$$g_0 = \frac{g}{E_0} = n_o n_e r_{51} \frac{c}{\lambda} \int_{-\pi}^{\pi} \cos(\Delta m \phi) f_{RF}(w_0, 0, \phi) d\phi.$$

$$G = \frac{P_{RF\ out}}{P_{RF\ in}} = \rho \mathcal{R}^2 P_0 P_{LO} \frac{4 g_0^2}{\gamma_a \gamma_b \alpha_W},$$

λ	R	r	n_o	n_e	r_{51}	γ_{TM}	γ_{TE}	P_0	P_{LO}	ρ	$\mathcal{R}$	Δm
1558.6	490	104	2.1189	2.1231	20	2×10^7	4×10^8	10	2	50	0.9	7
nm	μm	μm			pm/V	1/s	1/s	mW	mW	Ohm	A/W	



Angular window function : $\cos 6\varphi$

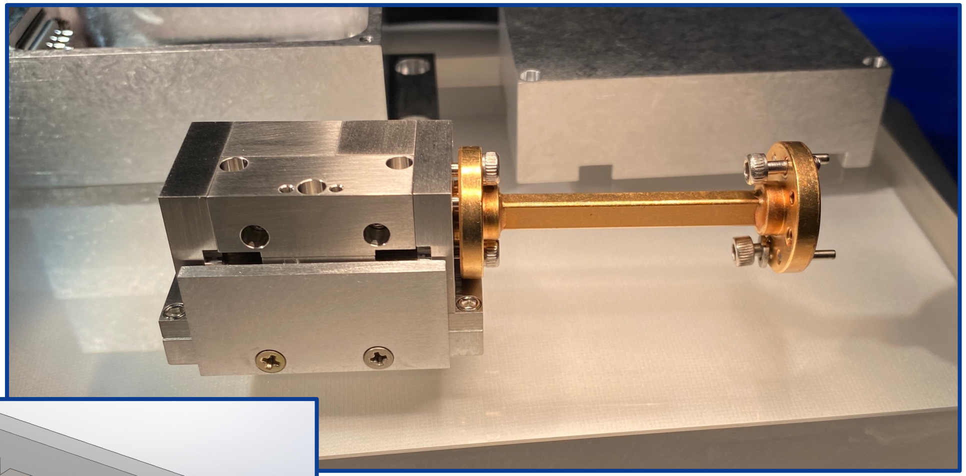
Normalized Coupling rate	2200 m/(V s)
Gain	6.3 (8dB)
Shot Noise Contribution	0.19 T_{rec}
Thermal Noise Contribution	0.04 T_{rec}
Effective Noise Temperature (T_e)	0.23 T_{rec}

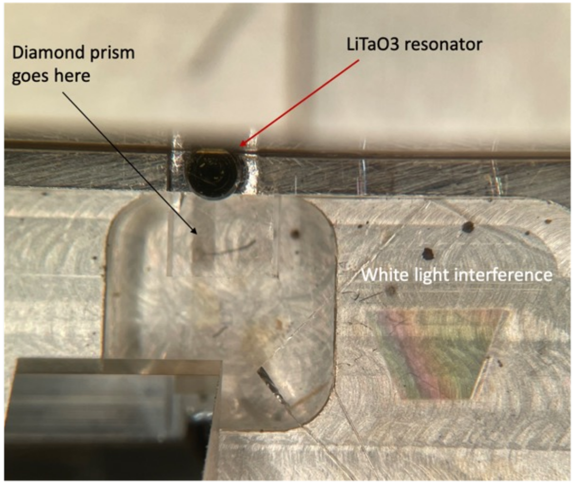
Atypical for photonics device to have positive gain

