Demonstration of Photonic Correlation of GHz Signals for 10.6 um Astronomical Heterodyne Interferometry

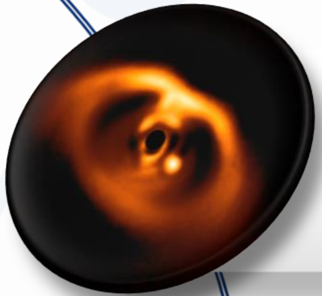
150 ans SFP 2023 (3-7 July, Paris)

Tituan Allain[a,b], Guillaume Bourdarot[b], Carlo Sirtori[c], and Jean-Philippe Berger[a]

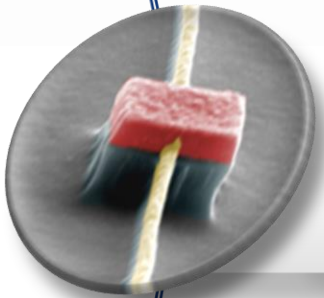
[a] Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France

[b] Max Planck Institute for Extraterrestrial Physics (MPE), Garching, Germany

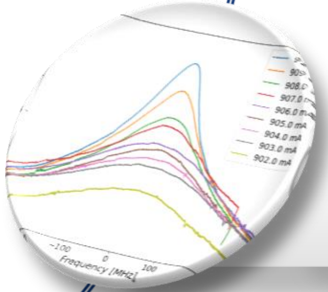
[c] Laboratoire de Physique de l'Ecole Normale Supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université de Paris, 75005, Paris, France



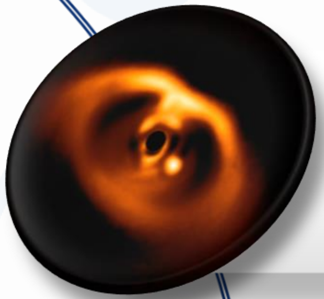
- Mid-Infrared heterodyne interferometry



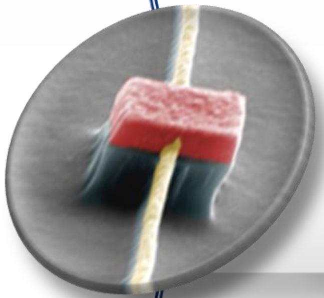
- Presentation of the 2T heterodyne demonstration bench



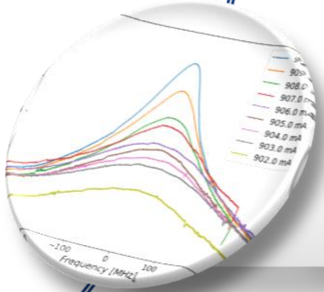
- Correlation of ASE signals and current detection limit of the bench



Mid-Infrared heterodyne interferometry



Presentation of the 2T heterodyne demonstration bench



Correlation of ASE signals and current detection limit of the bench

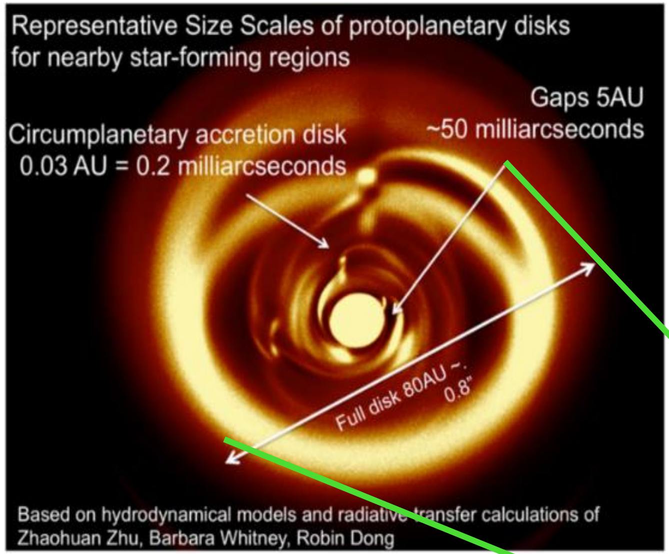
Mid-Infrared heterodyne interferometry

Astronomical context: exoplanets and planet formation

- Extreme sensivity to detect faint planets mJy $(10^{-29} W/m^2/Hz)$ flux in mid-infrared
- Mid-infrared for good planet light/star light ratio and for spectroscopic features
- Very high angular resolution:

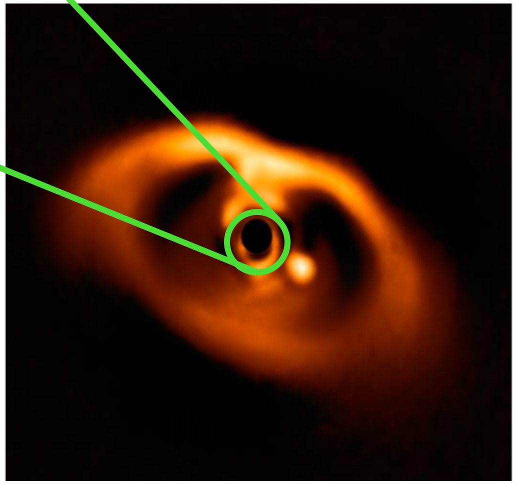
$1\ AU$ resolution at $\simeq 100\ pc$ $(\sim nrad)$

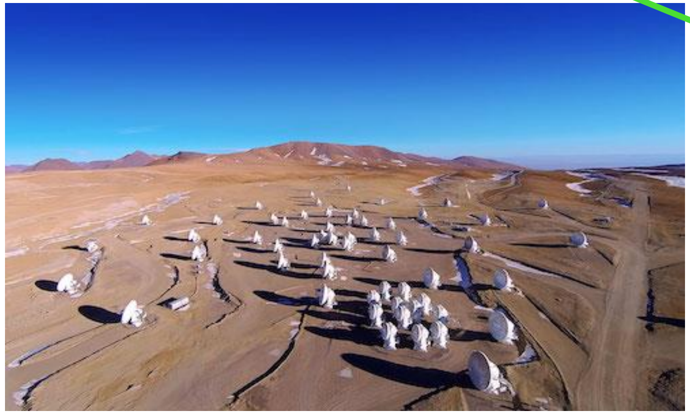
$\frac{\lambda}{d} \sim 1\ nrad \rightarrow \mathrm{d} \sim 1\ km$ at $10\ \mu m \rightarrow$ interferometry



Simulation of protoplanetary disk, taken from Dong et al., 2015, ApJ, 809, 93. Only interferometry can obtain images with such resolution.

Observation of PDS 70 using the Sphere instrument 2.2 um Credit: ESO, VLT, André B. Müller (ESO)





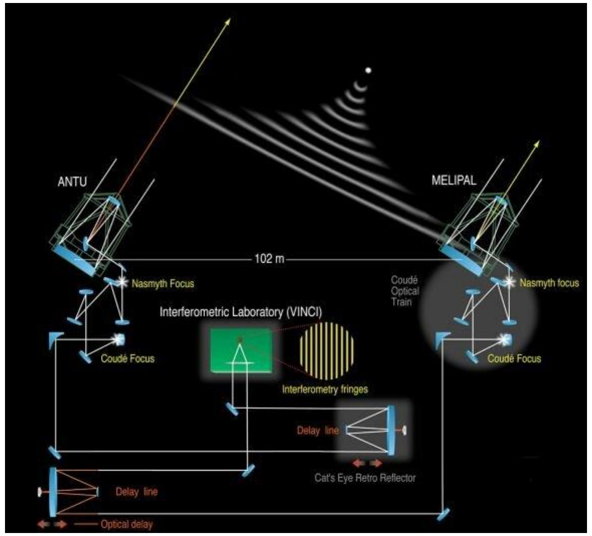
Credit: ESO, Alma (sub-millimeter array)

Mid-Infrared heterodyne interferometry

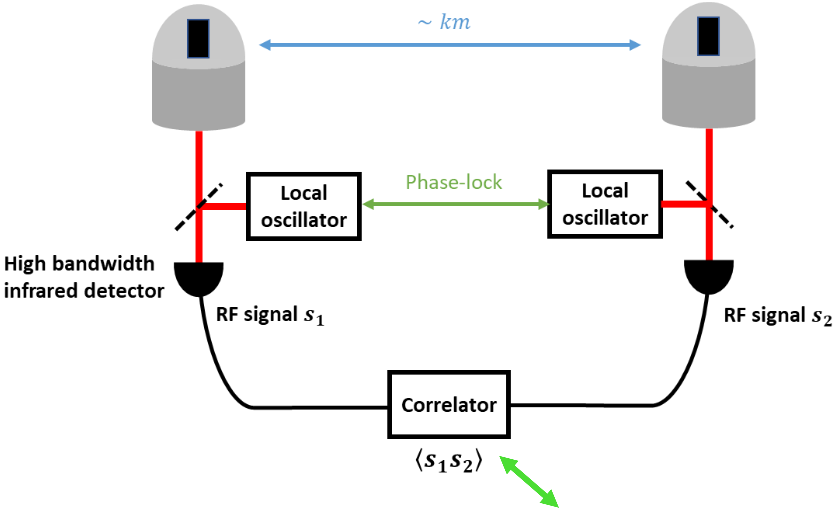
Principle of heterodyne interferometry

- **Principle:**
  1. Measure E_1 and E_2 indirectly at the telescope's level using heterodyne detection
  2. Delay correction and photonic correlation of the two signals to retrieve the visibility $\boldsymbol{V}$ between E_1 and E_2: only way to handle signals with very large bandwidths

  Main advantage:
  - **Simplified** infrastructure
  - **Scalability** to N telescopes and long distances with limited additional noise
- **Main limitations:**
  - **Sensitivity** & **bandwidth**



Credit: ESO



$$|E_1 + E_2|^2 = |E_1|^2 + |E_2|^2 + \boxed{2\,\mathbf{V}\,|E_1||E_2|\cos(\Delta\Phi)}$$

$\boldsymbol{V}$: visiblity (coherence) between E_1 from telescope 1 and E_2 from telescope 2

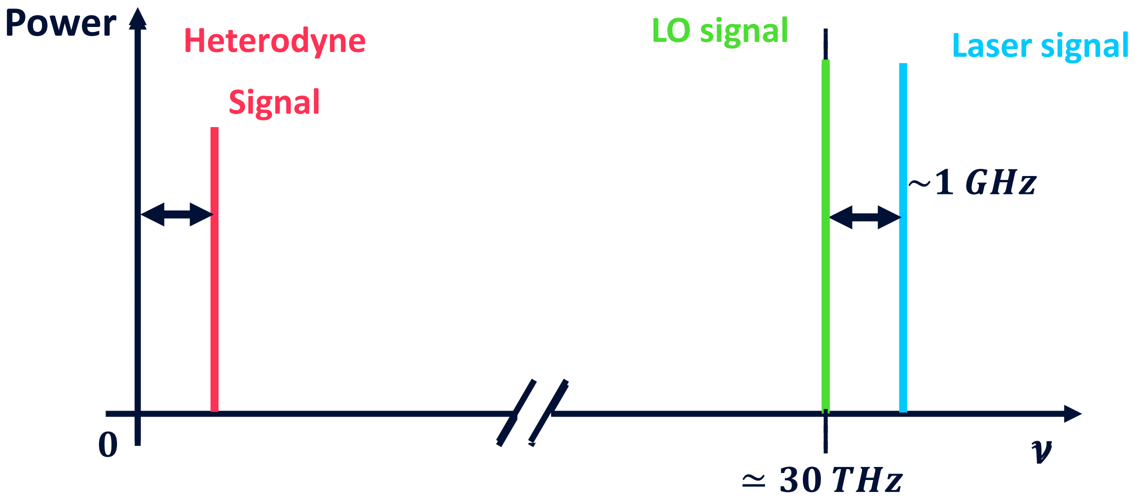
→ Carries the astronomical information on the observed objet

Mid-Infrared heterodyne interferometry

Limitations of heterodyne interferometry: bandwidth

- Heterodyne detection can only detect signals up to the electronic bandwidth of the infrared detector (few nm)

$$s(t) \propto |E_{LO} + E_s|^2 \propto i_{LO} + i_s + 2\sqrt{i_{LO} i_s}\cos(\Delta\omega t + \Delta\phi)$$

