Cavity enhanced optical frequency comb spectroscopy

Lucile Rutkowski

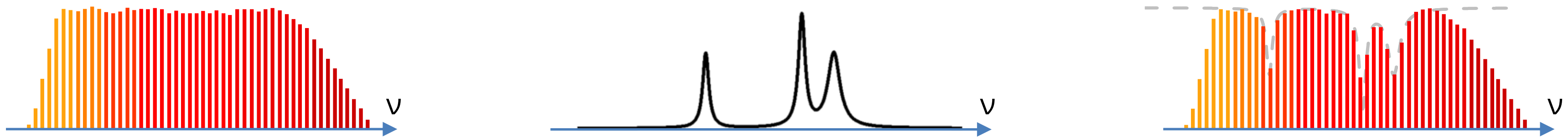
Univ Rennes, CNRS, IPR (Institut de Physique de Rennes)-UMR 6251, F-35000 Rennes, France

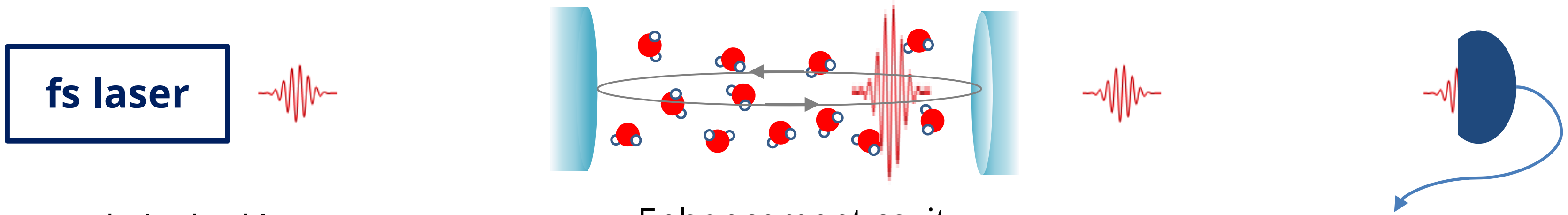
lucile.rutkowski@univ-rennes1.fr

Introduction

High resolution AND broad bandwidth
*Efficient coupling with an **enhancement cavity***

Comb spectrum | *Molecular absorption* | *Spectral transmission*





Mode locked laser

Enhancement cavity
Sensitivity

Broadband detection

~10^5 equidistant cw lasers

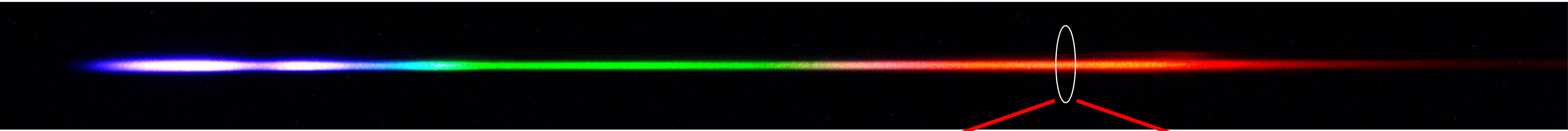
Interaction length ∝ finesse

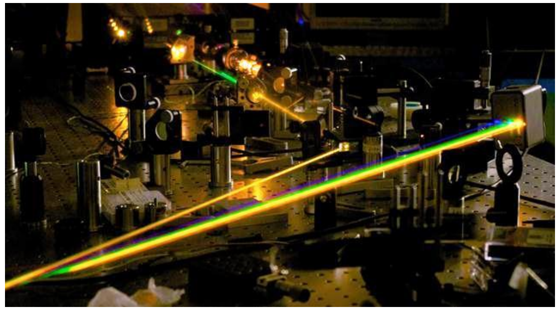
Vernier
FTS
VIPA
DCS
…

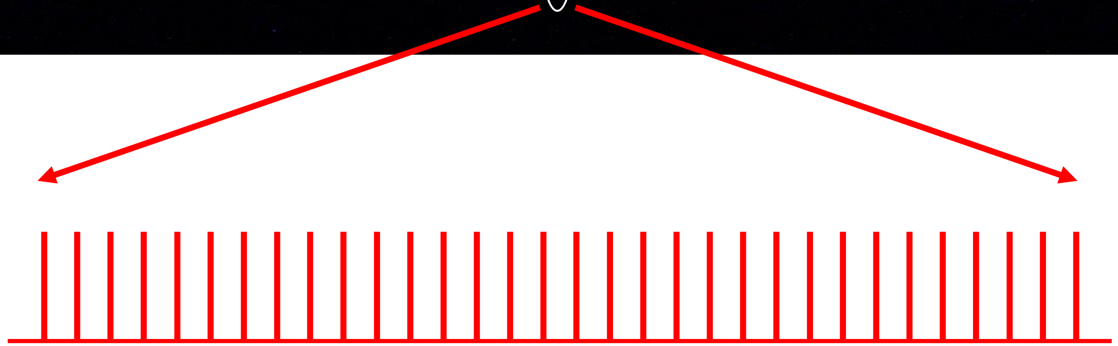
*Measure entire absorption bands and/or different species **simultaneously**, with **high sensitivity** and in **short acquisition times***

Optical frequency combs

The bandwidth of incoherent light sources with the resolution of cw lasers







Thousands of synchronized laser lines

Prix Nobel 2005

John Hall & Theodor Hänsch

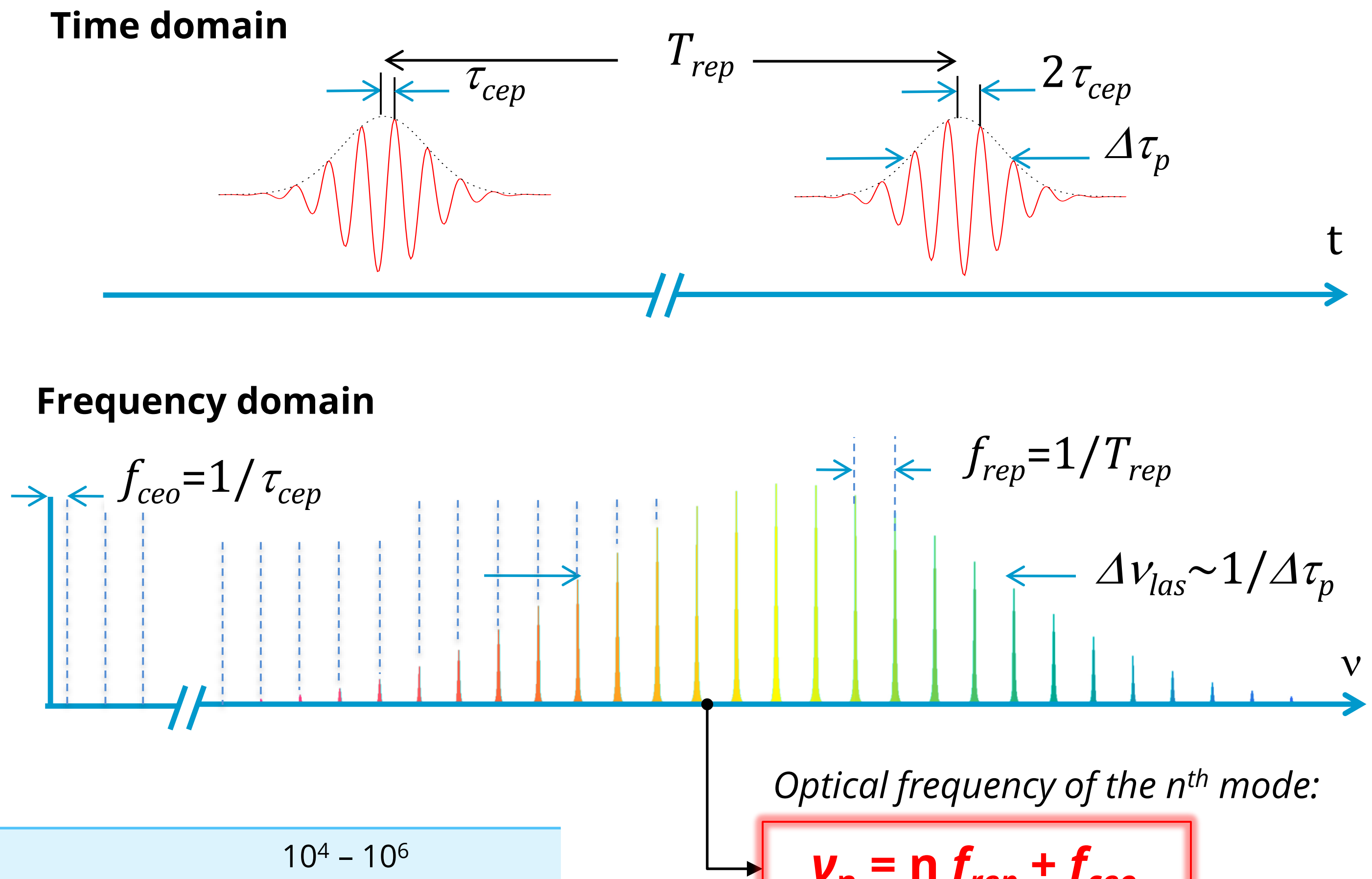
for their contributions to the development
of laser-based precision spectroscopy,
including the optical frequency comb technique

S. Cundiff & J. Ye, Rev. Mod. Phys. 75, 325 (2003)
http://www.fisi.polimi.it/en/research/research_structures/laboratories/54063
http://www.nobelprize.org/nobel_prizes/physics/laureates/2005/

Lucile Rutkowski, CES, Lecco, 2022 – lucile.rutkowski@univ-rennes1.fr

From pulsed lasers to combs

Mode locked femtosecond lasers



n	Mode index	10^4 – 10^6
f_{rep}	Repetition rate	50 MHz – 10 GHz
f_{ceo}	Carrier-envelop offset frequency	0 – f_{rep}

Optical frequency of the nth mode:

$$\nu_n = n\, f_{rep} + f_{ceo}$$

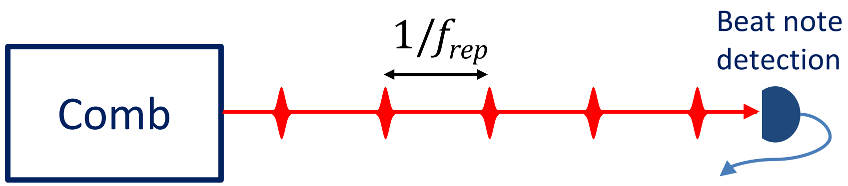
The perfect link between radio and optical frequency ranges

Stabilization

Repetition rate

Measurement: *fast detector*

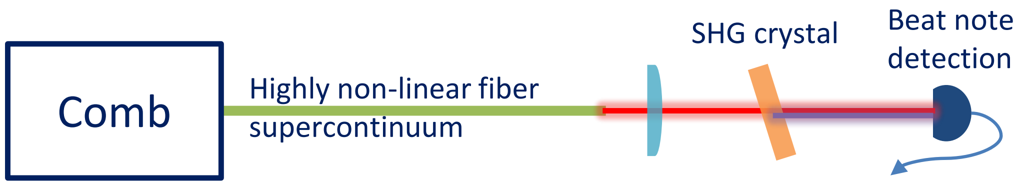
Actuators: *cavity length (stepper motor, PZT, EOM) and/or pump current*

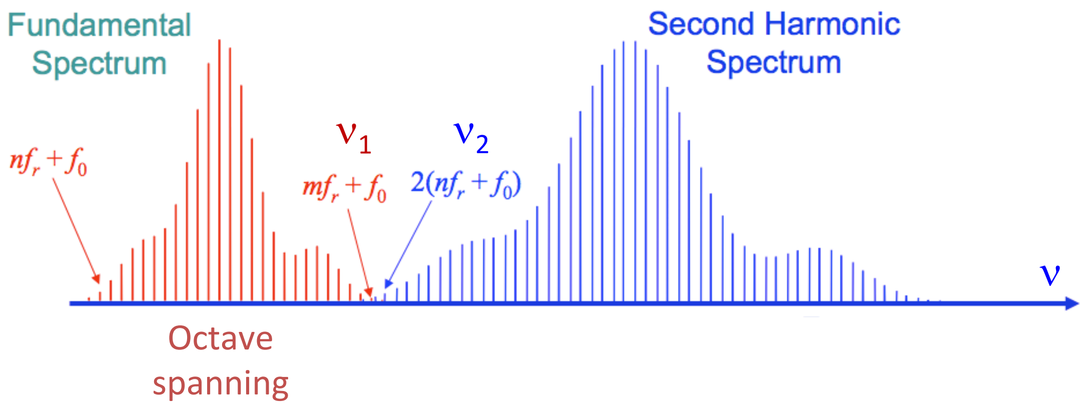


Offset frequency

Measurement: *f-2f interferometry*

Actuators: *oscillator pump current, intracavity dispersion and/or external A/EOM*



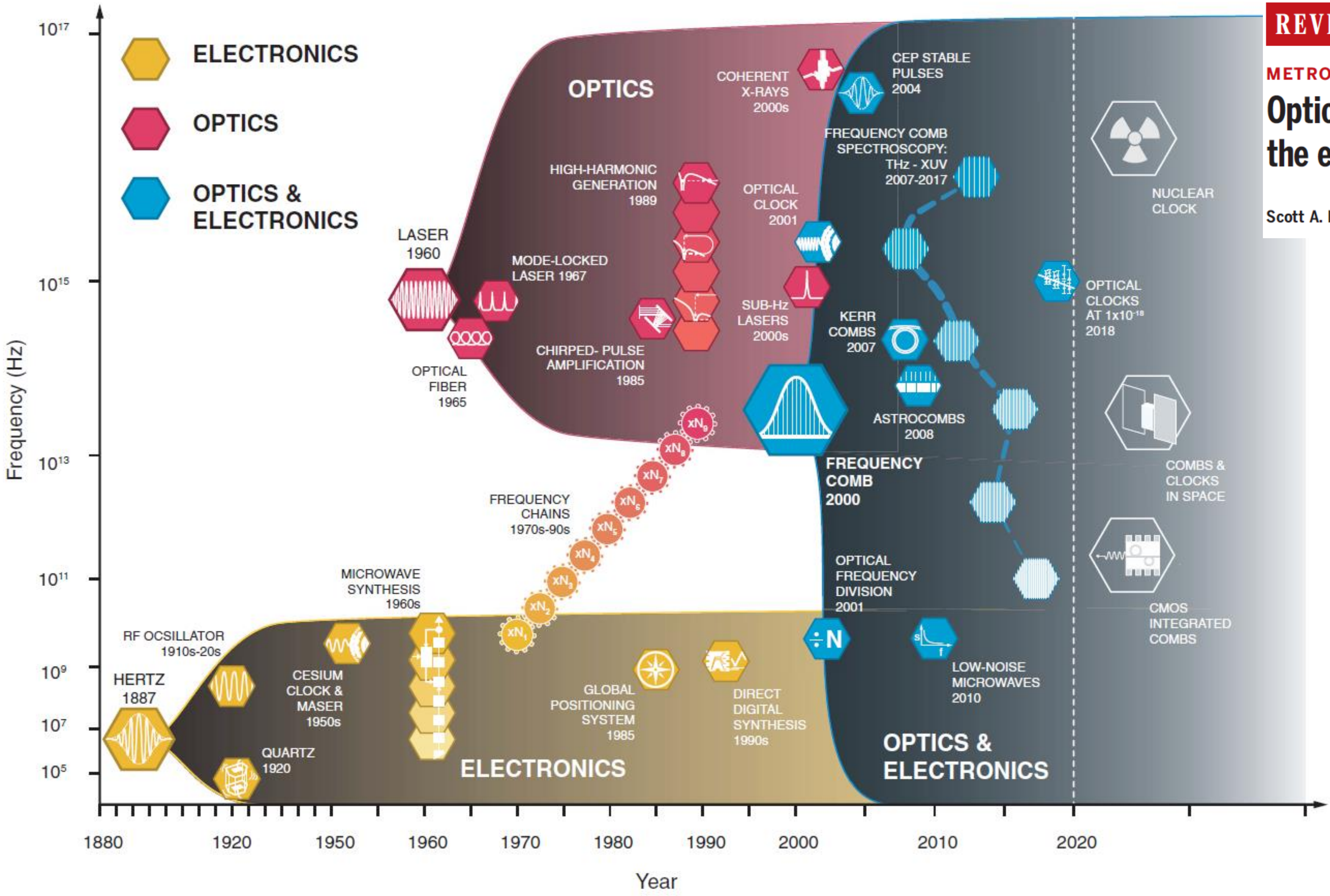


$m = 2n$

$$\nu_2 - \nu_1 = 2(nf_{rep} + f_0) - (mf_{rep} + f_0) = f_0$$

D.J. Jones *et al.*, Science **288**, 635 (2000)