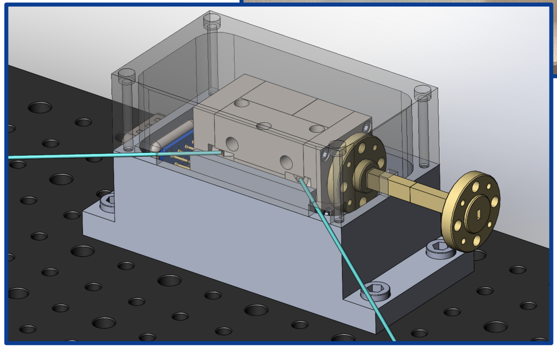
T_e = 70K for device temp of 300K
Typical RF-receiver T_e = 1200K

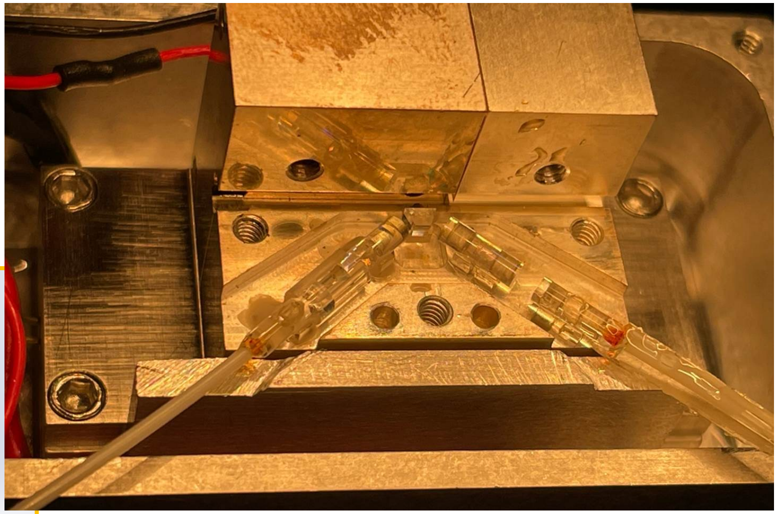
Strekalov, D.; Majurec, N.; Matsko, A.; Ilchenko, V.; Tanelli, S.; Ahmed, R. *W-Band Photonic Receiver for Compact Cloud Radars*. *Sensors* **2022**, *22*, 804.

