Spectroscopy using terahertz quantum cascade laser

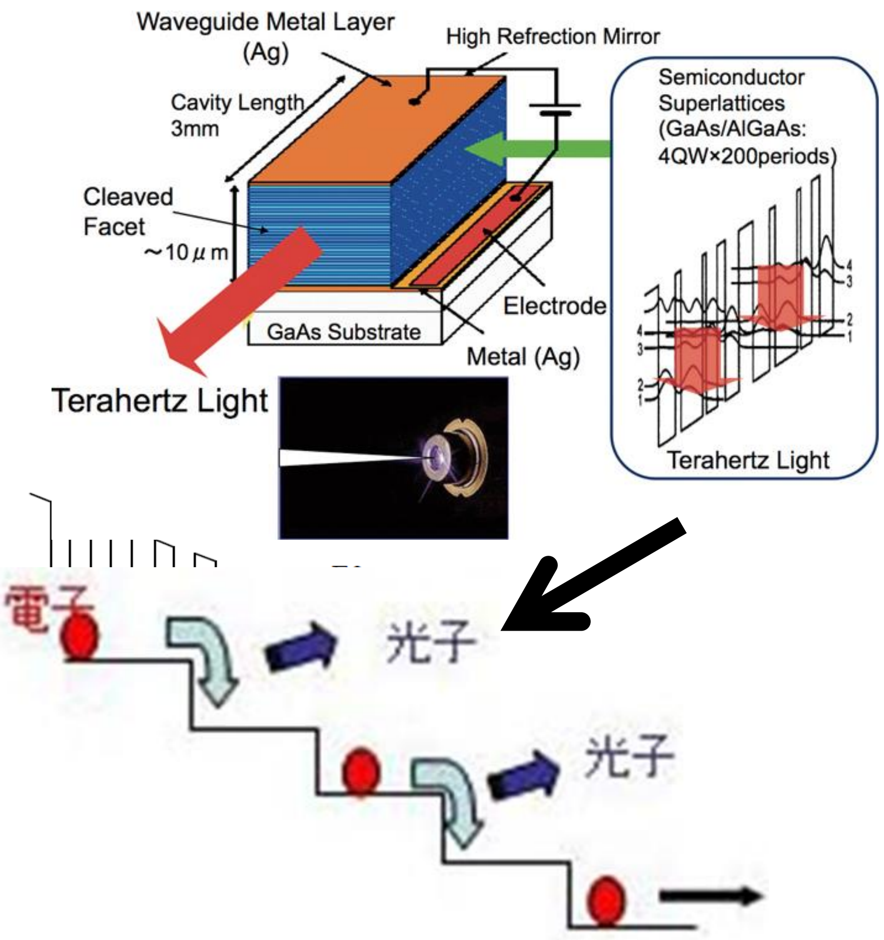
journal seminar

2014/6/4 M2 Hayashi

THz-QCL

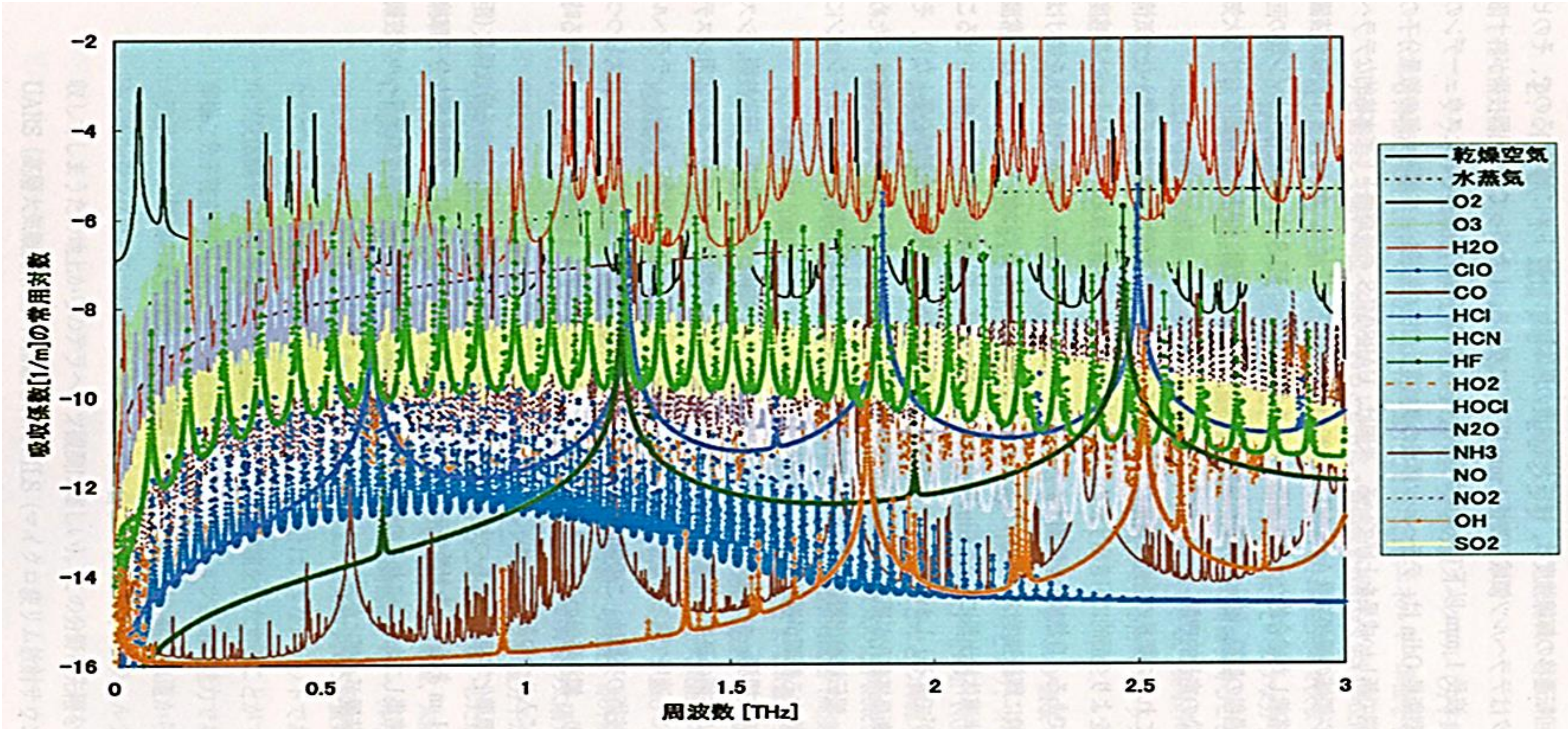
Advantage

- compact
- high power
  (several mW)
- narrow linewidth
  (~10kHz)



It is expected as an imaging light source and gas spectroscopy!!

