Compact Laser-Spectroscopic Gas Sensors Using Vertical-Cavity Surface-Emitting Lasers

Jia Chen

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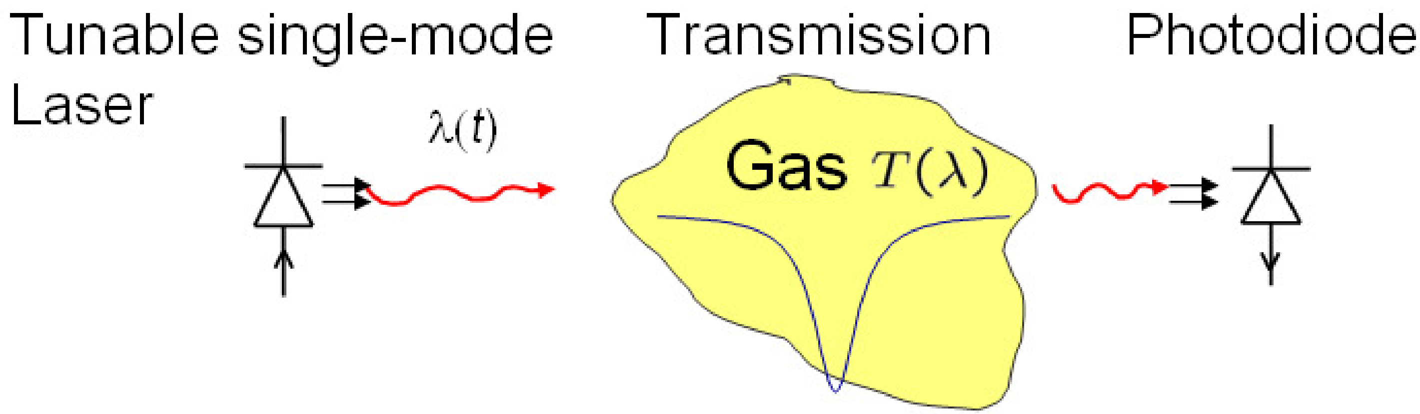
12.01.2011

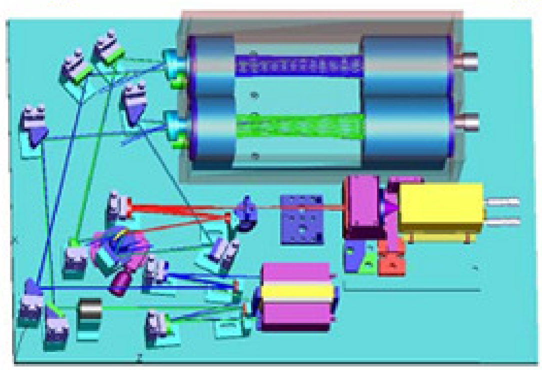
Tunable Diode Laser Spectroscopy (TDLS)



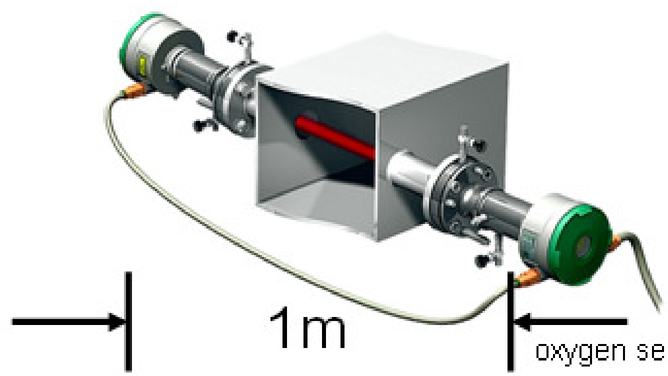
TDLS is a reference technique for gas sensing …

- highest possible selectivity - long term stable - in-situ measurement…

Existing sensor technology: complex, large in dimension, expensive

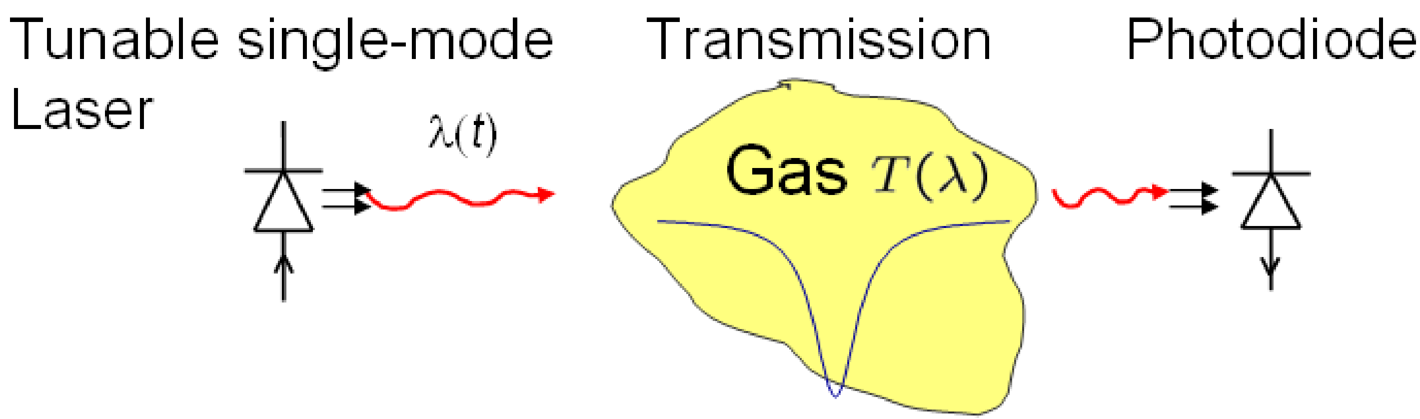


isotopic ratio intrument: Aerodyne Research



oxygen sensor: Siemens Analytic

Tunable Diode Laser Spectroscopy (TDLS)



TDLS is a reference technique for gas sensing …
- highest possible selectivity - long term stable - in-situ measurement…

Existing sensor technology: complex, large in dimension, expensive

Goal: develop miniaturized TDLS sensor

Dräger: electro-chemical cell

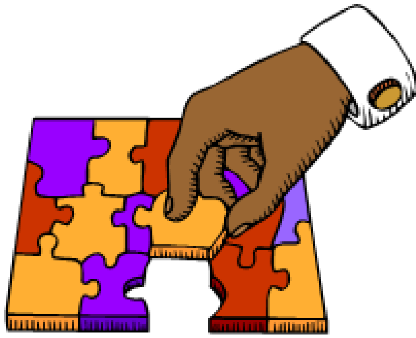
Questions of interest …

- How fast can the detection be carried out? (→ Laser)

- Can small sample volume be combined with high sensitivity? (→ Gas cell)

- What is theoretically lowest possible noise on sensor output values? (→ Signal Processing)

- Can compactness be combined with reliability? (→ Signal processing, Gas cell)



Task: develop and examine components → facilitate optimum selection for each sensor application.

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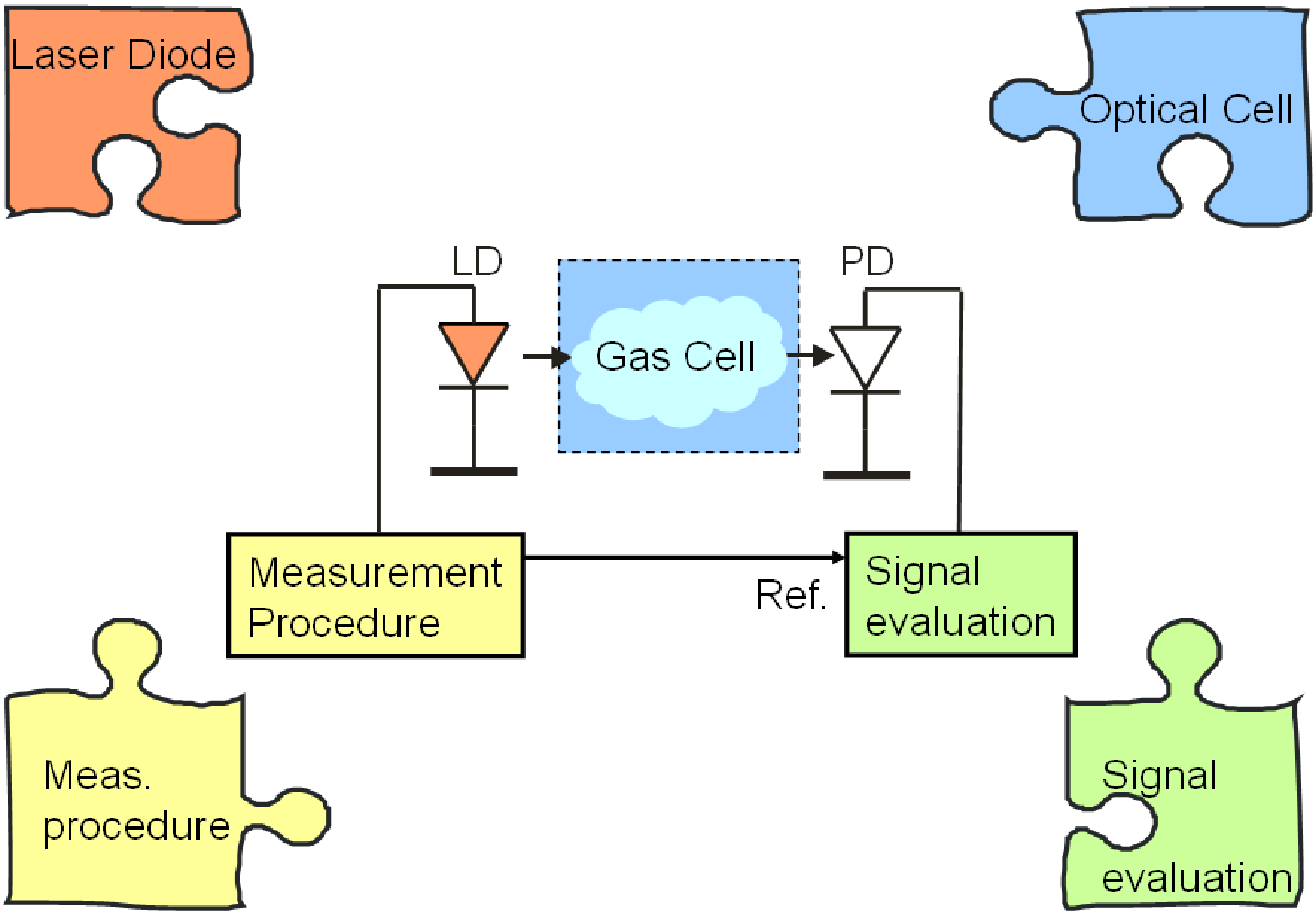
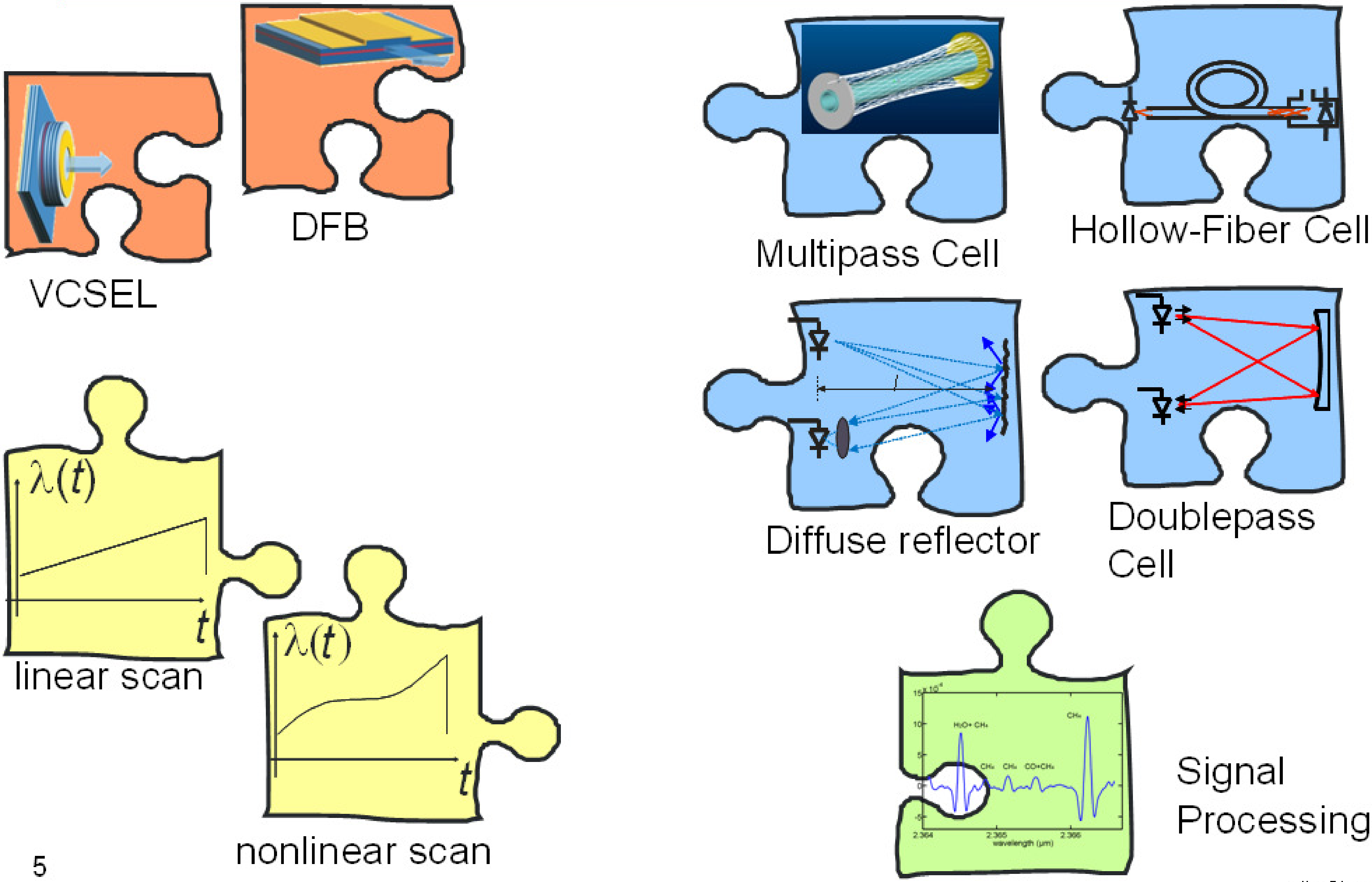
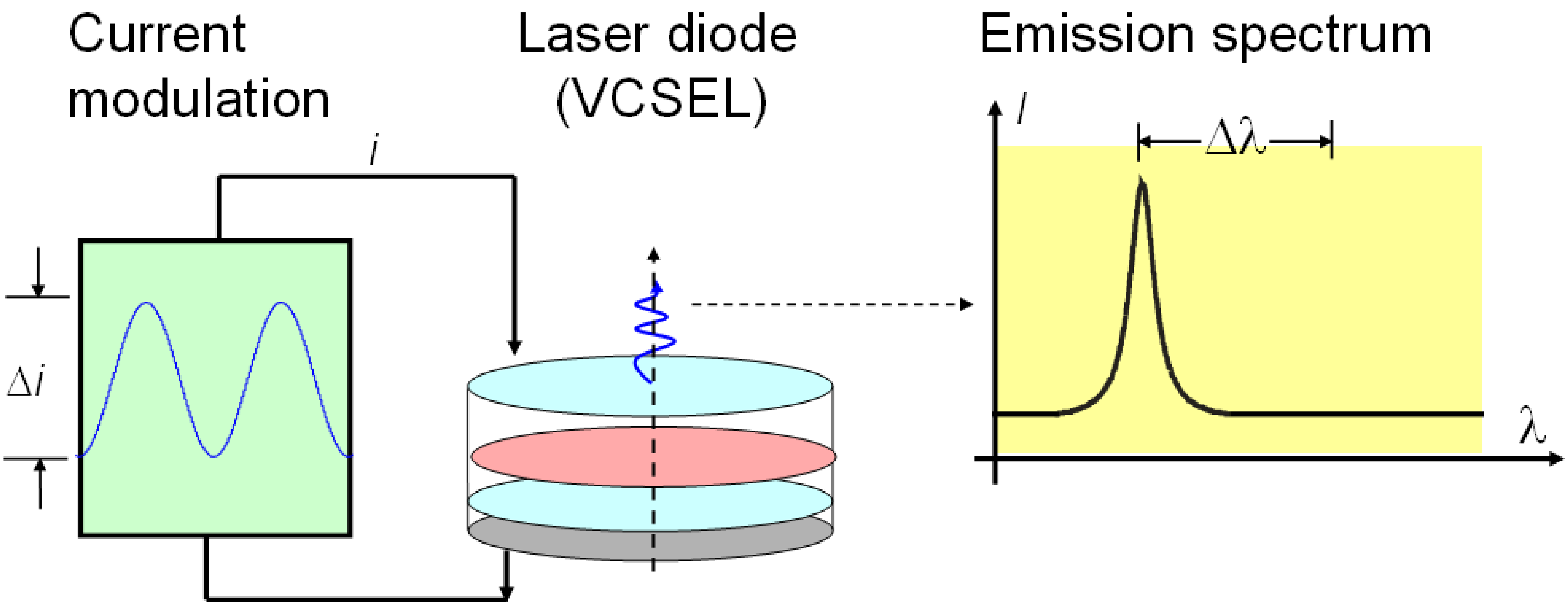
Key Sensor Components



