Noise-Immune Cavity-Enhanced Optical Frequency Comb Spectroscopy

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and Aleksandra Foltynowicz
Department of Physics, Umeå University, Sweden

CLEO:2015, San Jose, May 2015

Laser-based Spectroscopic Technique

Expectations

- Broad spectral bandwidth
- High spectral resolution
- High absorption sensitivity
- Short measurement time with high SNR

Laser-based Spectroscopic Technique

Solutions

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✓ Optical Frequency Comb →

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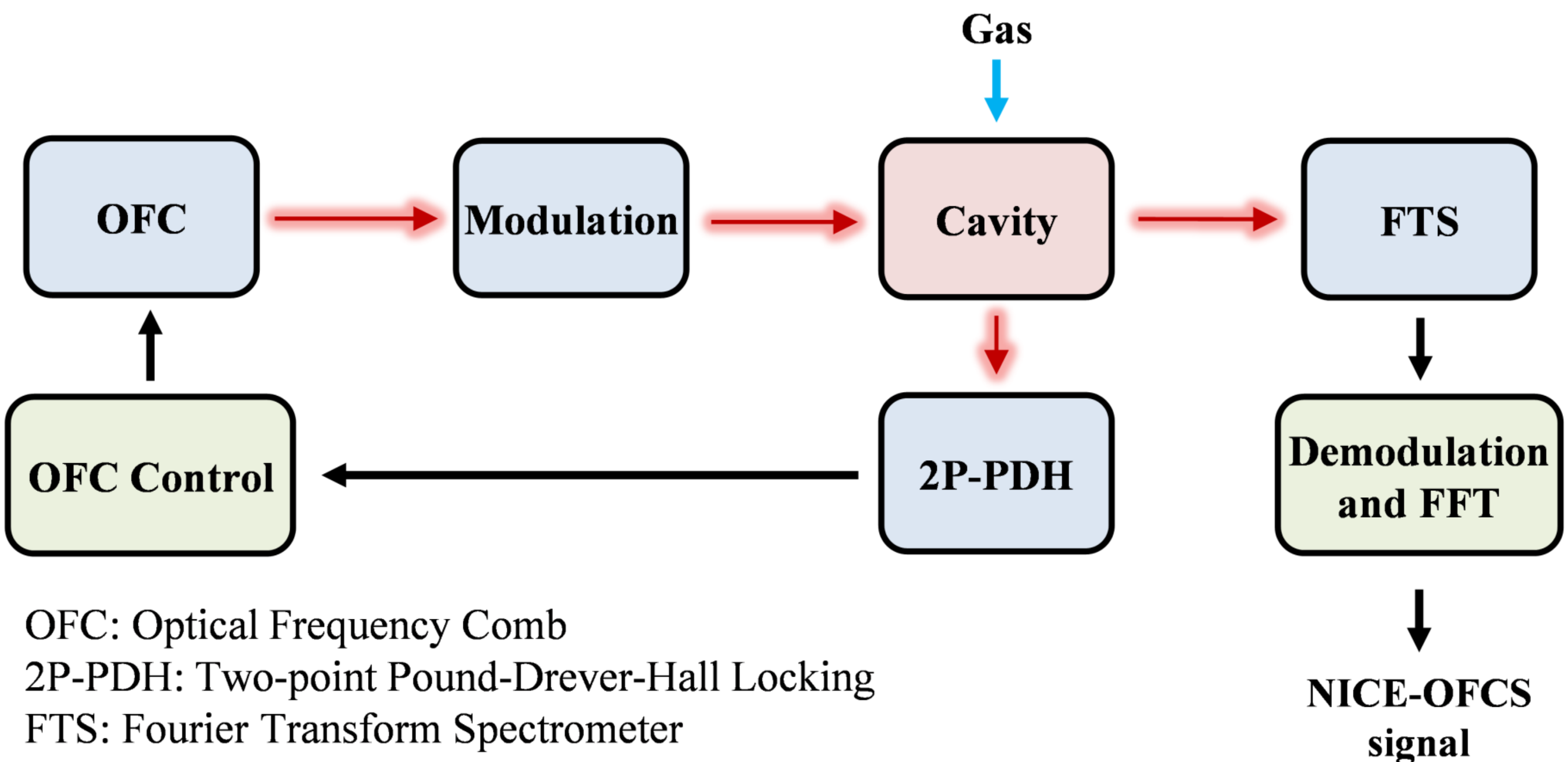
Fourier-Transform-Based Noise-Immune Cavity-Enhanced Optical Frequency Comb Spectroscopy (FT-Based NICE-OFCS)

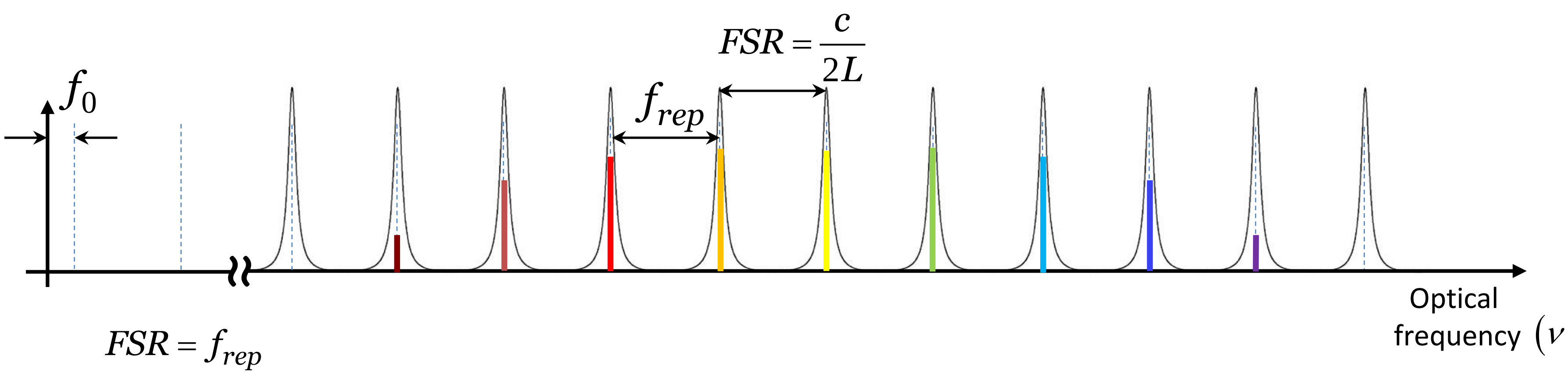
FT-based NICE-OFCS Principle



OFC: Optical Frequency Comb
2P-PDH: Two-point Pound-Drever-Hall Locking
FTS: Fourier Transform Spectrometer
FFT: Fast Fourier Transform

Optical Connection
Electrical Connection
Pipline Connection

OFC and Enhancement Cavity

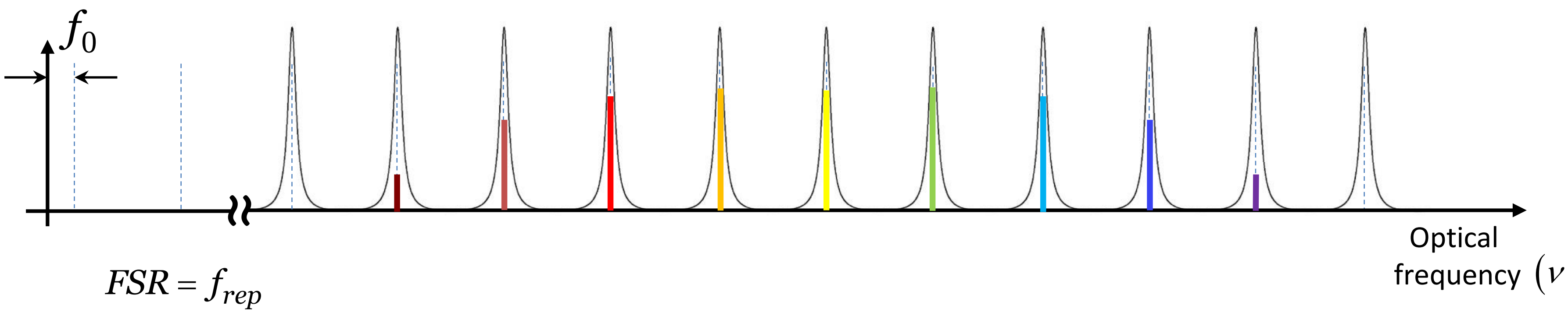


$FSR = f_{rep}$

Proper f_0

A. Khodabakhsh *et al.*, Opt. Lett. **39**, 5034 (2014)
A. Foltynowicz *et al.*, Phys. Rev. Lett. **107**, 233022 (2011)

OFC and Enhancement Cavity



$FSR = f_{rep}$

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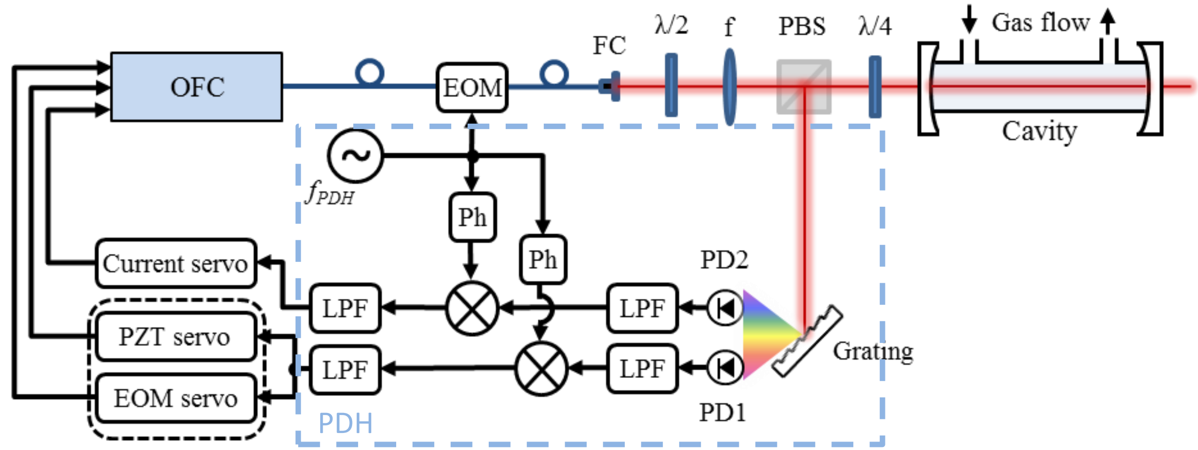
Two point PDH locking:



