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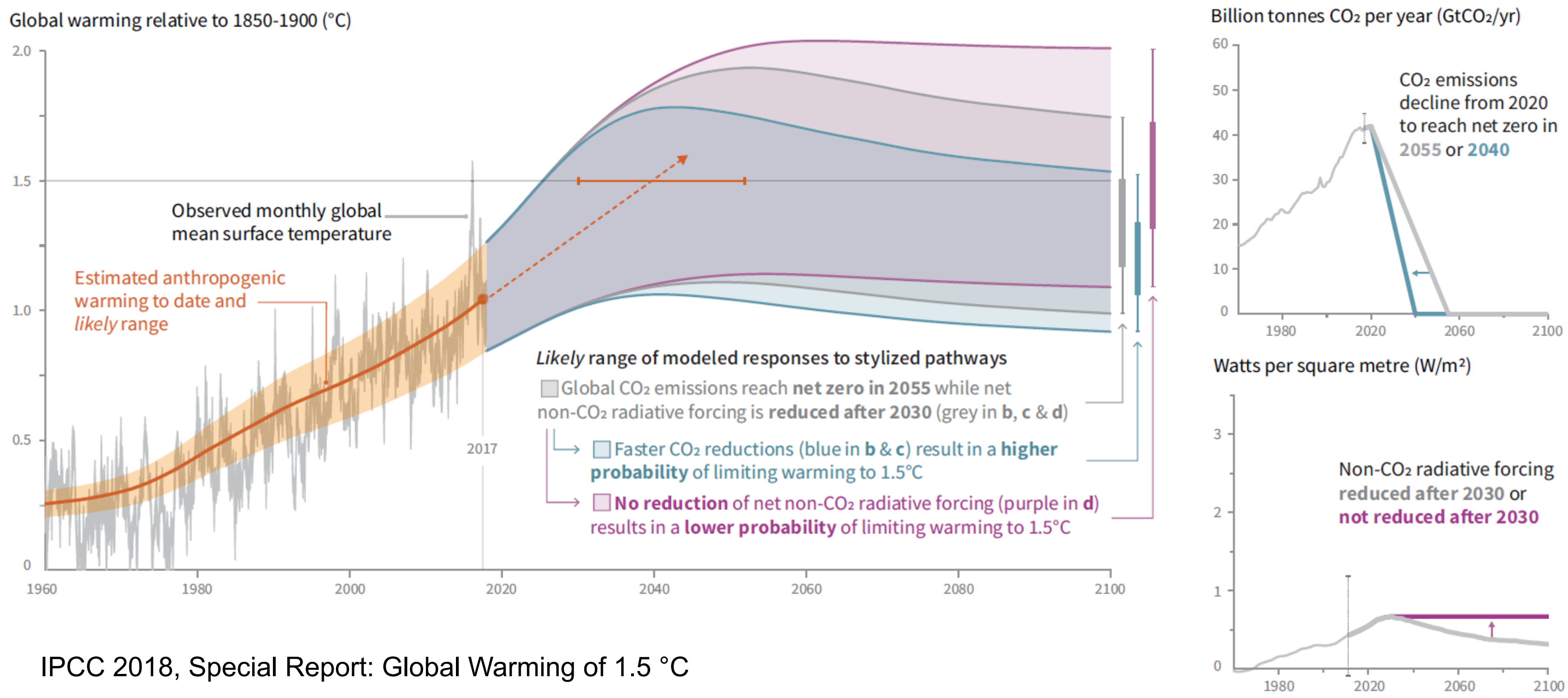
Mid-infrared tunable diode laser spectroscopy for the detection of fugitive methane emissions

Jalal Norooz Oliaee, Nicaulas Sabourin, James A. Gupta, Prem Lobo, Kevin Thomson, Greg Smallwood

Council for Optical Radiation Measurements 2019
Ottawa, Canada

Motivation: Climate Impacts



IPCC 2018, Special Report: Global Warming of 1.5 °C

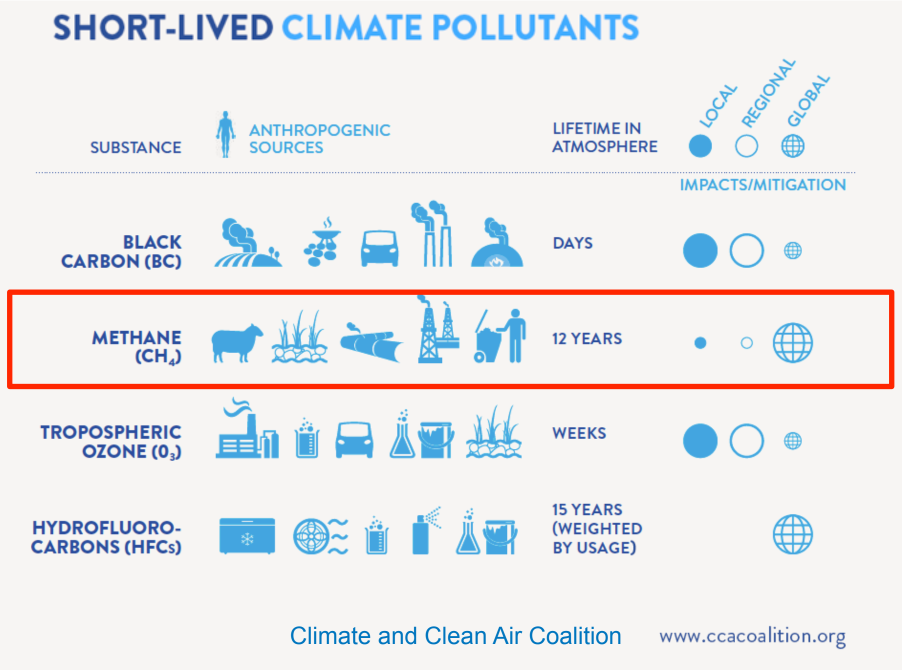
Non-CO_2 climate forcers

Short-lived climate forcing agents

- Black Carbon (BC)
- Methane (CH_4)
- Some fluorinated gases (e.g. HFCs)
- Ground-level ozone (O_3)

Long-lived climate forcing agents

- Nitrous oxide (N_2O)
- Some fluorinated gases (e.g. CF_4)



20/100-year
84/28 x CO_2

Global action on CH_4

IPCC 1.5°C Special Report, Section C.1.2.:

"Modelled pathways that limit global warming to 1.5°C with no or limited overshoot involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010)."

"Non-CO_2 emissions can be reduced as a result of broad mitigation measures in the energy sector."

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"Non-CO_2 emissions can be reduced as a result of broad mitigation measures in the energy sector."

Other motivations to reduce emissions:

For example:
$$$ Lost methane is also lost potential energy and revenue $$$

METHANE

A potent greenhouse gas with a short lifetime

Uncertainties in inventory estimates exist*

Gaps attributed to unreported venting or fugitive emissions due to episodic emissions, abnormal operating conditions, leaks, etc.

These emissions are often ignored but need to be monitored.

* M. R. Johnson et al. *Environ. Sci. Technol.* 51, 13008-13017 (2017)
R. A. Alvarez et al. *Science* 361, 186-188 (2018)

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UAV-based measurements

- Autonomous and flexible flight patterns
- Lower operation cost vs. manned aircrafts
- Near-surface operation
- Relaxed regulatory requirements

Requires sensitive, small, lightweight, power-efficient, and fast response time sensors.

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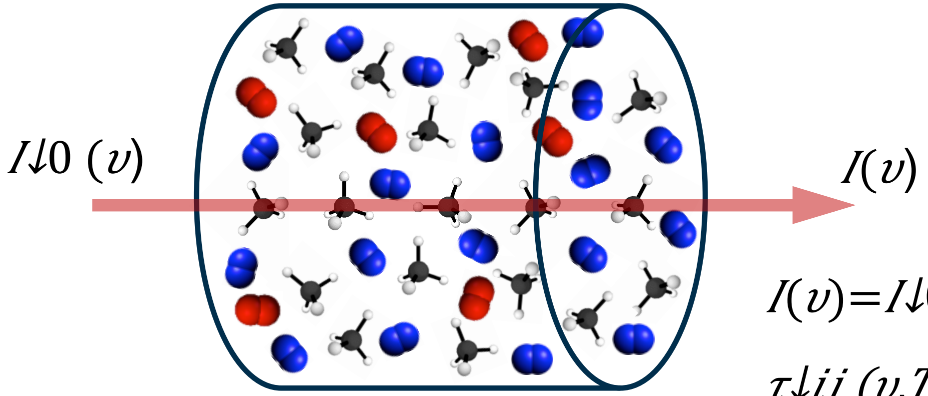
SPECTROSCOPY

Wavelength Modulation Spectroscopy (WMS) using mid-infrared Tunable Diode Laser Absorption Spectroscopy (TDLAS)

Direct Absorption Spectroscopy (DAS)