Key Sensor Components

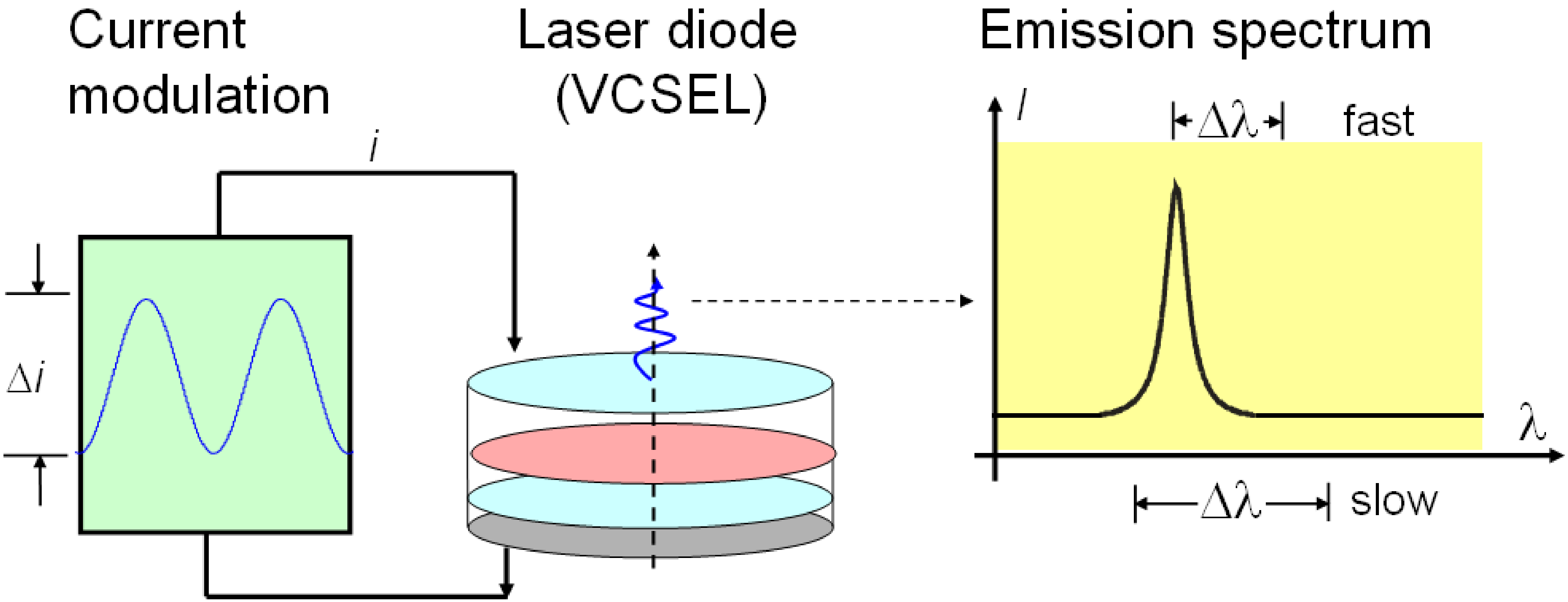


Dynamic Laser Wavelength Tuning Behavior



Current modulation Δi causes wavelength variation $\Delta\lambda$

Dynamic Laser Wavelength Tuning Behavior



Faster current modulation → smaller wavelength variation
Tuning coeff. Δλ/ Δ*i* drops with increasing frequency

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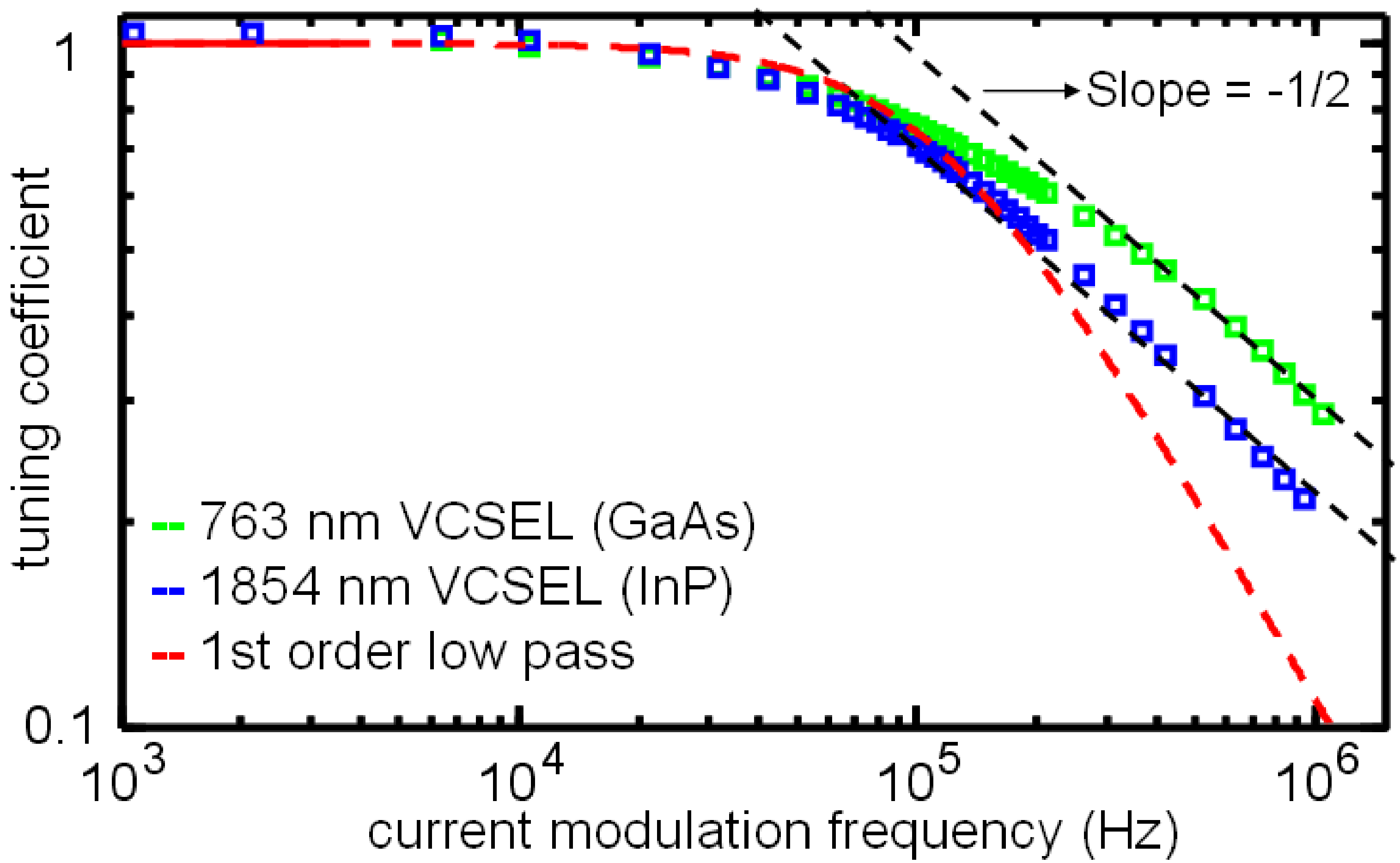
Experiment: VCSEL Tuning Coeff. vs. Modulation Freq.*



VCSEL tuning is fast enough for TDLS (several kHz)

New finding: tuning coefficient follows a square root law!

→ different from model used in literature for other lasers. Why?

*) *Experimental characterization of the frequency modulation behavior of vertical cavity surface emitting lasers,*
J. Chen, A. Hangauer, R. Strzoda, M.-C. Amann, Appl. Phys. Lett. ***91****, 141105 (2007)*

Modeling of Laser Tuning

New thermal modeling of heat conduction in laser describes dynamic tuning behavior

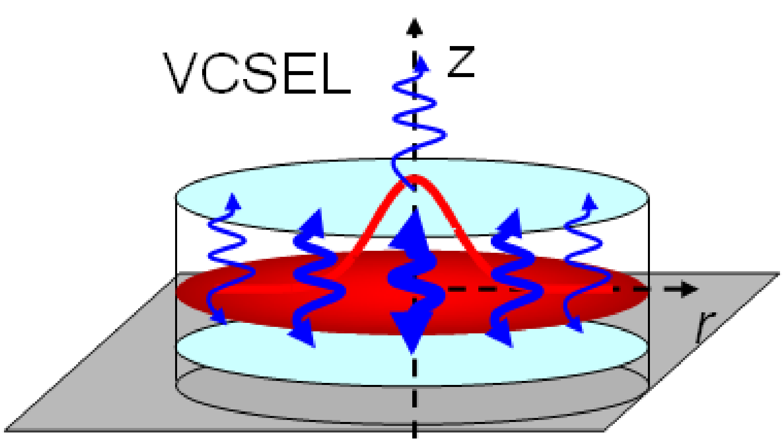
Modeling of Laser Tuning*

Assumptions:

Heat source: *heat generation is only in the optical active region*
Infinitely thin, laterally Gaussian - shaped

Heat sink: *substrate is at constant temperature and laterally extends infinitely*

Mode distribution: *wavelength is proportional to averaged temperature*
Gaussian - shaped light distribution



*) *Simplified Model of the Dynamic Thermal Tuning Behavior of VCSELs, J. Chen et.al. IEEE Photon. Tech. Lett.* ***20****, 1082-1084 (2008)*

Analytical Formula for FM Response

Tuning coefficent has a closed form expression!

$$\frac{\Delta\lambda}{\Delta i}(f) \propto \exp\left(\frac{if}{f_0}\right)\mathrm{erfc}\left(\sqrt{\frac{if}{f_0}}\right) - \exp\left(\frac{if}{f_0}+d^2\right)\mathrm{erfc}\left(\sqrt{\frac{if}{f_0}}+d\right)$$

f_0 : “Frequency scale parameter”, depends on thermal diffusivity κ and aperture R_0

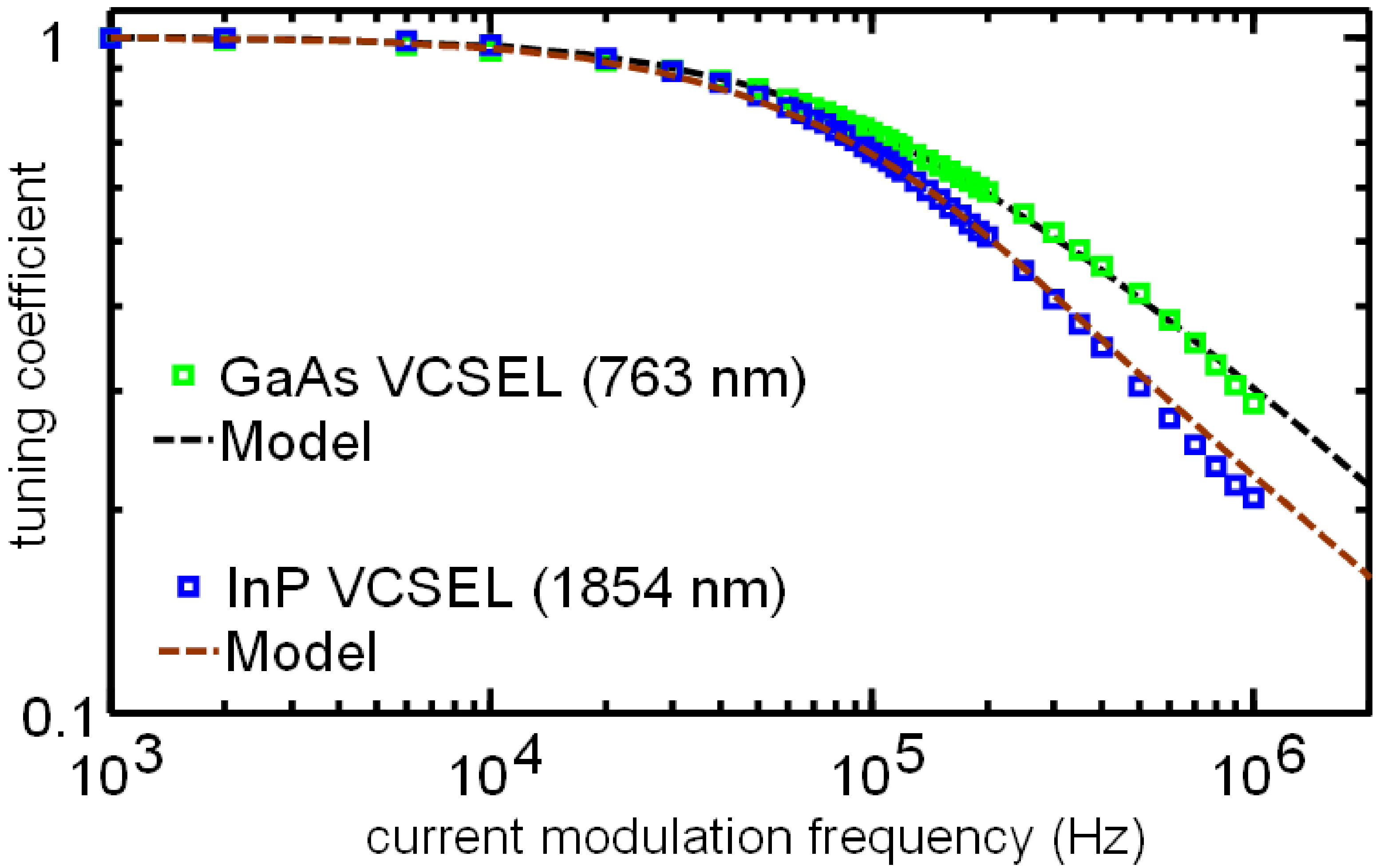
d : distance between heat sink and heat source

Formula has asymptotic square root behavior!

