Sensor Applications for DFB-ICLs and QCLs

Presented by:

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LC Workshop
October 28, 2019

Princeton University
Princeton, NJ

Physical Sciences Inc.

PSI Physical Sciences Inc.

VG-2019-142-1

PSI does:

- Applied research and development for all major agencies of the U.S. government
- Technology transition and product development for government and industrial customers
- Prototyping for commercial applications
- Limited production of specialized systems and components for DoD and commercial markets
- Licensing to strategic partners and spin-outs

PSI is:

- A 46 year-old company of 200 scientists, engineers, and administrative personnel
- Headquartered in Andover, MA,; additional R&D operations in Pleasanton, CA
- Subsidiaries:
  - Q-Peak (Bedford, MA) manufactures lasers and optical devices
  - Research Support Instruments (Lanham, MD; Princeton, NJ) supports space ops
  - Faraday Technology (Dayton, OH) develops electrochemical industrial processes

PSI has:

- Spun-out four venture-supported companies
  - PSI Medical Products (1990)
  - Spectrum Diagnostix (1992)
  - Confluent Photonics (2000)
  - Laser Light Engines (2008)
- Acquired (2009) and divested (2012) Maxion Technologies Inc. (now ThorLabs Quantum Electronics)

Industrial Sensors Group: invents, develops, and applies leading-edge photonic technologies to meet unique sensor and control needs of industrial, government, and consumer clients

Previously at MIRTHE …..

Current and Emerging Laser Sensors for Greenhouse Gas Detection and Monitoring

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MIRTHE Workshop on Air Monitoring in Energy Extraction
August 9, 2013

Princeton University
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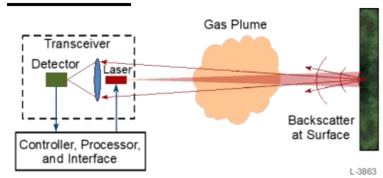
RMLD®

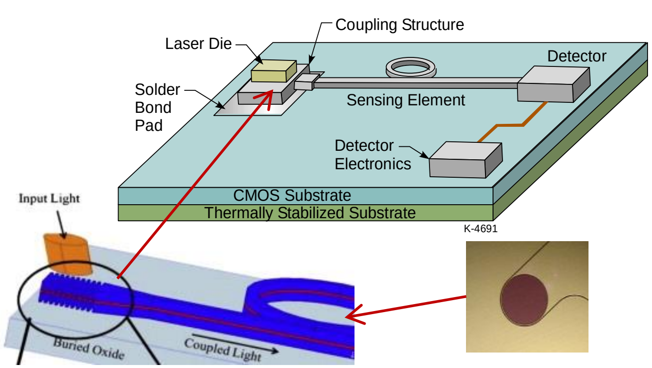


Measures methane column density (PPM-M) along laser path

Remote Methane Leak Detector (RMLD™)
Commercial product (since 2005)

- **Portable Standoff near-IR TDLAS**
- **>4000 in use for natural gas leak survey**

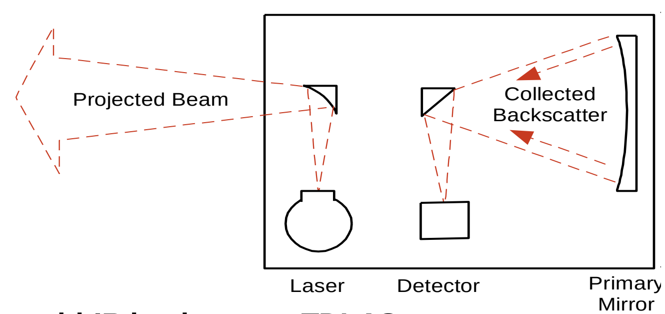
Integrated-Optic Sensors



Naiini, M.M, et.al., Solid-State Electronics,74,58 (2012).