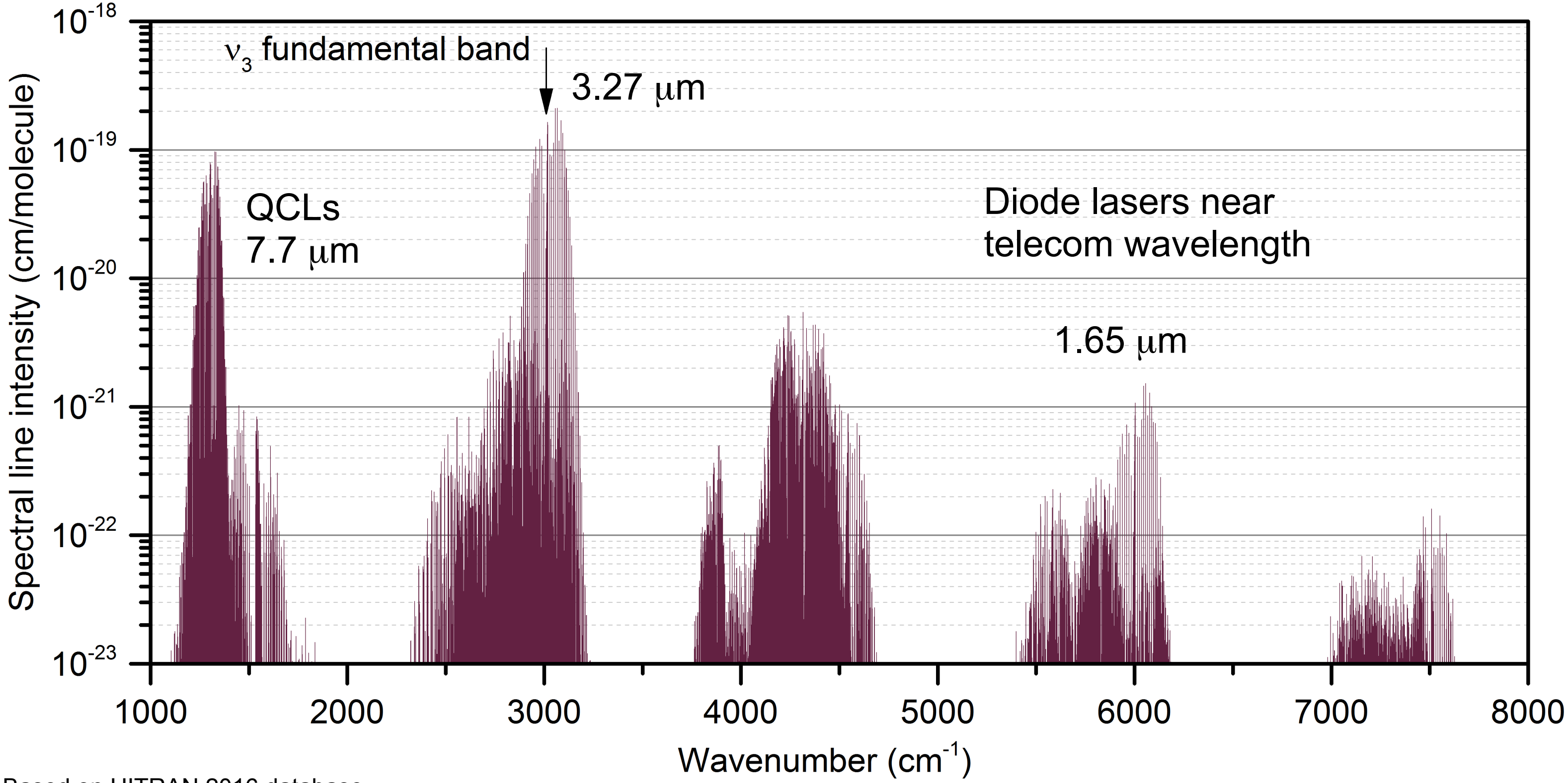
$$I(\nu) = I_0(\nu)\, e^{-\tau_{ij}(\nu,T,p)}$$

$$\tau_{ij}(\nu,T,p) = [CH_4]\, l\, S_{ij}(T)\, f(\nu;\, \nu_{ij}, T, p)$$

For fugitive emissions detection

- Strongest absorption line, S_{ij}
- Increase the absorption pathlength, l
- Wavelength modulation spectroscopy, $\nu = \nu_{ij} + a_M \sin(\omega_M t)$

Absorption bands of Methane



Based on HITRAN 2016 database

Mid-infrared light sources

Past

Mid-IR lead-salt diode lasers

- Multi-mode with mode-hops (i.e. dispersive optics)
- Cryogenic cooling (typically <130K)

Not suitable for portable applications

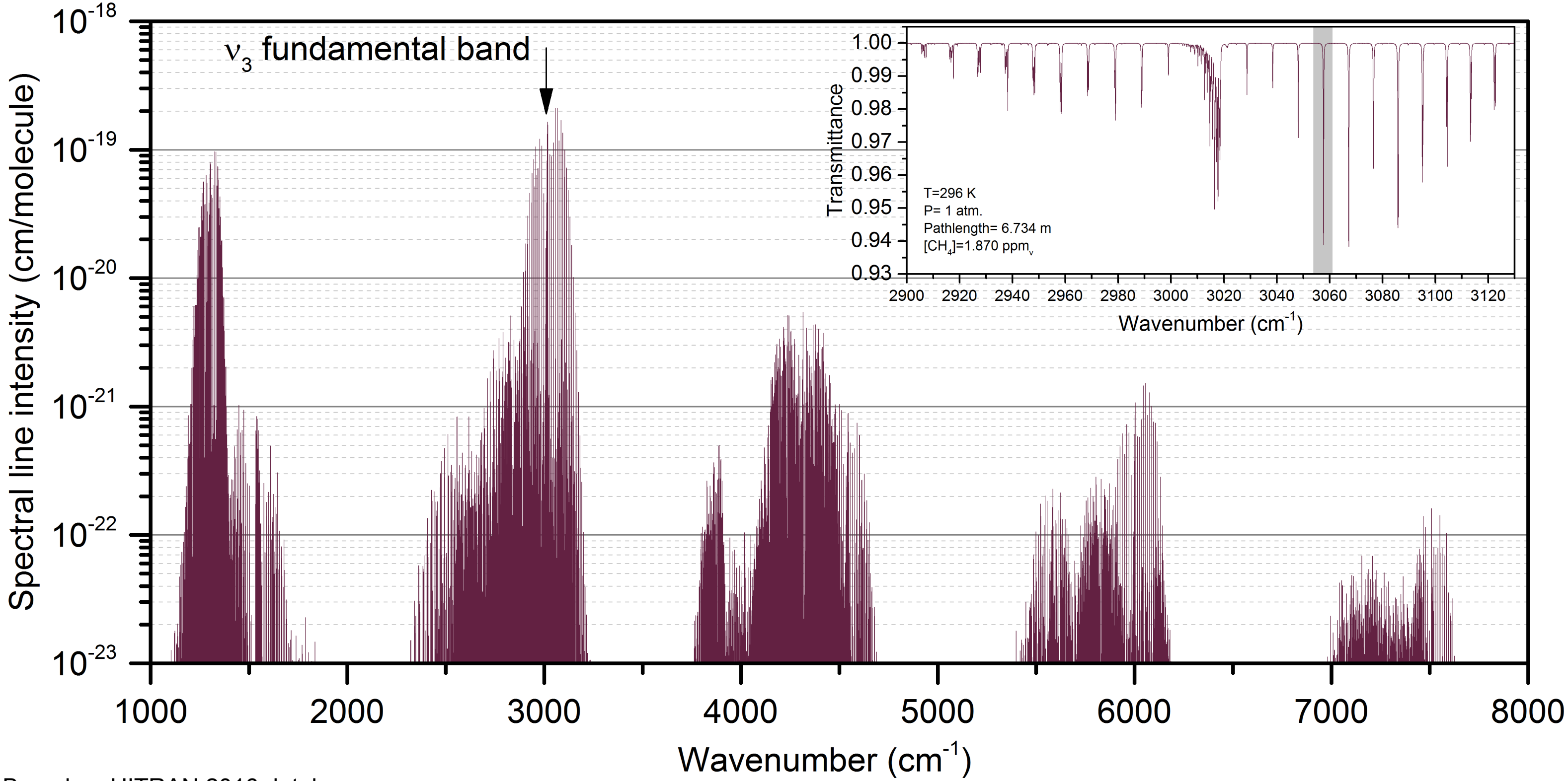
State of the art

GaSb-based DFB diode laser

- Single mode emission: 3270 nm
- Near room temperature operation (TEC accessible)
- Small footprint
- Hermetically sealed