Interpretation:

- *Trade off between fast tuning and high tuning coeff.*
- *Simultaneous fast tuning and high tuning only with material change*
  low distance between heat sink and heat source
  low specific thermal conductivity of laser material

Experimental Model Verification



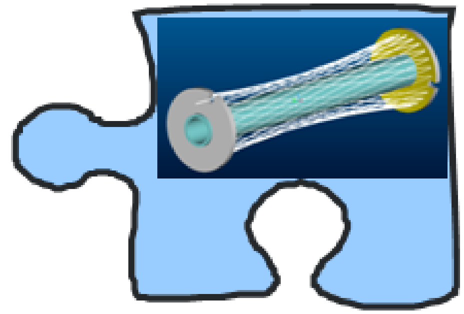
Square root law caused by *thin* heat generation in 3D space

High cutoff frequency caused by small laser dimensions

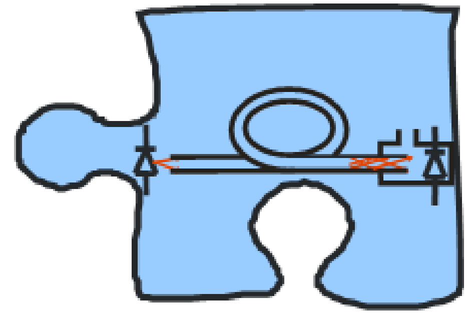
Sensor Components

VCSEL

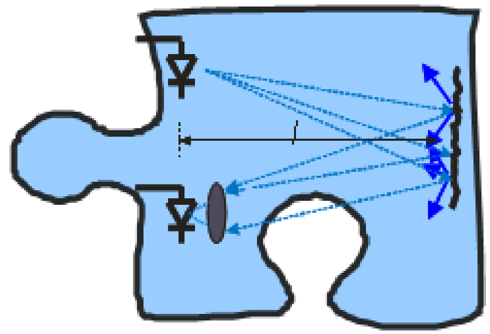
DFB



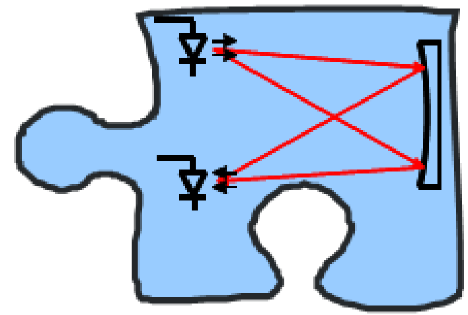
Multipass Cell



Hollow-Fiber Cell



Diffuse reflector



Doublepass Cell

linear scan

nonlinear scan

Signal Processing

Questions of interest …

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- Can small sample volume be combined with high sensitivity? (→ Gas cell)

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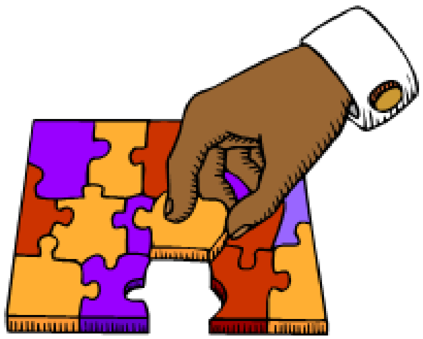
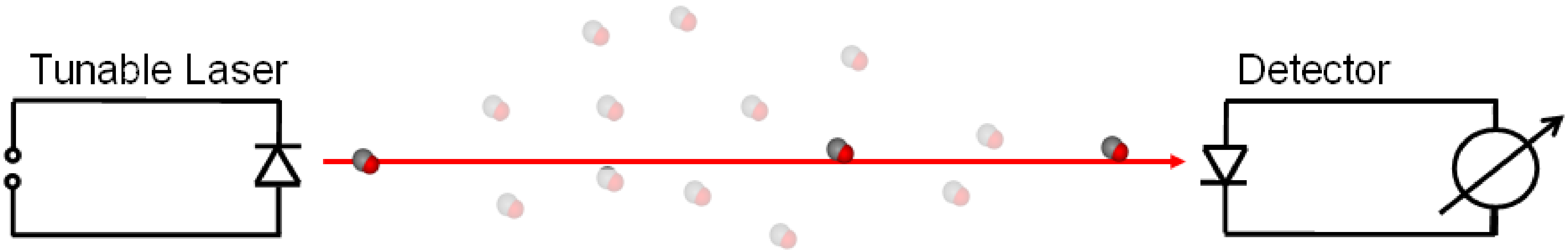
- Can compactness be combined with reliability? (→ Signal processing, Gas cell)

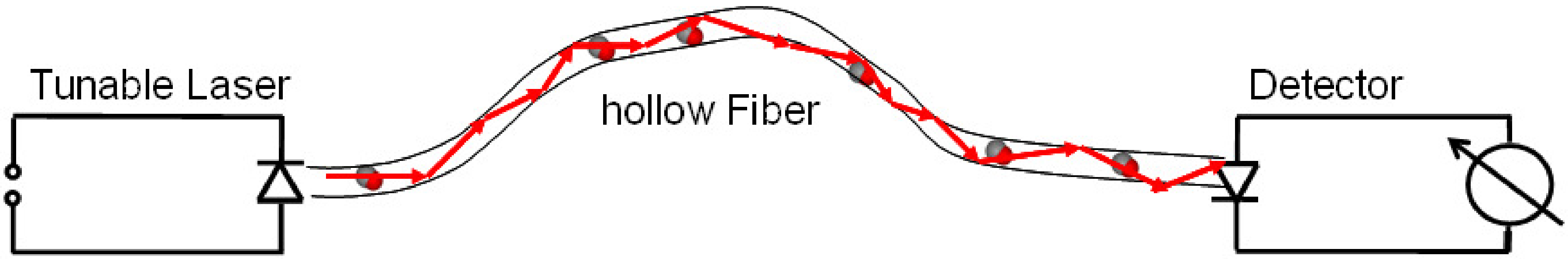
Task: develop and examine components → optimum selection for specific sensor applications.



Conventional Gas Cell

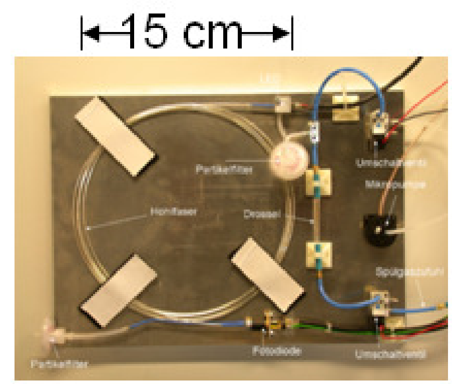


Fiber based Gas Cell



Advantages of a fiber - based gas sensor:

- *long absorption path length with small sample volume*
- *easy alignment*

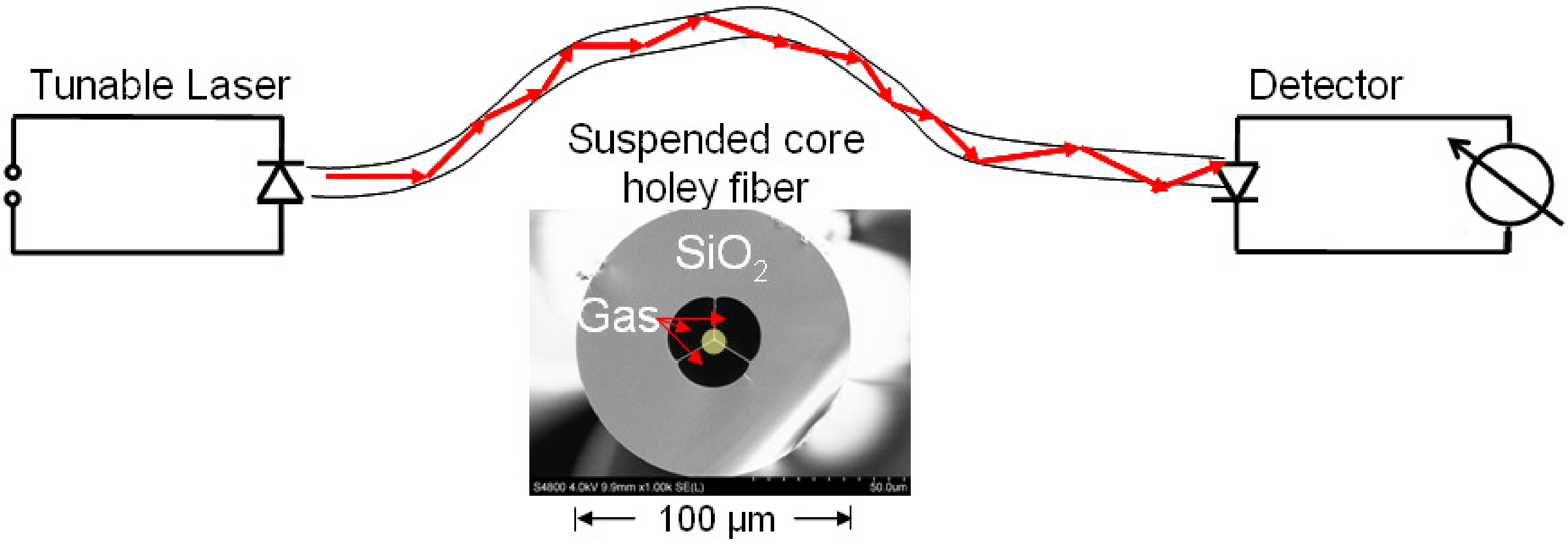


Suitable for compact sensor design!

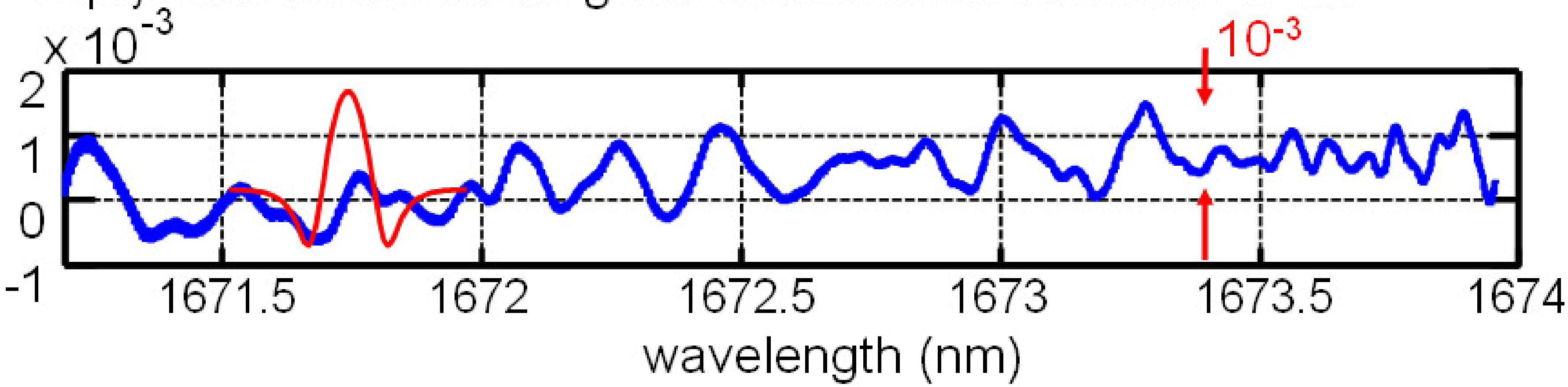
But for high sensitivity …

…. absorbance resolution must be good

Fiber based Gas Cell



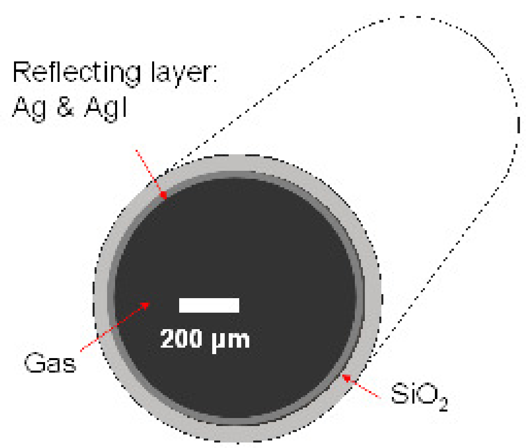
Empty fiber transmission gives absorbance resolution of 10^{-3}



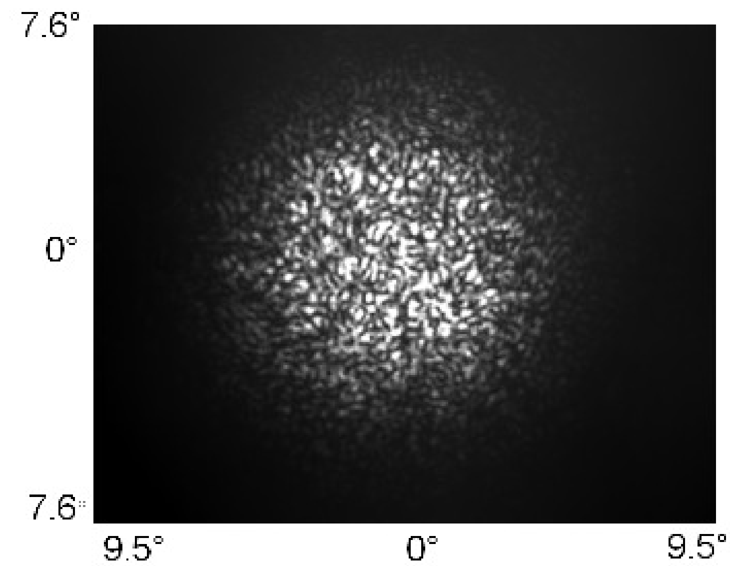
… caused by interference with additional weak core-modes

Hollow Capillary Fiber

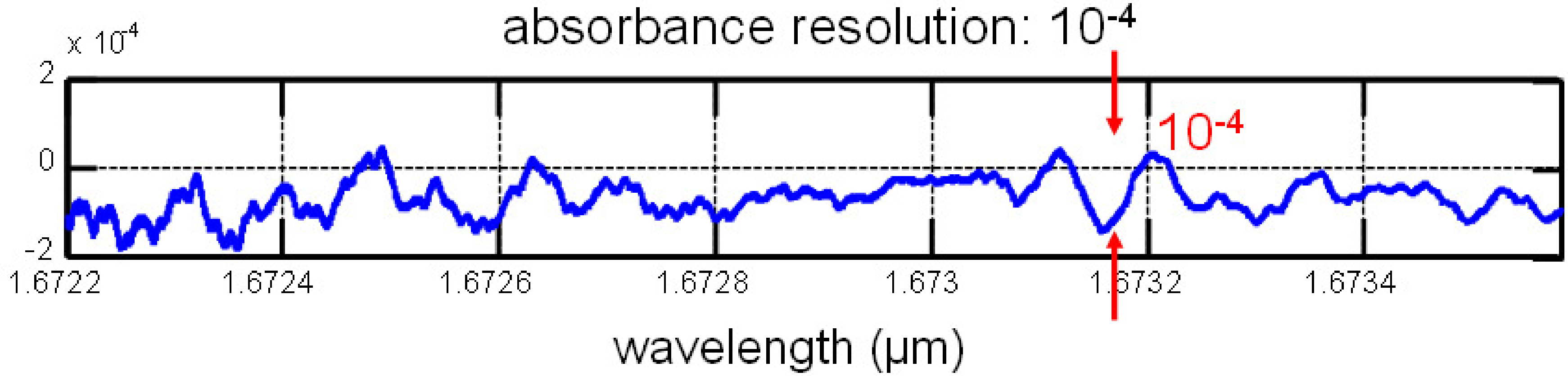
Highly Multimode Fiber



Fiber far-field: speckle pattern



absorbance resolution: 10^{-4}



Can absorbance resolution be further improved ?

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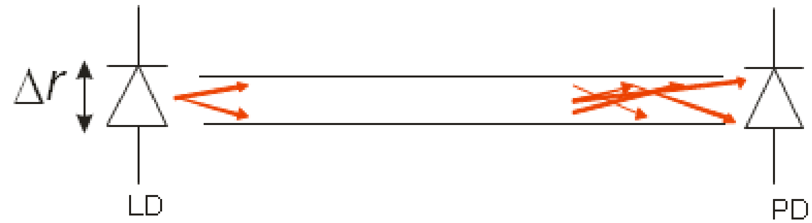
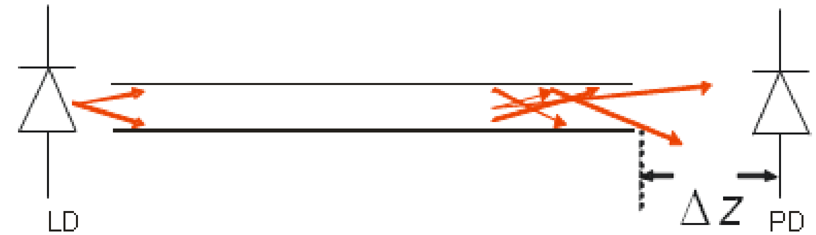
What influences absorbance resolution?

- Laser in-coupling ?

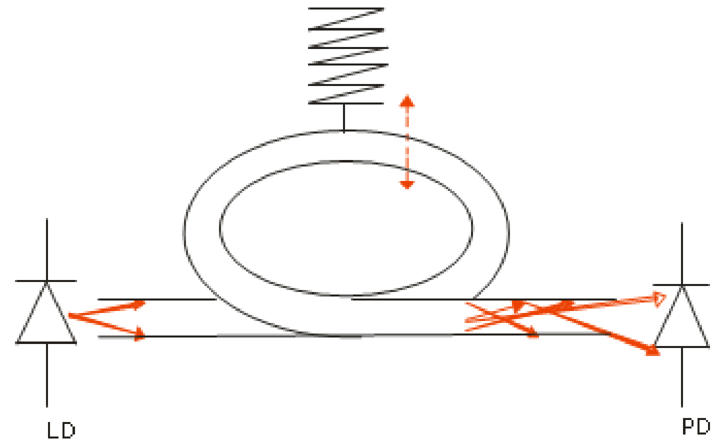


No relevant influence on absorbance resolution

- Detector out-coupling ?



