Quantitative Molecular Spectroscopy in Cavity

Presented by:

OSA Environmental Sensing Technical Group

Technical Group Leadership:

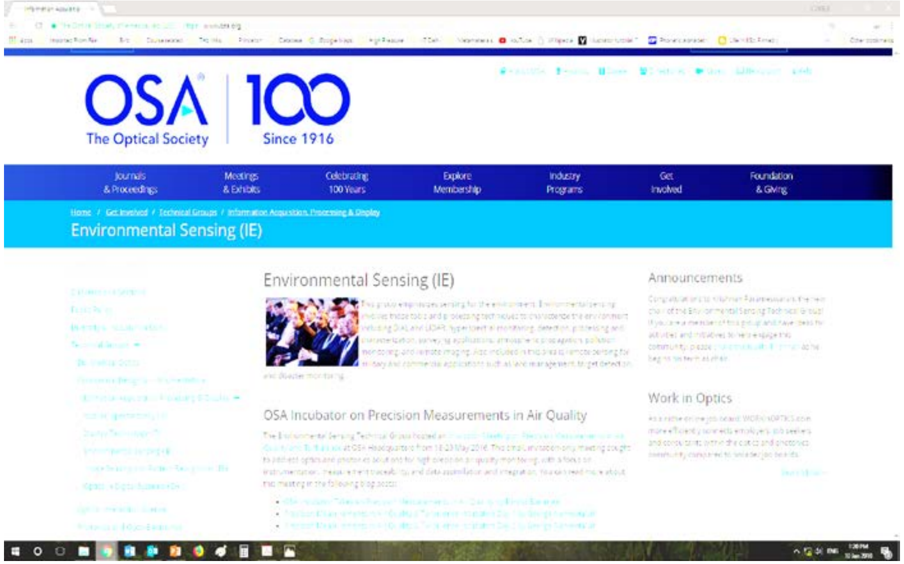
Krishnan Parameswaran, Analog Devices Inc., USA

Joachim Sacher, Sacher Lasertechnik GmbH, Germany

Amartya Sengupta, Indian Institute of Technology Delhi, India

OSA Environmental Sensing Technical Group

Technical Group Website:
www.osa.org/EnvironmentalSensingTG



Environmental Sensing (IE)

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OSA Incubator on Precision Measurements in Air Quality

Announcements

Work in Optics

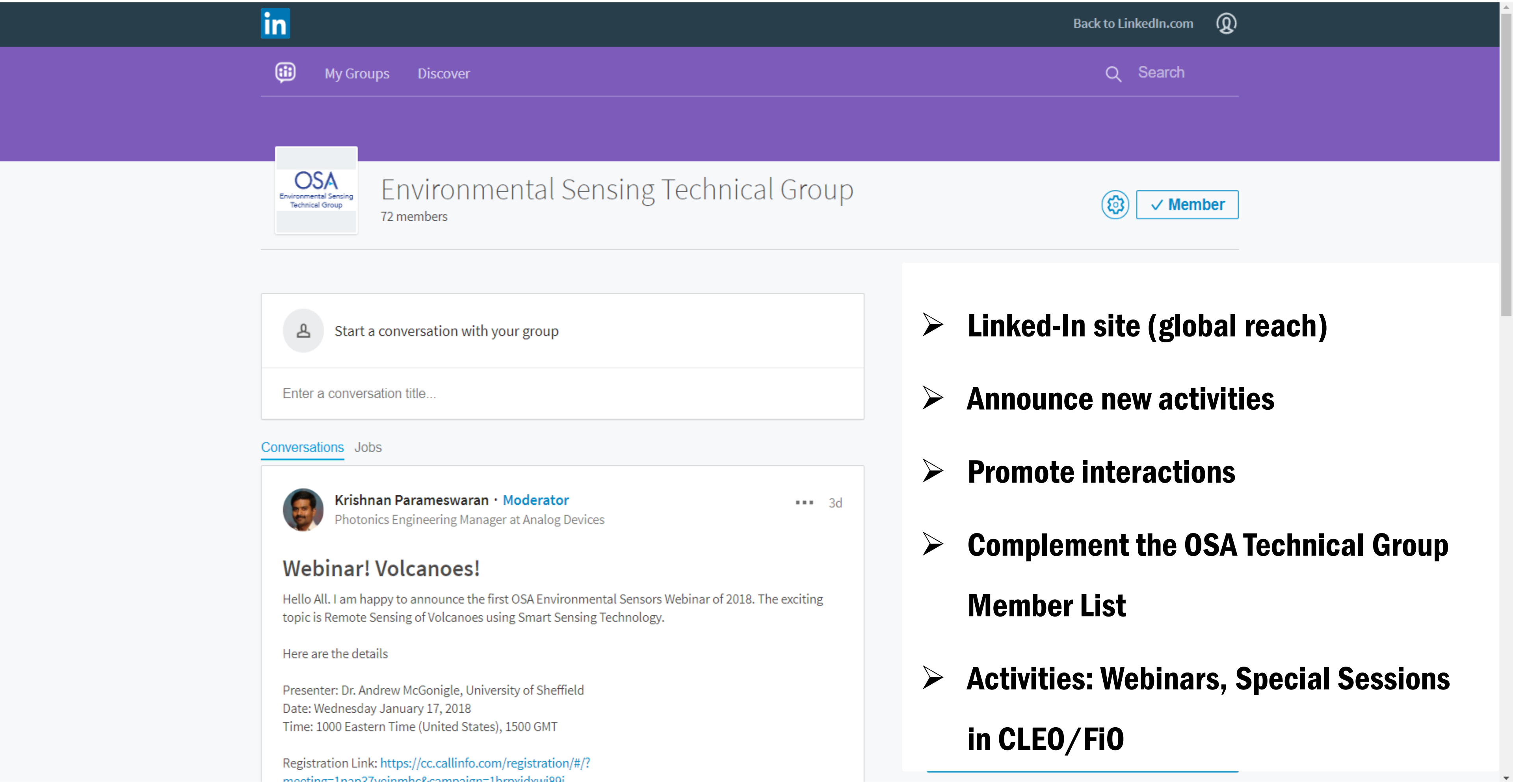
Over 1,100 Total Members

Scope:
This technical group covers optical tools and techniques used in environmental sensing, including DIAL and LIDAR, hyperspectral monitoring, detection, processing and characterization, surveying applications, atmospheric propagation, pollution monitoring, and remote imaging. Also included in this area is remote sensing for military and commercial applications such as land management, target detection, and disaster monitoring.

Environmental
Sensing
Technical Group

Contact your Technical Group and Get Involved!

www.linkedin.com/groups/12055528



Environmental Sensing Technical Group

72 members

Start a conversation with your group

Enter a conversation title...

Krishnan Parameswaran · Moderator

Photonics Engineering Manager at Analog Devices

Webinar! Volcanoes!

Hello All. I am happy to announce the first OSA Environmental Sensors Webinar of 2018. The exciting topic is Remote Sensing of Volcanoes using Smart Sensing Technology.

Here are the details

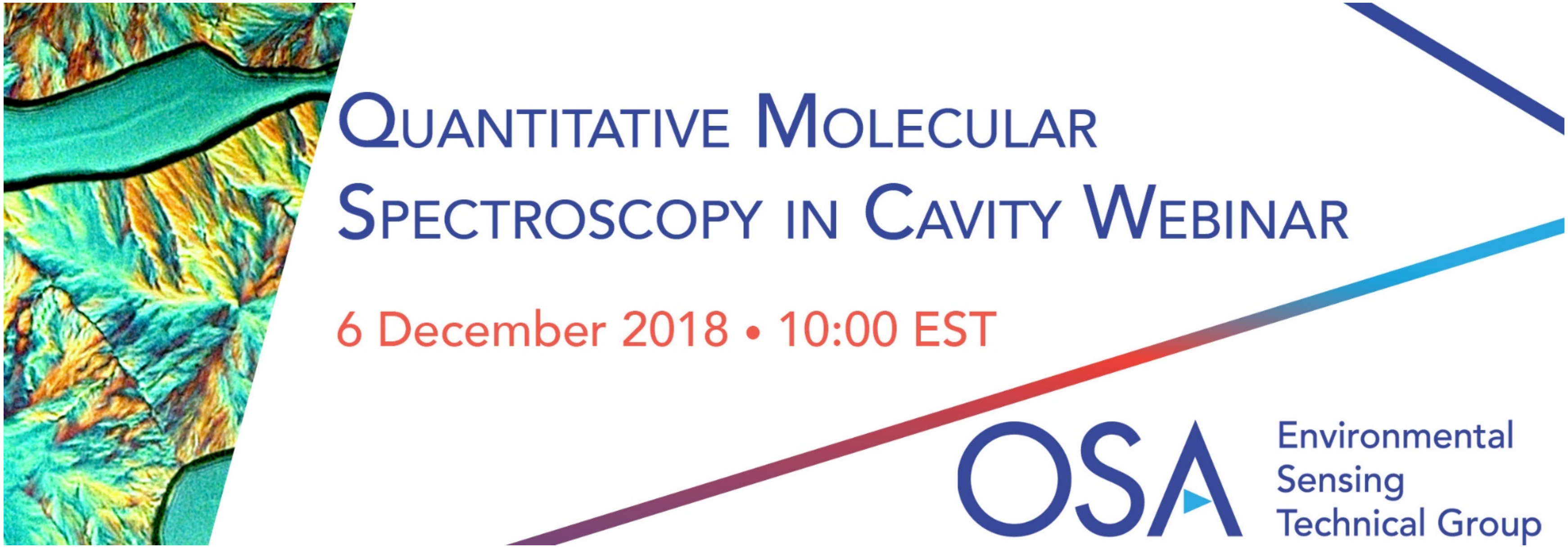
Presenter: Dr. Andrew McGonigle, University of Sheffield
Date: Wednesday January 17, 2018
Time: 1000 Eastern Time (United States), 1500 GMT

Registration Link: https://cc.callinfo.com/registration/#/?