- **Laser source, photodetector, and optical gas sampling element integrated on a miniature monolithic platform**
  - Gas sensing elements use solid-state waveguides
- **Fabricated using established production techniques**

FuelFinder™



- **mid-IR backscatter TDLAS**
  - Wavelength ~3 µm
  - Capitalizes on recent advances in *Interband Cascade Lasers (ICLs) that operate at room temperature*
- **Senses volatile complex hydrocarbon vapors**
- **Intended for locating leakage of petroleum products**

Laser Sources vs. Needs

Near-IR examples

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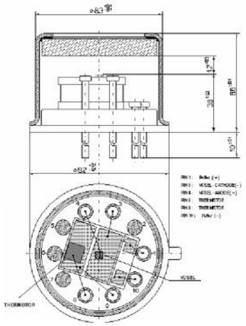
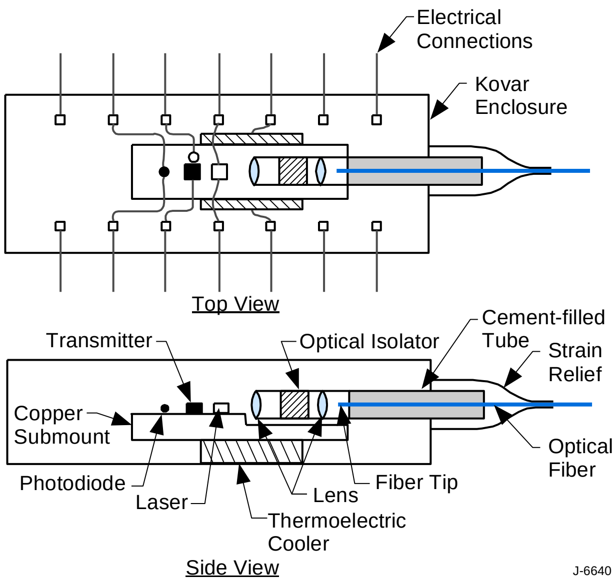
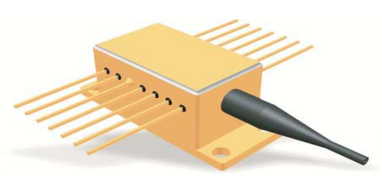
- **Distributed FeedBack (DFB) Laser**
  - 14-pin butterfly package with integral thermo-electric cooler
  - ~10 mW output power
  - Optically-isolated fiber optic output
  - ~ 700 – 2300 nm

- **Vertical Cavity Surface Emitting Laser (VCSEL)**
  - TO-8 package with integral thermo-electric cooler
  - ~0.4 mW output power
  - Fiber-coupling optional (w/reduced power)







- ***Monolithic spectrometers need:***
  - ***μW's of laser power***
  - ***Stable, but not necessarily sub-ambient, laser temperature***

COTS Lasers are Overkill

Need: Near and Mid-IR Lasers designed for widely-deployed gas sensing applications

Developing these sources is the challenge to the MIRTHE community

Some Applications

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Sector	Target Gas	Purpose	Production Rate/year	Cost/ unit	Spectral Region
Defense, Security	Chemical Agents (TEP as simulant)	Wide Area Chemical Monitoring	Thousands	$1000	MWIR (~4 μm, ~ 9 μm)
	TICS	Wide Area Chemical Monitoring	Thousands	$500	NIR, MWIR
Energy Production and Transmission	Methane	Ubiquitous natural gas leak detection	Millions	$200	NIR (1.6 μm) MWIR (3.3 μm)
	Alkanes	Liquid hydrocarbon leak detection	Thousands	$200	MWIR (~4 μm)
	Proprietary	Electricity transmission and distribution health monitoring	Millions	$200	NIR (1.5 μm)
Environmental	CO_2	• Atmospheric monitoring • Pipeline and sequestration leak detection • Emission control	Millions	$100 - $1000	NIR (1.5 μm, 2 μm) MWIR (4 μm)

TDLAS Technology Niche

- **Near-IR TDLAS now fulfills many gas sensor needs**
  - ***Near-IR is suitable and preferable for sensing many simple molecules***
  - ***Sensors utilize proven robust electronics platforms***
    - Reliable laser sources
    - High precision
    - Very low power consumption (< 1 W)
    - Compact
    - Minimal maintenance
    - Acceptable cost; ~$10,000 per sensor unit
- **Mid-IR interband cascade lasers (ICLs) and quantum cascade lasers (QCLs) enhance sensitivity over short paths**
  - ***Enables miniaturization and detection of trace pollutants and complex molecules***
- **Mass-produced chip-scale TDLAS sensors may enable future wide-area deployment of sensor networks**
- **Mid-IR Challenges:**
  - Low-noise uncooled mid-IR detectors
  - Laser cost, power consumption, wavelength diversity, availability, reliability

