Frequency stabilisation of QCL for Supra-THz applications

ESA ITT AO/1-9512/18/NL/AF

H.-W. Hübers[1], H. Richter[1], N. Rothbart[1], M. Wienold[1], H. T. Grahn[2], L. Schrottke[2], X. Lü[2], P. Sobis[3,4], V. Drakinsky[4],D. Jayasankar[4], J. Stake[4]

[1] German Aerospace Center (DLR), Institute of Optical Sensor Systems, Berlin, Germany

[2] Paul-Drude-Institut für Festkörperelektronik, Berlin, Germany

[3] Low Noise Factory, Gothenborg, Sweden

[4] Chalmers University of Technology, Gothenborg, Sweden

Final meeting, Oct. 21, 2022

heinz-wilhelm.huebers@dlr.de

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OMNISYS
INSTRUMENTS

Agenda

- 9:00 – 9:10 Welcome (E. Saenz, ESA; H.-W. Hübers, DLR)
- 9:10 – 10:00 Project overview: results and achievements (H.-W. Hübers, DLR)
- 10:00 – 10:30 Terahertz quantum-cascade lasers (L. Schrottke, PDI)
- 10:30 – 11:15 Harmonic and fundamental Schottky diode mixers (N.N., CTH)
- 11:15 – 11:30 Break
- 11:30 – 12:00 x64 multiplier source (P. Sobis, LNF, CTH)
- 12:00 – 12:30 Results of the 3.5-THz and 4.7-THz breadboards (H. Richter, DLR)
- 12:30 – 13:00 The way forward (H.-W. Hübers, DLR)
- 13:00 – 13:15 Closing remarks (E. Saenz, ESA; H.-W. Hübers, DLR)

Note:

30-min presentations include 5-10 min for discussion

45-min presentations include 10-15 min for discussion

Objective(s) of the Activity

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1.4.2 Objective(s) of the Activity

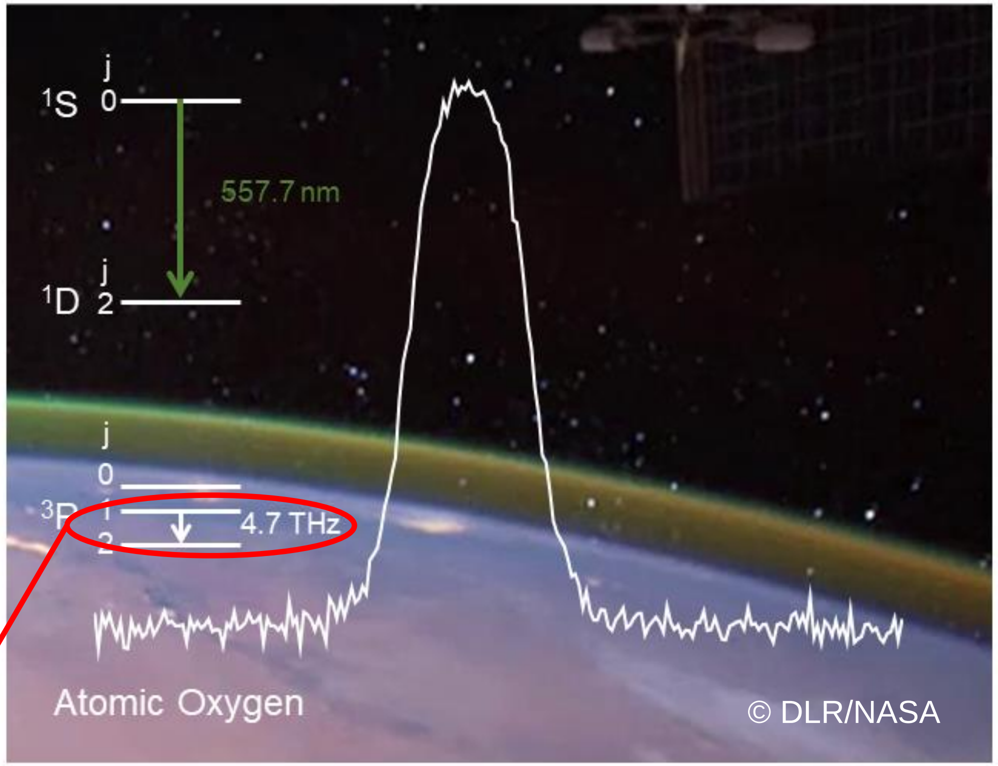
The objective of this activity is to demonstrate the feasibility of the frequency stabilization of a QCL and demonstrate the improvement of a stabilization loop with respect to passive stabilization based on thermal and electrical bias control.

The final application of the phase locked THz radiation will be to pump a Schottky diode based receiver at 4.7 THz. In order to de-risk the system, an intermediate step at 3.5 THz shall be considered.

Atomic oxygen in the mesosphere and lower thermosphere (MLT)

Atomic oxygen in the MLT (quick facts)

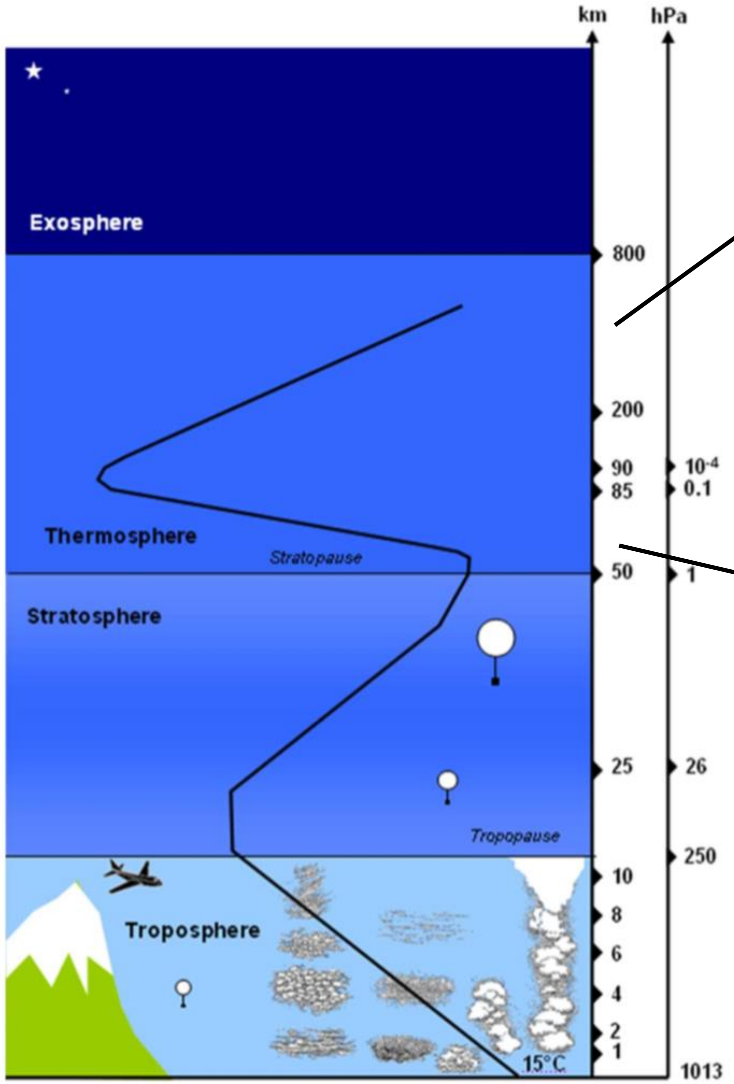
- is a main component of the Earth's mesosphere and lower thermosphere (MLT)
- extends from about 80 km to above 400 km
- governs photochemistry and energy balance
- is a tracer for dynamical motions in the MLT
- is responsible for corrosion of spacecrafts in Low Earth Orbits
- slows down spacecrafts and space debris in Low Earth Orbits
- is affected by global climate change



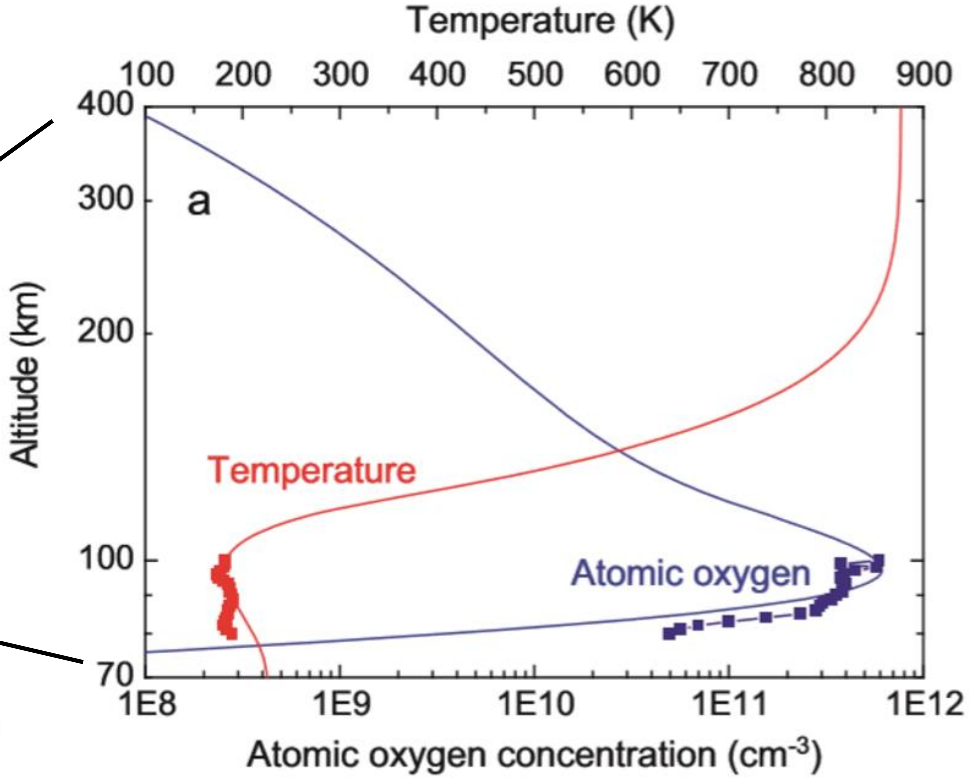
(energy levels not to scale)

$^3P_1 \rightarrow {}^3P_2$

Atomic Oxygen distribution



from: HEMERA zero-pressure balloon manual



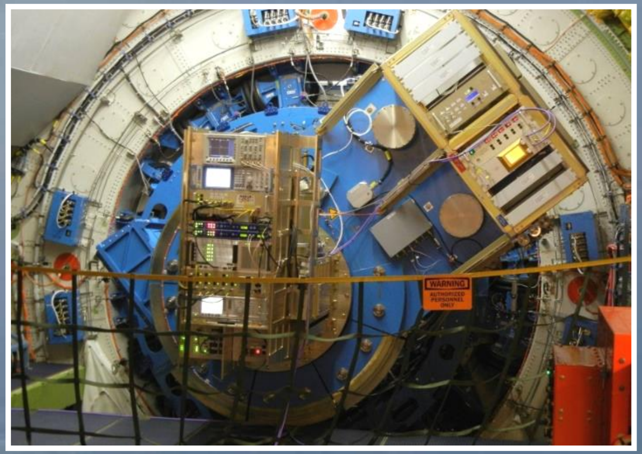
Lines: NRLMSISE-00 semi-empirical model
Squares: from SABER O_2 nightglow satellite measurements

H. Richter et al., Comm. Earth & Environ. 2:19 (2021)

SOFIA: Stratospheric Observatory for Infrared Astronomy

Method/instrument

- High-resolution THz heterodyne spectroscopy
- GREAT (German Receiver for Astronomy at THz Frequencies) heterodyne spectrometer



Atomic oxygen measurement with GREAT/SOFIA

NLRMSISE-00

Blue line: Atomic oxygen

Red line: temperature

SABER

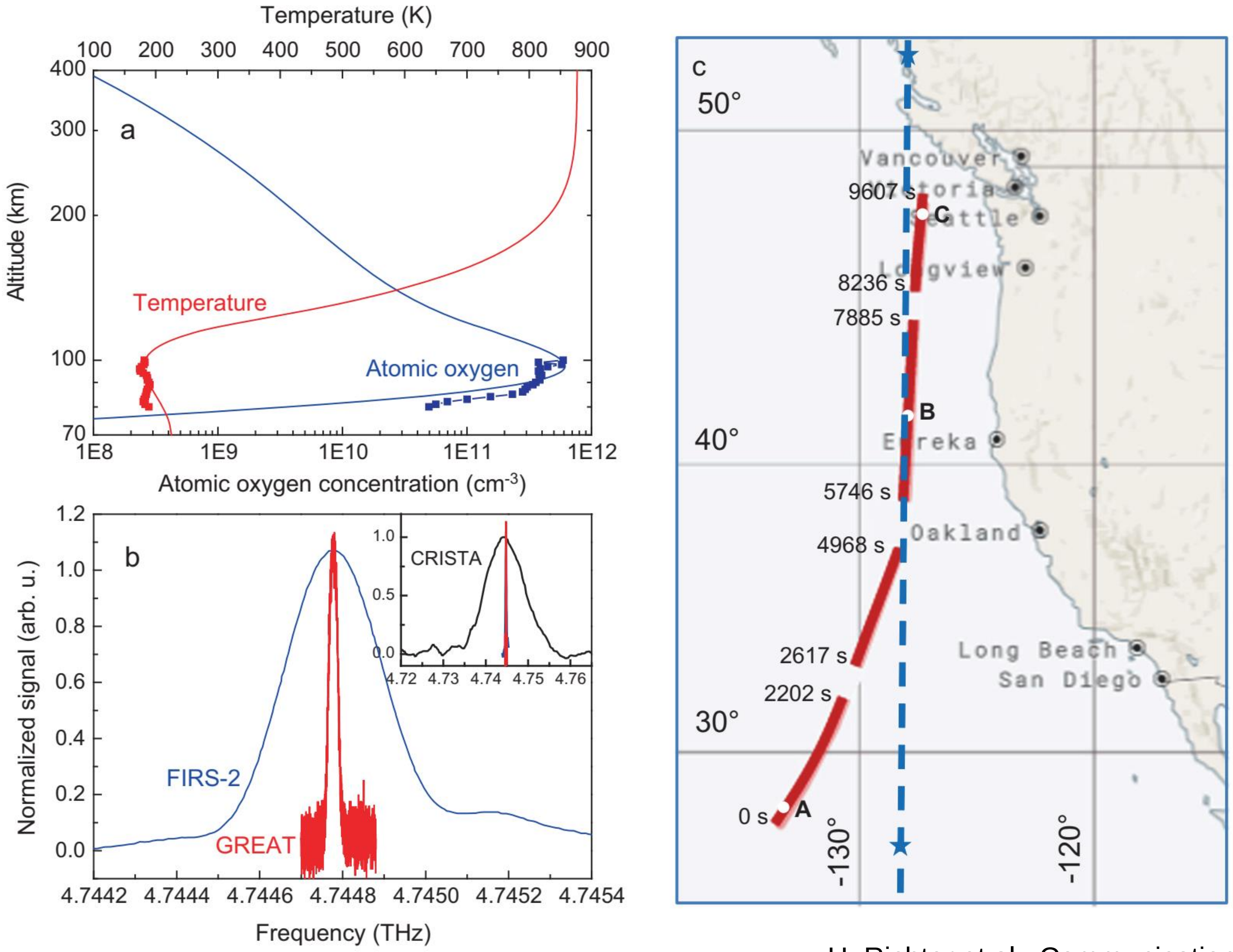
Blue squares: atomic oxygen

Red squares: temperature

Black: CRISTA (grating)

Blue: FIRS-2 (FTIR)

Red: GREAT (heterodyne)



Red line:

Trajectory of the SOFIA flight where the spectra have been acquired between 1:15 and 4:15 am on 14 January 2015.

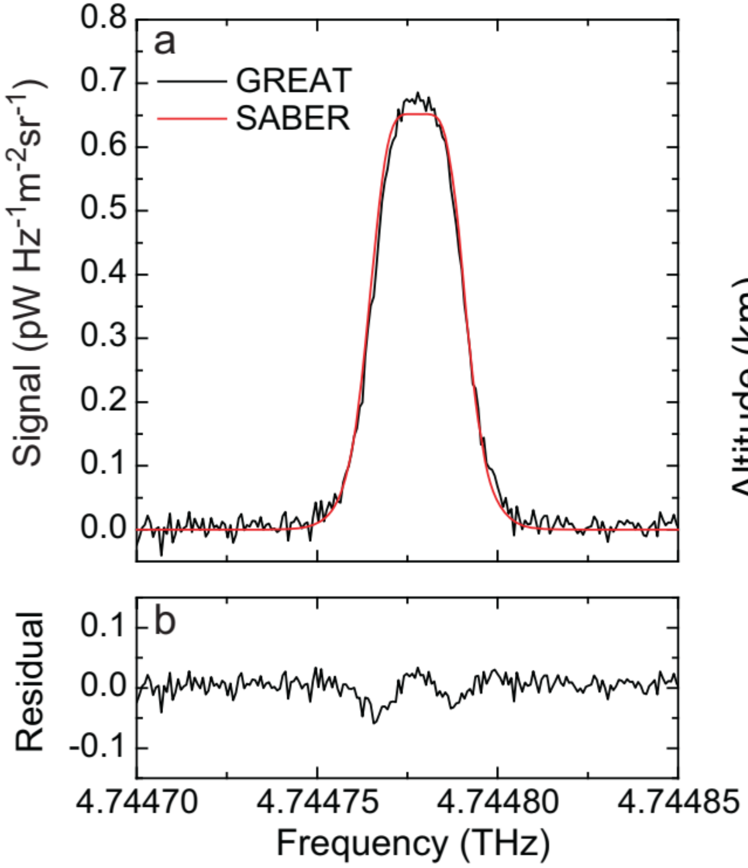
Dashed blue line:

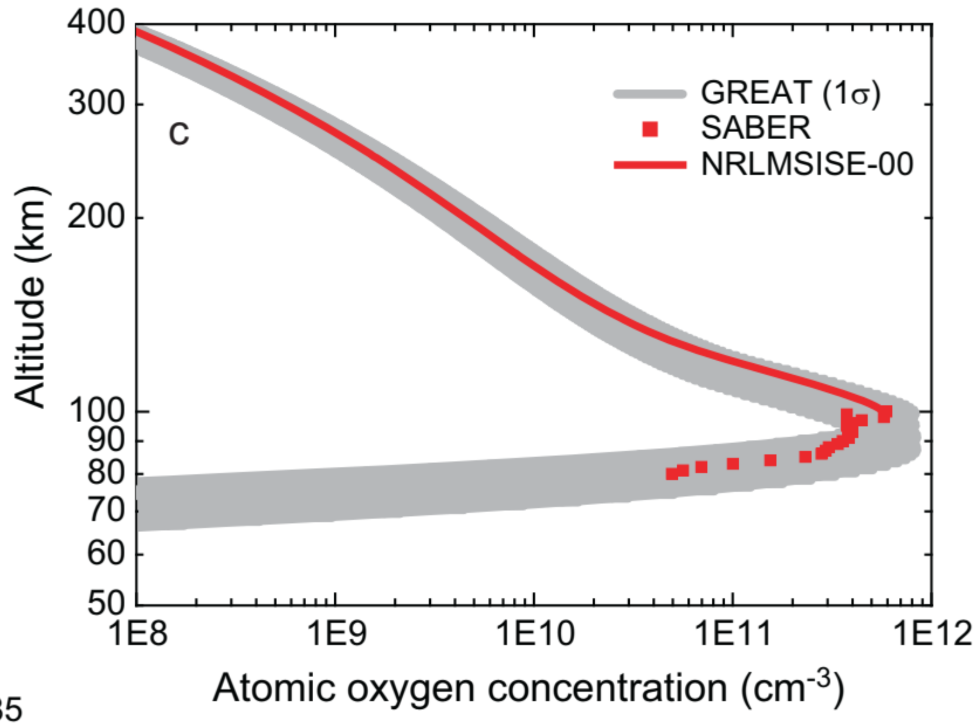
Flight trajectory of SABER at about the same time (0:22 - 0:30 am) as SOFIA.