- **Linked-In site (global reach)**
- **Announce new activities**
- **Promote interactions**
- **Complement the OSA Technical Group Member List**
- **Activities: Webinars, Special Sessions in CLEO/FiO**

OSA Environmental Sensing Technical Group

Welcome to Today’s Webinar!



QUANTITATIVE MOLECULAR SPECTROSCOPY IN CAVITY WEBINAR

6 December 2018 • 10:00 EST

OSA Environmental Sensing Technical Group

Dr. Patrick Dupré, Université du Littoral Côte d'Opale

Patrick Dupré is a recognized expert in molecular high resolution and quantitative laser Spectroscopy. His career has included work in physics and chemistry laboratories in France, the United States, the United Kingdom and Germany. His interests include experimental spectroscopy and modeling. He is presently involved in developing Noise-Immune Cavity-Enhanced Optical Heterodyne Molecular Spectrometry (NICE-OHMS) for metrology applications and for trace gas detection in the Mid-InfraRed. Spectroscopy with high finesse cavity is an ideal tool for saturated absorption, i.e. under sub-Doppler conditions.

Quantitative Molecular Spectroscopy in Cavity

Patrick DUPRÉ

Laboratoire de Physico-Chimie de l'Atmosphère, ULCO
Dunkerque, France

December 2018

Outline

1. Motivations
2. Introduction to CEAS
3. Absorption in Cavity
4. Saturated Absorption: Modeling and Simulations
5. NICE-OHMS: Principles and Implementation
6. C_2H_2 in the NIR
7. HD in the NIR (Forbidden Transition)
8. Bibliography
9. Conclusions

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Basic Idea: **Enhancing the Absorption Length**, i.e., the length of interaction between light and analyte. How?

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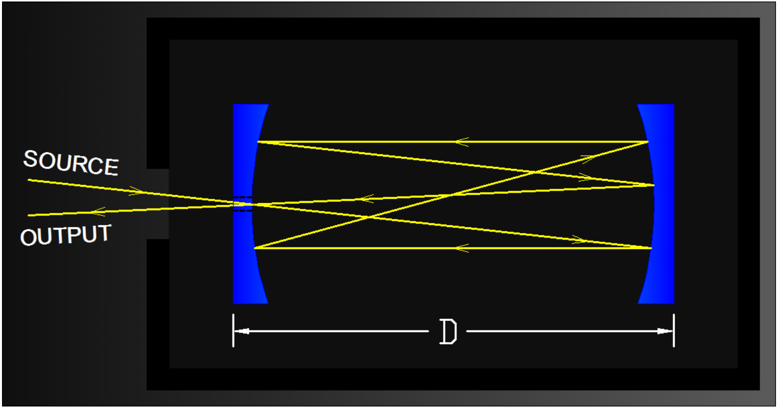

Large Metallic Mirrors

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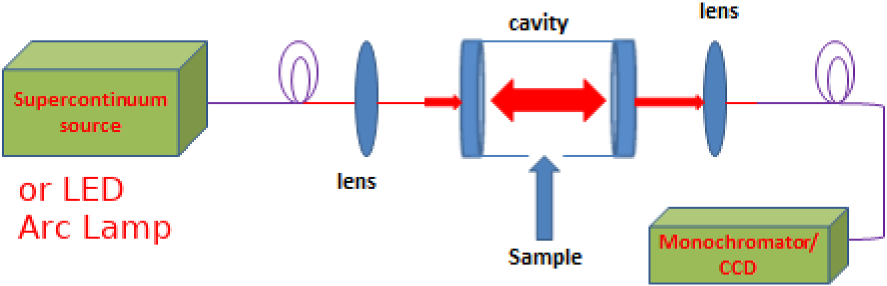

or LED
Arc Lamp

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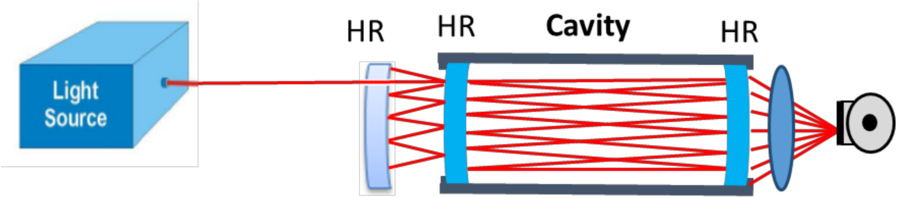

Off-Axis ICOS with recycling mirror to recover the leaking input power (with the permission of J. Mandon)

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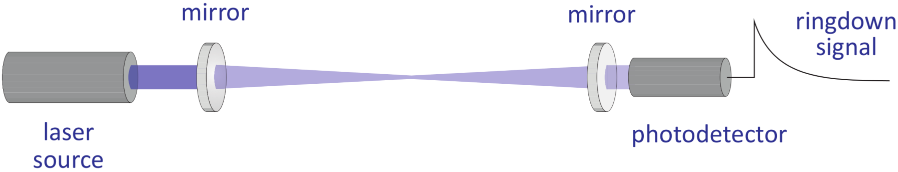

With the permission of C. Vallance

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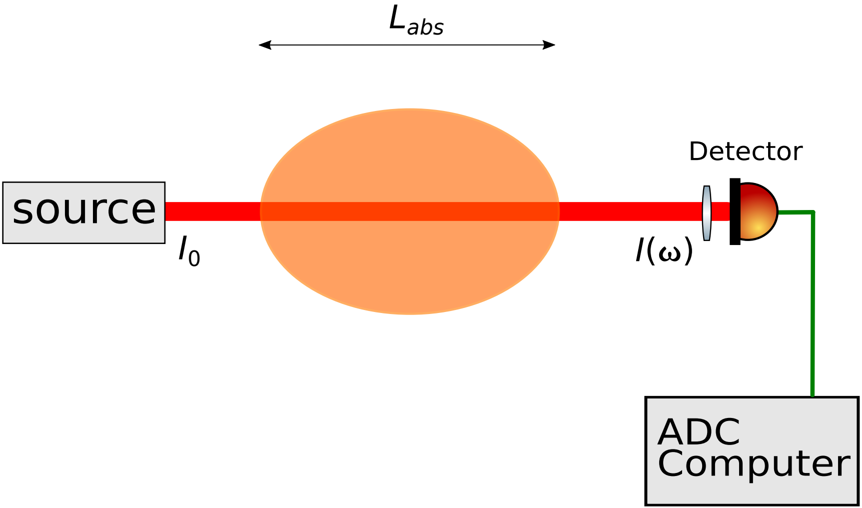
Outline

Absorption



Background

- The Absorption Beer-Lambert Law:

$$I\,(\omega) = I_0\,\mathrm{e}^{-\alpha(\omega)\,L_{abs}}$$

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- The line absorption Crossection ($\sigma(\omega)$ in cm^2/molecule), includes a Normalized Lineshape (like a Voigt profile whose width is pressure depending):

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where $\mathcal{S}$ is the Line Intensity (in cm/molecule if ω is in cm^{-1}).

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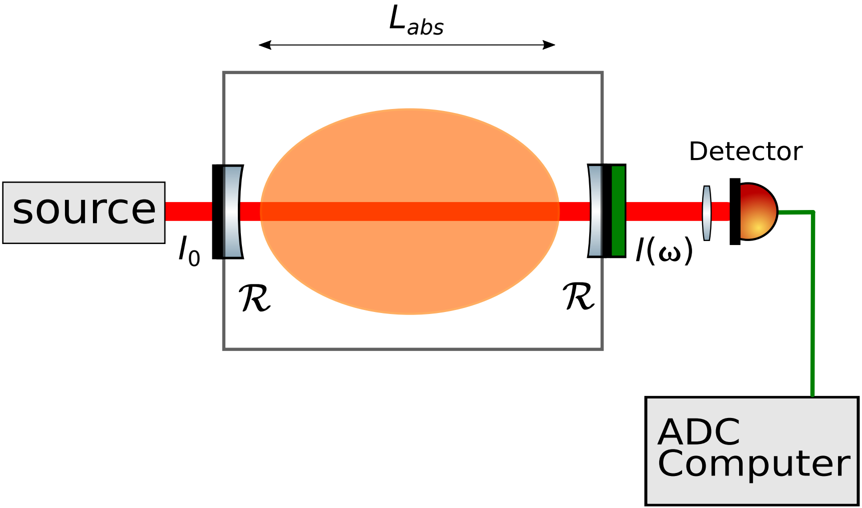
- $\mathcal{S}$ is available in the database like HITRAN (`http://hitran.org/`)

Absorption in a Resonant Cavity



Main Features of a Symmetric Resonant Cavity

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- Cavity Finesse (Enhancement Factor)