THz spectroscopy



Problem of using THz-QCL

- no tuning range
- free-running linewidth is several MHz

1. Y. Ren, J. N. Hovenier, R. Higgins, J. R. Gao, T. M. Klapwijk, S. C. Shi, B. Klein, T.-Y. Kao, Q. Hu, and J. L. Reno, “High-resolution heterodyne spectroscopy using a tunable quantum cascade laser around 3.5 THz”. APPLIED PHYSICS LETTERS **98**, 231109 (2011)

2. R. Eichholz, H. Richter, S. G. Pavlov, M. Wienold, L. Schrottke, R. Hey, H. T. Grahn, and H.-W. Hubers, ” Multi-channel terahertz grating spectrometer with quantum-cascade laser and microbolometer array”. APPLIED PHYSICS LETTERS **99**, 141112 (2011)

3. S. Bartalini, L. Consolino, P. Cancio, and P. De Natale, “Frequency-Comb-Assisted Terahertz Quantum Cascade Laser Spectroscopy”, PHYSICAL REVIEW X **4**, 021006 (2014)

Y. Ren, J. N. Hovenier, R. Higgins, J. R. Gao,
T. M. Klapwijk, S. C. Shi, B. Klein, T.-Y. Kao,
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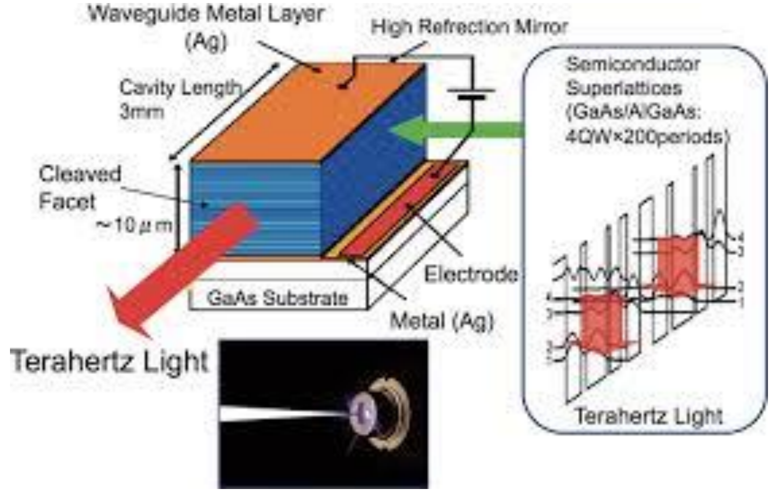
”High-resolution heterodyne spectroscopy using a tunable quantum cascade laser around 3.5 THz”

APPLIED PHYSICS LETTERS **98**, 231109 (2011)