- Fiber mechanical vibration ?



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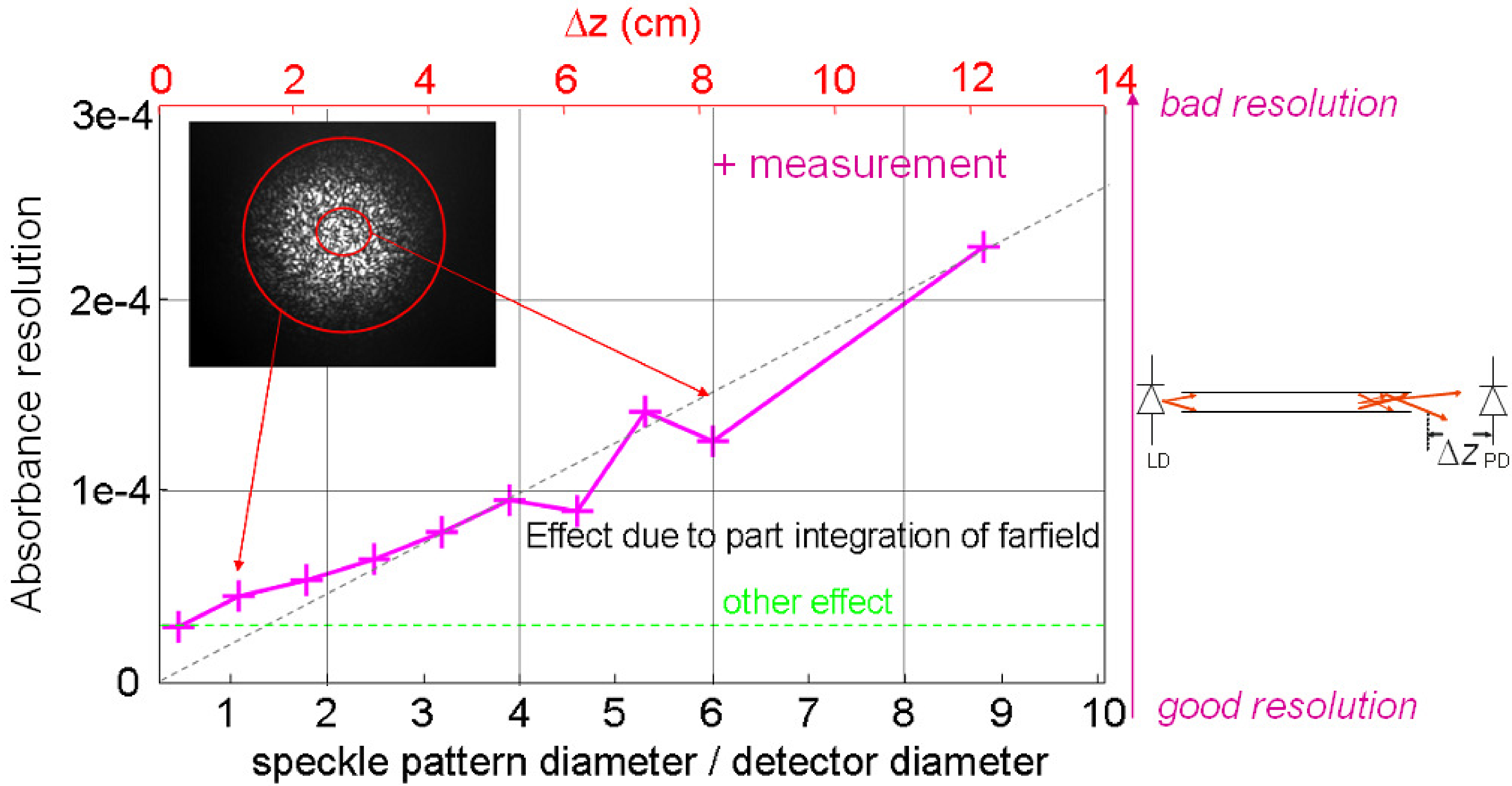
Influence of out-coupling



Finding: abs. resolution ~ $1/\sqrt{N}$ (number of integrated speckle)

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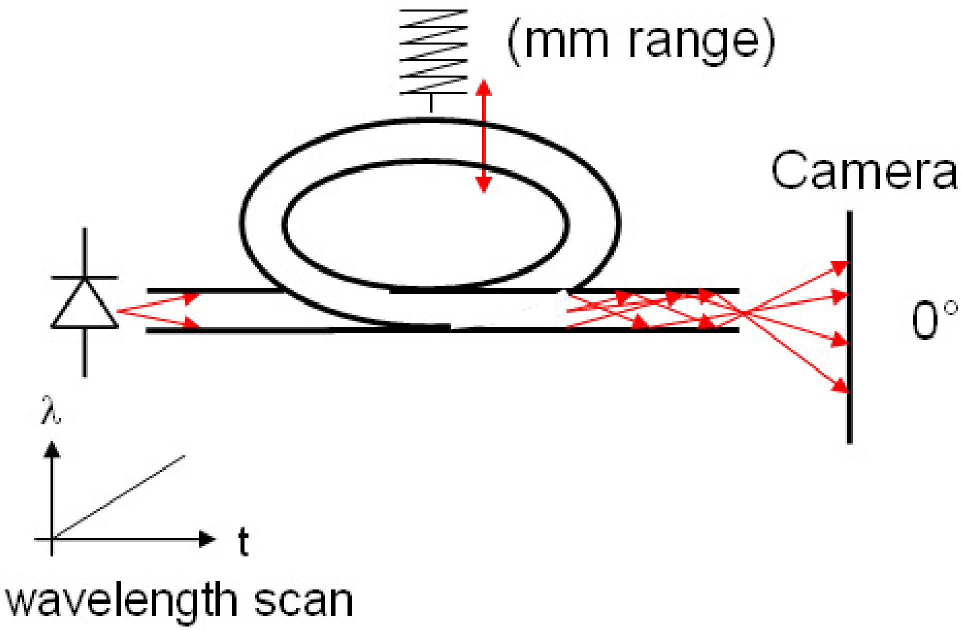
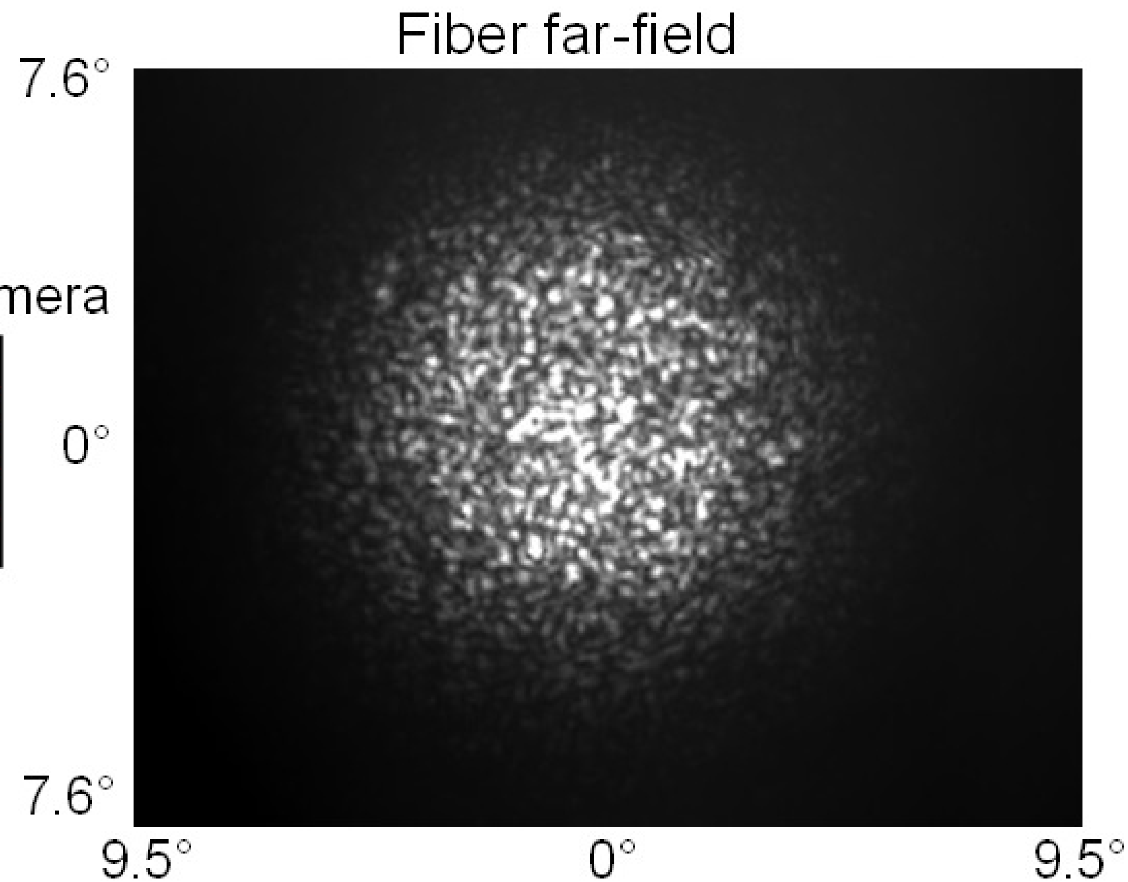
Influence Mechanical Vibration



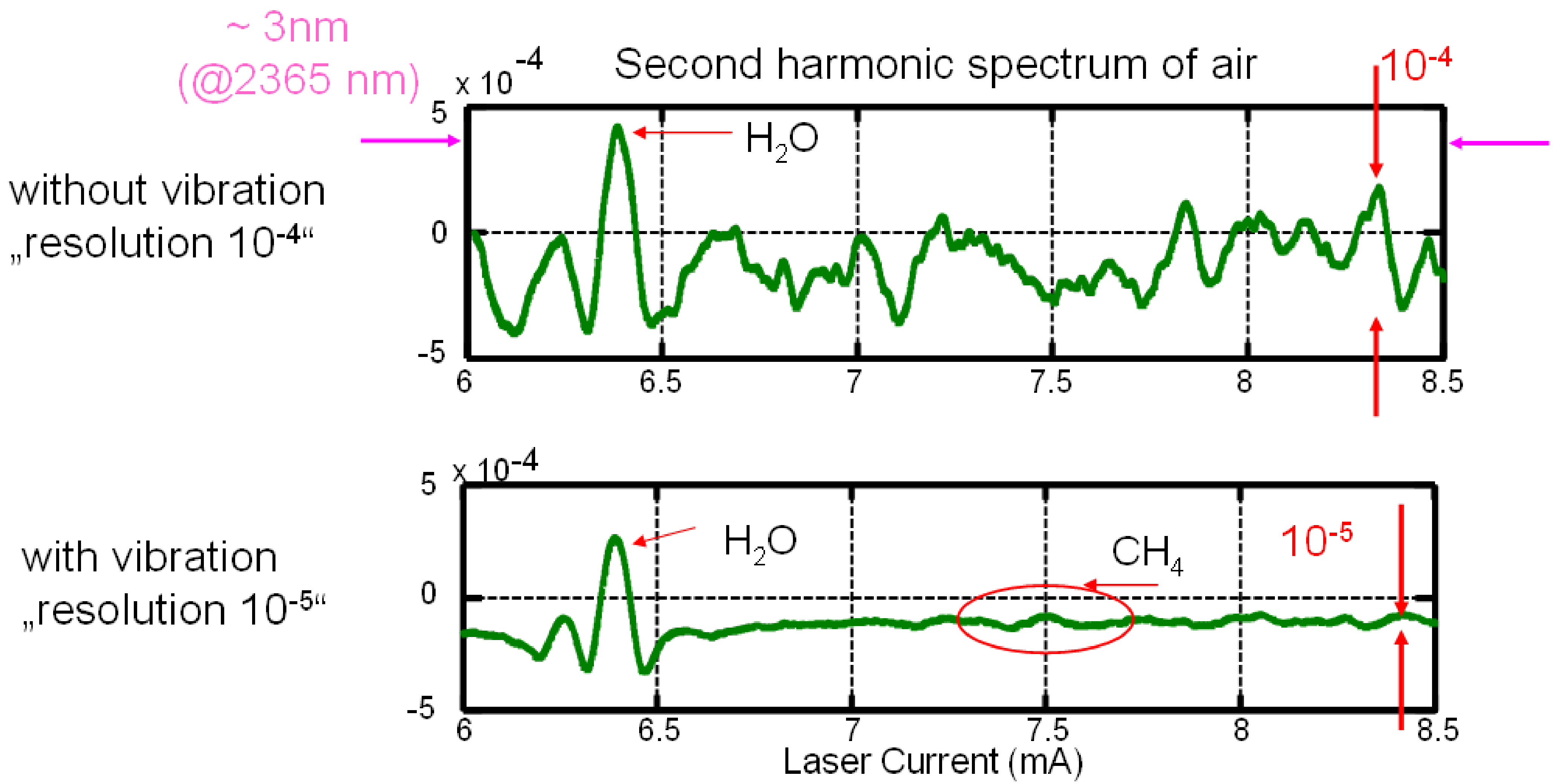


Speckle pattern changes strongly by vibration

→ Integration over time gives a smooth transmission

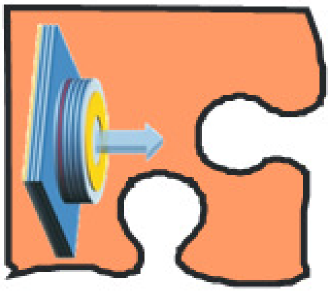
*J. Chen et.al., "Resolution Limits of Laser Spectroscopic Absorption Measurements with Hollow Glass Waveguides " Applied Optics 49, 5254-5261 (2010)

Sensing results with and without vibration

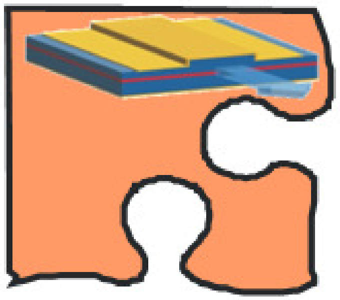


Absorbance resolution is a magnitude improved with vibration !