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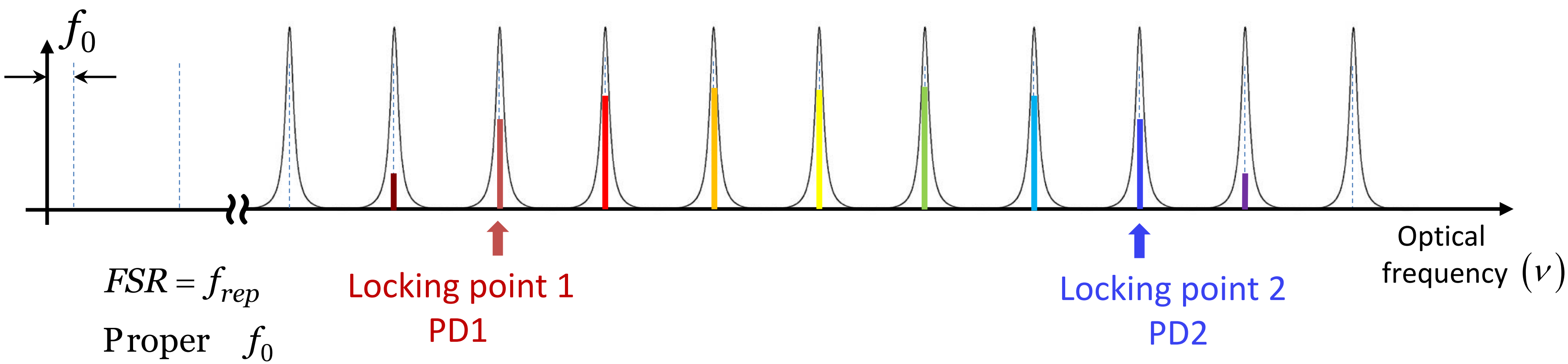
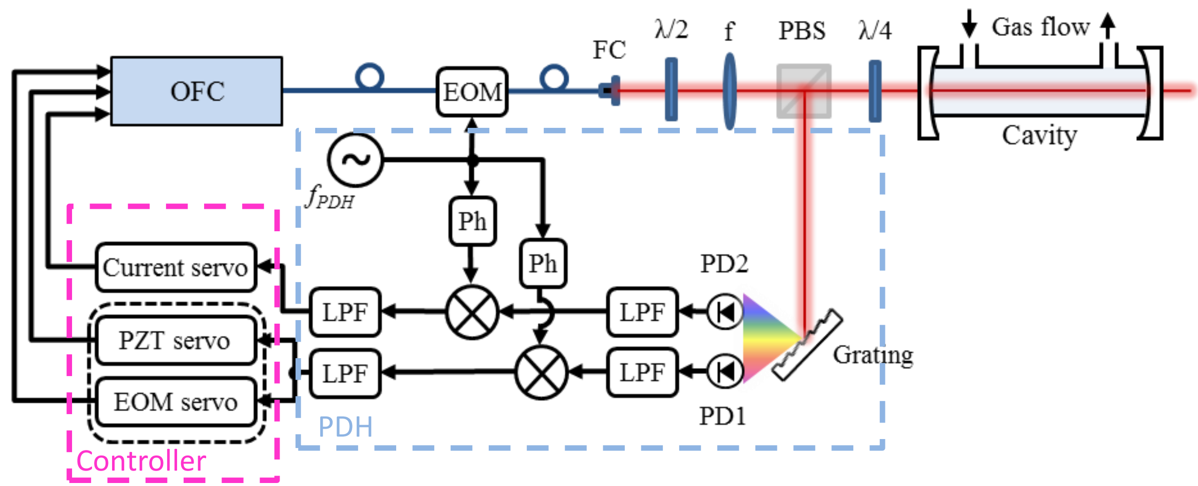


Two point PDH locking:

- Locking point 1 acts on f_0
- Locking point 2 acts on f_{rep}



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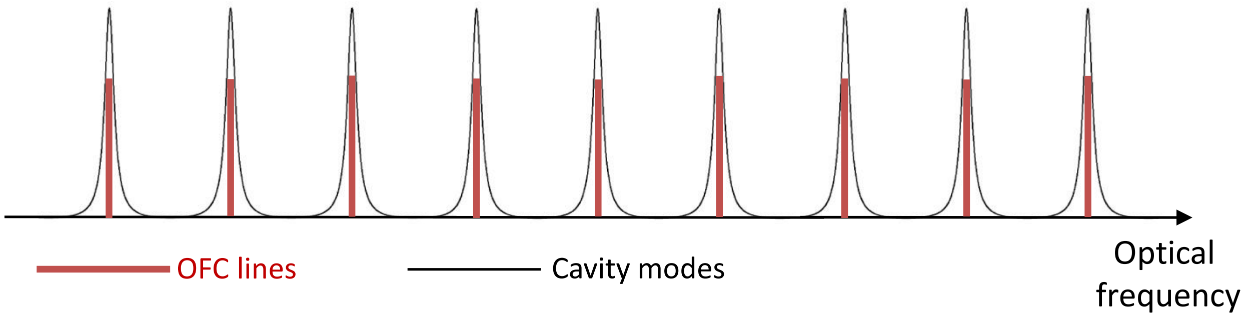
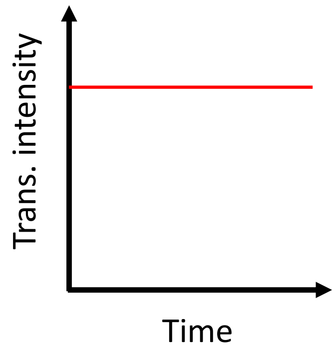
Noise Sources

Frequency to Amplitude Noise Conversion





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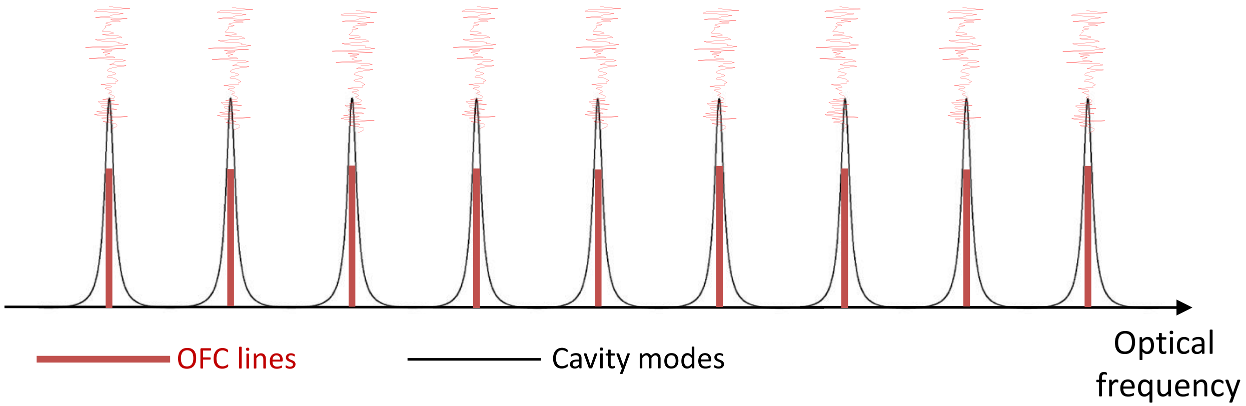

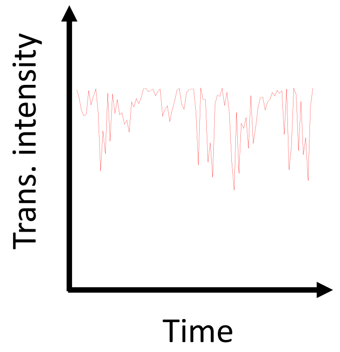

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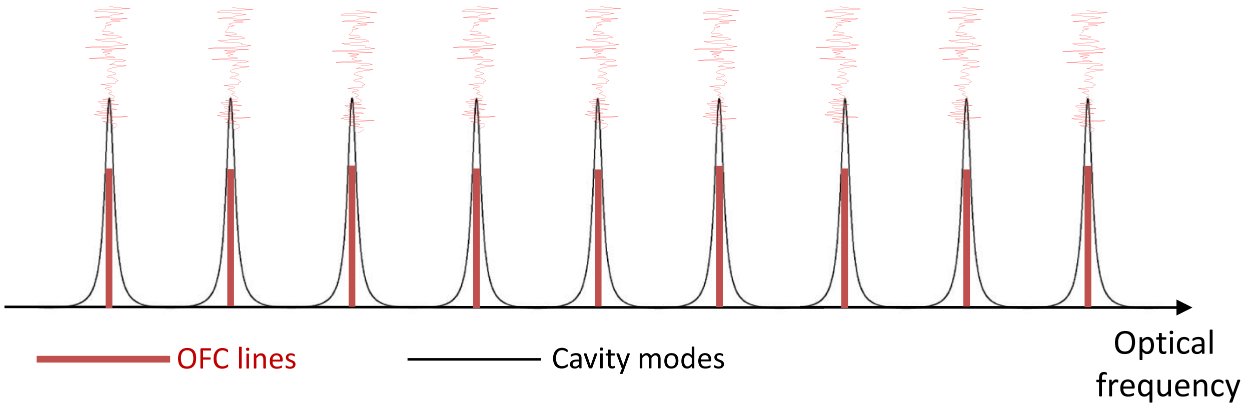
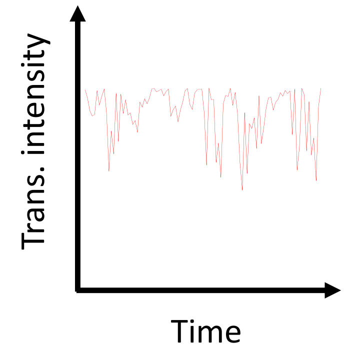
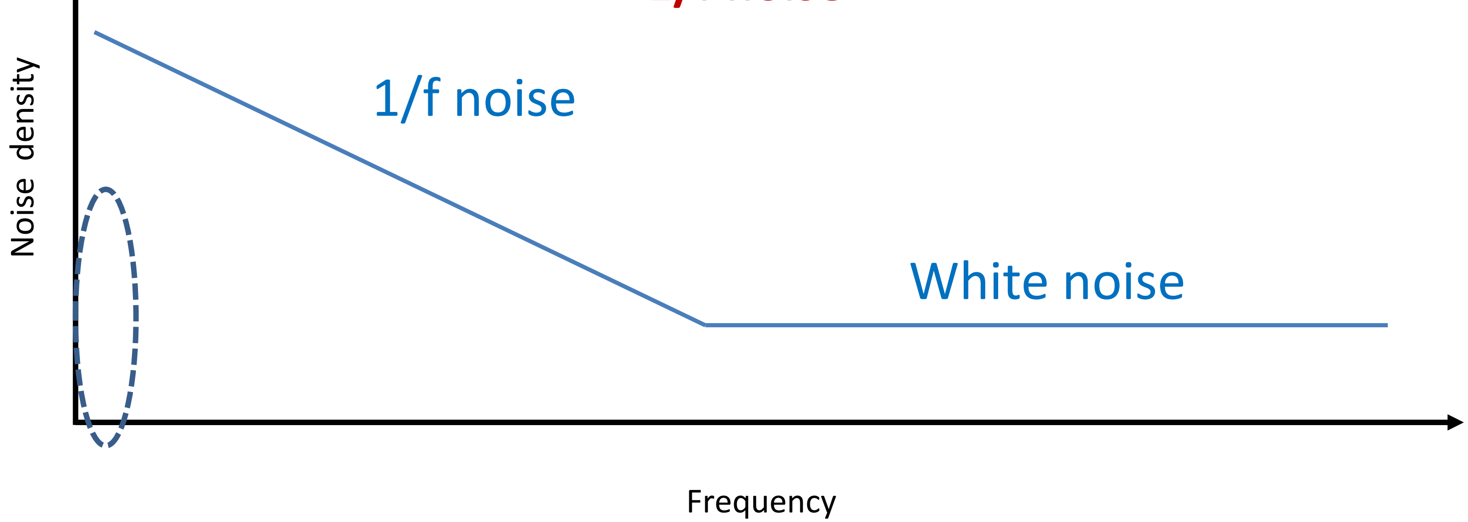