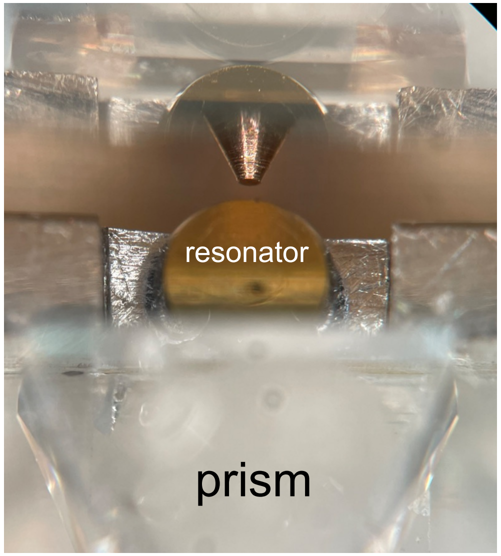
Opto-Mechanical Design and Assembly

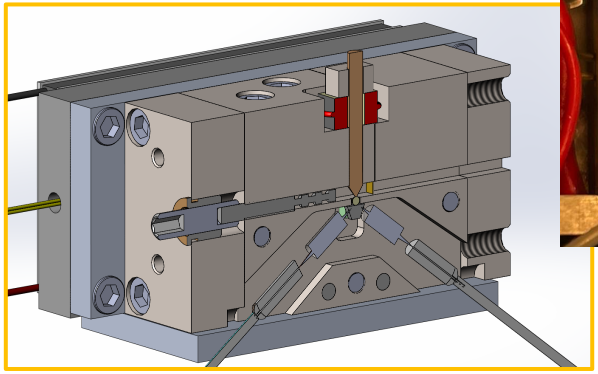






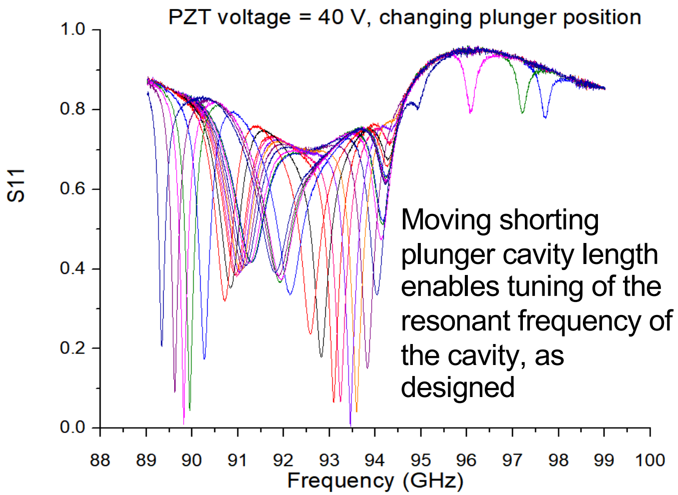


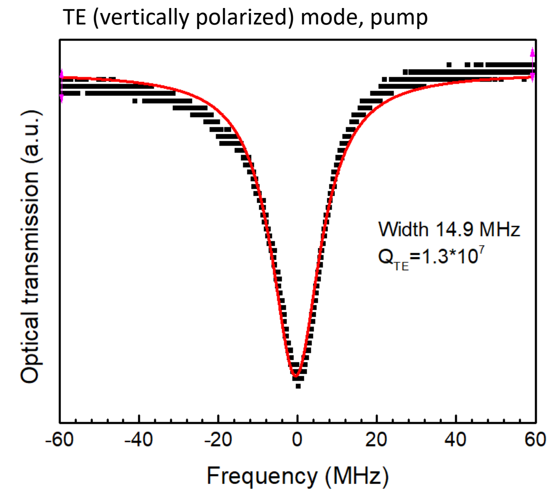


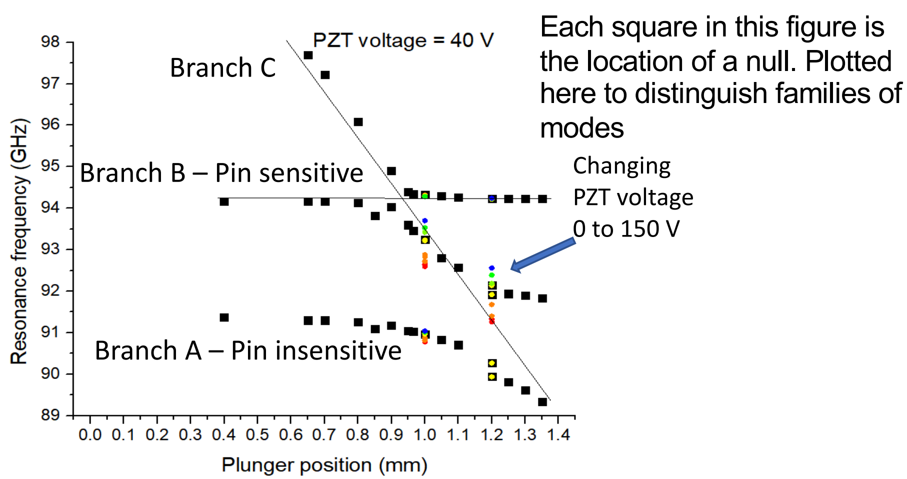


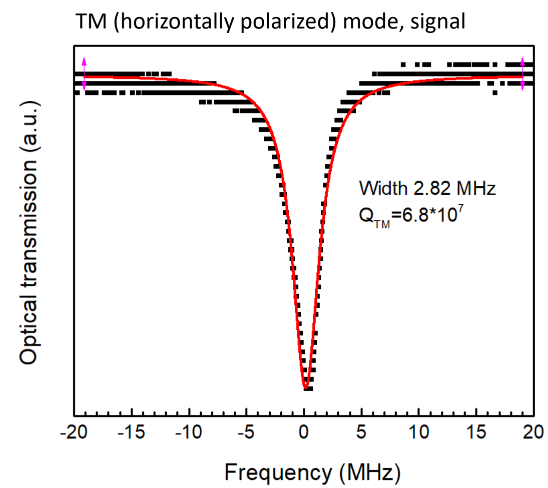
Initial Optical, RF testing

- S_{11} observations of RF structure consistent with a resonant RF cavity and tuning design
