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Current Status of Quantum Cascade Lasers for UFLS at 7.7, 11.8 and 16 μm

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http://ece.rice.edu/lasersci/

OUTLINE

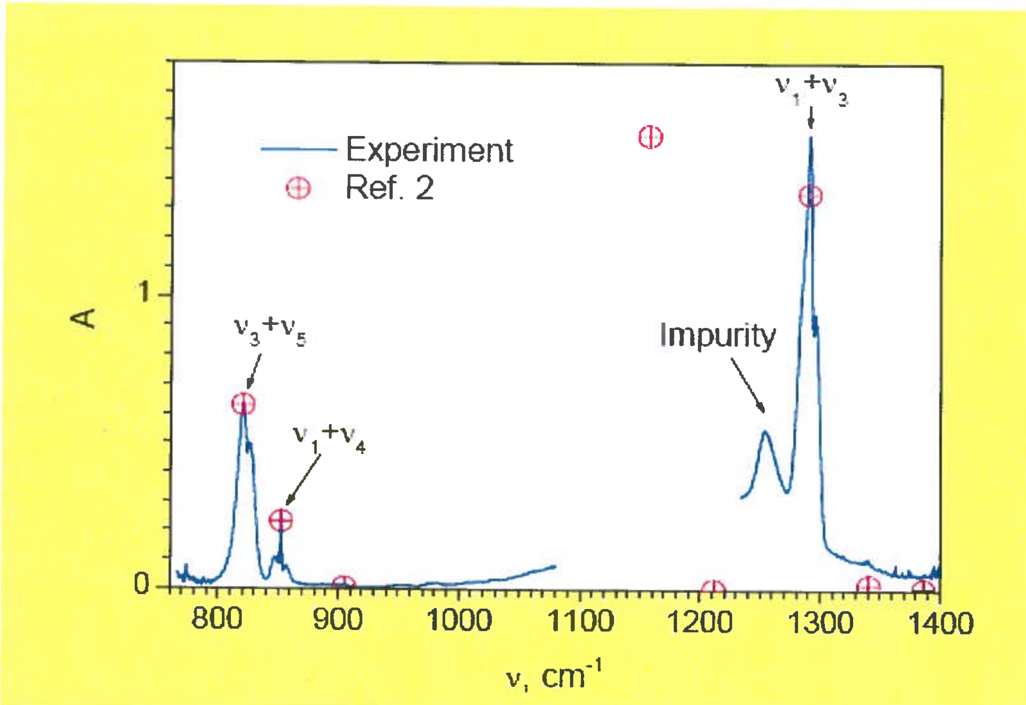
IAEA-TDLS WG

Vienna, Austria

Dec 5, 2008

- Motivation: Laser Absorption Spectroscopy of Uranium Hexafluoride (UF_6)
- High performance QC Laser Source
- Widely tunable External Cavity (EC) -QCLs
  - Daylight Solutions, Technical University Zuerich, Harvard
  - Rice University
- Future Directions and Conclusions

UF_6 Mid-Infrared Absorption Bands



Absorption spectrum of gas mixture under investigation and observed spectral features identification.

Assignment	ν, cm^{-1}	σ, cm^{-1}/atm
$2\nu_3+\nu_6$	1386±2	0.0018
$\nu_1+\nu_2+\nu_6$	1341	0.0088
$\nu_1+\nu_3$	1290.9±0.5	0.72
$2\nu_2+\nu_6$	1211±2	0.0007
$\nu_2+\nu_3$	1156.9±0.5	0.82
$\nu_3+2\nu_6$	905±2	0.0035
$\nu_1+\nu_4$	852.8±0.5	0.12
$\nu_3+\nu_5$	821	0.33
ν_3	625	350

R.S. McDowell, L.B. Asprey, R.T. Paine, Vibrational spectrum and force field of uranium hexafluoride. -J. of Chemical Physics, Vol. 61, No. 9, 1974.

Needs and Methods in IR Laser Monitoring

Requirements: Sensitivity, specificity, multi-gas species, rapid data acquisition, cost, portability, low electrical power consumption and autonomous operation

Optimum Molecular Absorbing Transition

- Overtone or Combination Bands (NIR)
- Fundamental Absorption Bands (MID-IR)

Long Optical Pathlengths

- Multipass Absorption Cell
- Cavity Enhanced, Cavity Ringdown & Intracavity Spectroscopy
- Open Path Monitoring (with and without retro-reflector)
- Evanescent Field Monitoring (fibers & waveguides)

Photoacoustic Spectroscopy

Spectroscopic Detection Schemes

- Frequency or Wavelength Modulation
- Balanced Detection
- Zero-air Subtraction

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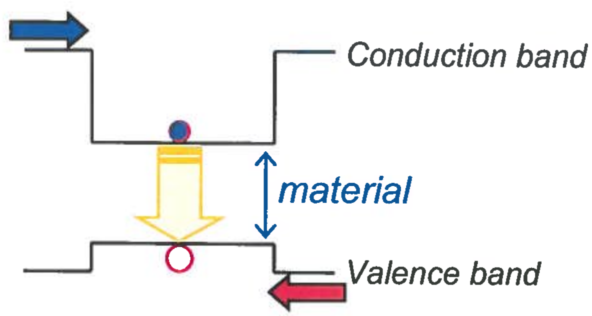
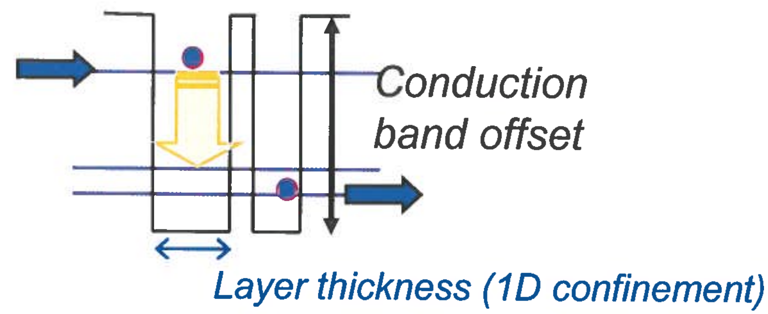
Quantum Cascade Lasers

Diode laser:



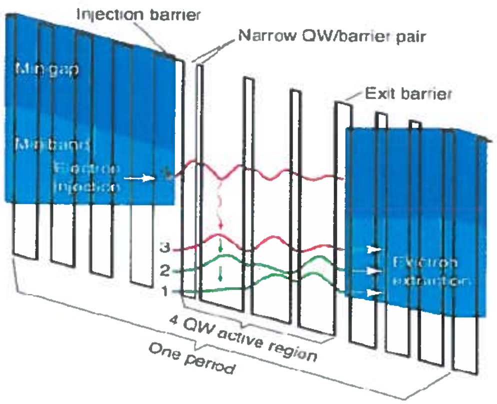
Quantum Cascade Laser:



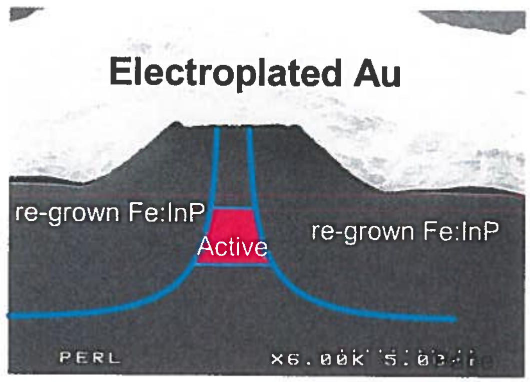
Advantages of QCLs:

- Traditional material systems (e.g., InGaAs/AlInAs/InP)
- Gain position by design
- Multi-wavelength and broadband emission possible
- Hundreds of milliwatts of CW output in mid-IR at RT
- Work in mid-IR and THz spectral range

Mid-IR QCLs: present status



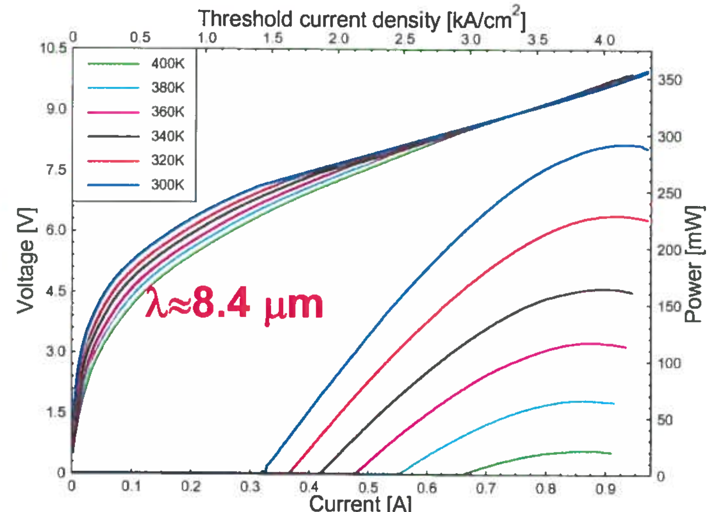
"2-phonon" design or "b2c" design



Thermal management

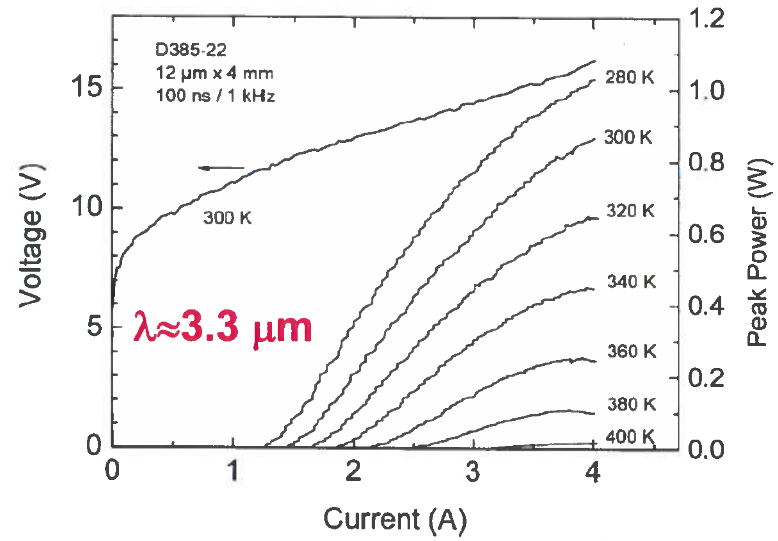
InP re-growth and/or electroplating

InGaAs/AlInAs system



Diehl et al., APL 2006

InAs/AlSb system



Devenson et al., APL 2007

RT operation ~3-12 μm

Wallplug efficiency up to ~10%

Hundreds of mW CW output at RT (400°K)

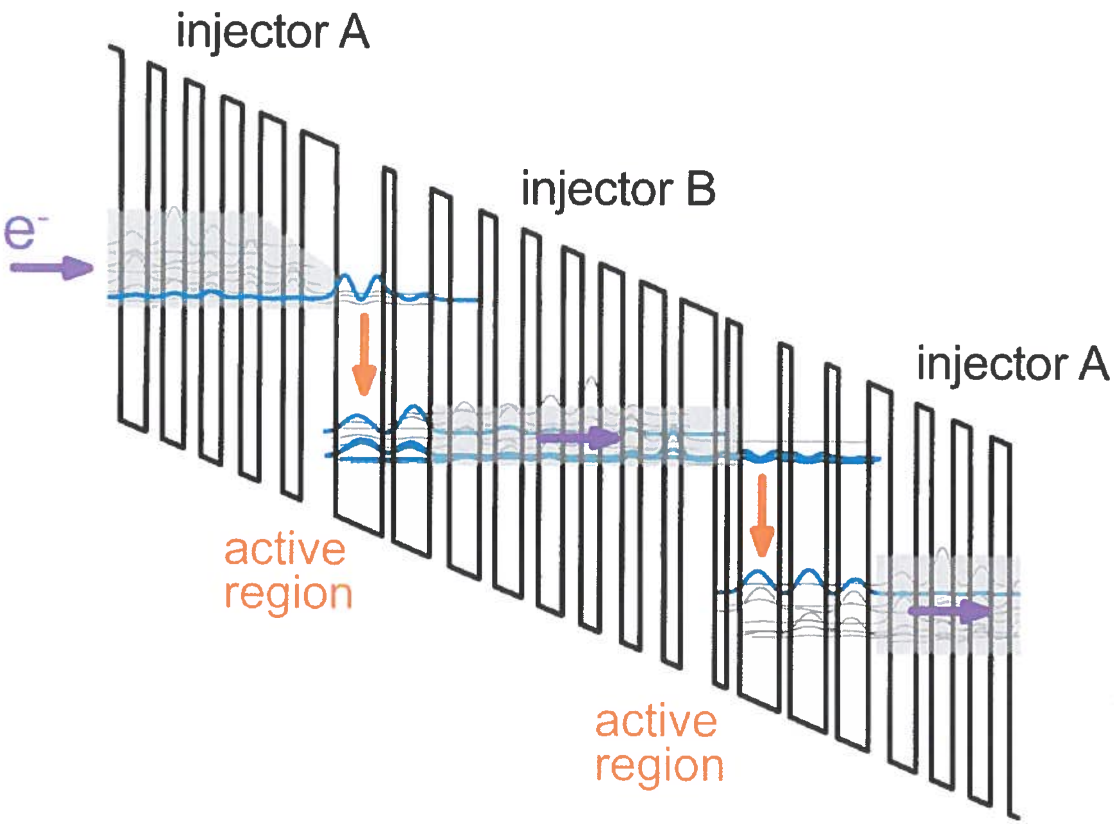
Motivation for High Wall Plug Efficiency

$$\eta_{wp} = \frac{P_{optical}}{P_{electrical}}$$

- High WPE essential for applications limited by:
  - Electrical power
  - Temperature
  - Size
  - Weight