Opto-electronics



REVIEW SUMMARY

METROLOGY

Optical frequency combs: Coherently uniting the electromagnetic spectrum

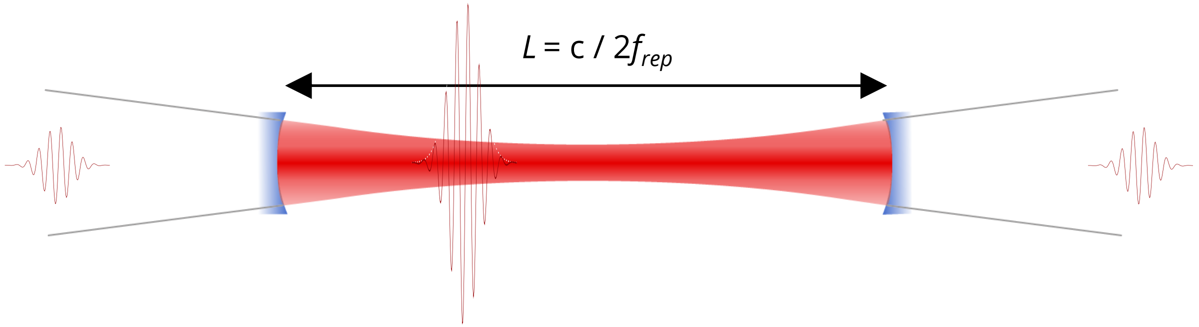
Scott A. Diddams*, Kerry Vahala*, Thomas Udem*

Science, **369**, 267 (2020)

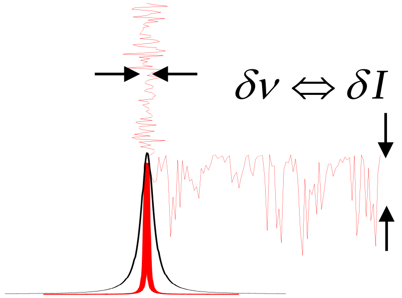
Cavity enhancement

Perfect comb-cavity matching

Time domain *Match the cavity length to the pulse separation*



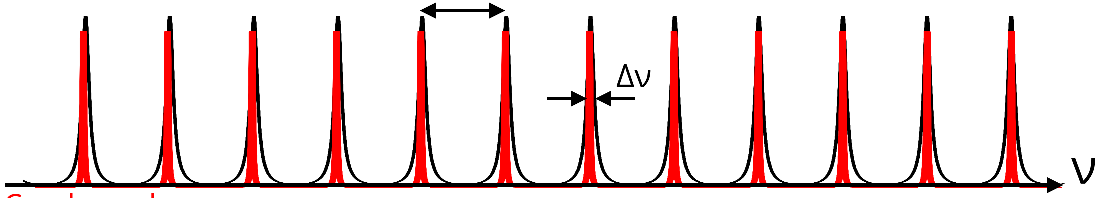
Frequency to amplitude noise conversion



Frequency domain *Match the cavity resonances to the comb modes*

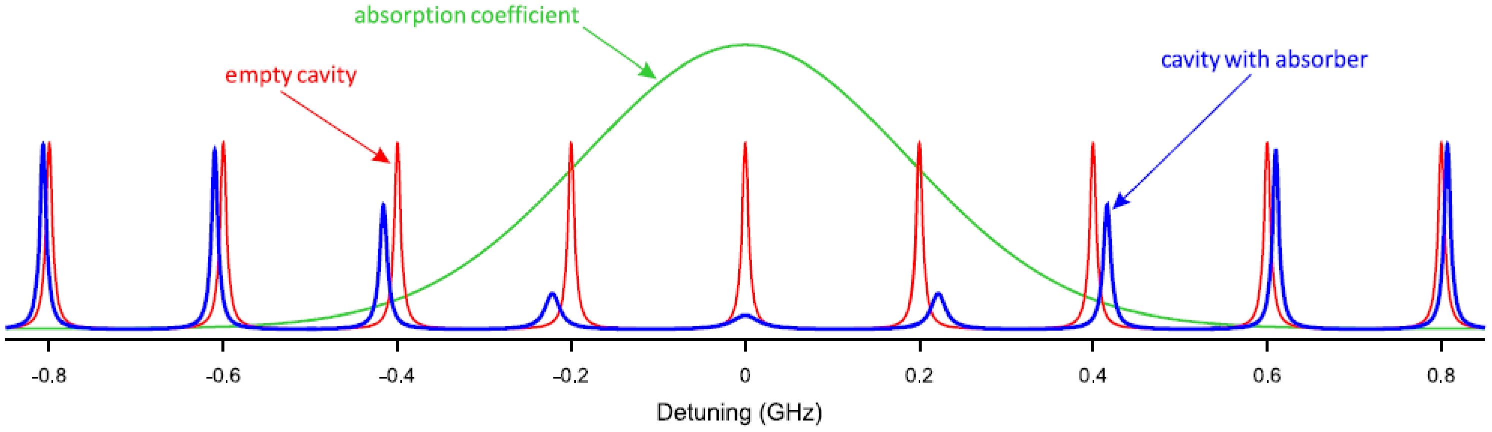
Cavity finesse: $F = FSR / \Delta\nu$

Cavity free spectral range: $FSR = c/2nL = f_{rep}$



Intra-cavity absorption

Molecular transition = absorption + local variation of the refractive index



Amplitude reduction

Resonance broadening

Shift of the resonant frequencies

One-dimensional frequency-based spectroscopy

Opt. Express 23(11), 14472 (2015)

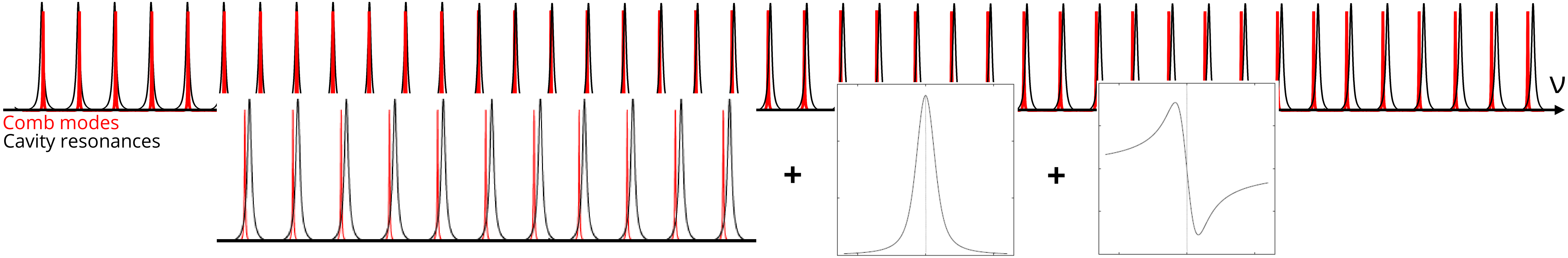
Agata Cygan,[1,*] Piotr Wcisło,[1] Szymon Wójtewicz,[1] Piotr Masłowski,[1] Joseph T. Hodges,[2] Roman Ciuryło,[1] and Daniel Lisak[1]

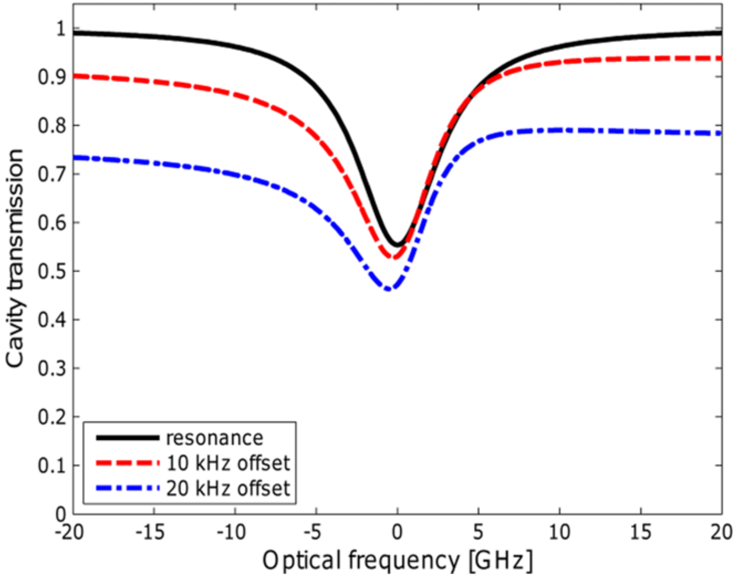
[1] *Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Torun, Grudziadzka 5, 87-100 Torun, Poland.*

[2] *National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, Maryland 20899, USA*

Intra-cavity dispersion

The FSR-f_{rep} matching cannot be perfect on the entire comb bandwidth.





Appl Phys B (2013) 110:163–175
DOI 10.1007/s00340-012-5024-7
Applied Physics B
Lasers and Optics

Cavity-enhanced optical frequency comb spectroscopy in the mid-infrared application to trace detection of hydrogen peroxide

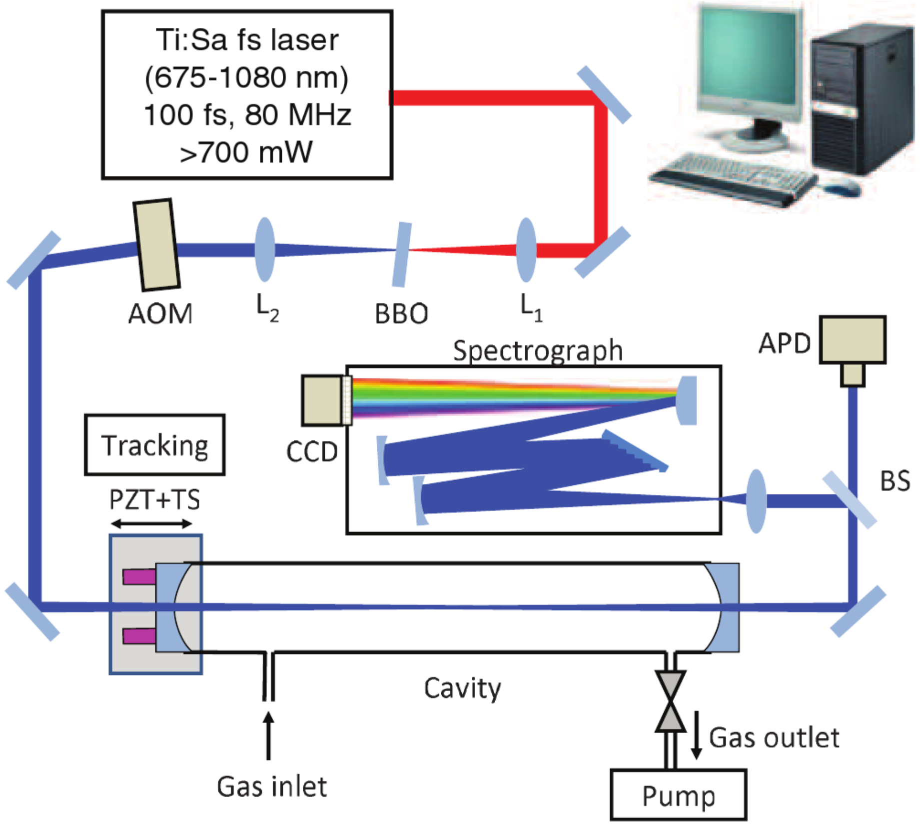
A. Foltynowicz · P. Masłowski · A.J. Fleisher · B.J. Bjork · J. Ye

Contents lists available at ScienceDirect
Journal of Molecular Spectroscopy
journal homepage: www.elsevier.com/locate/jms

Quantitative modeling of complex molecular response in coherent cavity-enhanced dual-comb spectroscopy

Adam J. Fleisher *, David A. Long, Joseph T. Hodges
Material Measurement Laboratory, National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899, USA

1D Dispersive spectrometers



1D dispersion

- Diffraction grating + CCD array
- Resolution > GHz
- Frequency calibration of the grating
- Spectral coverage – few nm
- Acquisition time – ms

Mode–locked cavity–enhanced absorption spectroscopy

Opt. Express **10**(19), 1033 (2002)

Titus Gherman and Daniele Romanini

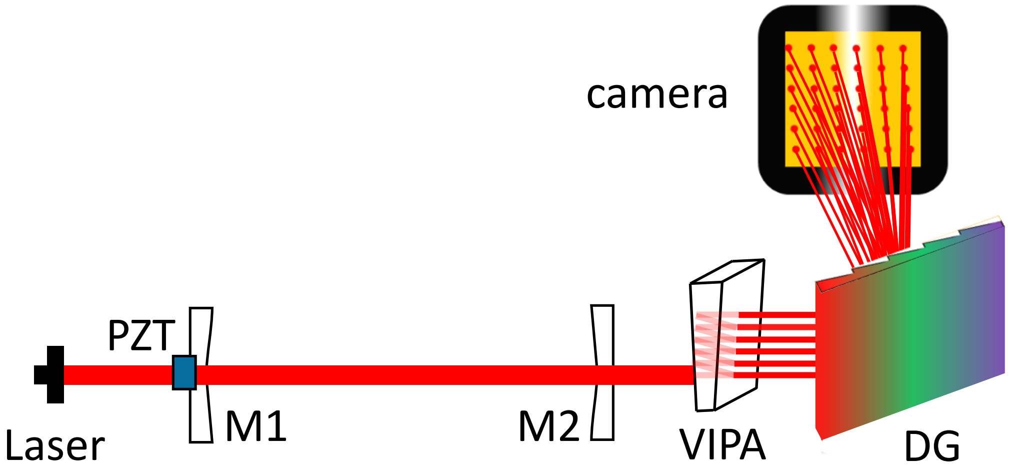
PHYSICAL REVIEW A **85**, 051804(R) (2012)

Cavity-enhanced multiplexed comb spectroscopy down to the photon shot noise

R. Grilli, G. Méjean, C. Abd Alrahman, I. Ventrillard, S. Kassi, and D. Romanini
Université de Grenoble 1 / CNRS, LIPhy UMR 5588, F-38041 Grenoble, France
(Received 8 February 2012; published 22 May 2012)

T. Gherman and D. Romanini, (2002)
R. Grilli *et al.*, Phys. Rev. A **85**, 051804 (2012)

2D Dispersive spectrometers



VIPA (NIR and MIR)

- Virtually Imaged Phased Array
  + orthogonal dispersion grating
  + camera
- Mode per mode resolution possible
- # spectral elements ~ # of pixels
- Acquisition time – ms

Nature **445**, 627 (2007) LETTERS

Molecular fingerprinting with the resolved modes of a femtosecond laser frequency comb

Scott A. Diddams[1], Leo Hollberg[1] & Vela Mbele[1,2,3]

Cavity-enhanced optical frequency comb spectroscopy: application to human breath analysis

Michael J. Thorpe, David Balslev-Clausen, Matthew S. Kirchner, and Jun Ye
JILA, National Institute of Standards and Technology and University of Colorado, Boulder, CO 80309-0440, USA
Department of Physics, University of Colorado, Boulder, CO 80309-0390, USA

Opt. Express **16**, 2387 (2008)