H. Richter et al., Communications Earth and Environment **2**, 19 (2021)

A new method to measure atomic oxygen in the MLT

- Good agreement with model based on the semi-empirical NRLMSISE-00 model (>100km) and satellite data (SABER, 80-100km).
- It is possible to derive the concentration profile of atomic oxygen from the measured emission line shape at 4.7THz.





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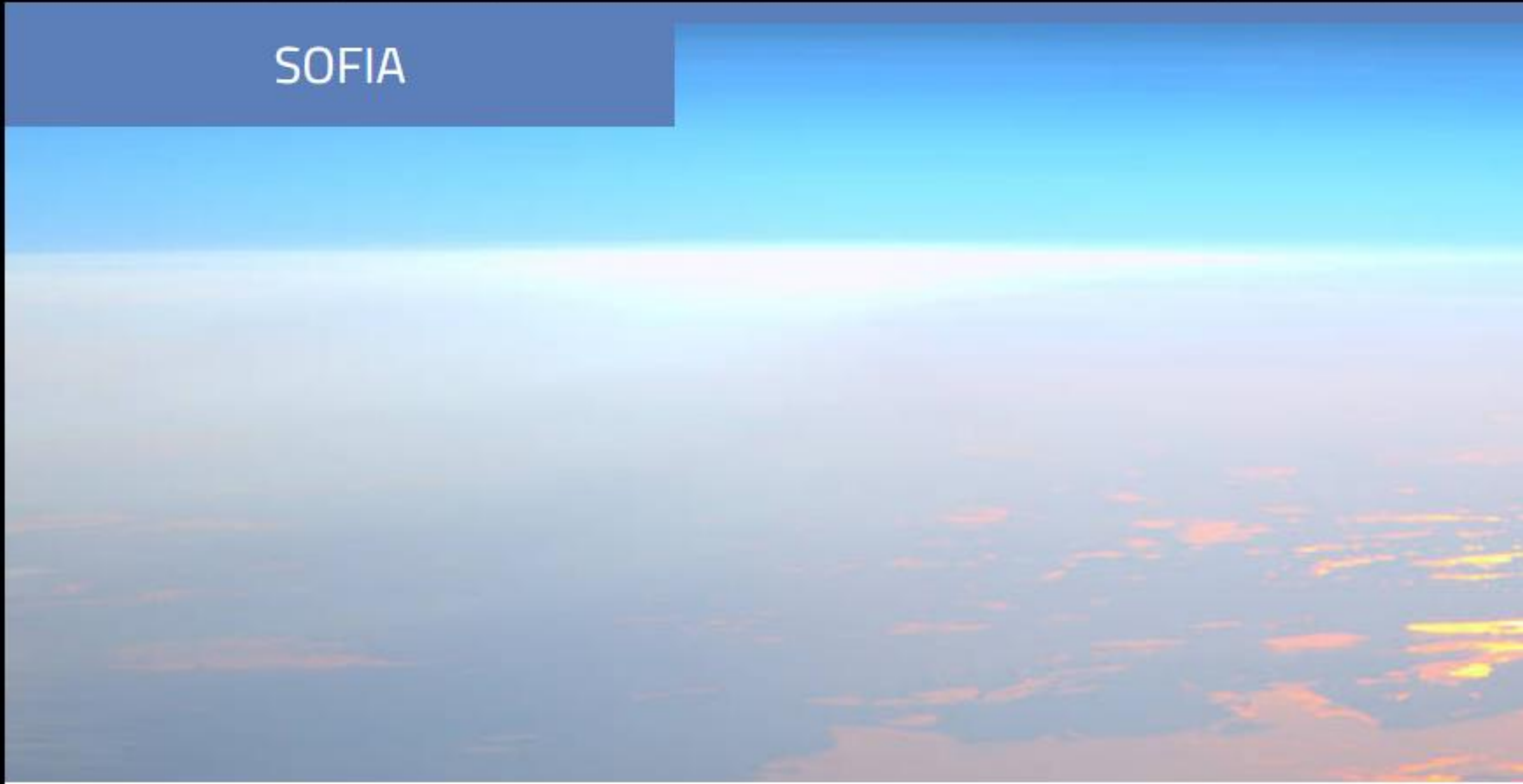
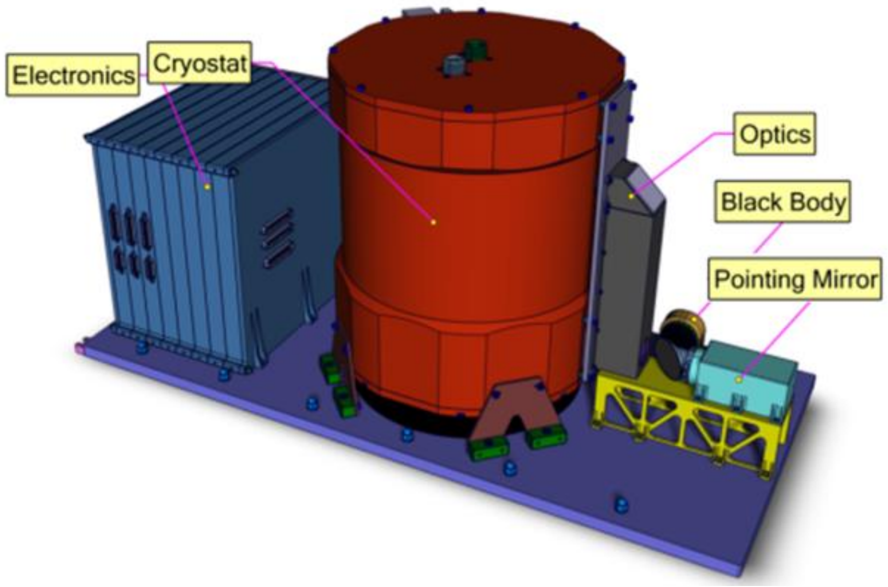
Comet Catalina Suggests Comets

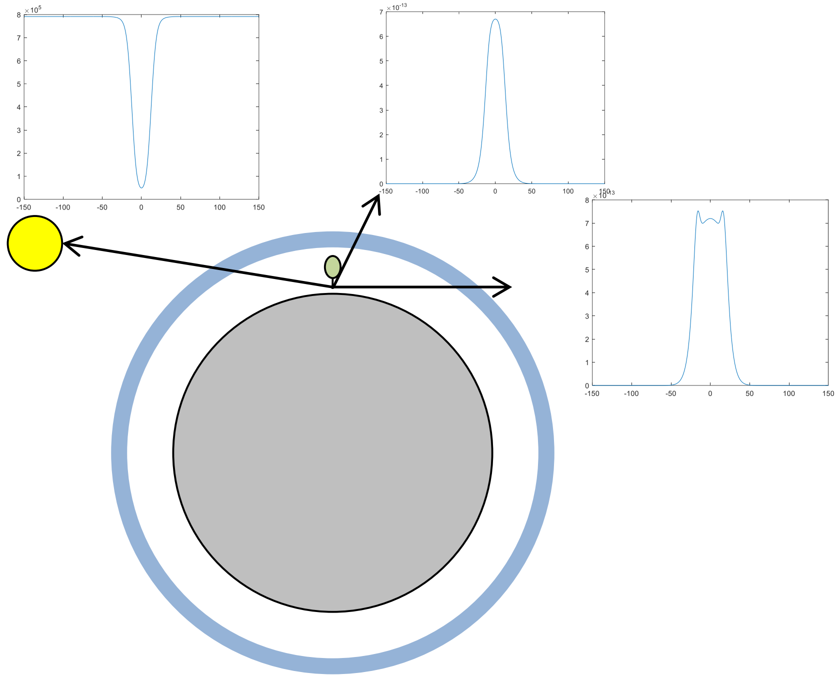


Apr 1, 2021

SOFIA Offers New Way to Study Earth's Atmosphere

OSAS-B: DLR’s Oxygen Spectrometer for Atmospheric Science from a Balloon





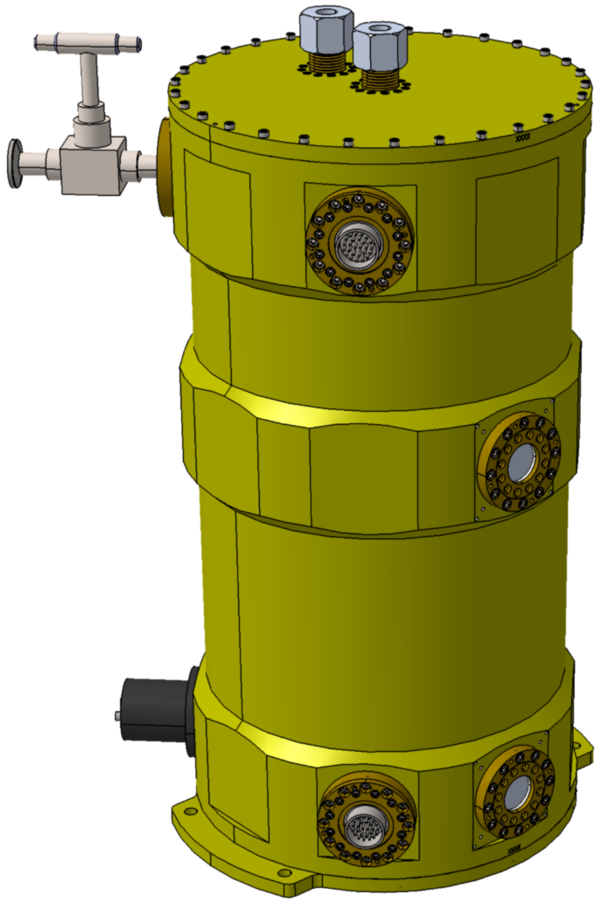
Measurement scenarios

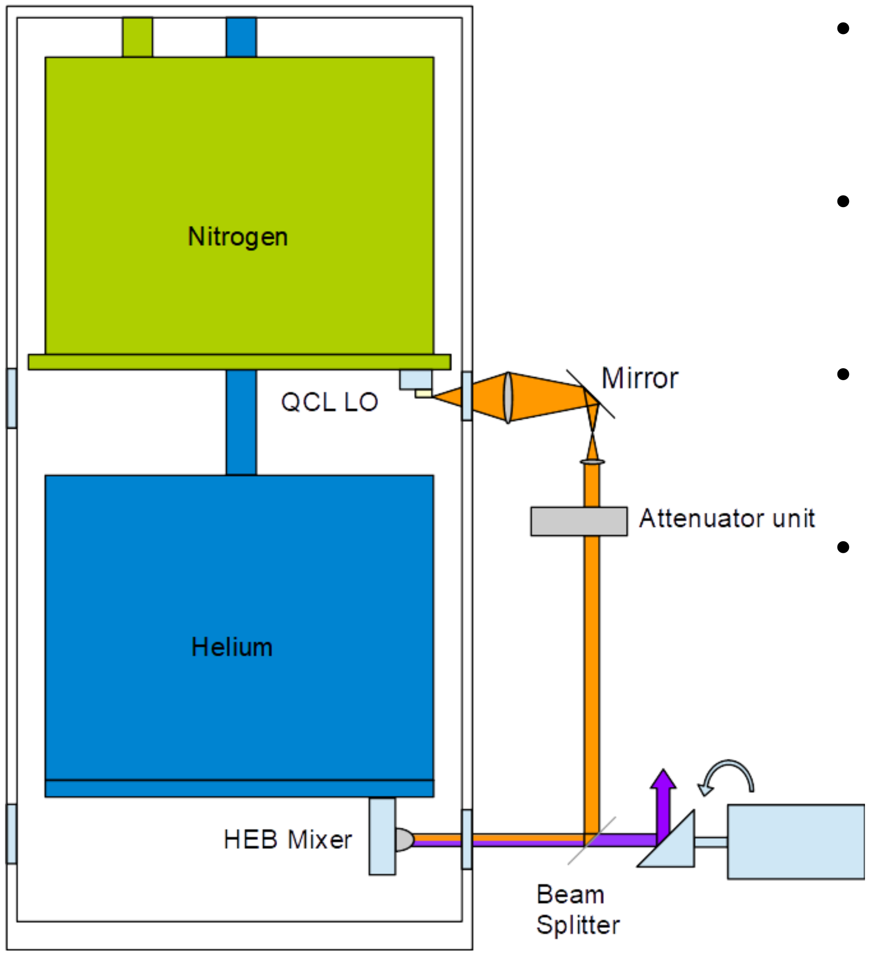
OSAS-B: Compact (70 kg, 100 W) 4.7-THz heterodyne spectrometer for a stratospheric balloon (35 km altitude)

Advantages over SOFIA: Quieter environment, no residual water absorption, observation of diurnal variations

Measurement: Different elevations, solar/lunar occultation

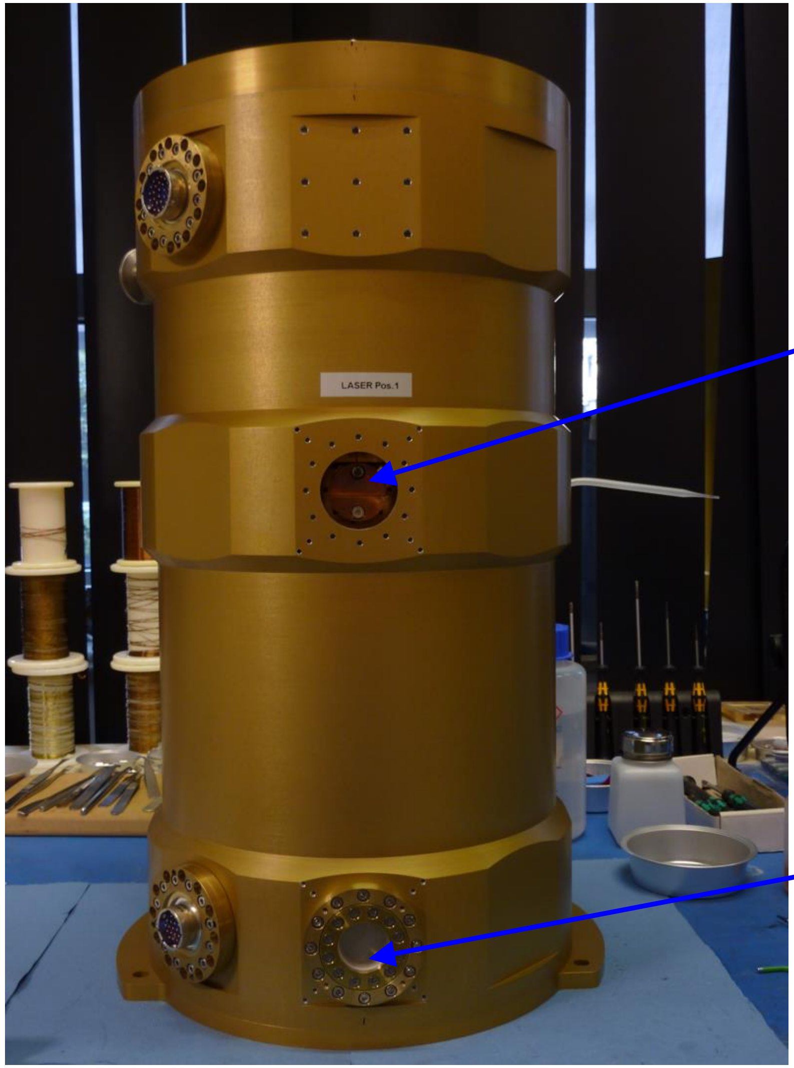
OSAS-B: Receiver frontend design

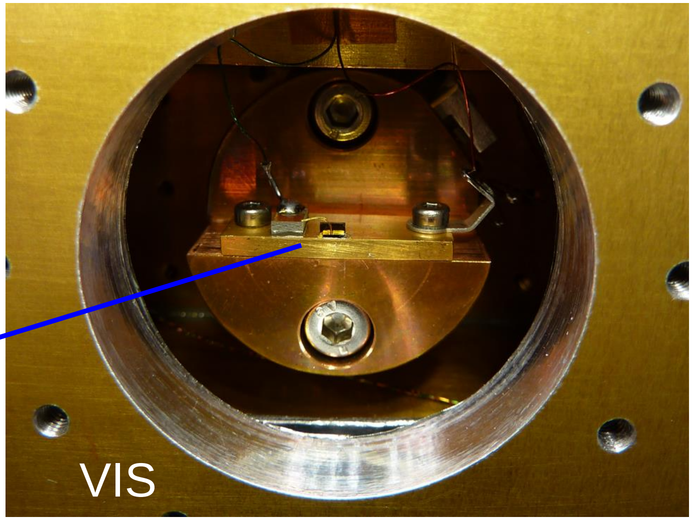


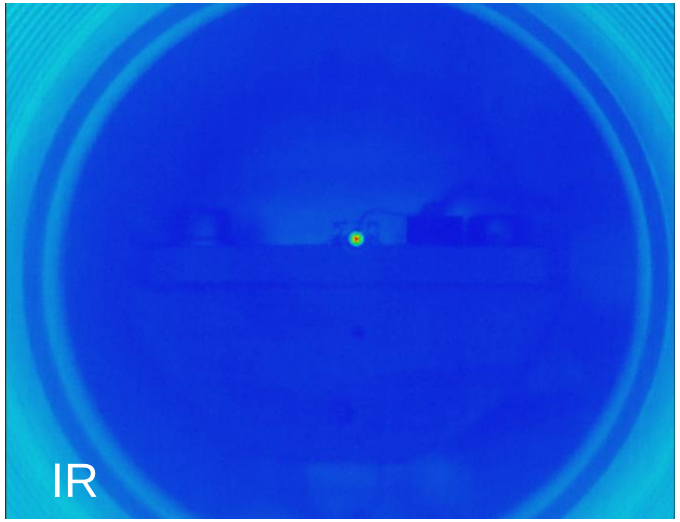


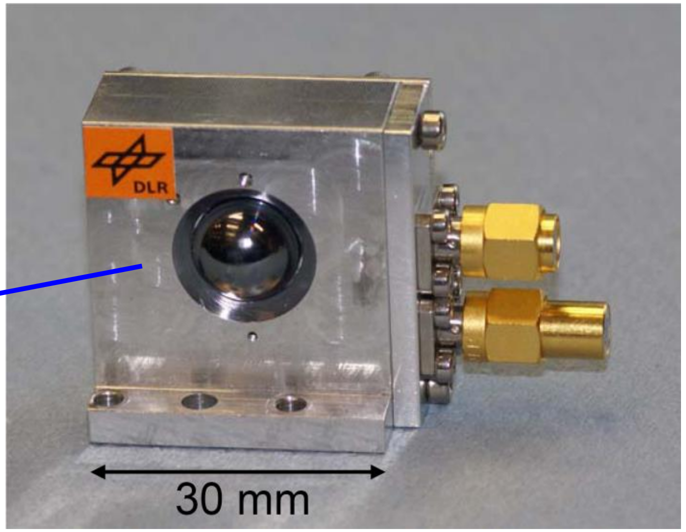
- Dewar: Solid Nitrogen / liquid Helium (60K/4K) with active pressure control
- Local oscillator: 4.7 THz quantum-cascade laser operated at 60 K
- Mixer: Quasi-optical superconducting hot-electron bolometer operated at 4K
- Backend spectrometer: Digital fast Fourier transform spectrometer (MPI Bonn)