1/f noise



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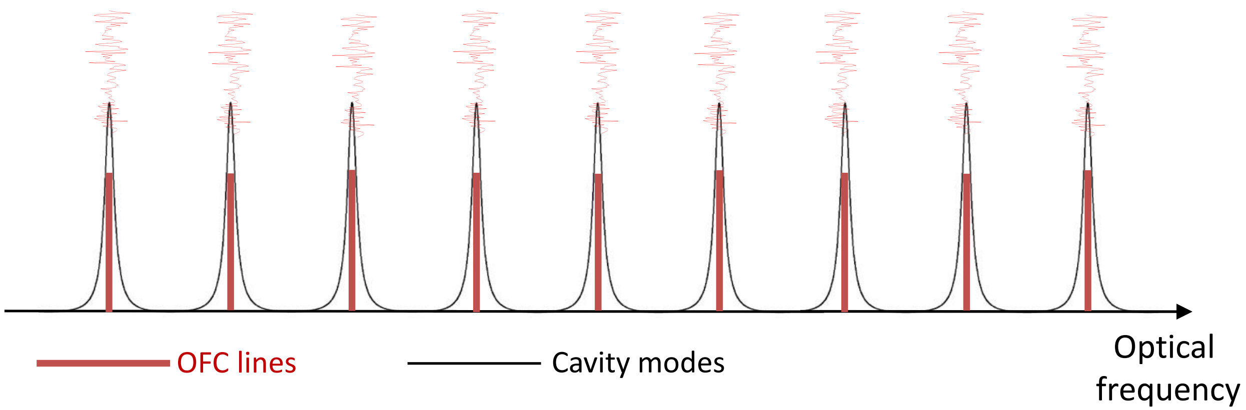

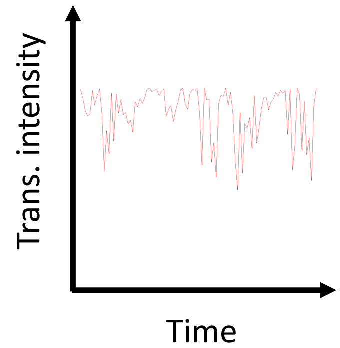

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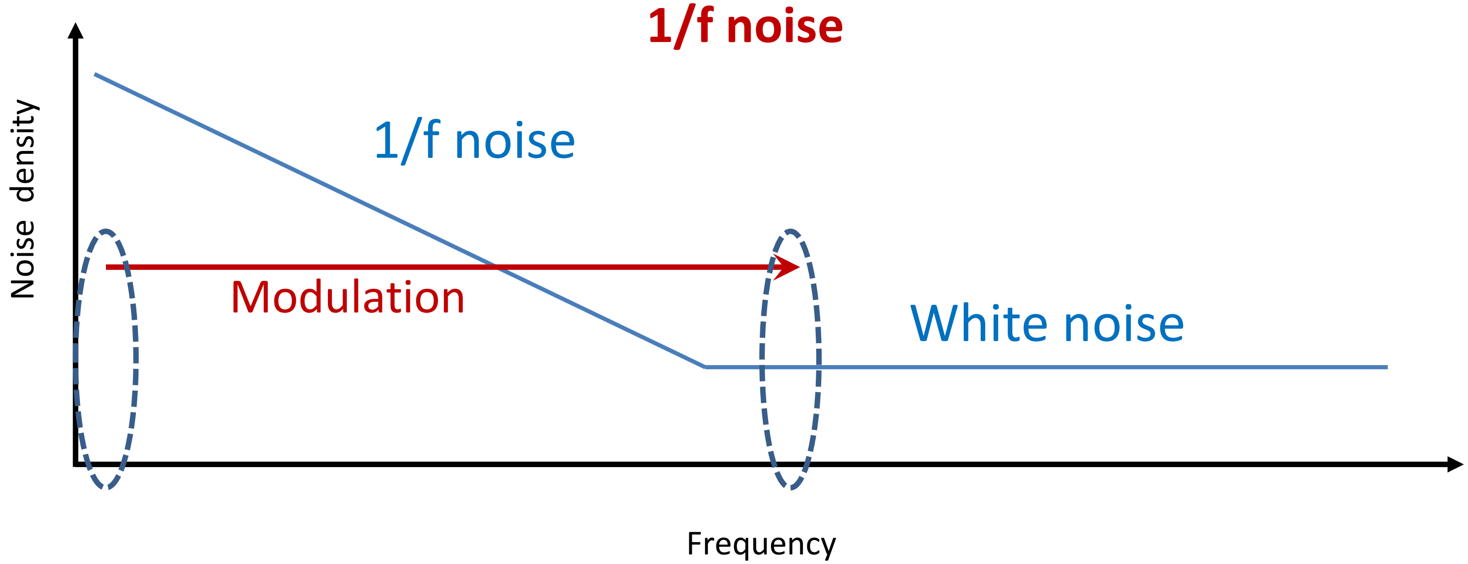
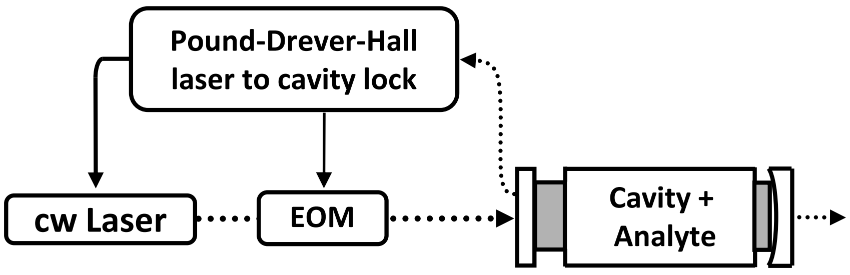
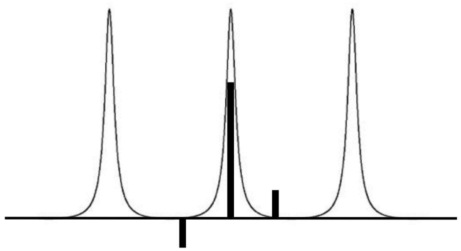


NICE-OHMS

Noise-Immune Cavity-Enhanced Optical Heterodyne Molecular Spectroscopy
(Alternative name: Cavity-Enhanced Frequency Modulation Spectroscopy)





J. Ye, *et al.*, J. Opt. Soc. Am. B **15**, 6 (1998)

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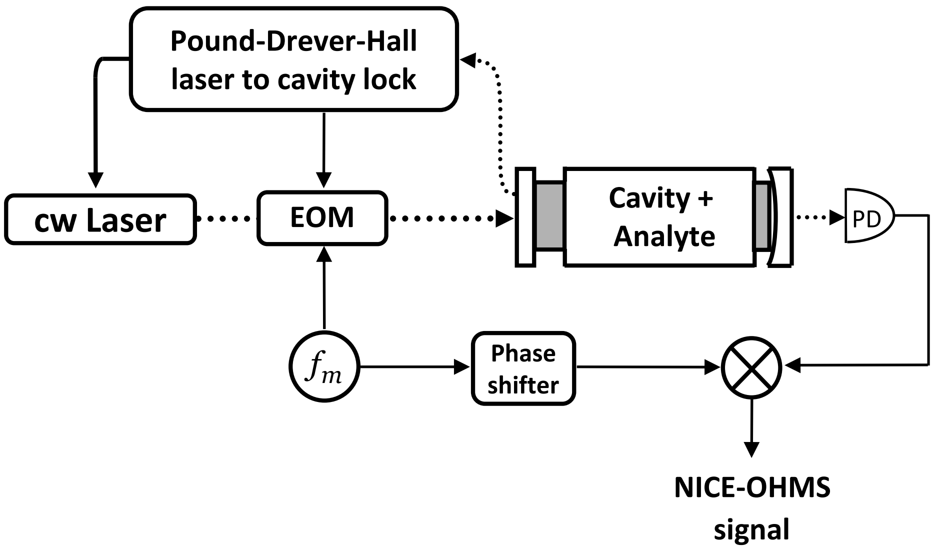

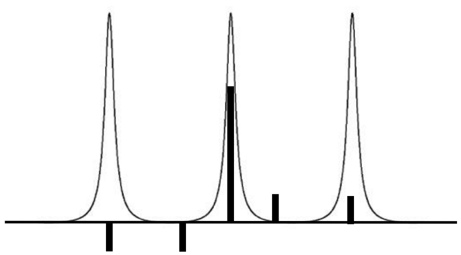

Noise Immunity: $f_m = qFSR$

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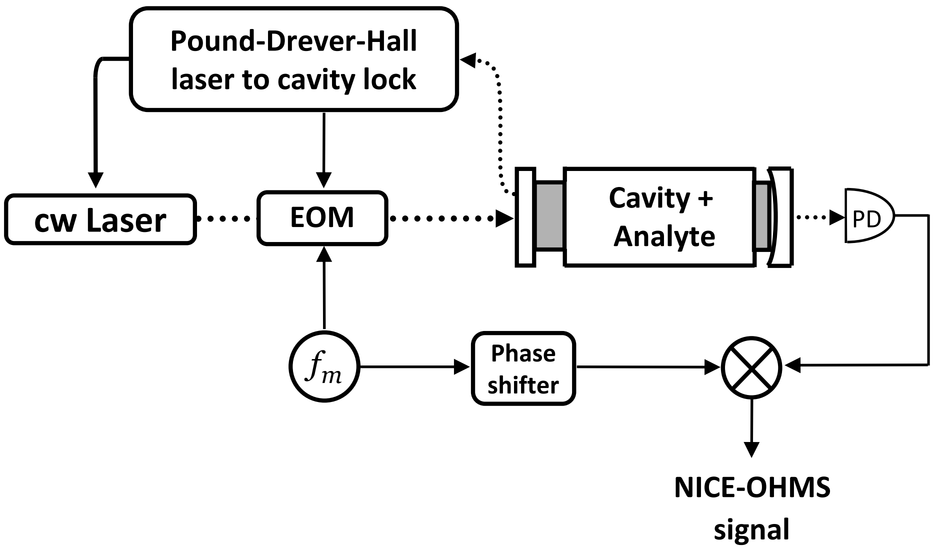