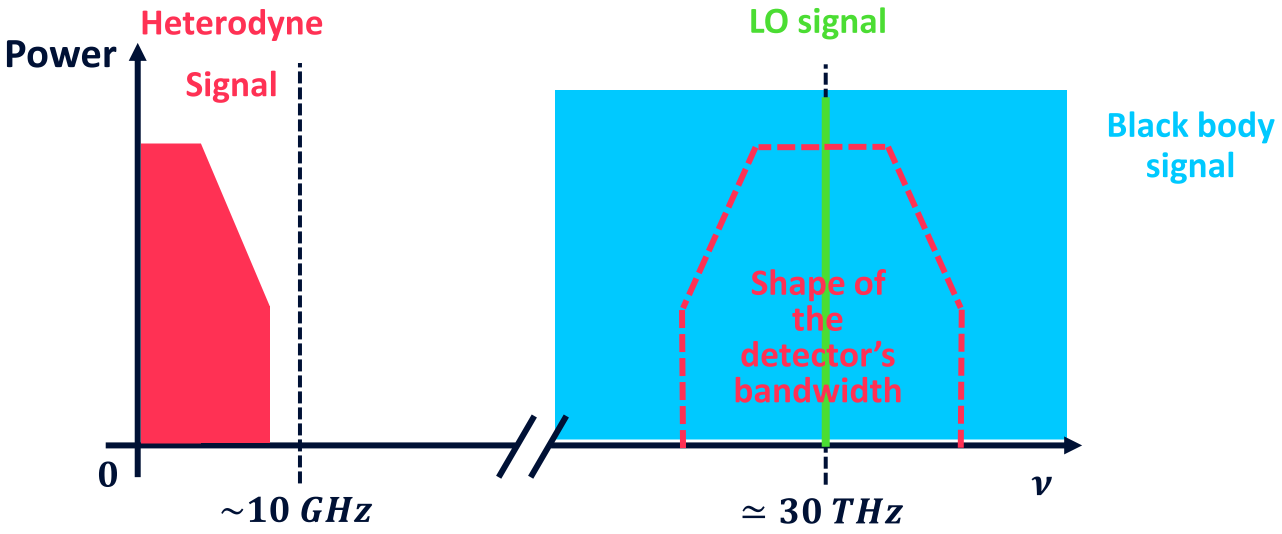


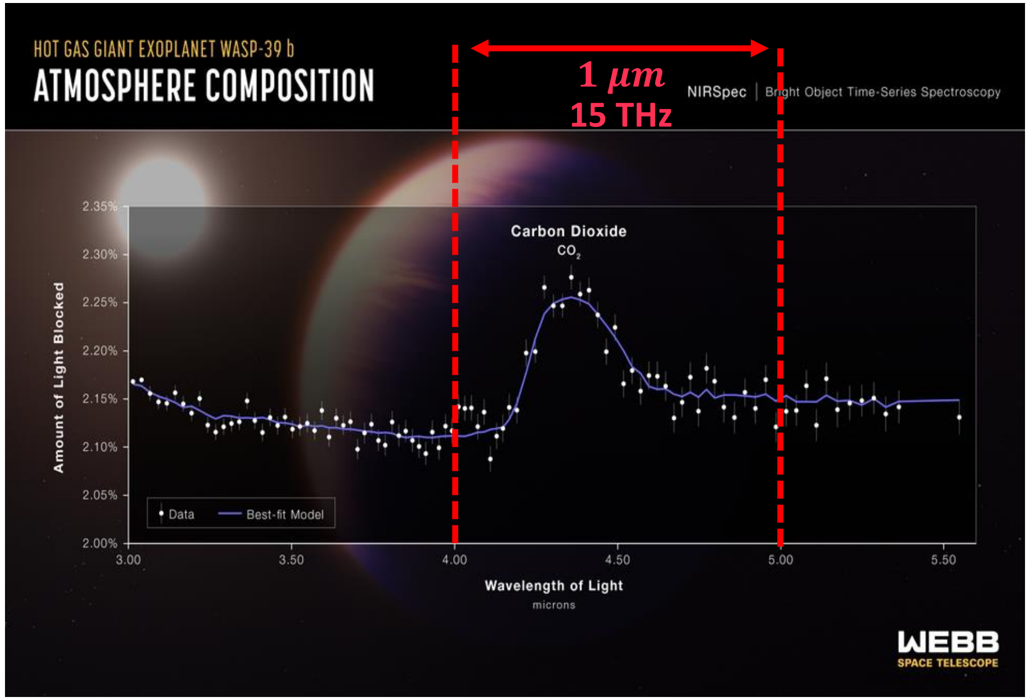
Mid-Infrared heterodyne interferometry

Limitations of heterodyne interferometry: bandwidth

- Heterodyne detection can only detect signals up to the electronic bandwidth of the infrared detector (few $\mathbf{nm}$)

$$s(t) \propto |E_{LO} + E_s|^2 \propto i_{LO} + i_s + 2\sqrt{i_{LO} i_s}\cos(\Delta\omega t + \Delta\phi)$$





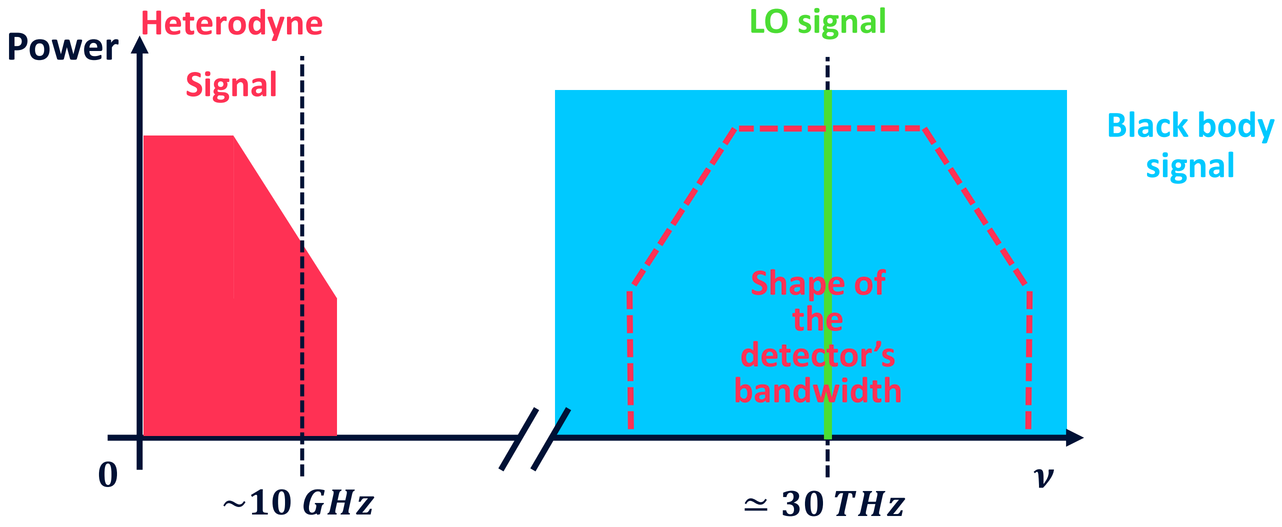
Credit: NASA

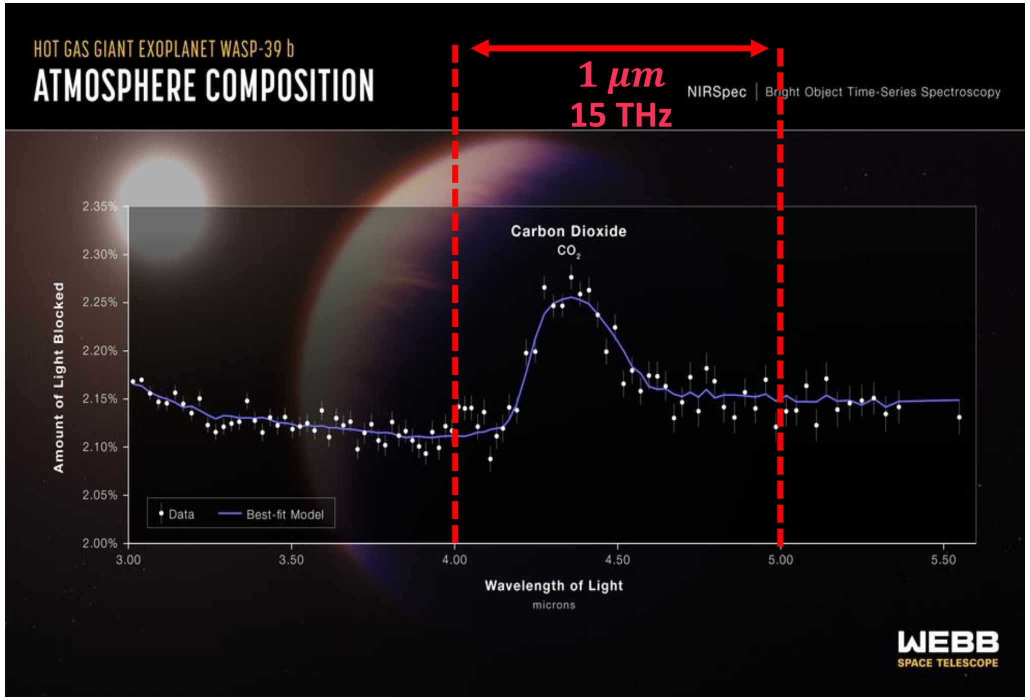
Mid-Infrared heterodyne interferometry

Limitations of heterodyne interferometry: bandwidth

- Heterodyne detection can only detect signals up to the electronic bandwidth of the infrared detector (few nm)

$$s(t) \propto |E_{LO} + E_s|^2 \propto i_{LO} + i_s + 2\sqrt{i_{LO} i_s}\cos(\Delta\omega t + \Delta\phi)$$





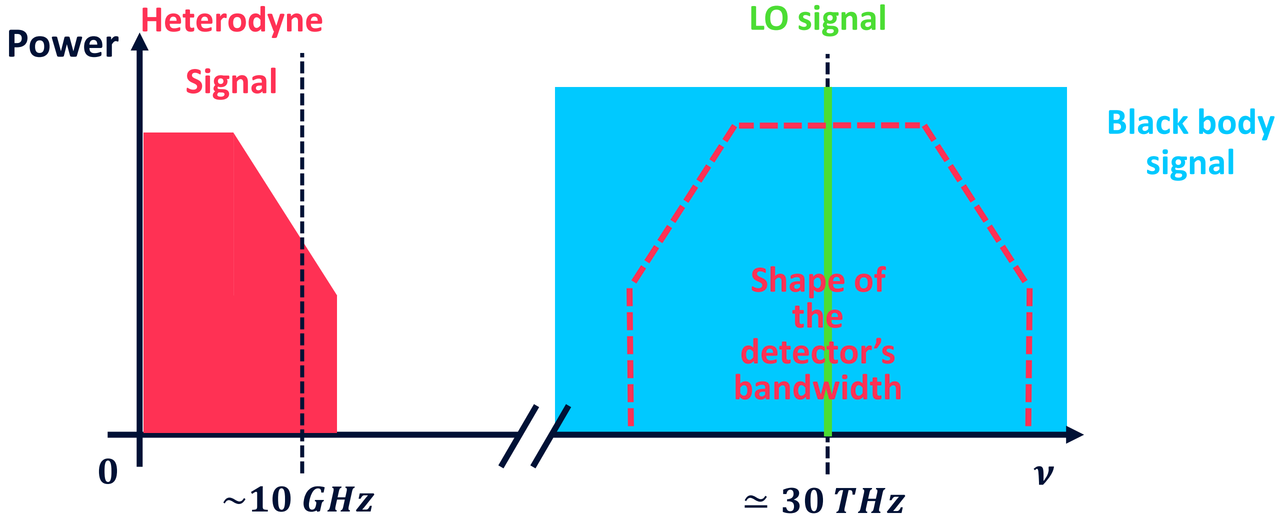
Credit: NASA

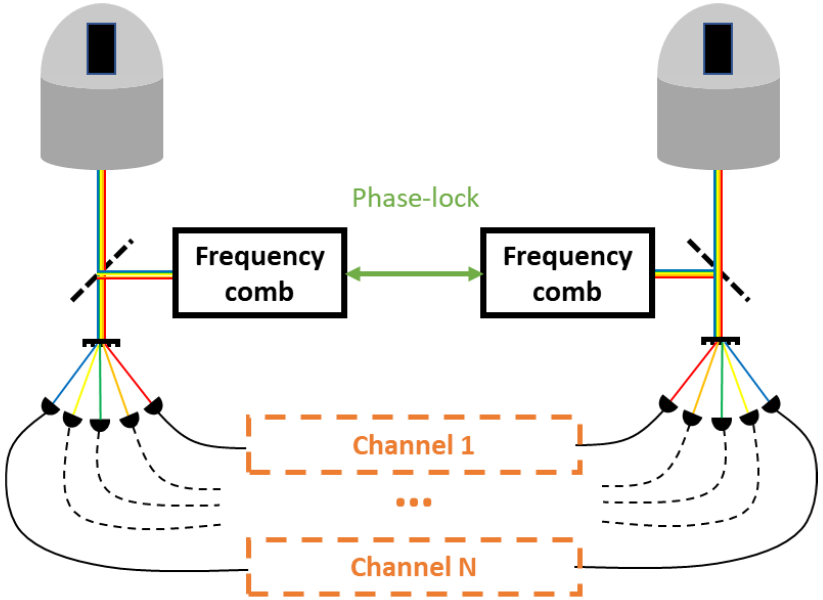
Mid-Infrared heterodyne interferometry

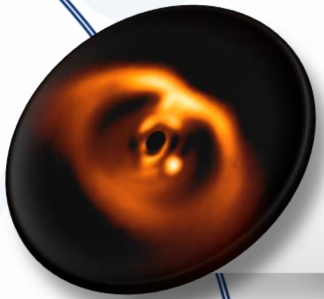
Limitations of heterodyne interferometry: bandwidth