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- Response Time (or Characteristics Time)

$$\tau_{RD} = \frac{\mathcal{F}\,L_{cav}}{\pi\,c} = \frac{\mathcal{F}}{2\pi}t_{rt} = \frac{1}{2\Delta_{cav}} = \frac{\mathcal{F}}{2\pi\,FSR}$$

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- Trapped Power

$$\boldsymbol{\mathcal{I}_{cav} = \frac{\mathcal{F}}{\pi}\mathcal{I}_{in}}$$

Formalism: Transfer Function ("Filter") of a Lossless Cavity

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- **In the Frequency Domain**

$$\mathcal{I}_{out}(\omega) = |\mathcal{T}_{cav}(\omega) \cdot \mathcal{E}_{in}(\omega)|^2$$

with (obtained from multiple interferences

$$\mathcal{T}_{cav}(\omega) = \frac{\mathcal{T}\,\mathrm{e}^{-\mathrm{i}\omega t_{rt}/2}}{1+\mathcal{R}\,\mathrm{e}^{\mathrm{i}\omega t_{rt}}} = \frac{\mathcal{T}}{1-\mathcal{R}} \sum_i \frac{1}{1+\mathrm{i}\left(\frac{\omega - i\omega_{FSR}}{\Delta_{cav}(\omega)}\right)}$$

and with

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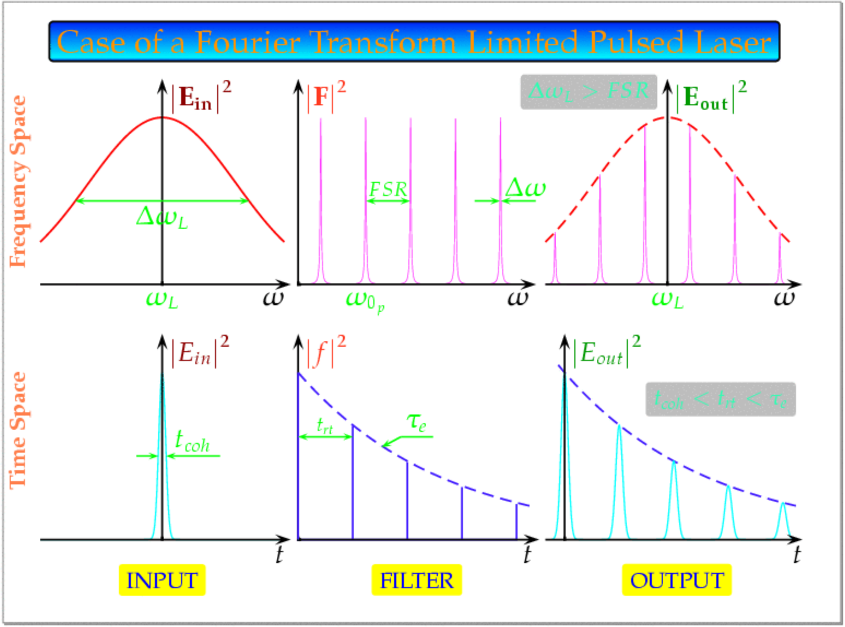
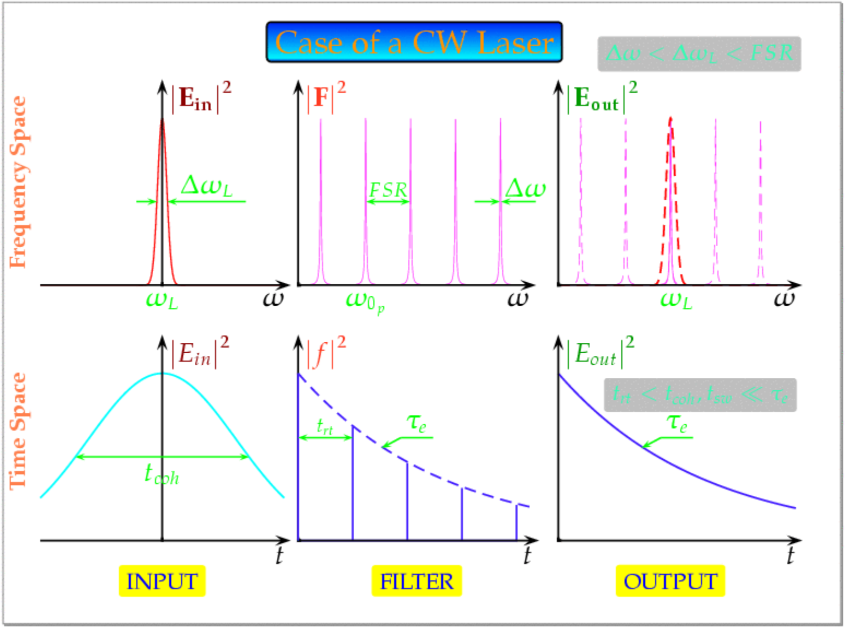
- **In the Time Domain**

$$I_{out}(t) = \left| FT^{-1}\left[\mathcal{T}_{cav}(\omega) \cdot \mathcal{E}_{in}(\omega)\right]\right|^2$$

Simulation: Pulsed Source



Simulation: CW Source



Absorption in a Resonant Cavity

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  - Alteration of the Characteristics Time (CRDS)

$$\frac{1}{\tau_{RD}(\omega)} - \frac{1}{\tau_0} = \alpha(\omega)\, c$$

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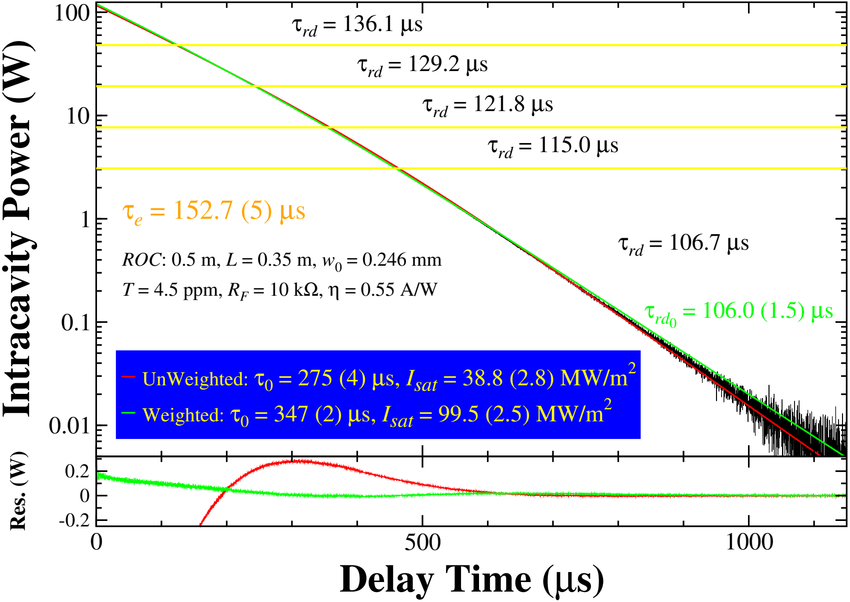
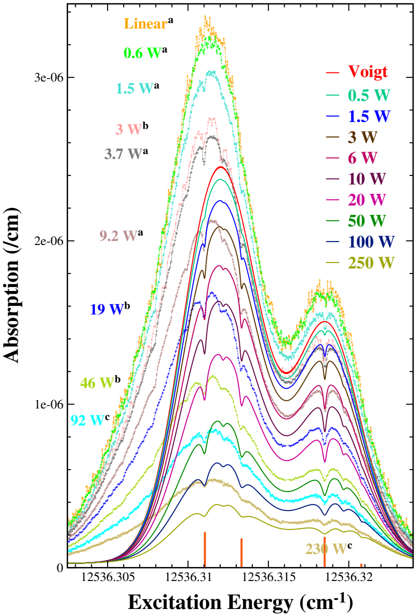
NonExponential Decay

CRDS of Jet-Cooled **NO_2**: *Decay of the line at* **12536.4464 cm^{-1} ($^qR_0(0)$, 3/2)**



Saturation in NO_2 (with Fine and Hyperfine Transitions)

Power dependence of the $^{q_0}Q_{21}(0.5)$ Line Pattern



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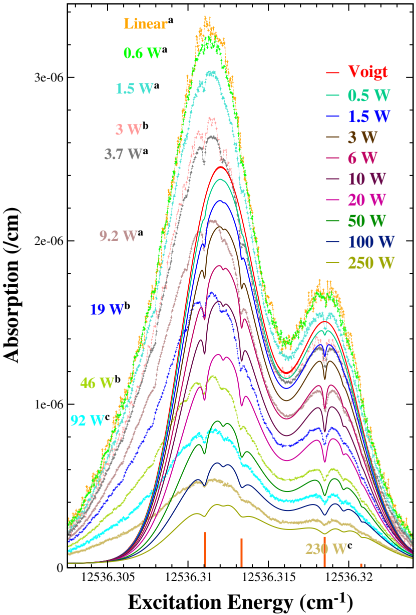