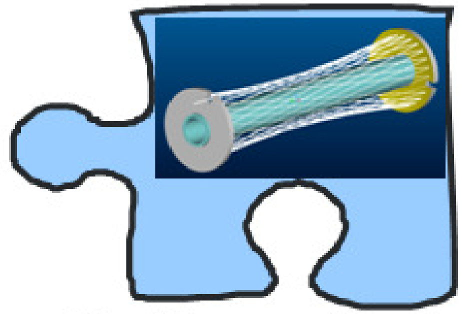
Sensor Components



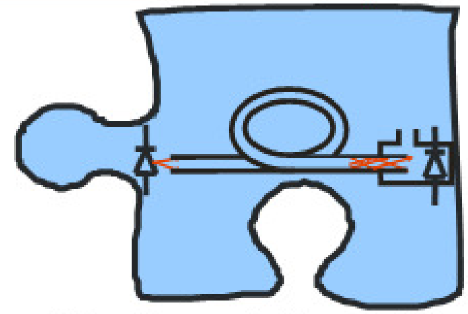
VCSEL



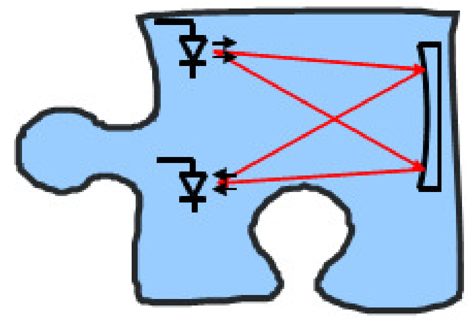
DFB



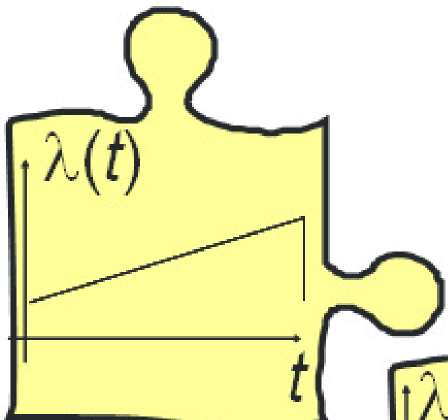
Multipass Cell



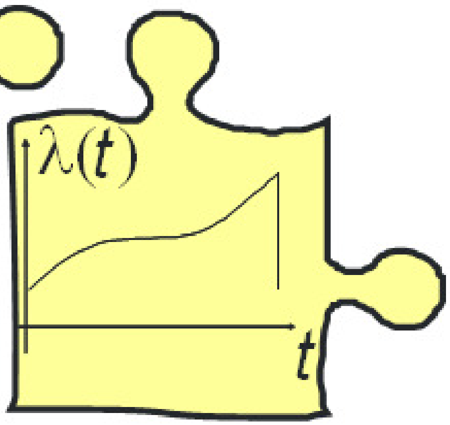
Hollow-Fiber Cell



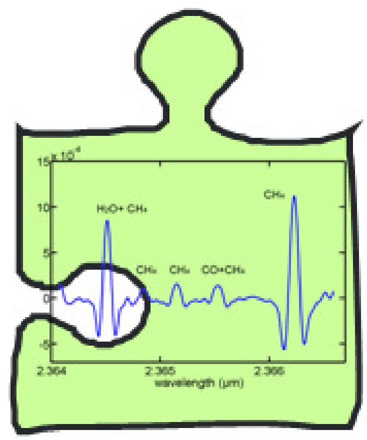
Doublepass Cell



linear scan



nonlinear scan



Signal Processing

Questions of interest …

- How fast can the detection be carried out? (→ Laser)

- Can small sample volume be combined with high sensitivity? (→ Gas cell)

- What is theoretically lowest possible noise on sensor output values? (→ Signal Processing)

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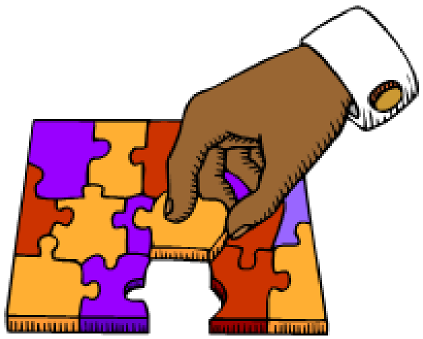
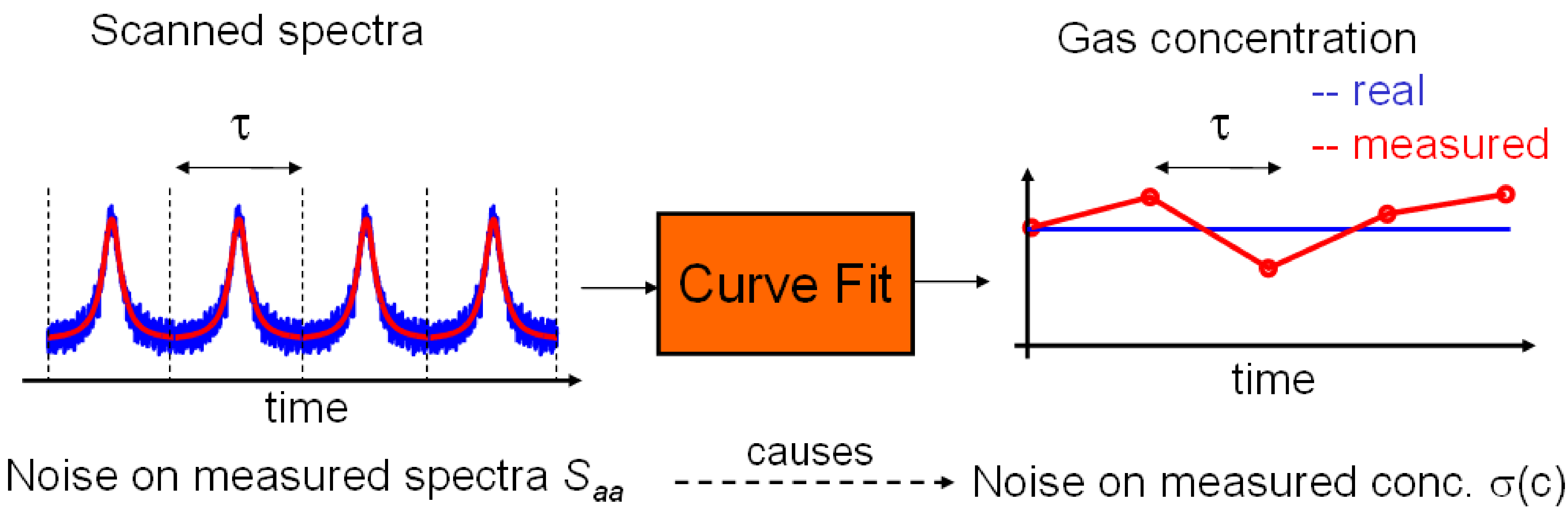
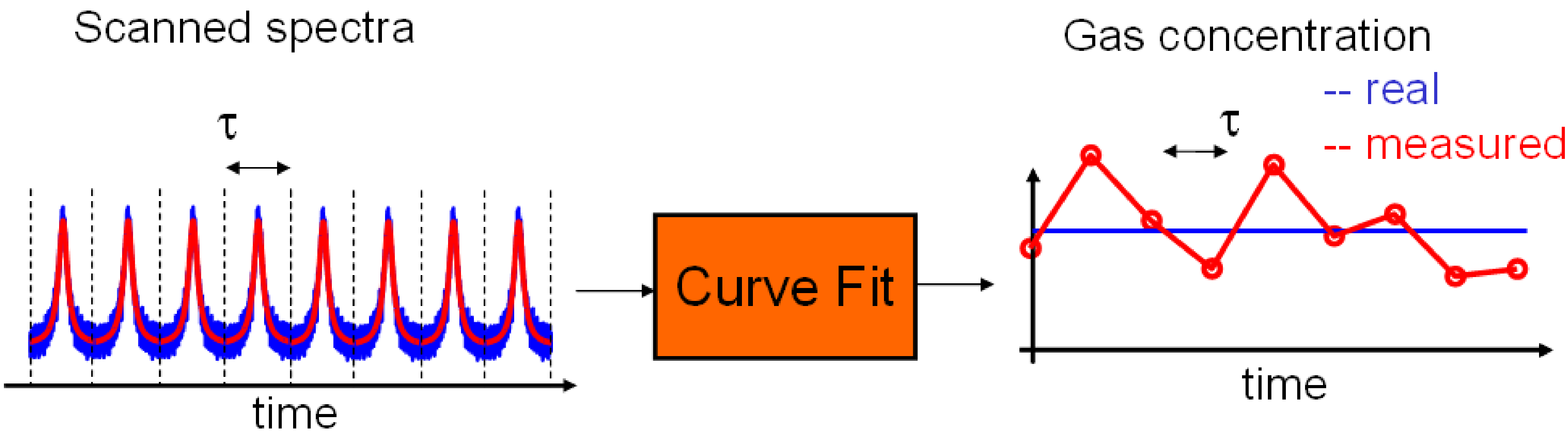


Task: develop and examine components → optimum selection for specific sensor applications.

Origin of Noise on Sensor Output Values



Origin of Concentration Noise

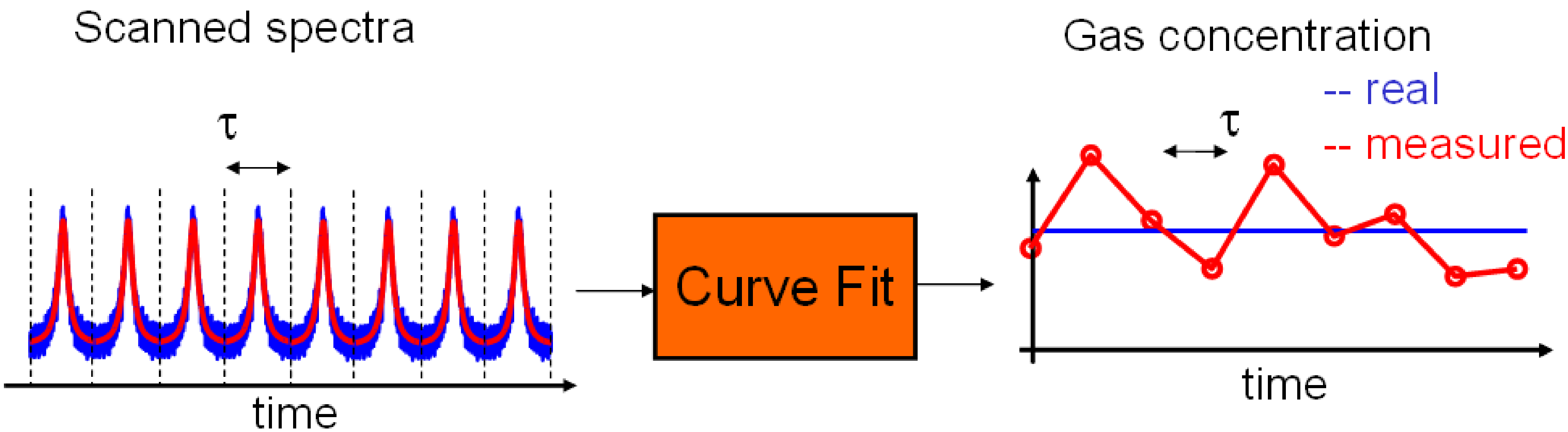


Noise on measured spectra S_{aa} --- causes ---> Noise on measured conc. $\sigma(c)$

Twice the measurement rate → increasing conc. noise by $\sqrt{2}$

Noise density N times → conc. noise increased by $\sqrt{N}$

Origin of Concentration Noise



Noise on measured spectra S_{aa} --- causes ---> Noise on measured conc. $\sigma(c)$

Precisely,

$$\sigma(c) = \sqrt{S_{aa}/\tau} \times k$$

k: proportional factor, named as ‚observation factor'

Discussion of 'observation factor'

- Describes how much target information is contained in the measured signal

- Higher (worse) if many spectral components involved

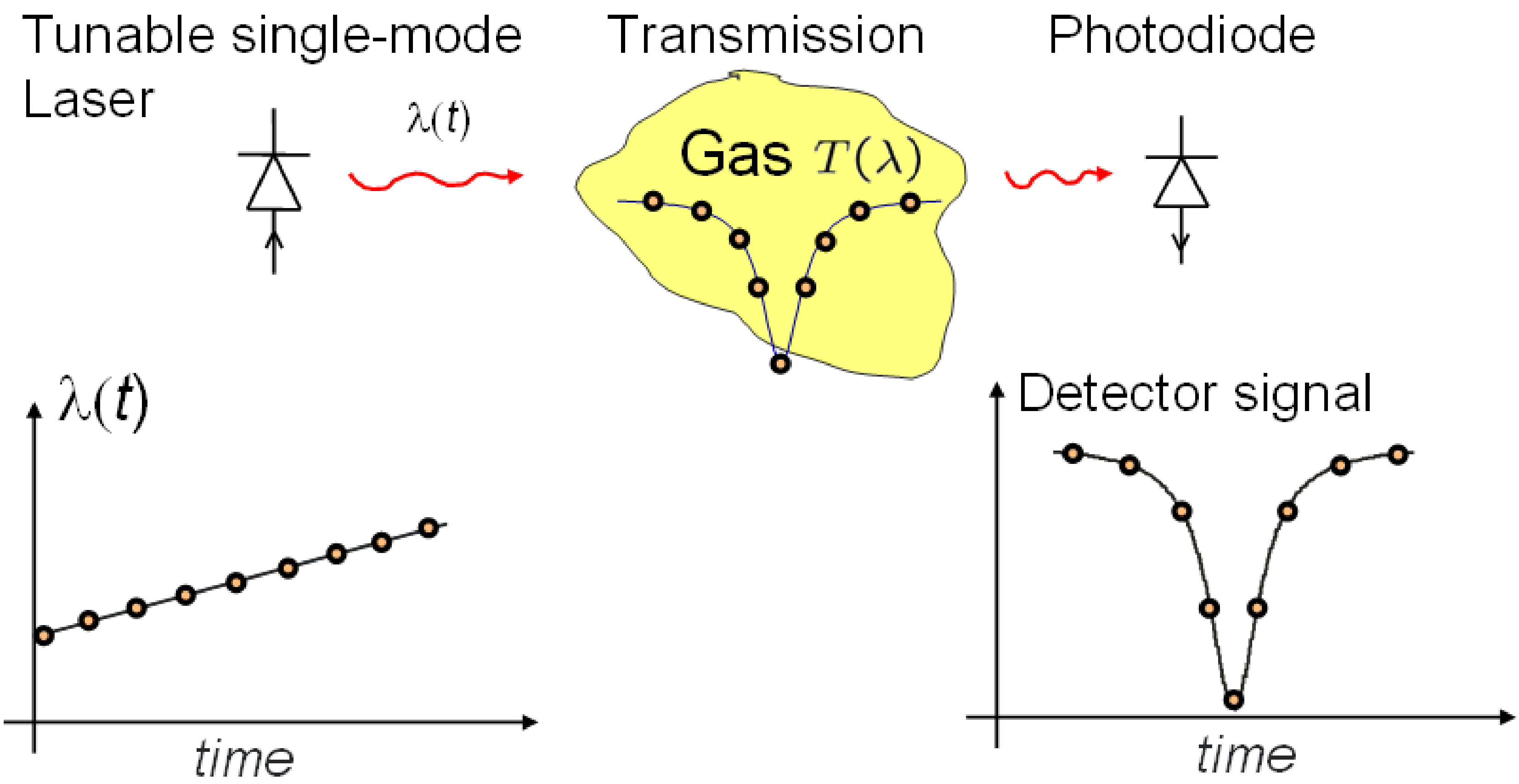
- Analytical formula found: $\sqrt{(\Psi^T\Psi)_{11}^{-1}\,N}$

Ψ : observation matrix, contains description of spectral components

N : number of measurement points per spectrum (unit: 1)

How to improve the ‚observation factor'?