- Optical modes, spectra, Q-factor in integrated $LiTaO_3$ resonator as expected
- RF+Optical testing happening now

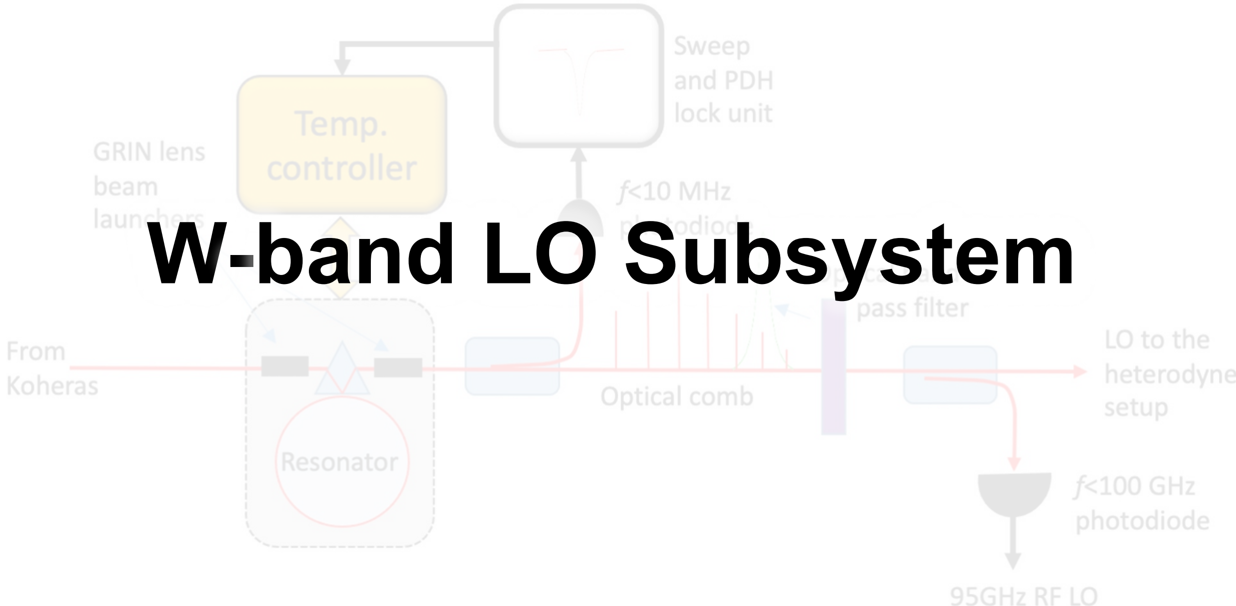








W-band LO Subsystem

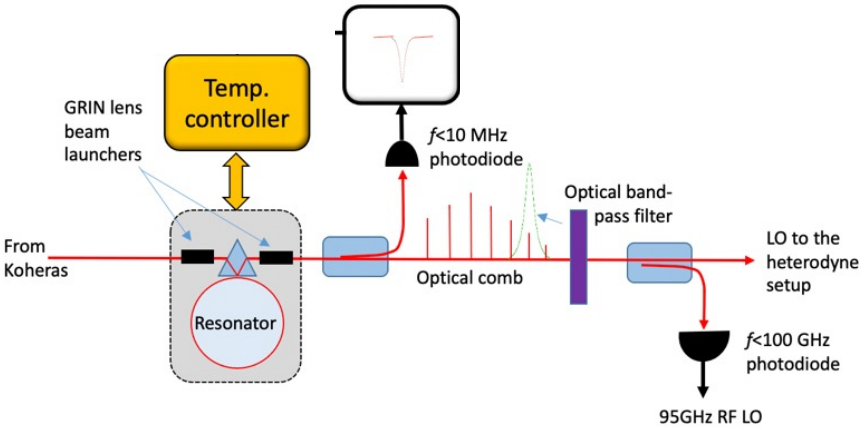


This document has been reviewed and determined not to contain export controlled technical data.