- CW, RT QC laser state of the art:
  - 2006: ~1%
  - 2008: ~12%

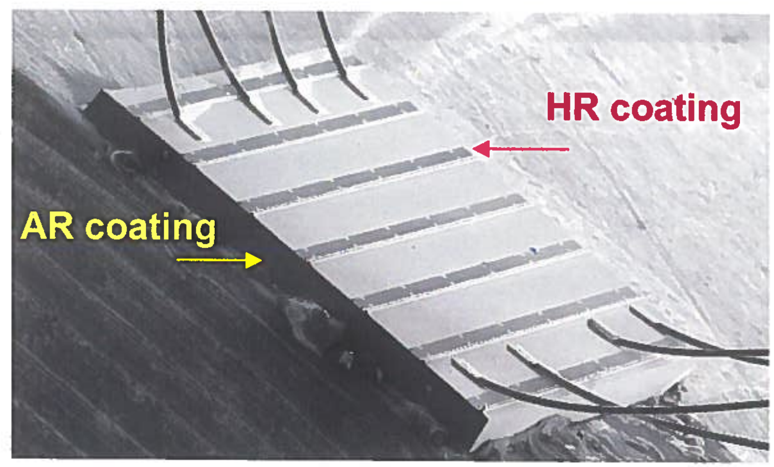
Quantum cascade laser



Optimization through design

- High power
- High temperature operation
- Multi-wavelength emission
- High wall-plug efficiency

Optimization through processing and packaging



Strategies for Improving WPE

Voltage Efficiency:
- Lower voltage defect
- Reduce contact resistance

Extraction Efficiency:
- Implement high reflection (HR) and anti-reflection (AR) coatings
- Employ low loss waveguides
- Optimize cavity length

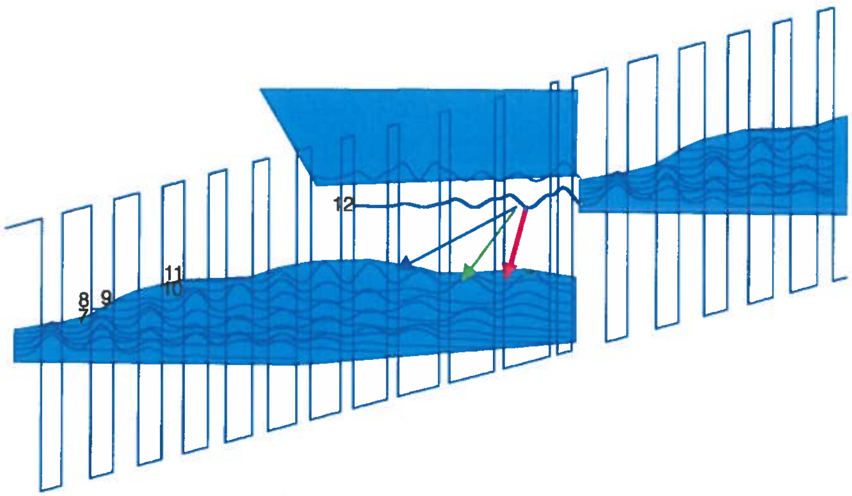
Internal Efficiency:
- Reduce thermionic emission
- Improve heat removal from active core
- Optimize injector barriers

Current Efficiency:
- Design high gain, low loss structures
- Lower threshold currents

optimization of
heat dissipation
Epi-down mounting

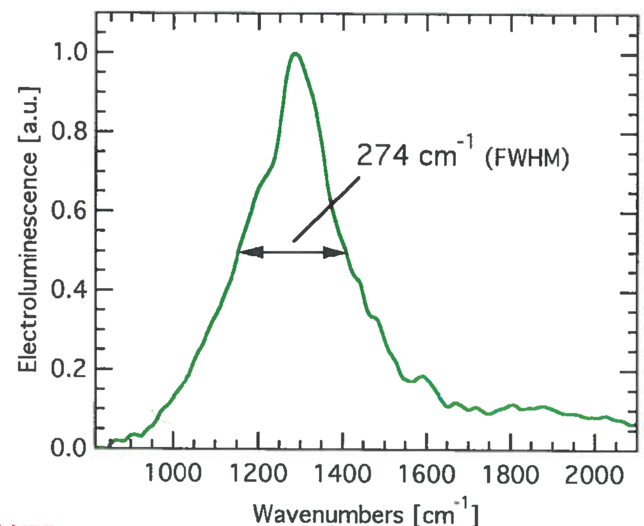
DEI SVB NVMINE VIGET

Quantum Cascade Gain medium



- Efficient injection in upper state
- Efficient extraction from lower state

⇒ Suitable for CW operation above RT



- Transition from bound state to miniband
- Several lower states
- Distributed oscillator strengths

⇒ Broad and quasi-homogeneous gain medium

$\Delta\upsilon$ = 274 cm^{-1} (FWHM)

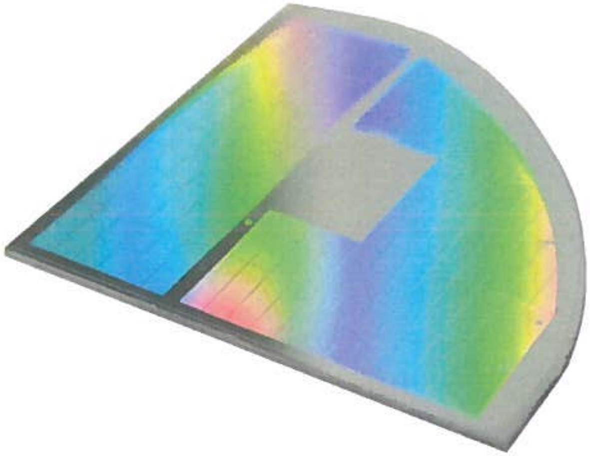
$\Delta\upsilon/\upsilon_0$= 21 %

Faist et al., APL **78**, 147 (2001)