Resonant Cavity Monolithic Sensor Package Concept

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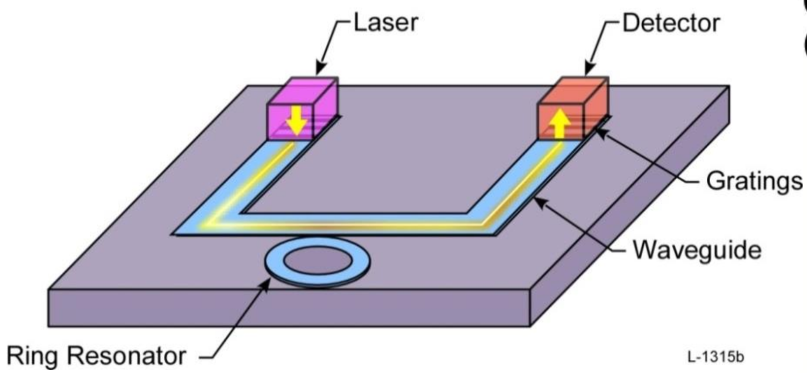

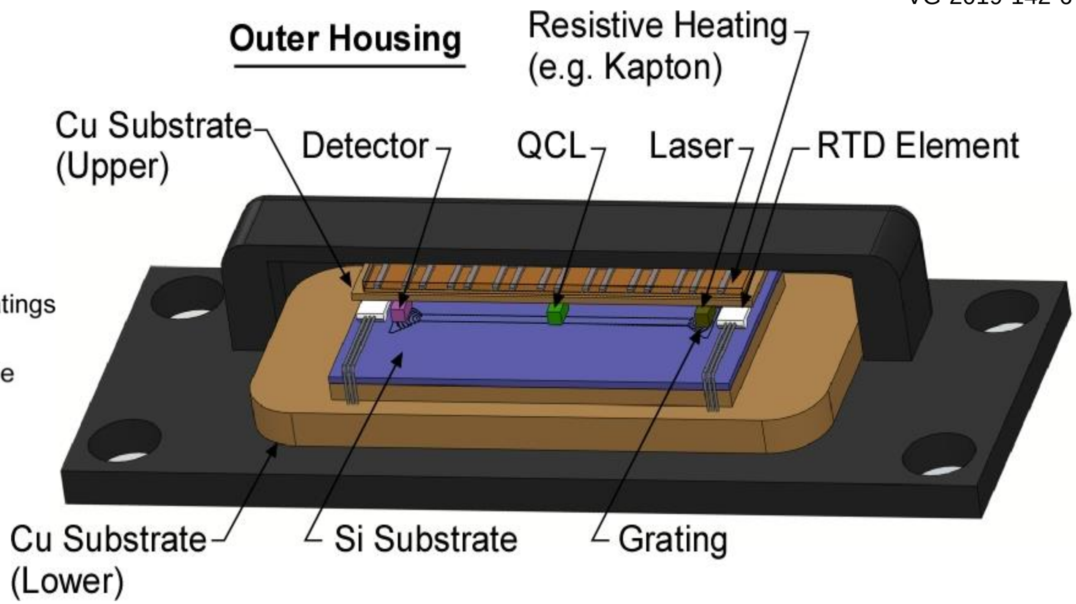

- **Accommodates near-IR (DFB,VCSEL) and mid-IR (ICL) lasers coupled to Si or InP sensor element**
  - Si propagates well to ~5 µm, can work up to 8 µm

- **Suitable for cavity enhanced, photothermal (with optional QCL), photoacoustic or free-space sensing**