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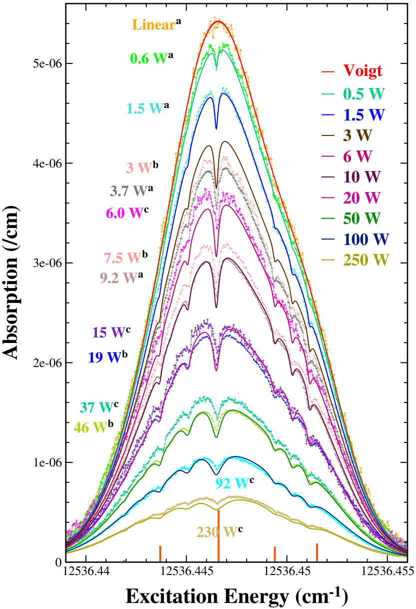
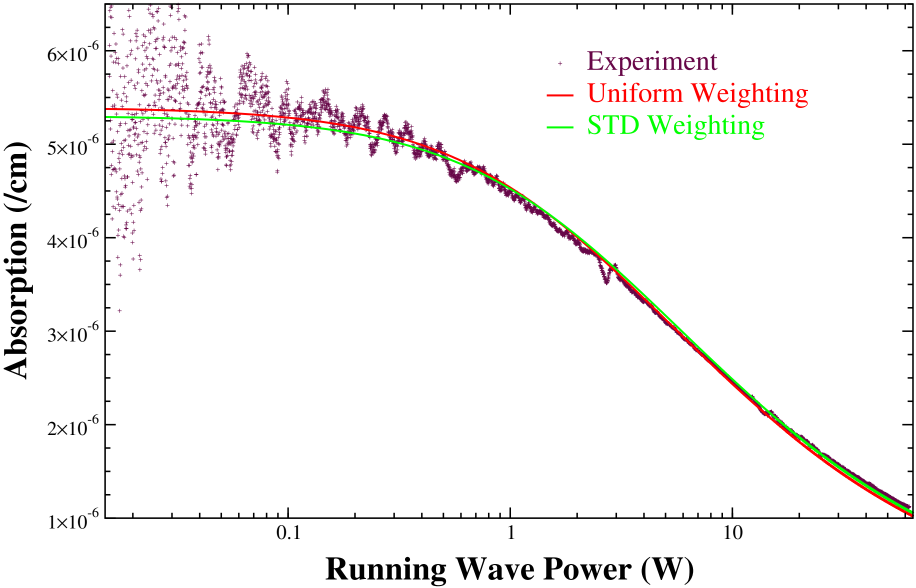


Absorption versus Intracavity Power

Absorption versus the Intracavity Power at the Center of the $^{q}R_{11}(0.5)$ Line Pattern



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Outline

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- Establishing the Saturated Absorption (based on the Rabi Frequency)
- Plugging specific EMFs (FMS) and considering the Stationary Response
  - Monochromatic (Radial Extension)
  - Gaussian (Impact Parameter)
    - Transit-Time Broadening (vs. Power Broadening)
    - Approximation based on the spectral extension of products involved ($\otimes$, $\times$)
- Numerical Integration over the Doppler Shift

Saturation Modeling: an Insight

- Establishing the complex absorption in the Frequency domain (coupling of the EMF with the susceptibility) for a given Doppler Shift
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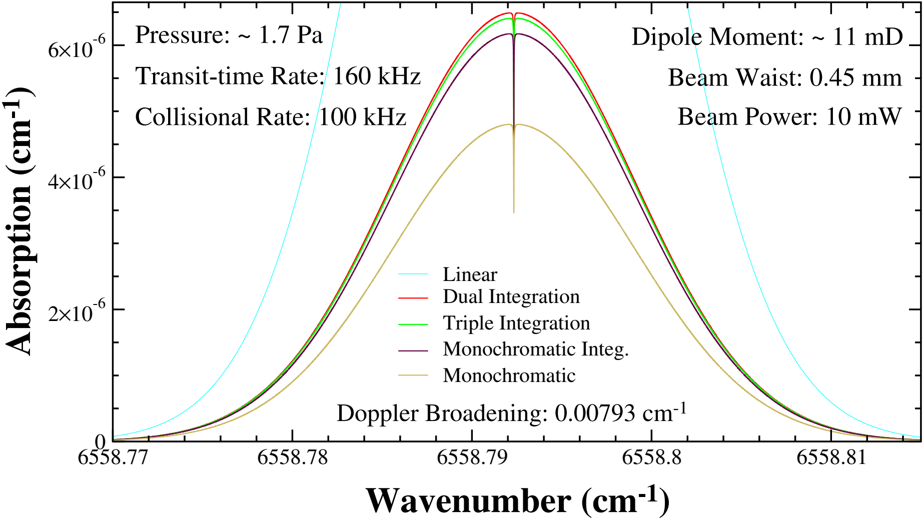
- Summation of the Degenerated Zeeman Sub-Transitions (Polarization)
- **No Saturation Coefficient is used**

Simulation and Line Profile Analysis

Saturation Analysis: C_2H_2 Transition R(0) at 6558.79233 cm^{-1} (polyad 10)



Pressure: ~ 1.7 Pa

Transit-time Rate: 160 kHz

Collisional Rate: 100 kHz

Dipole Moment: ~ 11 mD

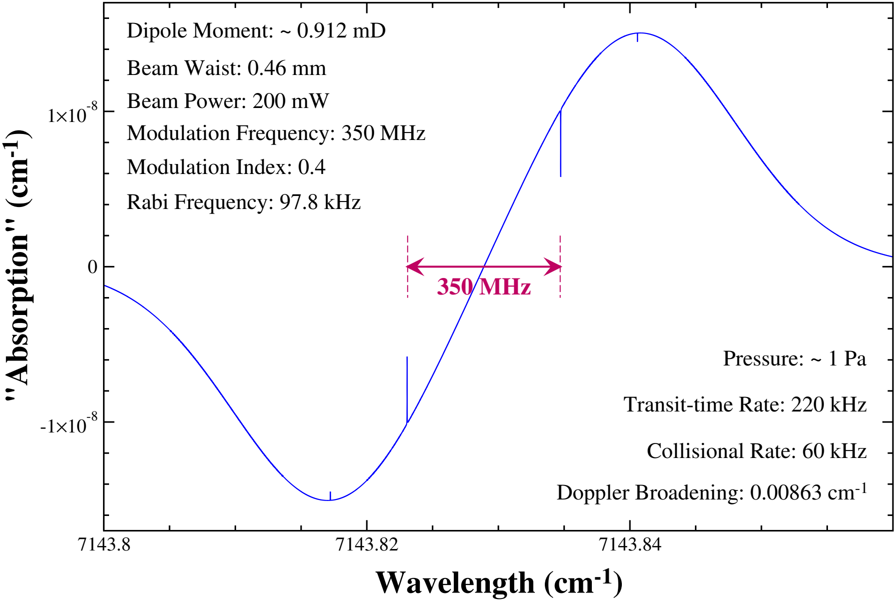
Beam Waist: 0.45 mm

Beam Power: 10 mW

Doppler Broadening: 0.00793 cm^{-1}

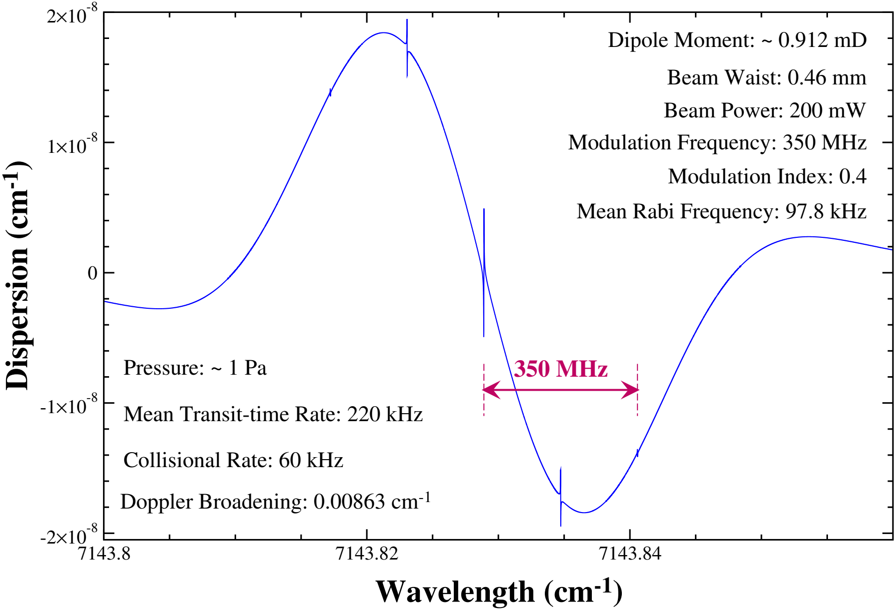
C_2H_2 NICE-OHMS Simulation (Absorption)

NICE-OHMS in Phase, C_2H_2 Transition R(0) at 7143.8289 cm^{-1} (polyad 11)



C_2H_2 NICE-OHMS Simulation (Dispersion)