Wavelength Selection

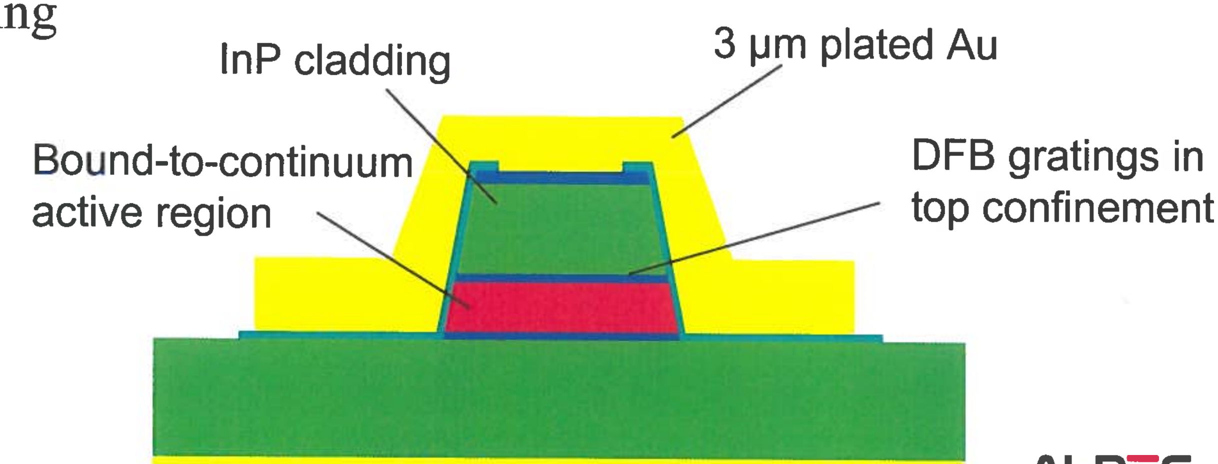
Feedback

- 25 different DFB grating periods
- Defined in a single photolithography step
- MOVPE regrowth



Processing of lasers

- Standard lithography processes
- Wet etching to 11-17 μm-wide ridges
- cleaved in 1.5 mm-long bars
- HR back facet coating



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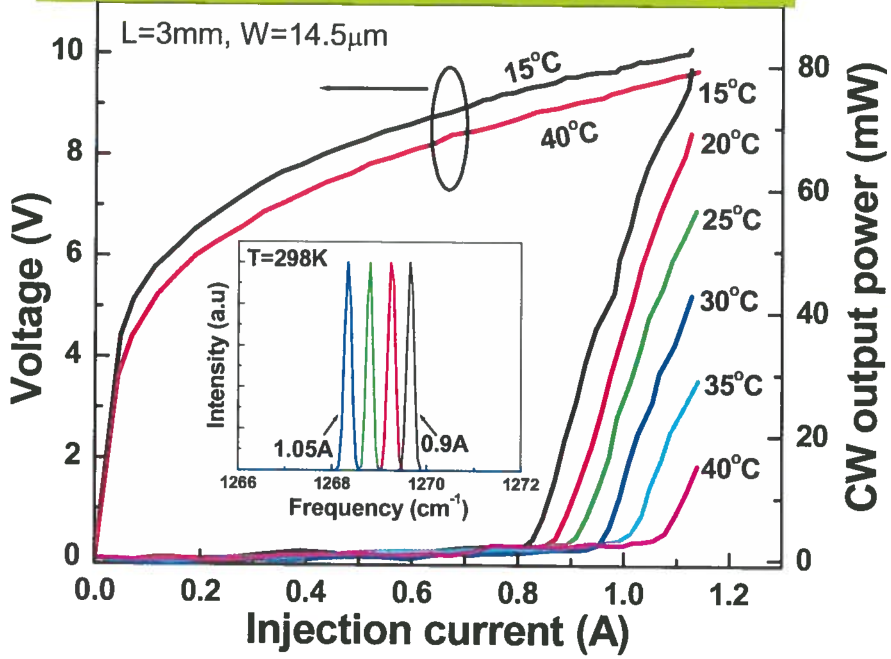
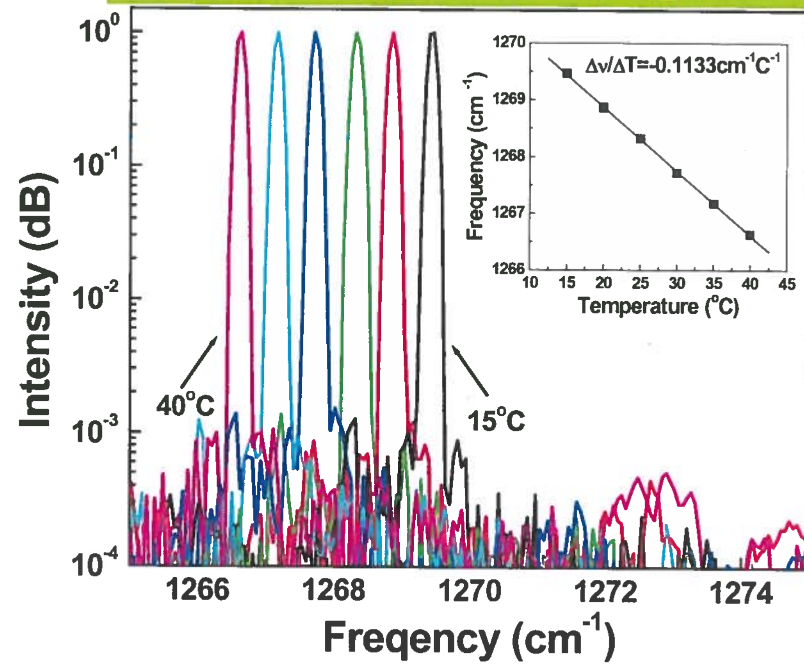
7.8μm DFB QCLCharacteristics