- Heterodyne detection can only detect signals up to the electronic bandwidth of the infrared detector (few nm)

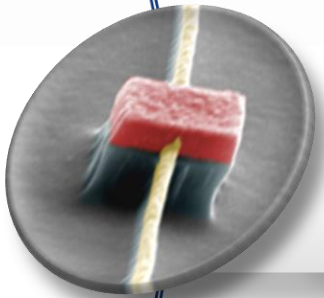
$$s(t) \propto |E_{LO} + E_s|^2 \propto i_{LO} + i_s + 2\sqrt{i_{LO} i_s}\cos(\Delta\omega t + \Delta\phi)$$



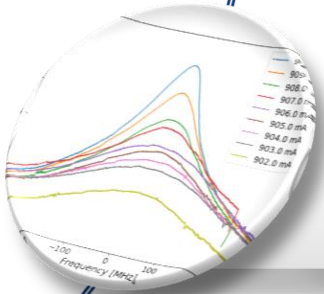




Mid-Infrared heterodyne interferometry for astronomy



Presentation of the 2T heterodyne demonstration bench



Correlation of ASE signals and current detection limit of the bench

Presentation of the 2T heterodyne demonstration bench

Scope of this work

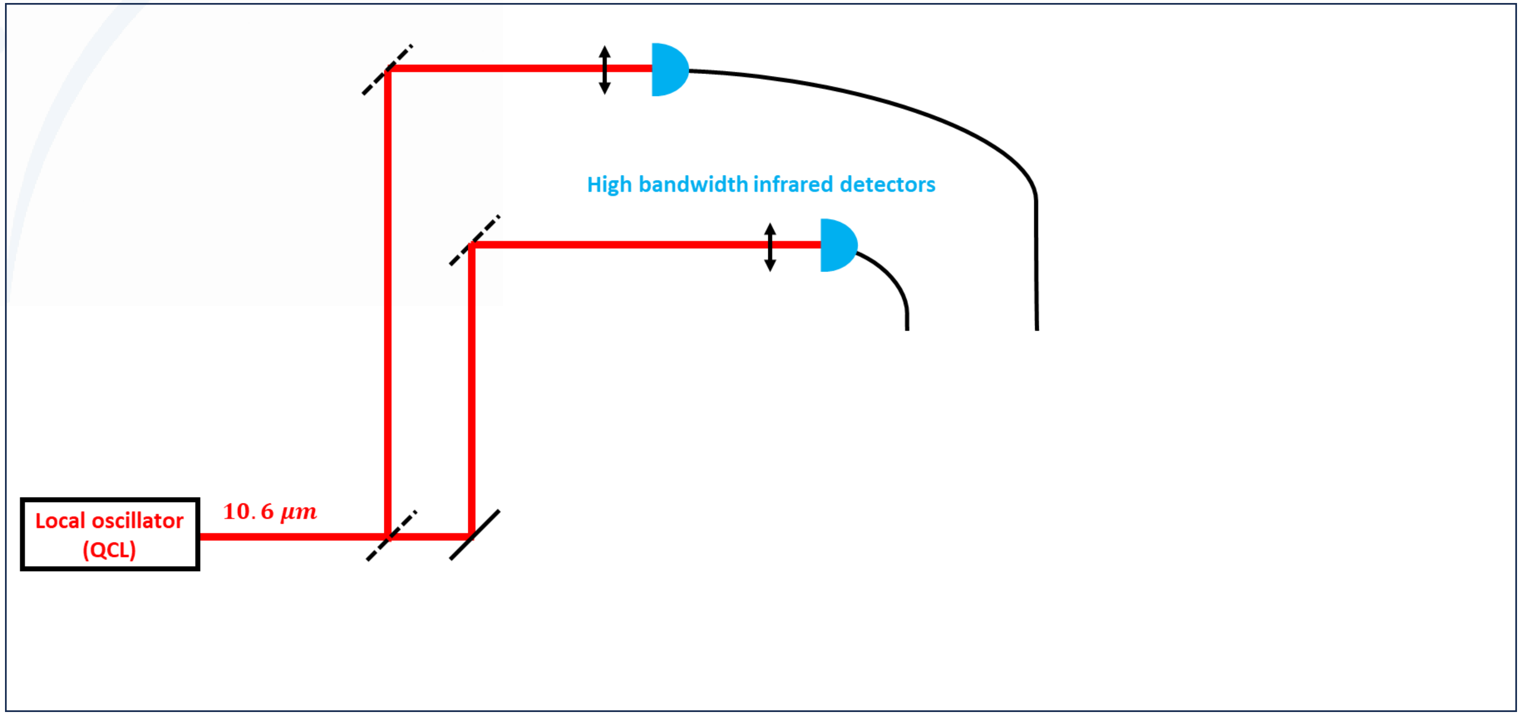
Demonstrate the **feasibility** of heterodyne interferometry

Identify the **key technologies** for future instruments

Test different methods to improve the sensitivity of the detection scheme

Presentation of the 2T heterodyne demonstration bench

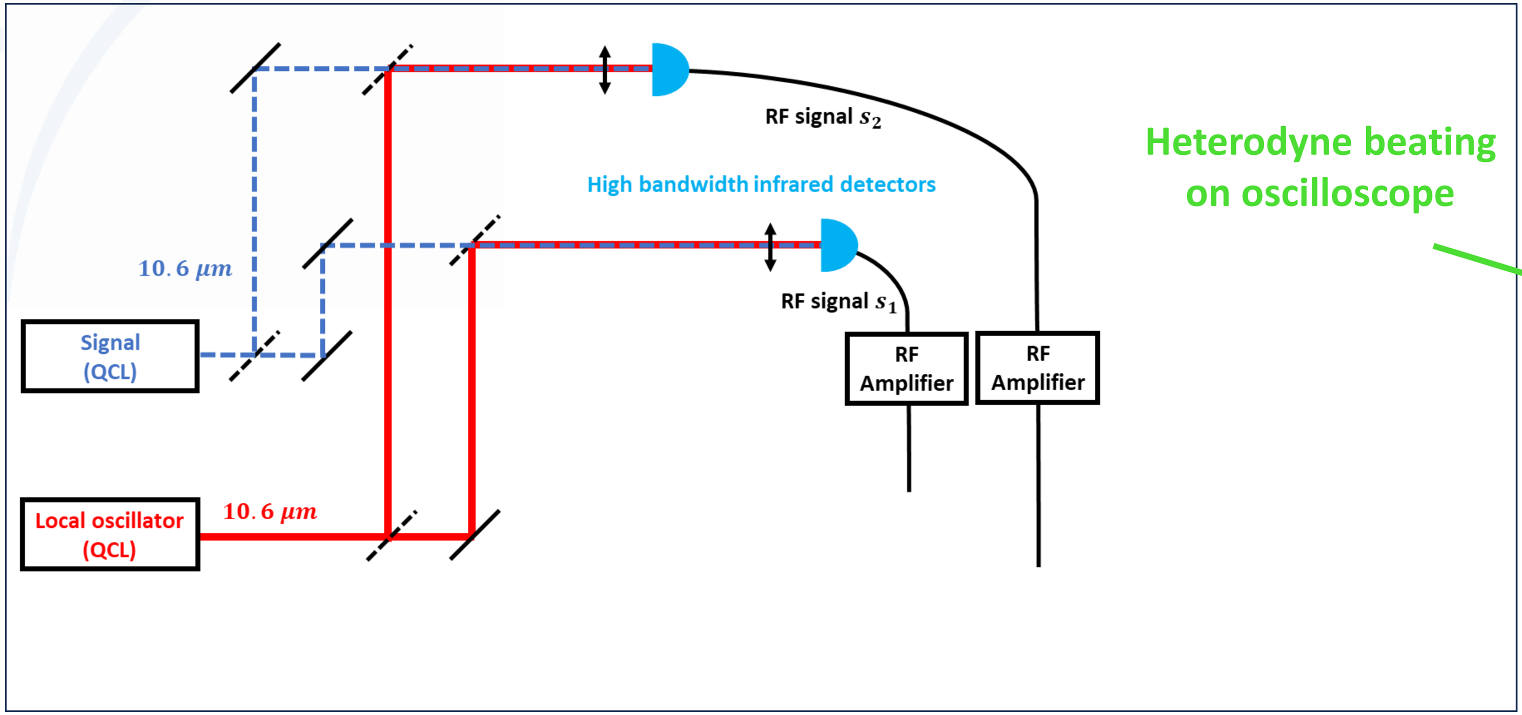
Current state of the bench emulation bench at IPAG



- One $10.6\ \mu m$ QCL as local oscillator
- Two VIGO PVI-4TE $10.6\ \mu m$ detectors with $1\ GHz$ bandwidths

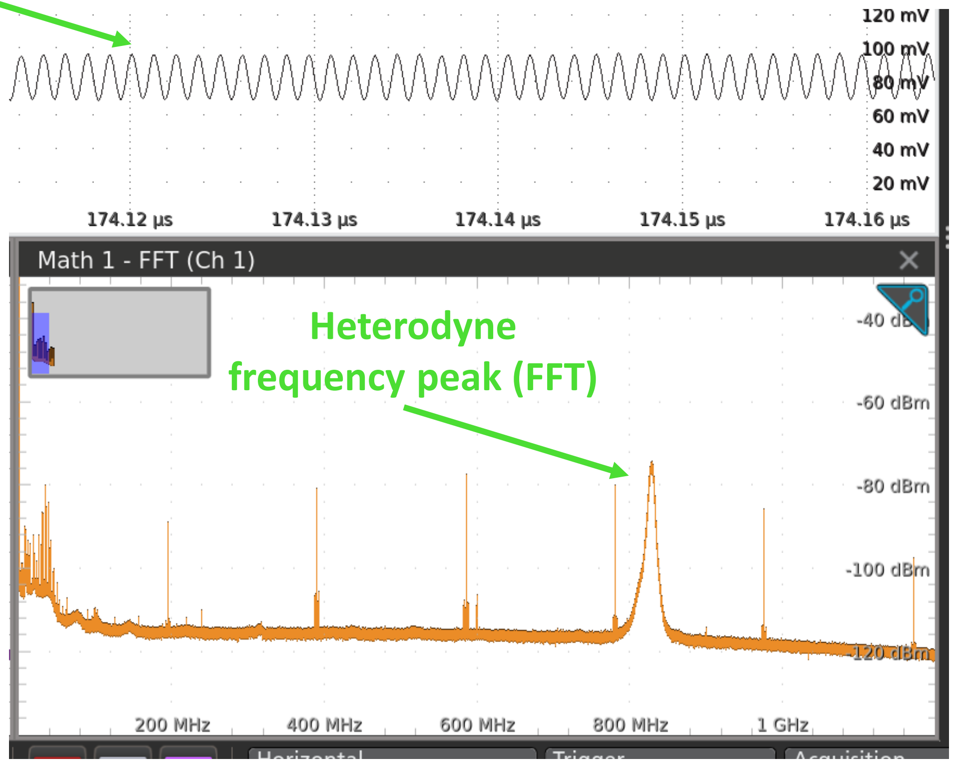
Presentation of the 2T heterodyne demonstration bench

Current state of the bench emulation bench at IPAG



- Another $10.6\ \mu m$ QCL as signal (scientific source)

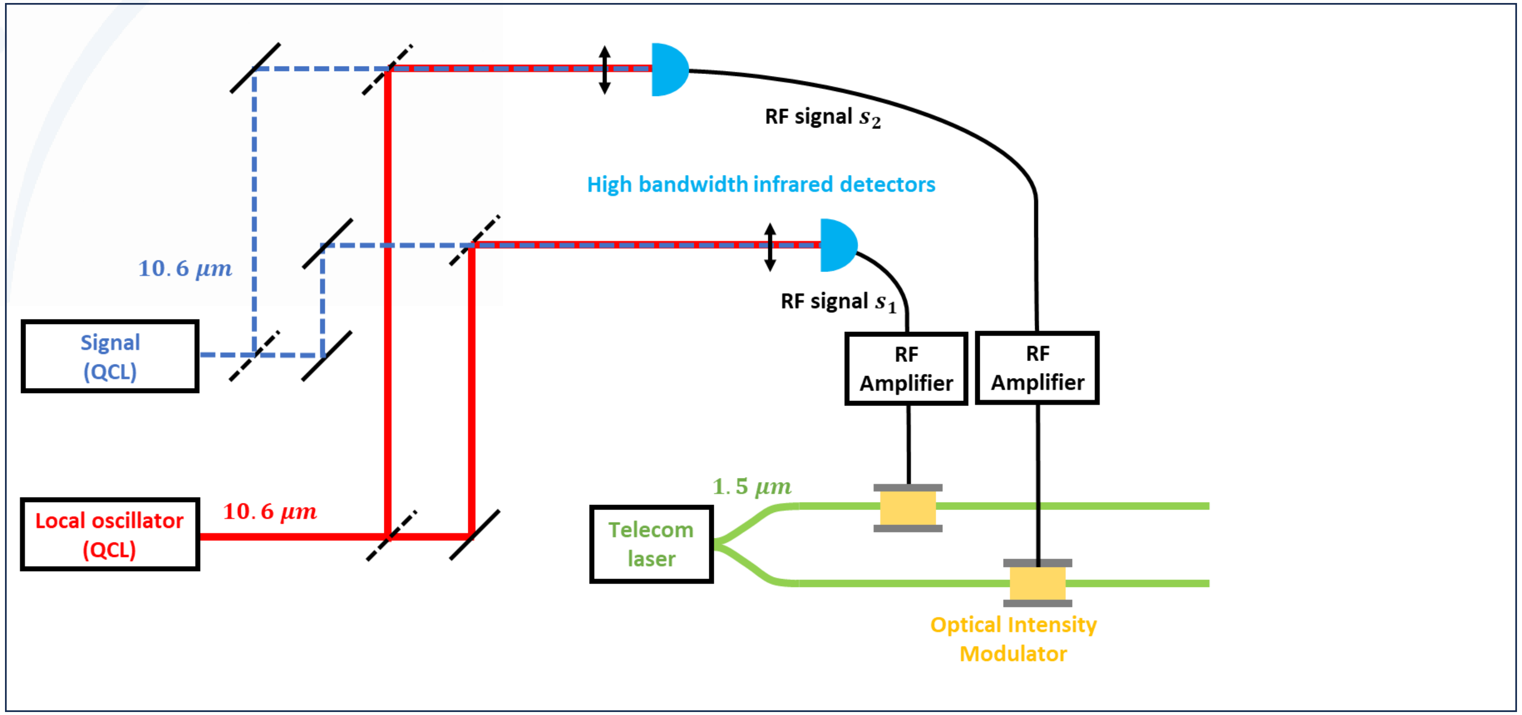
Heterodyne beating on oscilloscope



Heterodyne frequency peak (FFT)