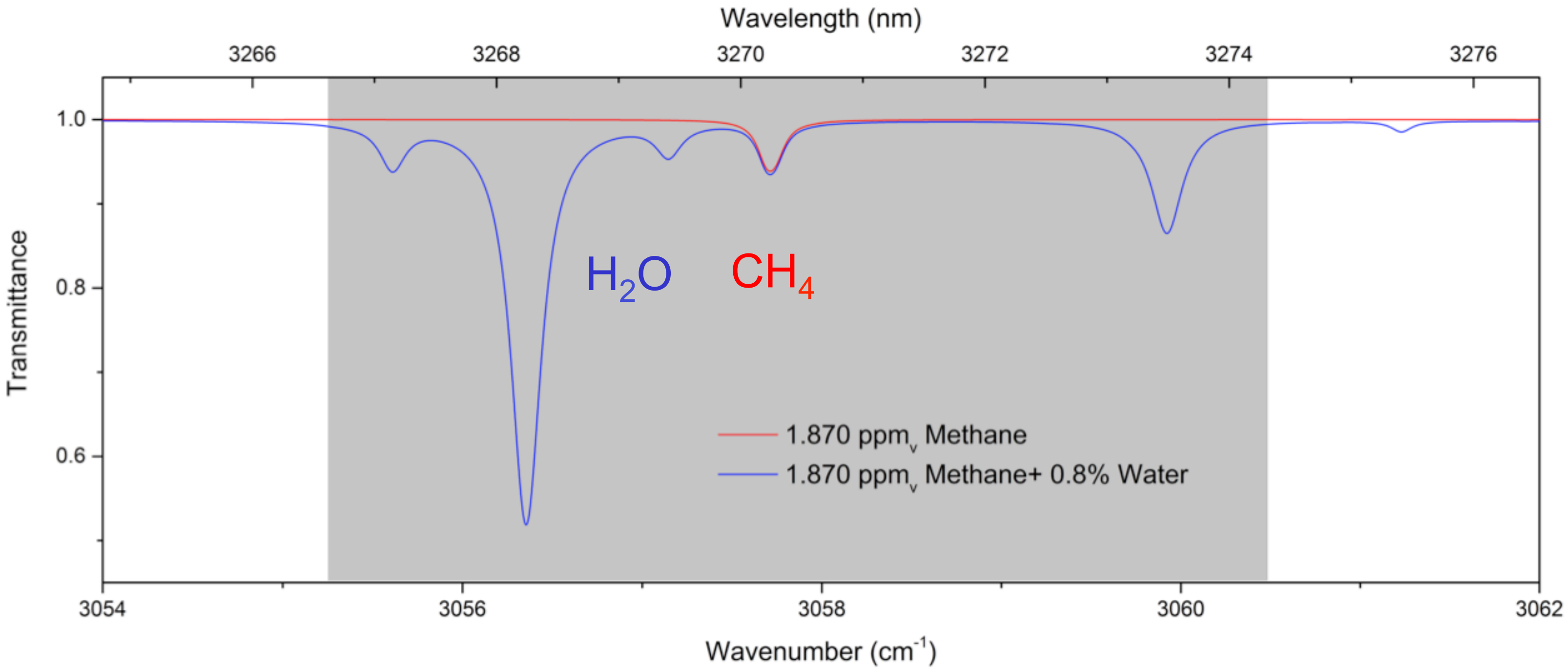
Suitable for space and mobile applications

Absorption bands of Methane



Based on HITRAN 2016 database

Spectral probing range

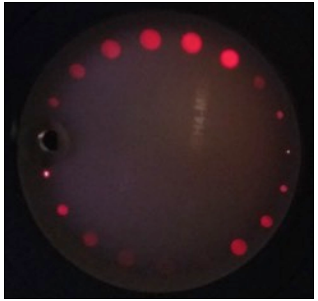


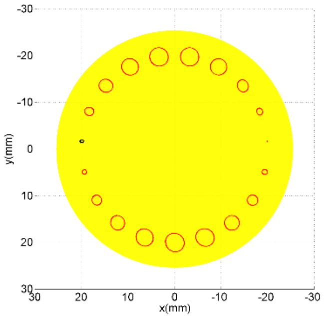
Calculated based on HITRAN 2016 database, P=1 atm., T=296 K, PL=6.734 m.

Multi-pass cell design

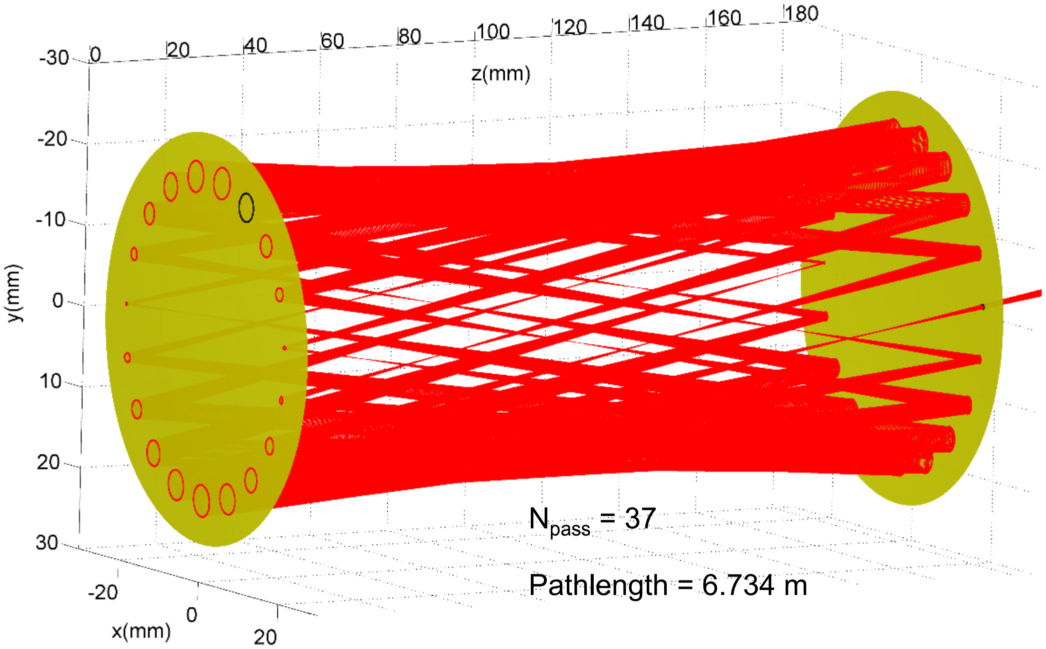
Herriott-type multi-pass cell

- 2-inch gold-coated (R>98.5%) spherical mirrors
- 37 passes, 6.734 meters of pathlength
- Open-path
- Not invoking the paraxial ray approximation

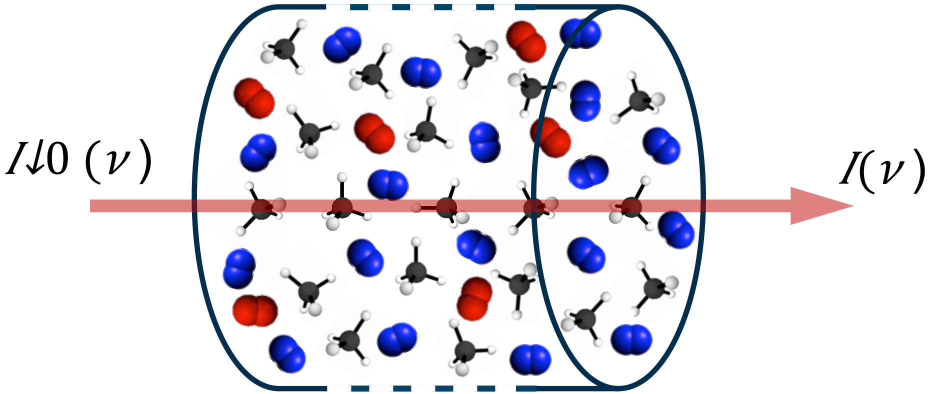




Spot pattern as seen from the back of the far mirror.



Direct Absorption Spectroscopy (DAS)



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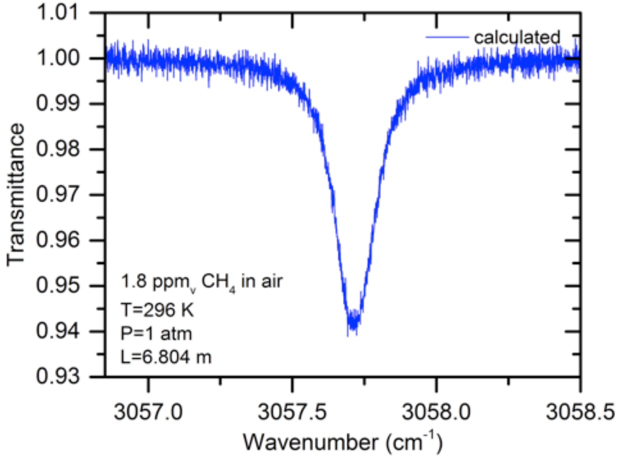
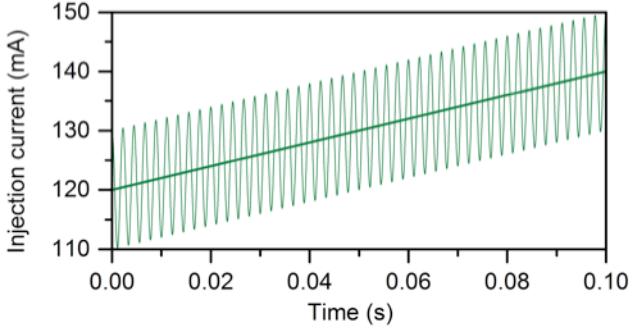