LO Motivation and Concept

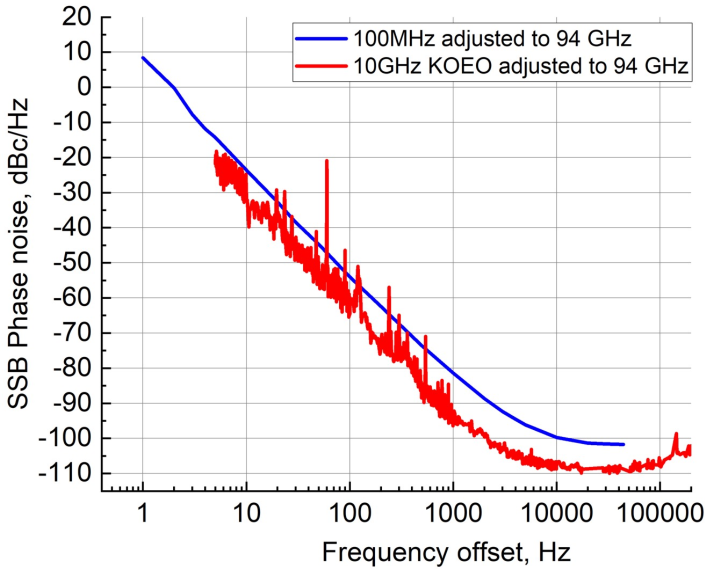
Motivation

- Photonic local oscillators are able to generate signals with much better phase noise than their electronic competitors
- The expected performance, based on prior experience, is -110 dBc/Hz (or better) at 10 kHz for 94GHz carrier



Concept of Operation

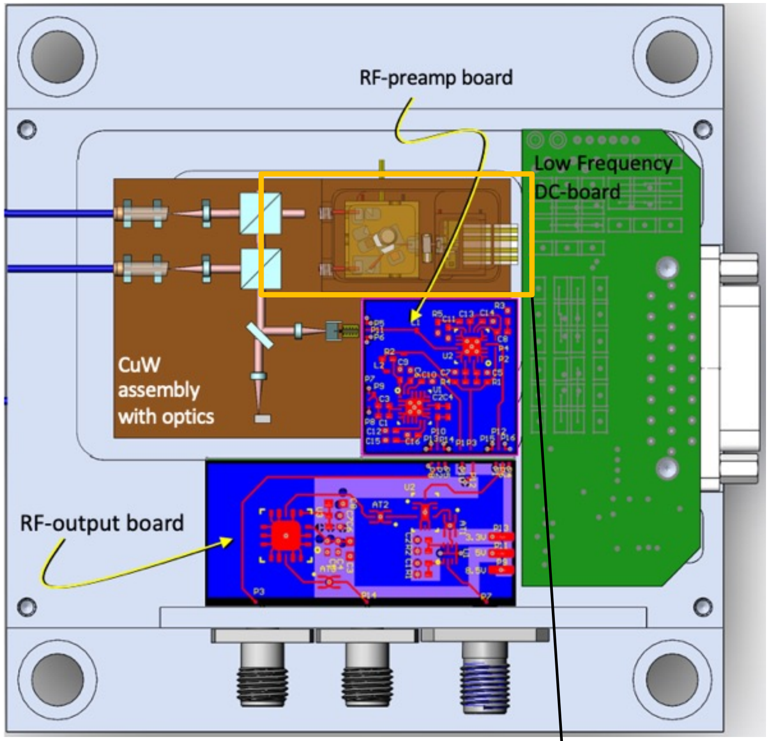
- LO subsystem consists of a MgF_2 WGM resonator that generates a self-injection locked comb
- Correct comb line is filtered, and converted to RF using photodiode
- Laser LO is used in the homodyne for coherent downconvesion