- **Provides low-power laser thermal stabilization via resistive heating**

Monolithic Integrated "Mini-Methane" Sensor

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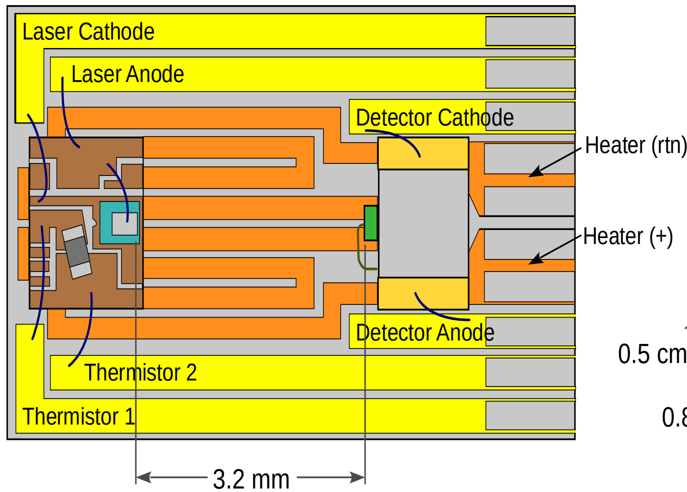
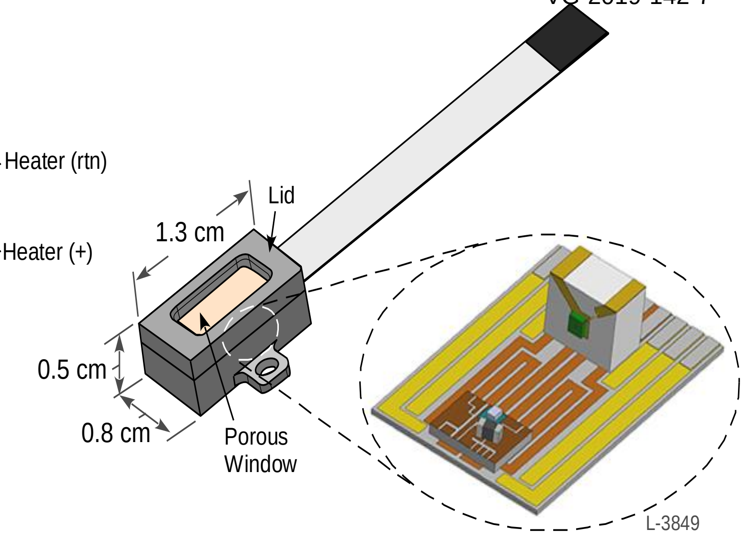
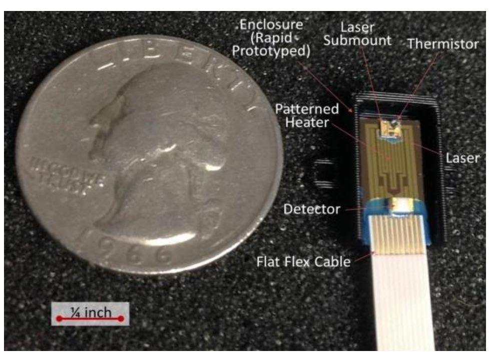
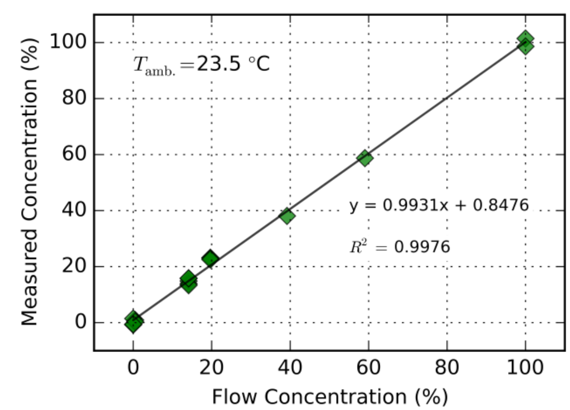
- **Near-IR Laser Chip-on-Submount**
  - *1 cm free-space measurement path*
- **Eliminates thermo-electric cooler (TEC)**
  - *Heat, don't cool*
- **Eliminates microlenses and optical isolator**









Herrera, O.D., Frish, M.B., Bamford, D.J., and Laderer, M.C., "Widely Deployable Natural Gas Leak Detection Sensor Networks," Final Report prepared for San Diego State University Foundation under P.O. No. Sub-57992A/14-01G, PSI-1856-FinalReport, December 2015.

This material is based upon work supported by the USA Contracting CMD-APG under Contract Number W911SR-12-C-0041, sponsored by the Edgewood Chem Bio Center.