Chemical Physics Letters 468 (2009) 1–8
Contents lists available at ScienceDirect
ELSEVIER Chemical Physics Letters CPL FRONTIERS
journal homepage: www.elsevier.com/locate/cplett

FRONTIERS ARTICLE

Tomography of a supersonically cooled molecular jet using cavity-enhanced direct frequency comb spectroscopy

Michael J. Thorpe*, Florian Adler, Kevin C. Cossel, Marcio H.G. de Miranda, Jun Ye
JILA, National Institute of Standards and Technology and University of Colorado, Department of Physics, University of Colorado, Boulder, CO 80309-0440, USA

The Journal of Physical Chemistry Letters Letter
pubs.acs.org/JPCL

Mid-Infrared Time-Resolved Frequency Comb Spectroscopy of Transient Free Radicals

Adam J. Fleisher,*,†,‡ Bryce J. Bjork,† Thinh Q. Bui,§ Kevin C. Cossel,† Mitchio Okumura,*,§ and Jun Ye*,†
†JILA, National Institute of Standards and Technology and University of Colorado, Department of Physics, 440 UCB, Boulder, Colorado 80309, United States
‡Material Measurement Laboratory, National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, Maryland 20899, United States
§Arthur Amos Noyes Laboratory of Chemical Physics, Division of Chemistry and Chemical Engineering, California Institute of Technology, 1200 East California Boulevard, Pasadena, California 91125, United States

SCIENTIFIC REPORTS

OPEN

Broadband Optical Cavity Mode Measurements at Hz-Level Precision With a Comb-Based VIPA Spectrometer

Received: 18 December 2018
Accepted: 8 May 2019
Published online: 03 June 2019

Grzegorz Kowzan, Dominik Charczun, Agata Cygan, Ryszard S. Trawiński, Daniel Lisak & Piotr Masłowski

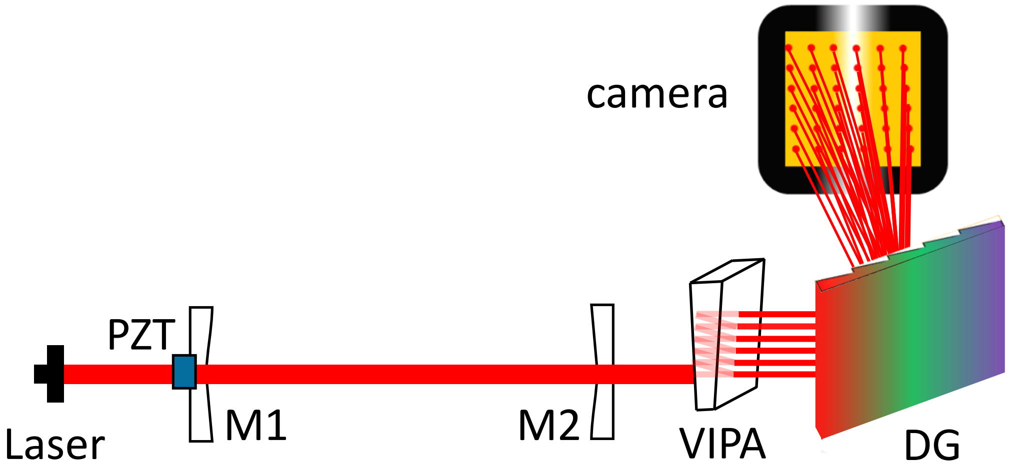
MOLECULAR PHYSICS
2020, VOL. 118, NO. 16, e1733116 (9 pages)
https://doi.org/10.1080/00268976.2020.1733116
Taylor & Francis
Taylor & Francis Group
Check for updates

NEW VIEW

A rapid, spatially dispersive frequency comb spectrograph aimed at gas phase chemical reaction kinetics

Frances C. Roberts[a], H. J. Lewandowski[a,b], Billy F. Hobson[a] and Julia H. Lehman[a]
[a]School of Chemistry, University of Leeds, Leeds, UK; [b]JILA and Department of Physics, University of Colorado and the National Institute of Standards and Technology, Boulder, CO, USA

2D Dispersive spectrometers



VIPA (NIR and MIR)

- Virtually Imaged Phased Array
  + orthogonal dispersion grating
  + camera
- Mode per mode resolution possible
- # spectral elements ~ # of pixels
- Acquisition time – ms

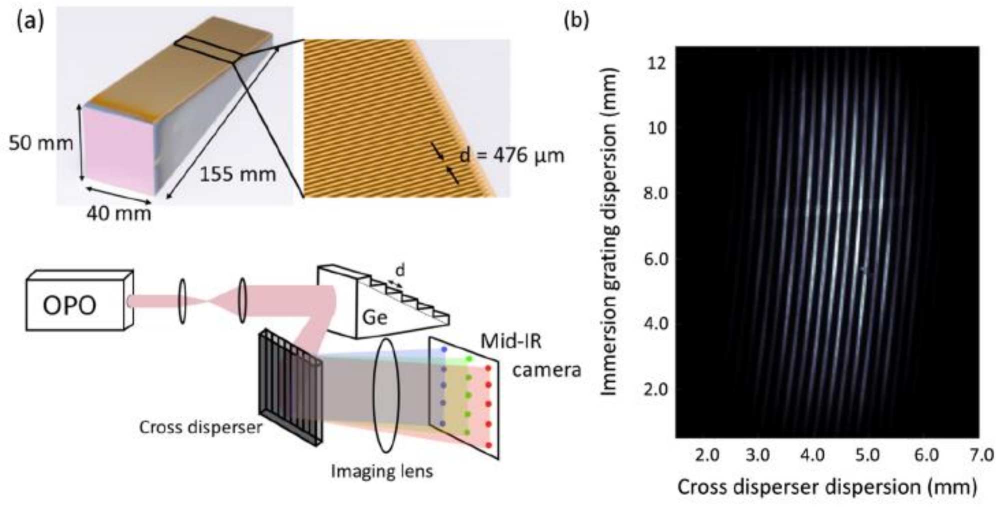
Immersion grating (10 μm)

Research Article | Vol. 27, No. 3 | 4 Feb 2019 | OPTICS EXPRESS 1911
Optics EXPRESS

Comb-resolved spectroscopy with immersion grating in long-wave infrared

K. Iwakuni,[1,*] T. Q. Bui,[1] J. F. Niedermeyer,[1] T. Sukegawa,[2] and J. Ye[1]

[1]JILA, National Institute of Standards and Technology and University of Colorado, and Department of Physics, University of Colorado, Boulder, CO 80309, USA
[2]Canon Inc., 20-2, Kiyohara-Kogyodanchi, Utsunomiya, Tochigi 321-3292, Japan



Vernier filtering approaches

- Use the cavity as a frequency filter
- Mismatch between *FSR* and f_{rep}

photonics MDPI

Review

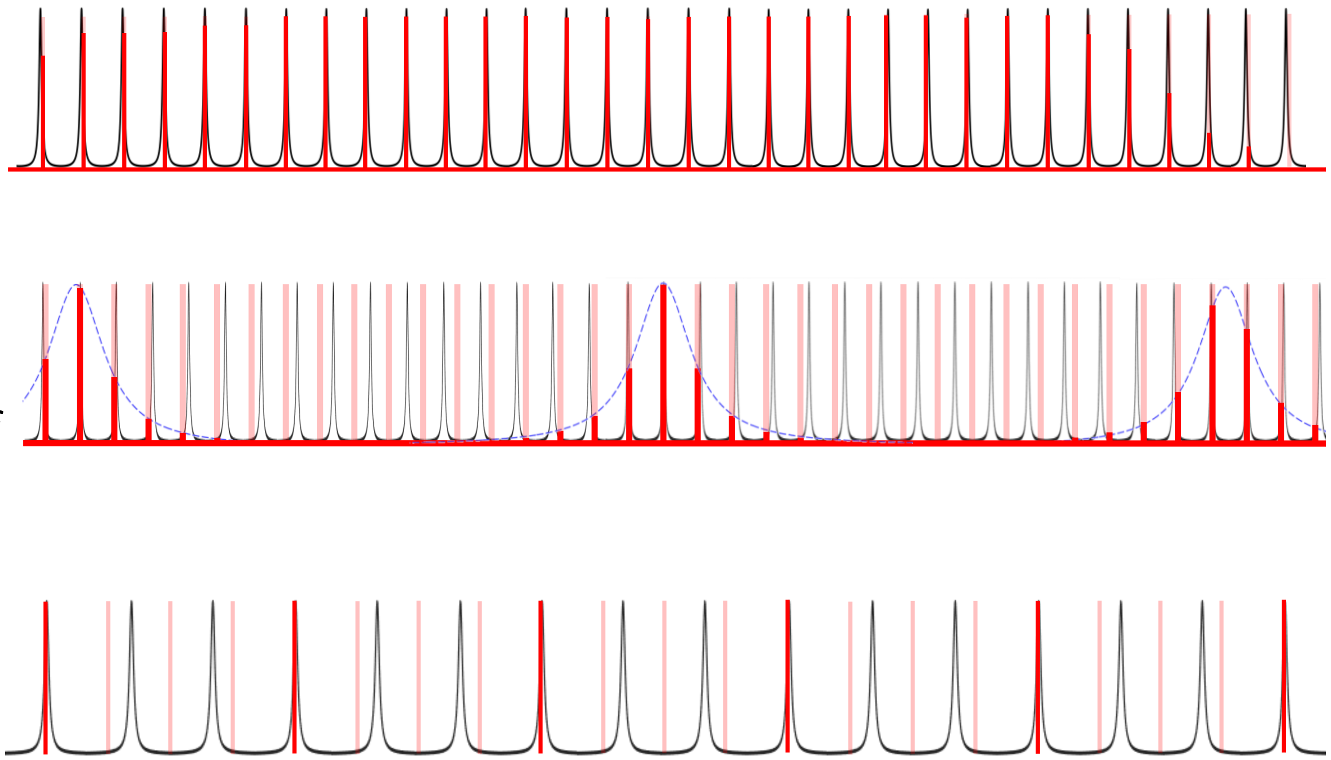
Cavity-Enhanced Frequency Comb Vernier Spectroscopy

Chuang Lu [1], Jerome Morville [2], Lucile Rutkowski [3], Francisco Senna Vieira [1] and Aleksandra Foltynowicz [1,*]

FSR = f_{rep}

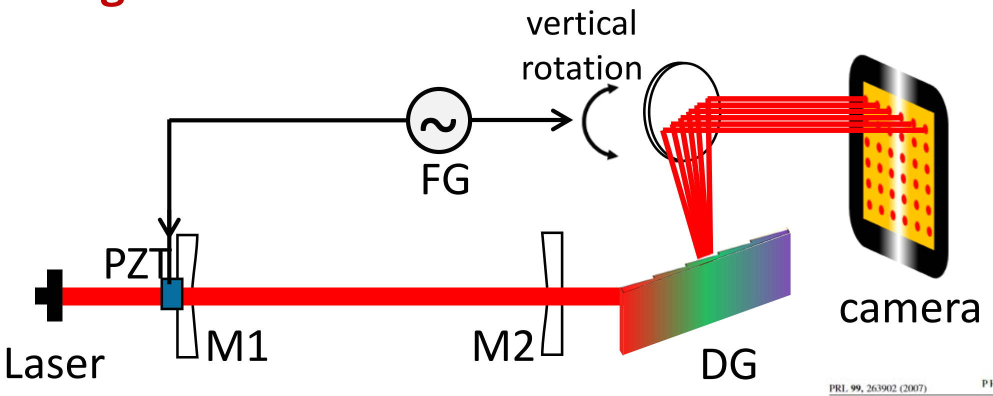
FSR = f_{rep} + df

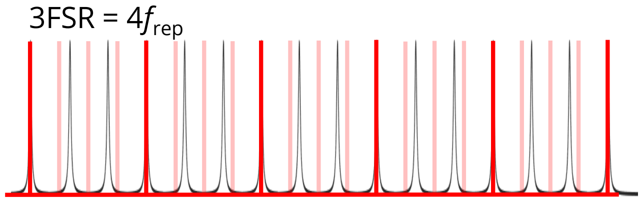
3FSR = 4f_{rep}



Mode resolved Vernier

Using a femtosecond laser





PRL 99, 263902 (2007) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2007

Frequency Comb Vernier Spectroscopy for Broadband, High-Resolution, High-Sensitivity Absorption and Dispersion Spectra

Christoph Gohle,* Björn Stein,† Albert Schliesser, Thomas Udem, and Theodor W. Hänsch
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, D-85748 Garching, Germany

Vernier in mode per mode filtering

- Spectral coverage : entire comb
- Comb mode resolution
- Acquisition time < sec
- Sensitivity limited by intensity noise

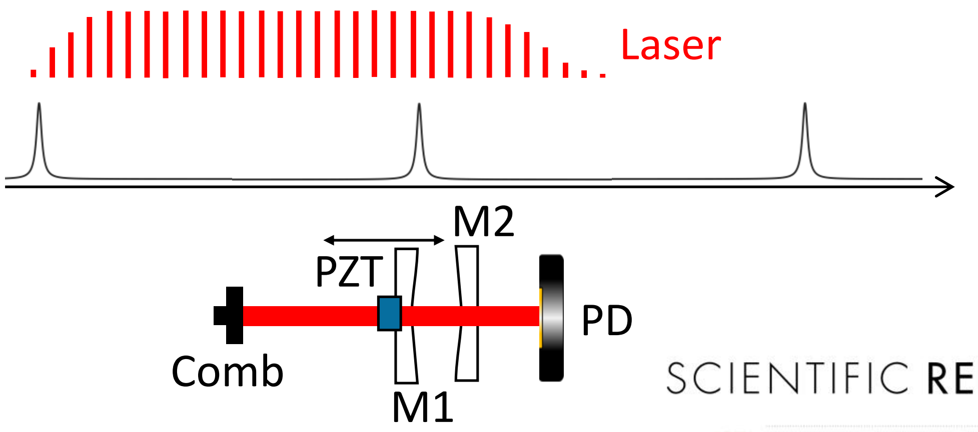
ACS Photonics

pubs.acs.org/journal/apchd5 Article

Cavity-Enhanced Vernier Spectroscopy with a Chip-Scale Mid-Infrared Frequency Comb

Lukasz A. Sterczewski,*,‖ Tzu-Ling Chen,‖ Douglas C. Ober, Charles R. Markus, Chadwick L. Canedy, Igor Vurgaftman, Clifford Frez, Jerry R. Meyer, Mitchio Okumura,* and Mahmood Bagheri*