Introduction

High resolution heterodyne spectrometer

→QCL



problem

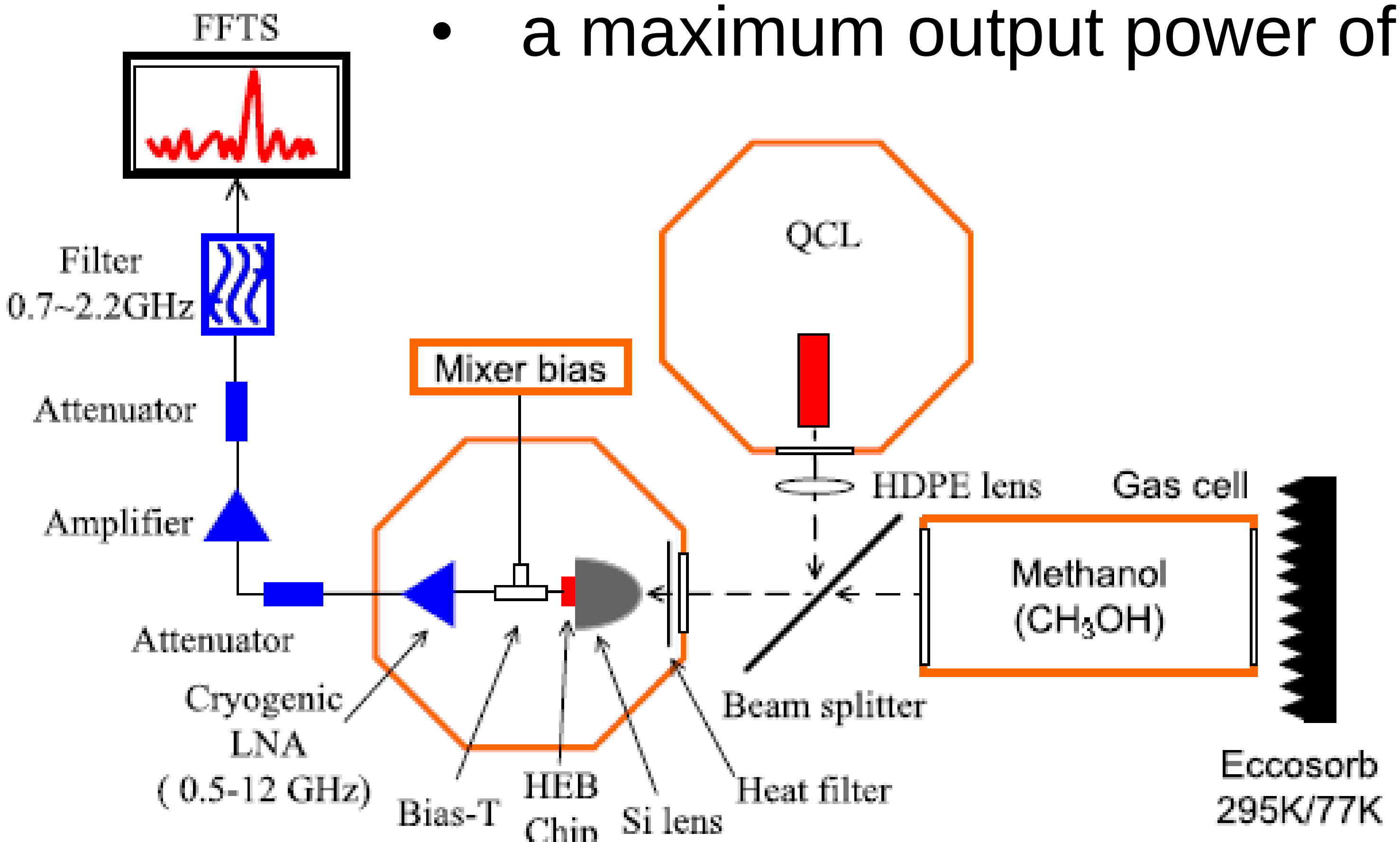
- QCL no tuning range

In this letter

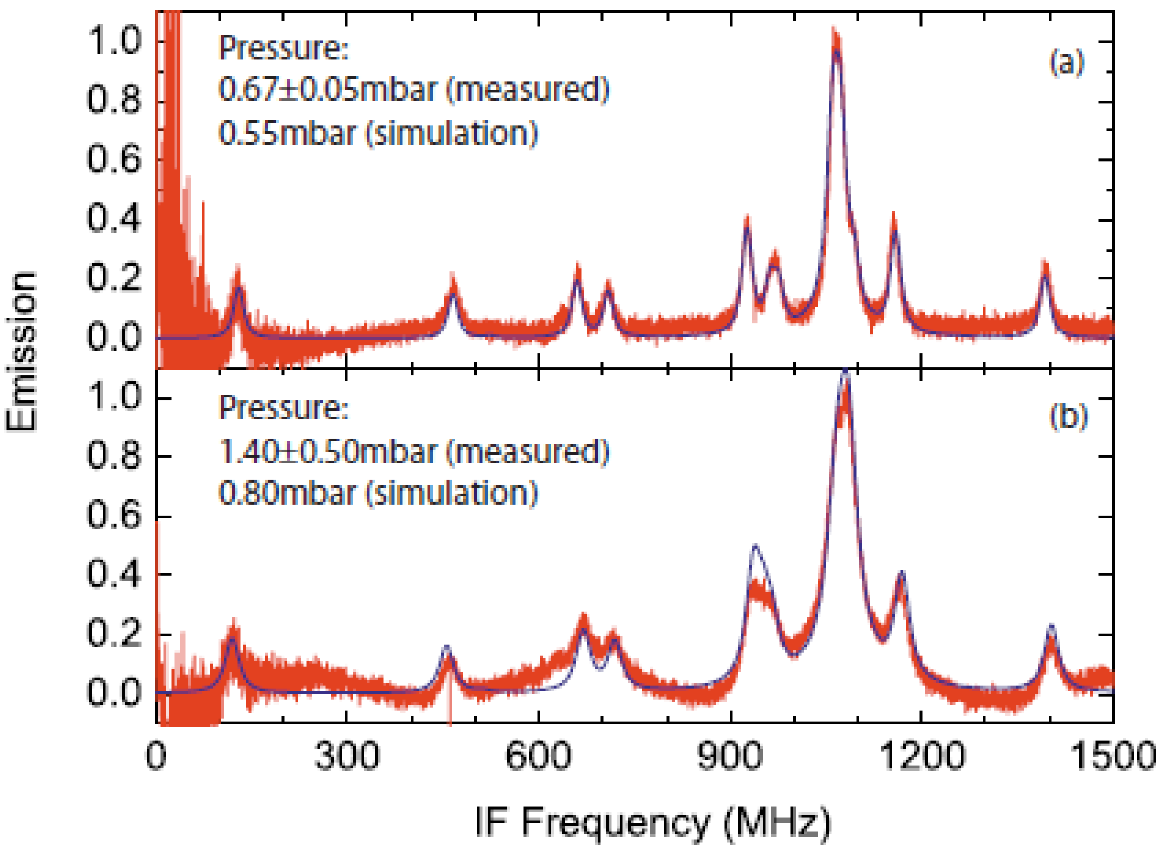
- Using a tunable THz-QCL
- Observation methanol molecular lines at 3.5THz

Setup

- a single mode emission from 3452.0 to 3450.8 GHz by increasing the bias voltage from 13.9 to 14.9 V
- a maximum output power of 0.8 mW