CW output power at high-temp



Temperature Tuning

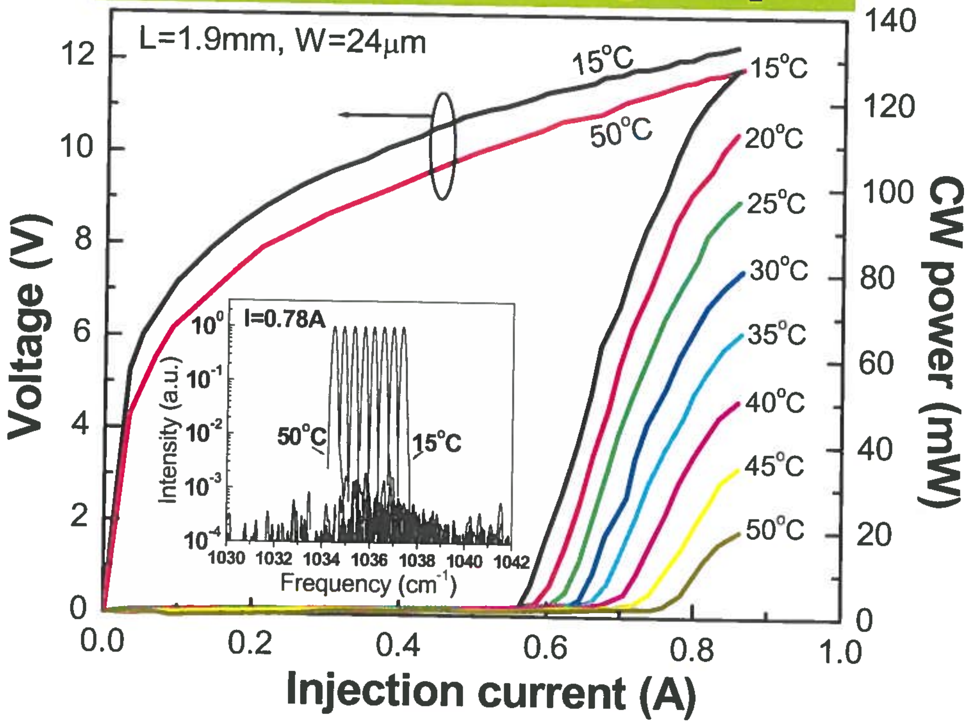


- High cw output power =80mW@15°C
- High temp. operation>40°C
- large temp. tunability
- 30dB side mode suppression ratio

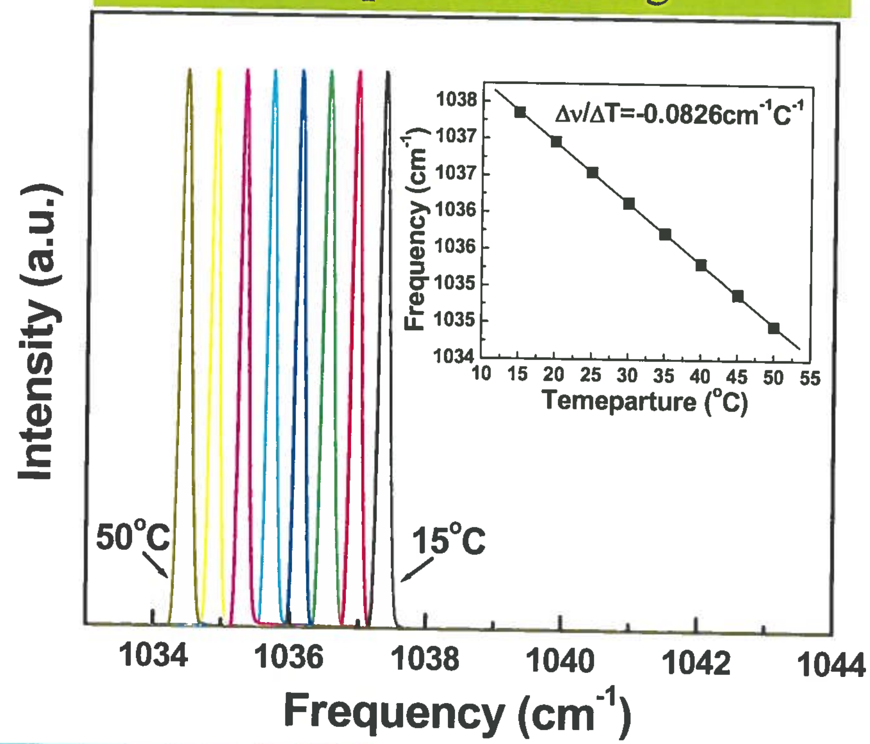
S.R. Darvish, W. Zhang, A. Evans, J.S. Yu, S. Slivken, and M. Razeghi, Applied Physics Letters, Vol. 89, p. 251119 (2006)