Using micro-cavities

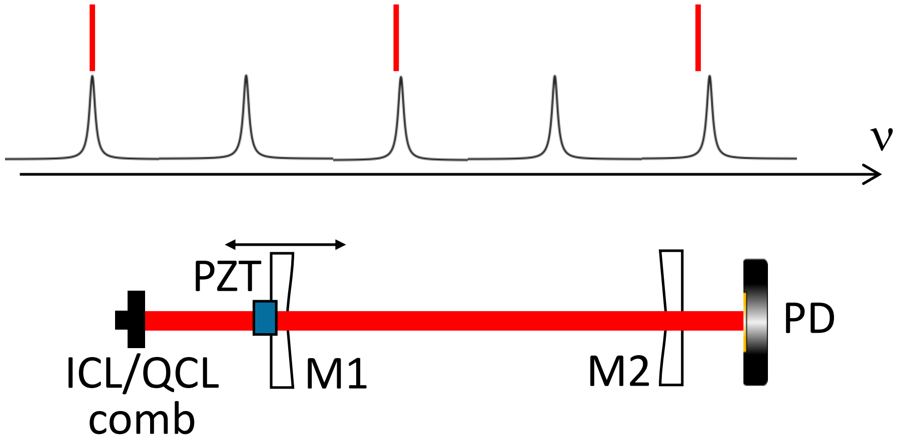


SCIENTIFIC REPORTS

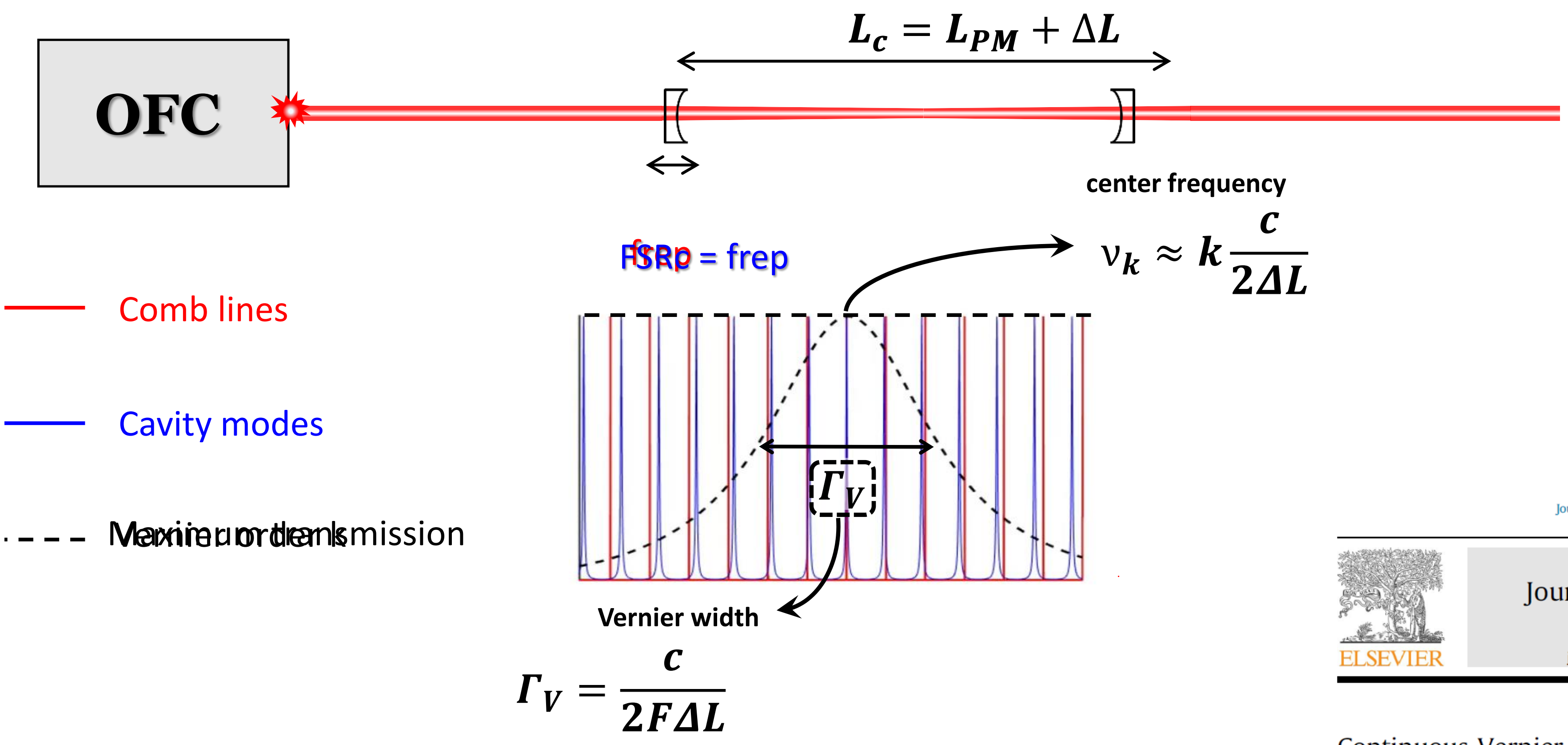
OPEN **Scanning micro-resonator direct-comb absolute spectroscopy**

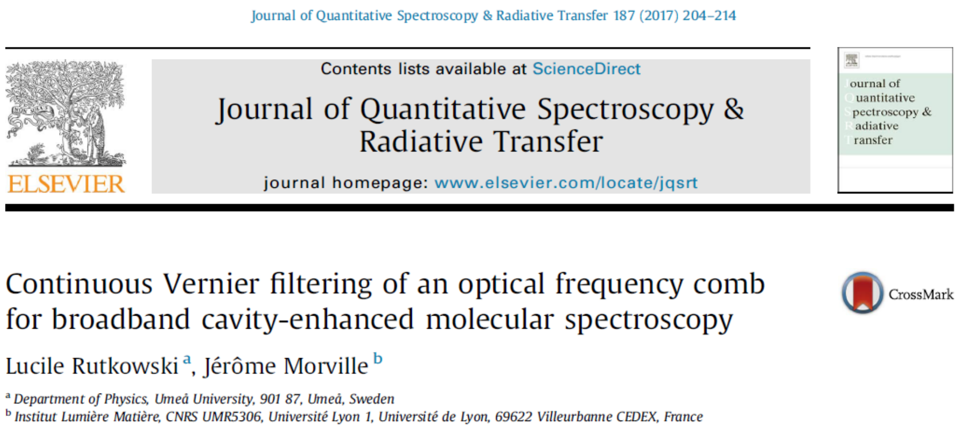
Alessio Gambetta[1,2], Marco Cassinerio[1,3], Davide Gatti[2], Paolo Laporta[1,2] & Gianluca Galzerano[1,2]

Using QCL-combs



Continuous filtering




Journal of Quantitative Spectroscopy & Radiative Transfer 187 (2017) 204–214

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

ELSEVIER

Continuous Vernier filtering of an optical frequency comb for broadband cavity-enhanced molecular spectroscopy

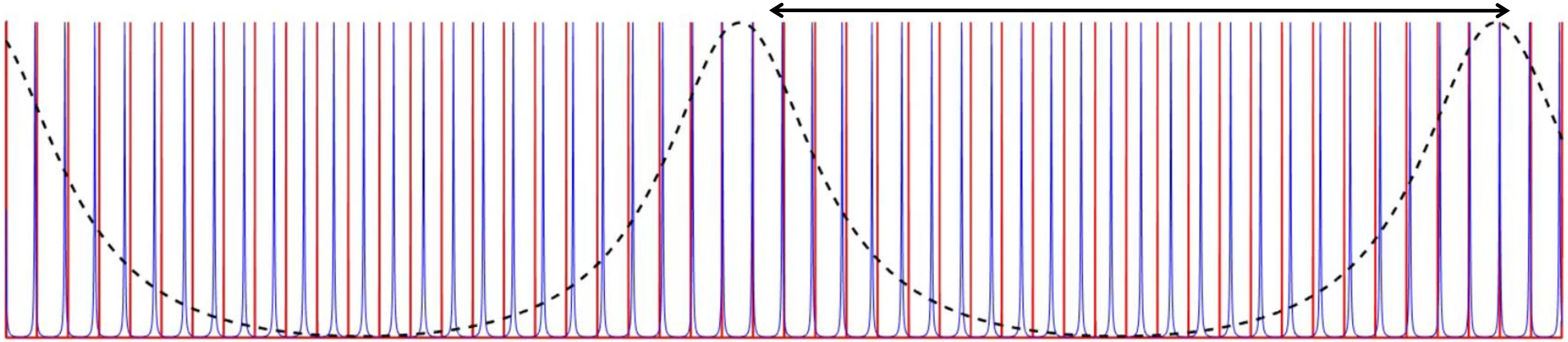
CrossMark

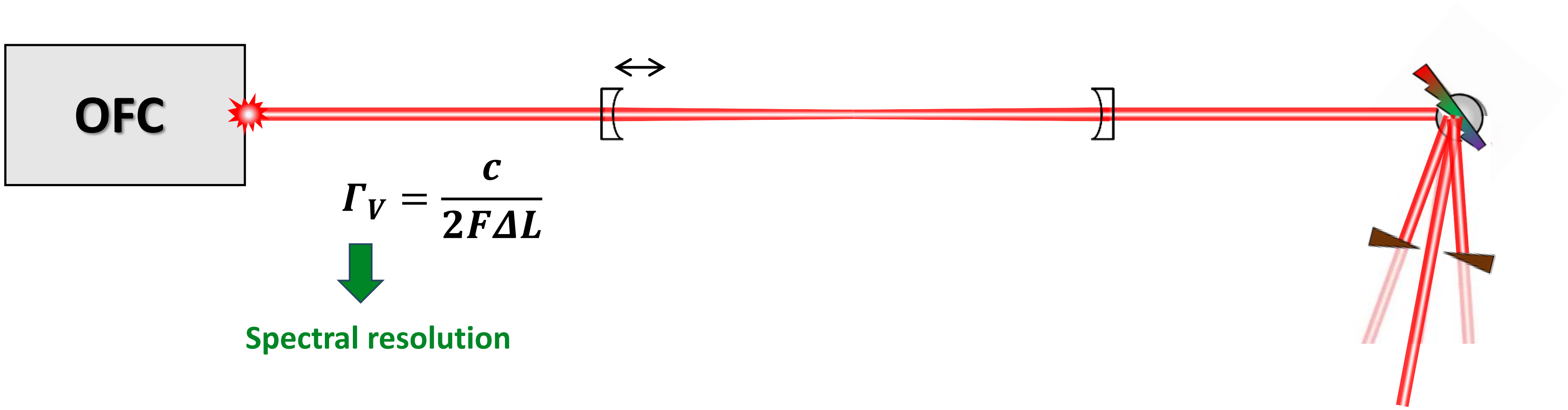
Lucile Rutkowski [a], Jérôme Morville [b]

[a] Department of Physics, Umeå University, 901 87, Umeå, Sweden
[b] Institut Lumière Matière, CNRS UMR5306, Université Lyon 1, Université de Lyon, 69622 Villeurbanne CEDEX, France

Continuous filtering

$$FSR_V = \frac{L_{PM}}{\Delta L} FSR_c$$ ➡ THz





$$\Gamma_V = \frac{c}{2F\Delta L}$$

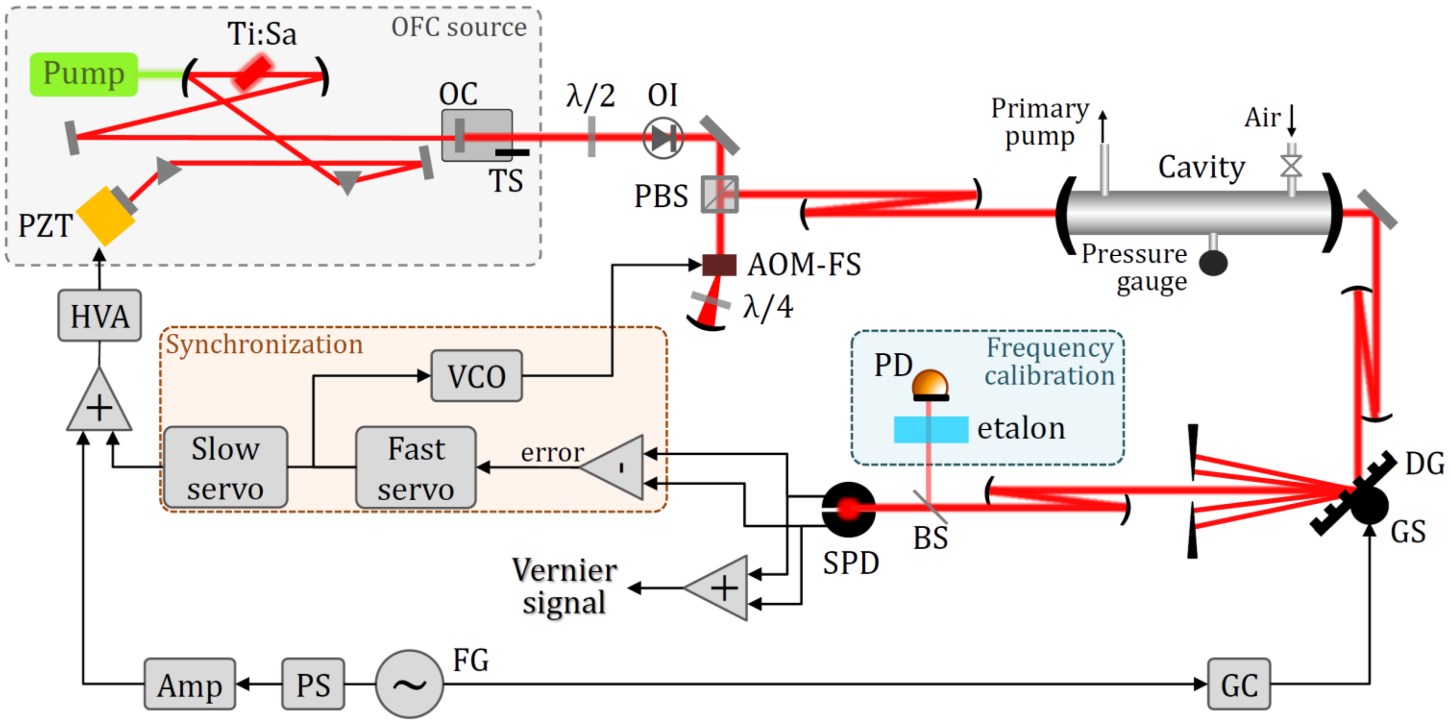
⬇ Spectral resolution

Vernier in continuous filtering

- Spectral coverage : entire comb
- Tunable resolution > $5f_{rep}$
- Acquisition time ~ sec
- Immune to intensity noise
- Require external frequency calibration

Discharge spectroscopy

ILM INSTITUT LUMIÈRE MATIÈRE



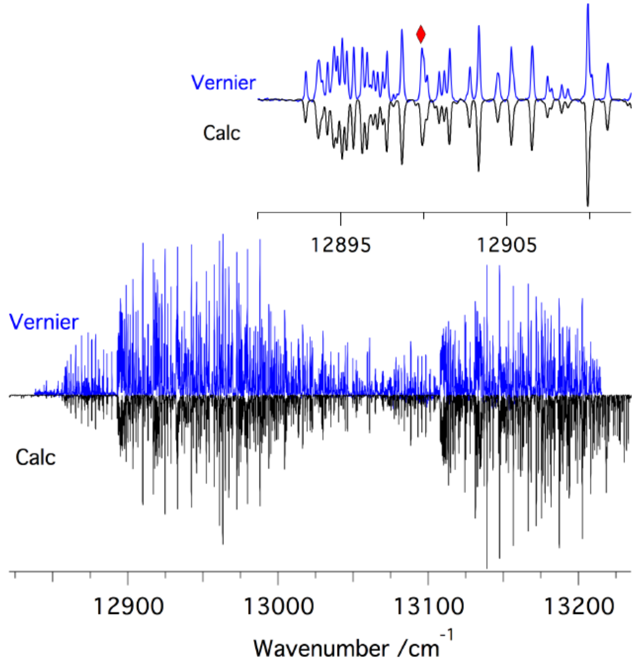


Figure 8. Comparison between Vernier spectrum (upper (blue) trace) and PGOPHER simulation of the $^{14}N_2$ B-A (2-0) band (black trace). The discharge was operating with 0.5 Torr in pure N_2, with 50 mA DC current; the simulation was performed setting T = 380 K, and a Gaussian FWHM of 0.18 cm^{-1}. The red diamond highlights an overlap of 3 lines (see Fig 7).

photonics MDPI

Review

Cavity-Enhanced Frequency Comb Vernier Spectroscopy

Chuang Lu [1], Jerome Morville [2], Lucile Rutkowski [3], Francisco Senna Vieira [1] and Aleksandra Foltynowicz [1,*]