Presentation of the 2T heterodyne demonstration bench

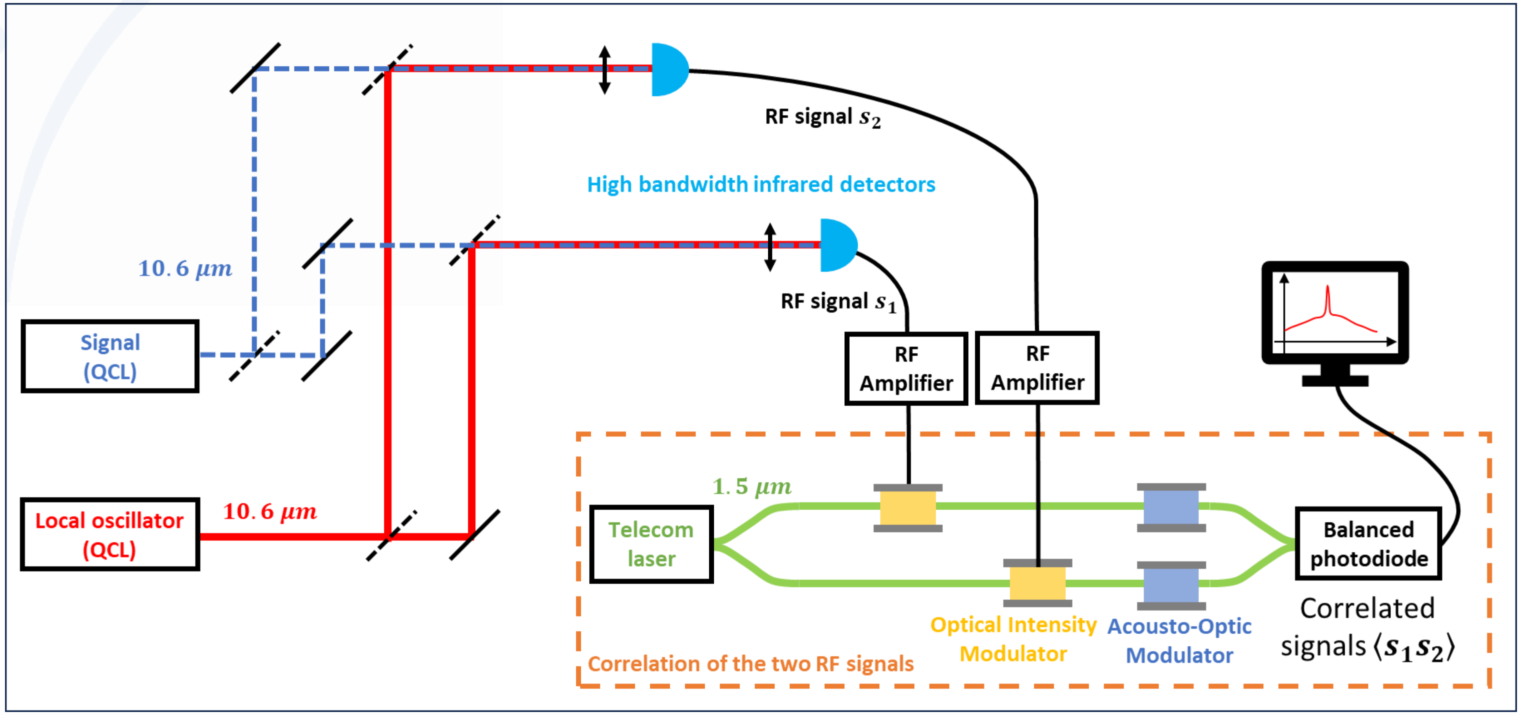
Current state of the bench emulation bench at IPAG

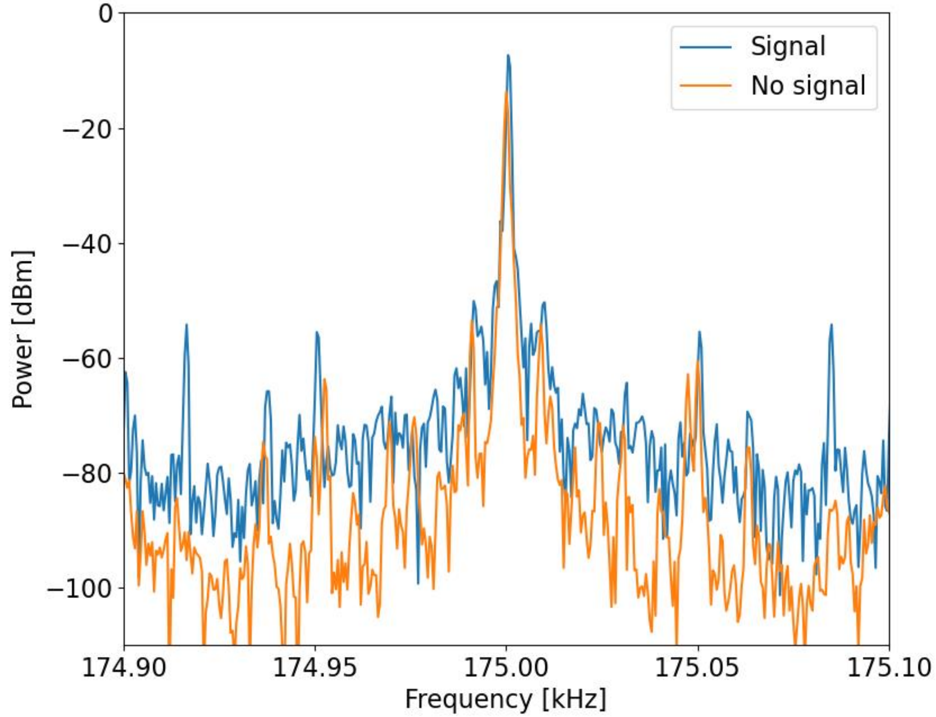


- The heterodyne signals are encoded (intensity modulation) on $1.5\ \mu m$ optical fibers

Presentation of the 2T heterodyne demonstration bench

Current state of the bench emulation bench at IPAG

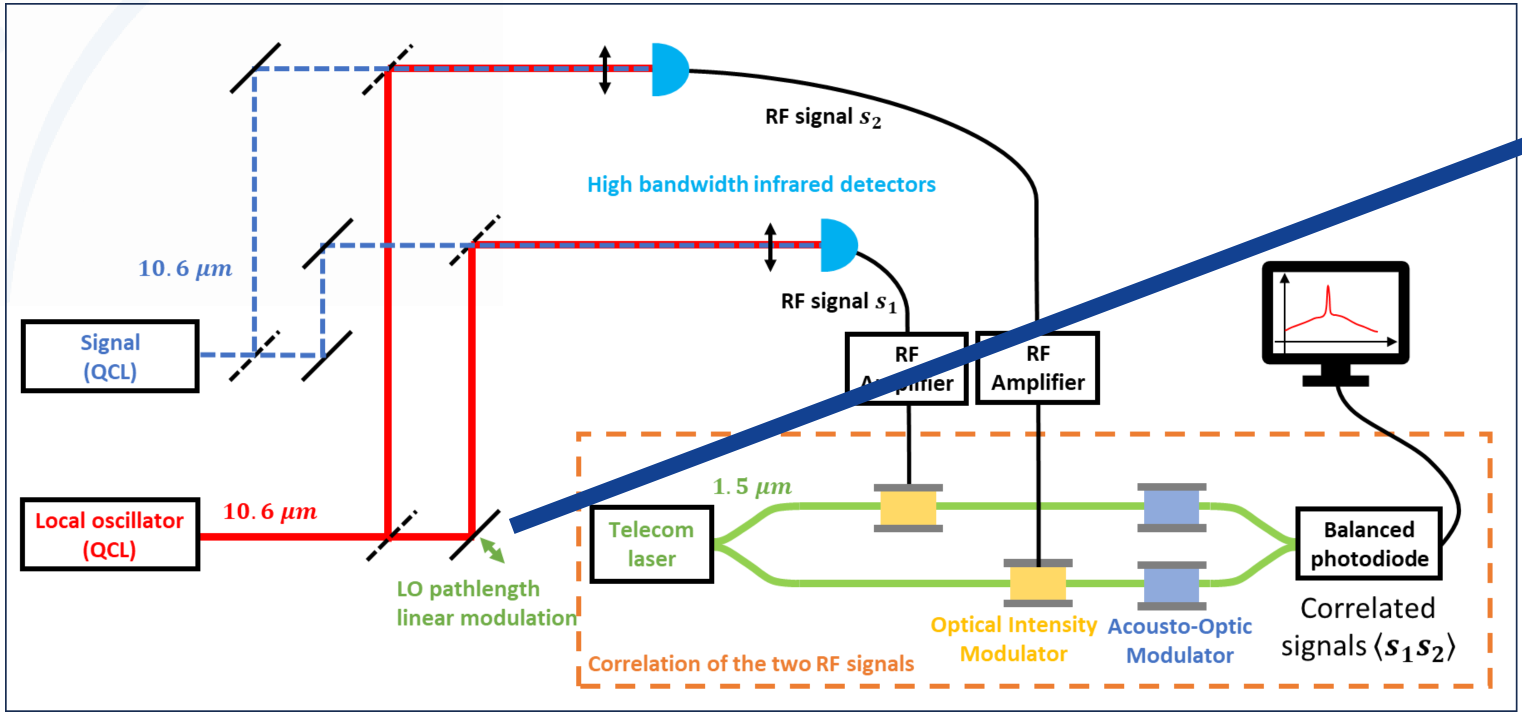




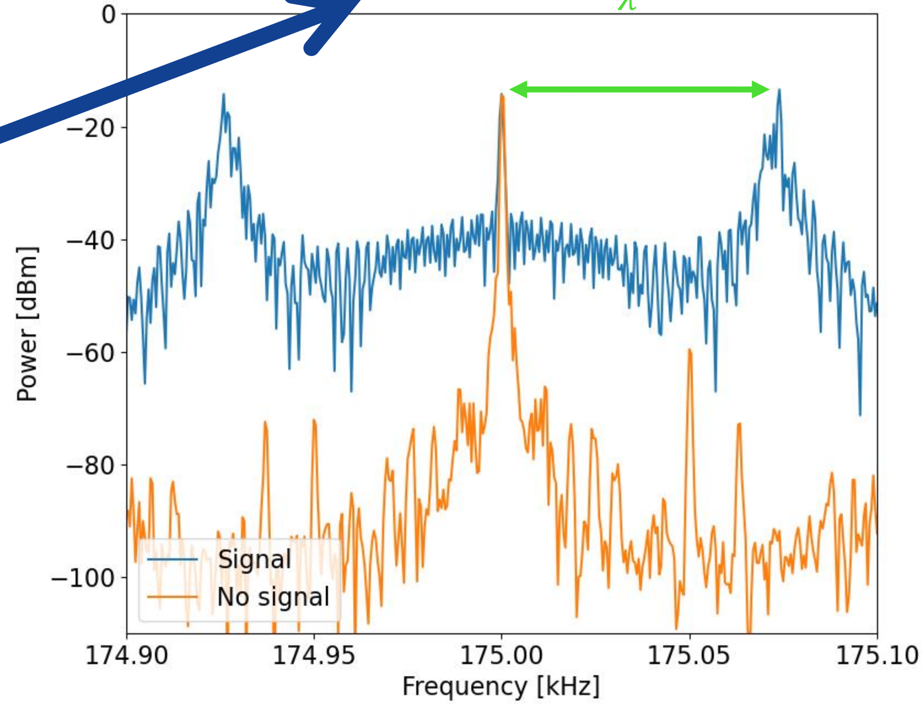
- The two signals are recombined on a balanced photodiode. The output is read on an oscilloscope.
- Accousto optic modulators are used to encode the correlation signal at given frequency
  ($80.175\text{ MHz} - 80.000\text{ MHz} = 175\ kHz$ in this example)