Integration in lHe/sN2 cryostat

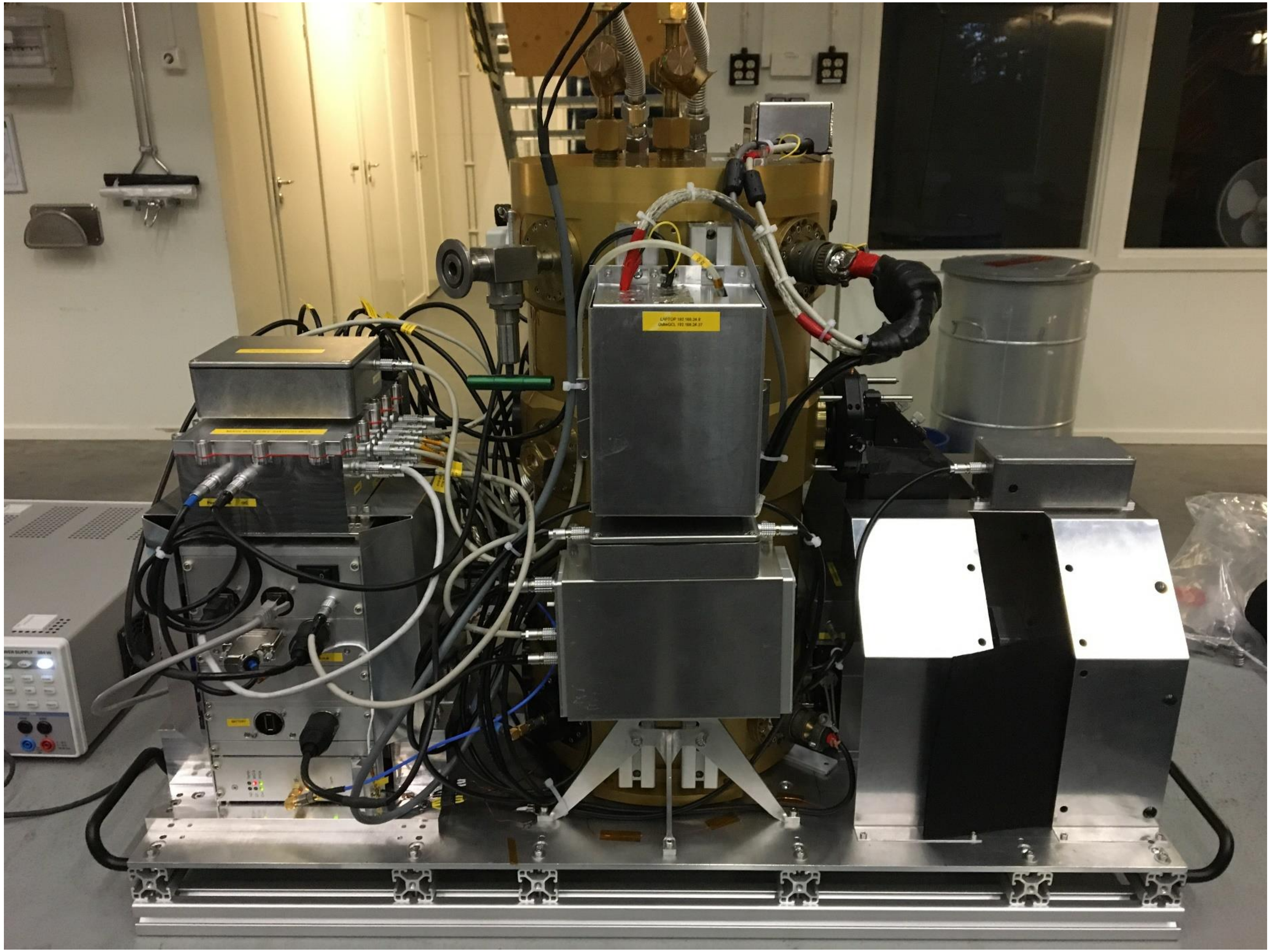






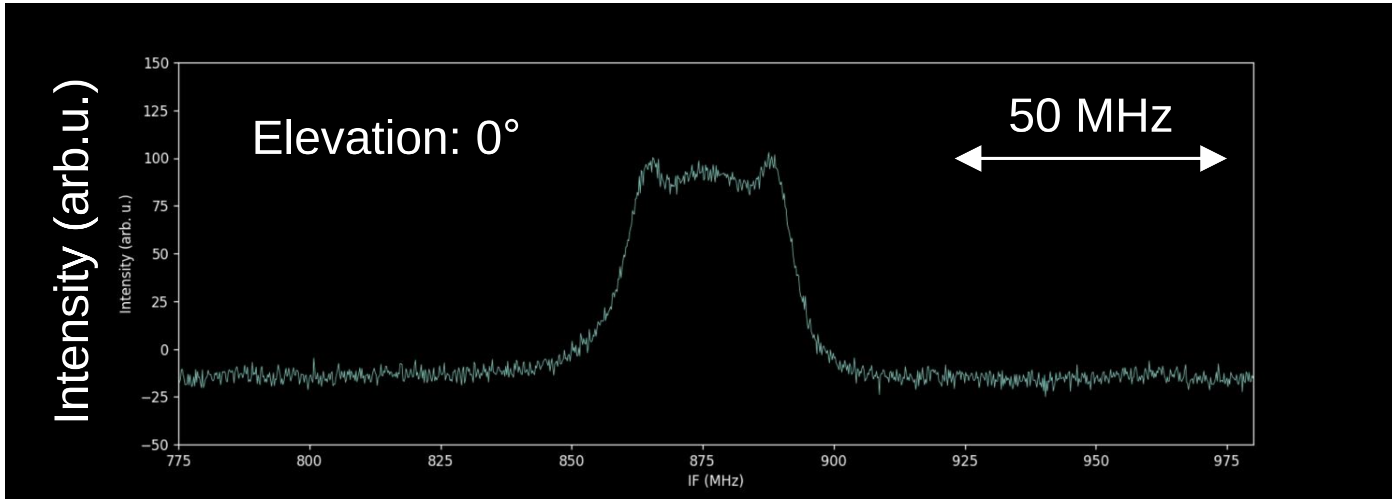


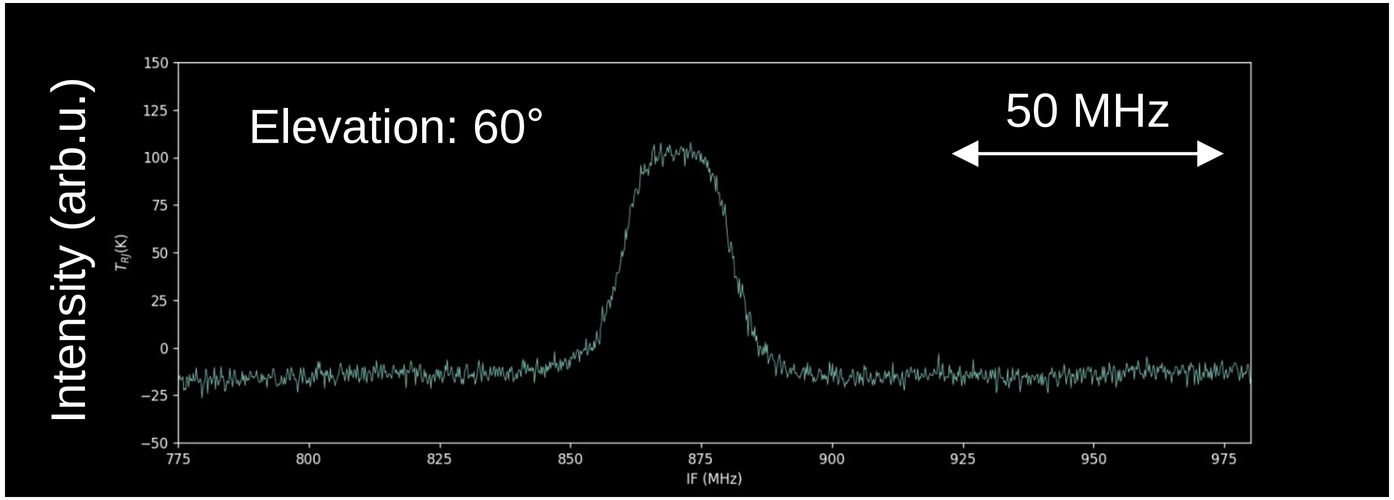
OSAS-B



Launch from Esrange/Kiruna (Sept. 7, 2022, 7:19 hours)

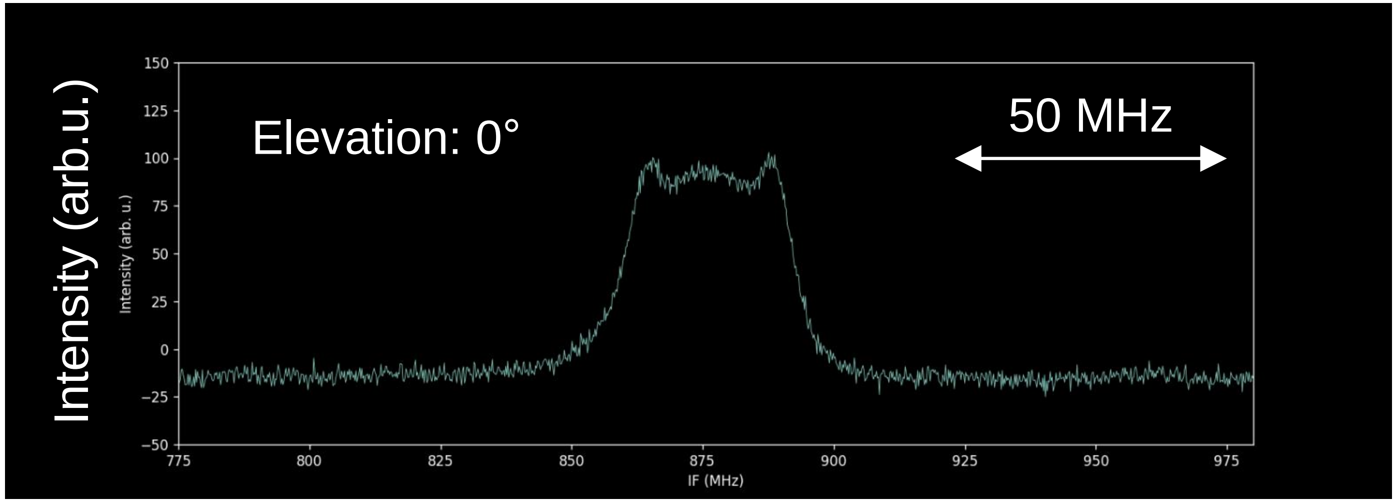
First spectra: Atomic oxygen @ 4.7 THz

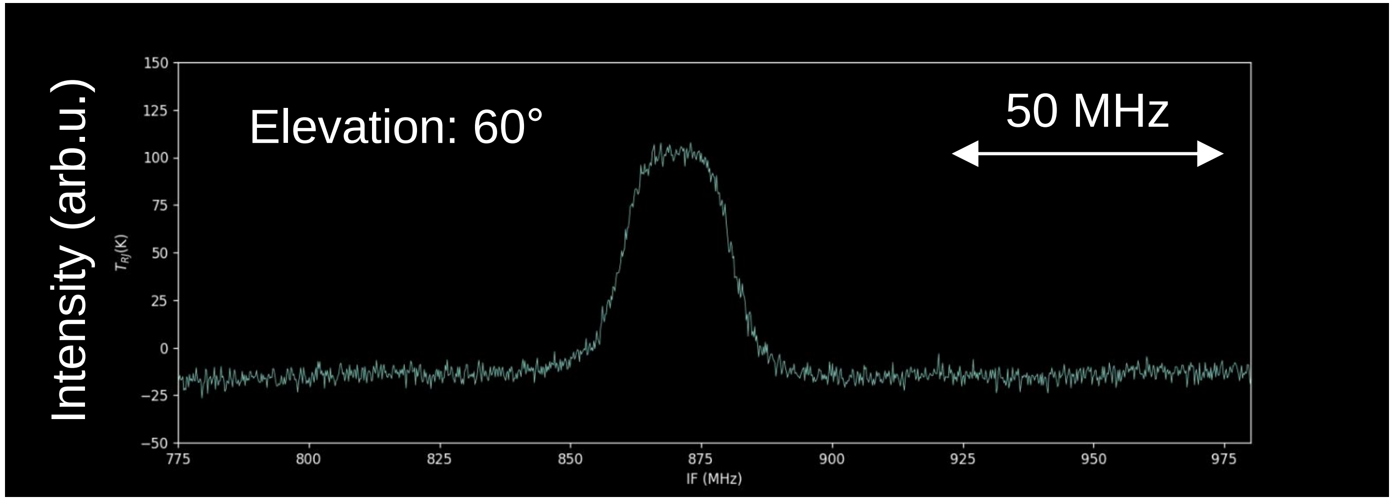


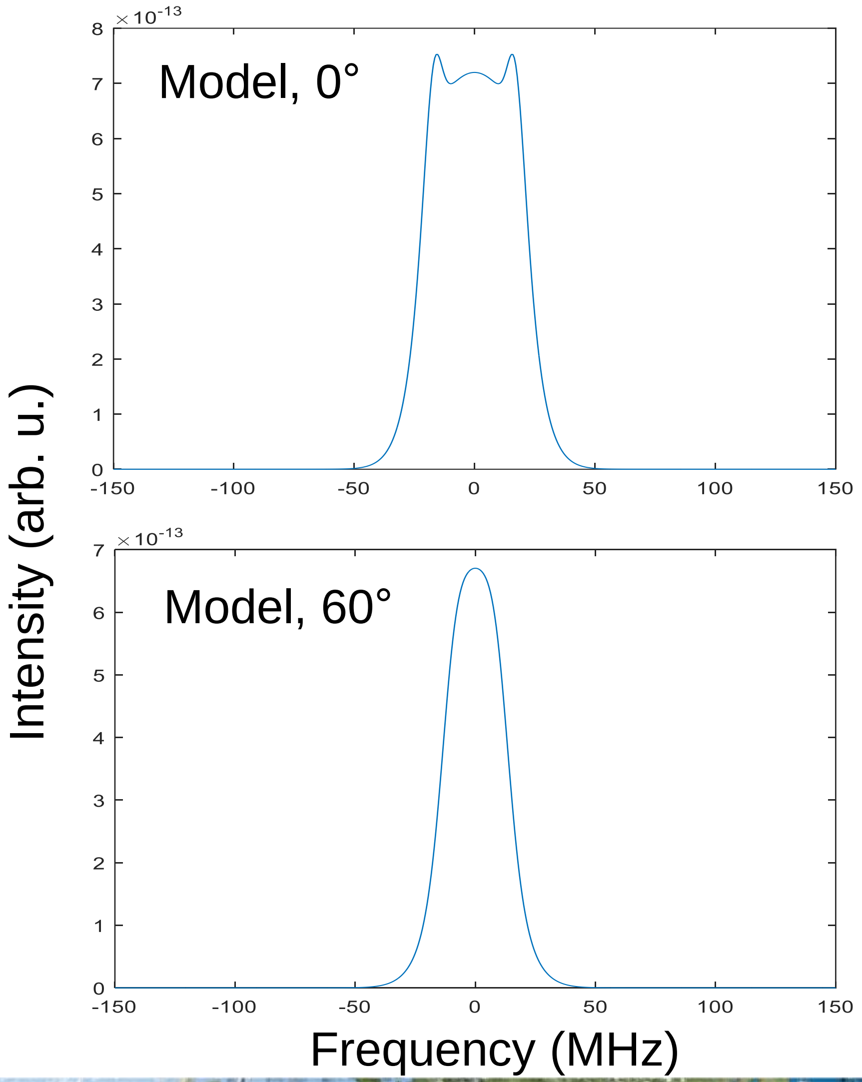


View out of the gondola along the line of sight of OSAS-B (33km altitude).