9.6 μm DFB QCL Characteristics

CW output power at high-temp



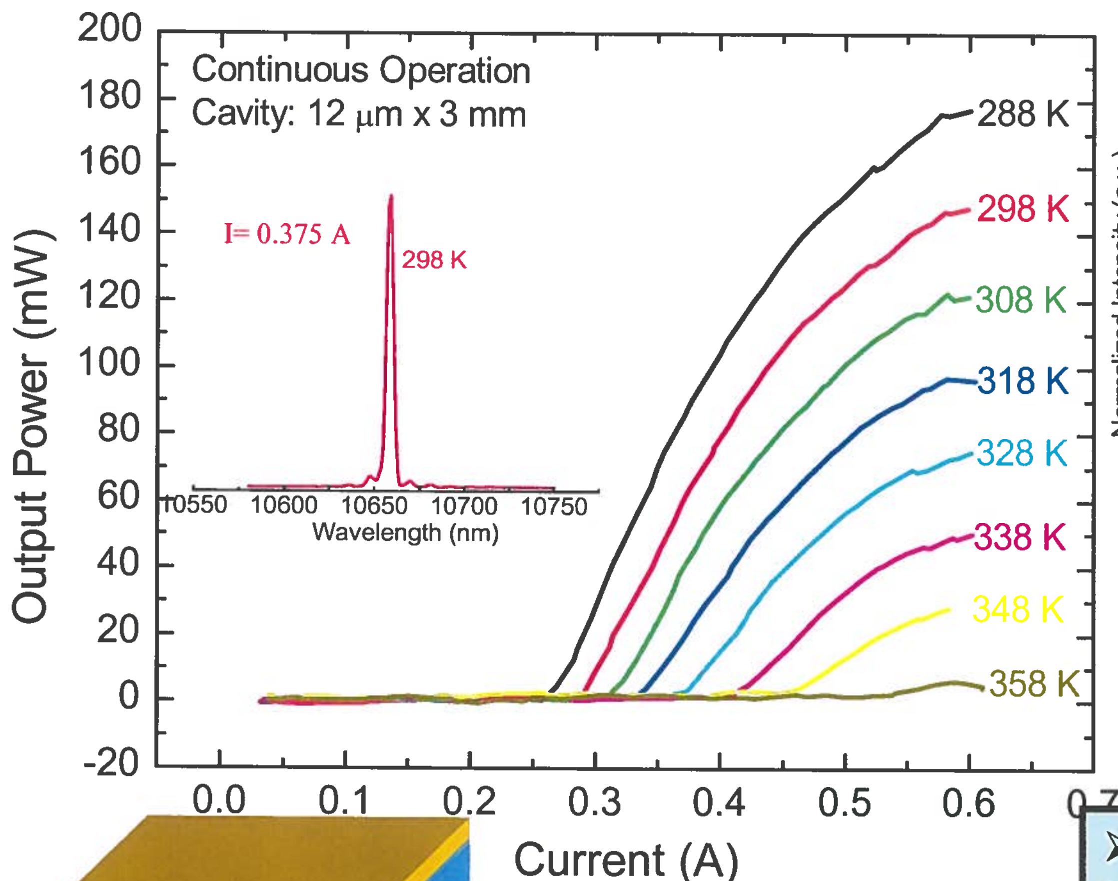
Temperature Tuning

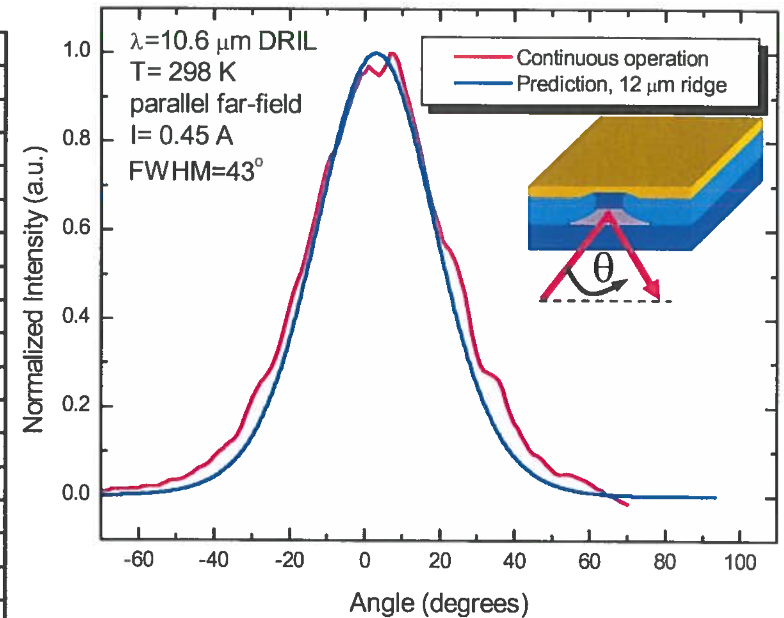


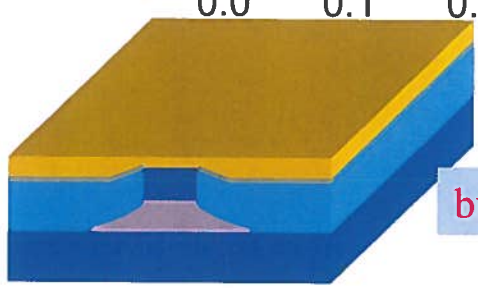
- High cw output power (100mW @25°C)
- High temp. operation>50°C
- large temp. tuneability

S.R. Darvish, S. Slivken, A. Evans, J.S. Yu and M. Razeghi, Applied Physics Letters, Vol. 88, p. 201114 (2006)

10.65 μm CW QCL (Buried ridge) Characteristics (288K-358K)