Experimental and simulated methanol spectral lines

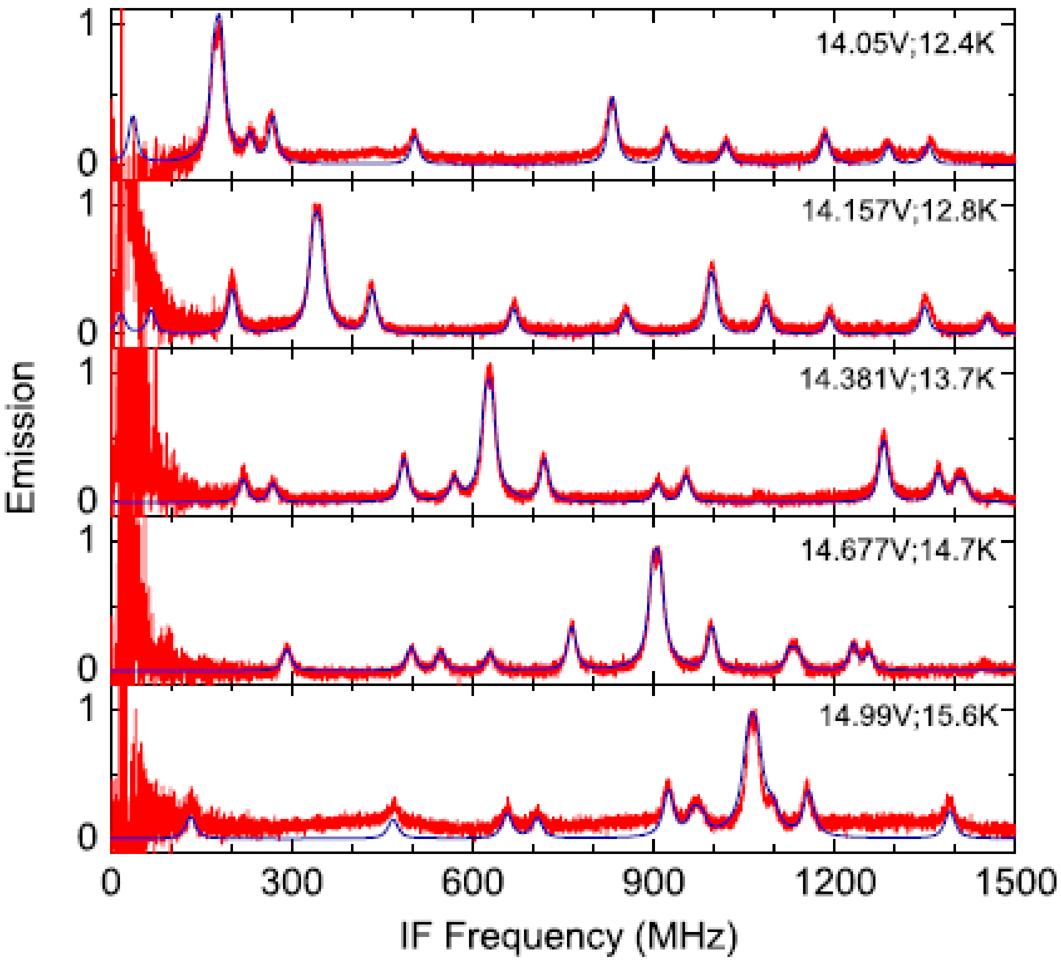


$f_{THz} = 3450.232GHz$

(a) : low pressure spectrum

(b) : high pressure spectrum

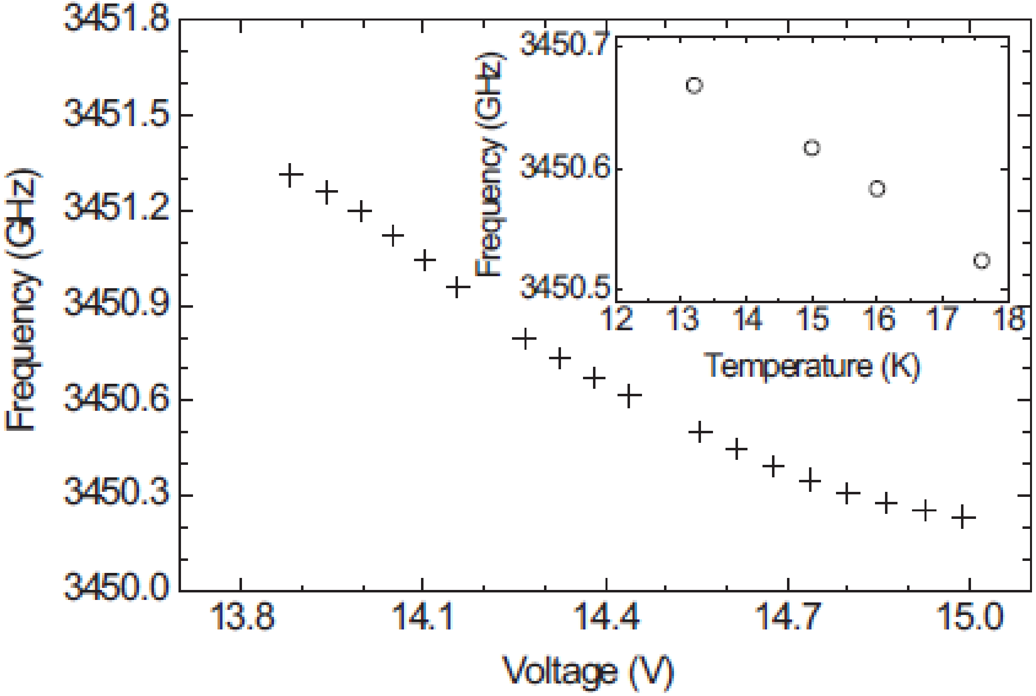
Several methanol spectra recorded at different QCL frequencies



- tuned with the bias voltage of the QCL from 14.05 to 14.99V

→ excellent agreements were achieved for the entire frequency region

QCL emission frequency



① thermal tuning coefficient →33 MHz/K

② electrical tuning coefficient → 859 MHz/V

- 150 MHz tuning range is shown for a temperature range from 13.2 to 17.6 K
- 1GHz tuning range is shown for a bias voltage range from 13.90 to 14.99V

Summary

- A tunable high-resolution heterodyne spectrometer using 3.5THz-QCL is demonstrated.

- Within the entire frequency tuning range, the measured spectra show excellent agreement with the theoretical simulations.

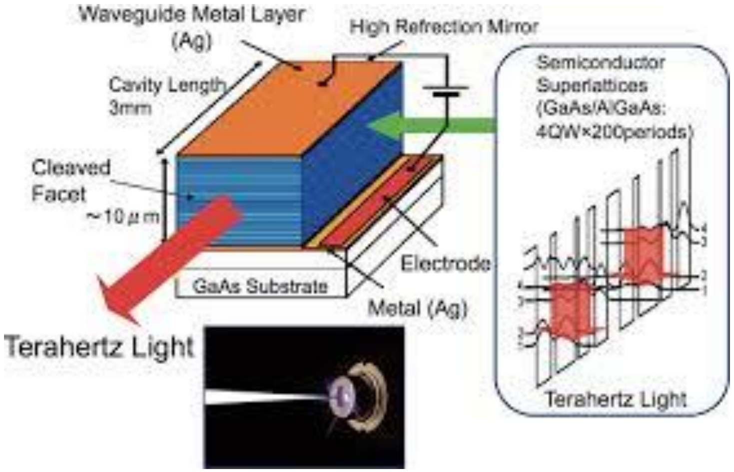
R. Eichholz, H. Richter, S. G. Pavlov, M. Wienold, L. Schrottke, R. Hey, H. T. Grahn, and H.-W. Hubers,

“Multi-channel terahertz grating spectrometer with quantum-cascade laser and microbolometer array”

APPLIED PHYSICS LETTERS **99**, 141112 (2011)

Introduction

THz-QCL is very attractive radiation sources for laser-based absorption spectroscopy



advantage

- emission is narrow

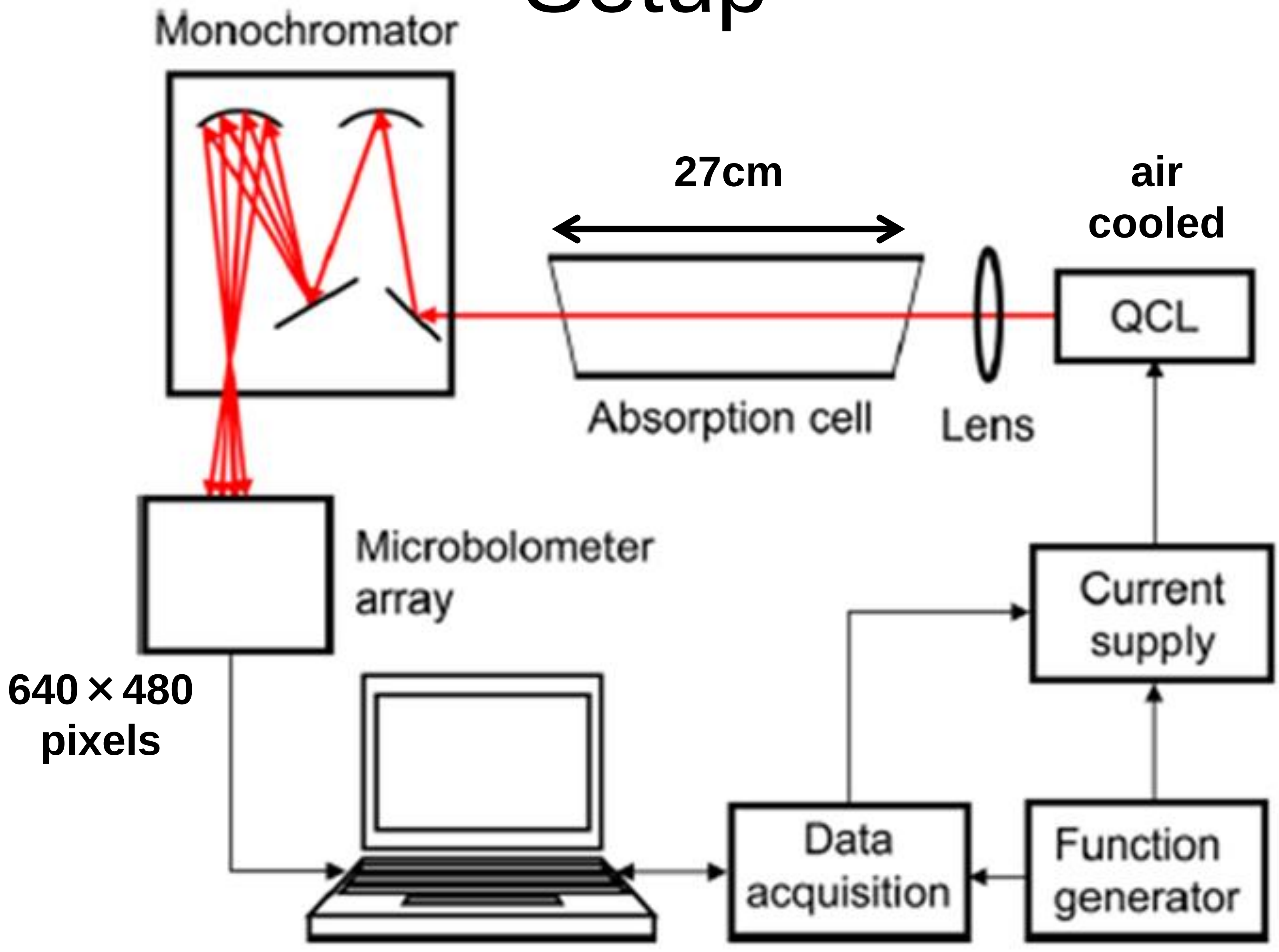
(less than 20 kHz)