First spectra: Atomic oxygen @ 4.7 THz



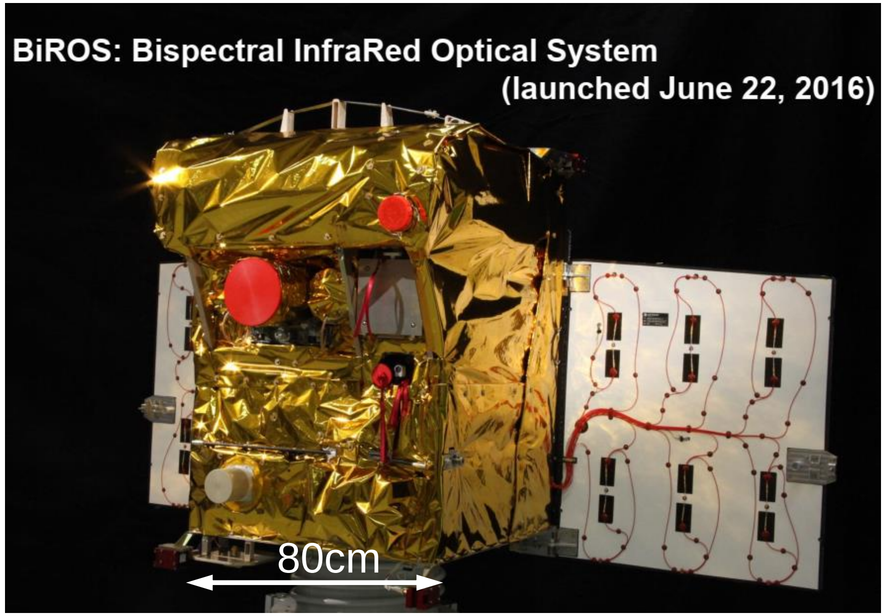


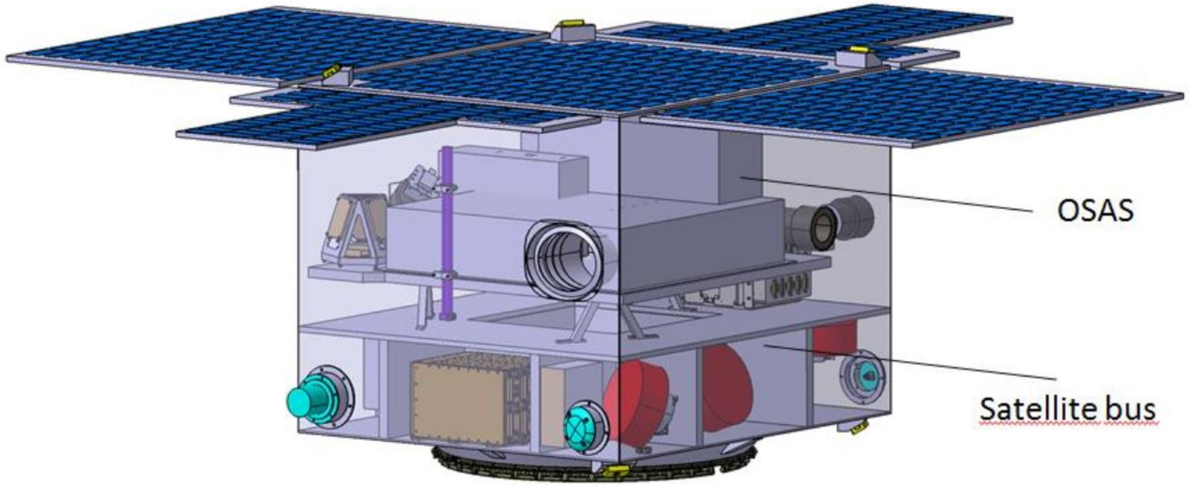


Towards space: OSAS on a satellite

- DLR Phase 0/A study
- 2.06 THz and 4.7-THz heterodyne spectrometer, Schottky diode mixer, multiplier and QCL LO, digital Fast Fourier spectrometer as backend
- 240 kg mass (incl. 50 kg for payload)
- 260 W electrical power
- Heritage: DLR‘s BIROS satellite

Proposals to ESA (LOCUS, KEYSTONE)





Objective(s) of the Activity

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The final application of the phase locked THz radiation will be to pump a Schottky diode based receiver at 4.7 THz. In order to de-risk the system, an intermediate step at 3.5 THz shall be considered.

Objectives

- Development of 3.5-THz LO based on a QCL and a PLL
- Development of 4.7-THz LO based on a QCL and a PLL

Common features of the LOs:
- QCL with surface-plasmon waveguide and Fabry-Pérot resonator in a mechanical cooler
- PLL with a subharmonic mixer and multiplier-based reference source at 600GHz

- Development of a 3.5-THz FE based on a 3.5-THz QCL LO and a Schottky diode mixer
- Development of a 4.7-THz FE based on a 4.7-THz QCL-LO and a Schottky diode mixer

Common features of the FEs:
- Fundamental Schottky diode mixer with waveguide coupling and diagonal horn antenna
- QCL-LO with PLL
- Quasi-optical coupling of LO and RF radiation with a Martin-Pupplett diplexer

Project partners and tasks

• DLR, Institute of Optical Sensor Systems:	System design, breadboards
• Paul-Drude Institut für Festkörperelektronik:	THz QCLs
• Omnisys SA:	600 GHz reference oscillator
• Chalmers University of Technology:	Harmonic mixers, fundamental mixers

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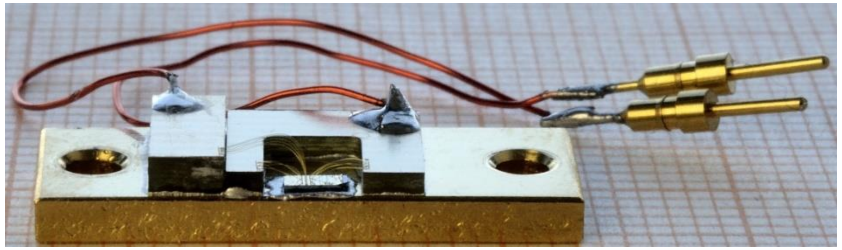
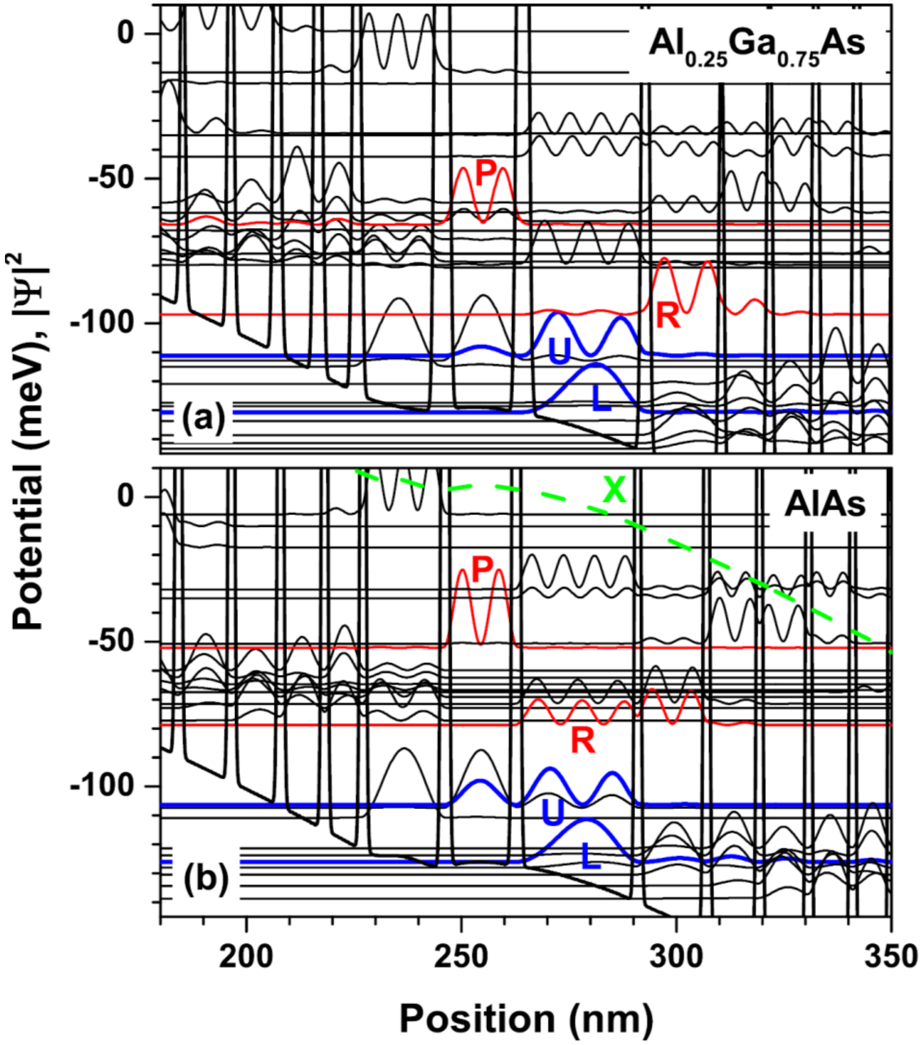
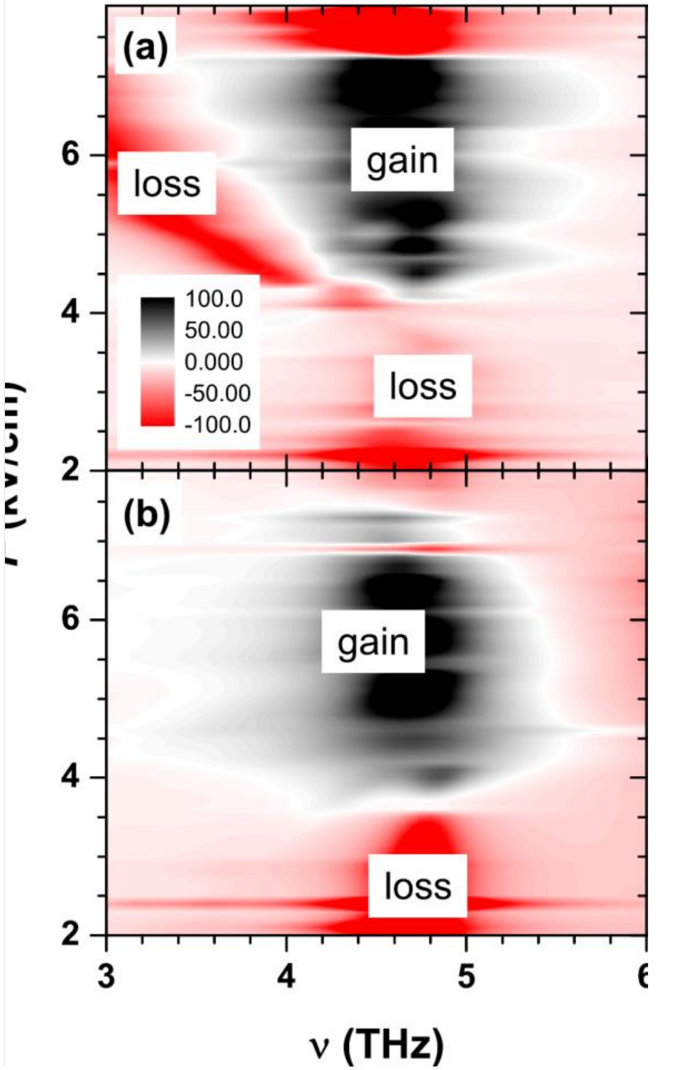
QCL with AlGaAS and AlAs barriers

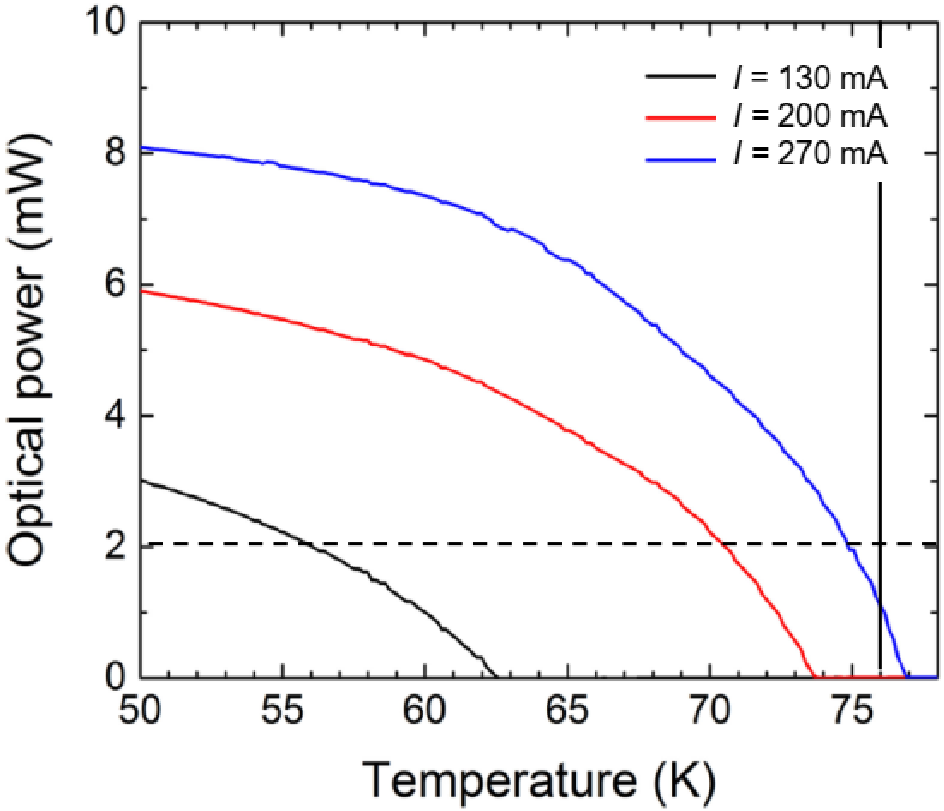
- AlAs barriers (instead of AlGaAs)
  - Larger subband separation, lower leakage current
  - Scaled barrier thickness
  - No ternary alloy (“better“ barriers)
- Otherwise the same:
  - SP waveguide
  - Around 1 mm ridge length
  - Facets as cleaved



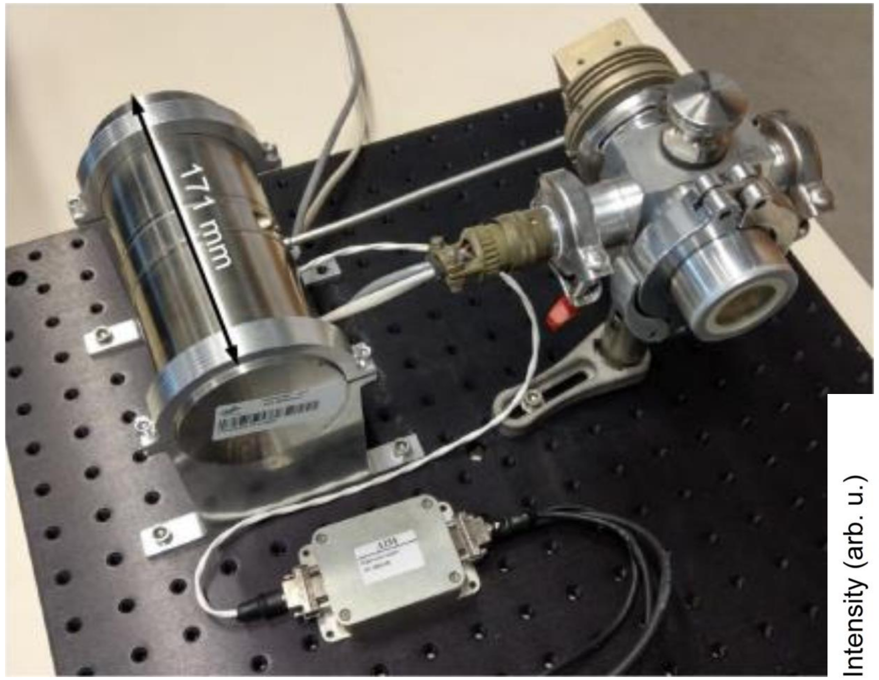


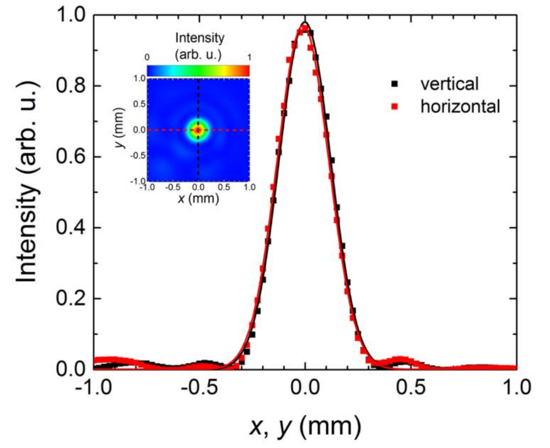


4.7-THz QCL

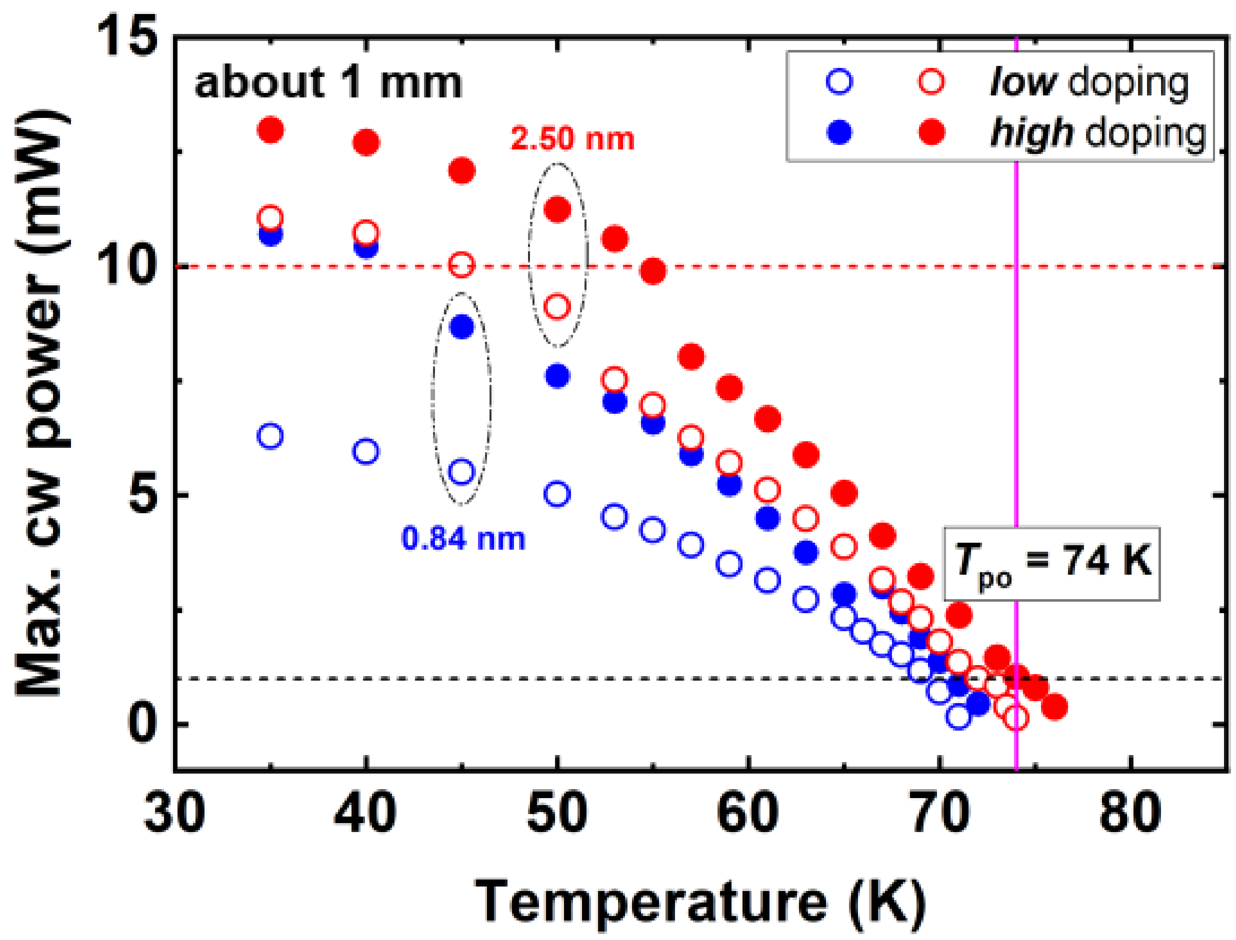


- Ridge dimensions: 0.08 x 0.583 mm^2
- Practical operating temperature T_{po} = 76 K
- $M^2 \approx 1.2$
- Measured in a miniature cryocooler (AIM SL400)