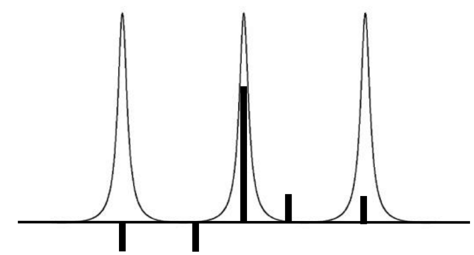

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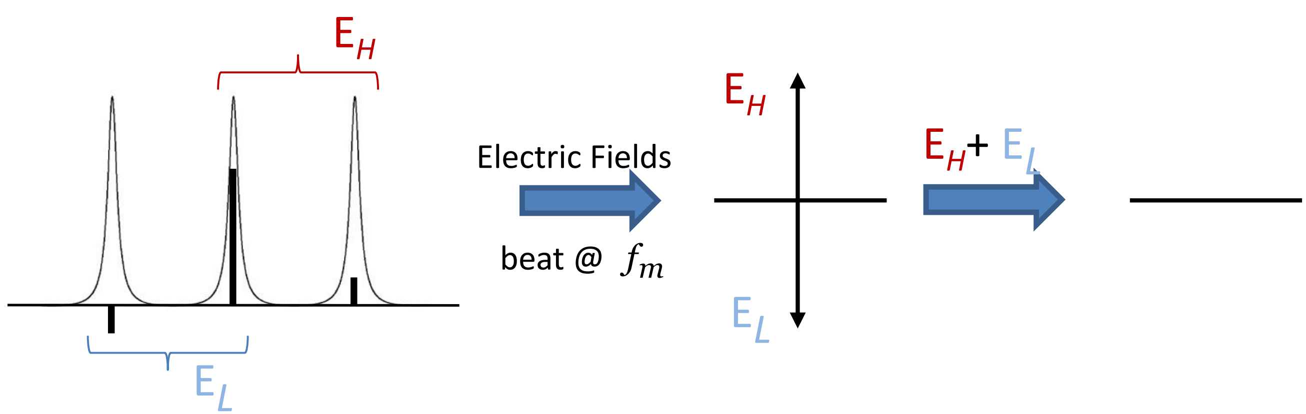


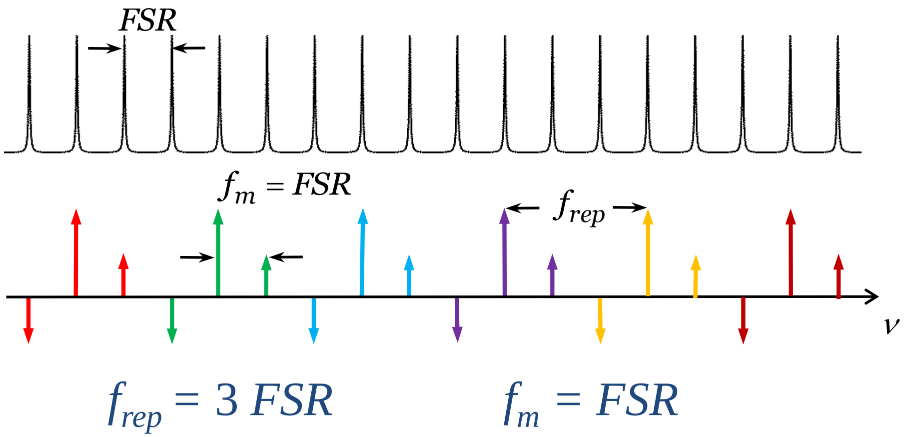
Frequency to amplitude
noise immune signal

J. Ye, *et al.*, J. Opt. Soc. Am. B **15**, 6 (1998)

Comb-Cavity Matching

- Impractically long linear cavity for typical OFC sources (e.g. 1.8 m for f_{rep} 250 MHz)

General case



A. Khodabakhsh *et al.*, Appl. Phys. B **119**, 87 (2015)

Comb-Cavity Matching

- Impractically long linear cavity for typical OFC sources (e.g. 1.8 m for f_{rep} 250 MHz)
- Instability/cross-talk from sideband-sideband beatings

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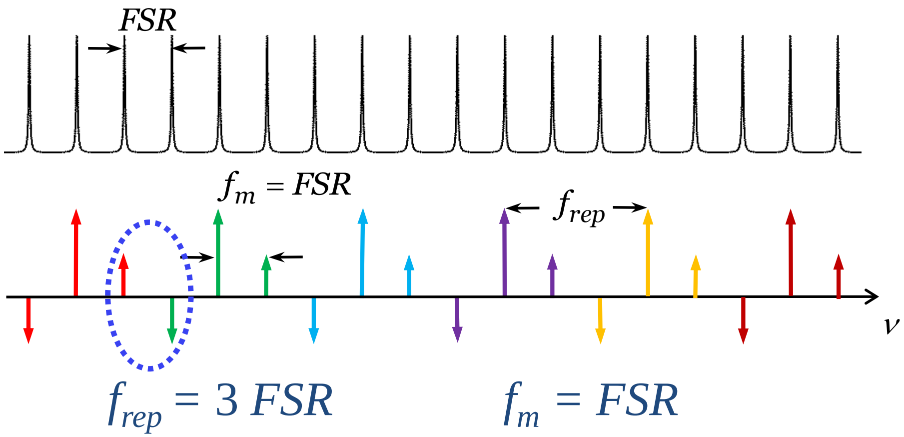

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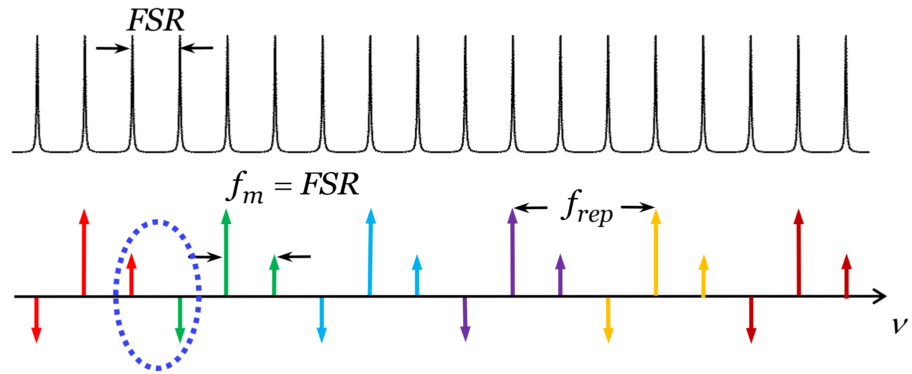
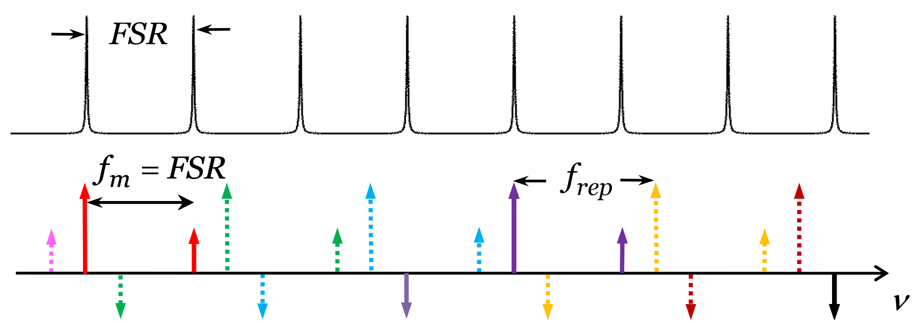


$f_{rep} = 3\ FSR$ $\quad$ $f_m = FSR$

- Shorter linear cavity (80 cm)

Filter solution



$f_{rep} = 4/3\ FSR$ $\quad$ $f_m = FSR$

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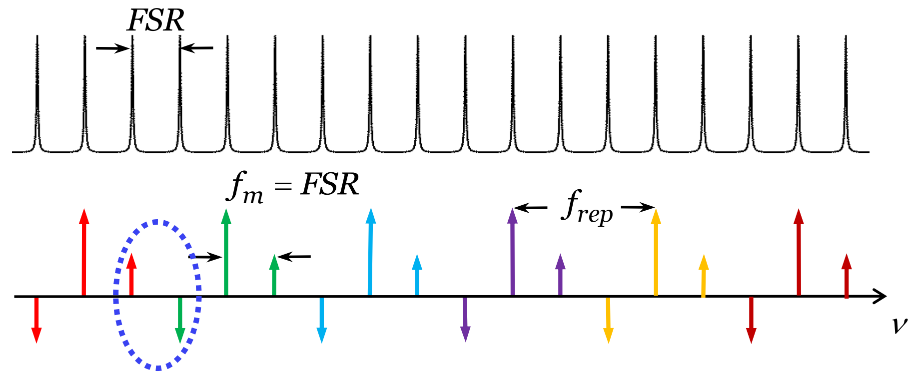
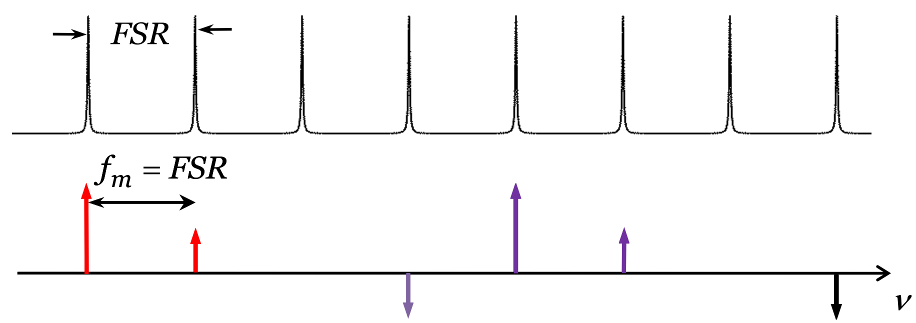


$f_{rep} = 3\ FSR$ $\quad$ $f_m = FSR$

- Shorter linear cavity (80 cm)
- Lower transmitted power
- No sideband-sideband beatings – higher stability

Filter solution



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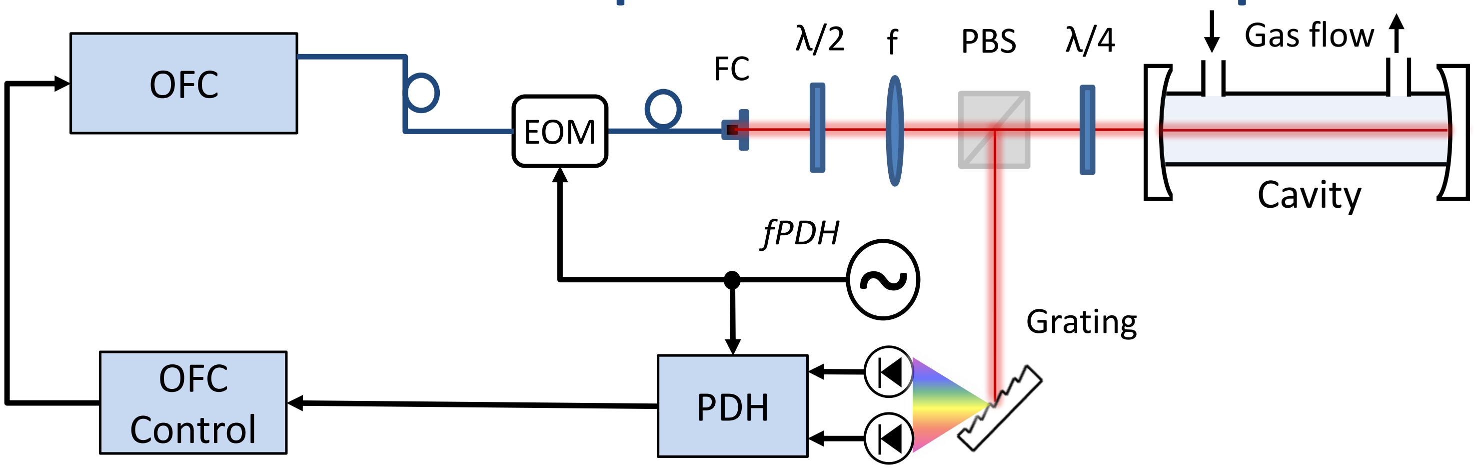
Experimental Setup



- Er:fiber femtosecond laser:
  1.5-1.6 µm, 250 MHz repetition rate, 120 mW
- Cavities:
  finesse ~1100 / ~9000, length 80 cm, FSR 187 MHz
- Two-point Pound-Drever-Hall lock

OFC – optical frequency comb
EOM – electro-optic modulator
FC – fiber collimator
PBS – polarizing beam splitter
FTS – Fourier transform spectrometer
BPF – band-pass filter
LPF – low-pass filter
FFT – fast Fourier transform
Ph – phase shifter
DDS – direct digital synthesizer
PDH – Pound-Drever-Hall locking electronics
f_{PDH} – PDH modulation frequency
f_m – NICE-OFCS modulation frequency.