***NICE-OHMS in Quadrature*, C_2H_2 Transition R(0) at 7143.8289 cm^{-1} (polyad 11)**


Dipole Moment: ~ 0.912 mD

Beam Waist: 0.46 mm

Beam Power: 200 mW

Modulation Frequency: 350 MHz

Modulation Index: 0.4

Mean Rabi Frequency: 97.8 kHz

Pressure: ~ 1 Pa

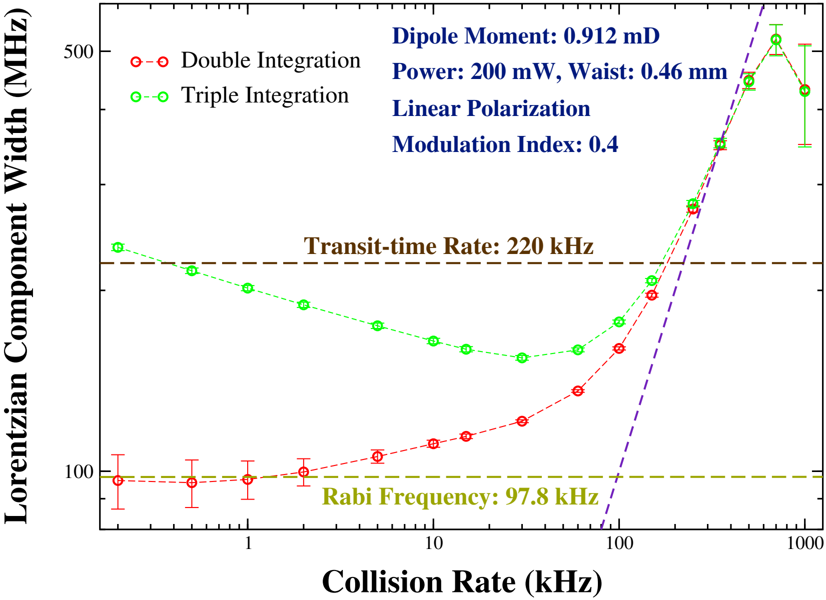
Mean Transit-time Rate: 220 kHz

Collisional Rate: 60 kHz

Doppler Broadening: 0.00863 cm^{-1}

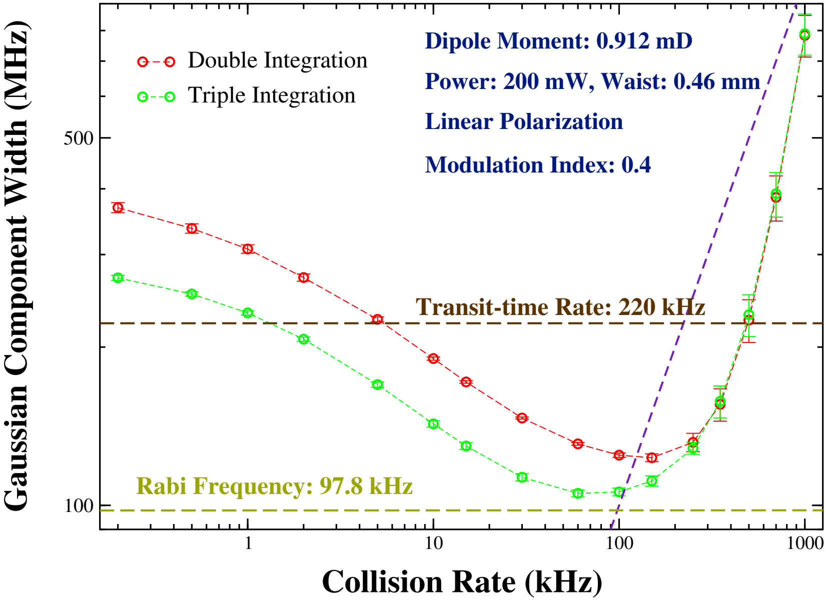
C_2H_2 Simulation (Dispersion): Lorentzian Component

Saturation Analysis: **C_2H_2 Transition R(0) at 7143.8289 cm^{-1} (polyad 11)**



C_2H_2 Simulation (Dispersion): Gaussian Component

Saturation Analysis: C_2H_2 Transition R(0) at 7143.8289 cm^{-1} (polyad 11)



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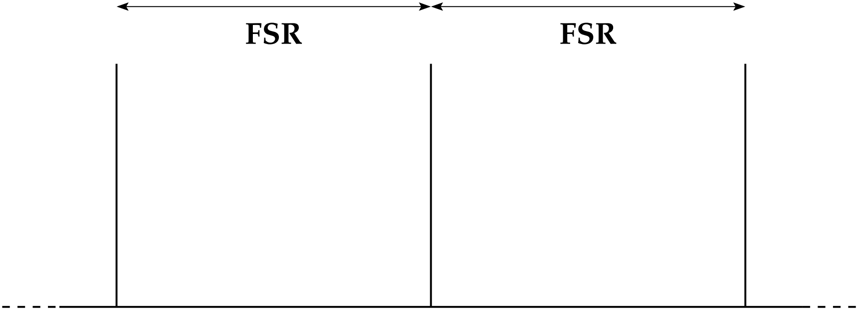
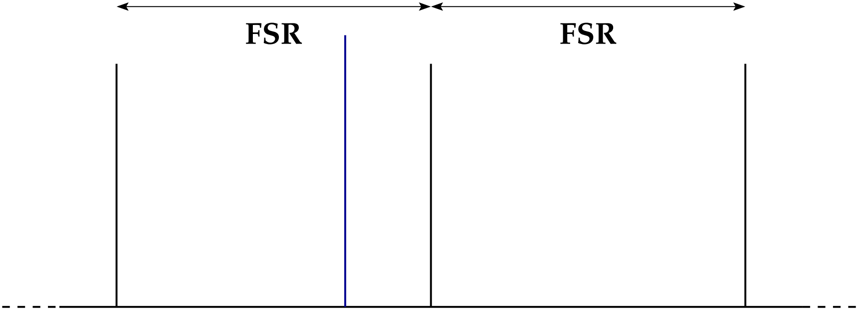
Frequency Modulation in Cavity



Phase Modulations in NICE–OHMS

Frequency Modulation in Cavity



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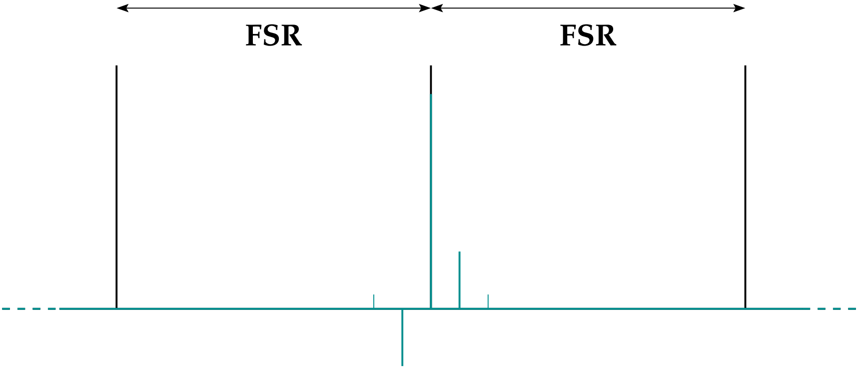

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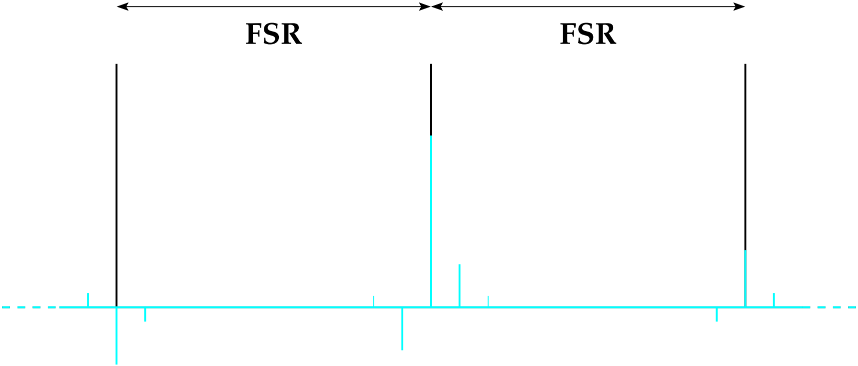
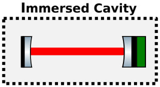
Frequency Modulation in Cavity



Phase Modulations in NICE–OHMS

NICE-OHMS Implementation



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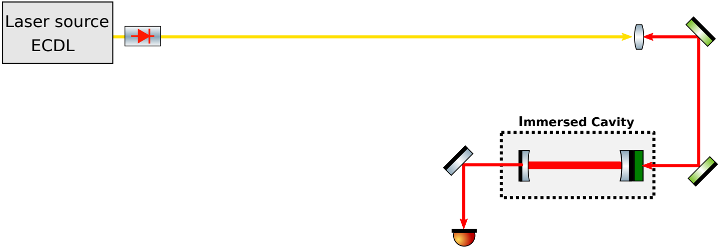

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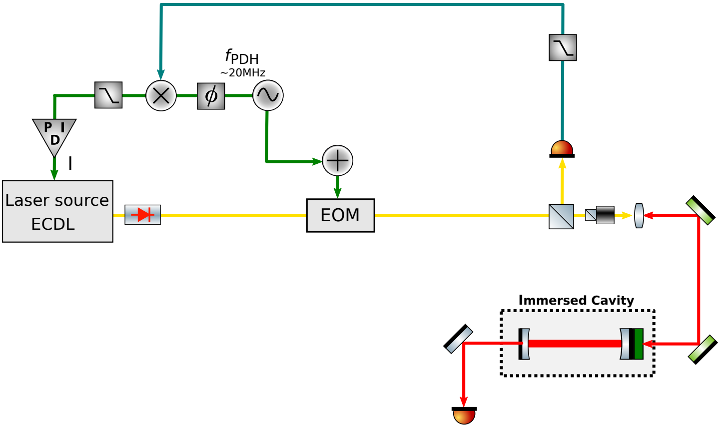

