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

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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 instrument: Aerodyne Research

oxygen sensor: Siemens Analytic
Tunable Diode Laser Spectroscopy (TDLS)

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- in-situ measurement...

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Goal: develop miniaturized TDLS sensor
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.
Key Sensor Components

- Laser Diode
- Optical Cell
- Measurement Procedure
- Signal evaluation
- Gas Cell
- LD
- PD
- Ref.

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Key Sensor Components

VCSEL

DFB

Multipass Cell

Hollow-Fiber Cell

Diffuse reflector

Doublepass Cell

Signal Processing

linear scan

nonlinear scan
Dynamic Laser Wavelength Tuning Behavior

Current modulation $\Delta i$ causes wavelength variation $\Delta \lambda$
Dynamic Laser Wavelength Tuning Behavior

Current modulation

Laser diode (VCSEL)

Emission spectrum

Faster current modulation $\rightarrow$ smaller wavelength variation
Tuning coeff. $\Delta \lambda / \Delta i$ drops with increasing frequency
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?

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*

Analytical Formula for FM Response

Tuning coefficient has a closed form expression!

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

Parameter Definitions:
- \( f_0 \): “Frequency scale parameter”, depends on thermal diffusivity \( \kappa \) 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

- DFB
- Multipass Cell
- Hollow-Fiber Cell
- Diffuse reflector
- Doublepass Cell

VCSEL

- Linear scan
- Nonlinear scan

Signal Processing
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Conventional Gas Cell

Tunable Laser

Detector
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

Reflecting layer: Ag & AgI
Gas
SiO₂

200 μm

absorbance resolution: $10^{-4}$

Can absorbance resolution be further improved?
What influences absorbance resolution?

- Laser in-coupling?

  *No relevant influence on absorbance resolution*

- Detector out-coupling?

- Fiber mechanical vibration?
Influence of out-coupling

Finding: abs. resolution $\sim 1/\sqrt{N}$ (number of integrated speckle)
Influence Mechanical Vibration

Speckle pattern changes strongly by vibration
→ Integration over time gives a smooth transmission

Sensing results with and without vibration

\[ \sim 3\text{nm} \quad (@2365\text{ nm}) \]

without vibration

„resolution 10^{-4}“

with vibration

„resolution 10^{-5}“

Absorbance resolution is a magnitude improved with vibration!
Sensor Components

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Origin of Noise on Sensor Output Values

Scanned spectra

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

Gas concentration -- real
-- measured

$\tau$

Curve Fit

\[ (-\frac{1}{2}, \frac{1}{2}) \rightarrow (0, 0) \]
Origin of Concentration Noise

Scanned spectra

\[ \tau \]

Noise on measured spectra \( S_{aa} \)

causes

Noise on measured conc. \( \sigma(c) \)

Gas concentration

\[ \tau \]

-- real
-- measured

Twice the measurement rate \( \rightarrow \) increasing conc. noise by \( \sqrt{2} \)

Noise density \( N \) times \( \rightarrow \) conc. noise increased by \( \sqrt{N} \)
Origin of Concentration Noise

Scanned spectra

\[ \tau \]

time

Noise on measured spectra \( S_{aa} \)

\[ \text{causes} \]

Noise on measured conc. \( \sigma(c) \)

\[ \text{Curve Fit} \]

Gas concentration

\[ \tau \]

time

-- real

-- measured

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

Selection of Components for CO Monitor

DFB

Multipass Cell

nonlinear scan
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Optical Cell for CO Sensing

Conventional:

Laser → Beam splitter → meas. cell

Reference cell with 100% CO → Photodetector reference cell

New:

Laser → meas. cell → Photodetector

Reference gas CH₄
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

CO Sensor Live
Sensing results*

- Sensor is suited for fire detection
- CO peaks after ignition resolvable

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

CO Monitor with improved Sensitivity

DFB

Multipass Cell

nonlinear scan
Experimental Setup of Fiber-based CO Sensor

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

Result smoker exhalation test

Sensor resolution (1 $\sigma$): 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!

Journal papers:


30 Conference papers