Linear Sampling of Gas Spectrum



Linear scanning: detector signal has same shape as gas spectrum

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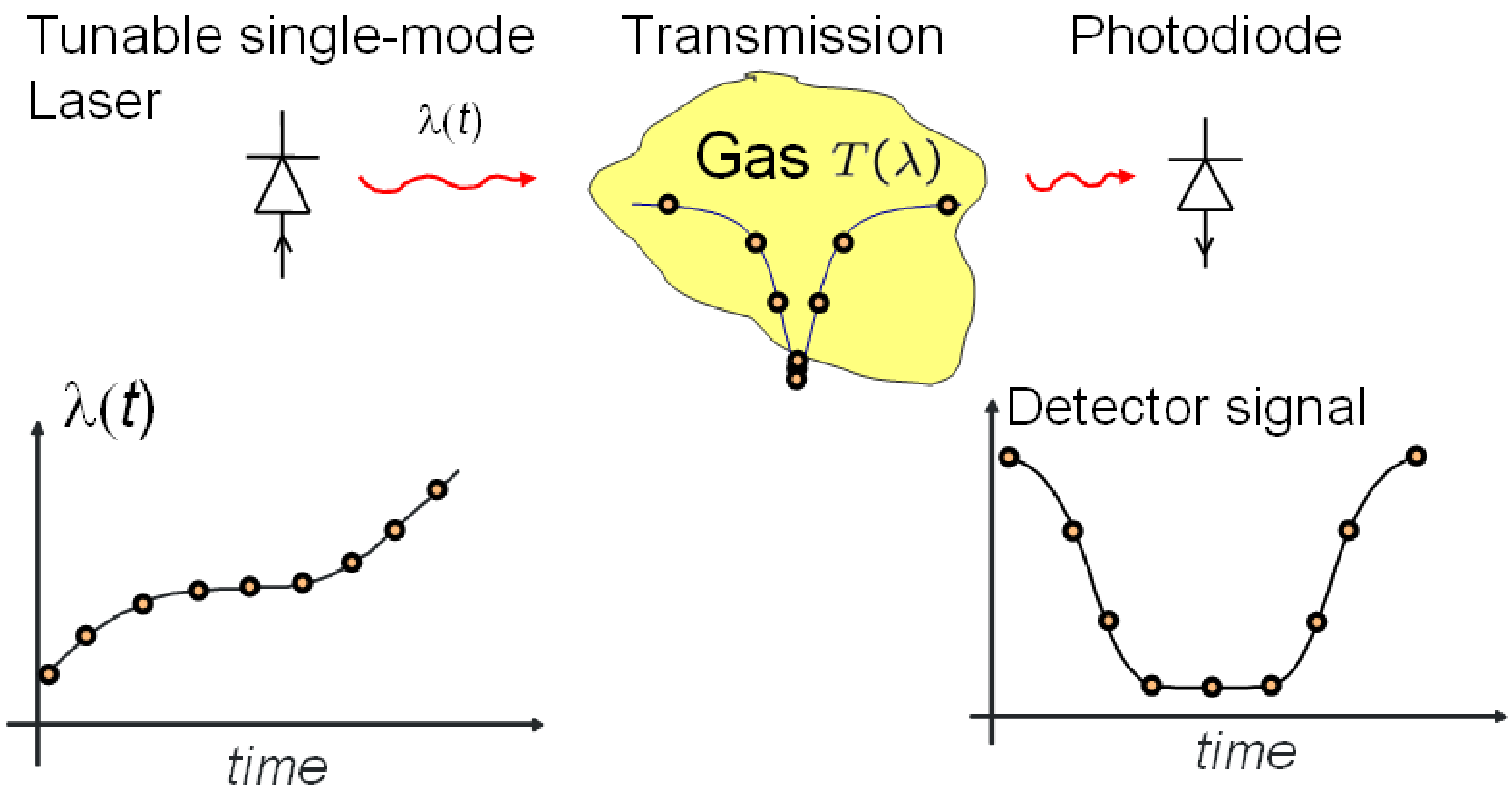
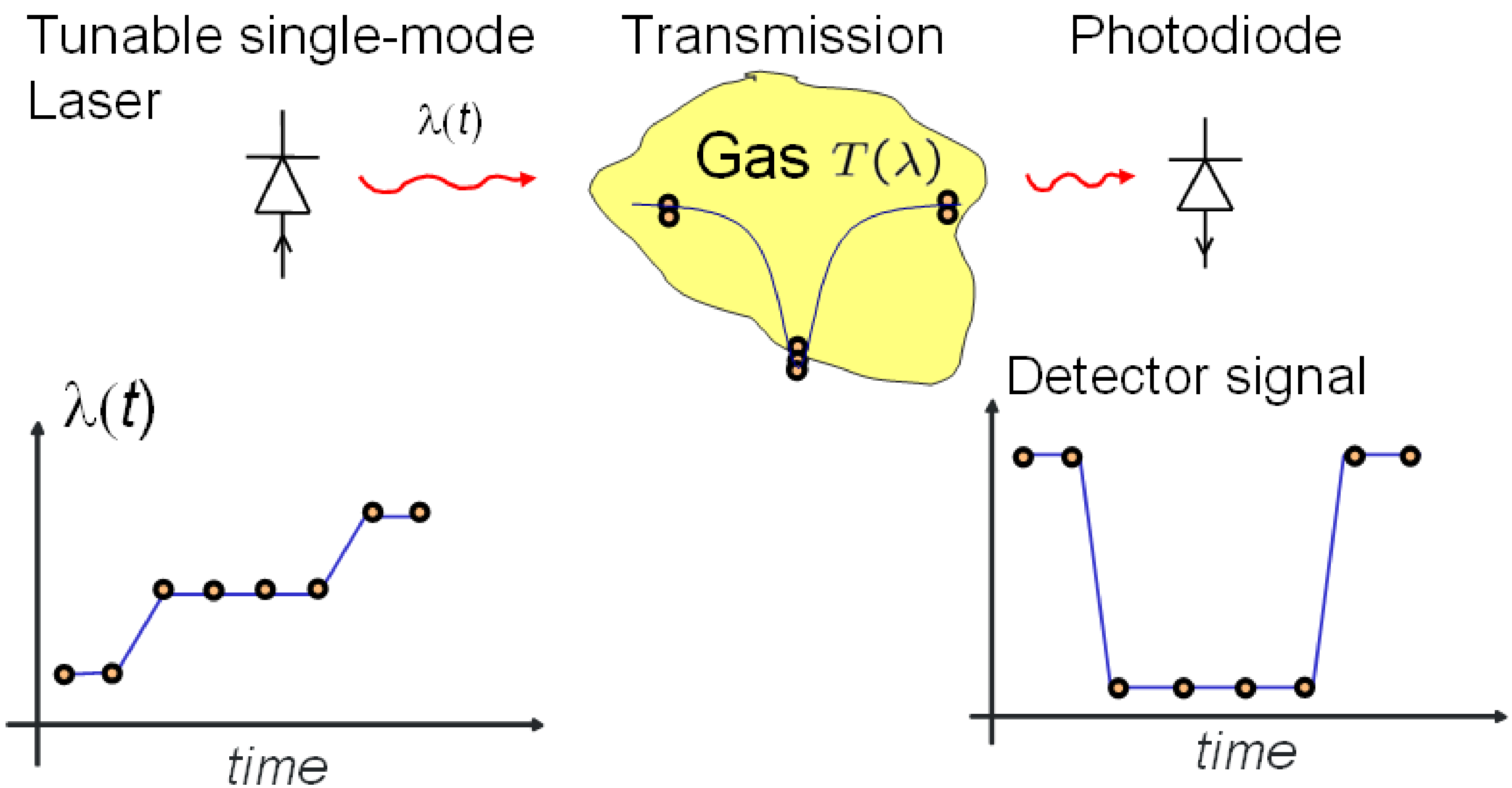
Nonlinear Sampling of Gas Spectrum



Nonlinear scanning: detector signal has a more cascade form

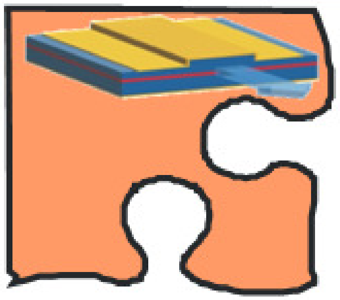
Optimized Sampling of Gas Spectrum



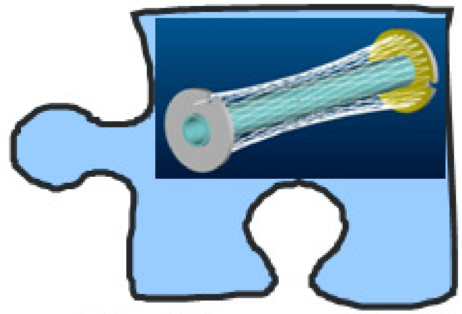
Optimum scanning is ‚jump scanning‘ (analytical result)
‚Observation factor‘ 2 times better than linear scanning
Theory provides position and duration of sampling points

*'Tunable diode laser spectroscopy with optimum wavelength scanning', J. Chen et. al., Appl. Phys. B. **100** (2010)

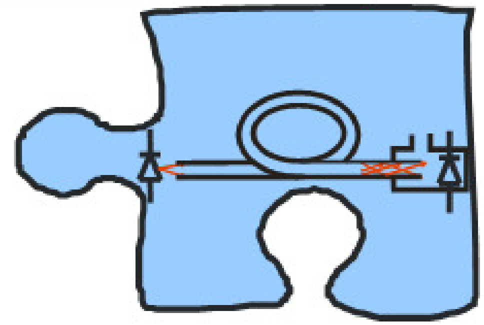
Selection of Components for CO Monitor

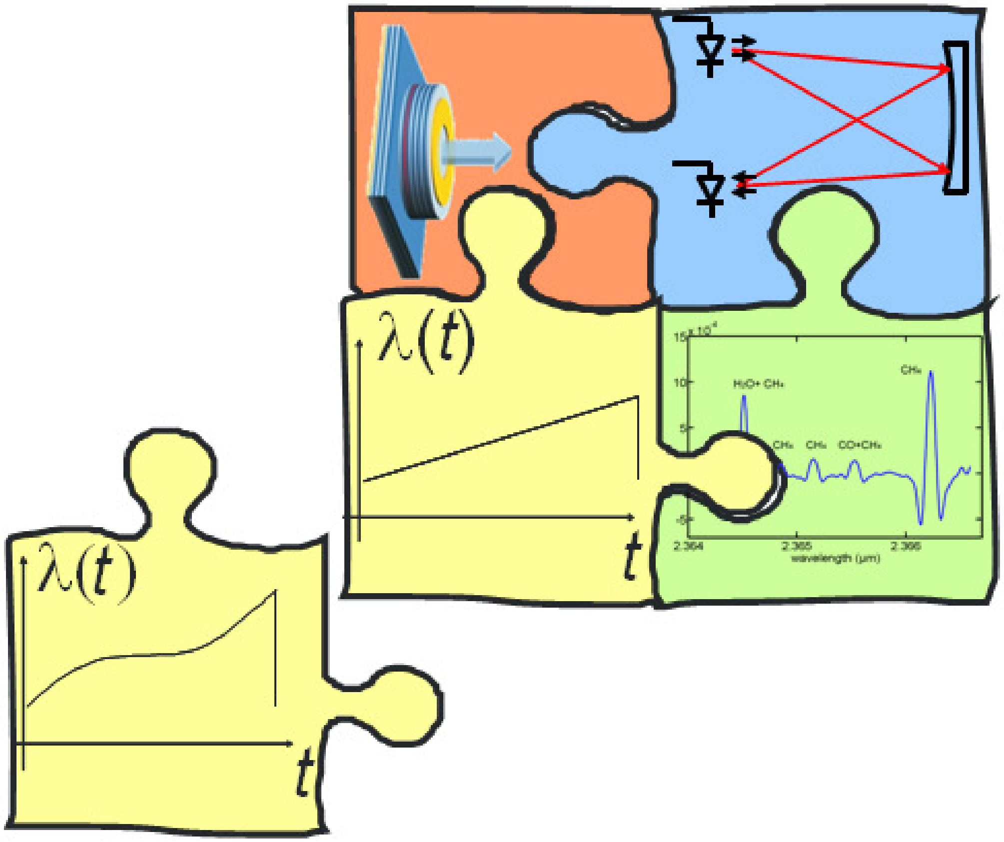


DFB



Multipass Cell





nonlinear scan

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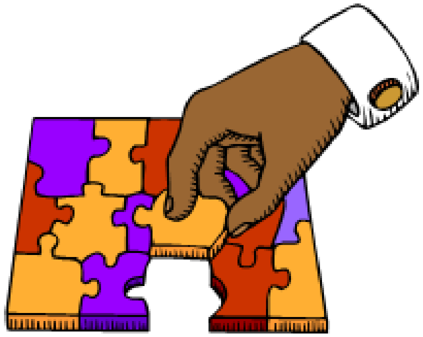
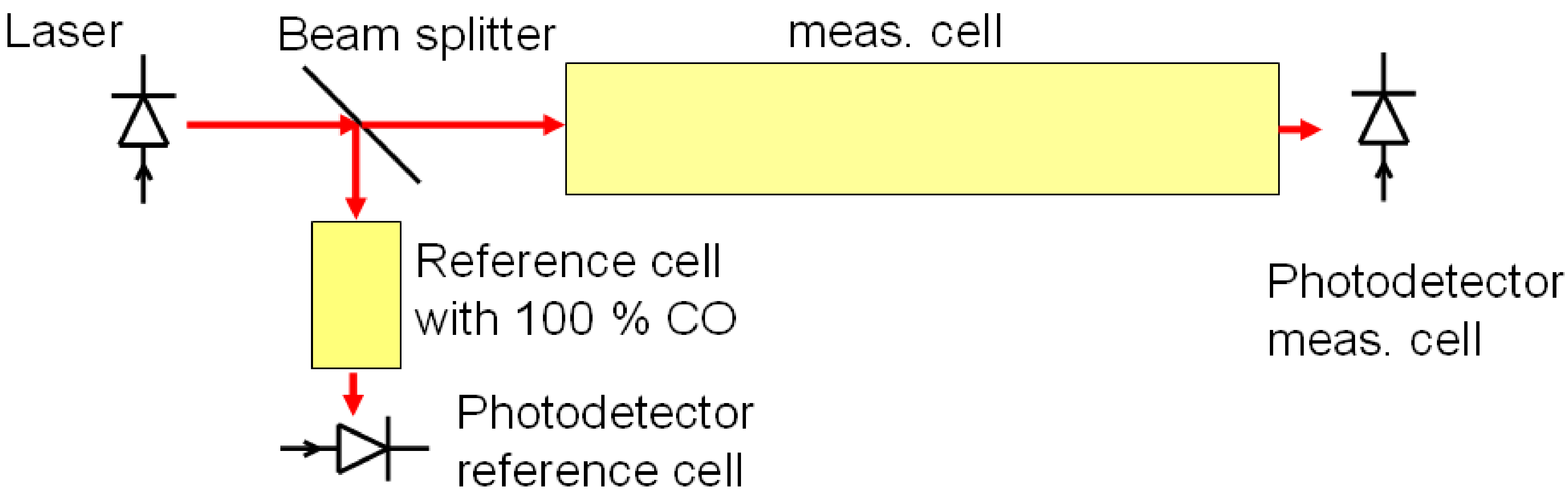


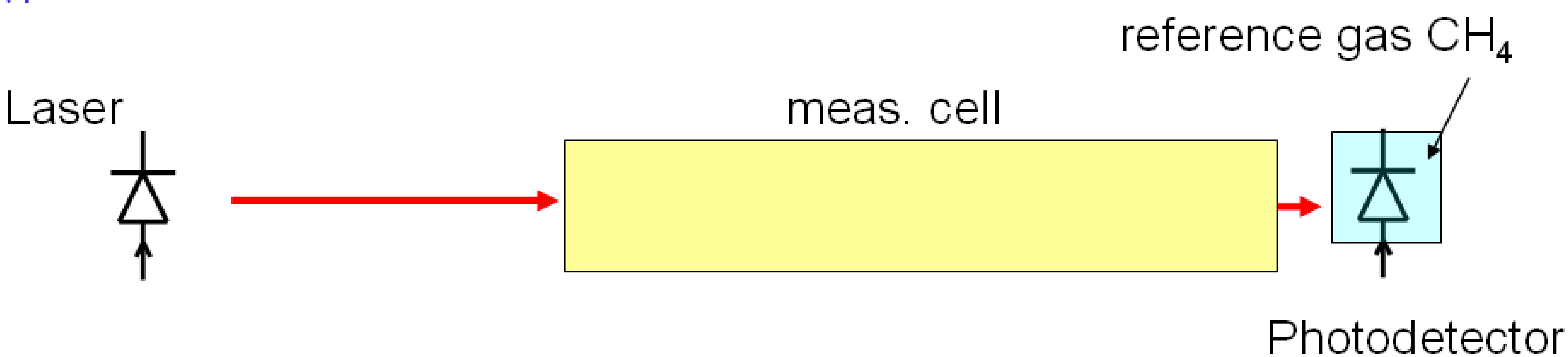
Task: develop and examine components → optimum selection for specific sensor applications.