Journal of Quantitative Spectroscopy & Radiative Transfer 219 (2018) 127–141

Contents lists available at ScienceDirect

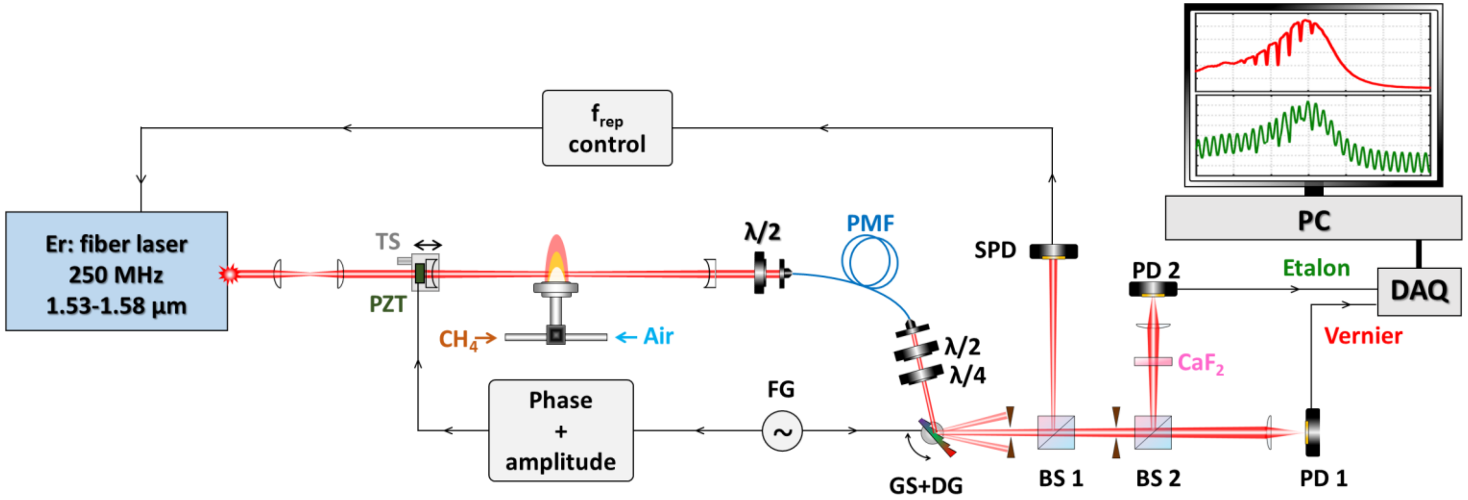
ELSEVIER Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

The spectrum of N_2 from 4,500 to 15,700 cm^{-1} revisited with PGOPHER

Colin M. Western [a], Luke Carter-Blatchford [a], Patrick Crozet [b], Amanda J. Ross [b,*], Jérôme Morville [b], Dennis W. Tokaryk [c]

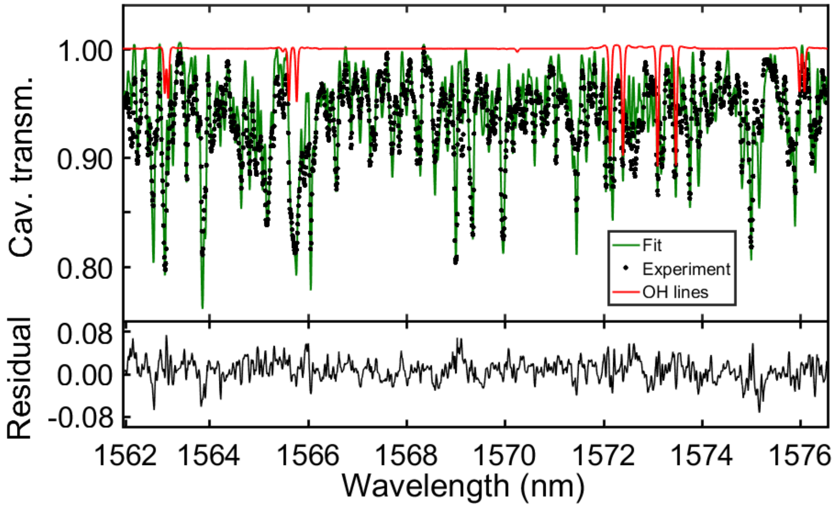
NIR detection in a flame



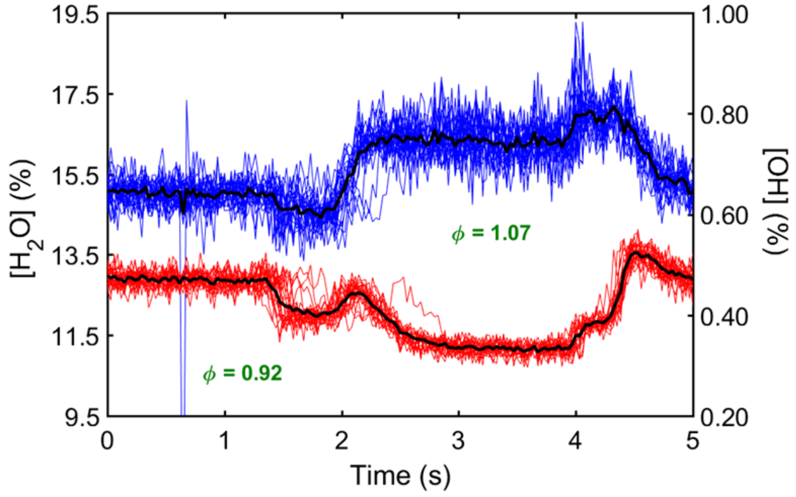
Flat flame burner*
- Flame diameter = **3.8 cm**
- Flame temperature ~**1950 K**

Measurements at stoichiometry
- CH_4 flow rate = **950 mL/min**
- Air flow rate = **9050 mL/min**

- Background spectrum recorded with flame off
- H_2O and OH radical transitions



[H_2O] and **[OH]** overlapped cycles and **averages**



Research Article Vol. 27, No. 21 / 14 October 2019 / Optics Express 29521
Optics EXPRESS

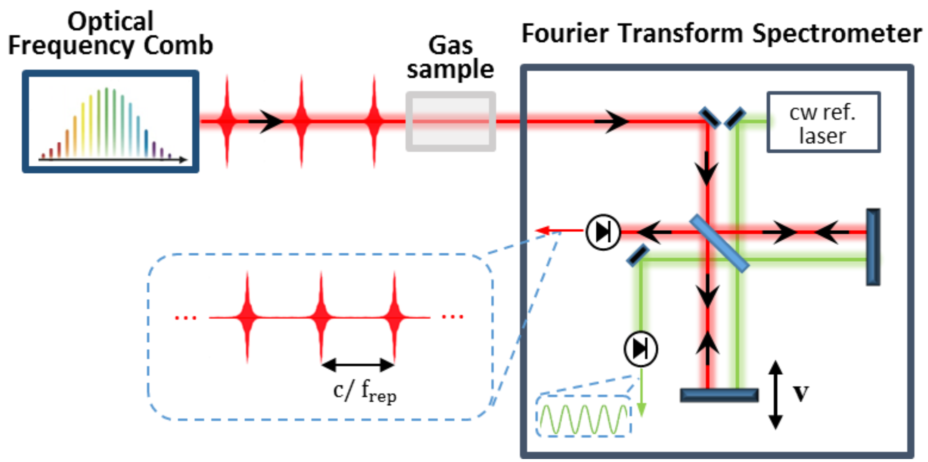
Time-resolved continuous-filtering Vernier spectroscopy of H_2O and OH radical in a flame

CHUANG LU,[1,3] FRANCISCO SENNA VIEIRA,[1,3] FLORIAN M. SCHMIDT,[2] AND ALEKSANDRA FOLTYNOWICZ[1,*]

[1]Department of Physics, Umeå University, 901 87 Umeå, Sweden
[2]Department of Applied Physics and Electronics, Umeå University, 901 87 Umeå, Sweden

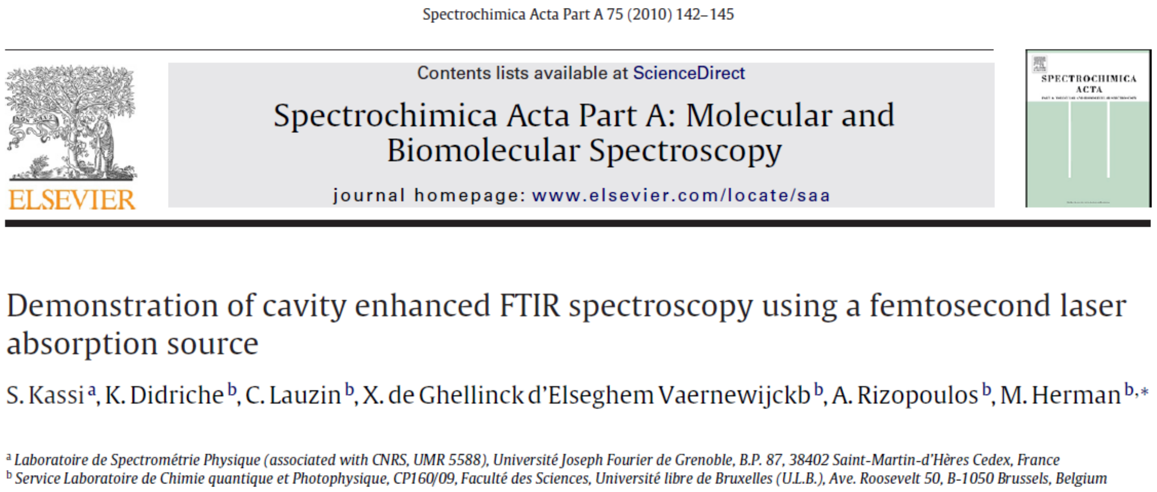
Fourier transform approaches

Mechanical FTS
Michelson interferometer



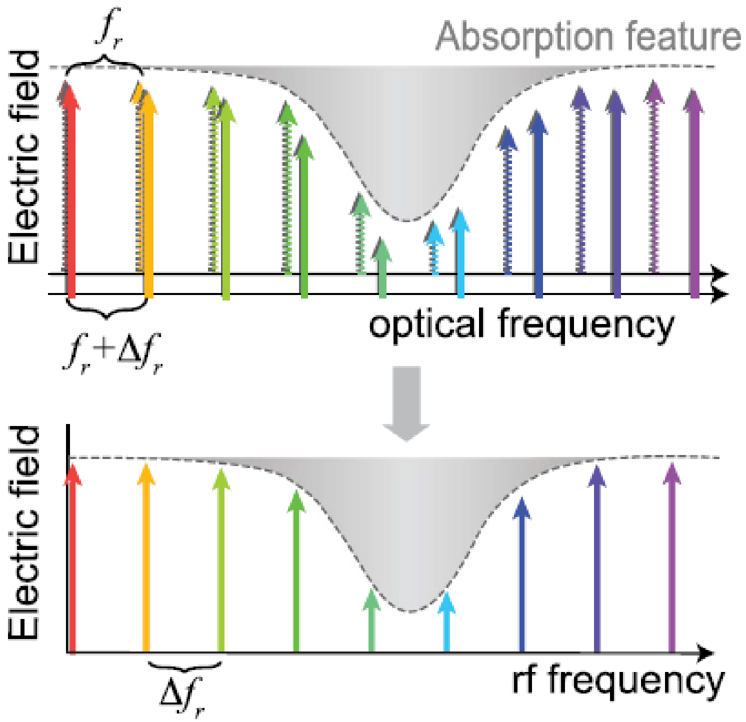
Measurement in optical path difference (OPD)

- Interferogram + FFT
- Single detector
- Comb modes resolution possible
- Spectral coverage – entire comb range



Dual comb spectrometers

FTS without mechanical movement, instead two combs with different repetition rates



Time domain measurement

- Interferogram + abs(FFT)
- Single detector
- Comb modes resolution
- Spectral coverage – entire comb range
- Acquisition time – ms

Review Article — Vol. 3, No. 4 / April 2016 / *Optica* 414

optica

Dual-comb spectroscopy

IAN CODDINGTON,[1,*] NATHAN NEWBURY,[1,2] AND WILLIAM SWANN[1]

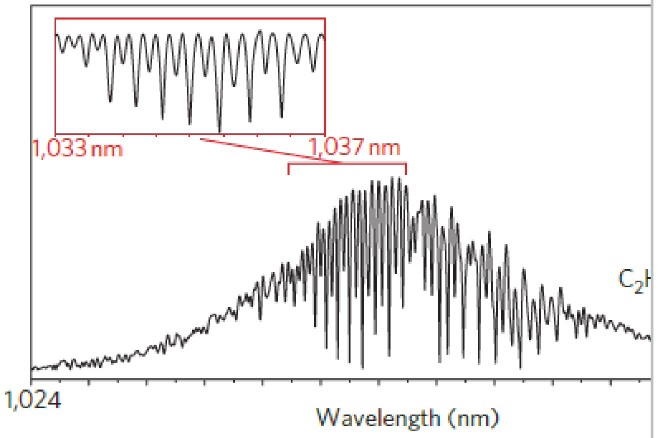
[1]*National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA*

Cavity-enhanced DCS

nature photonics
LETTERS
PUBLISHED ONLINE: 29 NOVEMBER 2009 | DOI: 10.1038/NPHOTON.2009.217

Cavity-enhanced dual-comb spectroscopy

Birgitta Bernhardt[1], Akira Ozawa[1], Patrick Jacquet[2], Marion Jacquey[2], Yohei Kobayashi[3],
Thomas Udem[1], Ronald Holzwarth[1,4], Guy Guelachvili[2], Theodor W. Hän



Coherent cavity-enhanced dual-comb spectroscopy

Adam J. Fleisher,[1,*] David A. Long,[1,3] Zachary D. Reed,[1] Joseph T
F. Plusquellic[2]
[1]Material Measurement Laboratory, National Institute of Standards and Technolo
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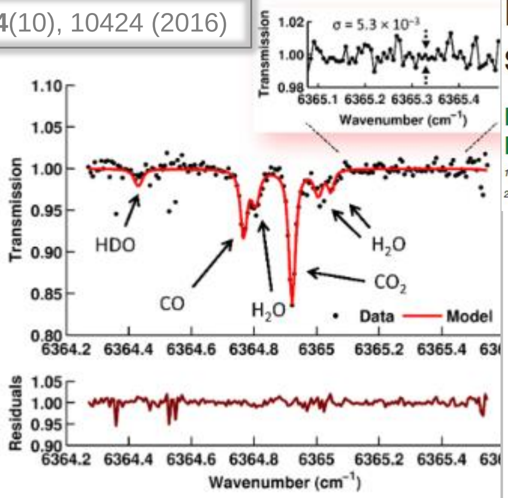
Colorado, 80305, USA

Opt. Express **24**(10), 10424 (2016)