- high output powers up to several tens of mW

In this letter

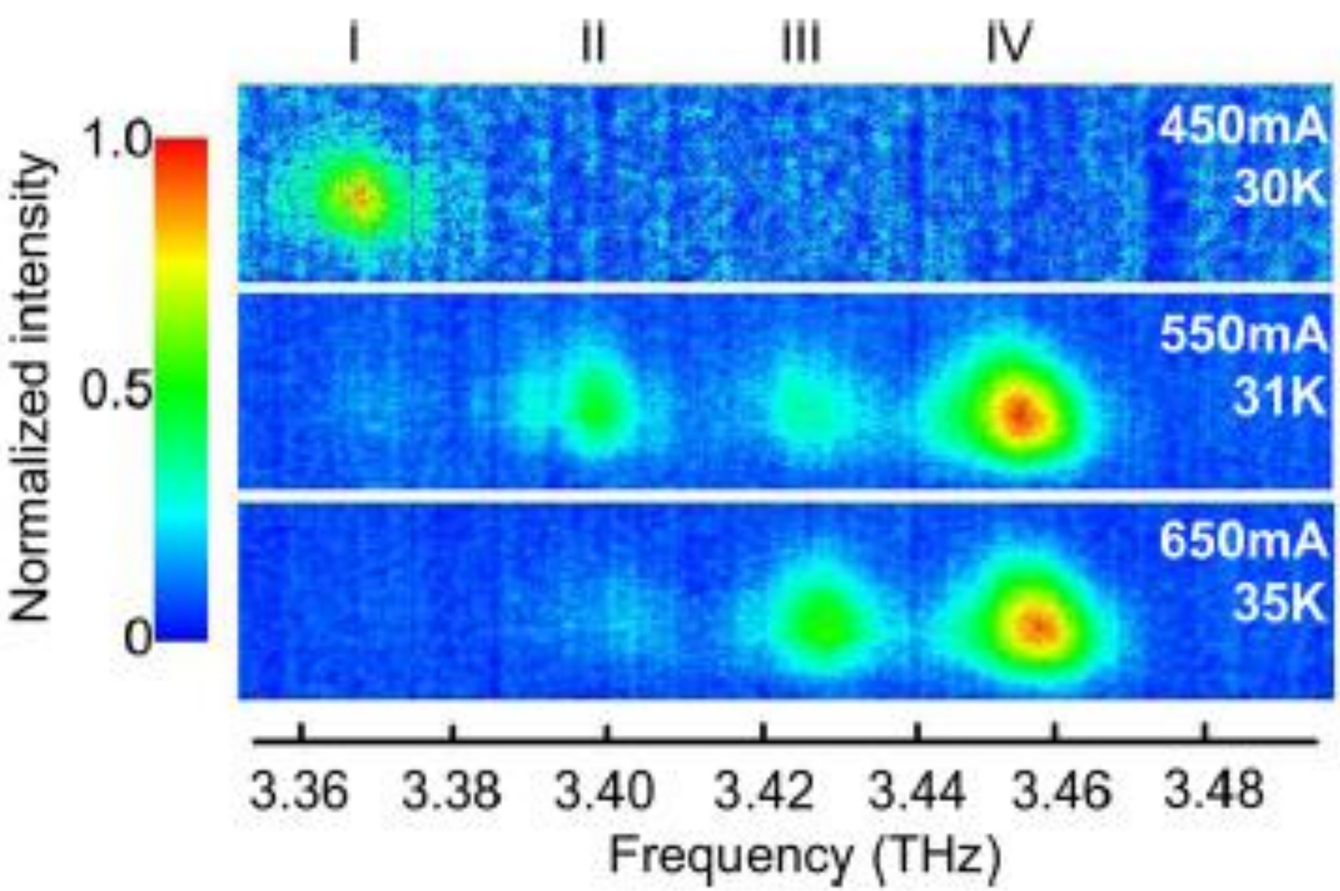
Multi-channel THz grating spectrometer

Setup


Monochromator
27cm
air
cooled
QCL
Absorption cell
Lens
Microbolometer
array
640×480
pixels
Current
supply
Data
acquisition
Function
generator

The emission spectrum of the QCL

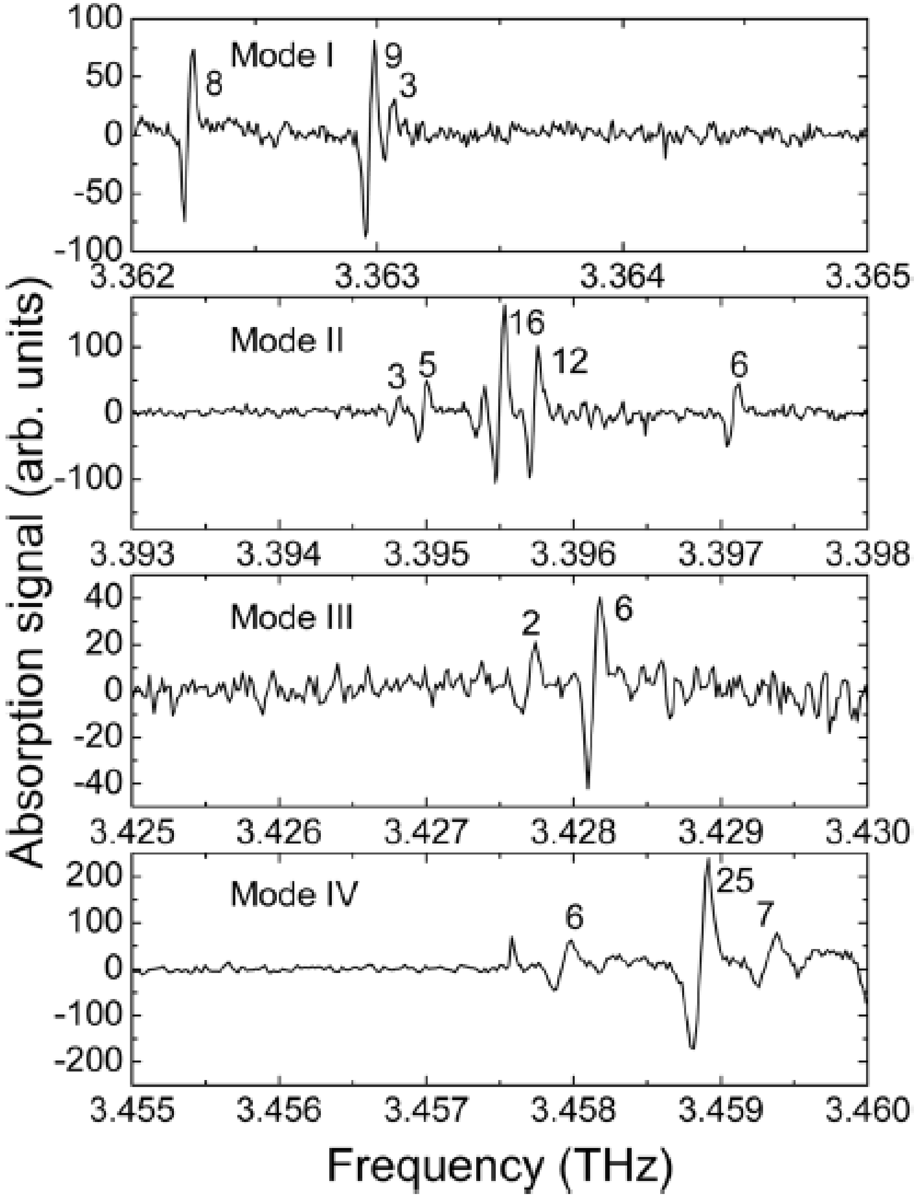
- Each image contains 100 × 500 pixels of the full image of the microbolometer array width