Presentation of the 2T heterodyne demonstration bench

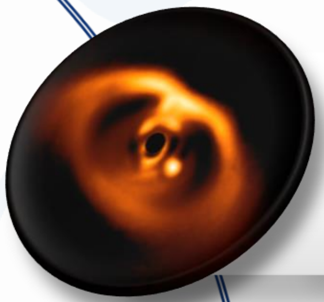
Current state of the bench emulation bench at IPAG



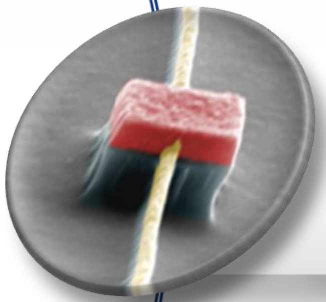
$$\Delta f = \frac{mirror\ speed}{\lambda} \simeq 70\ Hz$$



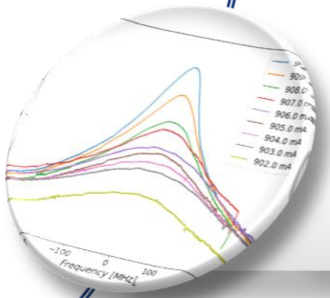
- A pathlength modulation on the local oscillator (equivalent to frequency shift) is added to modify the frequency of the correlation signal



Mid-Infrared heterodyne interferometry for astronomy



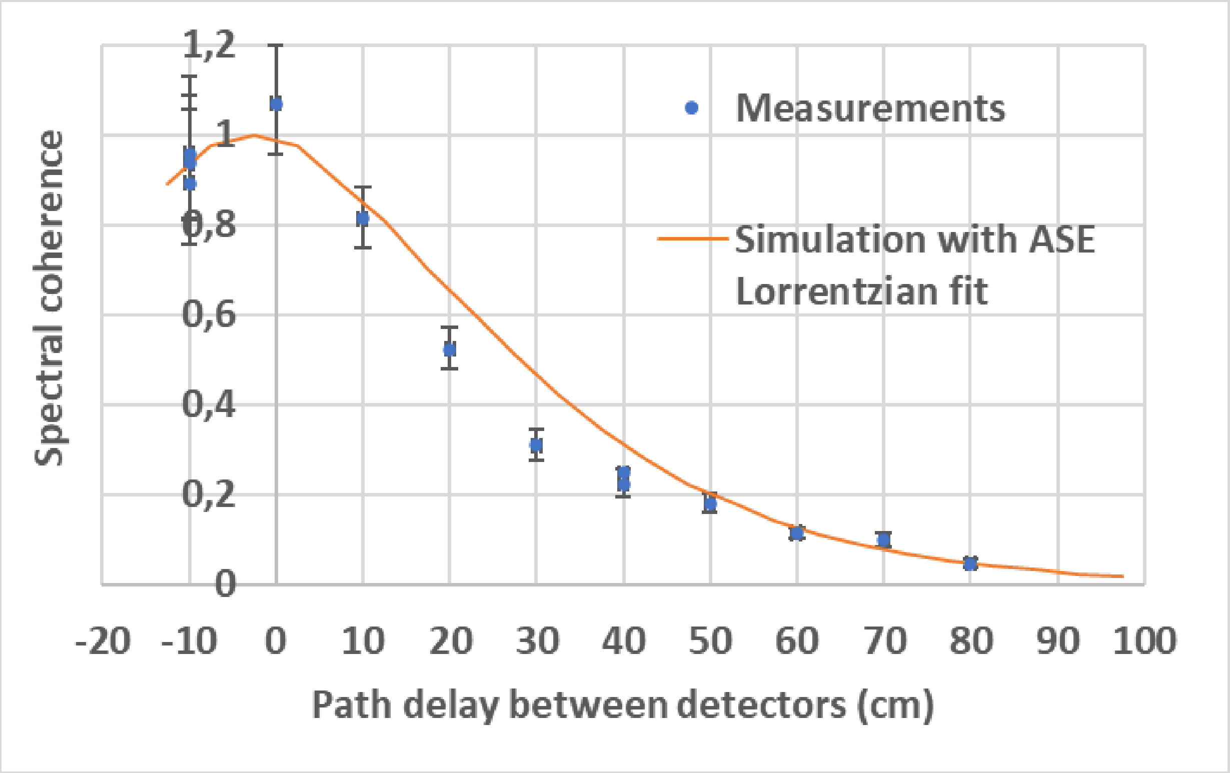
Presentation of the 2T heterodyne demonstration bench



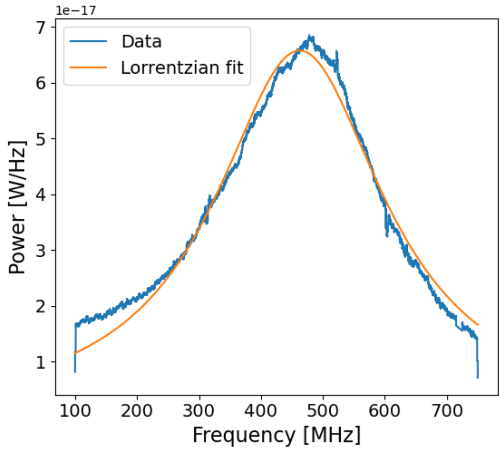
Correlation of ASE signals and current detection limit of the bench

Correlation of ASE signals and current detection limit of the bench

Correlation of ASE signals

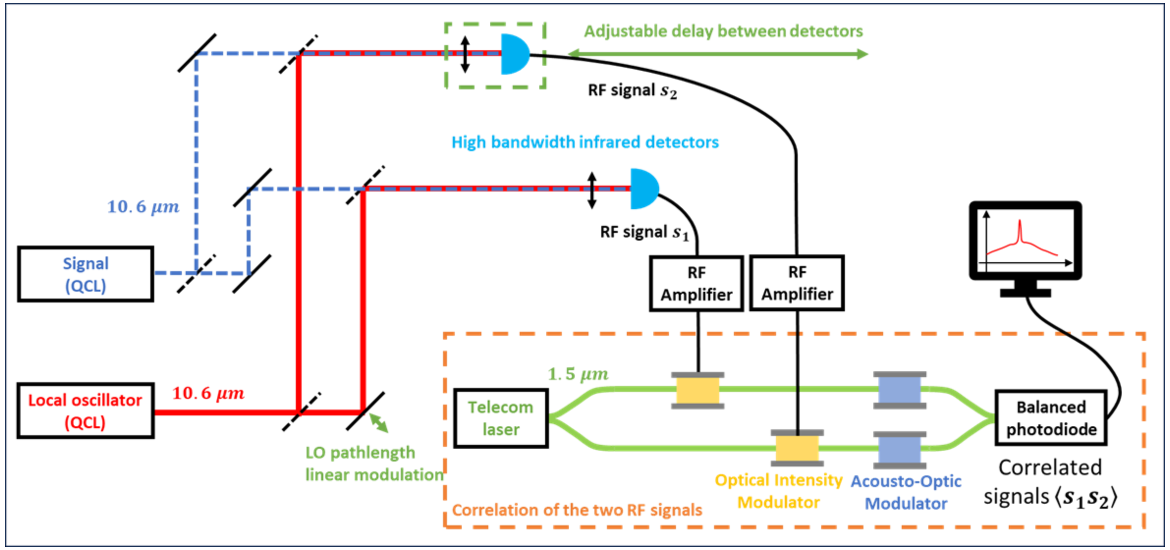


Experimental correlation curve



ASE spectrum at $902.0\ mA$

Total optical power: $\simeq 2\ nW$



Correlation of ASE signals and current detection limit of the bench

Photonic correlation « Noise equivalent voltage »

No amplifier: Noise equivalent voltage:

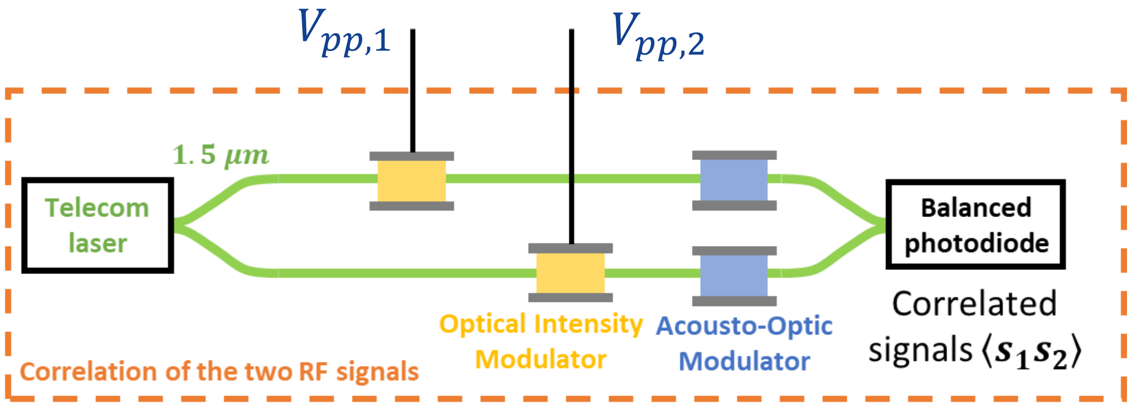
→ $V_{pp,1} = 10\ mV$ & $V_{pp,2} = 10\ mV$

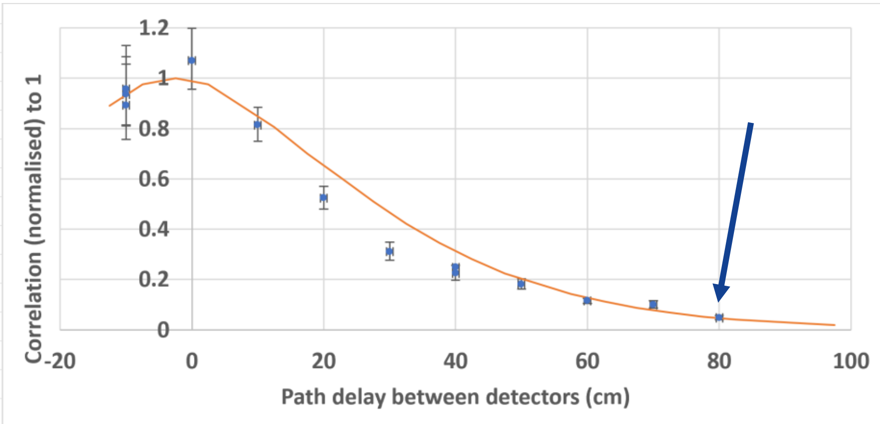
With **two +20 dB amplifiers**: Noise equivalent

→ $V_{pp,1} = 1\ mV$ & $V_{pp,2} = 1\ mV$

Translating this into signal optical power:

The signal NEP is $\sim 10^{-11}\ W = 10\ pW$





In practise, we only went down to $\mathbf{2\ nW}$ with 5% correlation → $\simeq \mathbf{10^{-10}\ W = 100\ pW}$

Key takeaways

Heterodyne interferometry is an alternative to direct interferometry in mid-infrared with:

- **Easier scalability** to large baselines and high number of telescopes
- **Limited sensivity** due to high density of frequency modes in mid-infrared

We demonstrated the photonic correlation of infrared signals with:

- **Up to $\mathbf{1}\ \boldsymbol{GHz}$** bandwdith (limited by $10.6\ \mu m$ detectors)
- **Down to $\simeq \mathbf{100}\ \boldsymbol{pW}$** (limited by infrared detection and amplification scheme)
- With the ability to **recover the coherence envelop** from an ASE signal