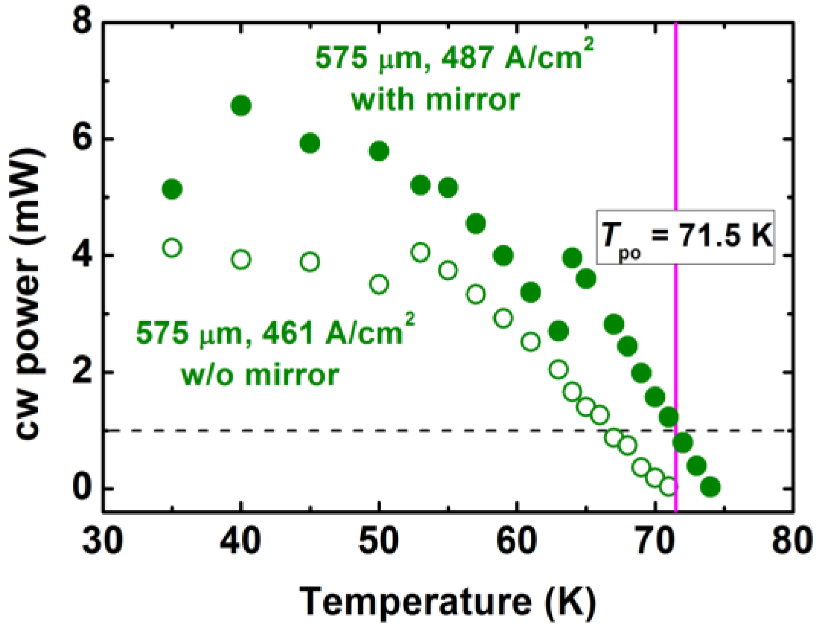




Example: 3.5-THz QCLs with different doping density and top barrier thickness

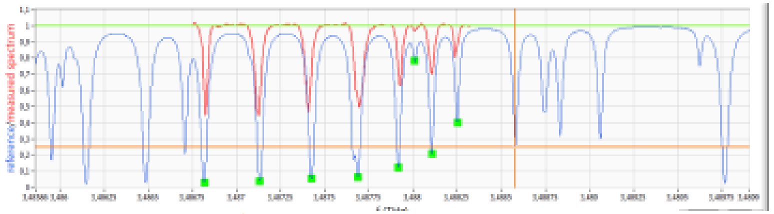


For comparison best 3.5-THz QCL before:

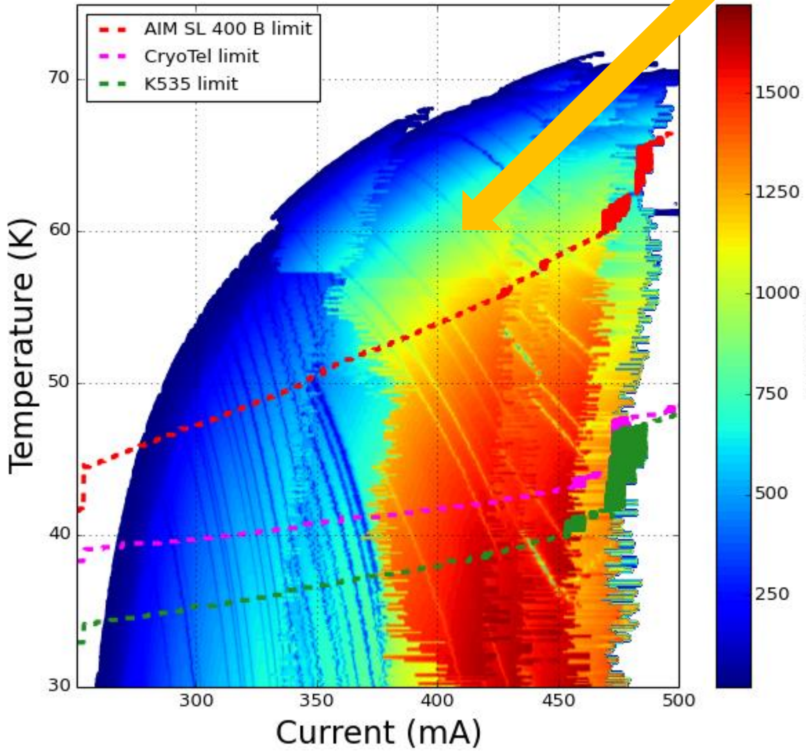


QCL performance

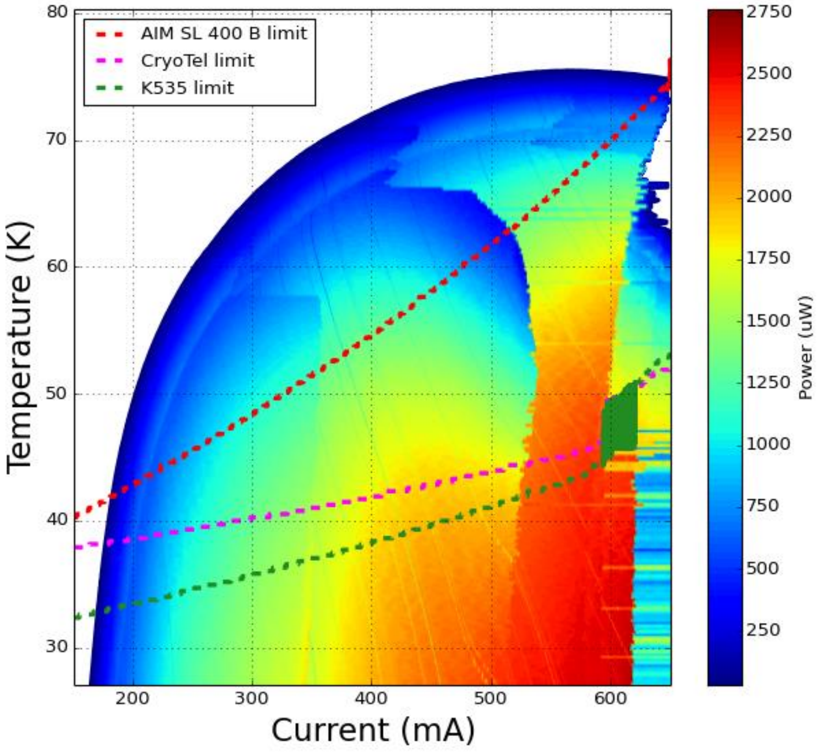
Fingerprint identification: comparison with reference Methanol spectrum



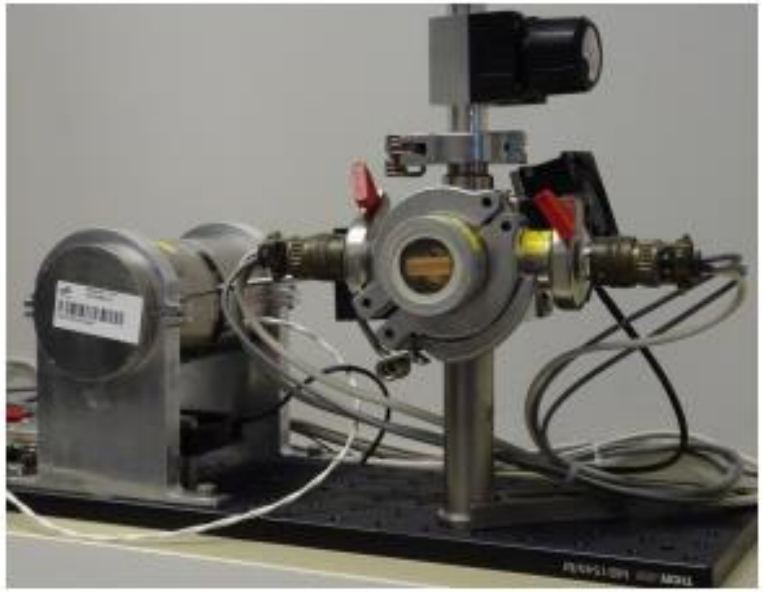
3.5 THz

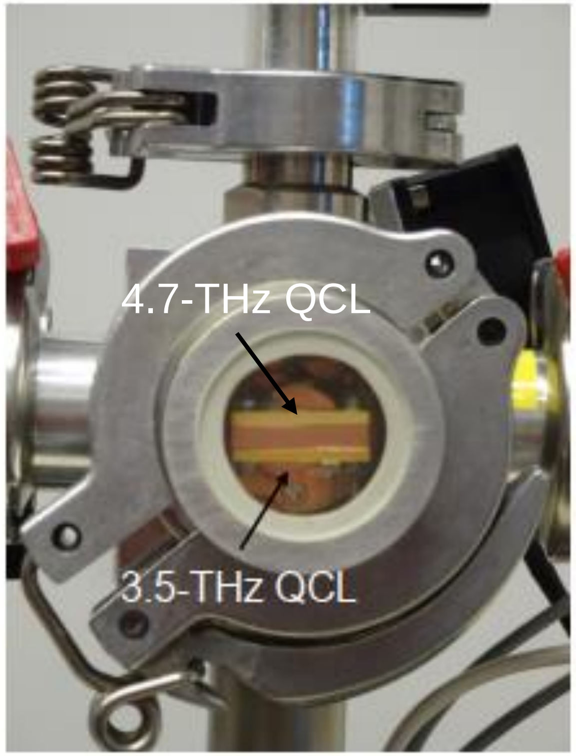


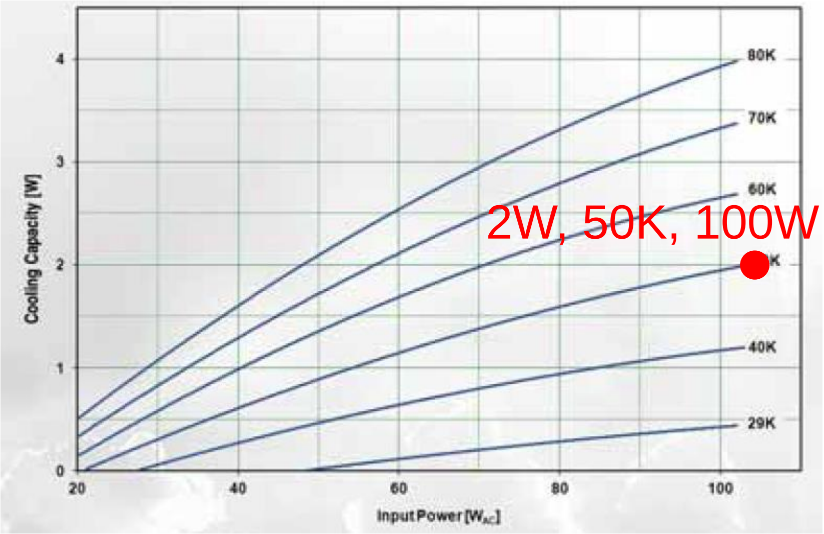
4.7 THz



QCL in AIM cryocooler

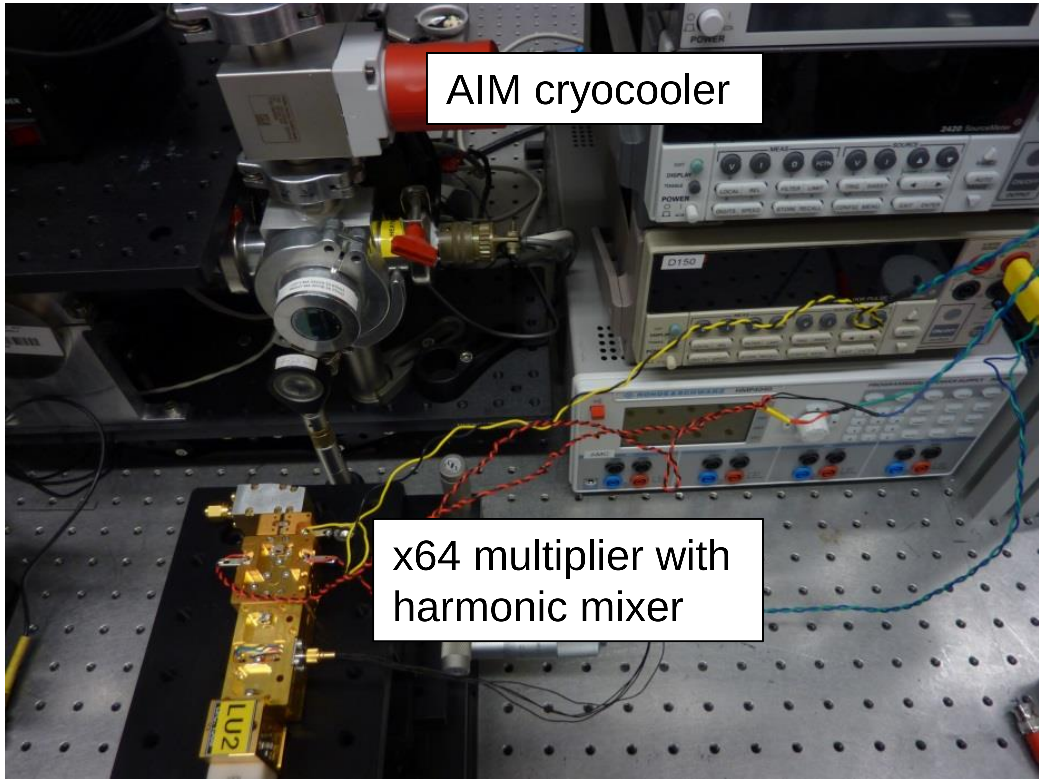


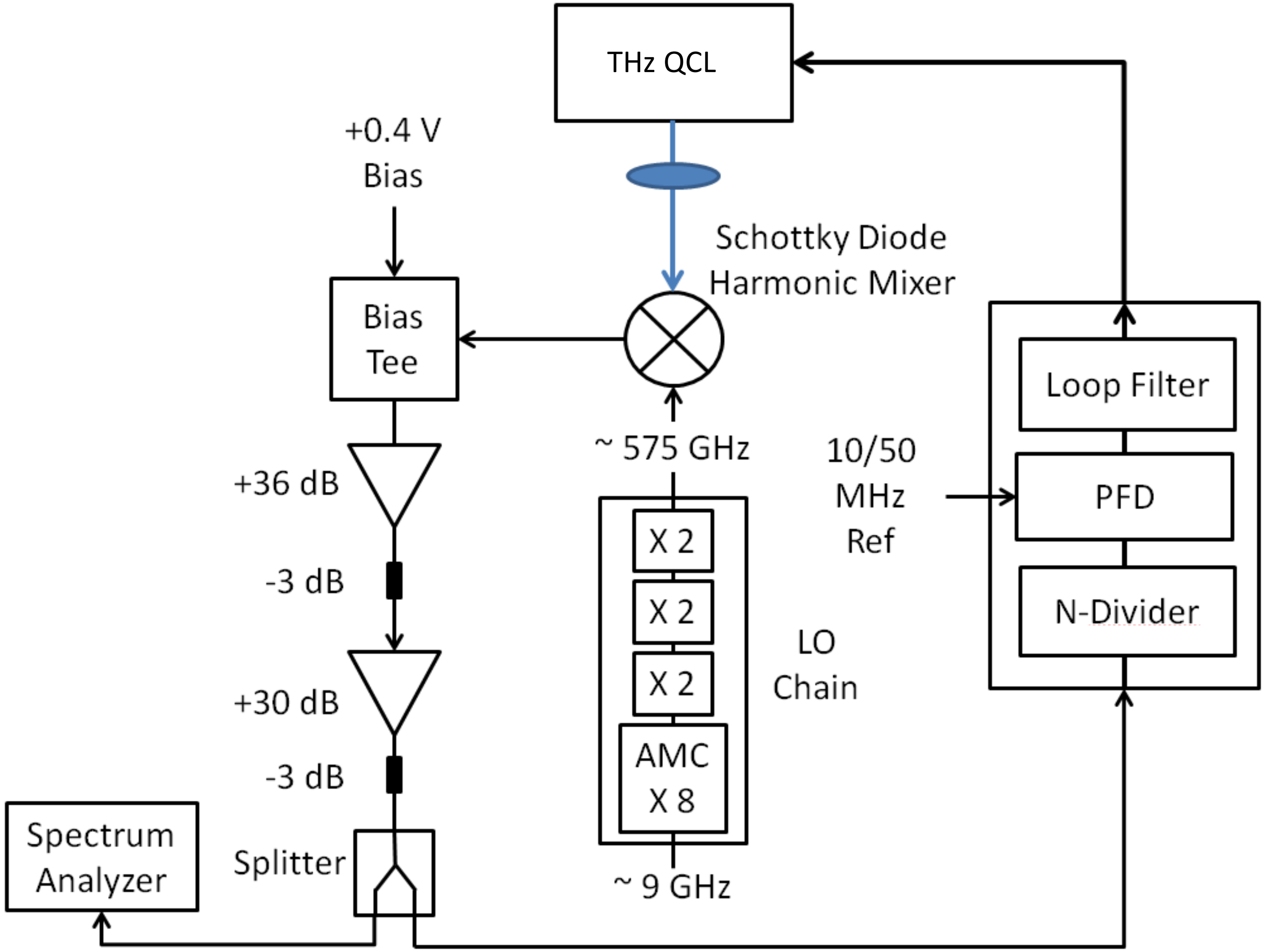




- AIM SL 400 cryocooler (has been used in several space missions)
- 3.2 kg, 170 mm long
- 2 W cooling capacity at 50 K and 100 W electrical input power

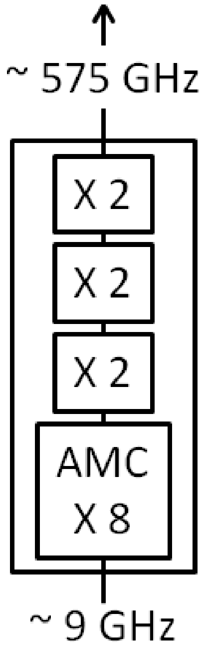
THz quantum-cascade laser: Phase-locking