emission power is about 0.1 mW

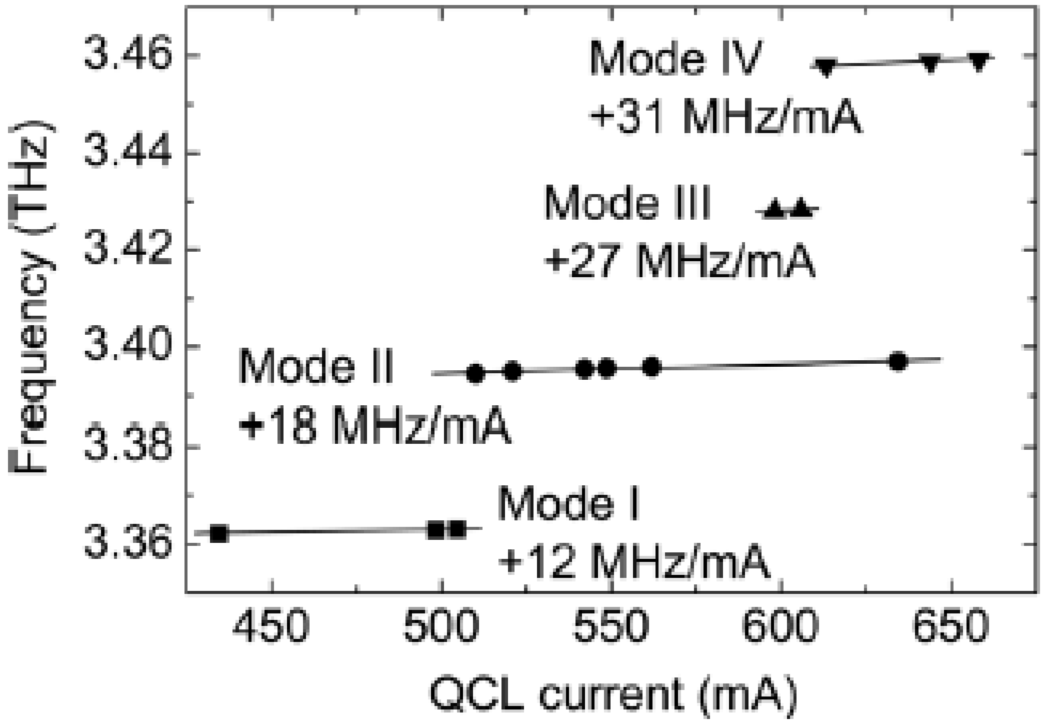
emission power is about 0.3 mW

Spectrum of CH_3OH at 1 hPa



- The numbers given next to each absorption line are the SNR
- The poor SNR in the spectrum of mode 3 is caused by the rather small available laser power

Frequency tuning of the emission modes



- The straight lines are linear fits to the data points
- It varies between 12 and 31 MHz/mA

The measured FWHM of the absorption lines

- about 30 MHz at 3.363 THz
- about 100 MHz at 3.459 THz

Summary

- A broadband THz spectrometer based on a THz QCL is demonstrated

Several improvements

- By using more sensitive detector array, SNR is improved
- By using more precise reference data, it is possible to significantly improve the accuracy

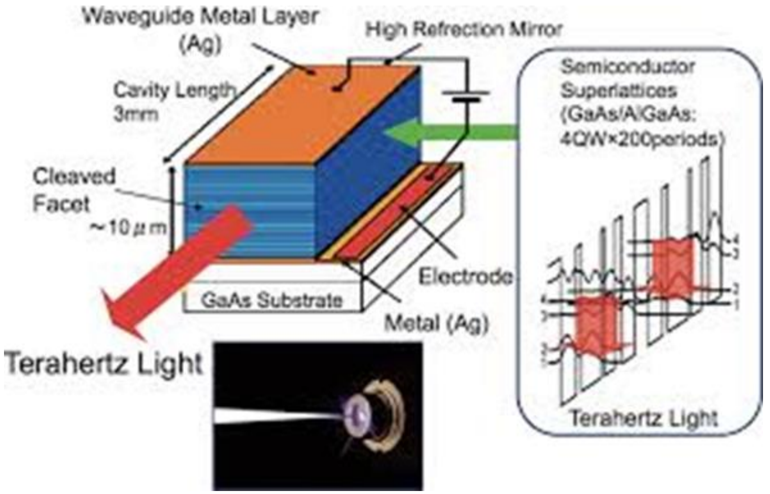
S. Bartalini, L. Consolino, P. Cancio,
and P. De Natale,

” Frequency-Comb-Assisted Terahertz Quantum Cascade Laser Spectroscopy”

PHYSICAL REVIEW X **4**, 021006 (2014)