Perspectives

Optimizing the set-up to decrease the NEP

Implementing Quantum Well Infrared Detectors to reach $\sim 10\ GHz$ bandwidths

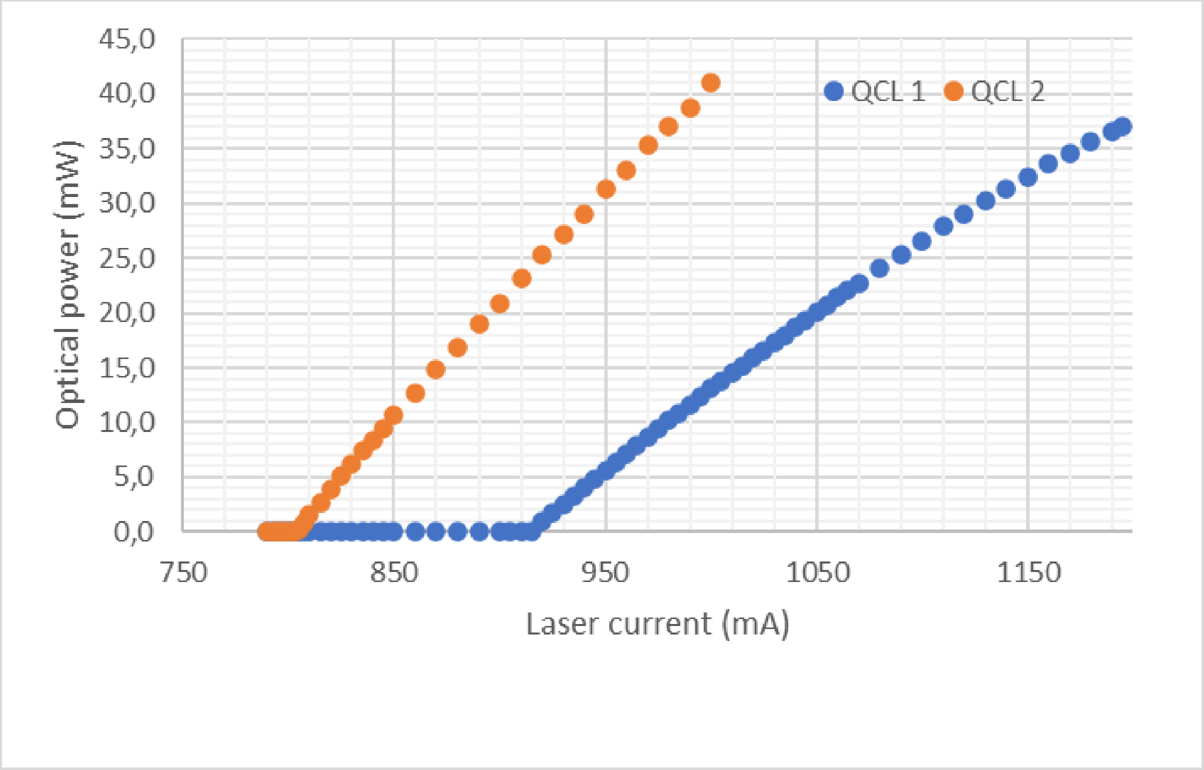
Using the set-up with a black-body source of radiation

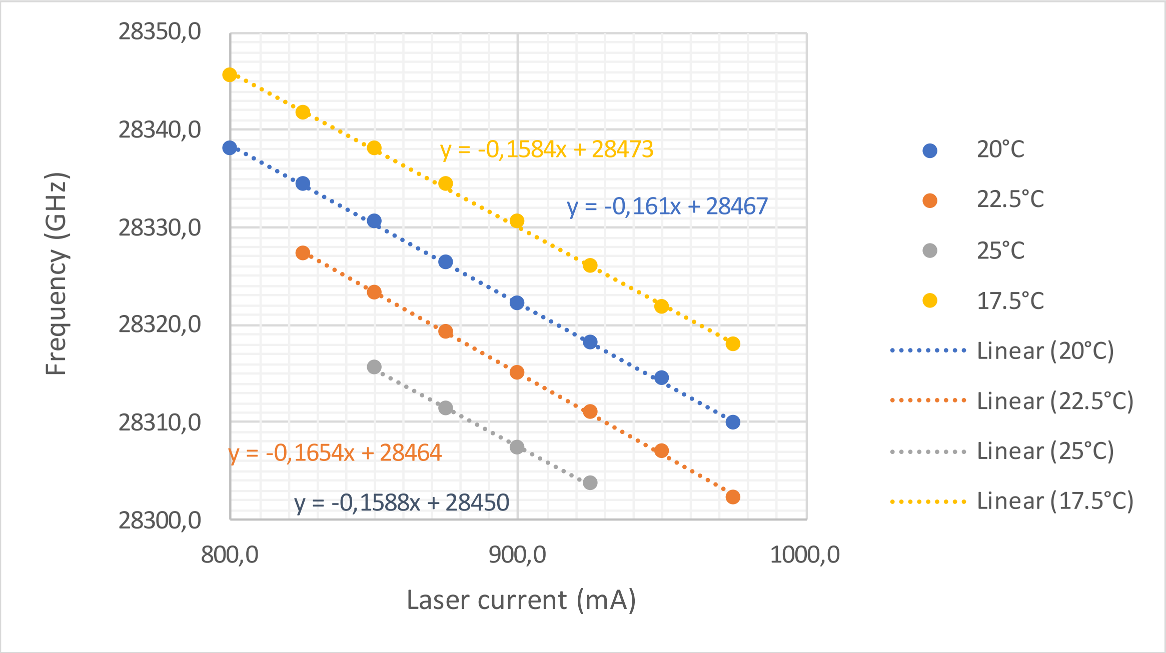
Long range transmission of the correlation signal on fibers