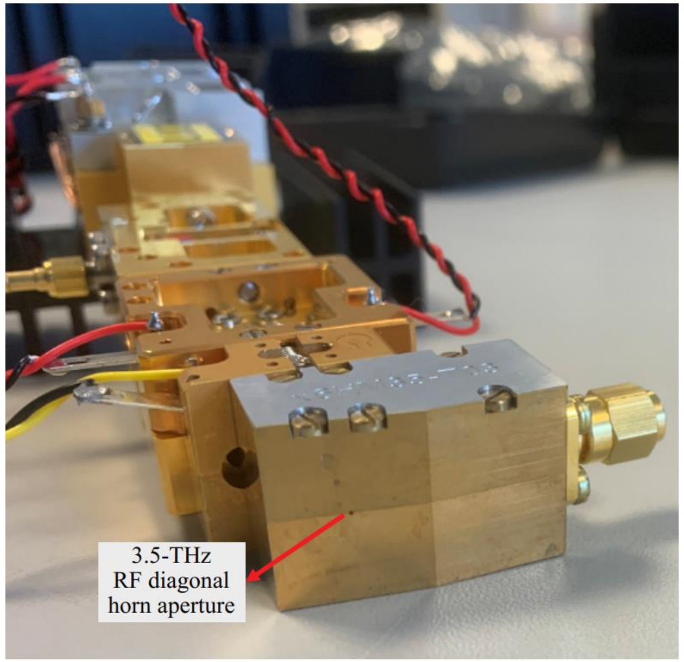


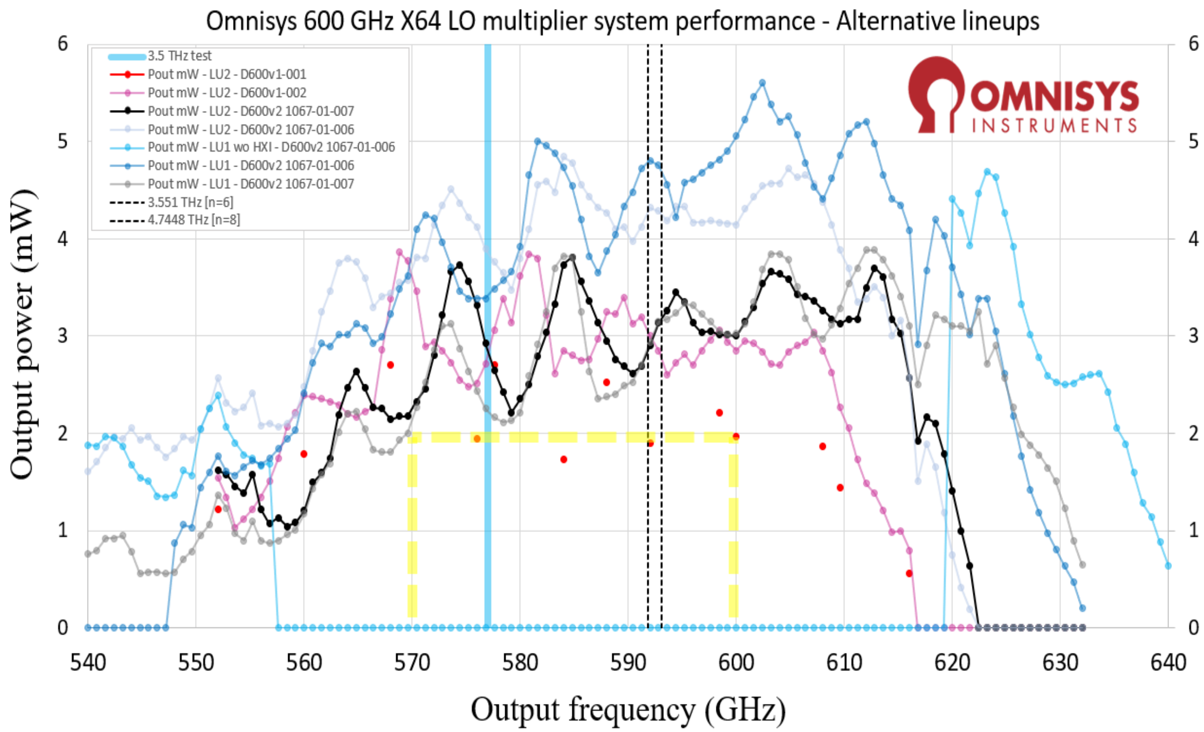


- x64 multiplier chain
- Harmonic mixer (x6 @ 3.5 THz, x8 @ 4.7 THz)

Harmonic mixer with x64-active frequency multiplier chain

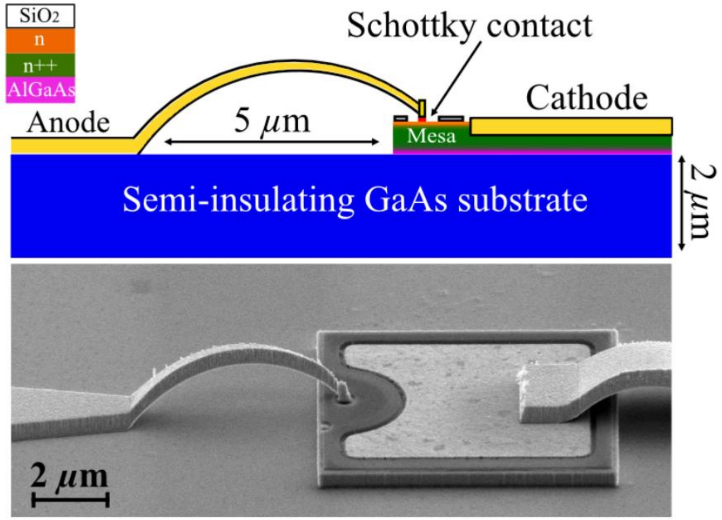




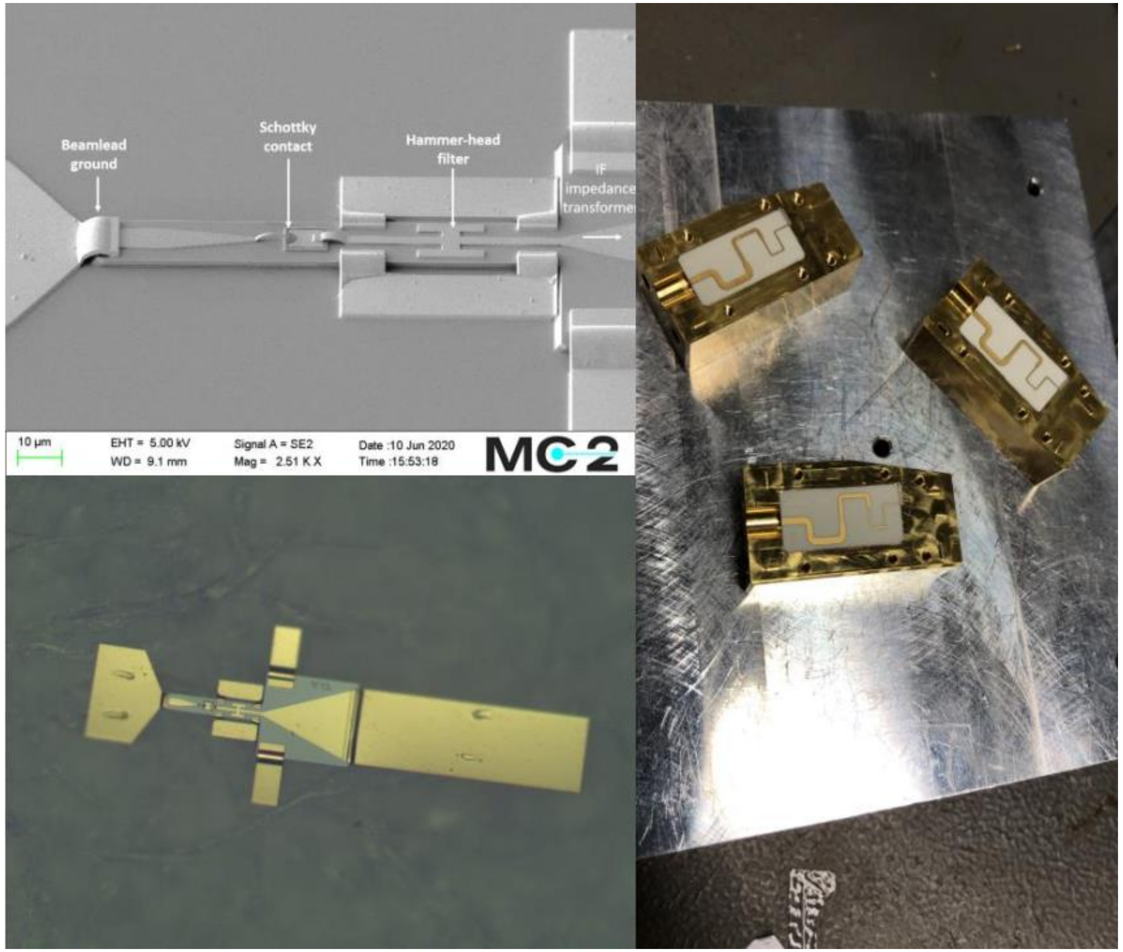


- LO: ×8 E-band active multiplier from Millitech (Smiths Interconnect), followed by a high-power isolator from HXI, and a cascaded three stage frequency multiplier chain from Omnisys based on GaAs Schottky membrane diode varactor doublers
- Diagonal horn antenna for coupling of QCL radiation to harmonic mixer

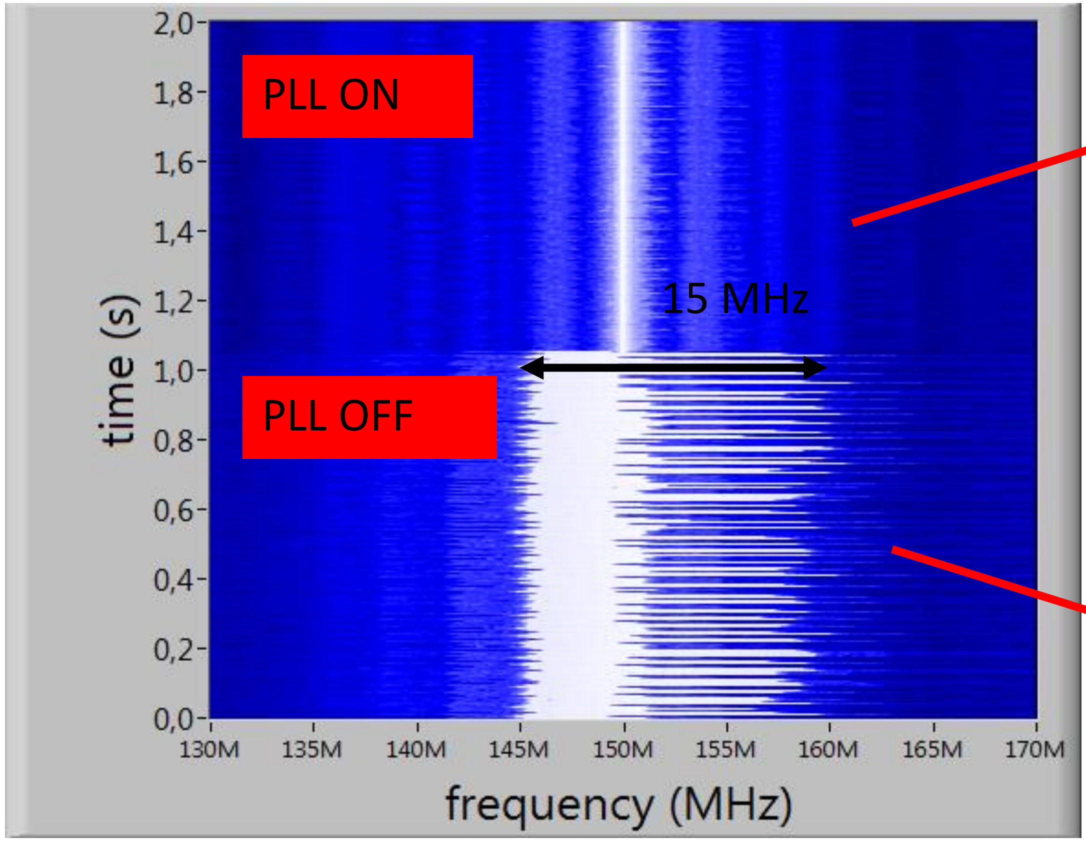
Harmonic mixer

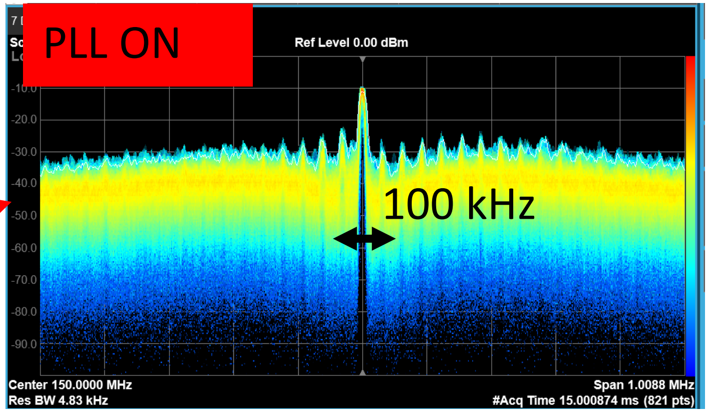


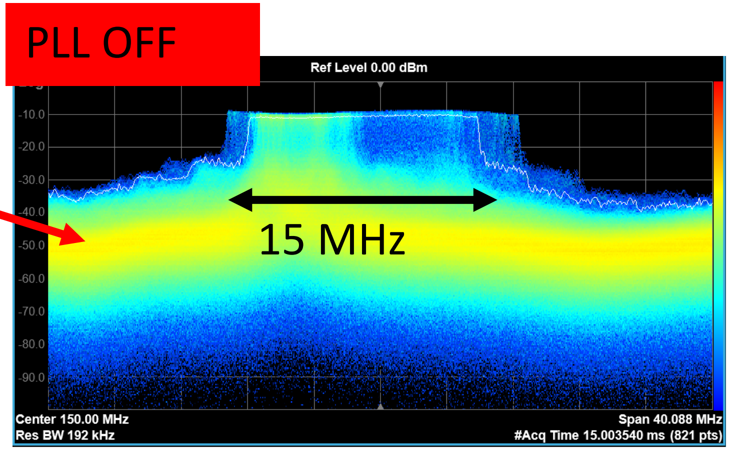
- Optimized for 600 GHz input, x6 (3.5 THz)
- Single-ended, planar, air-bridged Schottky diode with sub-micron anode contact area on a suspended 2-µm thin GaAs substrate
- Measured mixer conversion loss: 59 dB at 200 MHz IF
- Operates also at 4.7 THz (x8)



3.5-THz QCL in AIM cryocooler

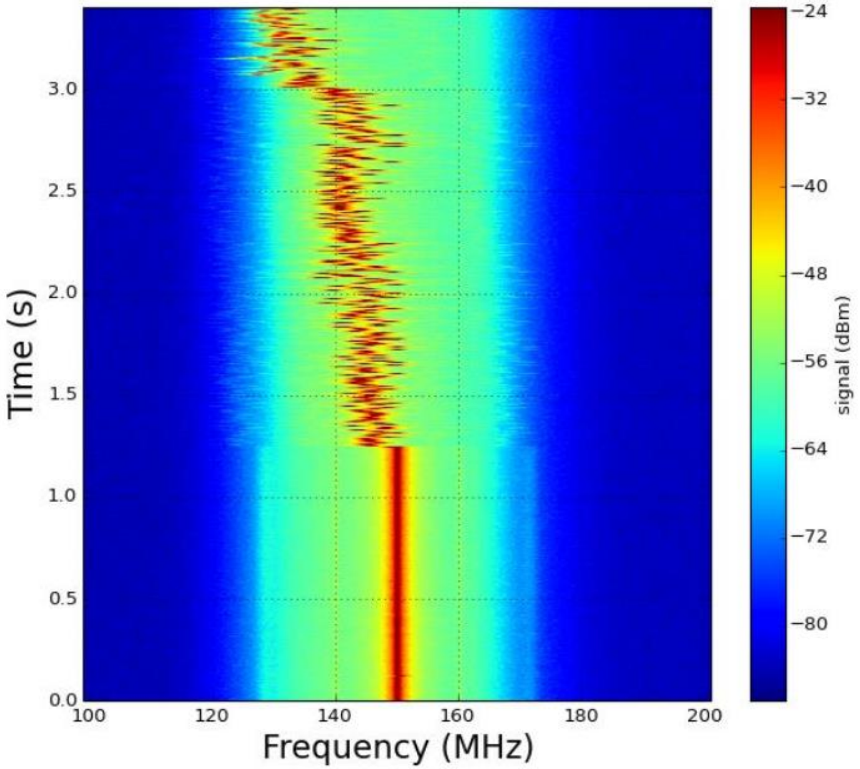


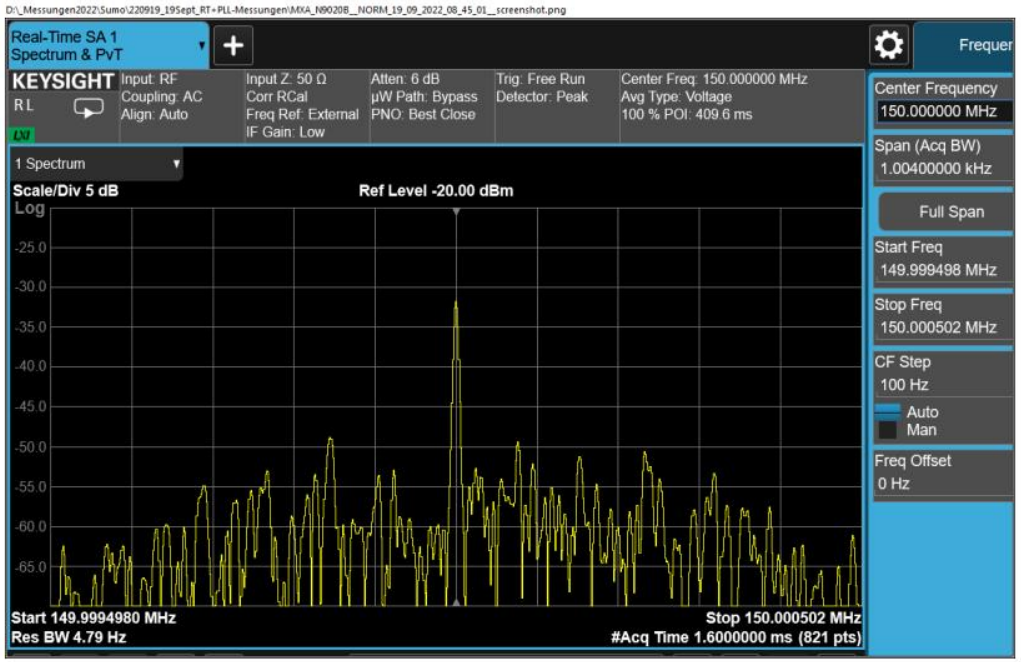




- Approx. 15 MHz frequency fluctuations with PLL=Off, due to cryocooler frequency (45 Hz, …)
- 3 dB linewidth << 100 kHz, when PLL=on

Minimum required LO power





- 3 dB linewidth <1 Hz
- Stabilization was possible down to a SNR of 18 dB
- The power in front of the harmonic mixer was below the measurement limit of the TK power meter Based on extrapolation we estimate the power to be below 50 µW.