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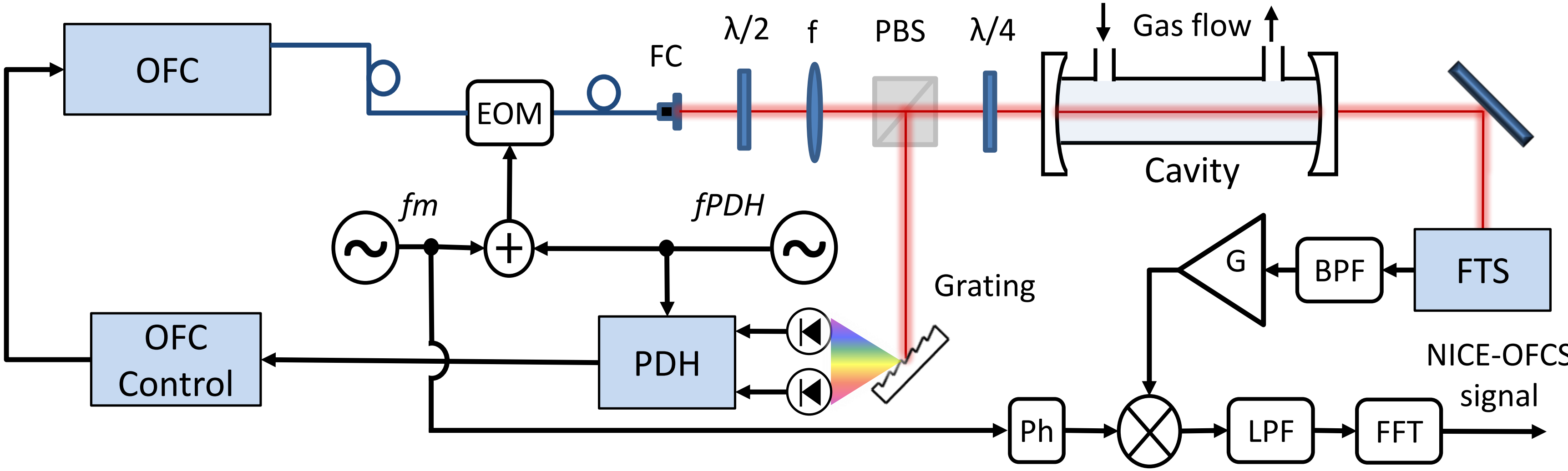

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- Fast-scanning FTS with a couple of moving back-to-back retro-reflectors:
  0.8 m/s OPD Scan, ~0.5 s measurement time for 750 MHz resolution
- Synchronous demodulation and FFT

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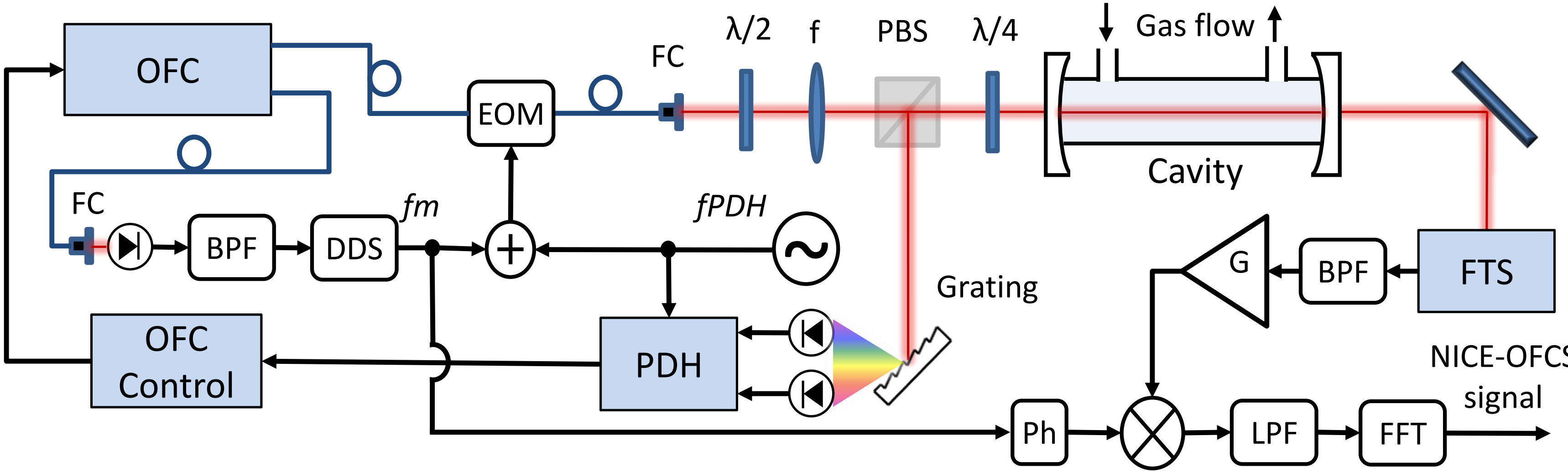

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- Passive lock of the f_m to the cavity FSR using f_{rep} clocked DDS

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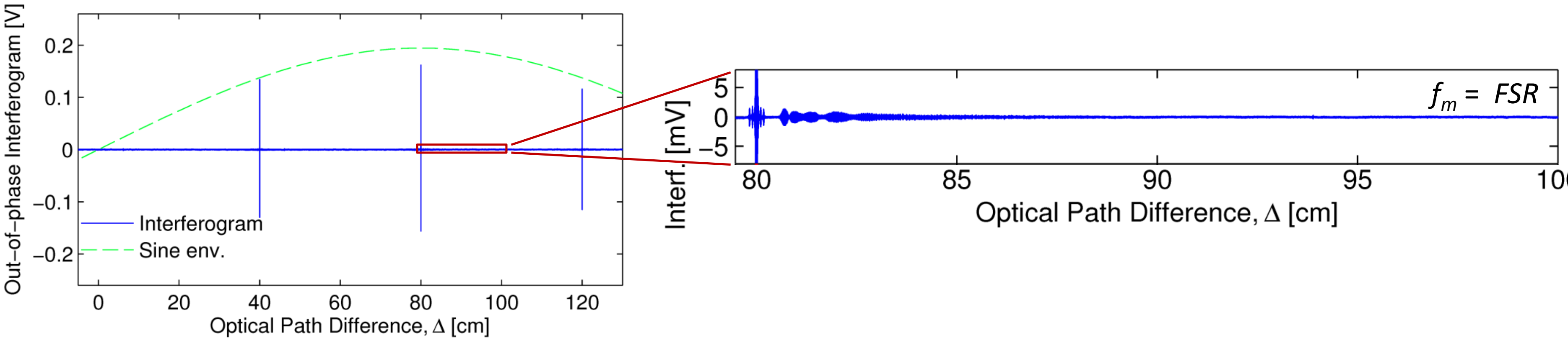
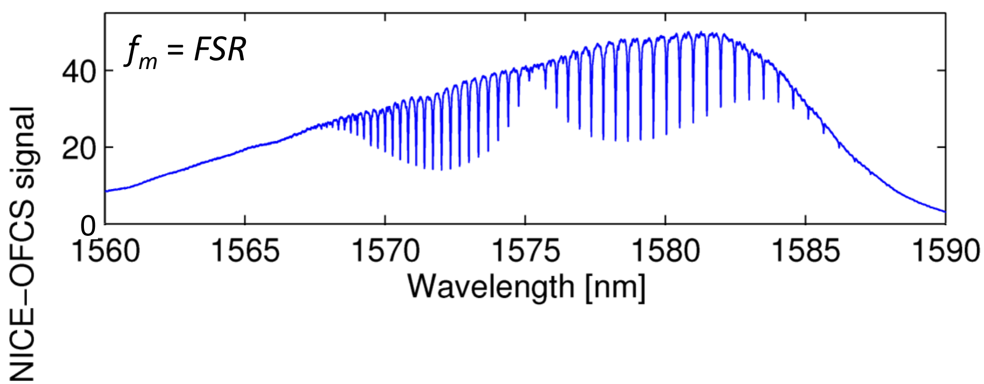
Spectra and Noise Immunity

OPD domain interferogram

- Absorption features clearly visible in the interferogram



After FFT



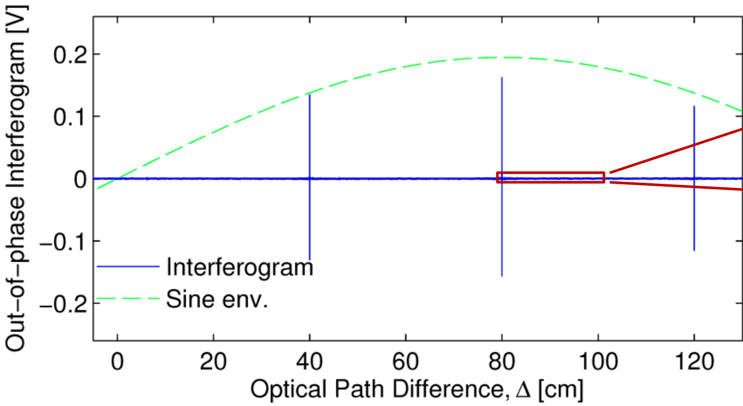
- 1% CO_2 in 500 Torr N_2
- Cavity finesse: ~1100
- Spectral Bandwidth: 40 nm
- Spectral resolution: 750 MHz
- Acquisition time: 0.5 s