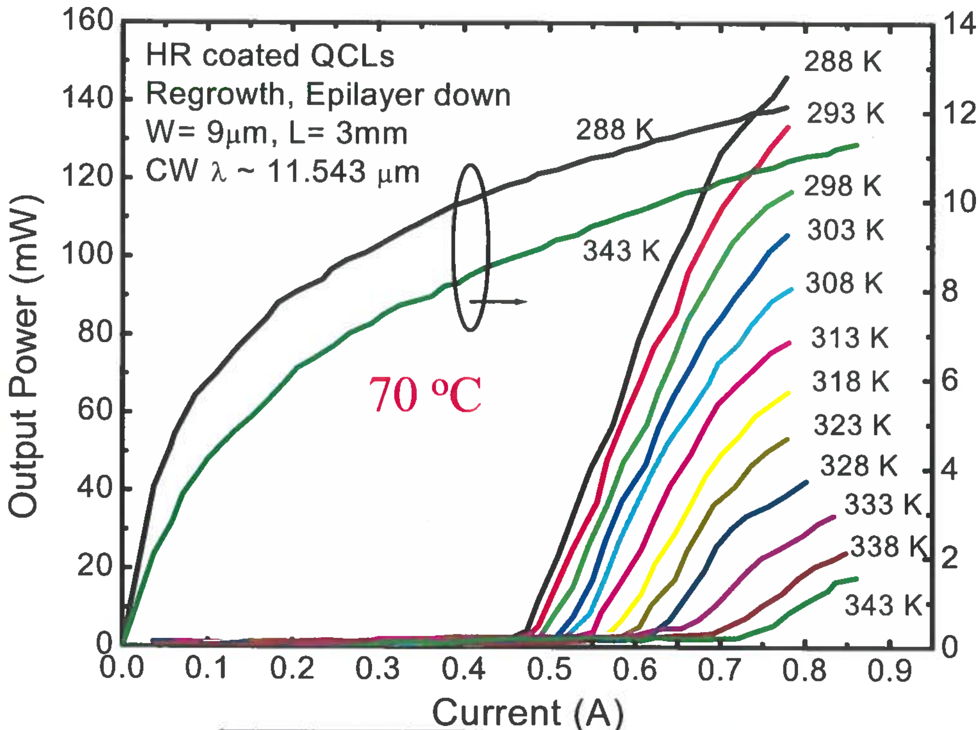


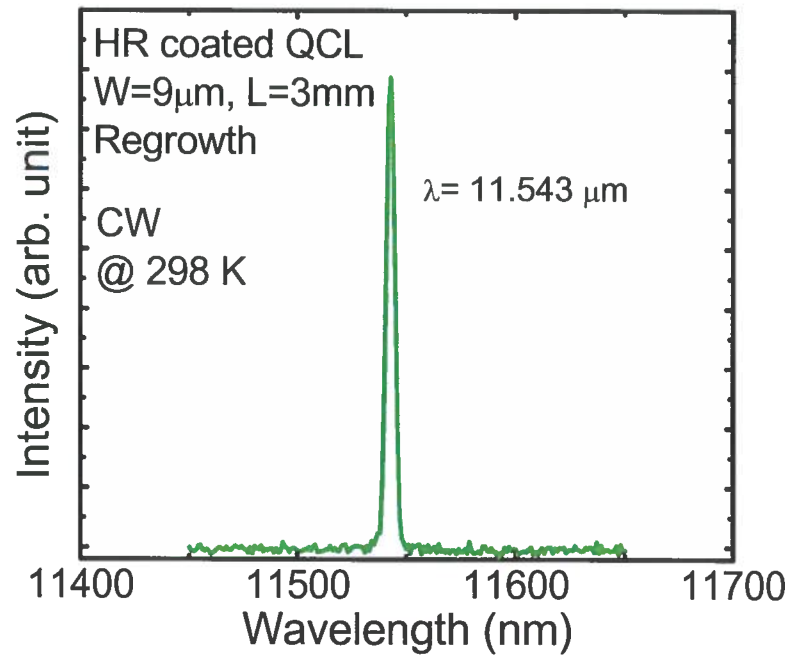
buried heterostructure

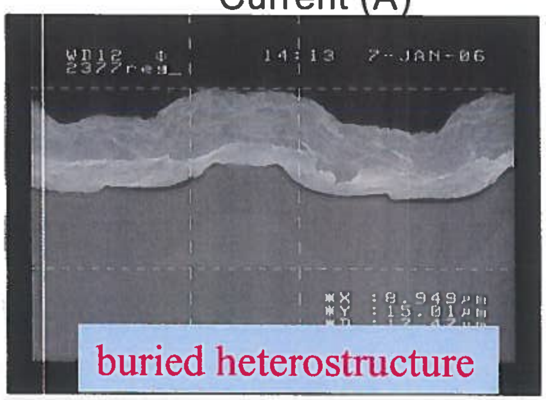
- **Max. CW operating temp > 350K**
- **Max. CW power @ 25°C = 143mW**
- **Emission wavelength @ 25°C =10.65μm**
- **Far-field FWHM=43°×67°**
- **Epi-up bonding**

S. Slivken, A. Evans, W. Zhang, M. Razeghi, Appl. Phys. Lett., **90, art. 151115 (2007)**

11.5 μm CW QCL (Buried ridge) Characteristics (288K-343K)



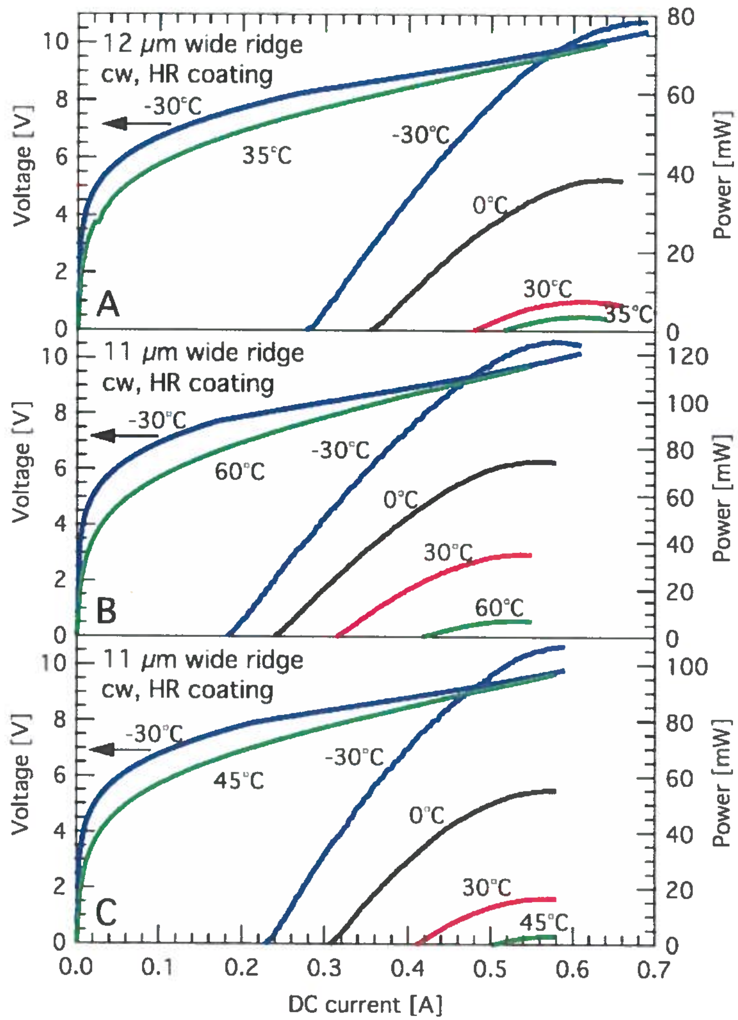




- ➢Max. CW operating temp > 340K
- ➢ Max. CW power @ 25ºC = 115mW
- ➢Emission wavelength @ 25ºC =11.54μm

Slivken, S., Evans, A., Nguyen, J., Bai, Y., Sung, P., Darvish, S. R., Zhang, W., and Razeghi, M., *Proc. SPIE* 6900, pp.

CW DFB QCL at 7.8μm: performances



j_{th} = 2.62 kA/cm^2 (+30°C)
T_0 = 113K
T_{max} = 35°C
λ ~ 1206 cm^{-1} (8.3μm)

j_{th} = 1.87 kA/cm^2 (+30°C)
T_0 = 109K
T_{max} = 60°C
λ ~ 1256 cm^{-1} (8.0μm)

j_{th} = 2.45 kA/cm^2 (+30°C)
T_0 = 98K
T_{max} = 45°C
λ ~ 1302 cm^{-1} (7.7μm)