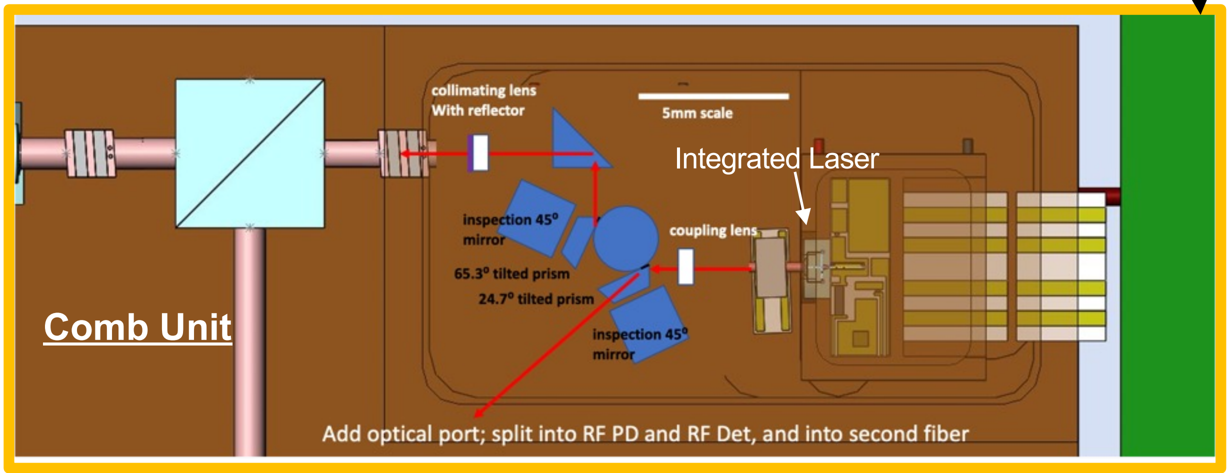


Photonic LO Design

- LO Subsystem Consists of
  - **Comb Unit**: Resonator + optics sit on Copper-Tungsten (CuW) bench tightly thermally controlled
  - **DC-board**: provides power and control signals via D-sub interface
  - **RF-boards**: Optional RF-preamp and RF-output board use 2nd comb line (Ka-band) for expedited testing

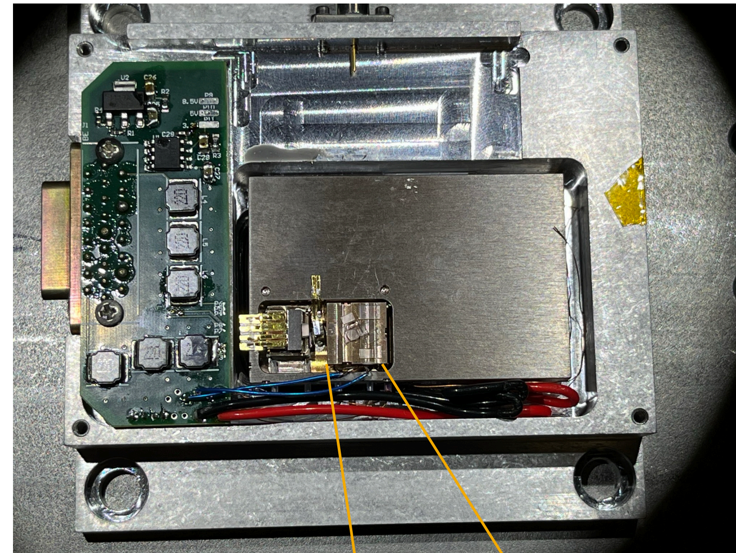
- Two optical signals from the packaged LO are split out for
  - 93GHz photodetector for RF-LO
  - Optical LO to be used in homodyne