Mid-IR SOI Ring Resonator Sensor

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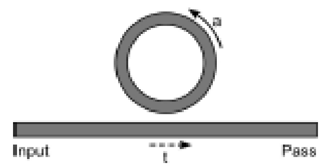
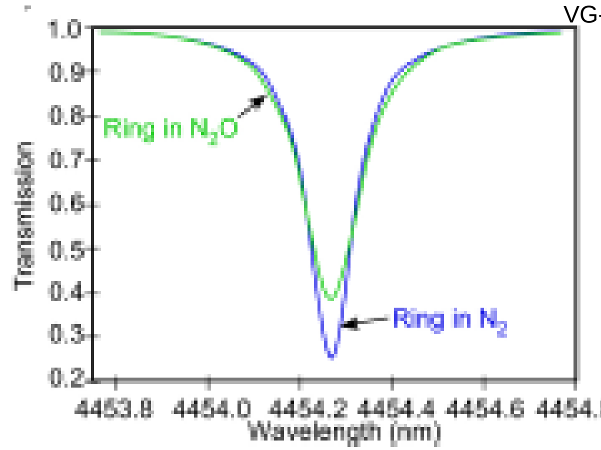
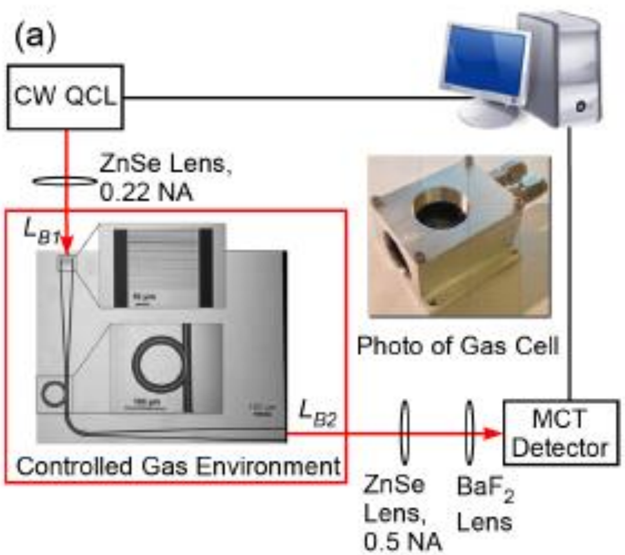
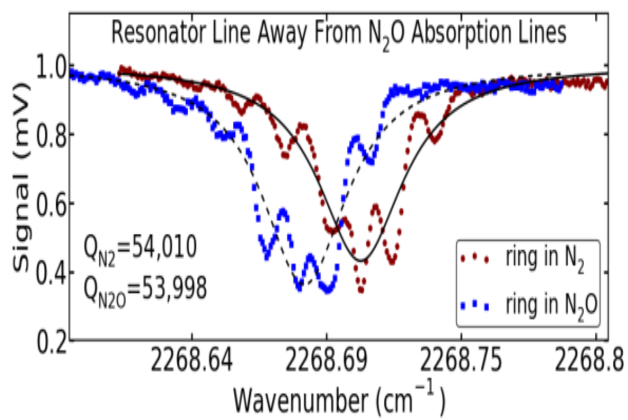
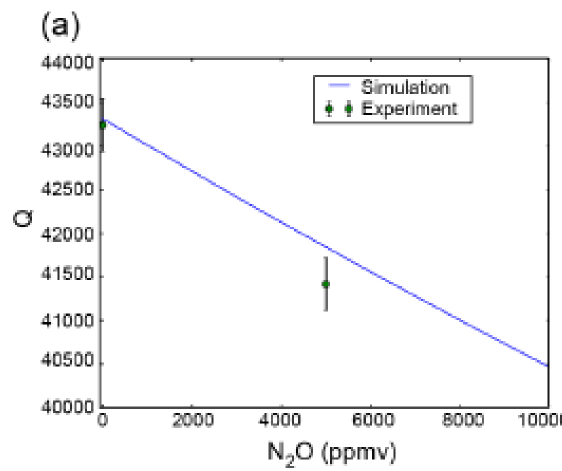
- SOI waveguides propagate to ~5 μm
- Waveguide Q varies with spectral absorbance in external evanescent field
  - ***Absorbing gases (e.g. N_2O, TEP) reduce Q***











Clinton J. Smith, Raji Shankar, Matthew Laderer, Michael B. Frish, Mark Loncar, and Mark G. Allen, "*Sensing nitrous oxide with QCL-coupled silicon-on-sapphire ring resonators*", Optics Express **23**, 5491-5499 (2015)

This material is based upon work supported by the USA Contracting CMD-APG under Contract Number W911SR-12-C-0041, sponsored by the Edgewood Chem Bio Center.