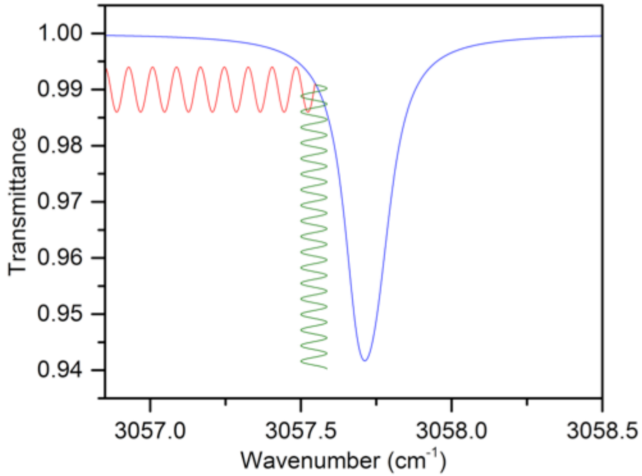
Optical depth about 0.06

Wavelength Modulation Spectroscopy (WMS)

Wavelength Modulation by TDL injection current

- Ramp for sweeping laser frequency
- High-frequency sine wave for modulation





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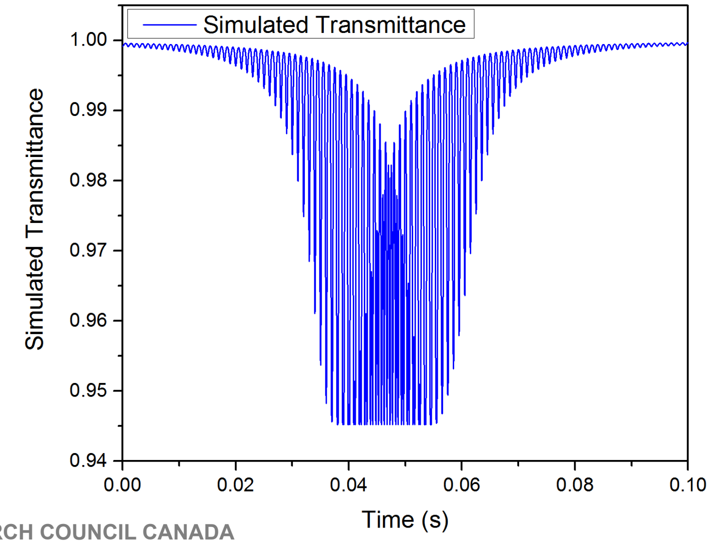
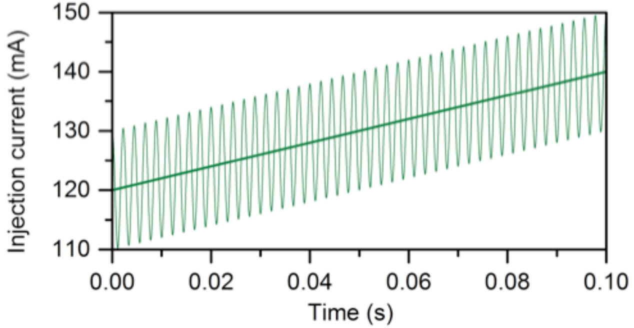
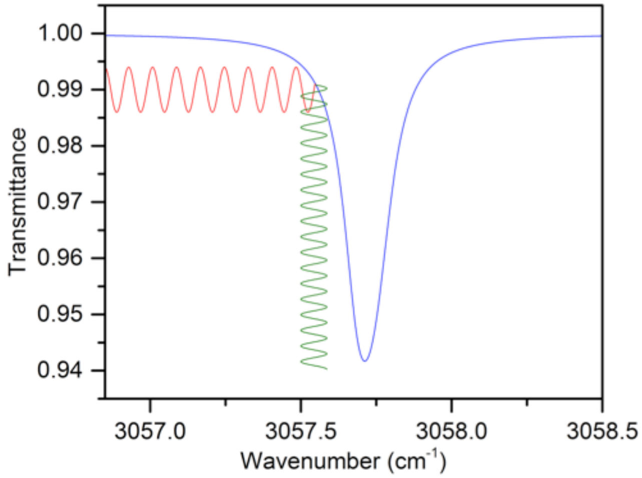


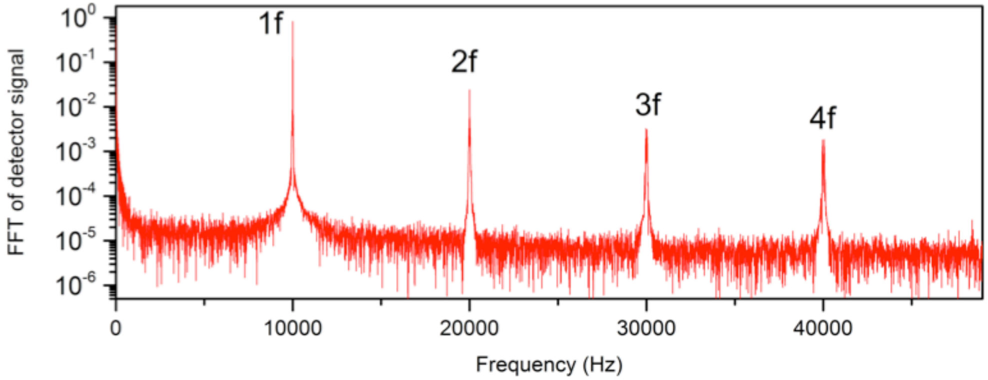


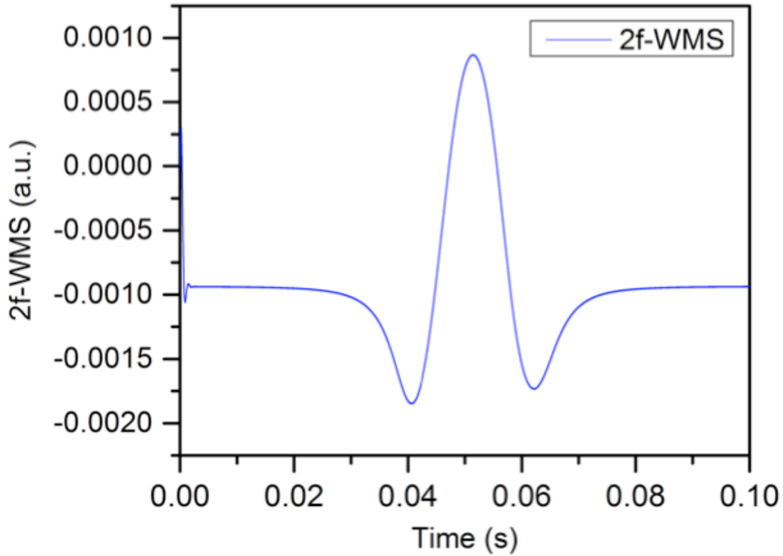


Wavelength Modulation Spectroscopy (WMS)

Modulation by TDL injection current

- Ramp for sweeping laser frequency
- High-frequency sine wave for modulation
- Detection at harmonics of the modulation frequency (i.e. lock-in amplifier)

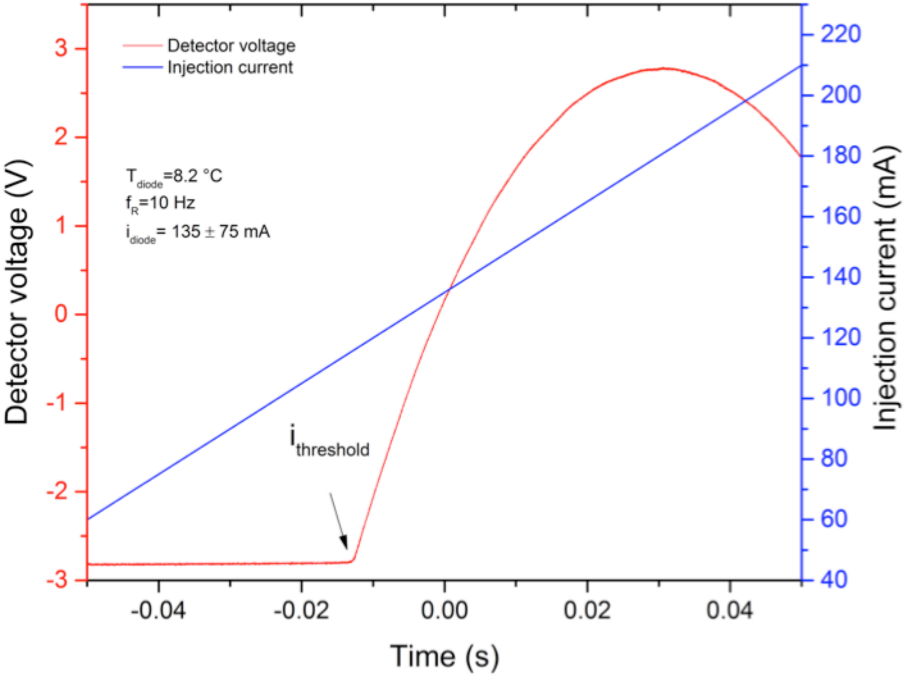


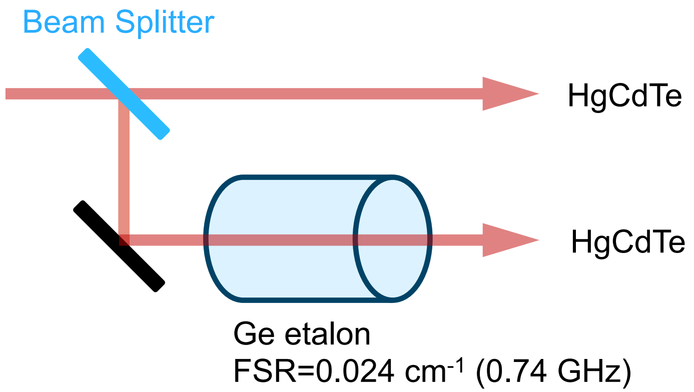


$$S_{2f}^{X}(t) = LP\left\{I_{\text{det.}}(t) \times \cos(2\omega_M t + \theta)\right\}$$