Optical Cell for CO Sensing

Conventional:

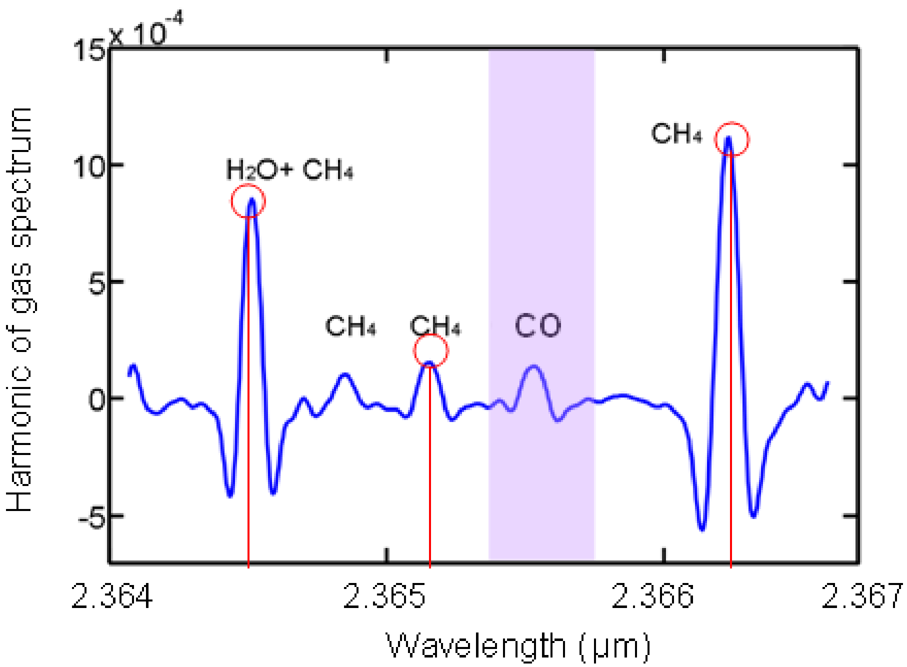


New:

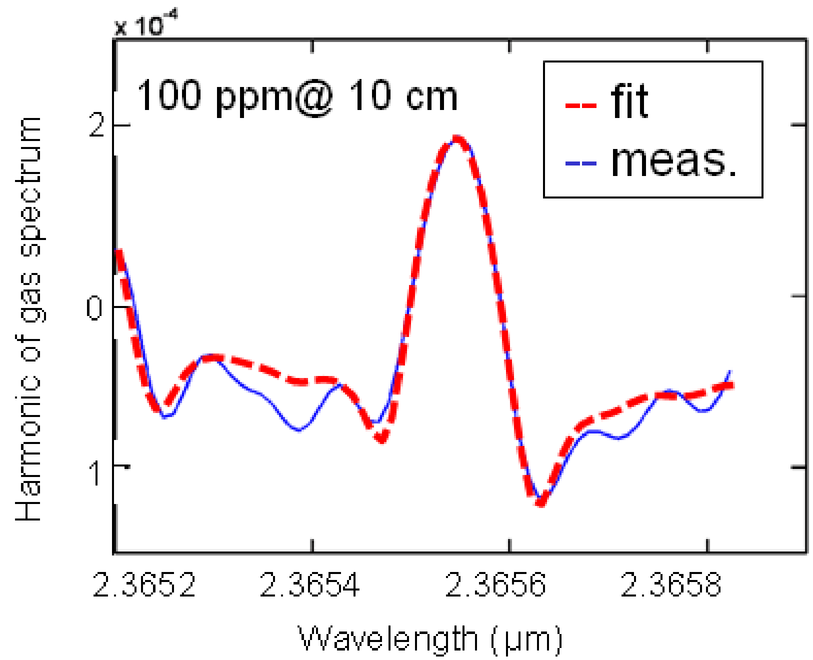


Inherent Wavelength Calibration

Wide Scan: (every few seconds)
wavelength scale calibration



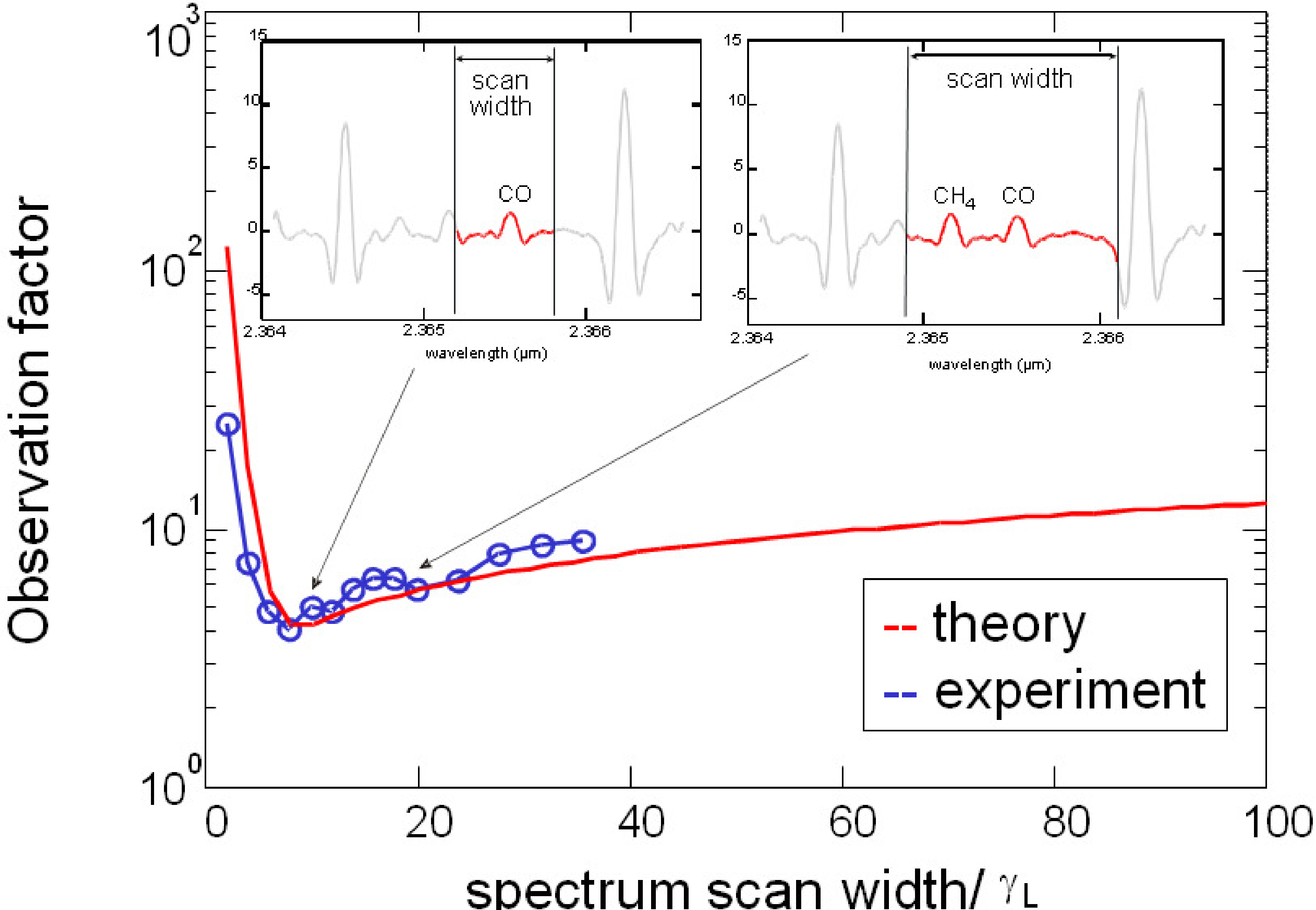
Narrow Scan: (every 100 ms)
CO concentration determination



Inherent wavelength calibration with spectral features

Linear curve fit for CO concentration determination

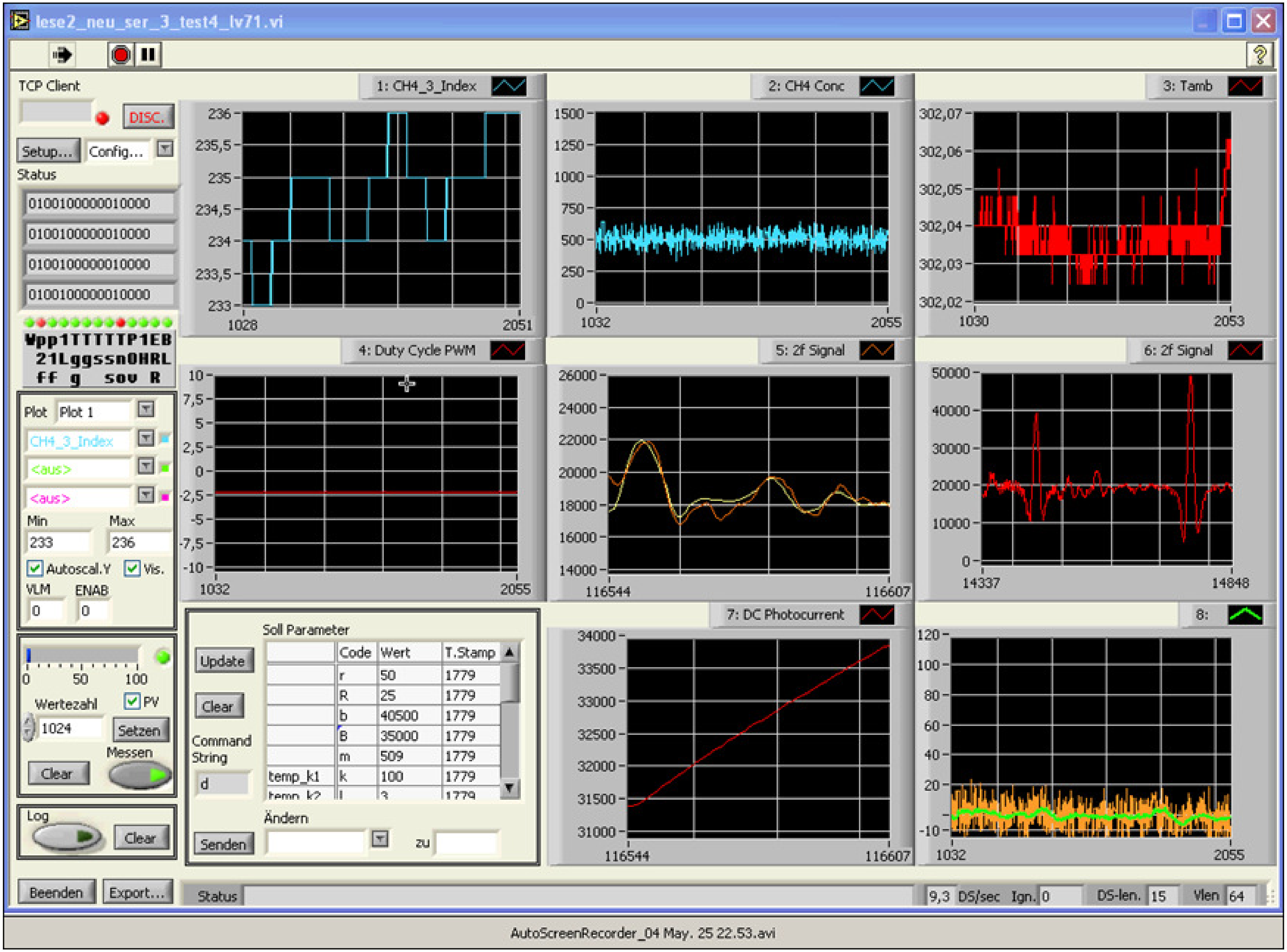
Observation Factor vs. Scan Width



Narrow scan uses optimum spectrum scan width

*'VCSEL-based calibration-free carbon monoxide sensor at 2.3 μm with in-line reference cell', J. Chen et. al. Appl. Phys. B. (2010)