Research Article
Vol. 6, No. 1 / January 2019 / Optica 28
optica

Broadband coherent cavity-enhanced dual-comb spectroscopy

Nazanin Hoghooghi,[1,*] Robert J. Wright,[1] Amanda S. Makowiecki,[1] William C. Swann,[2]
Eleanor M. Waxman,[2] Ian Coddington,[2] and Gregory B. Rieker[1]
[1]Precision Laser Diagnostics Laboratory, University of Colorado, Boulder, Colorado 80309, USA
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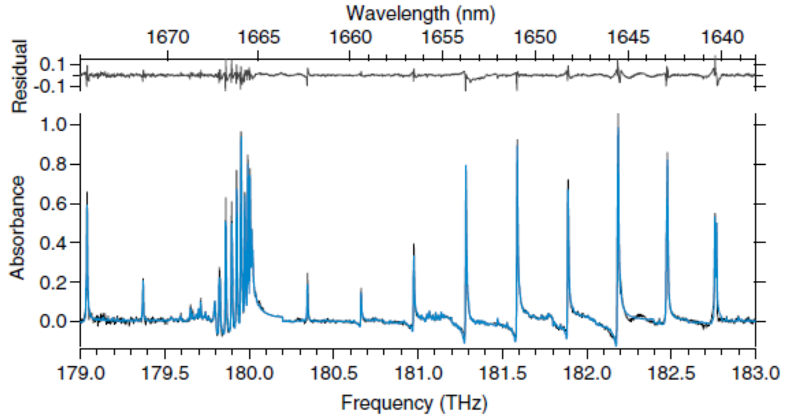
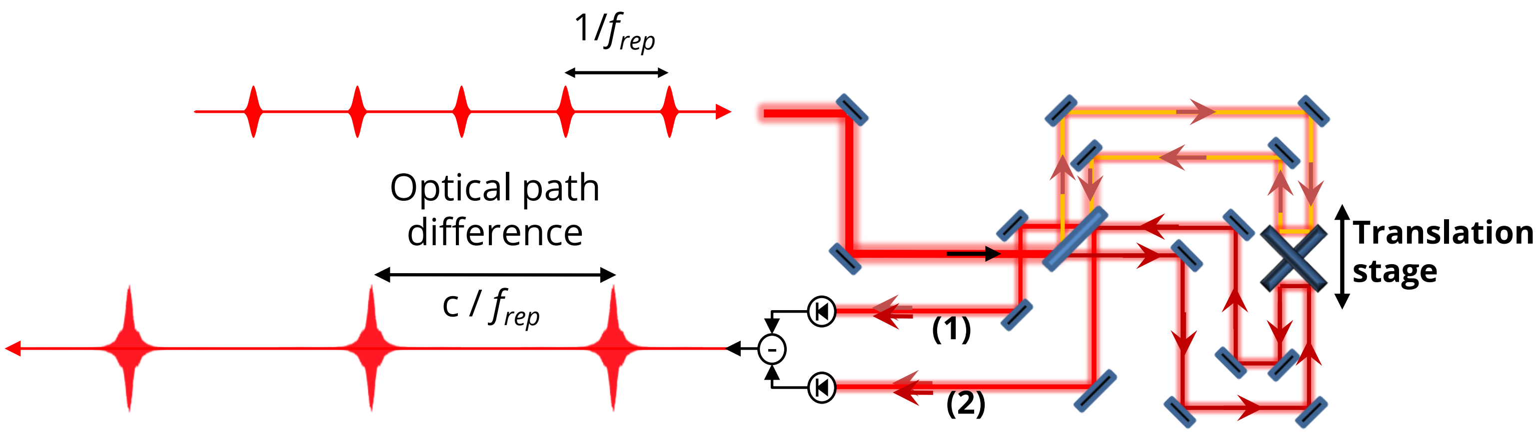


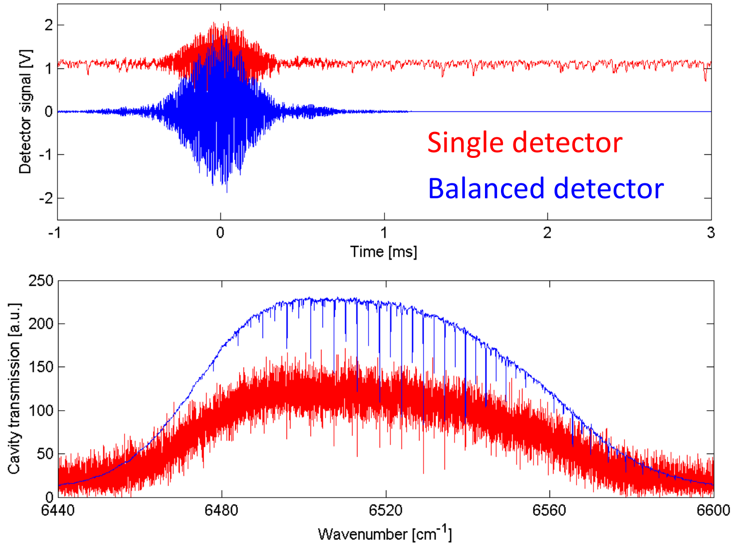
Mechanical FTS

Fast-scanning comb-based mechanical FTS



- Fast-scanning interferometer (1 m/s)
- 1 GHz resolution in 0.4 s
- Stabilized cw reference laser for OPD calibration

Auto-balanced detection



PRL 107, 233002 (2011) Selected for a Viewpoint in Physics PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2011

Quantum-Noise-Limited Optical Frequency Comb Spectroscopy

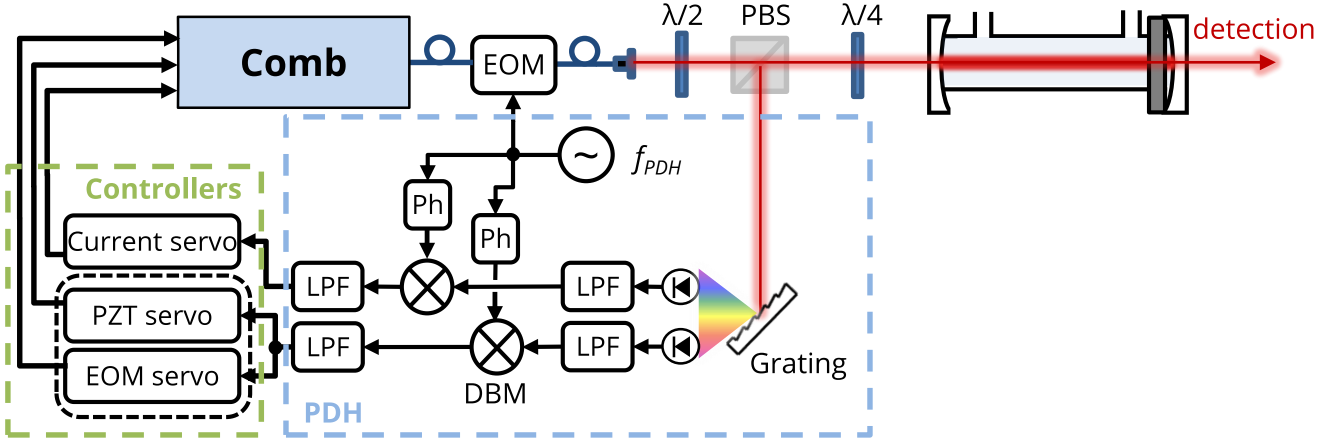
Aleksandra Foltynowicz,* Ticijana Ban,† Piotr Masłowski,‡ Florian Adler,§ and Jun Ye
JILA, National Institute of Standards and Technology and University of Colorado, Department of Physics, University of Colorado, Boulder, Colorado 80309-0440, USA

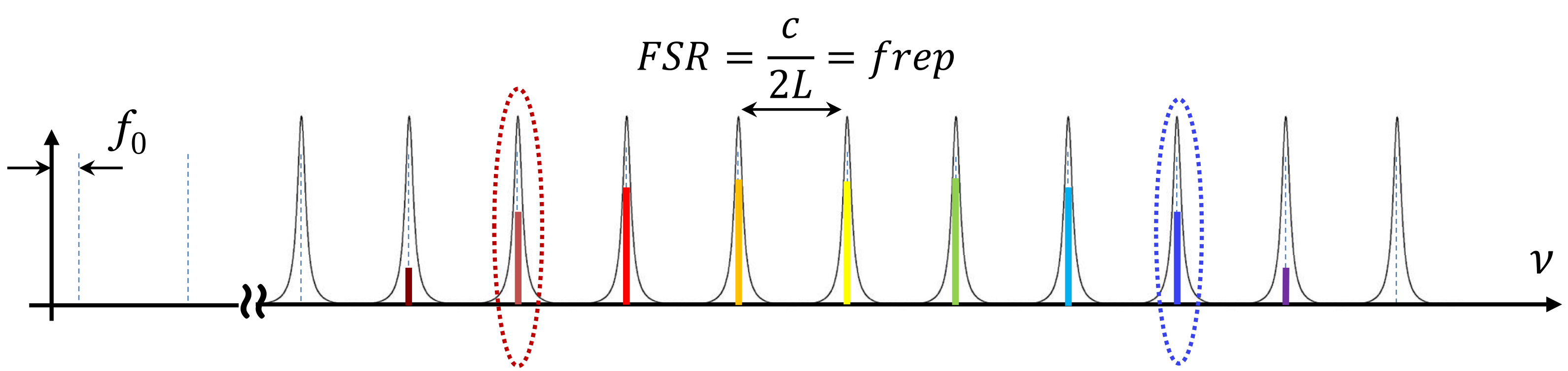
Comb-cavity coupling

Continuous transmission necessary:
2-point Pound-Drever-Hall locking technique

2nd locking point
Pump current ~150 kHz

1st locking point
PZT ~6 kHz; EOM ~500 kHz





Error signal #1
$\delta\nu_K = \mathbf{K}\ \delta f_{rep} + \delta f_{ceo}$

Error signal #2
$\delta\nu_P = \mathbf{P}\ \delta f_{rep} + \delta f_{ceo}$

Transmitted bandwidth usually limited by the cavity dispersion

E. D. Black, Am. J. Phys. **69**(1), 79 (2001)
A. Foltynowicz *et al.*, Appl. Phys. B **110**, 2 (2013)

Detection in a flame

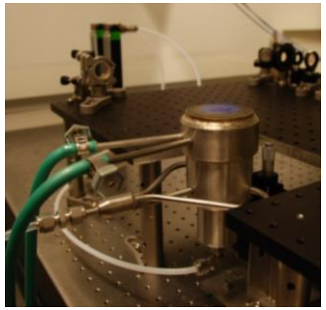
Premixed methane/air
flat flame burner

Cavity for flame measurement:

- finesse 150
- length 60 cm, FSR 250 MHz
- open air

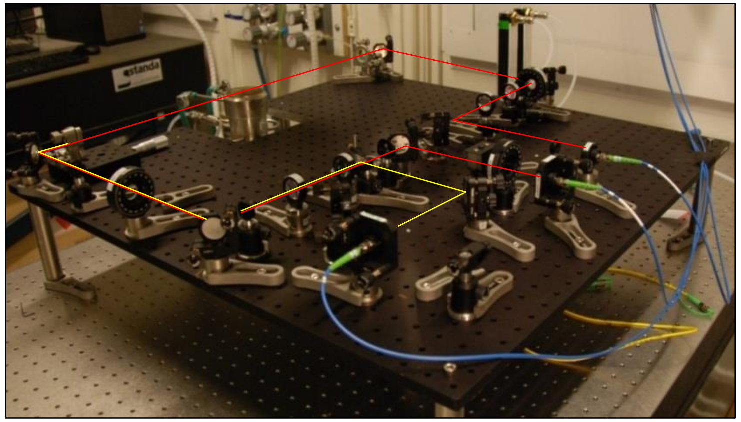
FTS:

- Resolution 1 GHz in 0.4 sec

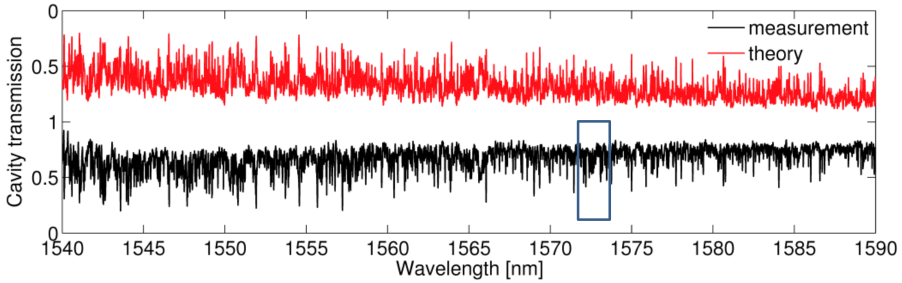


High-temperature water and OH spectra in a flame

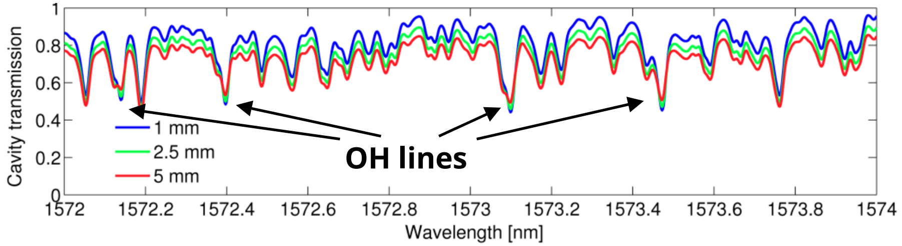
Remote operation



High temperature spectrum (2000 K)



Spectra at different heights above the burner

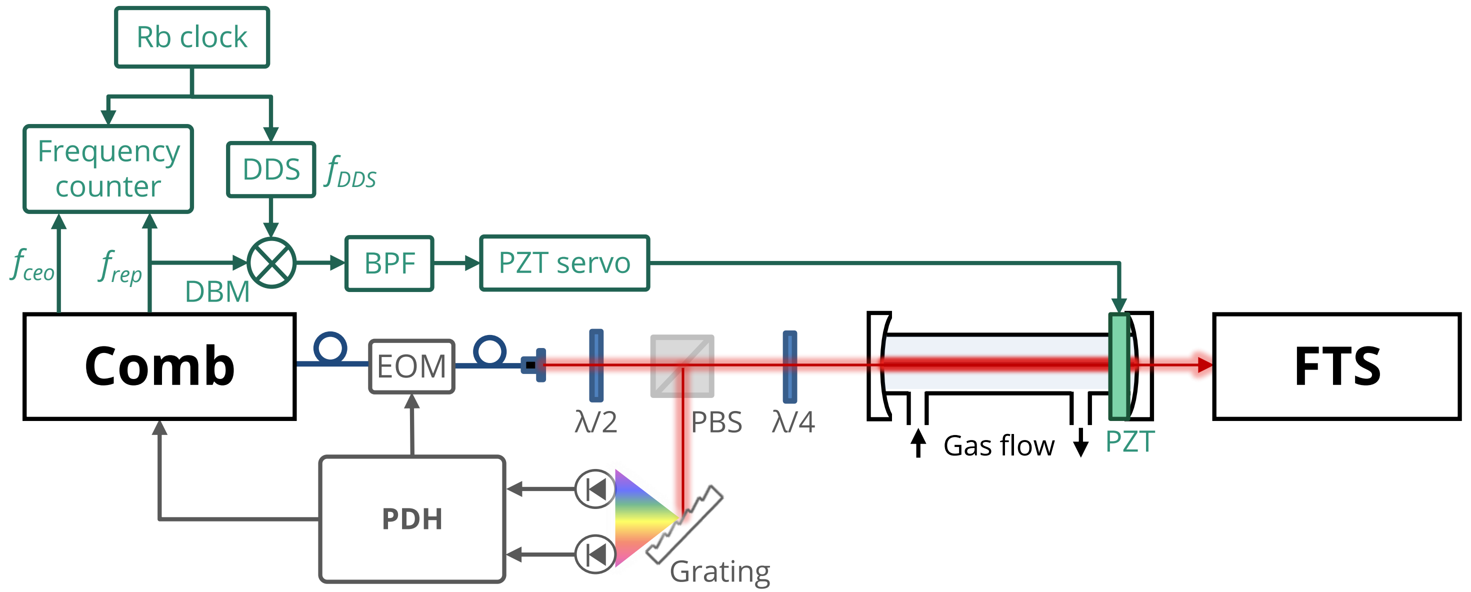


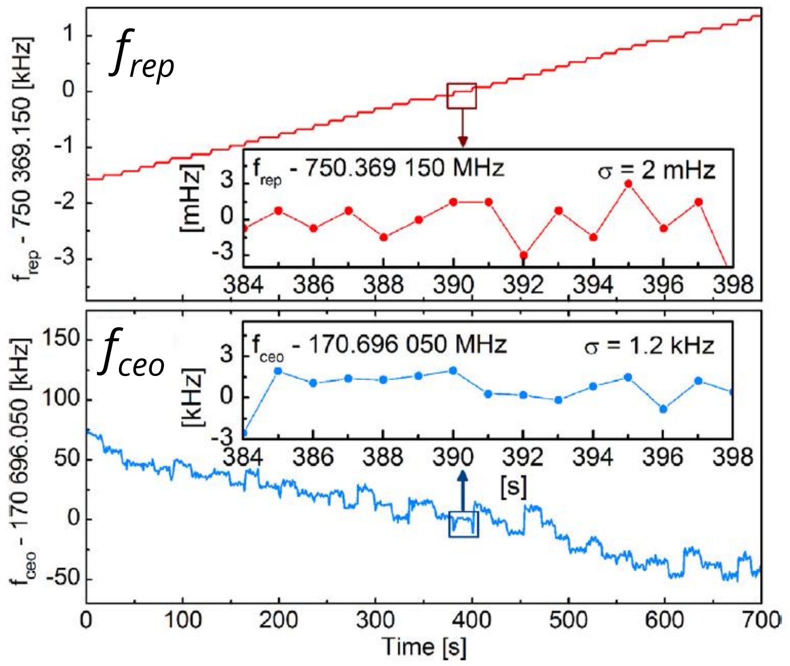
C. Abd Alrahman *et al.*, Opt. Express **22**, 13889 (2014)