Characterization of the diode laser for WMS

Wavelength tuning characteristics of GaSb DFB laser





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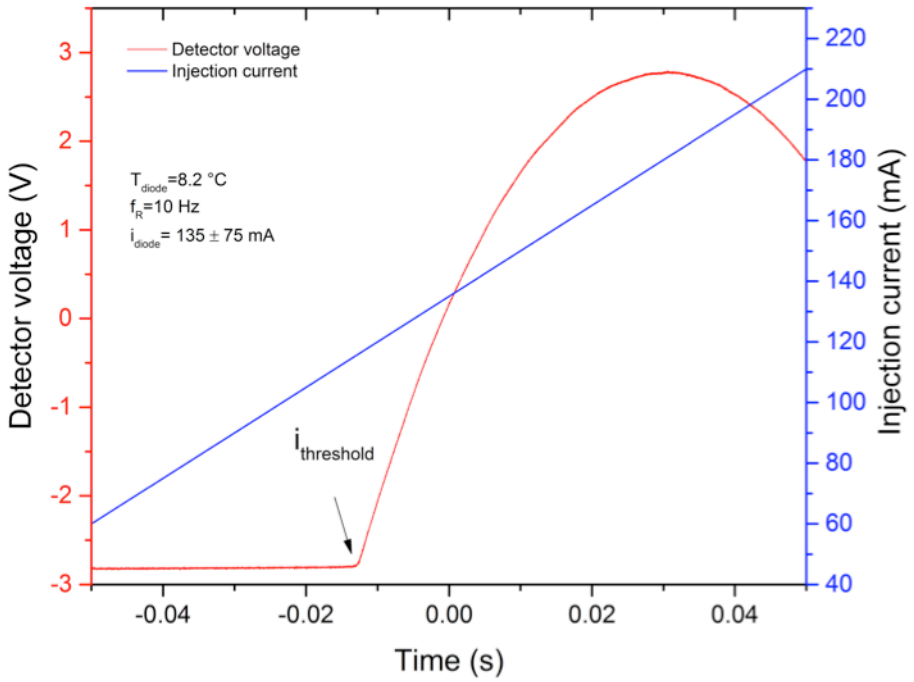
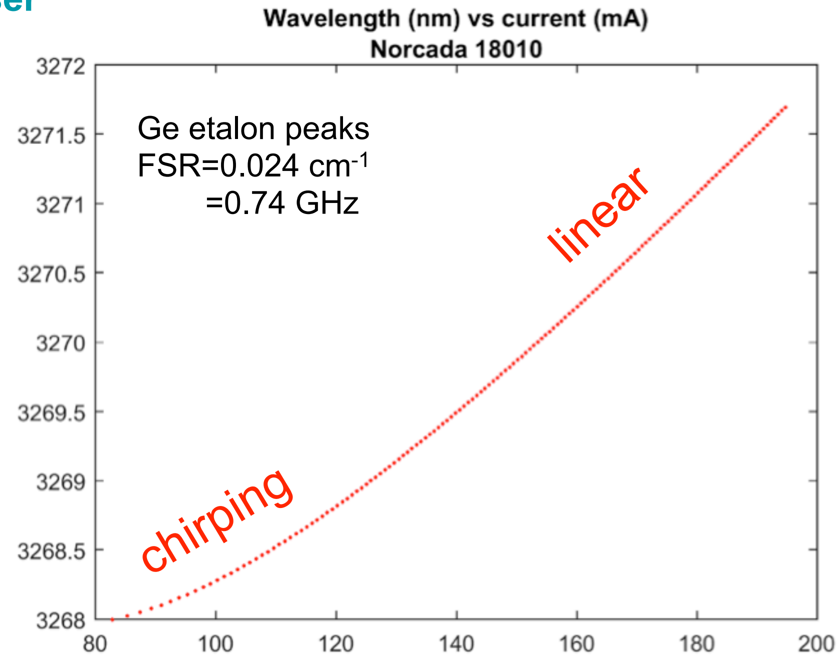
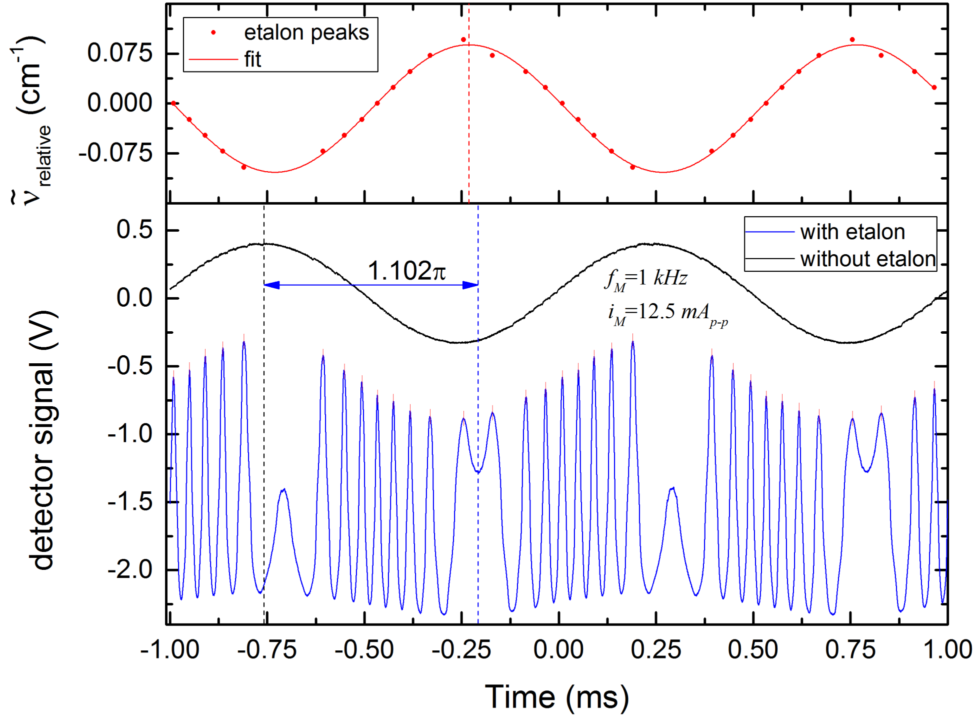




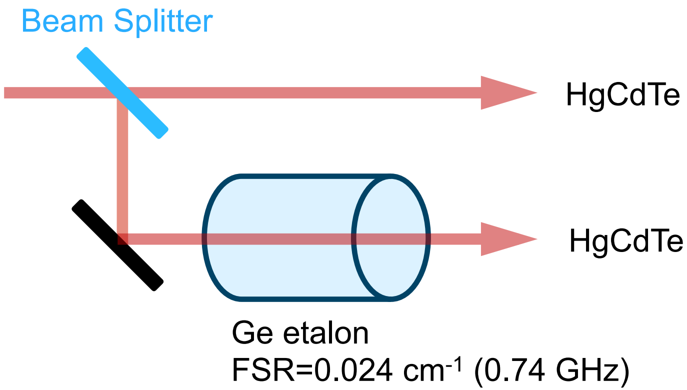
Characterization of the diode laser for WMS