Introduction

THz molecular spectroscopy



THz QCL source

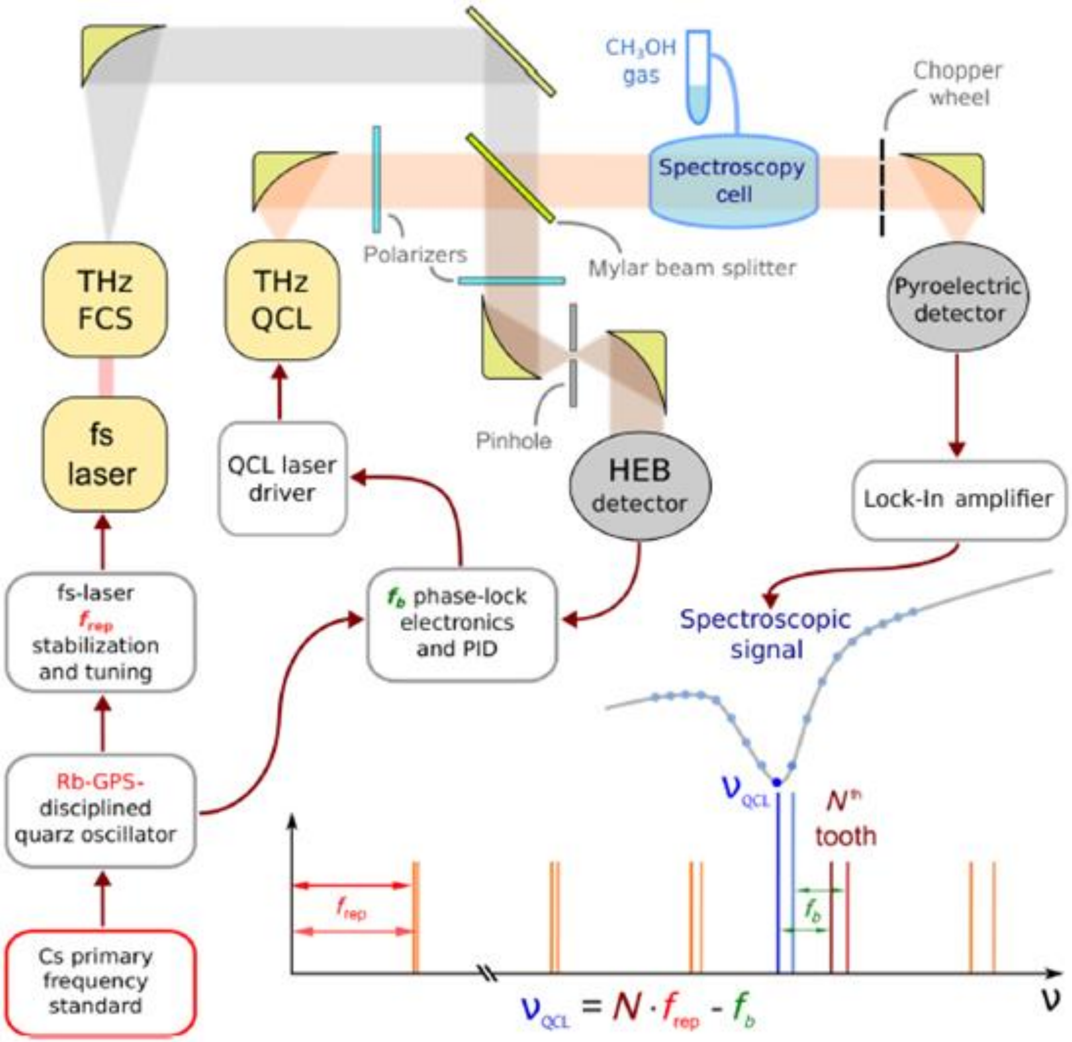
problem

- free-running linewidth is about 1MHz

In this letter → **using THz FCS**

- a reduction of QCLs frequency fluctuations down to the quantum limit
- control on their absolute emission frequency