Absolute comb stabilization

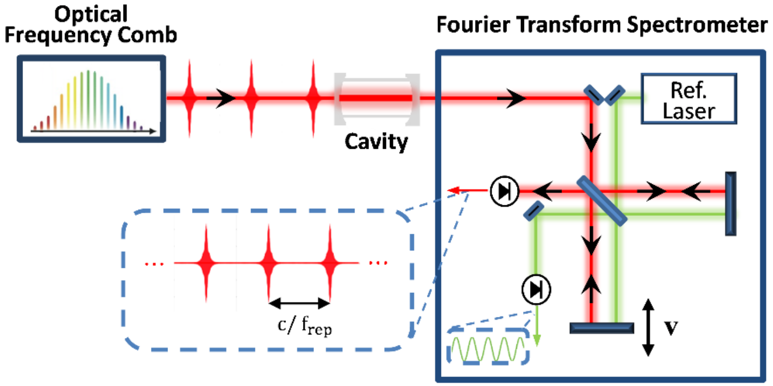
Stabilization of the absolute values of f_{rep} and f_{ceo}

➢ Require stabilization of the cavity length



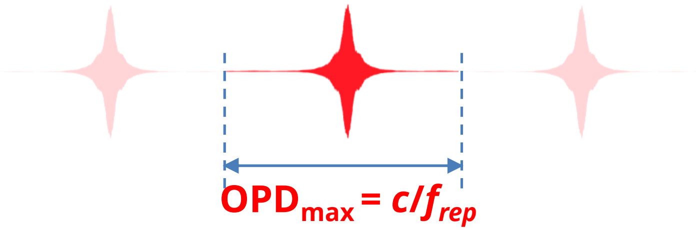


Sub-nominal resolution

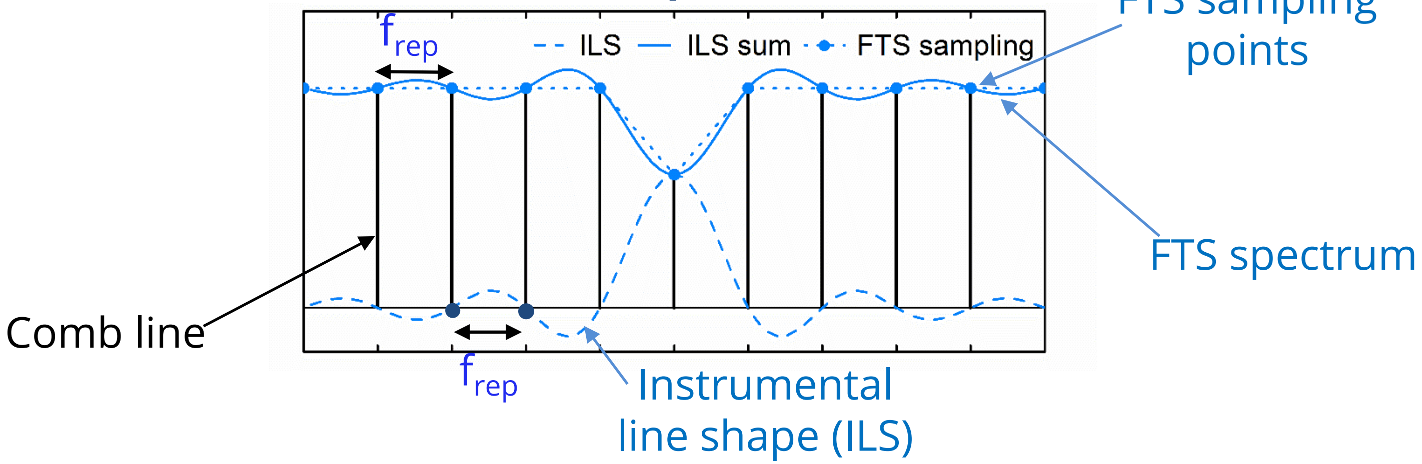


Train of bursts separated by c/f_{rep}

Single-burst interferogram
Nominal resolution matched to f_{rep}
Contains all spectral information



FTS spectrum



PHYSICAL REVIEW A **93**, 021802(R) (2016)

Surpassing the path-limited resolution of Fourier-transform spectrometry with frequency combs

Piotr Maslowski,[1] Kevin F. Lee,[2] Alexandra C. Johansson,[3] Amir Khodabakhsh,[3] Grzegorz Kowzan,[1] Lucile Rutkowski,[3] Andrew A. Mills,[2] Christian Mohr,[2] Jie Jiang,[2] Martin E. Fermann,[2] and Aleksandra Foltynowicz[3,*]
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Journal of Quantitative Spectroscopy & Radiative Transfer 204 (2018) 63–73

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Optical frequency comb Fourier transform spectroscopy with sub-nominal resolution and precision beyond the Voigt profile

Lucile Rutkowski[a], Piotr Masłowski[b], Alexandra C. Johansson[a], Amir Khodabakhsh[a], Aleksandra Foltynowicz[a,*]

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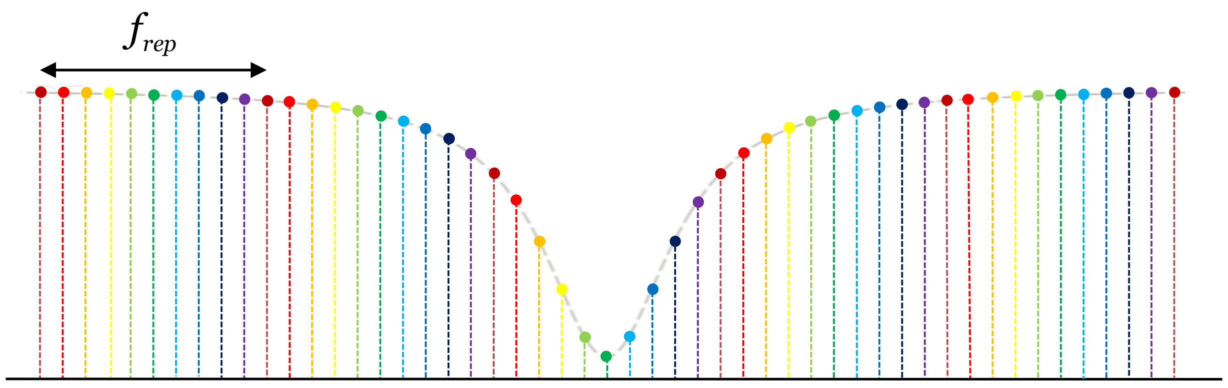
Lucile Rutkowski, CES, Lecco, 2022 – lucile.rutkowski@univ-rennes1.fr

Spectral interleaving

f_{rep} or f_{ceo} scan
to map the entire absorption lineshape

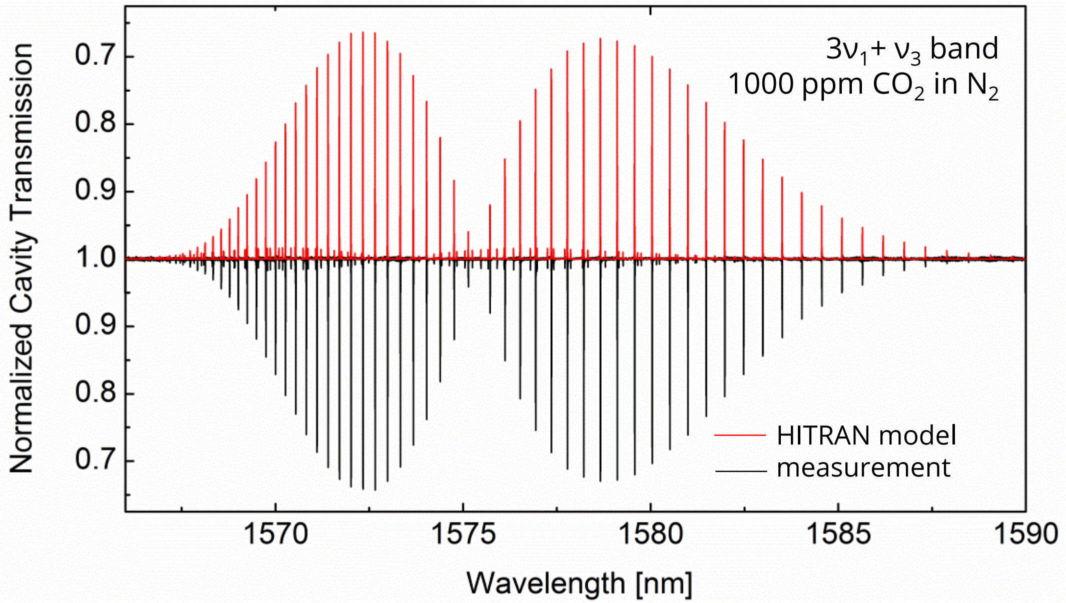


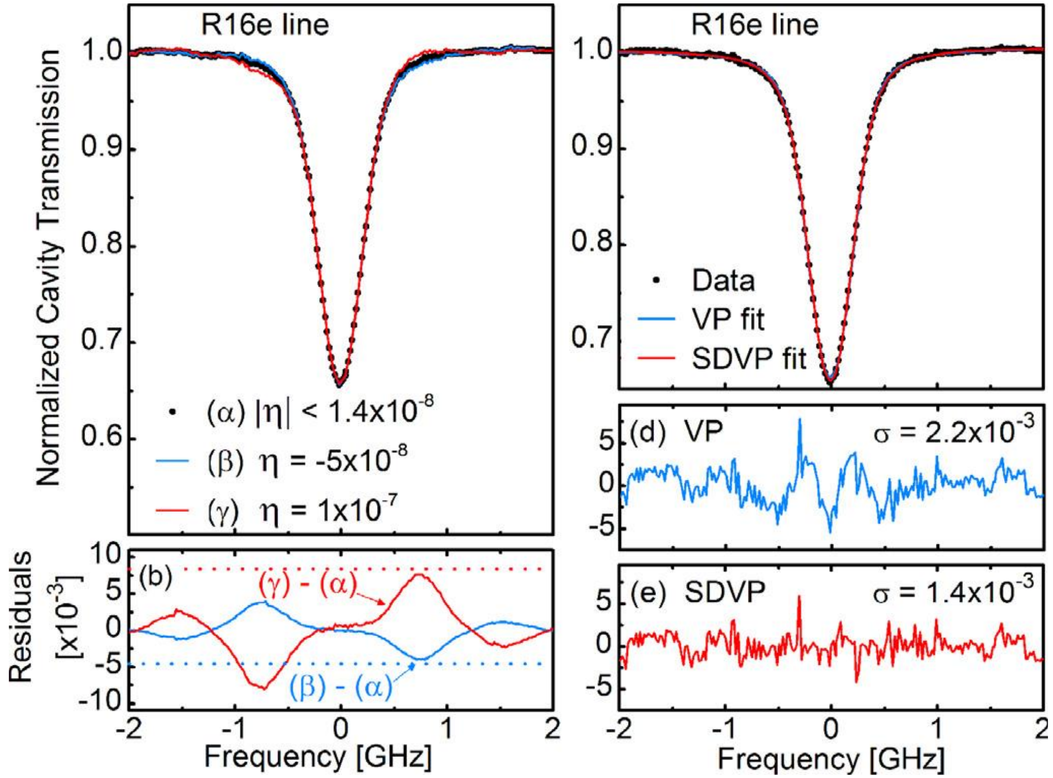
- Resolution – comb linewidth
- Frequency scale – given by the comb
- Sampling point spacing – arbitrary tuning
- Compact and fast spectrometer

S. Schiller, Opt. Lett. **27**, 766 (2002)
P. Maslowski *et al*., Phys. Rev. A **93**, 021802(R) (2016)
L. Rutkowski *et al*., JQSRT **204**, 63-73 (2017)

High precision spectroscopy

CO_2 in N_2 at 26 Torr





- Laser Er:fiber: 250 MHz
- Cavity - F = 10000, FSR = 187.5 MHz
- Interferogram: $\delta\nu_N$ = 750 MHz (OPD_{max} = 40 cm)
- Optical step: 18.75 MHz
- 40 interleaved spectra
- Total acquisition time: 700 s

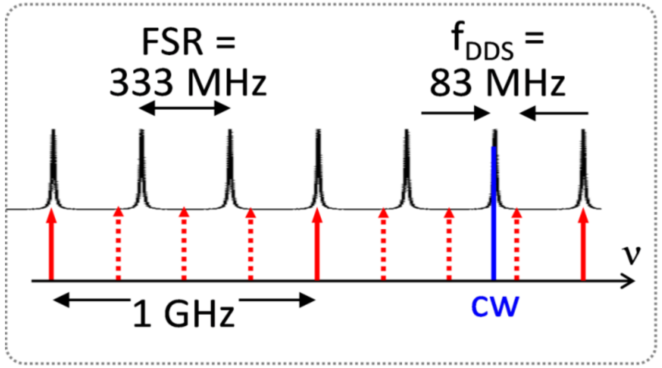
Optical frequency comb Fourier transform spectroscopy with sub-nominal resolution and precision beyond the Voigt profile

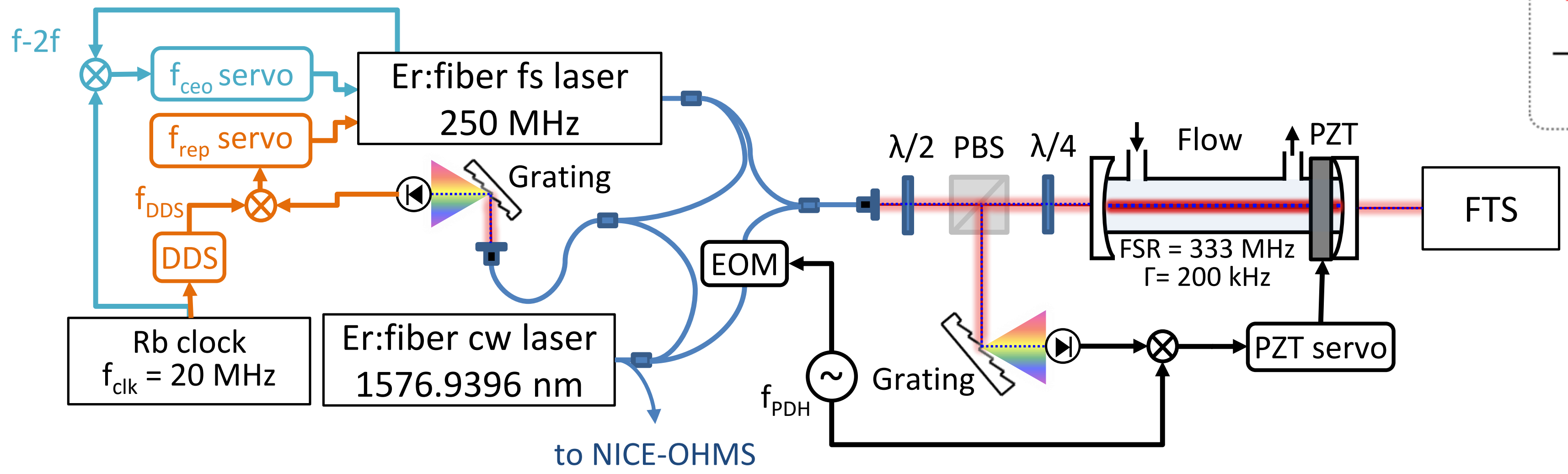
Lucile Rutkowski[a], Piotr Masłowski[b], Alexandra C. Johansson[a], Amir Khodabakhsh[a], Aleksandra Foltynowicz[a,*]