WM-IM phase shift



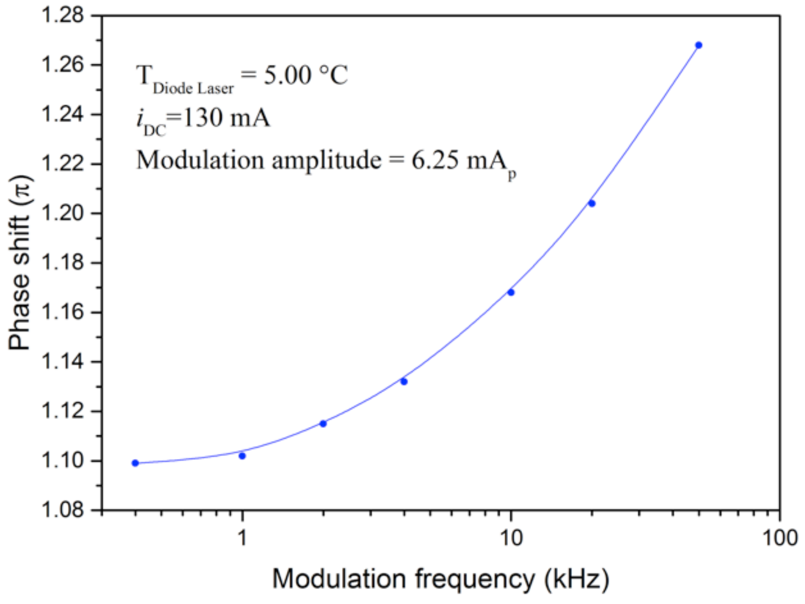
To the lowest order:

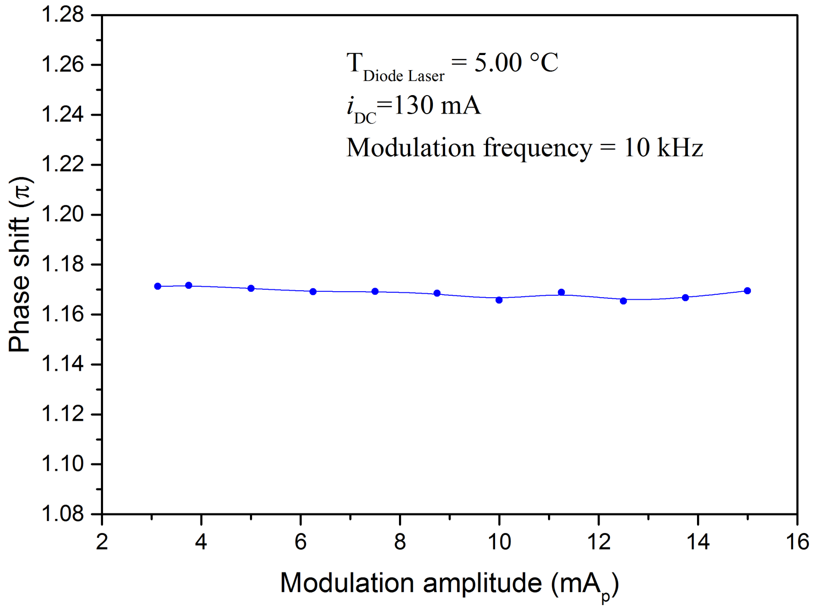
- Laser intensity varies inversely with laser frequency (i.e. phase shift = π)