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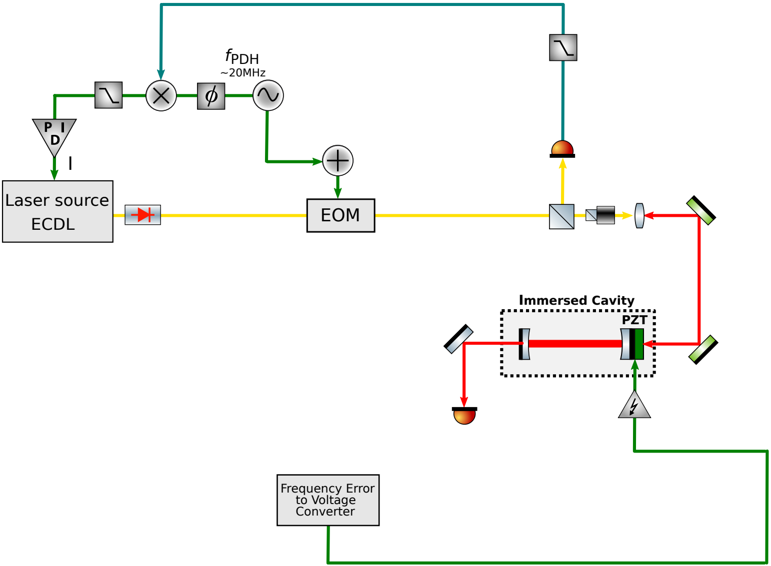

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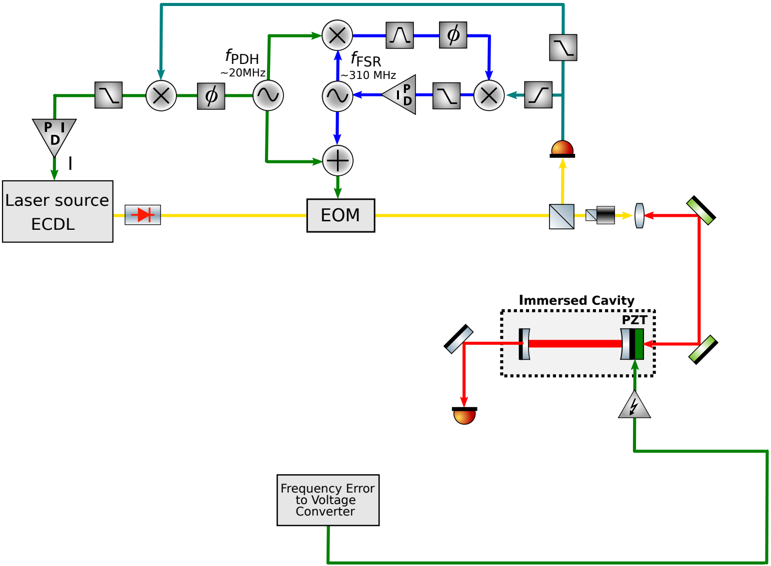

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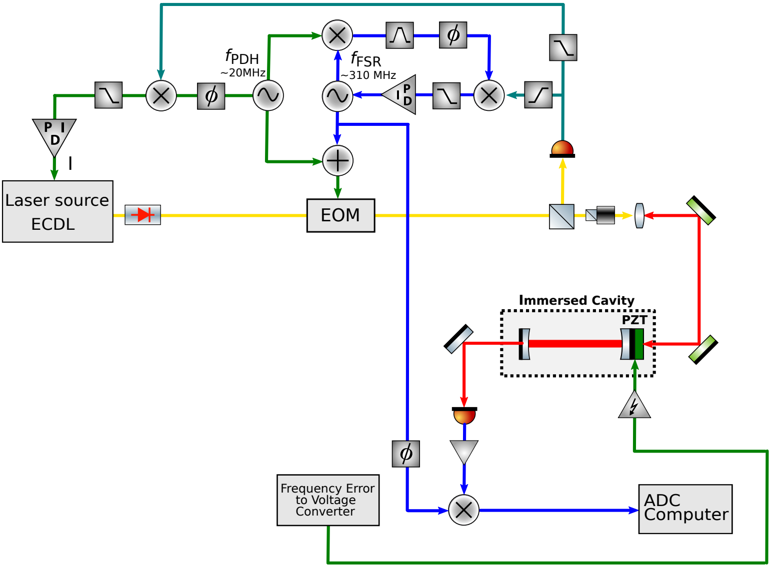

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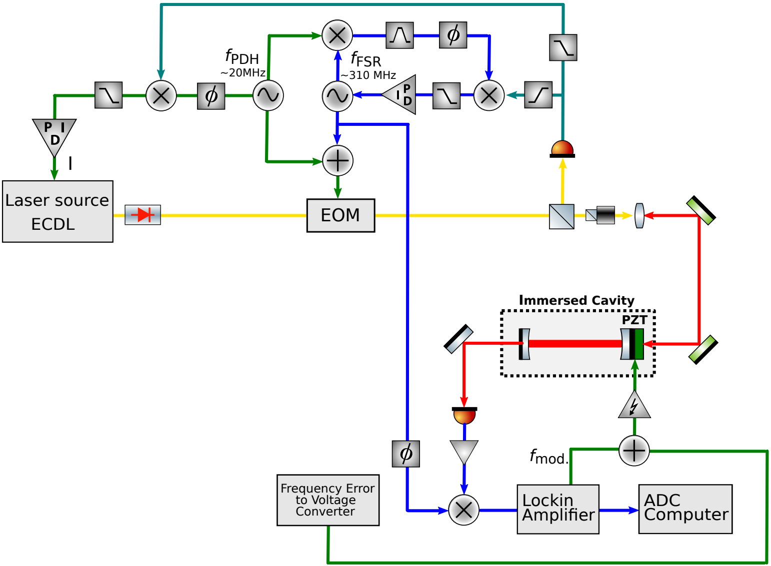

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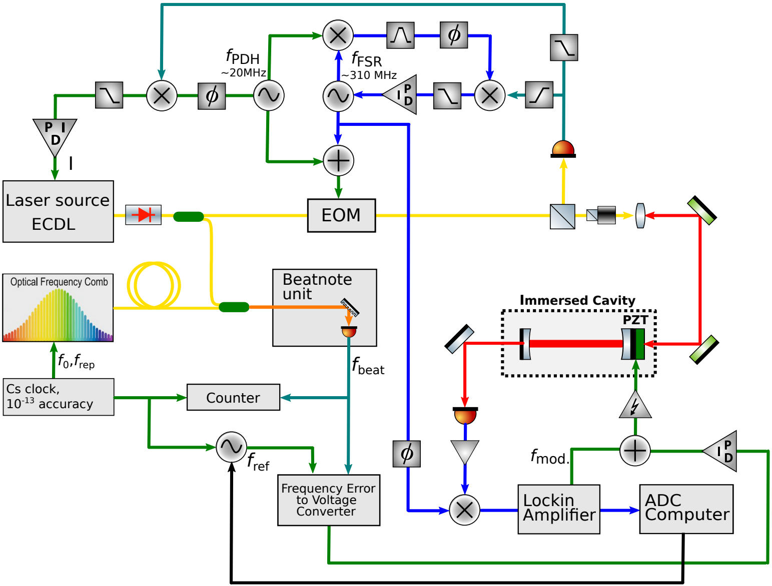

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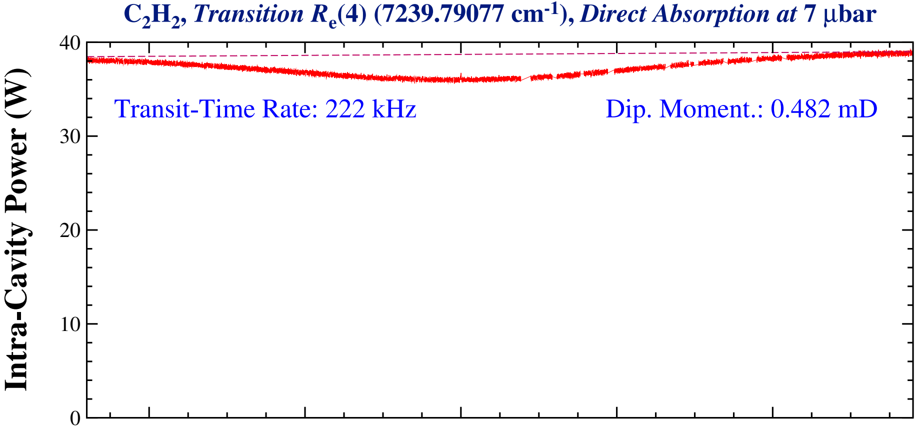
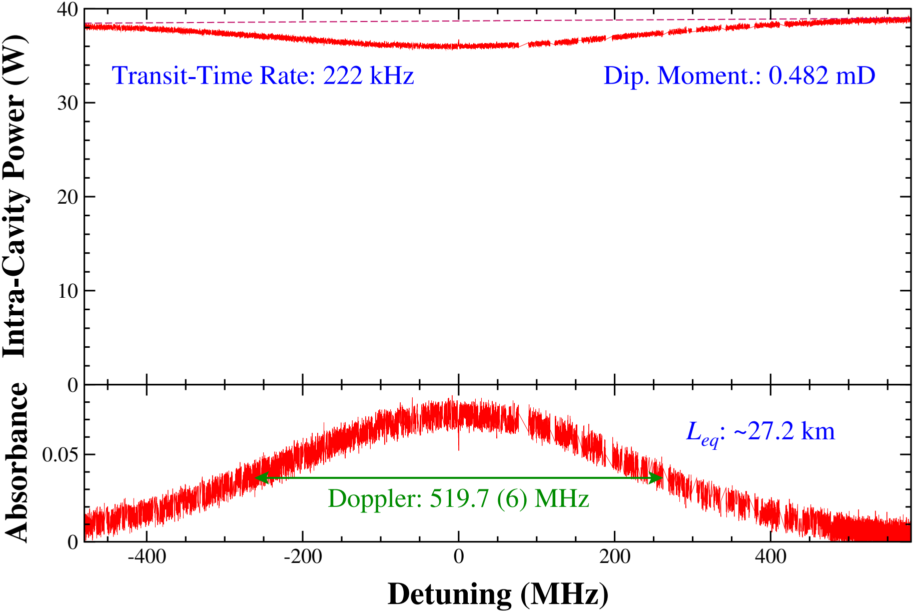
Direct Absorption of C_2H_2 (P 11, $\nu_1 + \nu_2 + (2\nu_4 + \nu_5)^1 \leftarrow 0$)