SONOI DFB-QCL

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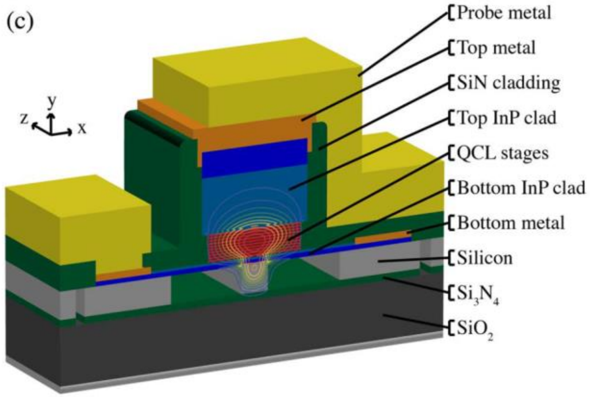
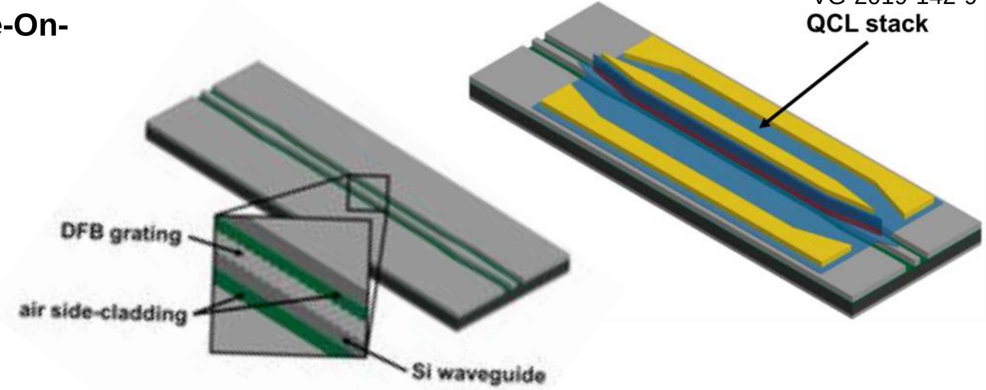
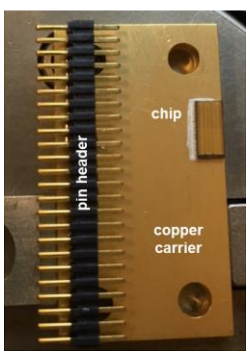
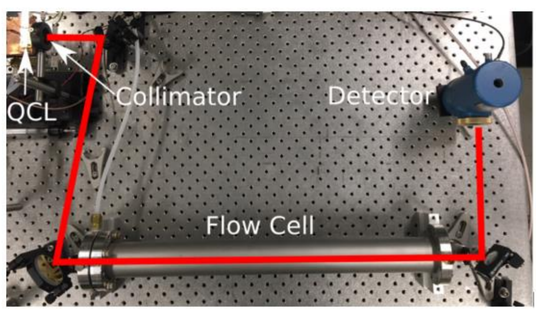
- **Replace SiO_2 substrate with Si_3N_4 Silicon-On-Nitride-On-Insulator (SONOI) platform**
  - *Transparent from 1.2 - 6.7 μm*
- **TM mode is guided within the silicon**
- **Electrically pumped QCL gain stages above silicon**

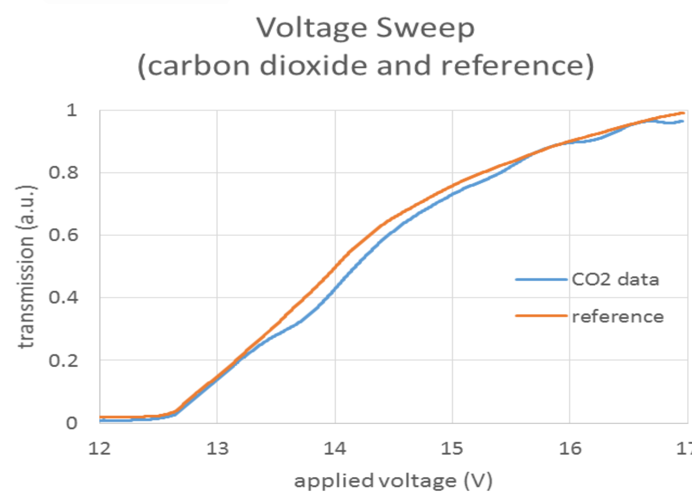




- **DFB grating structured directly in silicon**
- **Tapers support transition to Si waveguide**