Characterization of the diode laser for WMS

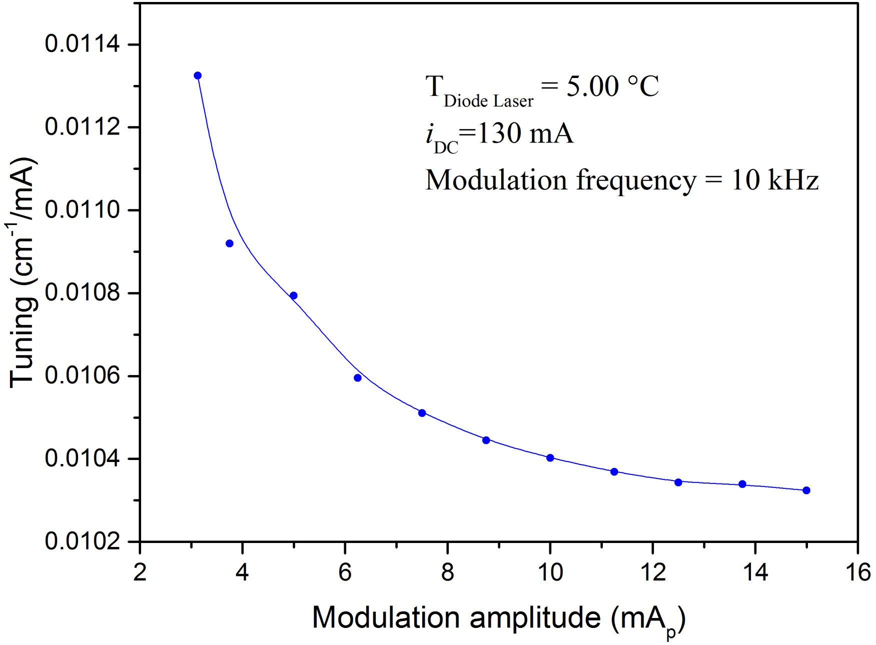
WM-IM phase shift

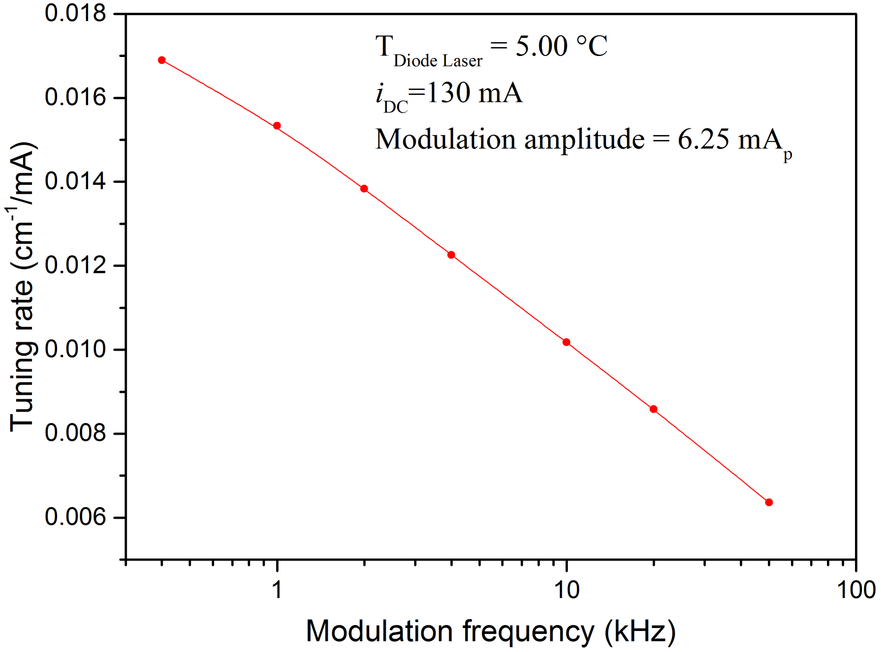




Characterization of the diode laser for WMS

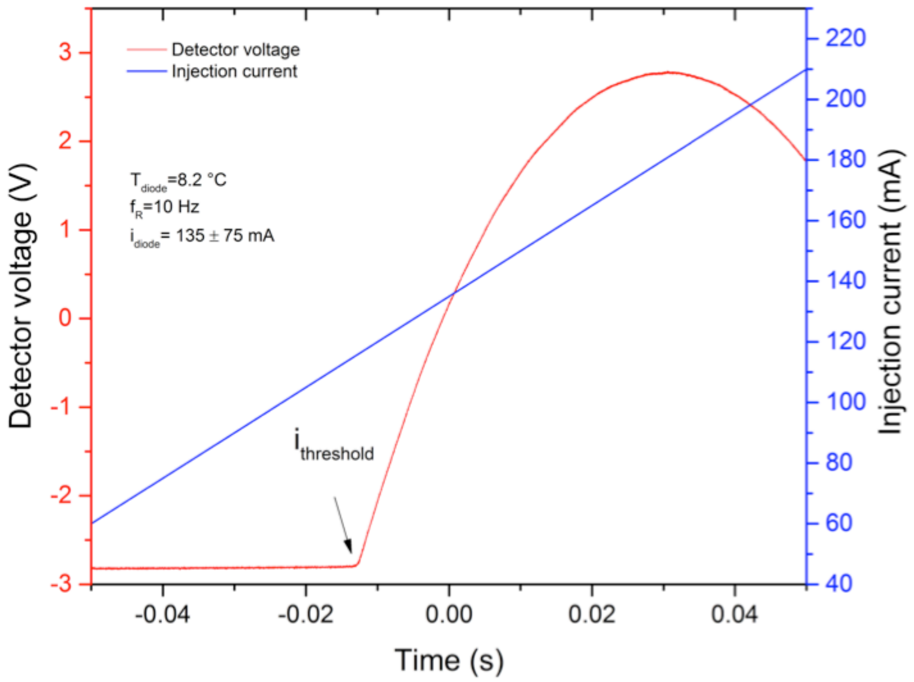
Modulation tuning rates

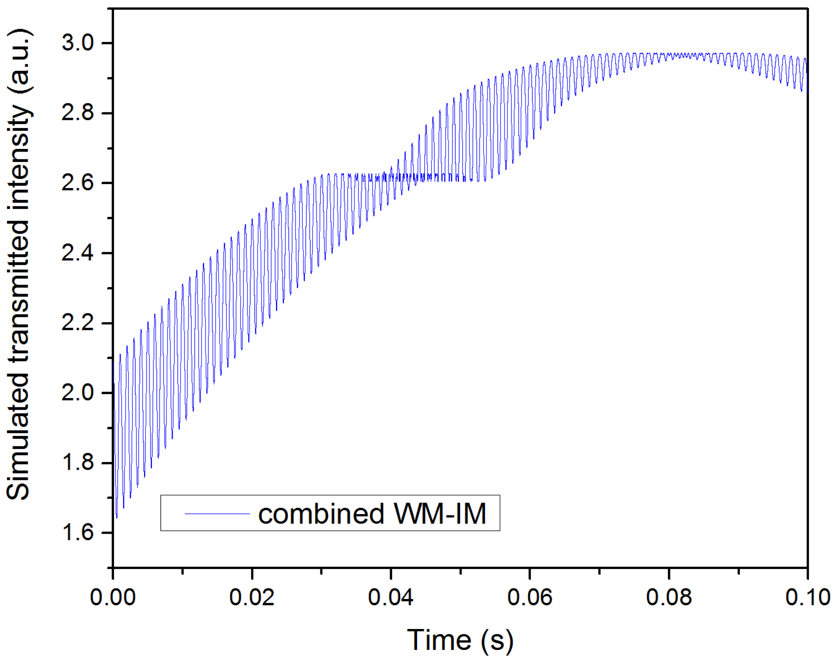




Characterization of the diode laser for WMS

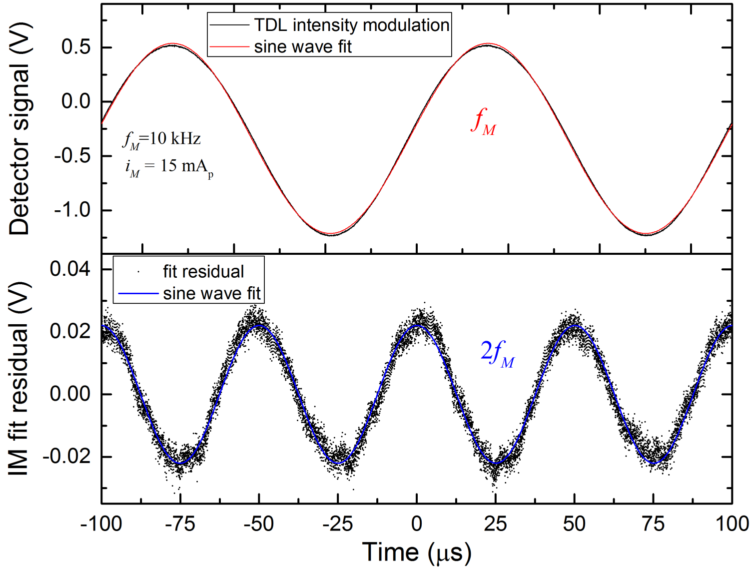
Laser induced intensity modulation (IM)

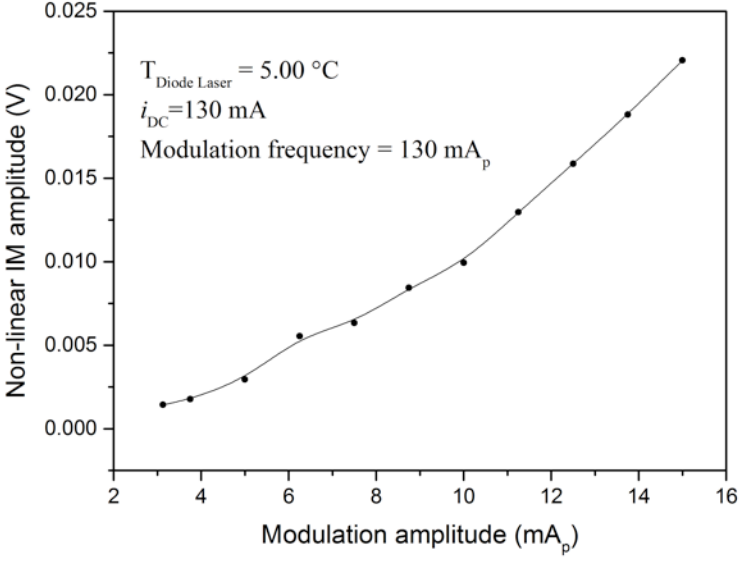




Characterization of the diode laser for WMS

Non-linear intensity modulation



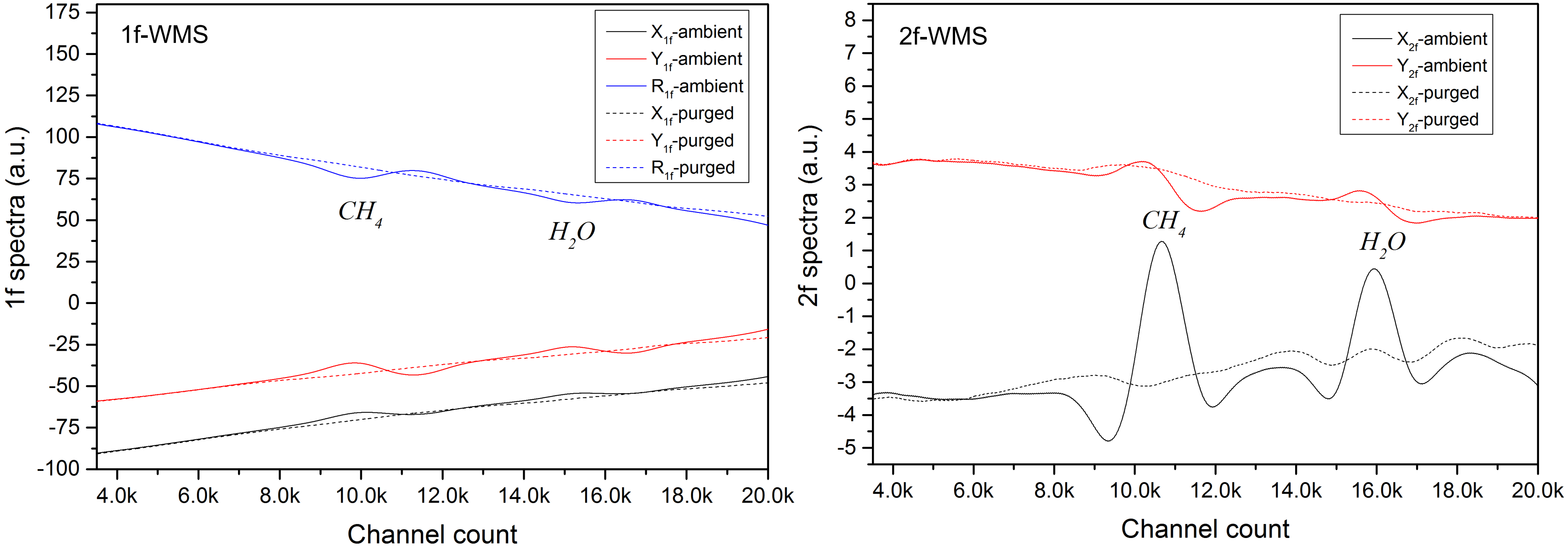


$$I_0(t)=\bar{I}_0\left[1+i_0\cos(\omega_M t+\phi_1)+i_2\cos(2\omega_M t+\phi_2)\right]$$

Linear and non-linear IM

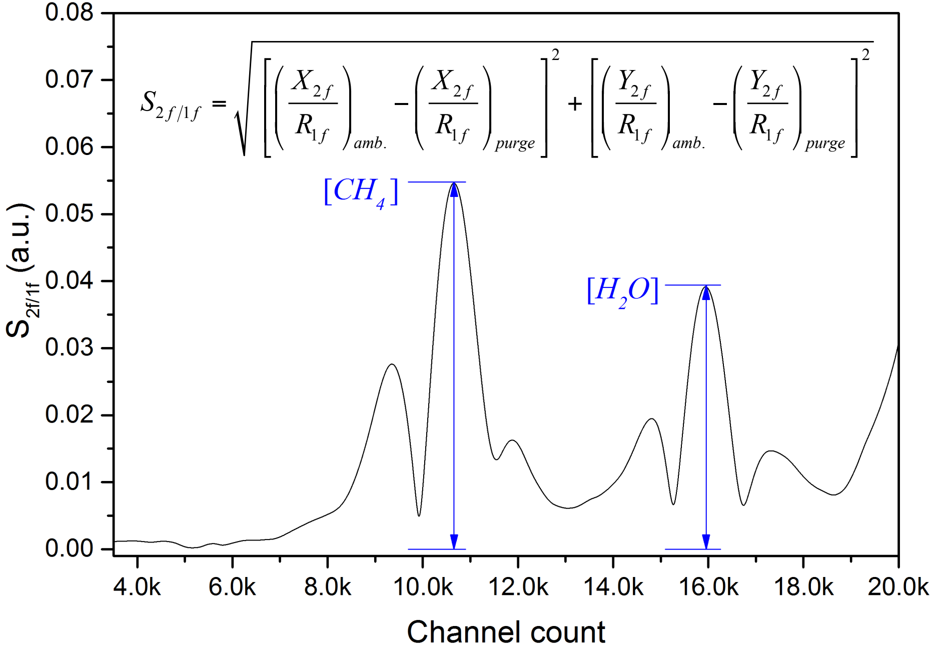
Background subtraction and 2f/1f normalization