L_{eq}: ~27.2 km

Direct Absorption of C_2H_2 (P 11, $\nu_1 + \nu_2 + (2\nu_4 + \nu_5)^1 \leftarrow 0$)

C_2H_2, *Transition* $R_e(4)$ (7239.79077 cm^{-1}), *Direct Absorption at* 7 μbar



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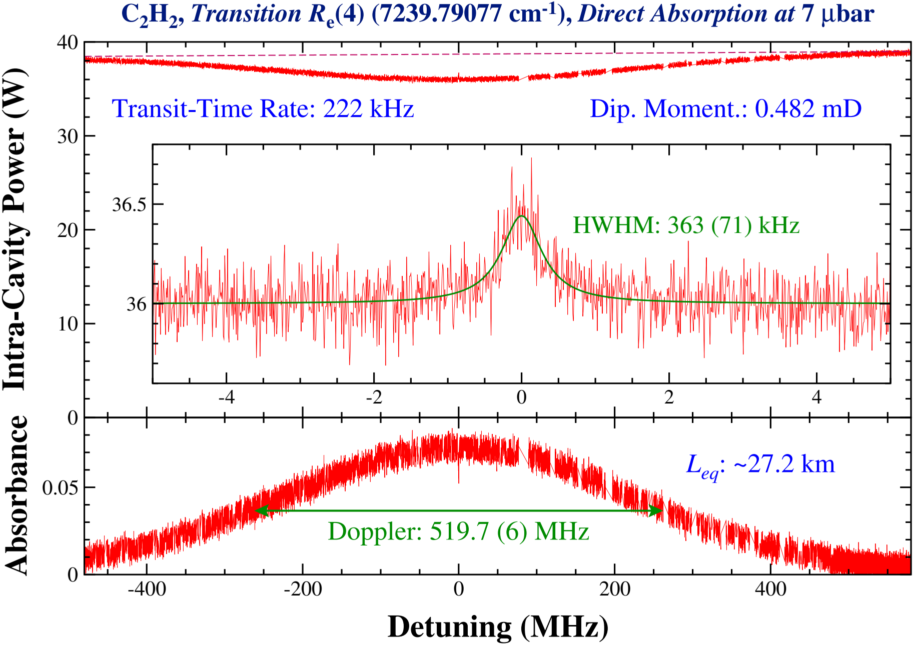
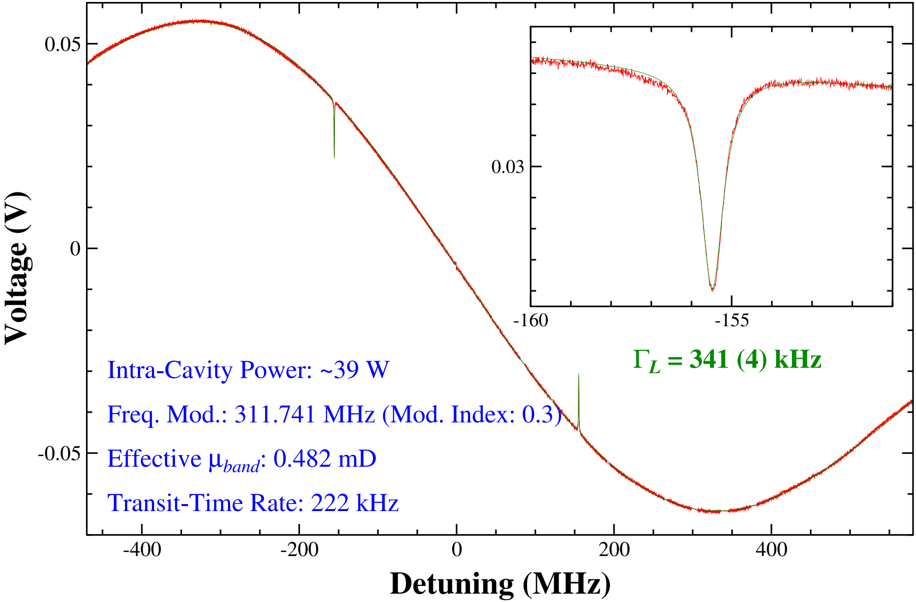


NICE-OHMS “Absorption” of C_2H_2 (Polyad 11)

C_2H_2, *Transition $R_e(4)$* (7239.79077 cm^{-1}), *NICE-OHMS in Phase at* 7 μbar



Intra-Cavity Power: ~39 W

Freq. Mod.: 311.741 MHz (Mod. Index: 0.3)

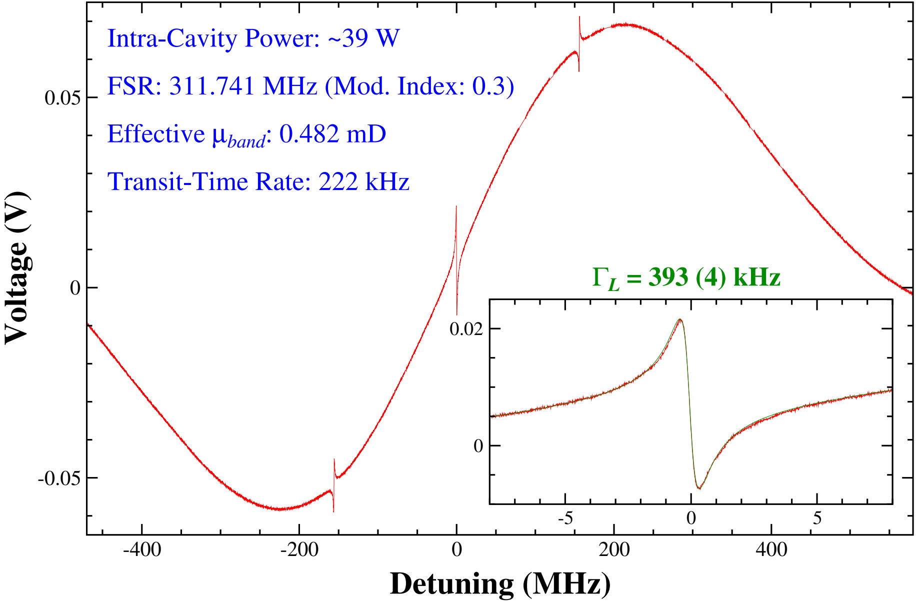
Effective μ_{band}: 0.482 mD

Transit-Time Rate: 222 kHz

Γ_L = 341 (4) kHz

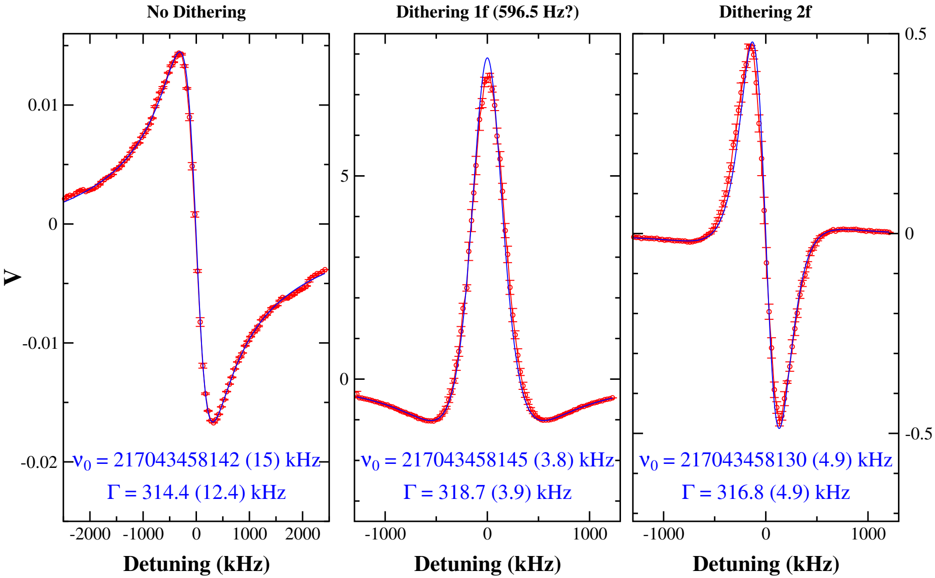
NICE-OHMS “Dispersion” of C_2H_2 (Polyad 11)

C_2H_2, *Transition R_e(4)* (7239.79077 cm^{-1}), *NICE-OHMS in Quadrature at* 7 μbar