Christopher C. Evans, Alexander Spott, Charles D. Merritt, William W. Bewley, Igor Vurgaftman, Chul Soo Kim, Jerry R. Meyer, Joel M. Hensley, John E. Bowers, and Michael B. Frish, *"Gas Sensing Using Heterogeneously Integrated Quantum Cascade Lasers on Silicon"*, CLEO_SI 2018 STu3N.1(2018)

This material is based upon work supported by the U.S. Army Small Business technology transfer program office and the Army research office under contract number W911NF-17-P-0055. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the U.S. Army small business technology transfer program office or the Army research office.

Mid-IR DFB-ICL for methane + ethane

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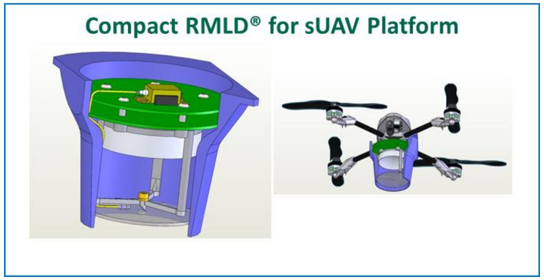
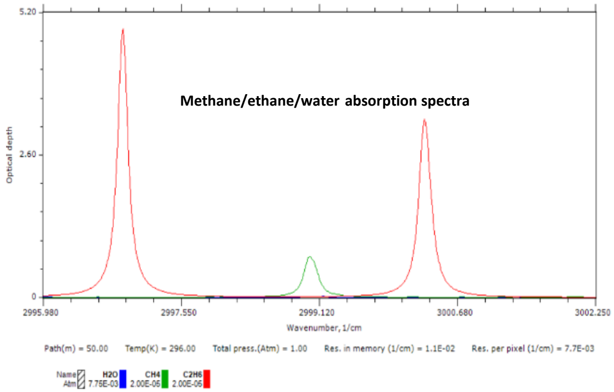
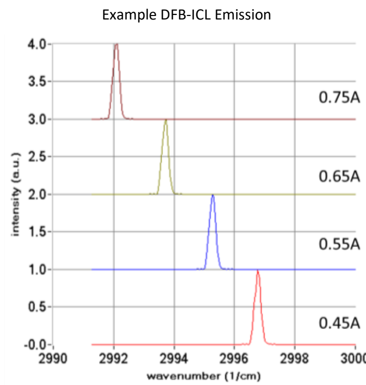
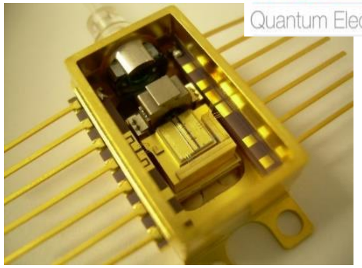


New Thorlabs DFB-Interband Cascade Laser (ICL), meets wavelengths for detection of methane *and ethane*





THORLABS
Quantum Electronics



- 14-pin butterfly package with optical fiber output can directly substitute the near-IR RMLD laser

M.B. Frish, "RMLD™ Sentry for Upstream Natural Gas Leak Monitoring", ARPA-E MONITOR Year 2 Annual Mtg – Ft. Collins, CO (5/24/2017)

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000547. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ThorLabs Laser Test