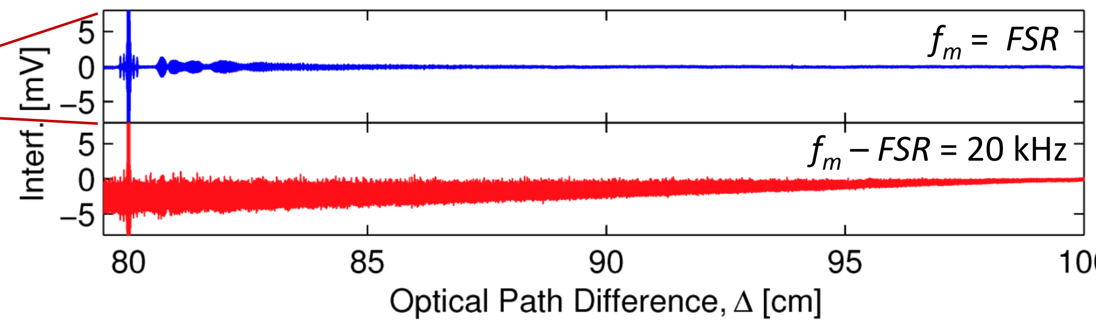
A. Khodabakhsh *et al.*, Opt. Lett. **39**, 5034 (2014)

Spectra and Noise Immunity

OPD domain interferogram

- Absorption features clearly visible in the interferogram
- Mismatch of f_m and FSR declines the noise immunity and decreases the SNR





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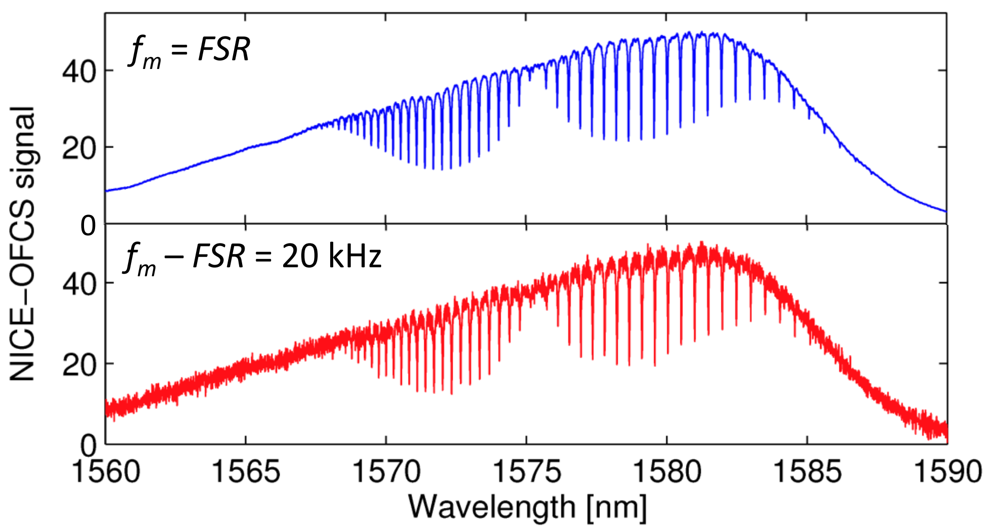

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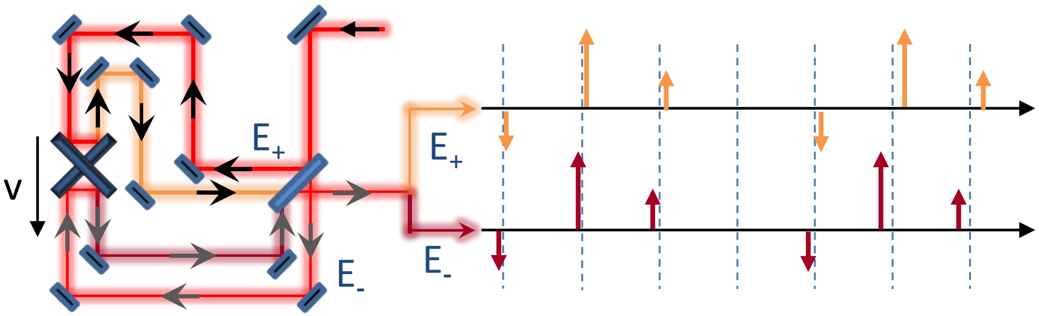
Signal modelization

Electric field: **comb modulated at f_m and Doppler shifted by v/c**



$$(\omega_n \pm \omega_m)\left(1+\frac{2v}{c}\right)$$

$$(\omega_n \pm \omega_m)\left(1-\frac{2v}{c}\right)$$

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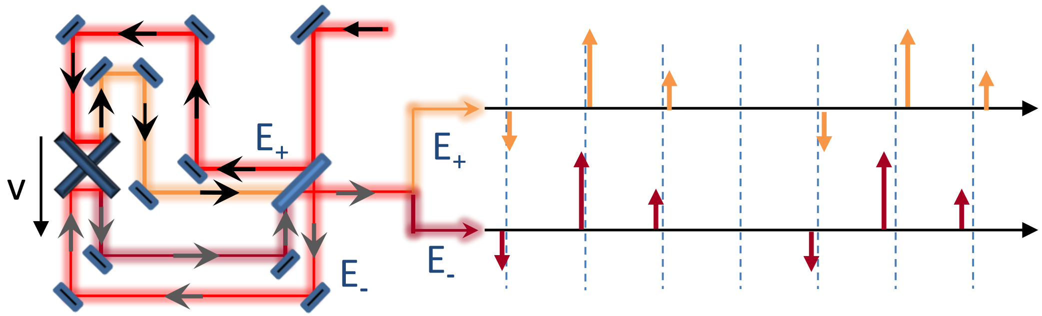

Doppler shift

$$(\omega_n \pm \omega_m)\left(1 + \frac{2v}{c}\right)$$

$$(\omega_n \pm \omega_m)\left(1 - \frac{2v}{c}\right)$$

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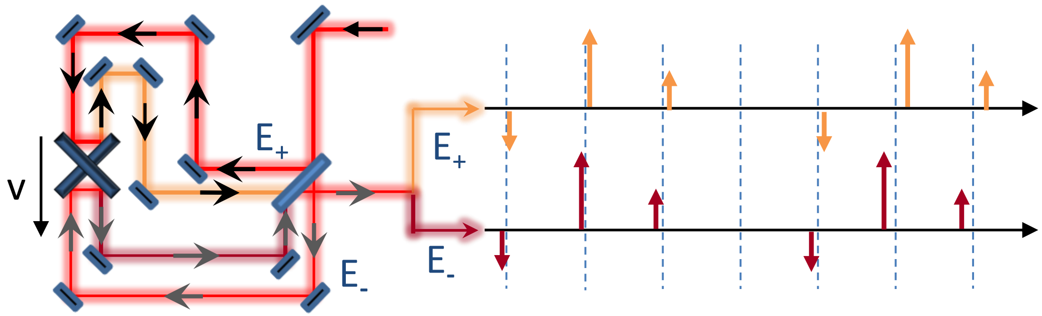

$$E_{\pm} = \sum_{n} \sum_{k=-1,0,1} \frac{E_n}{4} J_k(\beta) T_{n,k}\, e^{i\left[(\omega_n + k\omega_m)\left(t \pm \frac{\Delta}{c}\right)\right]} + \mathrm{c.c.}$$

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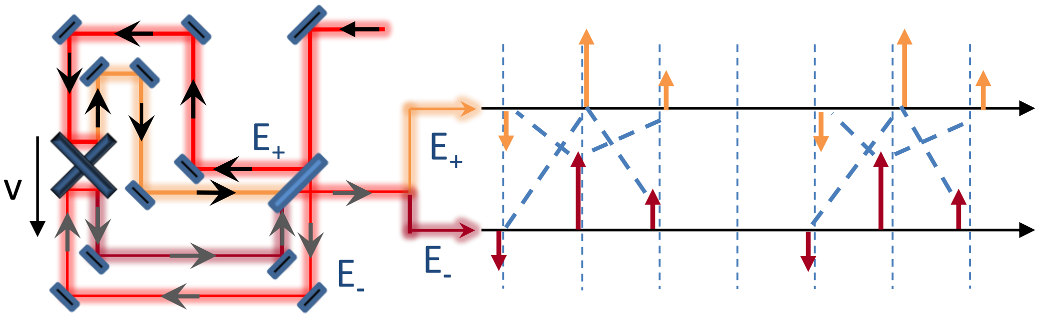

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Intensity: beating of the two combs demodulated at f_m and $\phi = \pi / 2$

$$I_{\omega_m} = J_0(\beta) J_1(\beta) \sum_n I_n \left\{ \begin{array}{l} \cos\left(\omega_n \frac{\Delta}{c}\right) \cos\left(\omega_m \frac{\Delta}{2c}\right) \mathrm{Re}\left(T_{n,0} T^*_{n,-1} - T^*_{n,0} T_{n,+1}\right) \\ + \sin\left(\omega_n \frac{\Delta}{c}\right) \sin\left(\omega_m \frac{\Delta}{2c}\right) \mathrm{Re}\left(T_{n,0} T^*_{n,-1} + T^*_{n,0} T_{n,+1}\right) \end{array} \right\}$$

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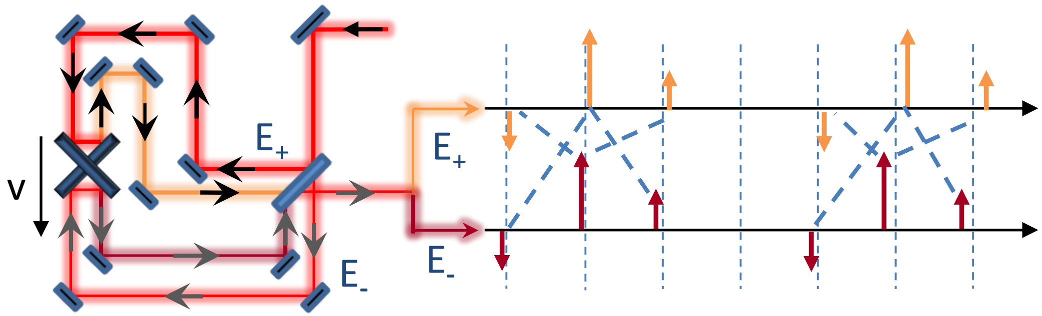

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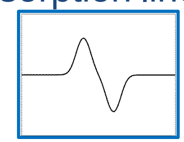
For weak absorption lines:

$$\left[\delta^F_{n,-1} - \delta^F_{n,+1}\right]$$



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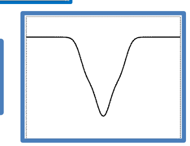
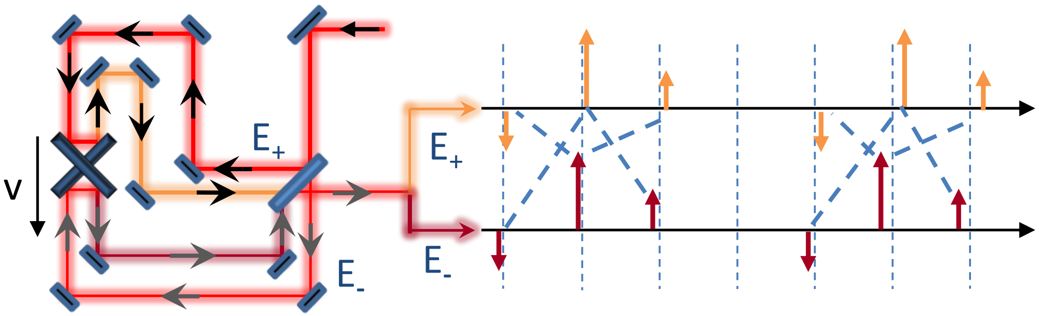