NICE-OHMS Dispersion of C_2H_2 (Polyad 11) with OFC

C_2H_2, *Transition* $R_e(4)$ (7239.79077 cm^{-1}), *NICE-OHMS in Quadrature at* 2 µbar



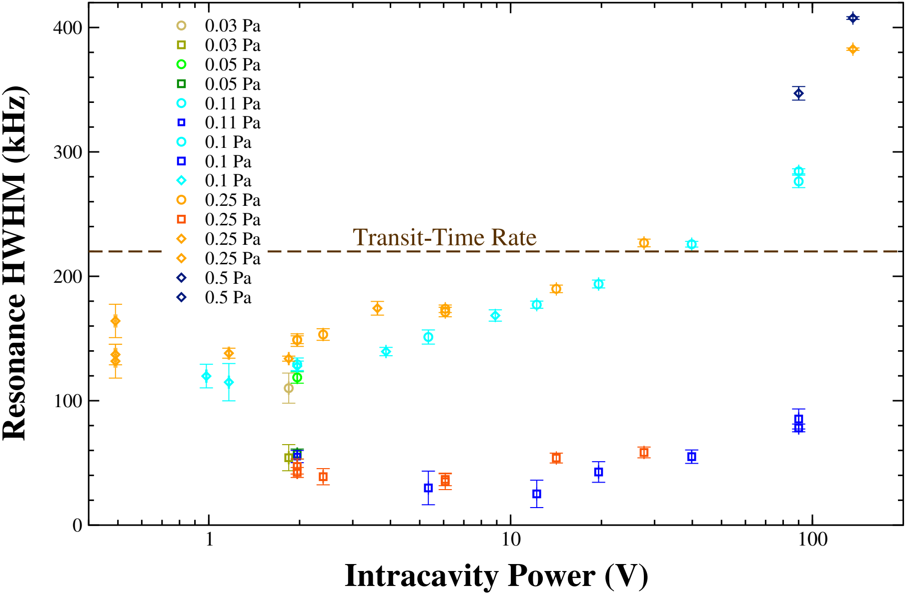
ν_0 = 217043458142 (15) kHz
Γ = 314.4 (12.4) kHz

ν_0 = 217043458145 (3.8) kHz
Γ = 318.7 (3.9) kHz

ν_0 = 217043458130 (4.9) kHz
Γ = 316.8 (4.9) kHz

Resonance Width Power Dependence

Power Broadening, NICE-OHMS of C_2H_2, Transition R_2, $\nu_1 + \nu_2 + (2\nu_4 + \nu_5)^1$



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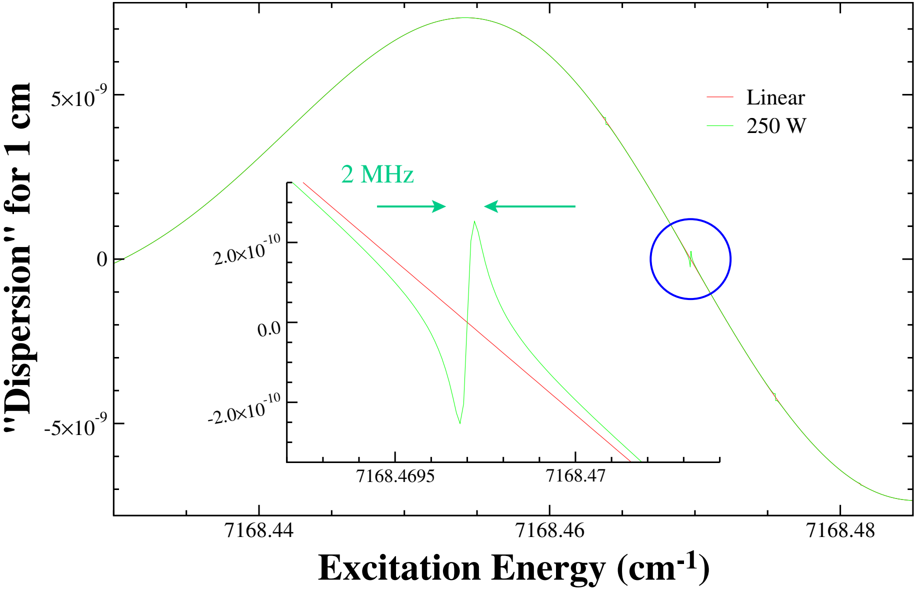
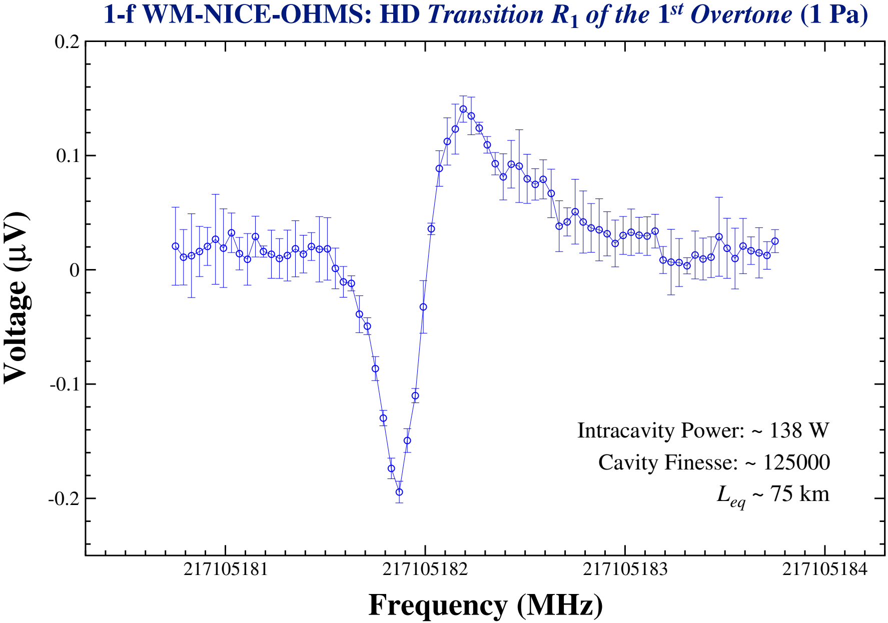
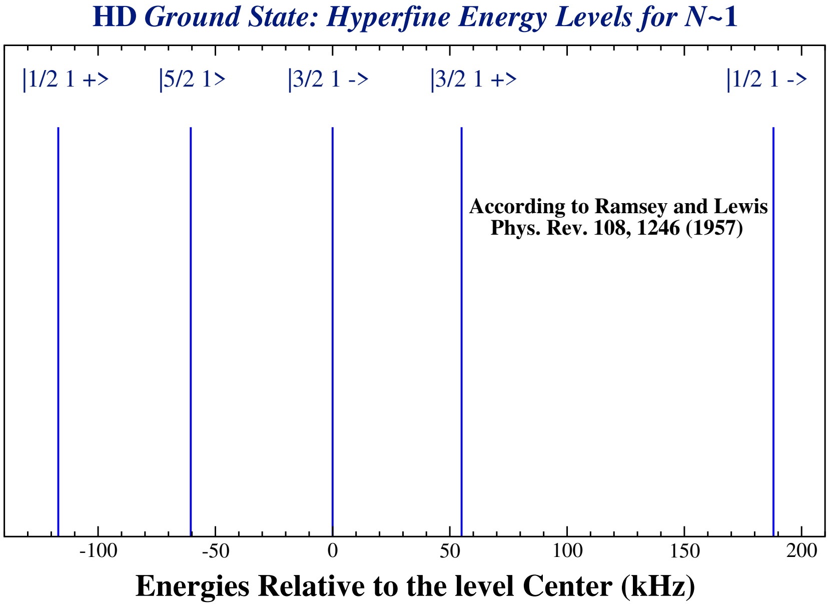
Simulation of HD: First Overtone, Transition *R*(0)



HD: 1st Overtone, Transition *R*(1)



HD Hyperfine Structure according to N. Ramsey



Discussion on HD (Work in Progress)

- New Transition Frequency: 217.105 181 891 (15) THz, $\mathbf{< 1 \times 10^{-10}}$, (published value: 217.105 192 (30) THz [Kassi/Campargue JMS, 2011])

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Bibliography

- Broad-Band Cavity Ring-Down Spectroscopy, Chem. Rev., 103, 5239 (2003)
- Chemical Sensing Using Fiber Cavity Ring-Down Spectroscopy, Sensors, 10, 1716 (2010)
- Probing Molecular Species by Cavity Ringdown Laser Absorption Spectroscopy, Application to the Spectroscopy and Dynamics of Jet-Cooled NO_2, CR. Acad. Sci. Paris Série IV, 2, 929 (2001)
- Cavity-Enhanced Spectroscopy and Sensing, Ed. by G. Gagliardi and H.-P. Loock, Springer (2014)
- Cavity Ringdown Spectroscopy: An Ultratrace-Absorption Measurement Technique, Ed. by K.W.~Busch and M.A.~Busch, ACS Symposium Series, 1999
- Sub-Doppler frequency metrology in HD for test of fundamental physics, Cozijn et al., Phys. Rev. Letters, 120, 153002 (2018)
- Toward a Determination of the Proton-Electron Mass Ratio from the Lamb-Dip Measurement of HD, Tao et al. Phys. Rev. Letters, 120, 153001 (2018)

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Acknowledgments

Thank for your Attention

Laboratoire de Physico-Chimie de l'Atmosphère

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