Phase-locking: summary

Frequency (THz)	Cryocooler	Synthesizer (GHz)	Waist (µm)	Power (µW)	S/N (dB)
3.5	AIM	8.964583	180	450	35
3.5	Sumitomo	9.015810	240	550	40
4.7	AIM	9.307480	130	1 100	30
4.7	Sumitomo	9.287450	230	360	30

- QCL PLL stabilization at 3.5 THz and 4.7 THz achieved with QCLs in two different cryocoolers
- Stabilization was possible down to a SNR of 18 dB
- Required LO power below 50 µW

-> A space-qualified 3.5/4.7 THz QCL LO with output power of 5-10mW and a Gaussian beam profile ($M^2 \approx 1.2$) is feasible (incl. 100% European technology)!

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1.4.2 *Objective(s) of the Activity*

The objective of this activity is to demonstrate the feasibility of the frequency stabilization of a QCL and demonstrate the improvement of a stabilization loop with respect to passive stabilization based on thermal and electrical bias control.

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Objective(s) of the Activity

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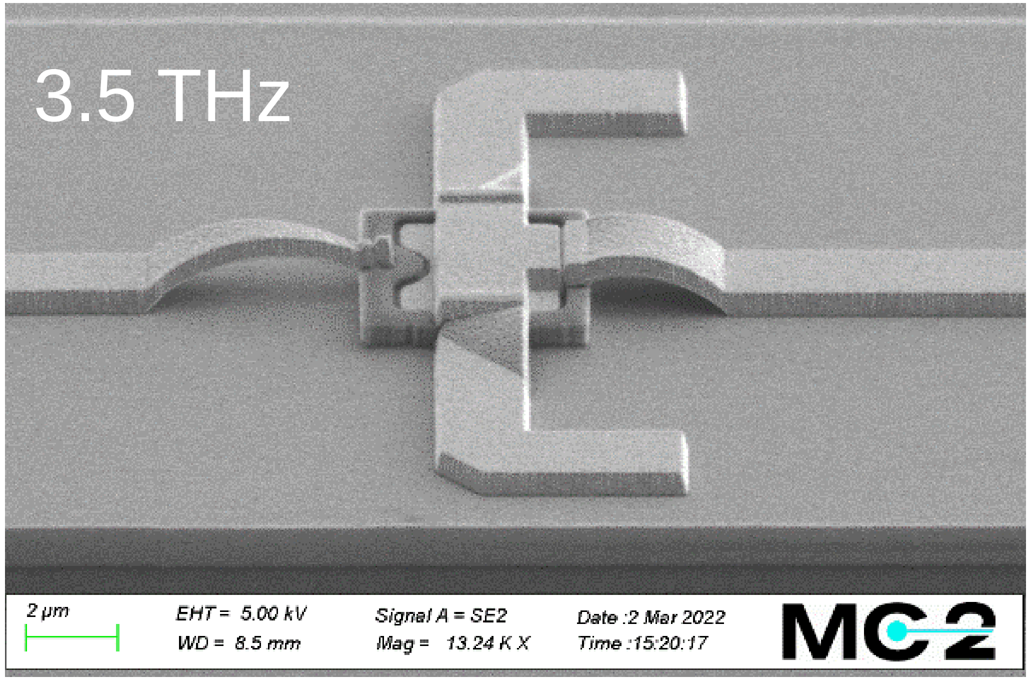
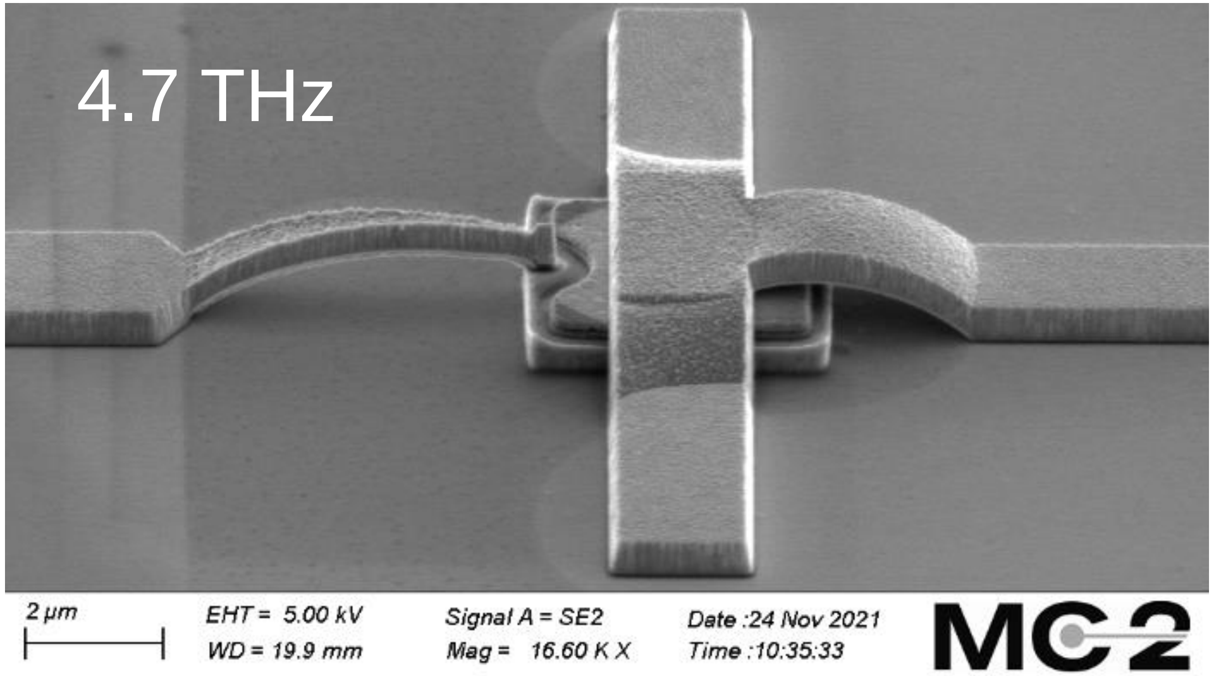
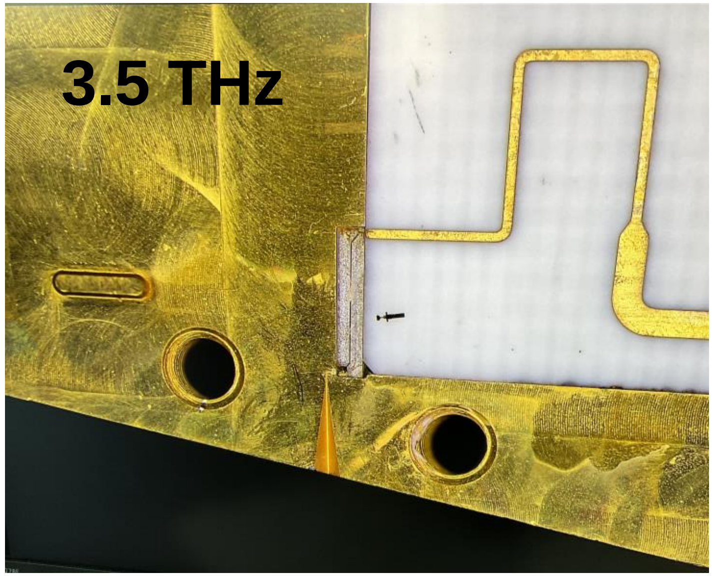
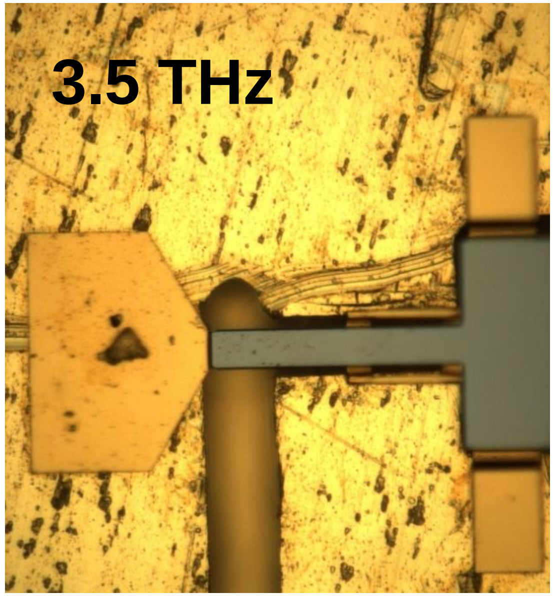
Fudamental Schottky diode mixers