- Direct cavity-enhanced absorption like signal which makes NICE-OFCS calibration-free

A. Khodabakhsh *et al.*, Appl. Phys. B **119**, 87 (2015)

Signal modelization

Electric field: comb modulated at f_m and Doppler shifted by v/c



$$E_{\pm} = \sum_{n} \sum_{k=-1,0,1} \frac{E_n}{4} J_k(\beta) T_{n,k}\, e^{i\left[(\omega_n + k\omega_m)\left(t \pm \frac{\Delta}{c}\right)\right]} + c.c.$$

Intensity: beating of the two combs demodulated at f_m and $\phi = \pi / 2$

$$I_{\omega_m} = J_0(\beta) J_1(\beta) \sum_{n} I_n \left\{ \begin{array}{l} \cos\left(\omega_n \frac{\Delta}{c}\right) \cos\left(\omega_m \frac{\Delta}{2c}\right) \mathrm{Re}\left(T_{n,0} T^*_{n,-1} - T^*_{n,0} T_{n,+1}\right) \\ + \sin\left(\omega_n \frac{\Delta}{c}\right) \sin\left(\omega_m \frac{\Delta}{2c}\right) \mathrm{Re}\left(T_{n,0} T^*_{n,-1} + T^*_{n,0} T_{n,+1}\right) \end{array} \right\}$$

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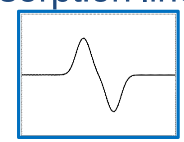

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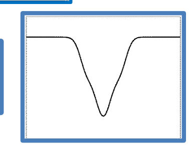

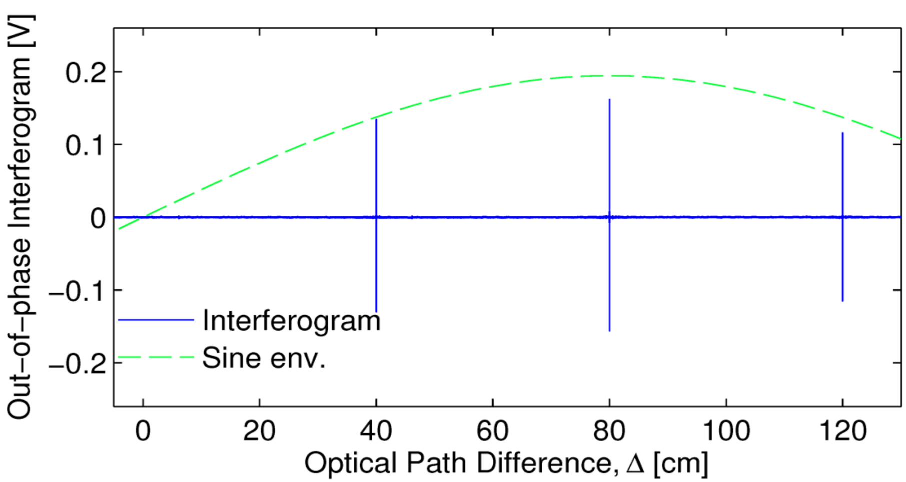

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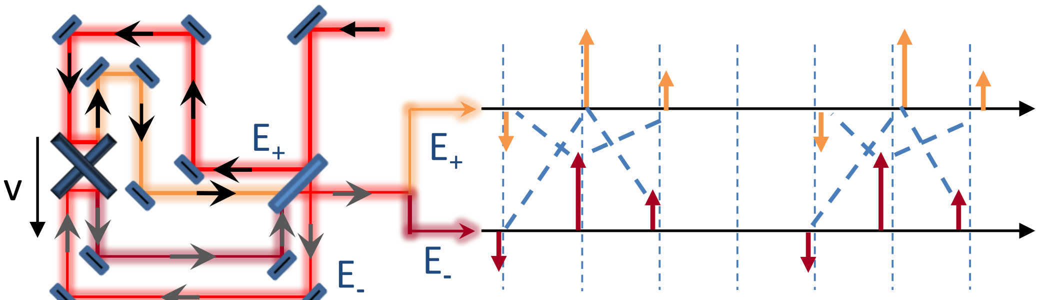

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Interferogram   Sine envelope

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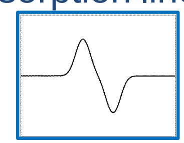

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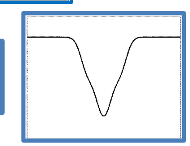

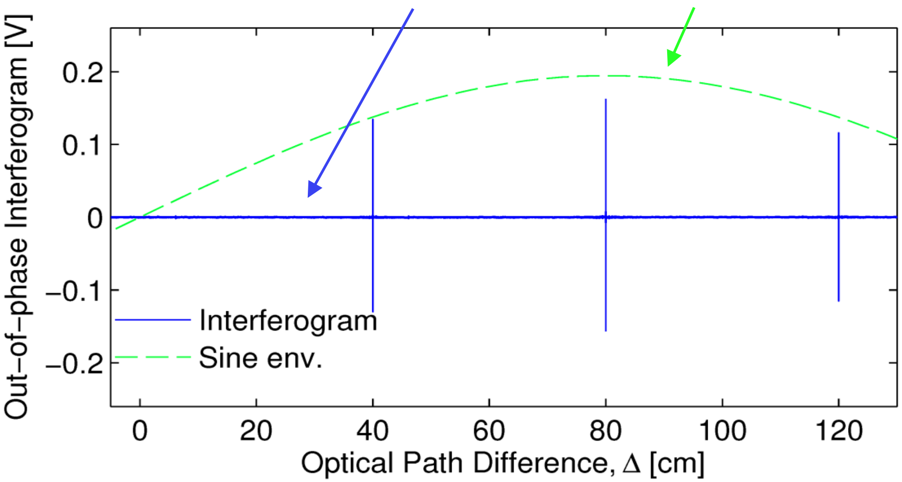

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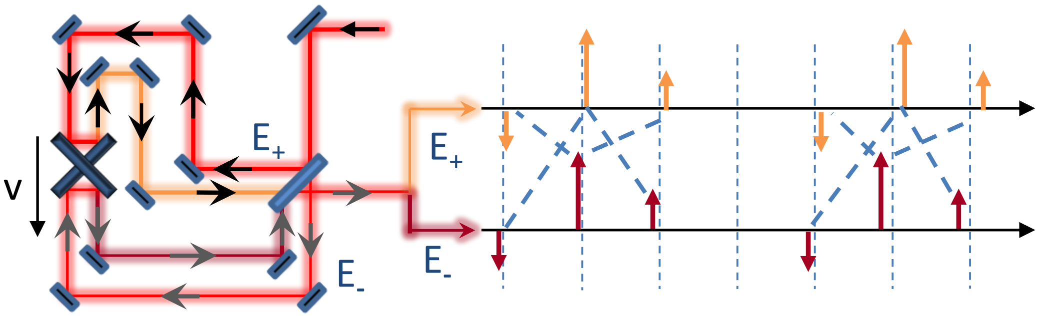

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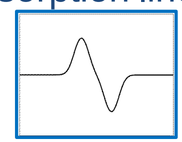

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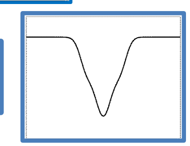

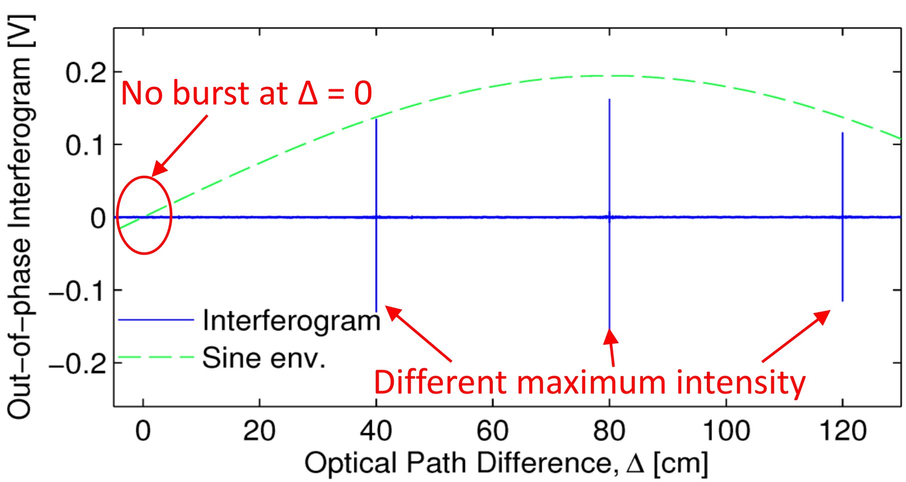

- Direct cavity-enhanced absorption like signal which makes NICE-OFCS calibration-free
- Interferogram intensity ponderated by the envelopes induced by the modulation frequency

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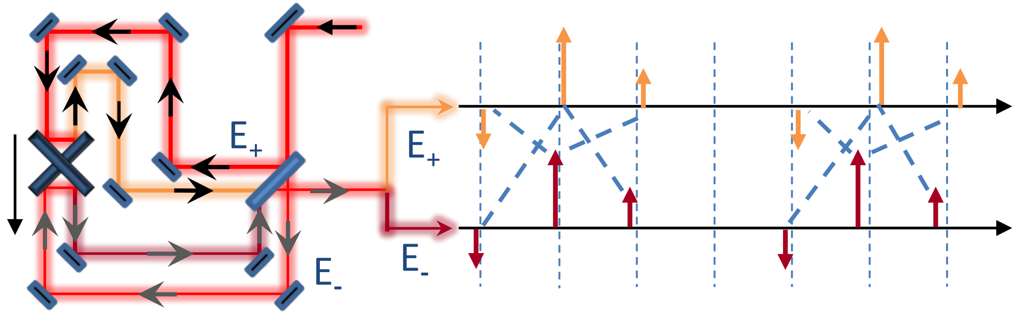

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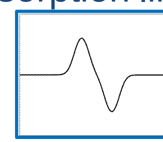

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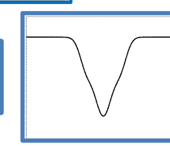