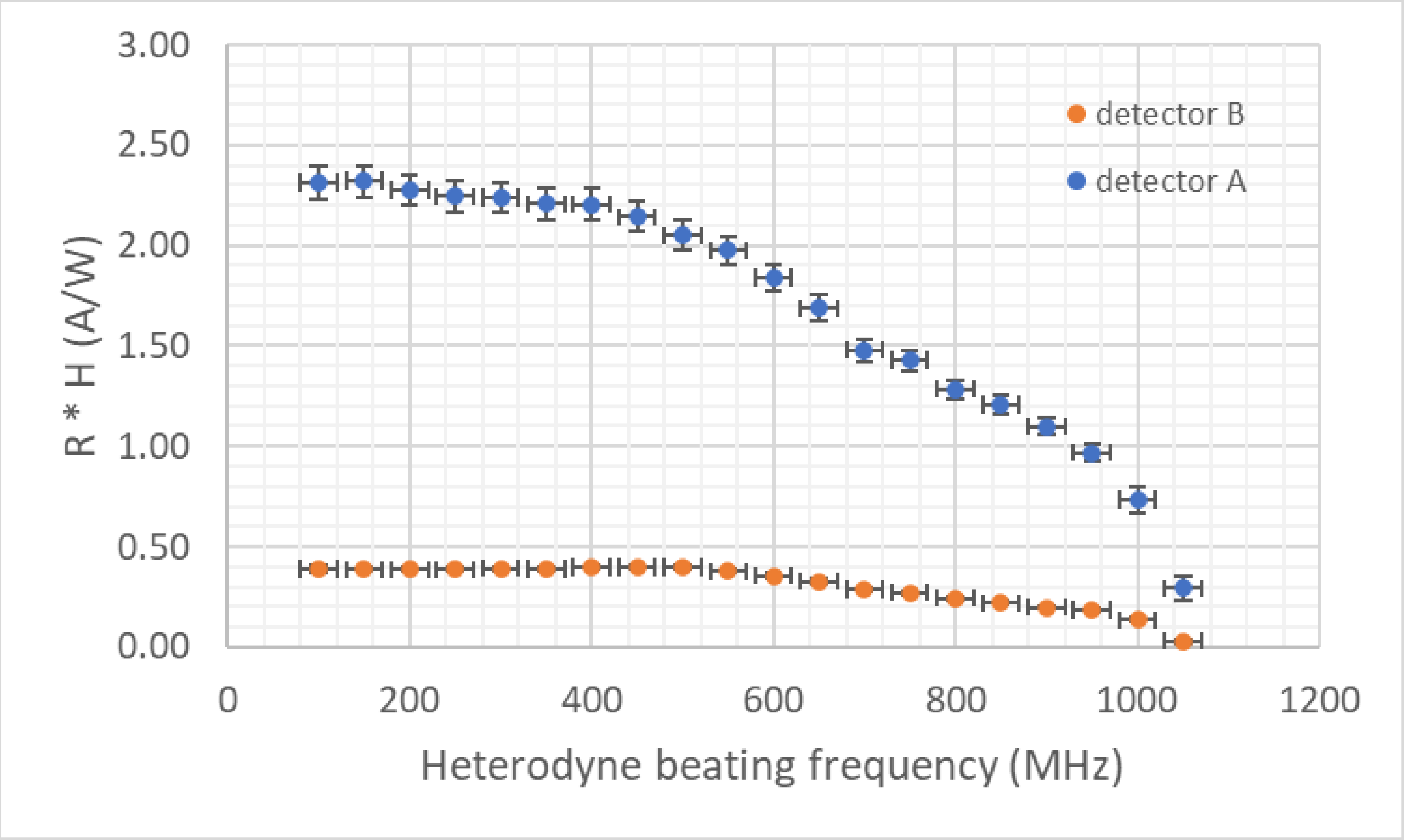
On sky prototype

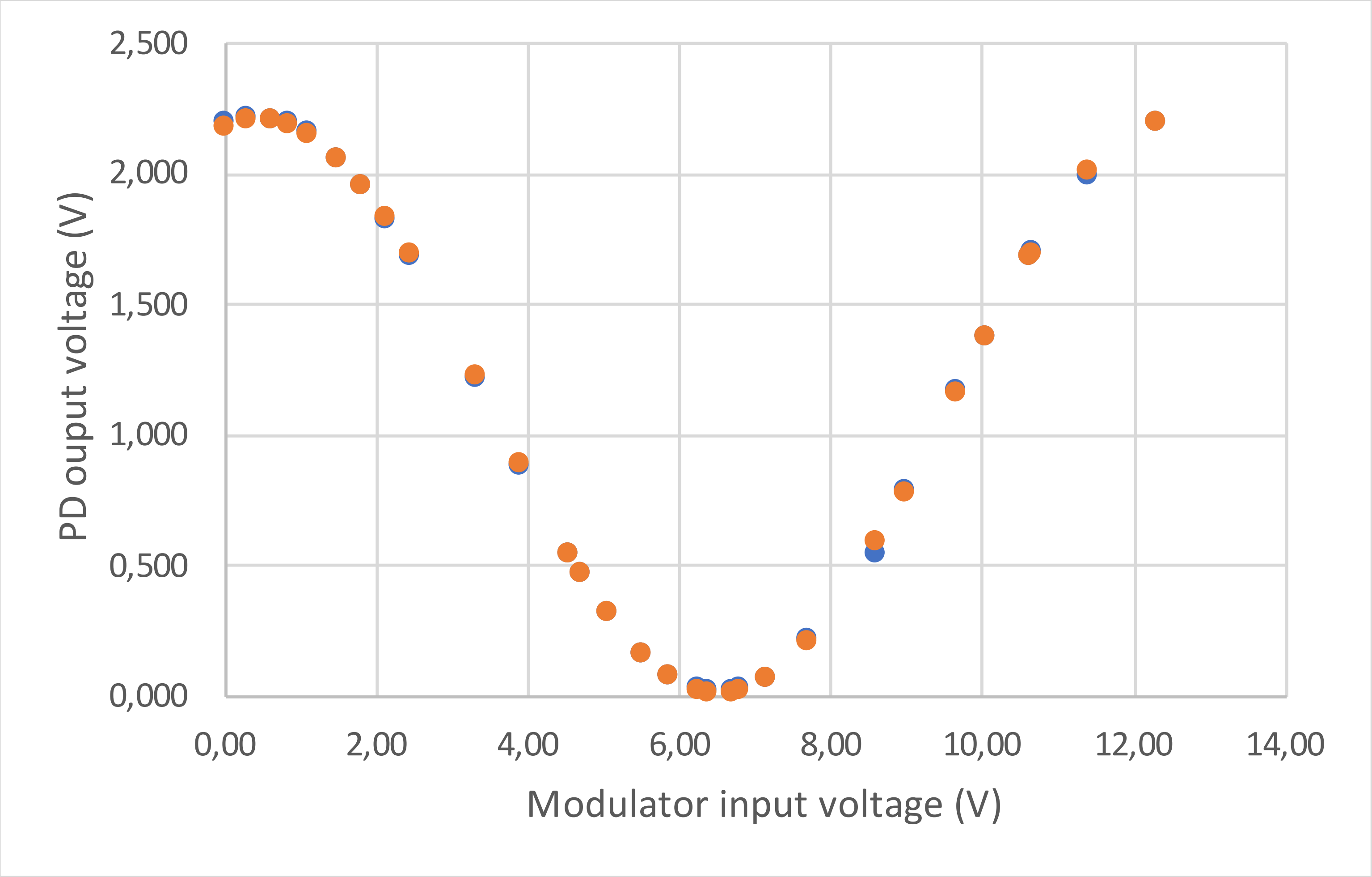
QCLs

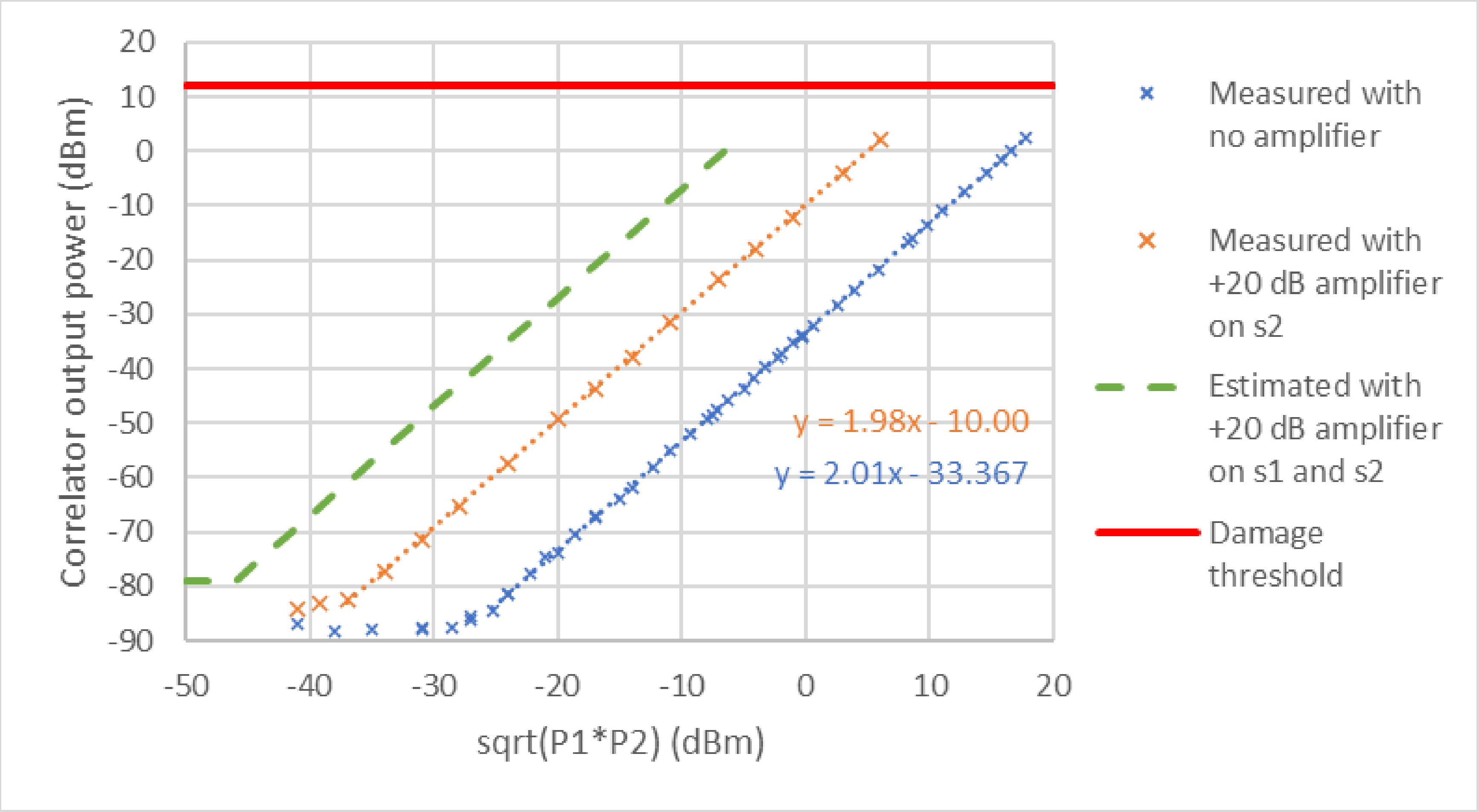
10,6 um QCL characterisation






3.00
2.50
2.00
1.50
1.00
0.50
0.00
R * H (A/W)
0
200
400
600
800
1000
1200
Heterodyne beating frequency (MHz)
● detector B
● detector A


2,500
2,000
1,500
1,000
0,500
0,000
PD ouput voltage (V)
0,00
2,00
4,00
6,00
8,00
10,00
12,00
14,00
Modulator input voltage (V)


Correlator output power (dBm)
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-50
-40
-30
-20
-10
0
10
20
sqrt(P1*P2) (dBm)
y = 1.98x - 10.00
y = 2.01x - 33.367
Measured with no amplifier
Measured with +20 dB amplifier on s2
Estimated with +20 dB amplifier on s1 and s2
Damage threshold

Characterization of a QWIP

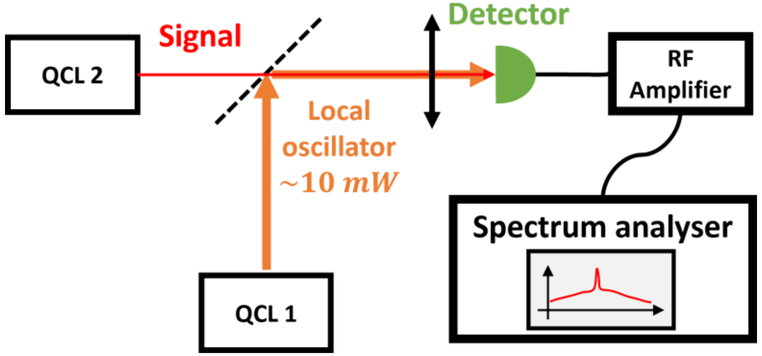
Bandwidth

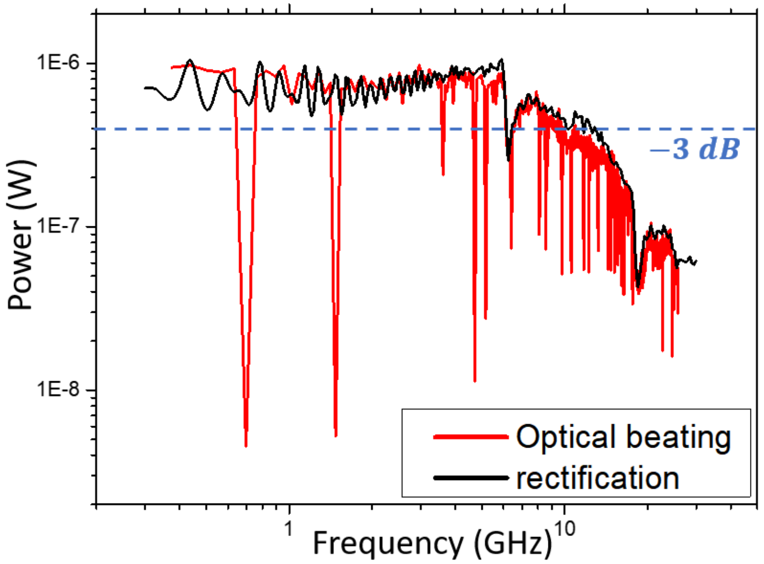
- Two measurement methods:
  - Measuring the power of **heterodyne beating** between two lasers at different frequencies
  - Sending electrical input RF signals to the detector and analyzing the output signals

- We obtained à $-3\ dB$ bandwidth of $\Delta\nu \simeq 10\ GHz$

  → Main limitation: electrical capacitance of the mesa

- To our knowledge: record bandwidth is $\Delta\nu = 67\ GHz^1$, obtained with patch-antenna





---

[1] Hakl et al, "Ultrafast quantum-well photodetectors operating at 10µmwith a flat frequency response up to 70 ghz at room temperature", ACS Photonics8(2), 464–471 (2021)

Principle of QCD and QWIP

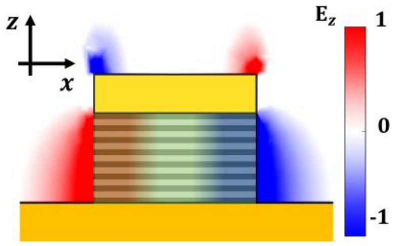
Mesa and patch-antenna resonators architecture

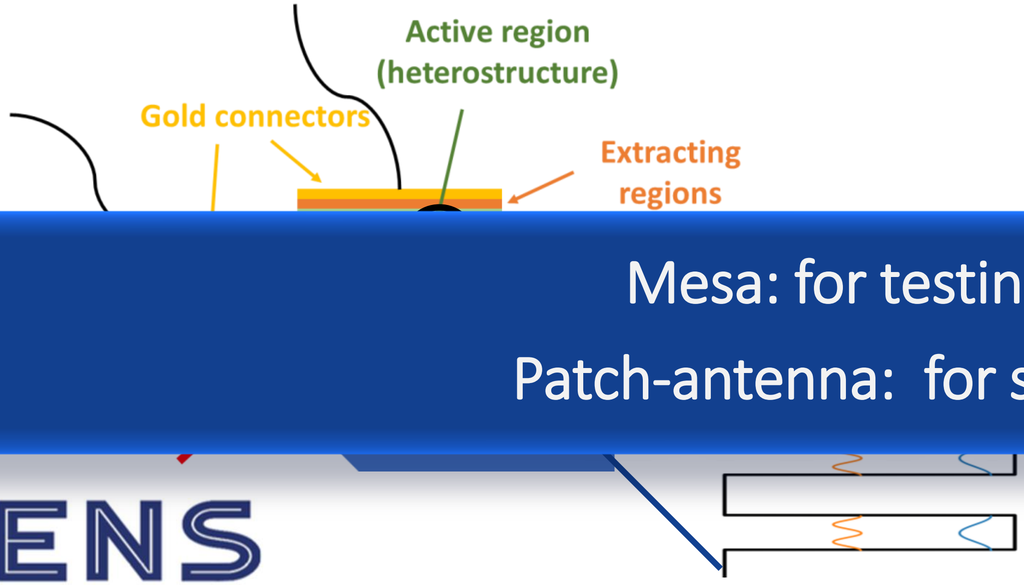
Mesa architecture:

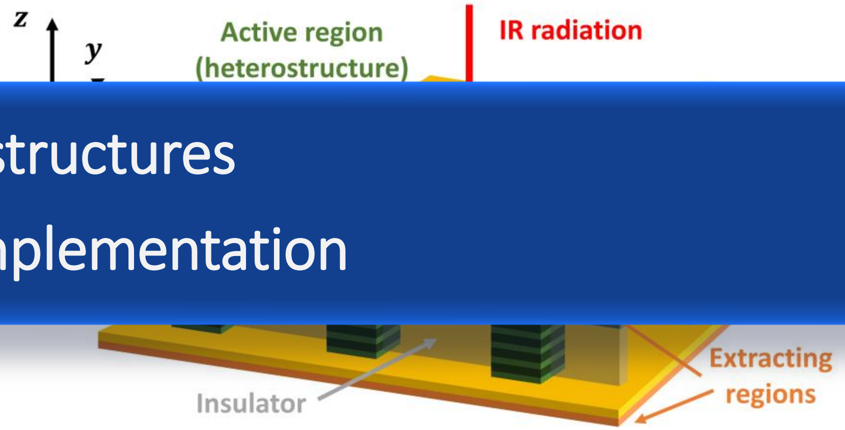
- Easy to process (already commercialized)
- 50 % losses caused by polarization selection rule

Patch-antenna architecture:

- More difficult to process
- No polarization losses
- Enhanced light coupling
- Reduced electrical area
  - Higher bandwidth
  - Reduced noise





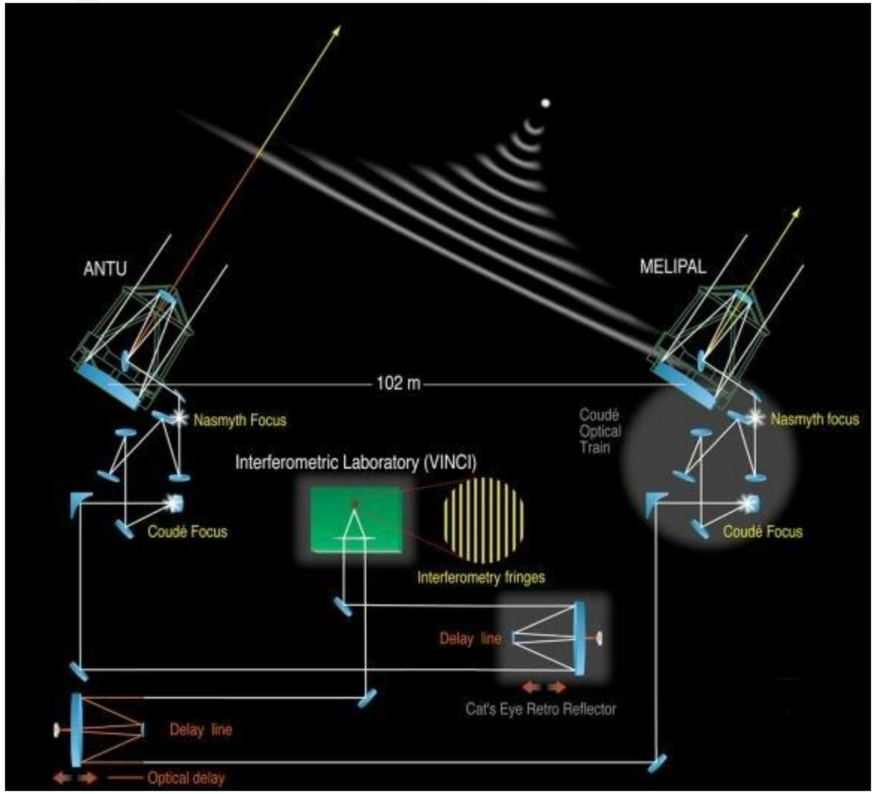


Mesa: for testing heterostructures

Patch-antenna: for system implementation

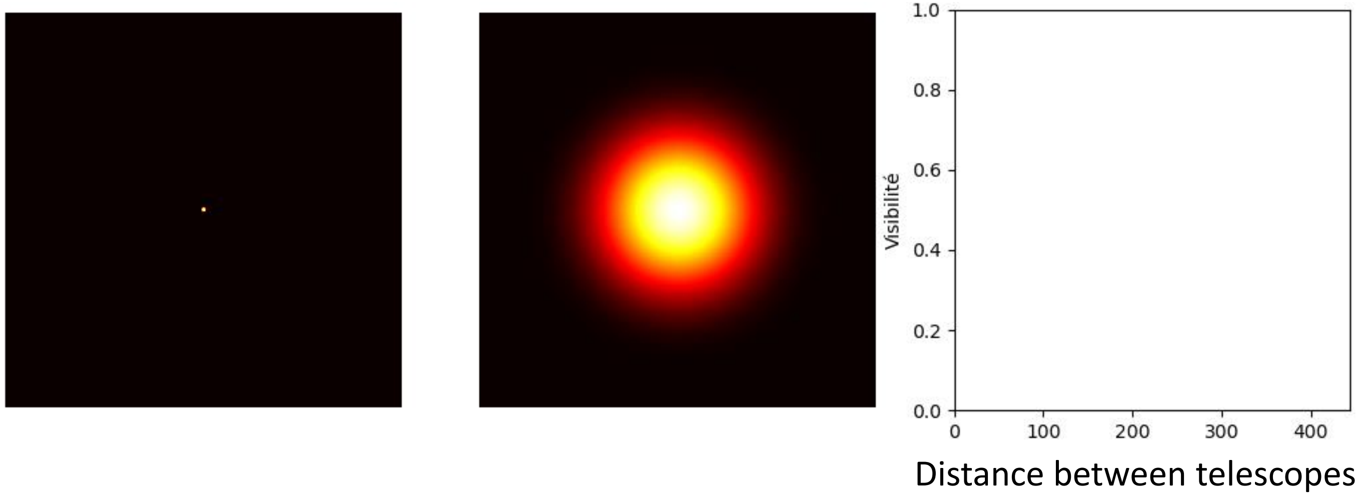
Mid-Infrared heterodyne interferometry

Direct astronomical interferometry



Credit: ESO

Simulation of a star (disk) observed by a two telescope interferometer



What we see on the sensor :