Second and first harmonic signals with and without absorber

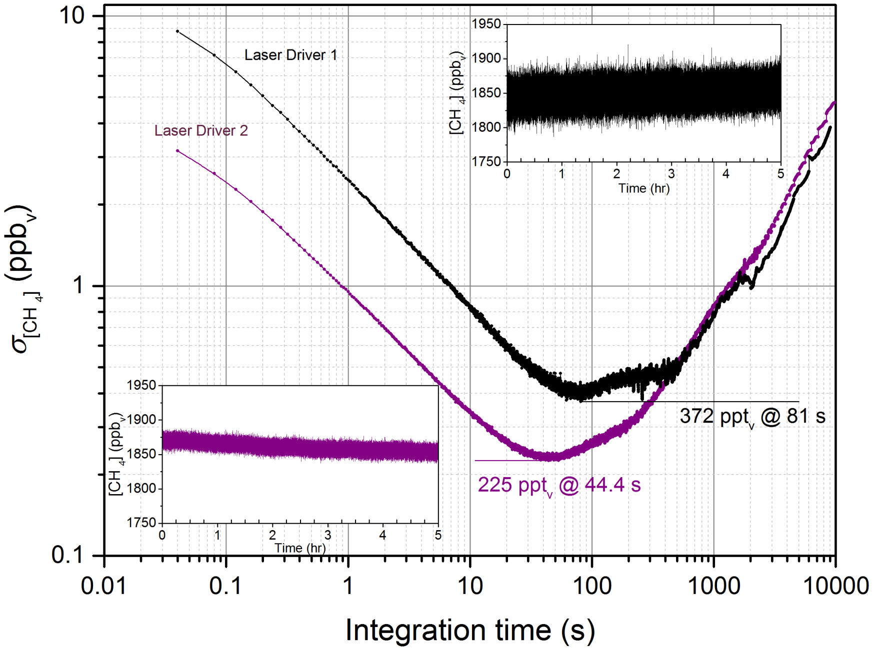


Background subtraction and 2f/1f normalization

Background subtracted 2f/1f normalized spectrum



Allan deviation plot after noise reduction



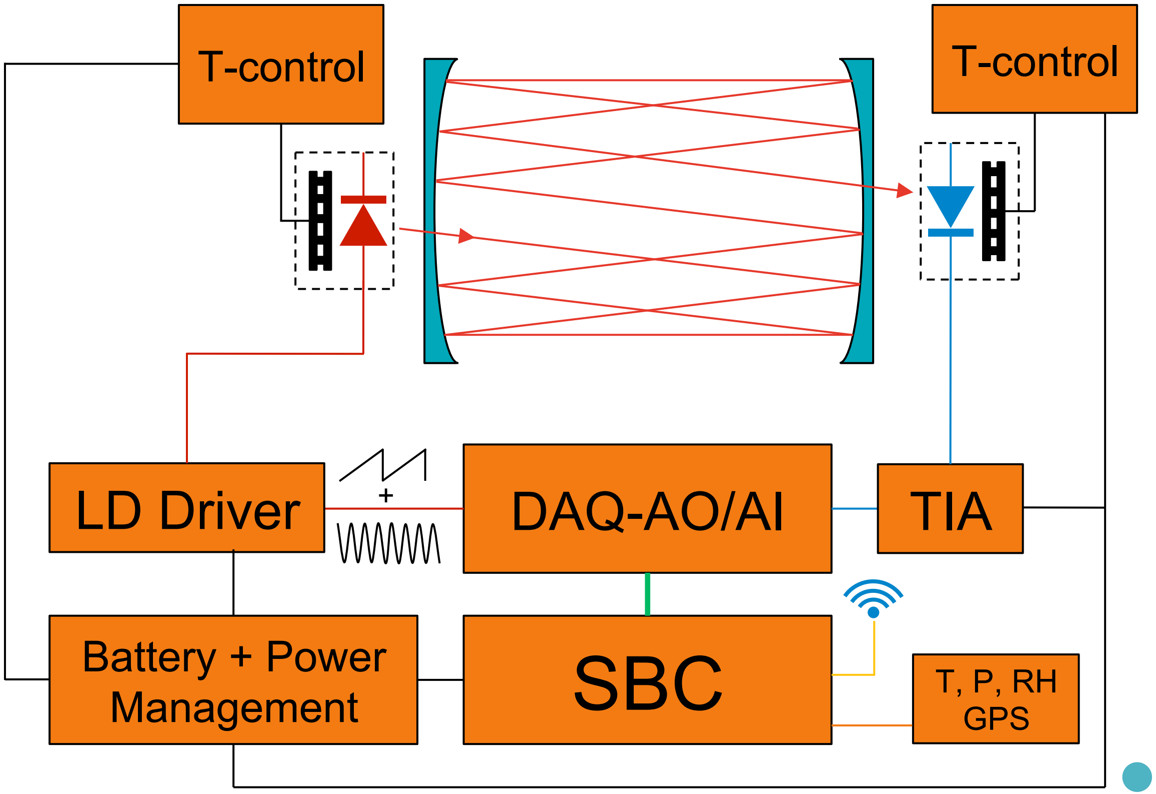
Sensor design: block diagram

- Fully programmable (LabView)

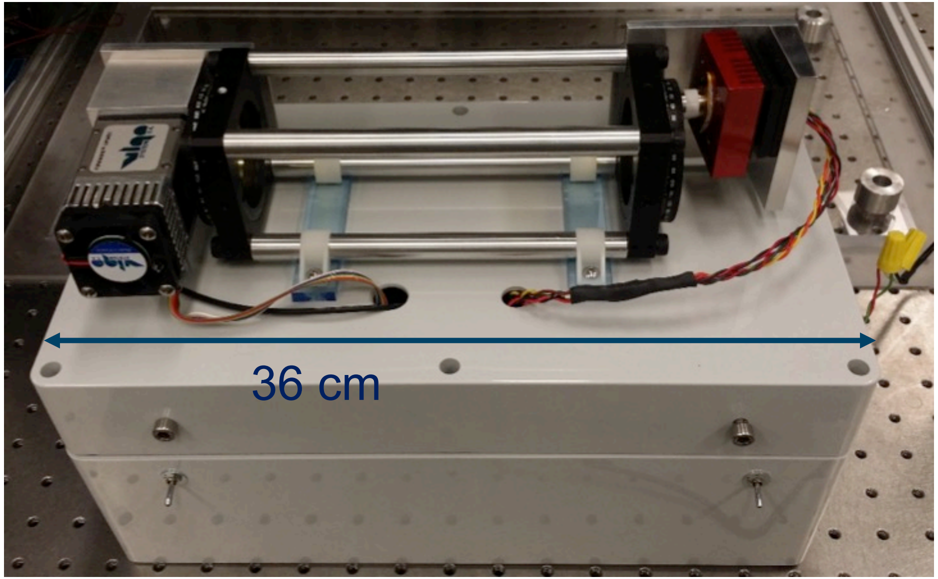
Laser drive signal

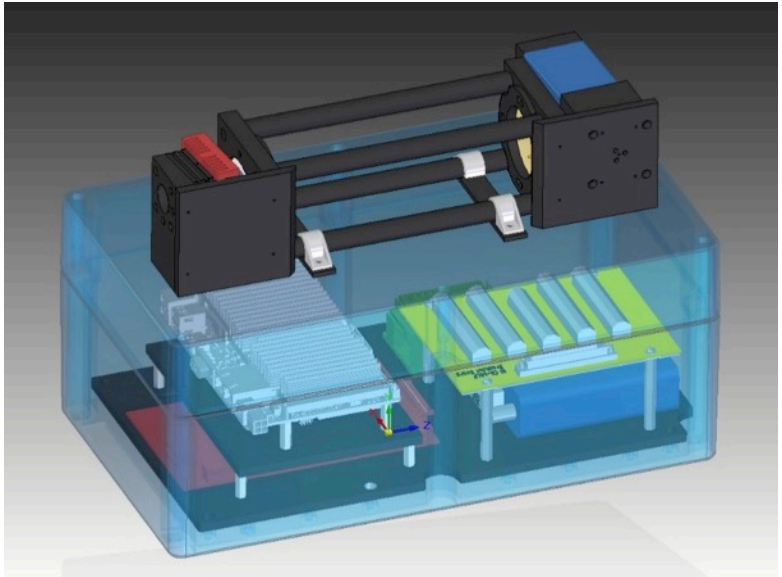
Software-based lock-in amplifier

- Ambient conditions sensors, GPS, Wi-Fi



Current prototype





Weight: 5 kg Power consumption: ~20 W

Future directions

Methane sensor

- Performance evaluation of the prototype in environmental chamber
- Mobile lab experiments in the field
- Further reduction in weight, size and power consumption
- UAV-based measurements over wetlands, farms, oil and gas facilities

THANK YOU