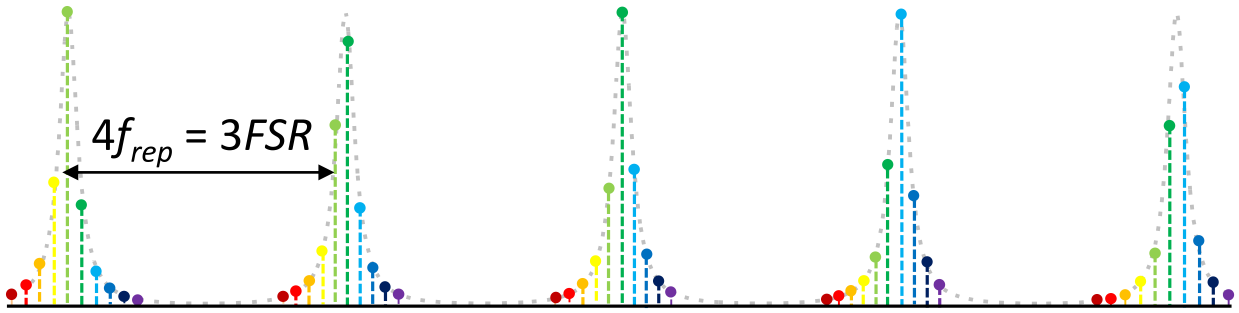
[a] Department of Physics, Umeå University, 901 87 Umeå, Sweden
[b] Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, ul. Grudziądzka 5, 87-100 Toruń, Poland

Cavity mode spectroscopy

- Comb-cavity locking via a stabilized cw reference
- Cavity filled with 1% CO_2 in N_2 at 750 Torr





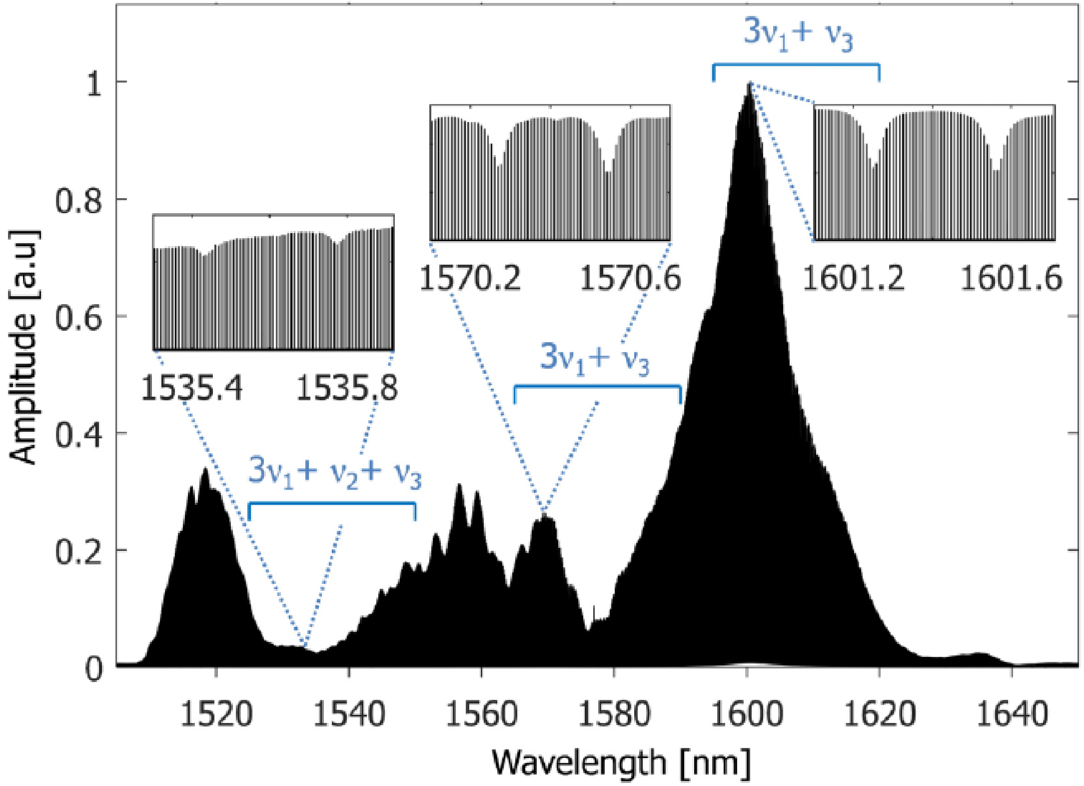


L. Rutkowski, et al., Opt. Express 25(18), 21711 (2017)
A.C. Johansson, et al., Opt. Express 26(16)20633 (2018)

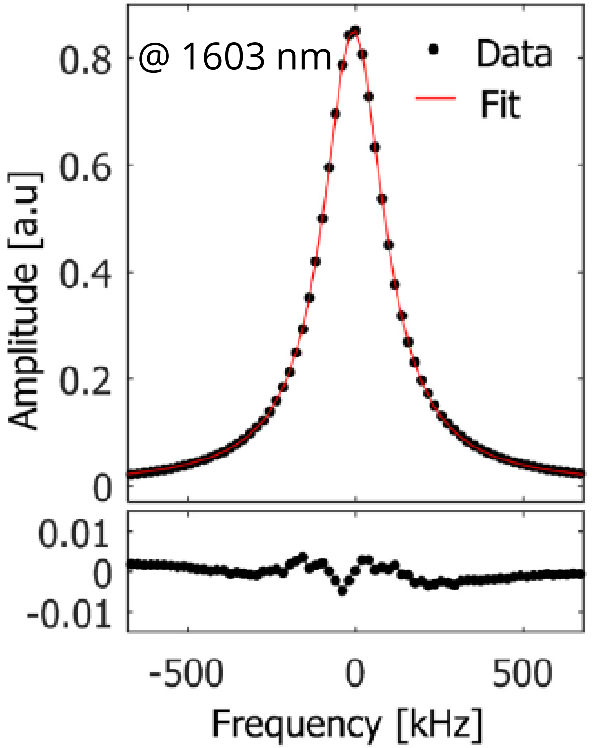
Cavity mode spectroscopy

Full spectrum

Interleaving of 120 spectra taken with a 20 kHz optical step.



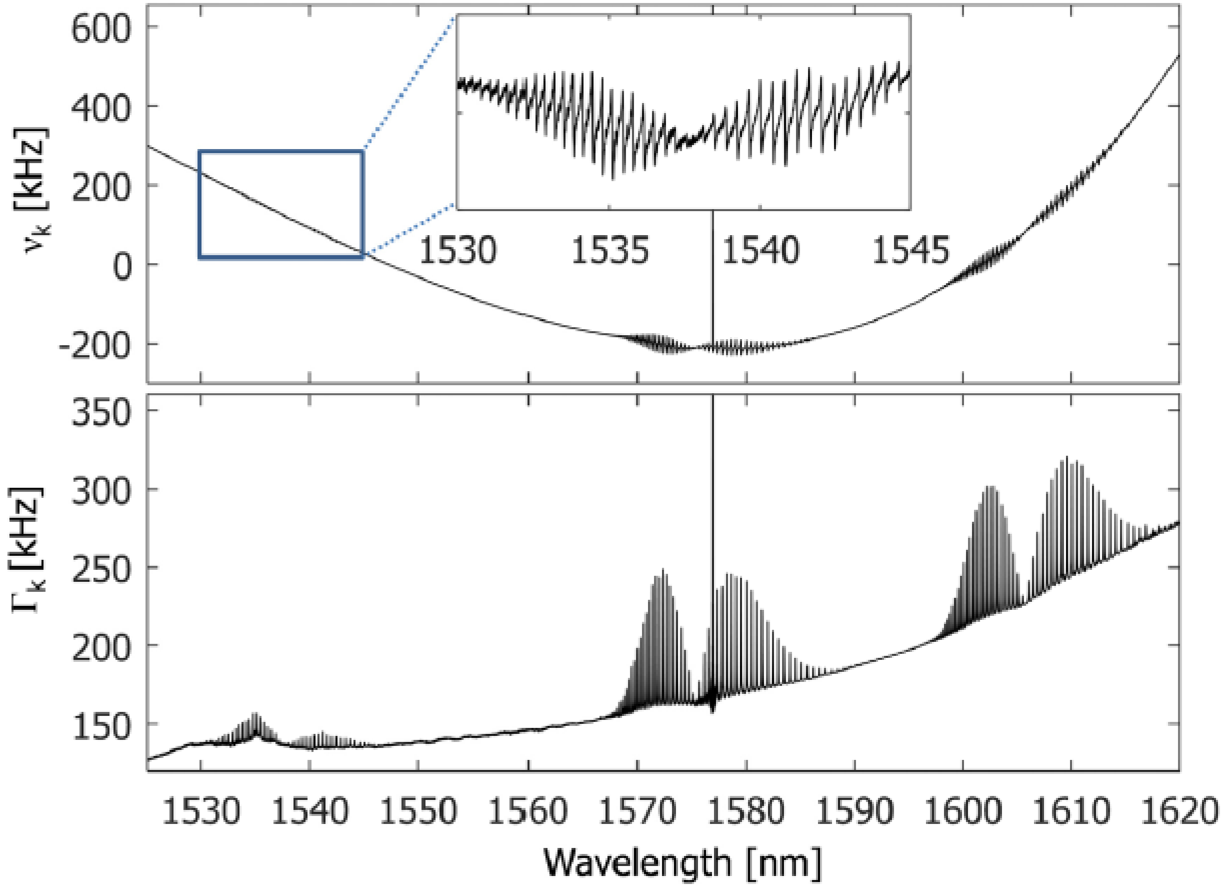
Lorentzian fit for each cavity mode:



Cavity mode spectroscopy

Absorption and dispersion spectra from mode widths and center frequencies

Three absorption bands measured, no need to consider broadband dispersion effects.



Research Article Vol. 26, No. 16 | 6 Aug 2018 | OPTICS EXPRESS 20633
Optics EXPRESS

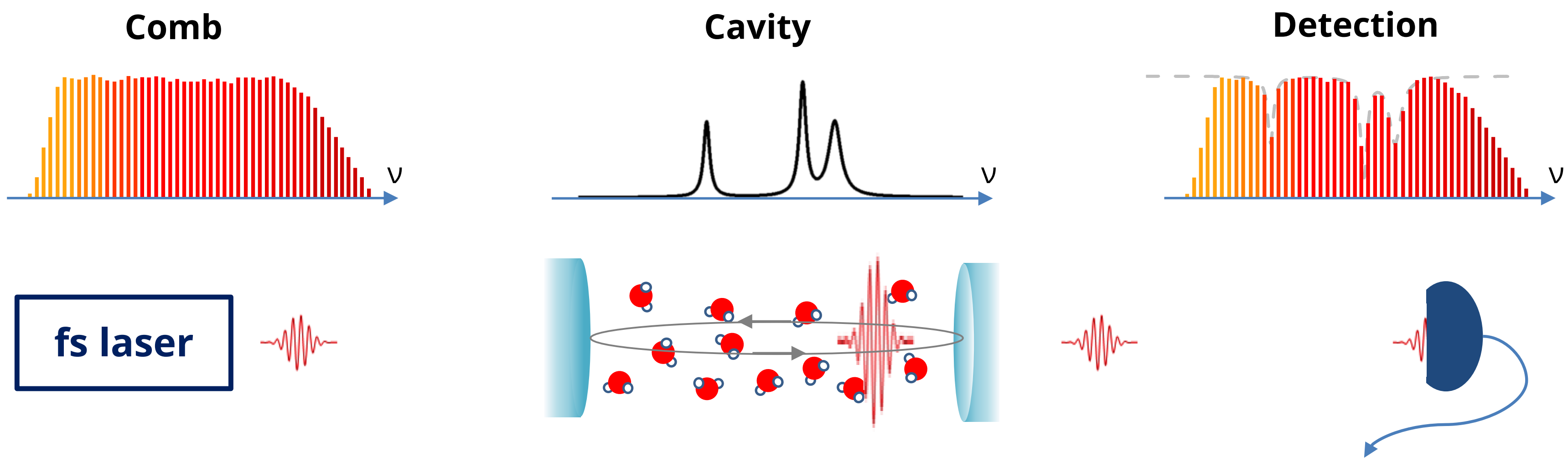
Broadband calibration-free cavity-enhanced complex refractive index spectroscopy using a frequency comb

Alexandra C. Johansson,[1] Lucile Rutkowski,[1] Anna Filipsson,[1] Thomas Hausmaninger,[1] Gang Zhao,[1,2] Ove Axner,[1] and Aleksandra Foltynowicz[1,*]

[1]*Department of Physics, Umeå University, 901 87 Umeå, Sweden*
[2]*State Key Laboratory of Quantum Optics and Optics Devices, Institute of Laser Spectroscopy, Shanxi University, Taiyuan 030006, China*

Conclusion

*Measure entire absorption bands and/or different species **simultaneously**, with **high sensitivity** and in **short acquisition times***



Many techniques, balance between:

- Spectral coverage
- Spectral resolution
- Time resolution
- Sensitivity
- Total acquisition time
- Robustness

Vernier spectrometer in continuous filtering

- Use the enhancement cavity as a frequency filter
- Entire comb bandwidth, but loose the frequency ruler

Fourier transform spectroscopy

- Multiplex measurement, rely on a Michelson interferometer
- Easily combined with cavity enhancement, comb mode resolution

Review of Reviews

Optical frequency comb technology:

- N. R. Newbury, “Searching for applications for a fine tooth comb”, Nat. Photon. **5**, 186 (2011).
- T. Fortier, E. Baumann, ”20 years of developments in optical frequency comb technology and applications”, Commun. Phys. **2**(1), 1 (2019).
- S.A. Diddams, K. Vahala, T. Udem, “Optical frequency combs: Coherently uniting the electromagnetic spectrum”, Science, **369**, 267 (2020).

Optical frequency combs spectroscopy:

General
- M.J. Thorpe, J. Ye, “Cavity-enhanced direct frequency comb spectroscopy”, Appl. Phys. B **91**, 397 (2008).
- F. Adler, M.J. Thorpe, K.C. Cossel, J. Ye, “Cavity-Enhanced Direct Frequency Comb Spectroscopy Technology and Applications” Annu. Rev. Anal. Chem. **3,** 175 (2010).
- A. Foltynowicz, P. Maslowski, T. Ban, F. Adler, K. C. Cossel, T. C. Briles, J. Ye, ”Optical frequency comb spectroscopy”, Faraday Discuss. **150**, 23 (2011).
- N. Picqué, T.W. Hänsch, ”Frequency comb spectroscopy”, Nat. Phot. **13**(3), 146 (2019).
- M.L. Weichman, P.B. Changala, J. Ye, Z. Chen, M. Yan, N. Picqué, ”Broadband molecular spectroscopy with optical frequency combs”, J. Mol. Spectrosc. **355**, 66 (2019).

Focus on one technique
- Ian Coddington, Nathan Newbury, William Swann, “Optical frequency comb spectrosocpy”, Optica **3**(4), 414 (2016).
- C. Lu, J. Morville, L. Rutkowski, F. Senna Vieira, A. Foltynowicz, “Cavity-Enhanced Frequency Comb Vernier Spectroscopy” Photonics **9**, 222 (2022).
- K. Twayana, I. Rebolledo-Salgado, E. Deriushkina, J. Schröder, M. Karlsson, V. Torres-Company, “Spectral Interferometry with frequency combs”, Micromachines **13**(4), 614 (2022).

Application oriented
- K.C. Cossel, E.M. Waxman, I.A. Finneran, G.A. Blake, J. Ye, N. Newbury, ”Gas-phase broadband spectroscopy using active sources: progress, status, and applications”, J. Opt. Soc. Am. B **34**(1), 104 (2017).
- J.H. Lehman, M.L. Weichman, ”Optical frequency comb for molecular spectroscopy, kinetics, and sensing”, *Emerging Trends in Chemical Application of Lasers*, book chapter, 61-88 (2021).