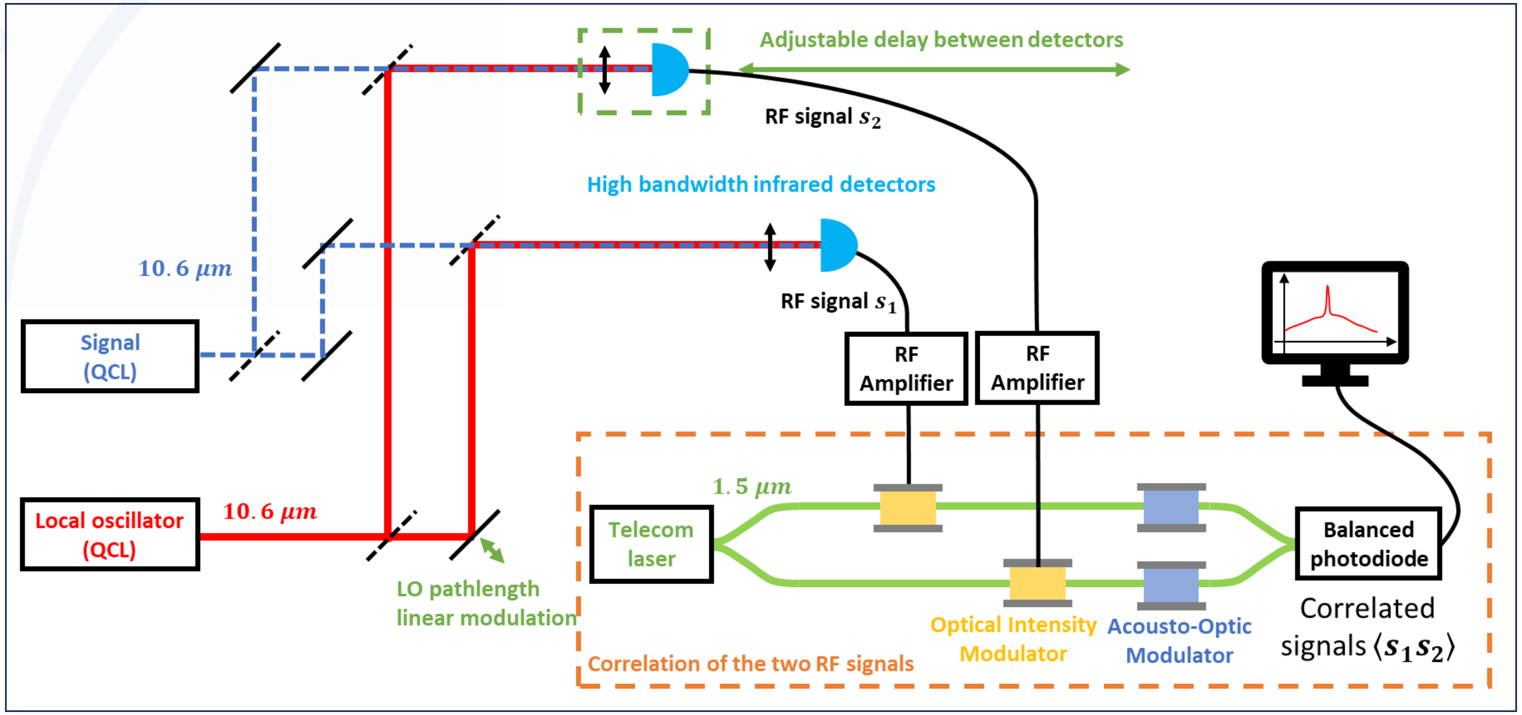
$$|E_1 + E_2|^2 = |E_1|^2 + |E_2|^2 + 2\,\boldsymbol{V}\,|E_1||E_2|\cos(\Delta\Phi)$$

$\boldsymbol{V}$: visiblity (coherence) between E_1 from telescope 1 and E_2 from telescope 2

→ Carries the astronomical information on the observed objet

Presentation of the 2T heterodyne demonstration bench

Current state of the bench emulation bench at IPAG

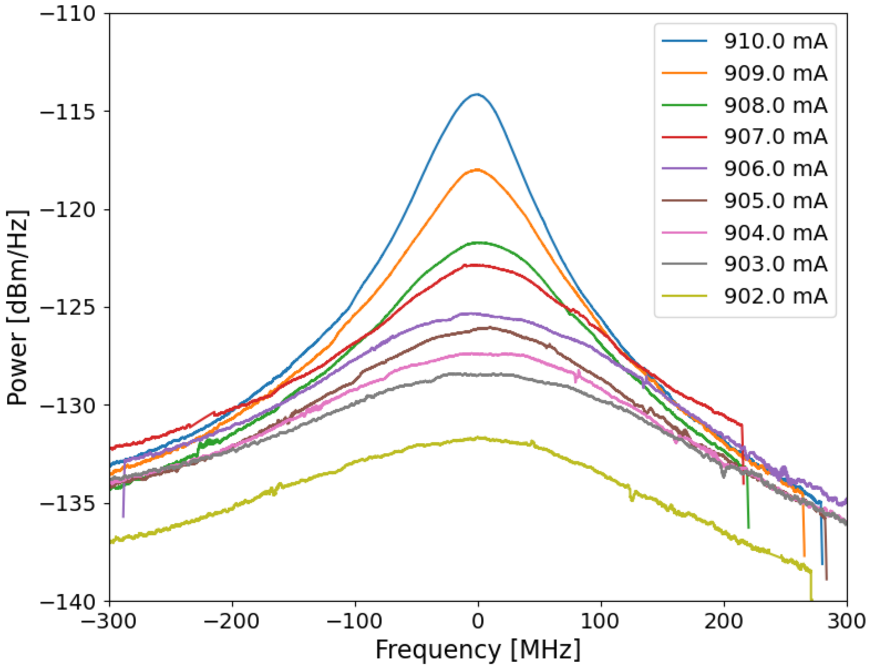


- Moveable detector to explore the coherence envelop $\boldsymbol{C}$ of the signal (caused by it's spectral extension)
- Extended sources:
  - Black-body
  - ASE

$$|E_1 + E_2|^2 = |E_1|^2 + |E_2|^2 + 2\ \boldsymbol{C}\ |E_1||E_2| \cos(\Delta\Phi)$$

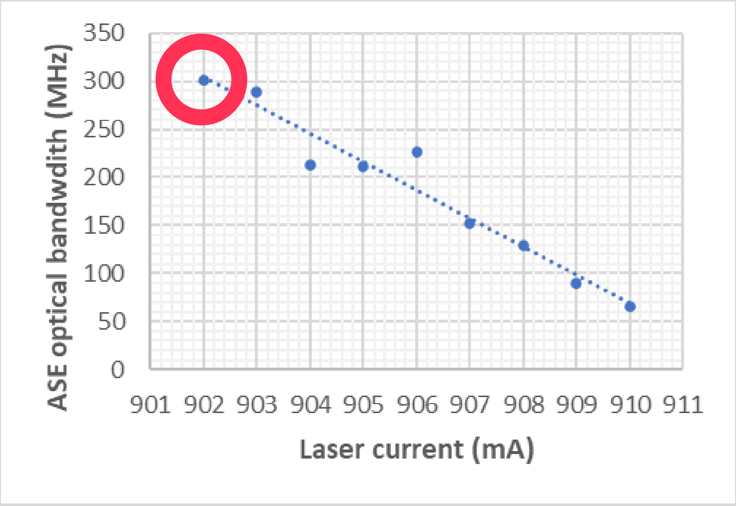
Correlation of ASE signals and current detection limit of the bench

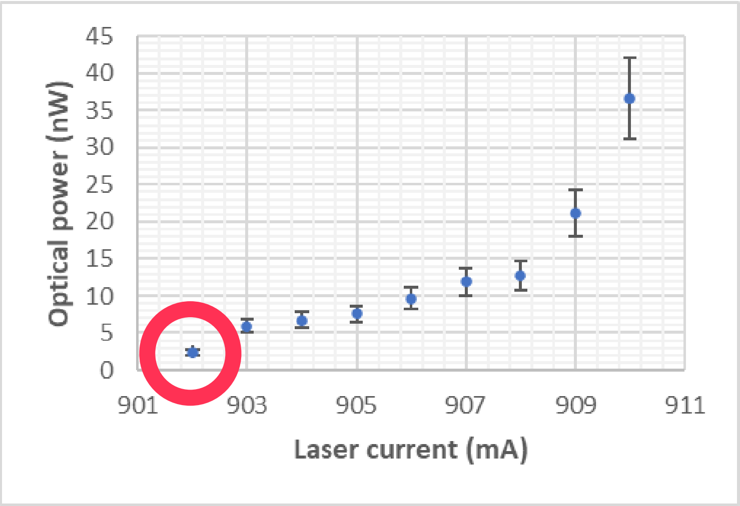
QCL ASE characterisation



ASE: Amplified Spontaneous Emission

- Below threshold, lasers emit large band radiation
  - Adjustable power/spectral bandwidth
  - No need to realign
- The spectra of the ASE were measured with heterodyne detection over 4s integration time
- We used the $902.0\ mA$ raditaiton of the signal QCL as a wide-band source to explore its correlation





Presentation of the 2T heterodyne demonstration bench

Estimation of signal NEP

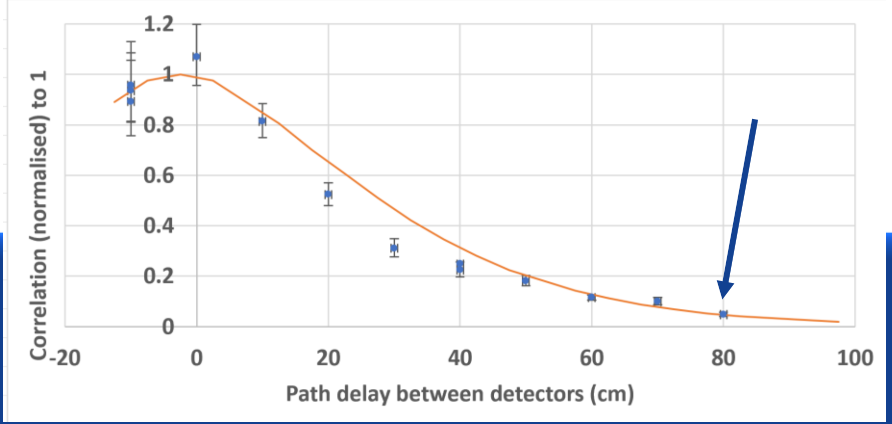
Noise equivalent V_{pp} for the correlator: $V_{pp,1} = 1\,mV$ & $V_{pp,2} = 1\,mV$

- Detector responsivity: $\mathcal{R} \simeq 1\,A/W$
- $\mathrm{G} = 8500\,V/A$ transimpedance gain

$$V_{pp,det} = 4\mathcal{R}G\sqrt{P_{LO}T_{system}P_{signal}}$$

Assuming $P_{LO} = 1\,mW$, and $T_{system} = 10\%$

The signal NEP is $\sim 10^{-11}\,W = 10\,pW$



In practise, we only went down to $\mathbf{2\,nW}$ with 5% correlation → $\simeq \mathbf{10^{-10}\,W = 100\,pW}$