Set up



QCL2.5THz

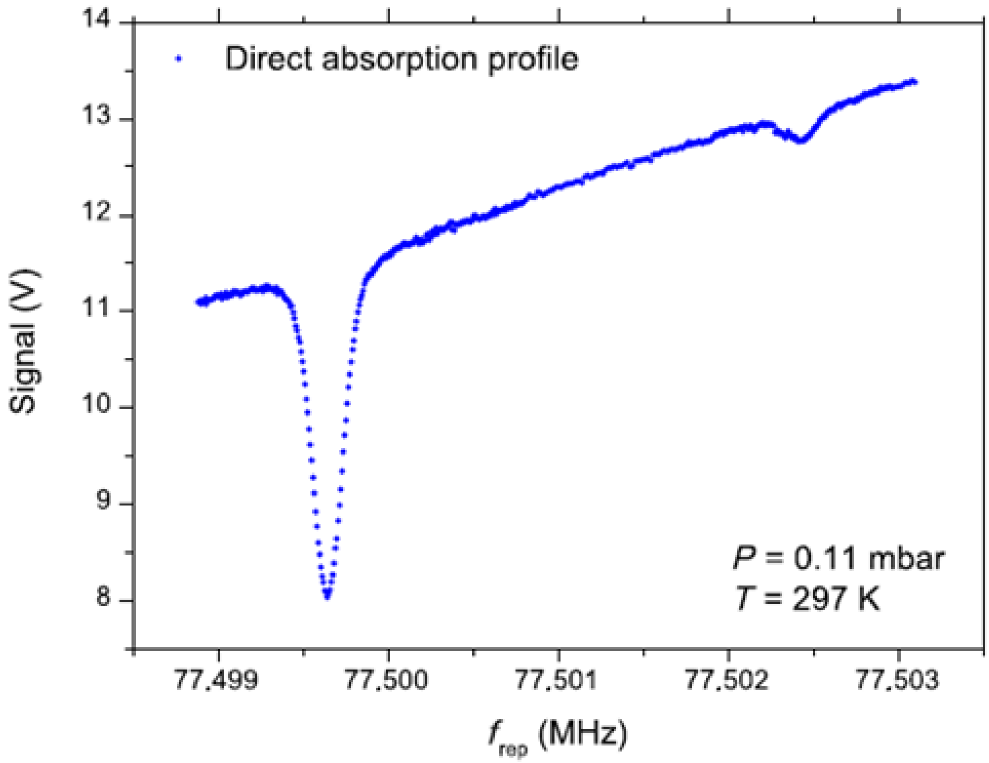
T=~47.5K

I=430mA→P=~1mW

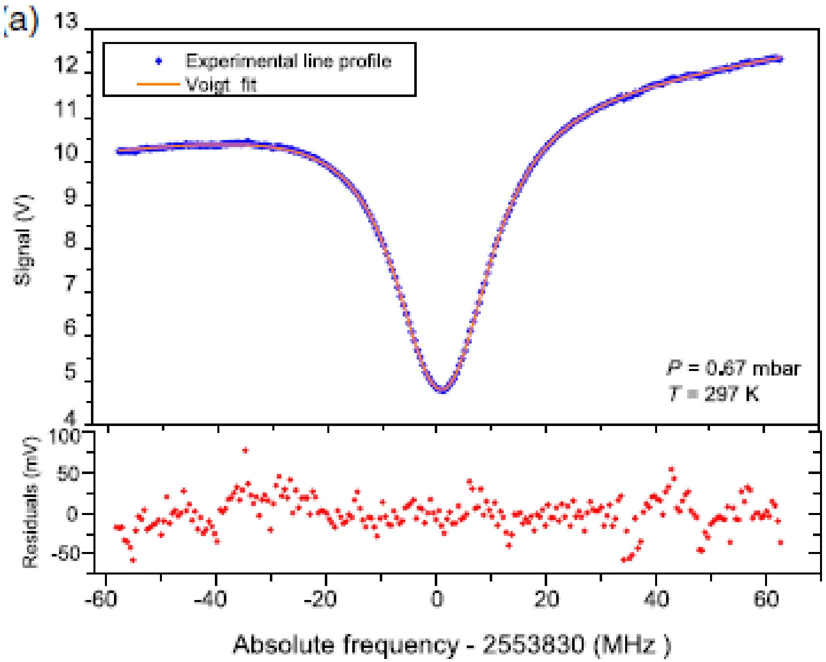
Ti:S laser

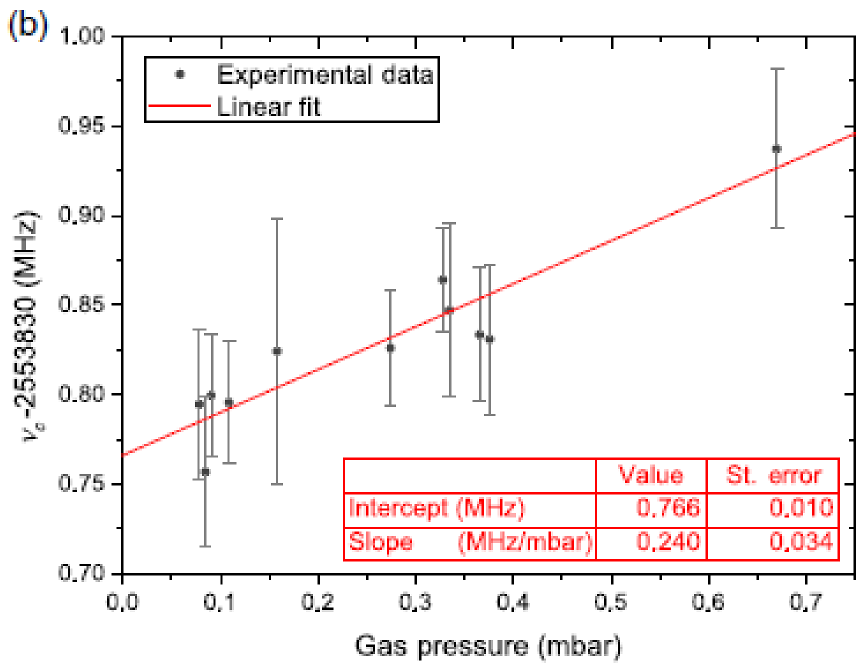
frep=77.5MHz

Spectroscopic signal



- Tuning f_{rep} of about 5 kHz, with a 1Hz step
- The 170MHz-wide frequency scan with 33kHz steps in QCL





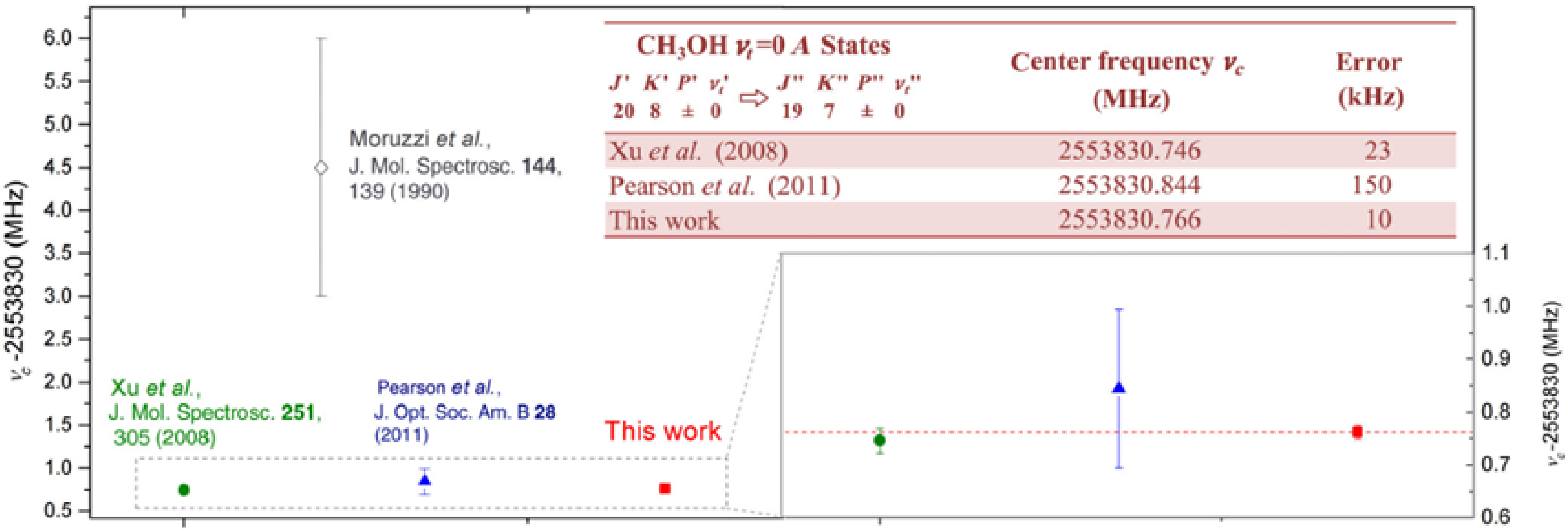
(a) Experimental absorption profile (blue dots) and Voigt function fit (red line)

- SNR is higher than 200

(b) Dependence of the center frequency on gas pressure

- pressure shift is about 240 kHz/mbar
- ν_{c0}=2553830.766(10) MHz

Comparison of absolute frequency with the previous measurements



CH_3OH ν_t=0 *A* States *J'* *K'* *P'* ν_t' ⇨ *J''* *K''* *P''* ν_t'' 20 8 ± 0 19 7 ± 0	Center frequency ν_c (MHz)	Error (kHz)
Xu *et al.* (2008)	2553830.746	23
Pearson *et al.* (2011)	2553830.844	150
This work	2553830.766	10

- relative uncertainty : 4×10^{-9}
- limited by SN ratio and Doppler-limited

Summary

- The combination of THz comb with the frequency stability and mW-level power of the THz-QCL allows us to achieve an unprecedented precision

This first demonstration paves the way to new scenarios for a number of different fields, including novel THz-based astronomy, high-precision trace-gas sensing, and cold-molecule physics

Conclusion

- THz-QCL is very attractive radiation sources for spectroscopy
- Various applications using THz-QCL is expected

Determine the THz-QCL frequency

$$\nu_{\mathrm{QCL}} = N f_{\mathrm{rep}} \pm f_b,$$

$$N = \mp \frac{\Delta f_b}{\Delta f_{\mathrm{rep}}}.$$