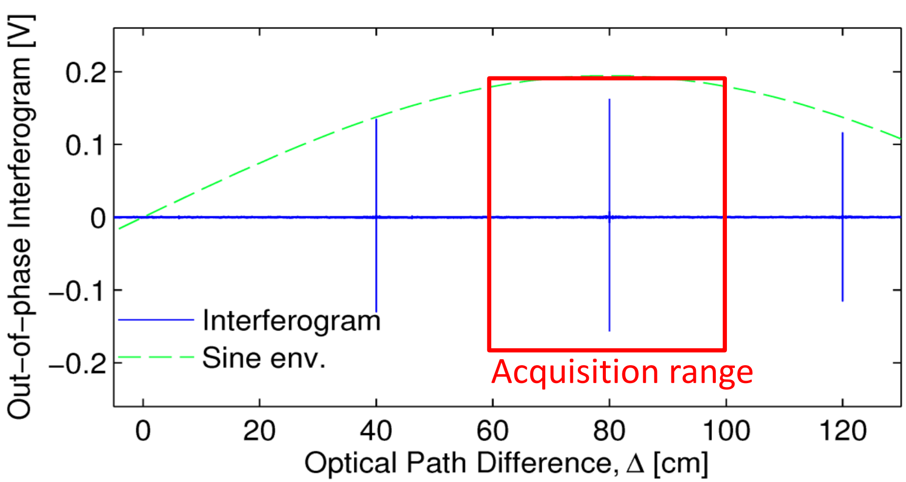

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Absorption lineshape model

Transmitted intensity

Molecular absorption

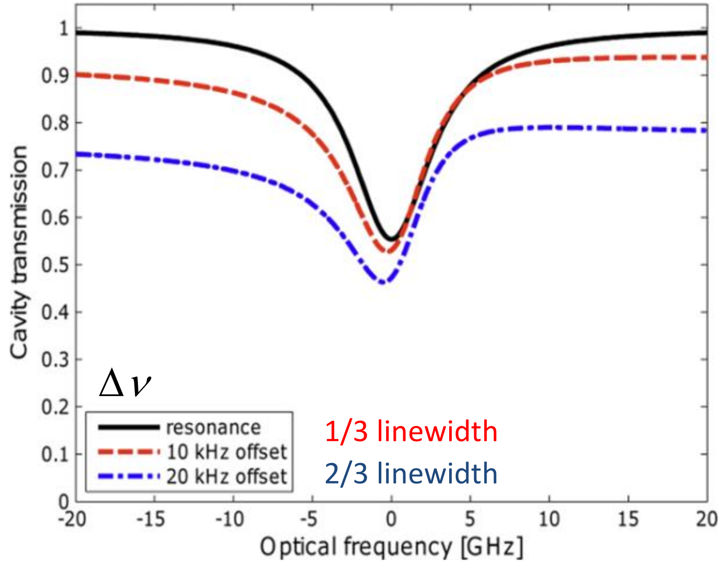
$$T_{n,k}(\nu) = \frac{T^2(\nu)e^{-\alpha(\nu)L}}{1 + R^2(\nu)e^{-2\alpha(\nu)L} - 2R(\nu)e^{-\alpha(\nu)L}cos[\phi(\nu)L + \varphi(\nu)]}$$

Molecular phase shift

Round trip intracavity phase shift

$$\varphi(\nu) = 4\pi\,\nu\frac{L}{c} = \frac{2\pi\nu}{FSR}$$

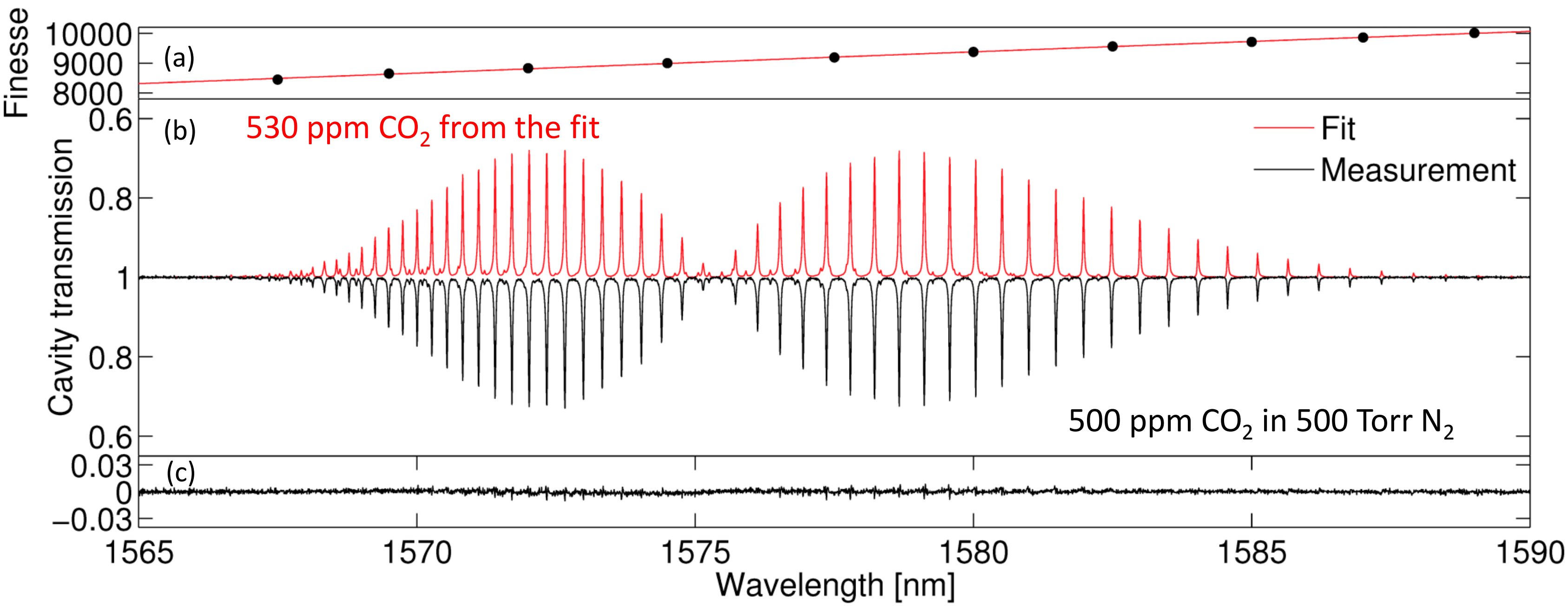
$$\varphi(\Delta\nu) = 2n\pi + 2\pi\frac{\Delta\nu}{FSR}$$



T – mirror transmission
R – mirror reflection
L – cavity length

A. Foltynowicz *et al.*, Appl. Phys. B **110**, 163 (2013)

Sensitivity and Detection Limit



- 500 ppm CO_2 in 500 Torr N_2
- Cavity finesse: ~ 9000
- Spectral Bandwidth: 40 nm
- Spectral resolution: 750 MHz
- Acquisition time: 0.5 s
- Noise equivalent absorption sensitivity:
  6.4×10^{-11} cm^{-1} Hz$^{-1/2}$ per spectral element

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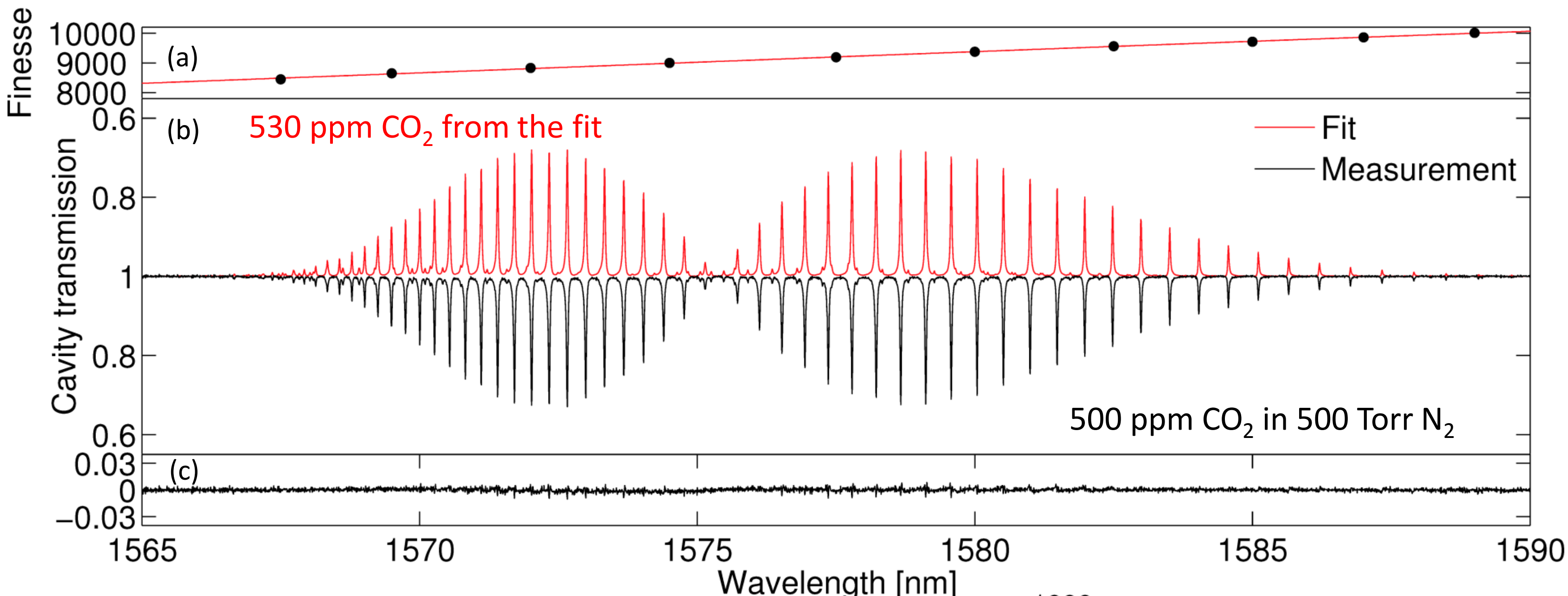

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- CO_2 detection limit (multiline fitting):
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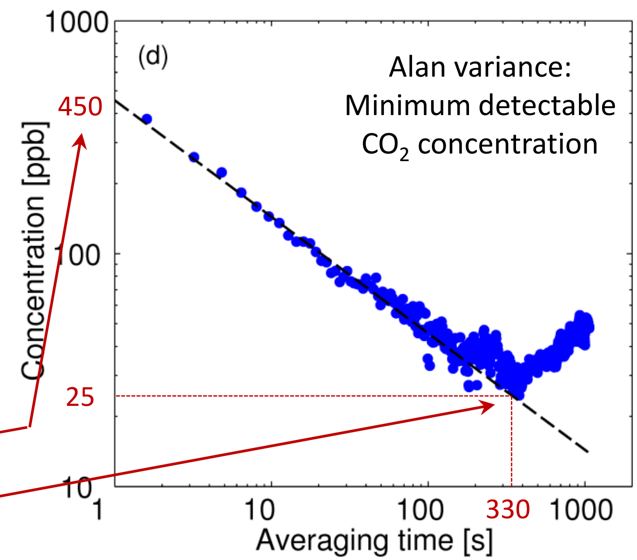
  25 ppb after 330 s



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Conclusions

- FT-based NICE-OFCS : broadband, highly sensitive, high resolution technique with a short acquisition time
- Calibration-free technique due to the existence of signal background (for a known cavity finesse)
- Stable, long term noise immune operation achieved with a simple passive lock
- Compatible with commercial FTIR instruments using a high bandwidth detector
- Standard and commercially available components
- Outlook: Improved model of the spectrum to decrease the concentration discrepancy

Acknowledgements

<u>Group leader</u>

Aleksandra FOLTYNOWICZ

<u>Postdoctoral fellows</u>

Lucile RUTKOWSKI

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<u>PhD students</u>

Amir KHODABAKHSH

Alexandra C. JOHANSSON

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Stiftelsen Lars Hiertas Minne

Thank you for your attention!