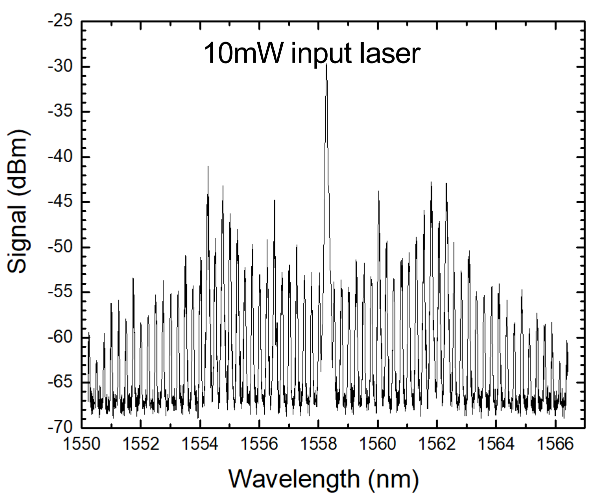


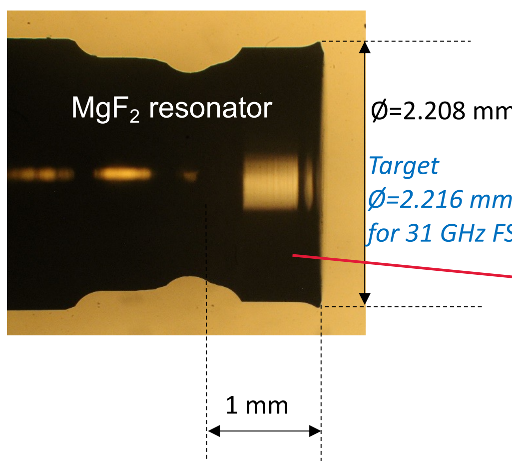
Initial Fabrication and Testing

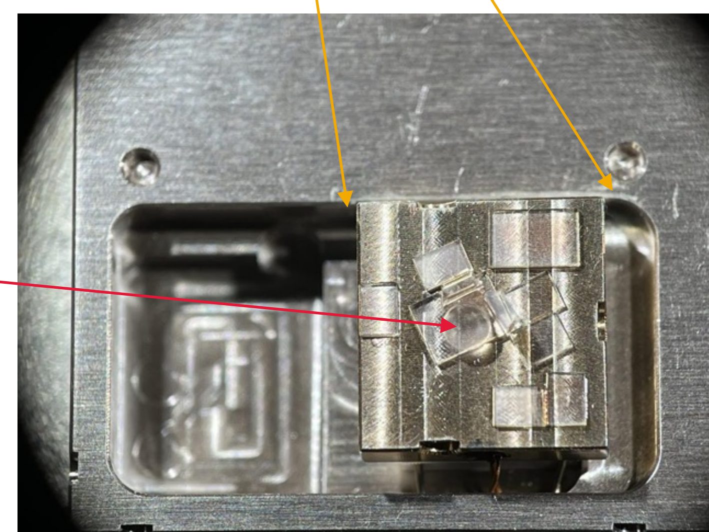
- Fabricated MgF_2 resonator achieves the targeted Q-factor ($>10^9$) and FSR
- Fabrication and testing of packaged optics is currently underway



	Q_{crit}	Q_0
TE	9×10^8	1.8×10^9
TM	1×10^9	2×10^9







Summary and Conclusions

- Presented development of a RF-photonics W-band receiver based on WGM micro-resonators
- The receiver subsystem targets an overall noise temperature <300K, 10MHz bandwidth, a demonstrated tolerance for large input powers (1W) and low volume
  - The initial performance analysis of design suggests noise temperature <100K
- The LO-subsystem targets a phase noise of -110dBc/Hz at 10kHz for a 94GHz tone
  - Initial measurements of LO resonator shows promising results

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