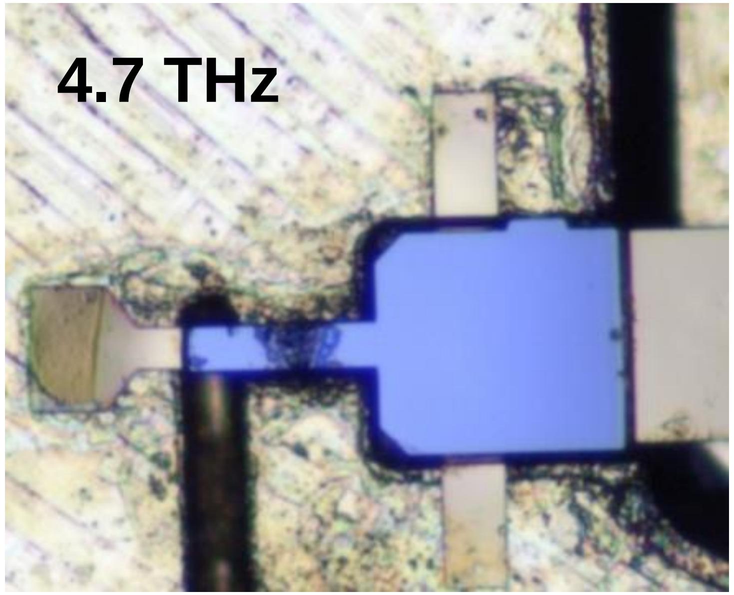


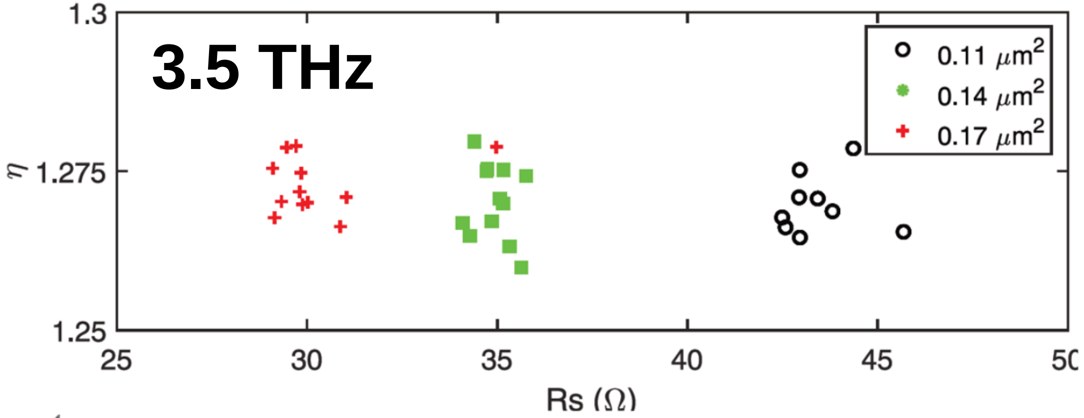


Schottky diode mixers: assembly



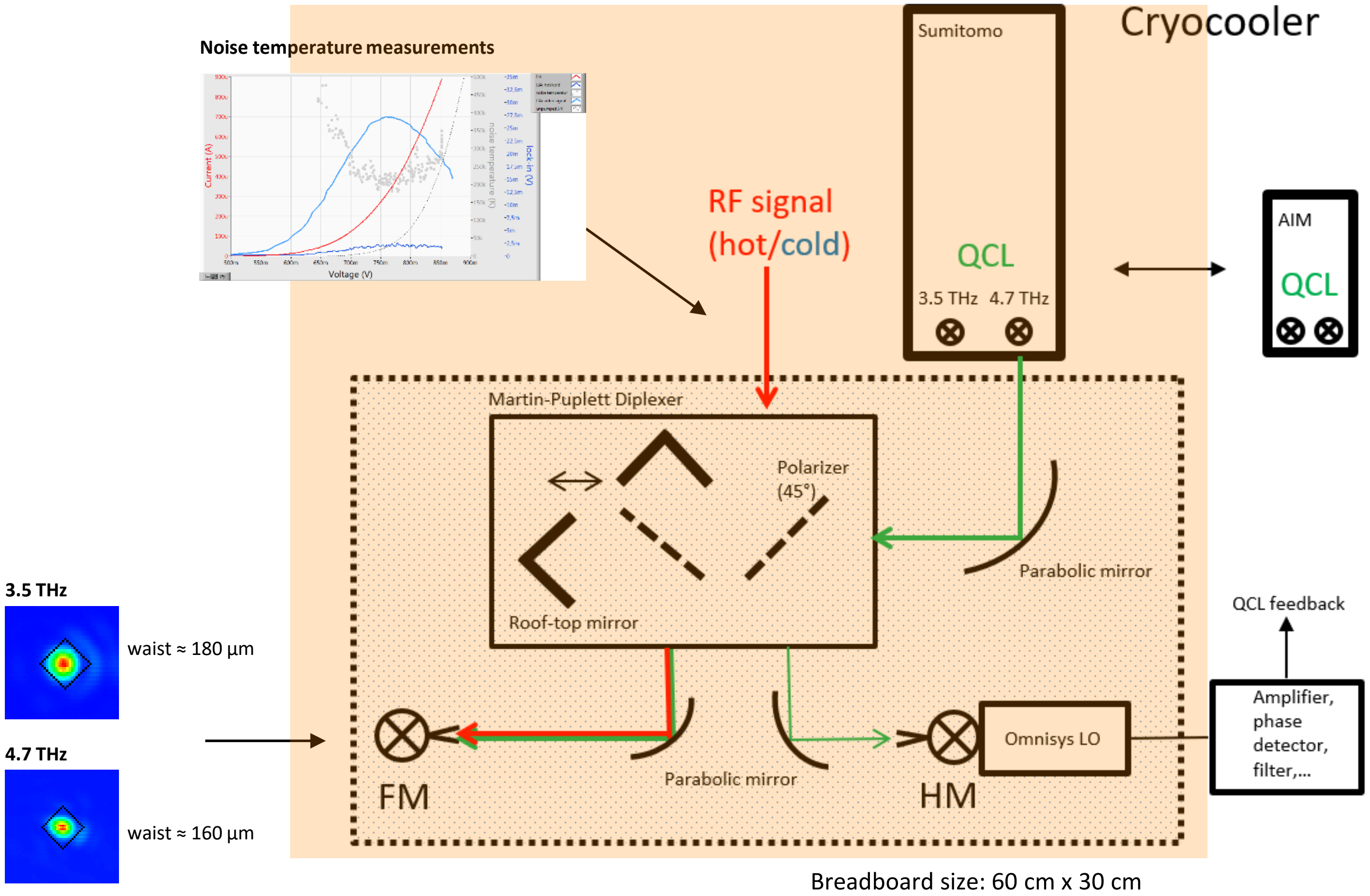


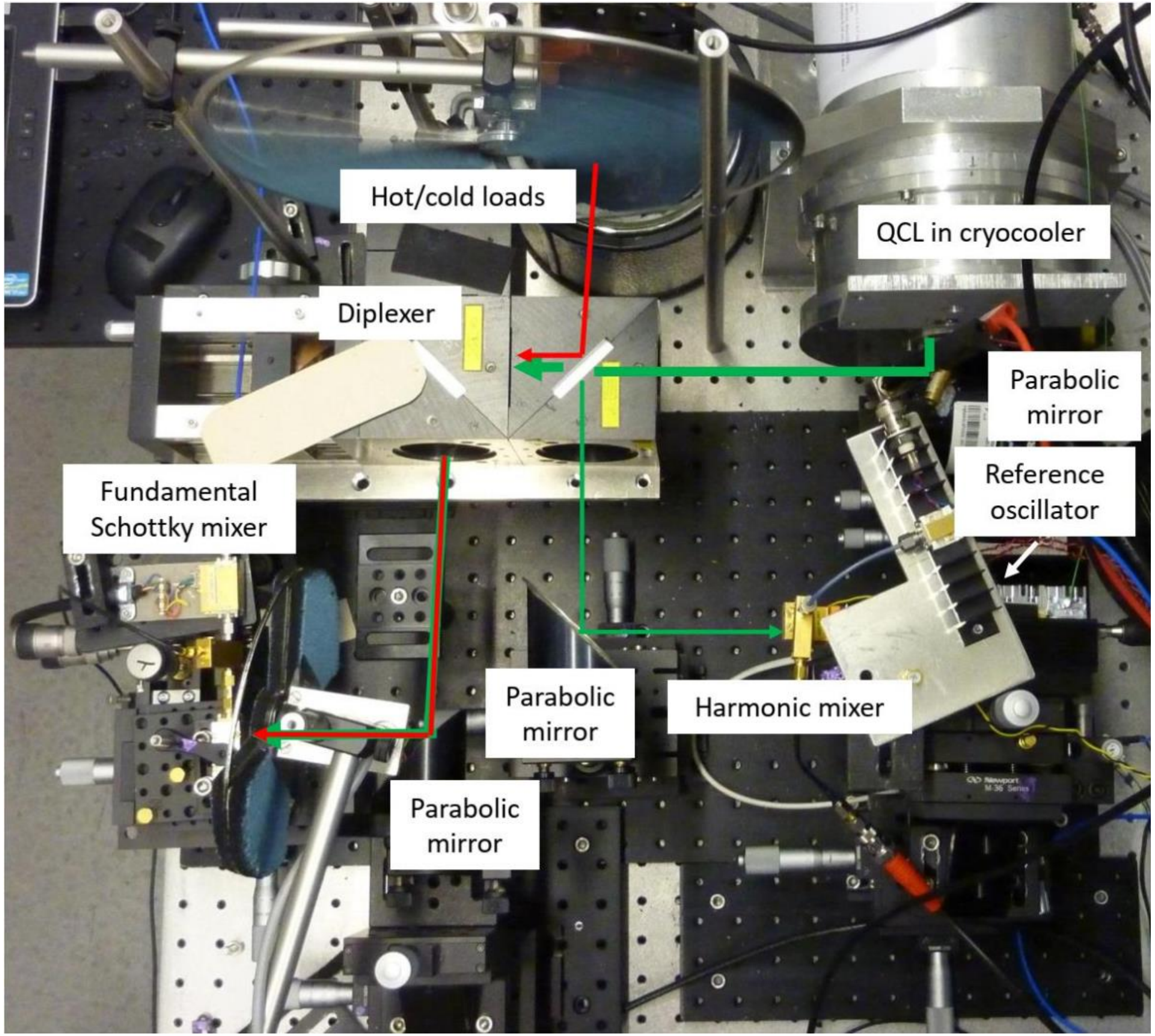




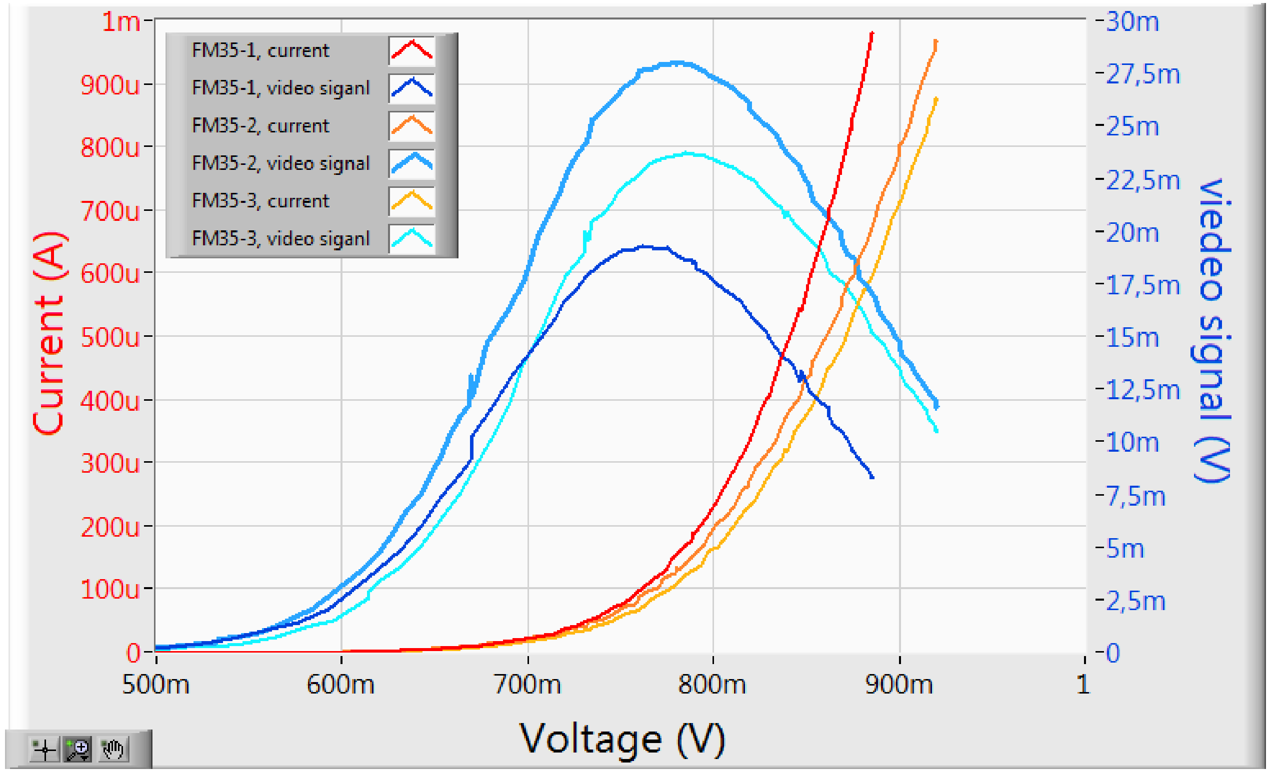
Area [μm²]	Series resistance [Ohm]	Ideality factor	Saturation current [fA]
0.11	44	1.27	5
0.14	35	1.27	4
0.17	30	1.27	5

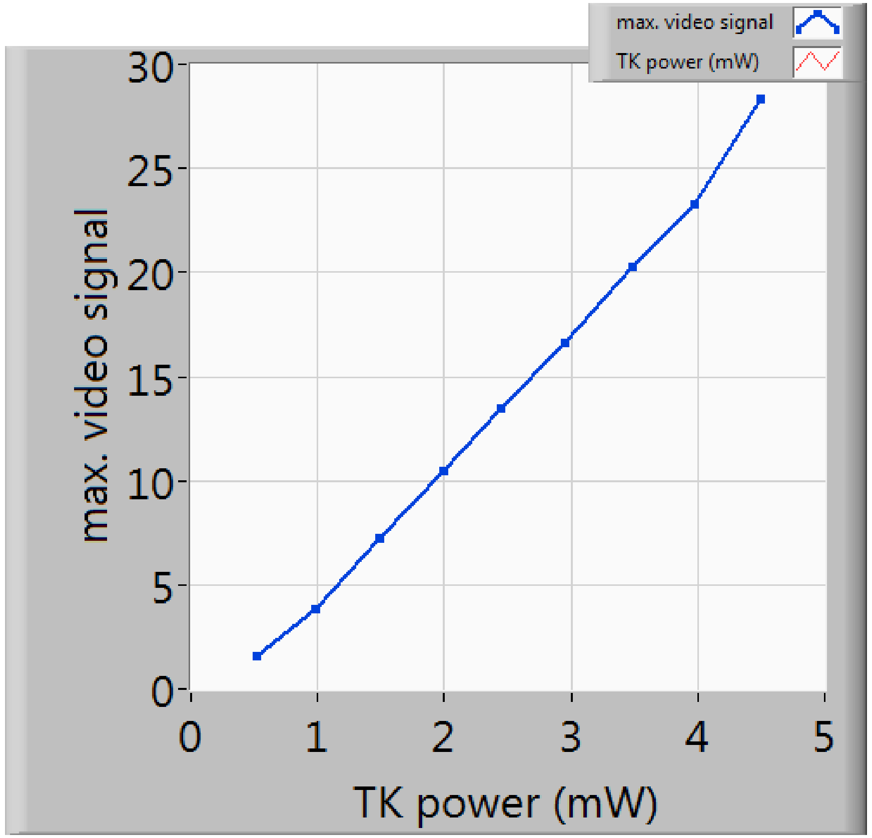
Breadboard: scheme




Hot/cold loads
QCL in cryocooler
Diplexer
Parabolic mirror
Reference oscillator
Fundamental Schottky mixer
Parabolic mirror
Harmonic mixer
Parabolic mirror

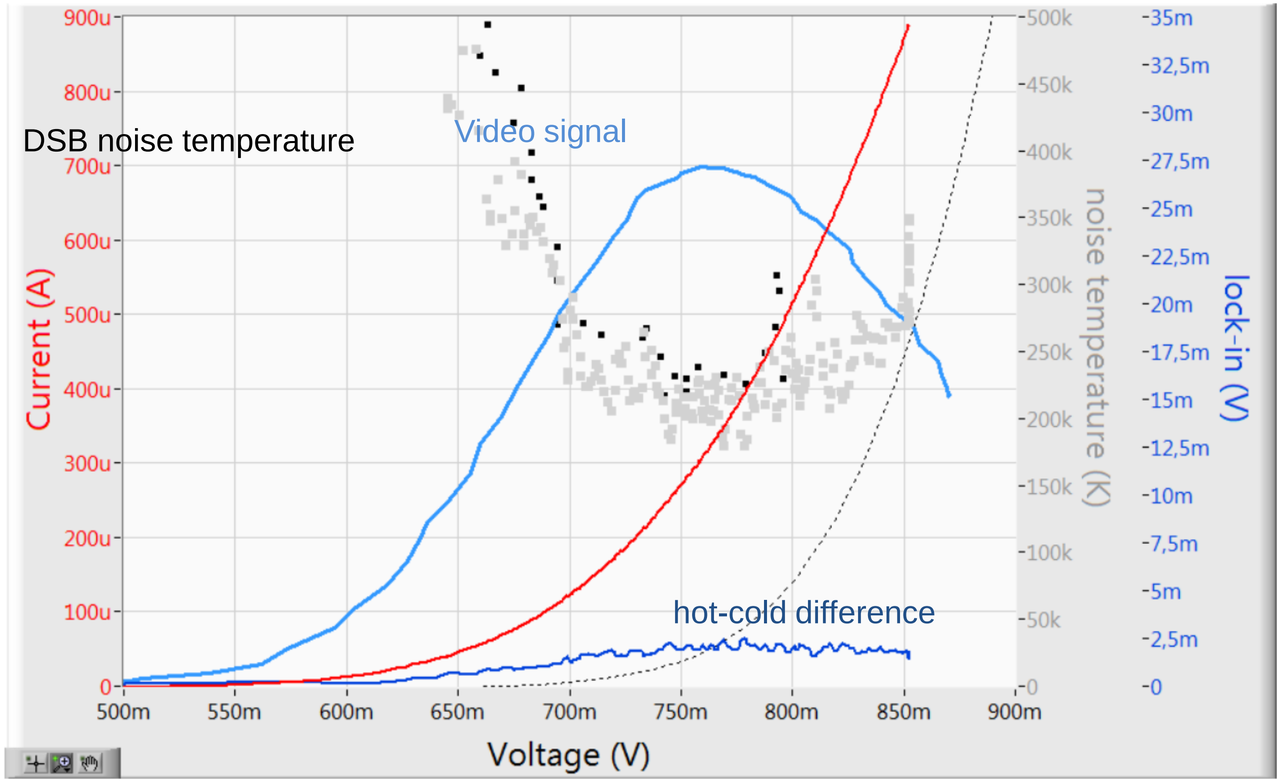
3.5-THz Schottky mixer as direct detector





- Video signal as a function of power from the QCL measured in front of the horn antenna.
- The video responsivity is about 14.4 V/W

DSB noise temperature as a function of diode bias voltage

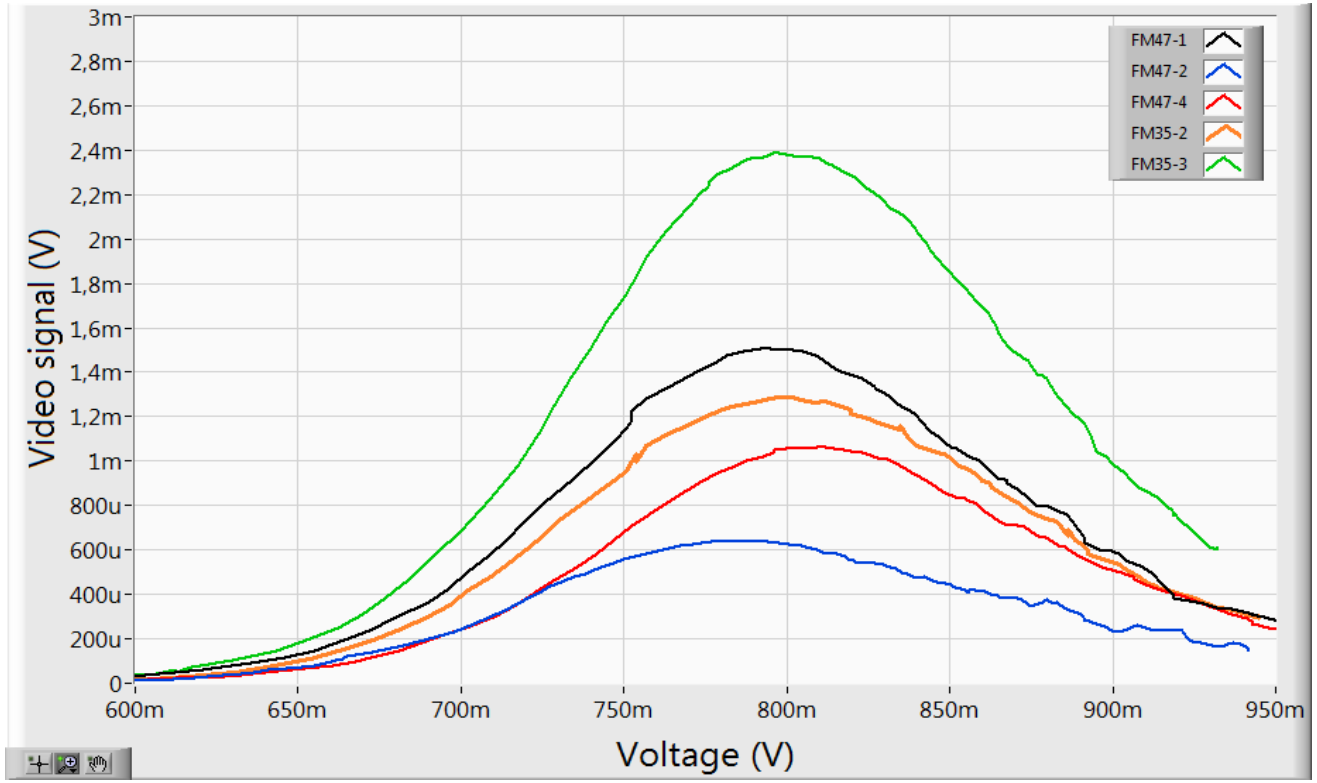


Noise temperature:
- 22 Nov. 2021
- 20 Jan. 2022

- The minimum DSB noise temperature is 210,000 K.
- The data are very reproducible as they have been measured twice with two months in between.
- When corrected for atmospheric absorption loss the DSB nose temperature is ~140,000 K.

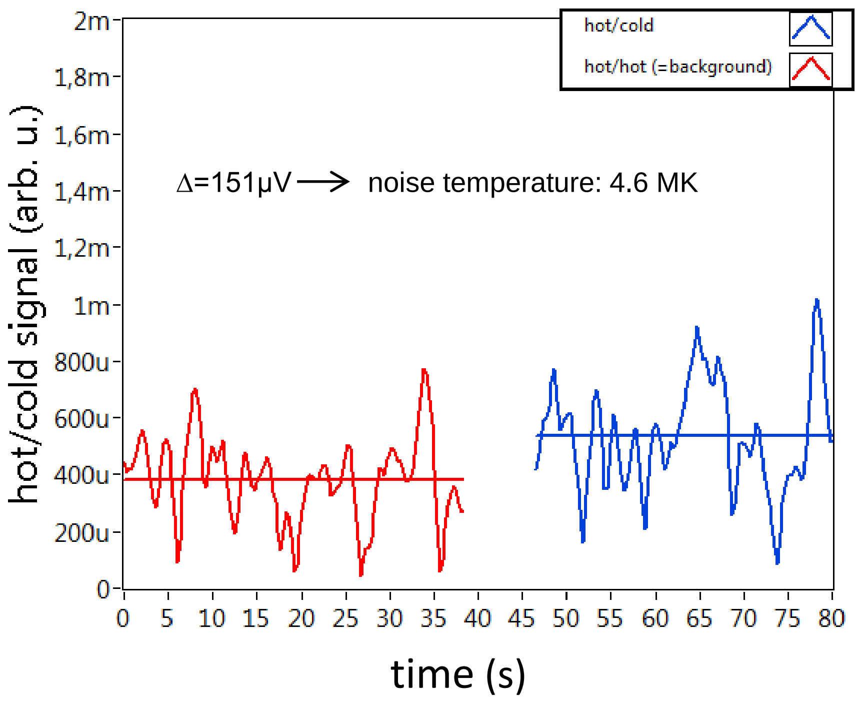
4.7-THz Schottky mixer as direct detector

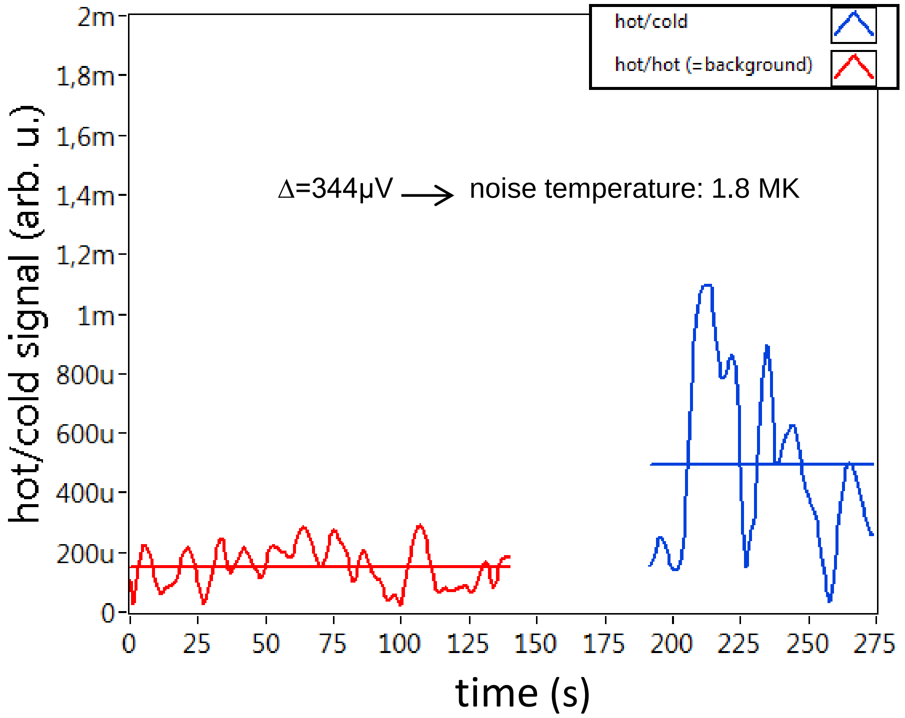
Video signal of three 4.7-THz mixers and two 3.5-THz mixers measured at 4.7 THz



- The maximum video signal of the 4.7-THz mixers varies between 0.6 mV and 1.5 mV.
- This is even less than the video signal of the best 3.5-THz mixer when detecting 4.7-THz radiation (2.4 mV)
  -> Indication that there is a problem with coupling of LO radiation into the 4.7-THz fundamental mixers.

4.7 THz: noise temperature measurements, examples





- Signal is noisy
- Estimated lower limit of DSB noise temperature: 1.5 MioK

Summary and conclusion: part I

The objective of this activity is to demonstrate the feasibility of the frequency stabilization of a QCL and demonstrate the improvement of a stabilization loop with respect to passive stabilization based on thermal and electrical bias control.

- 3.5-THz and 4.7-THz breadboards have been developed (first PLL-stabilized QCLs at 3.5 THz and 4.7 THz in the world)
- European technology
- TRL 4 achieved (at the start of the project: TRL 2)
- Way forward to TRL 6:
  - More compact breadboard (mechanical redesign)
  - Improve DC electronics (e.g. single voltage source, voltage distribution circuit)
  - Replace COTS power supply and PLL electronics of the QCL
  - Thermal-vacuum test of breadboard
  - Space-qualification of QCL chip (e.g. radiation test, test of wire bonds, mounting)
  - Long-term performance tests

- Development of a 3.5-THz and 4.7-THz QCL-LO with PLL and >5 mW output power in a fundamental Gaussian beam is feasible (3 year development time for TRL 8)

Summary and conclusion: part II

The final application of the phase locked THz radiation will be to pump a Schottky diode based receiver at 4.7 THz. In order to de-risk the system, an intermediate step at 3.5 THz shall be considered.

- 3.5-THz and 4.7-THz Schottky diode mixers have been developed (first in the world)
- European technology
- DSB noise temperatures have been measured, but these are still too high for application in a space instrument
- TRL 3 achieved (at the start of the project: TRL 2)
- Way forward to TRL 4:
  - Improve horn antenna and waveguide -> significantly lower noise temperature
  - Optimize chip design

  -> Project ESA AO /1-9931/19/NL/HK “Development of 4.7 THz Schottky device and mixer”

Thanks to

- ESA for funding this activity
- Elena Saenz for excellent, critical and constructive project supervision
- To the whole team for excellent work and smooth cooperation