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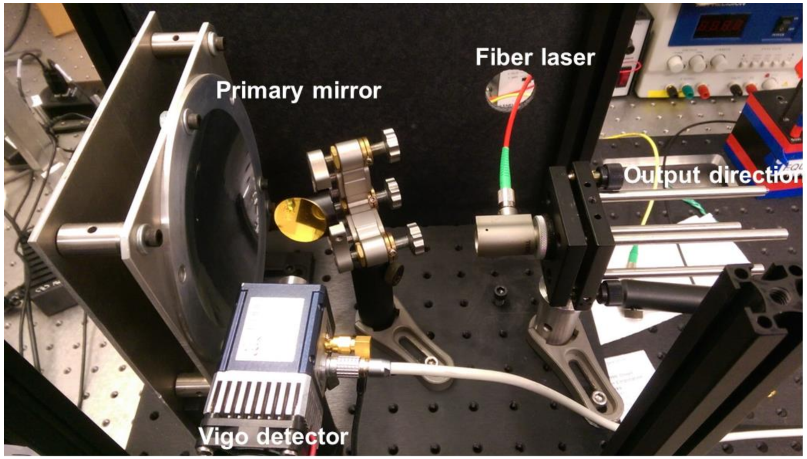
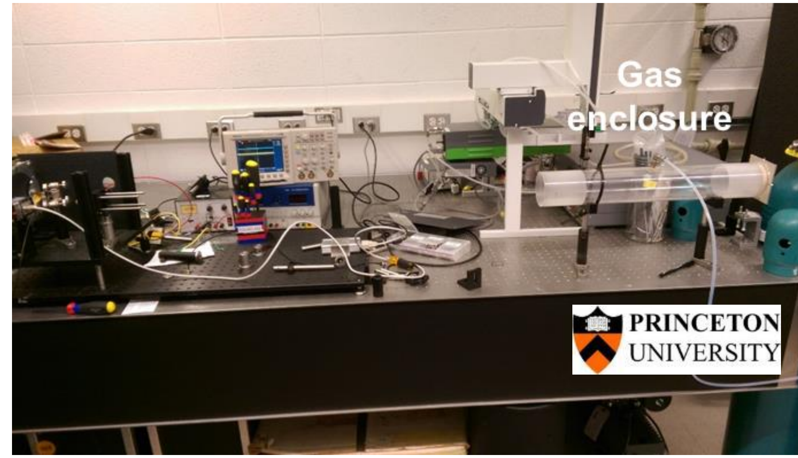
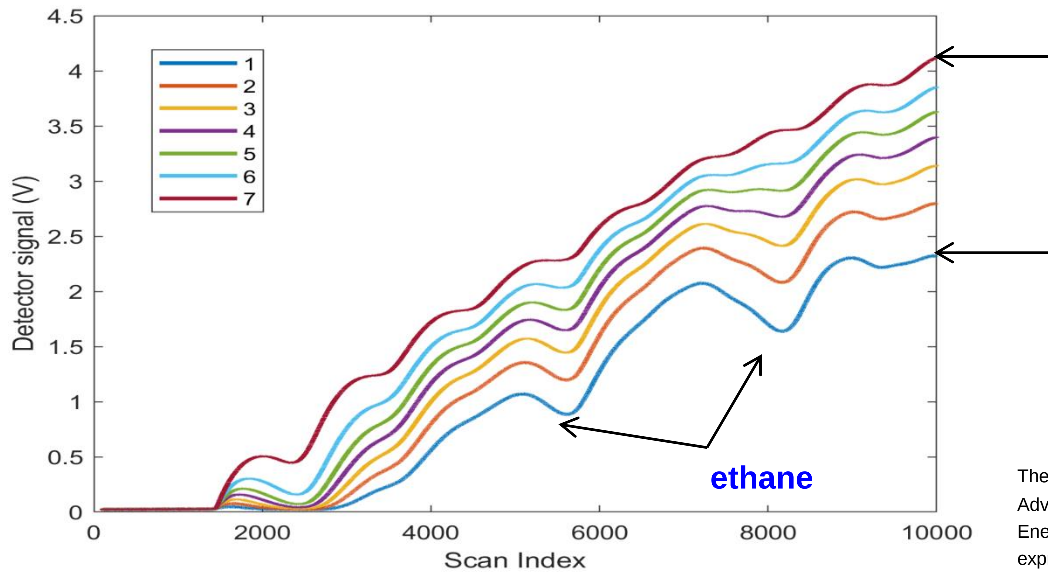
Installed in FuelFinder™ Backscatter TDLAS Apparatus at Zondlo Lab







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Closing

- **We have demonstrated laboratory feasibility of novel miniature sensor packaging, with integrated laser source, sensor element, and detector on a simple monolithic platforms**
- **"Ubiquitous monitoring" market opportunities for low-cost widely-deployable gas specific sensors remain unfulfilled**
  - Will benefit from mid-IR integrated optics
    - Requires laser sources designed for gas sensing application
    - Cost per laser <$100 in mass production