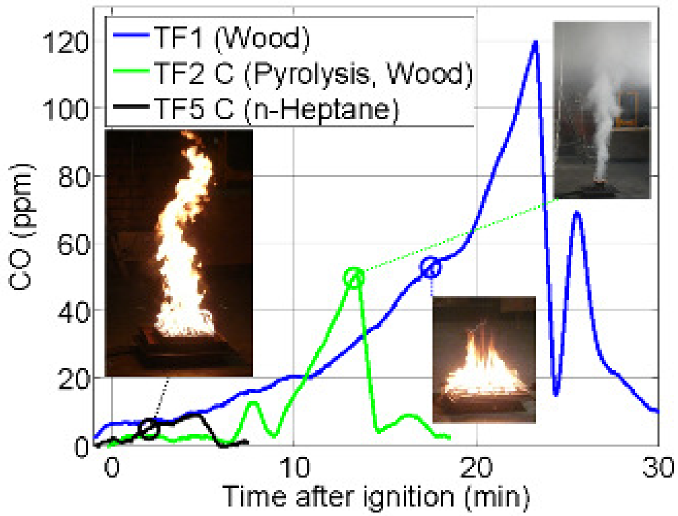
CO Sensor Live



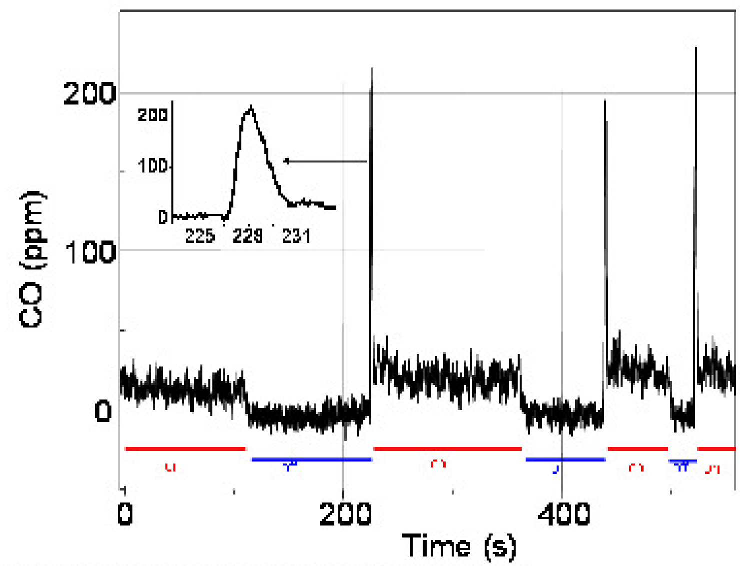
Jia Chen

Sensing results*

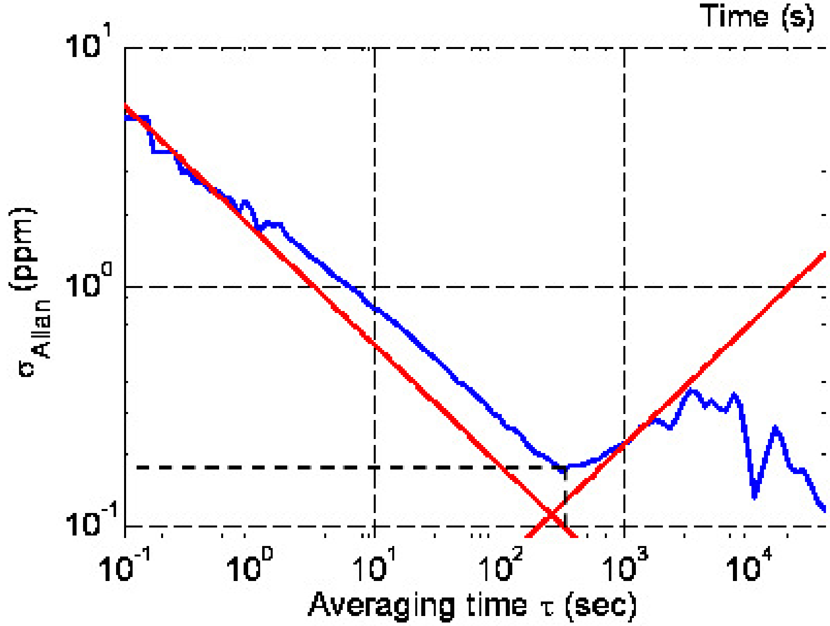
- *Sensor is suited for fire detection*



- *CO peaks after ignition resolvable*

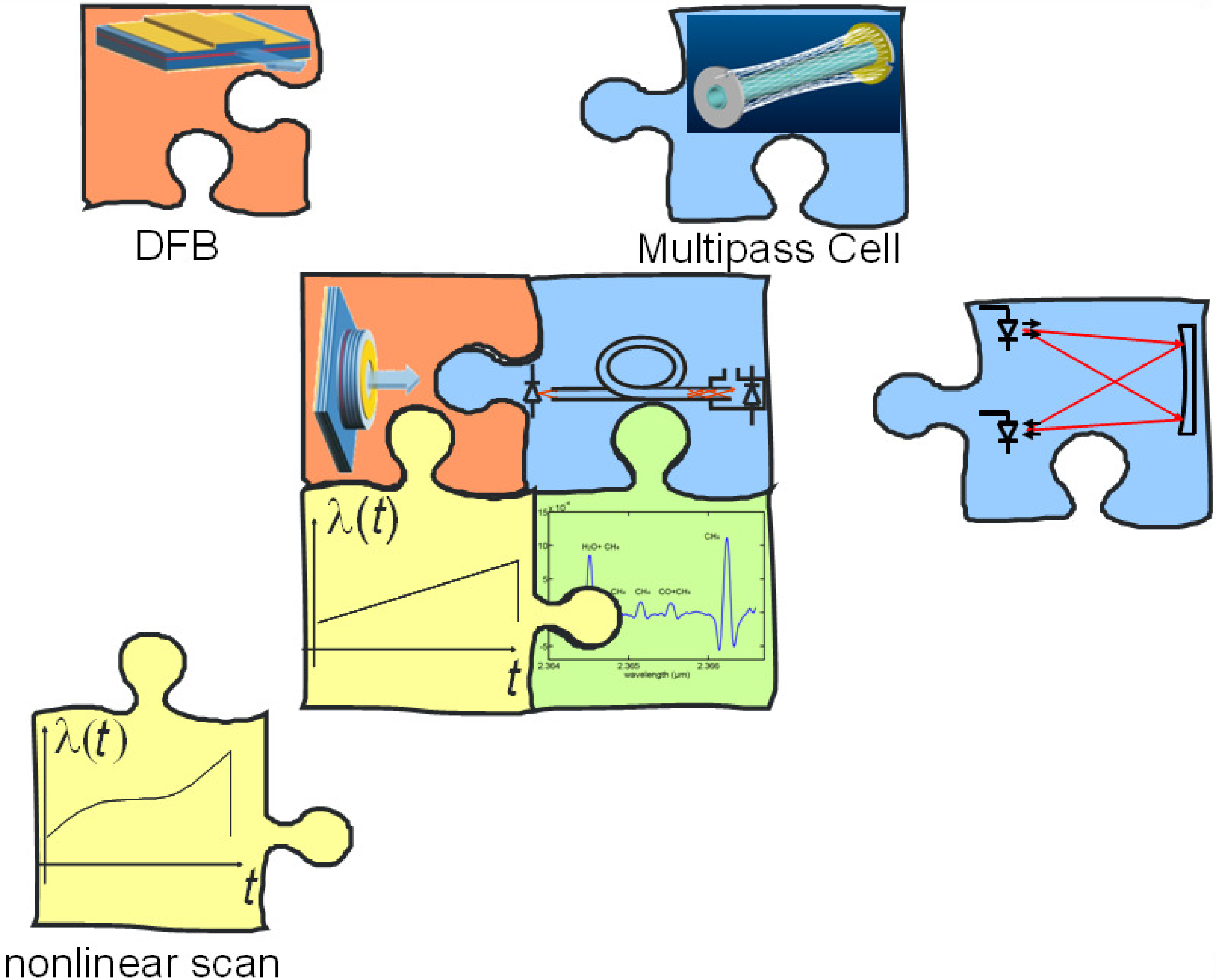


-170 ppb (1σ) achievable
5 min integrating without drift

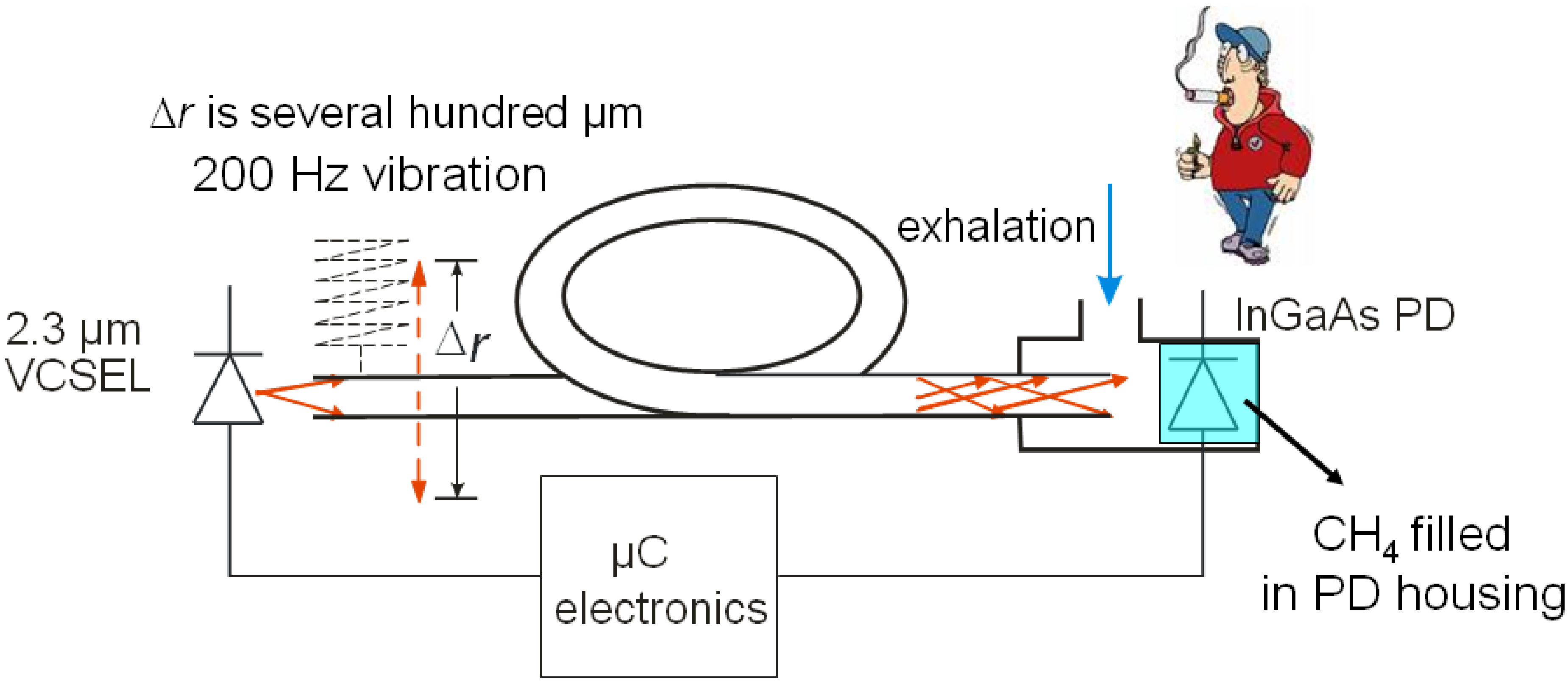


*"VCSEL-based calibration-free carbon monoxide sensor at 2.3 µm with in-line reference cell", J. Chen et. al., appl. Phys. B, (2010)

CO Monitor with improved Sensitivity



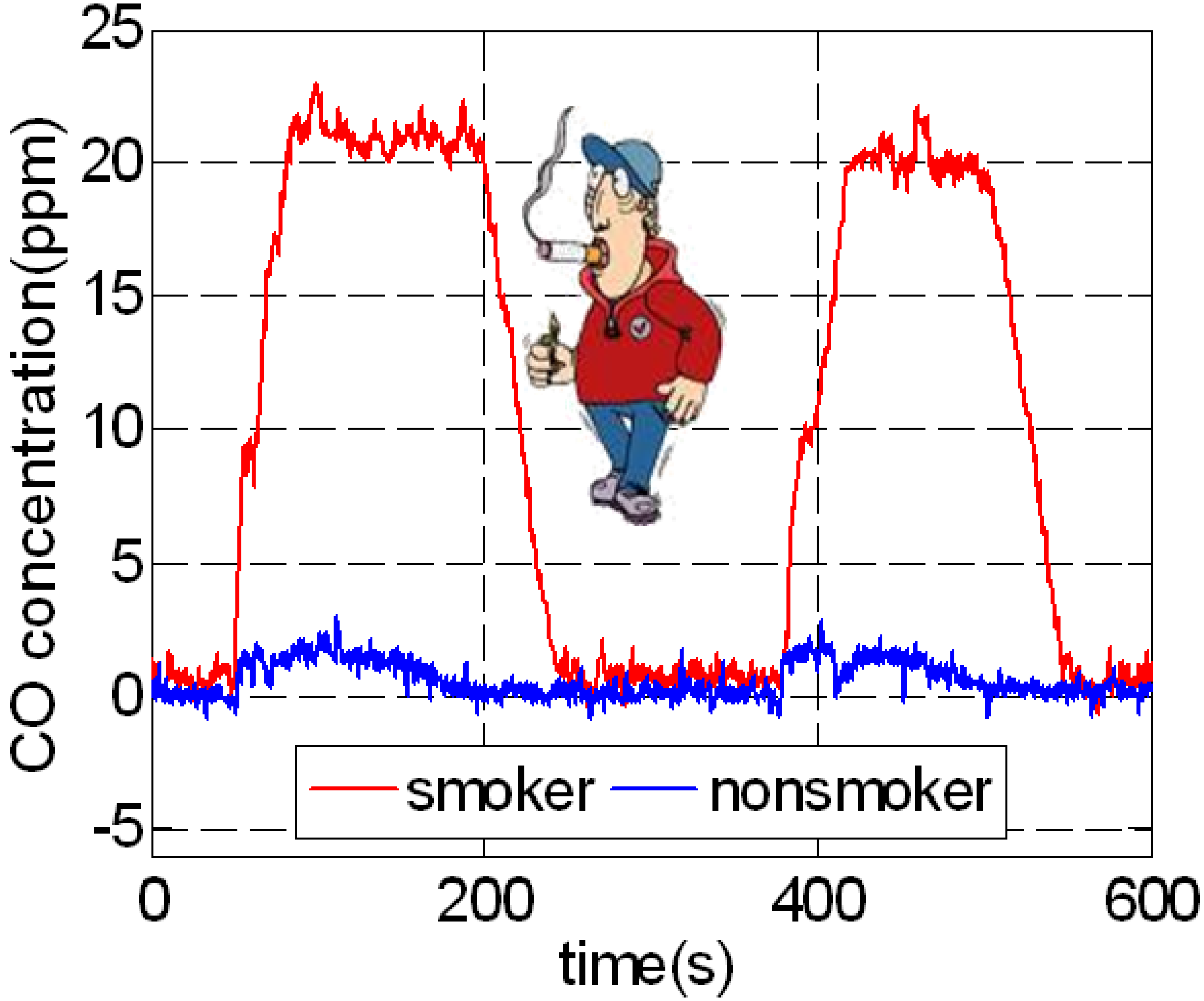
Experimental Setup of Fiber-based CO Sensor



How much carbon-monoxide is in the smoker's exhalation?

*) J. Chen, A.Hangauer, R.Strzoda, M.Fleischer, M. –C. Amann., "Low-Level and Ultra-Low Volume Hollow Waveguide Based Carbon Monoxide Sensor." Opt. Lett. 35, 3577-3579 (2010)

Result smoker exhalation test

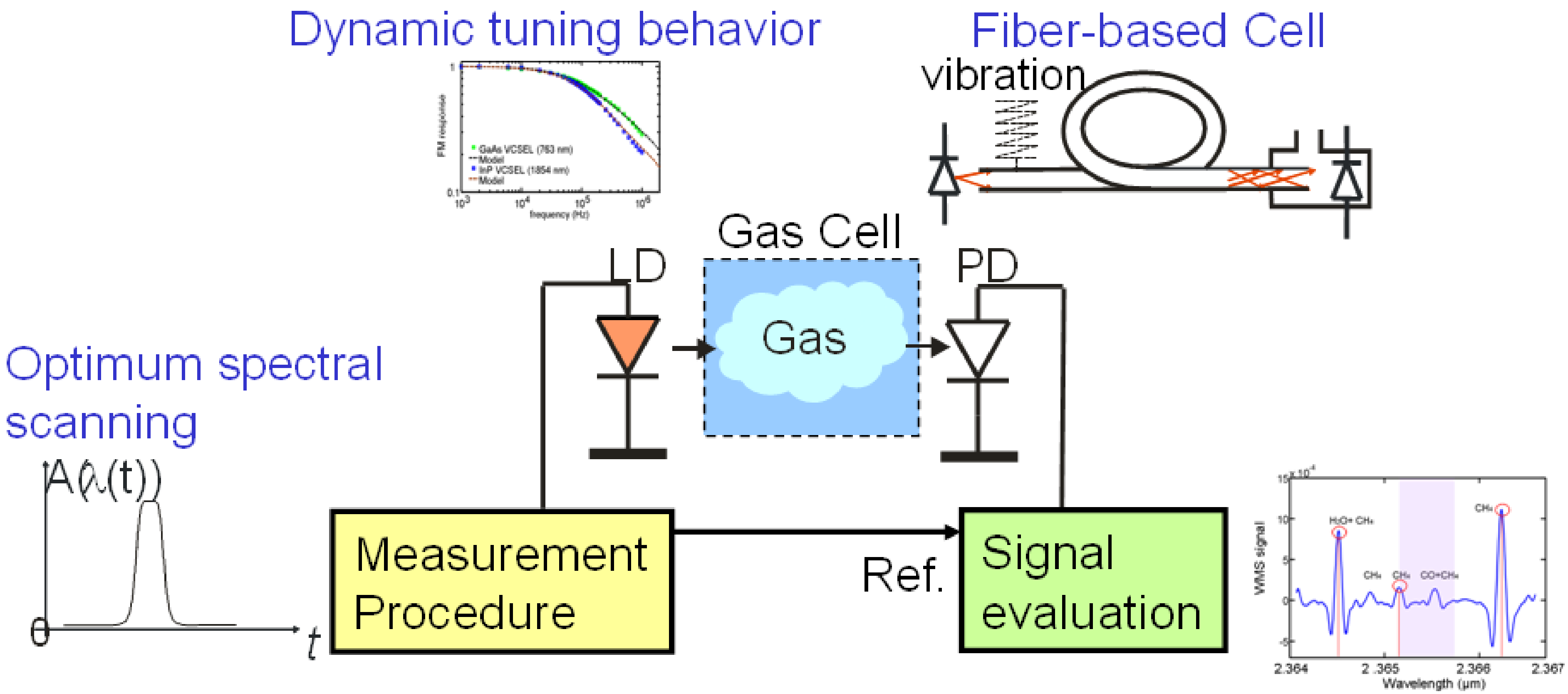


Sensor resolution (1 σ): 170 ppb @ 1s

Sample volume: 1.3 ml

Smallest detectable amount of CO: 40 pL (tip of hair)

Conclusion



Developed sensors / Applications:

- *Oxygen sensor for process optimization in furnace*
- *CO sensor for fire detection and working place monitoring*
- *CO fiber sensor for breath analysis*

Thank you!

Project NOSE

Journal papers:

J. Chen, A. Hangauer, R. Strzoda, M. Fleischer, M.-C. Amann, "Low-Level and Ultra-Low Volume Hollow Waveguide Based Carbon Monoxide Sensor." Opt. Lett. 35, 3577-3579 (2010)

A. Hangauer, ***J. Chen***, R. Strzoda, M. Fleischer, and M.-C. Amann, "Fire detection with a compact laser spectroscopic carbon-monoxide sensor," accepted for publication in Sensors and Actuators B: Chemical (2010)

J. Chen, A. Hangauer, R. Strzoda, M.-C. Amann, "Resolution Limits of Laser Spectroscopic Absorption Measurements with Hollow Glass Waveguides " Applied Optics 49, 5254-5261 (2010)

J. Chen, A. Hangauer, R. Strzoda, M.-C. Amann, "VCSEL-based Calibration-free Carbon Monoxide Sensor at 2.3 μm with in-line Reference Cell", Applied Physics B (2010)

J. Chen, A. Hangauer, R. Strzoda, M.-C. Amann, "Laser Spectroscopic Oxygen Sensor Using Diffuse Reflector-based Optical Cell and advanced Signal Processing", Applied Physics B 100, 417-425 (2010)

J. Chen, A. Hangauer, R. Strzoda, M.-C. Amann, "Tunable diode laser spectroscopy with optimum wavelength scanning", Applied Physics B 100, 331-339 (2010)

A. Hangauer, ***J. Chen***, R. Strzoda, M. Ortsiefer, M.-C. Amann, "Wavelength modulation spectroscopy with a widely tunable InP-based 2.3 μm vertical-cavity surface-emitting laser", Optics Letters 33, 1566-1568 (2008)

J. Chen, A. Hangauer, M.-C. Amann, "Simplified model of the dynamic thermal tuning behavior of Vertical-Cavity Surface-Emitting Lasers", IEEE Photonics Technology Letters 20, 1082-1084 (2008)

A. Hangauer, ***J. Chen***, M.-C. Amann, "Modeling of the n-th harmonic spectra used in wavelength modulation spectroscopy and their properties", Applied Physics B: Lasers and Optics 90, 249–254 (2008)

J. Chen, A. Hangauer, R. Strzoda, M-C. Amann, "Accurate extraction method of the FM response of VCSELs based on Wavelength Modulation Spectroscopy", Applied Physics B: Lasers and Optics 90, 243–247 (2008)

J. Chen, A. Hangauer, R. Strzoda, M. -C. Amann, "Experimental characterization of the frequency modulation behavior of vertical cavity surface emitting lasers", Applied Physics Letters 91, 141105 (2007)

30 Conference papers

IEEE LEOS Graduate Student Fellow