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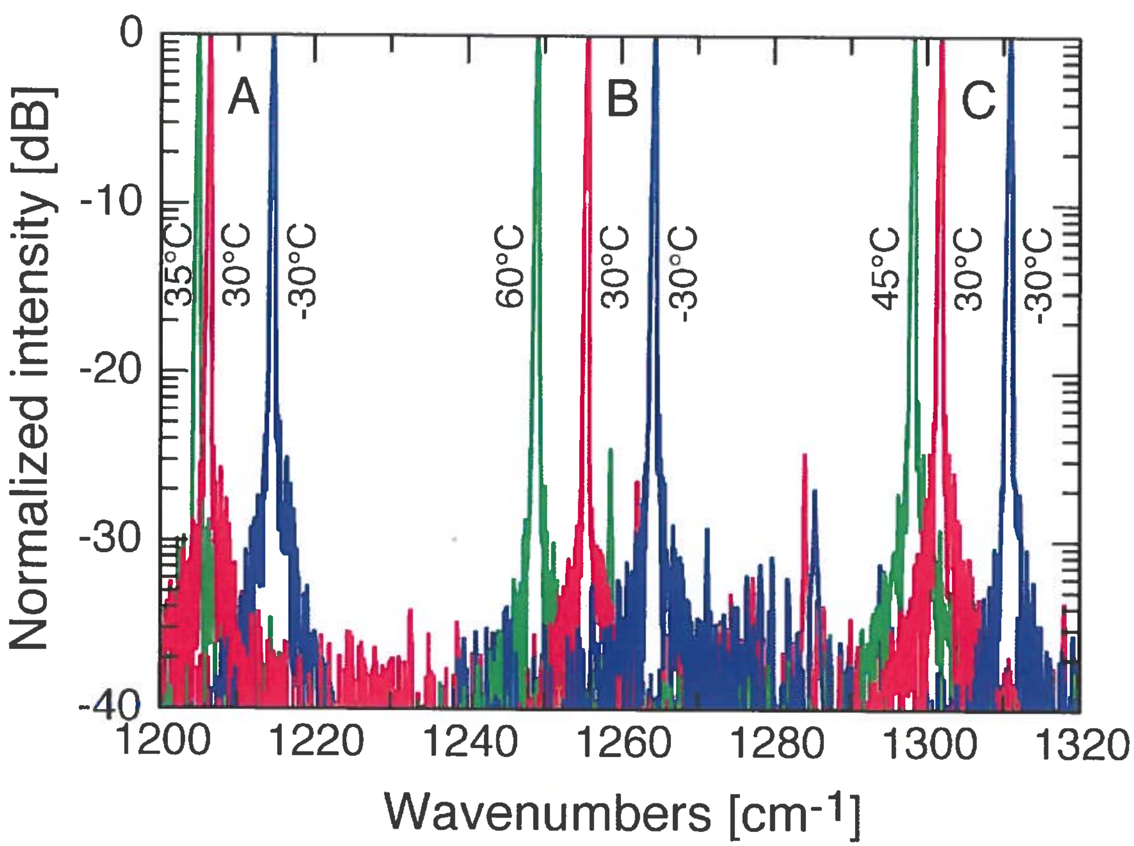
AlpesProduct:RT-CW-DFB-50-1270

CW DFB QCL at 7.8µm: Spectra



Single-mode emission with SMSR > 25 dB (resolution limited by FTIR)

Wavelength coverage:
One laser: $\Delta\nu$ ~ 10-15 cm^{-1}
In total: $\Delta\nu$ > 100 cm^{-1}
(7.7 - 8.3 µm)

Average R_{th} ~ 12.4 K/W
Average tuning coefficient
β ~ -8.88×10^{-5} K^{-1}

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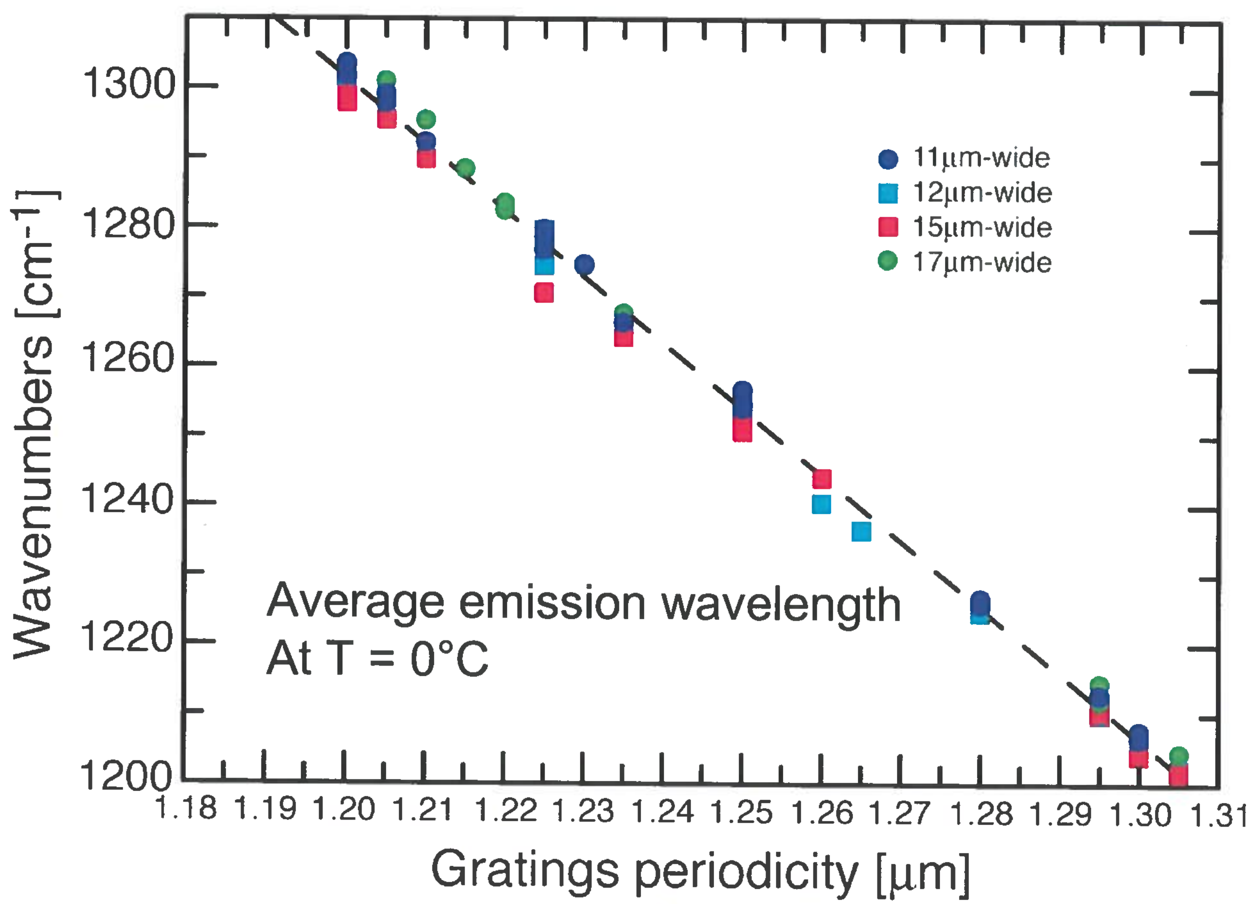
CW DFB QCL at 7.8µm: wavelength spreading



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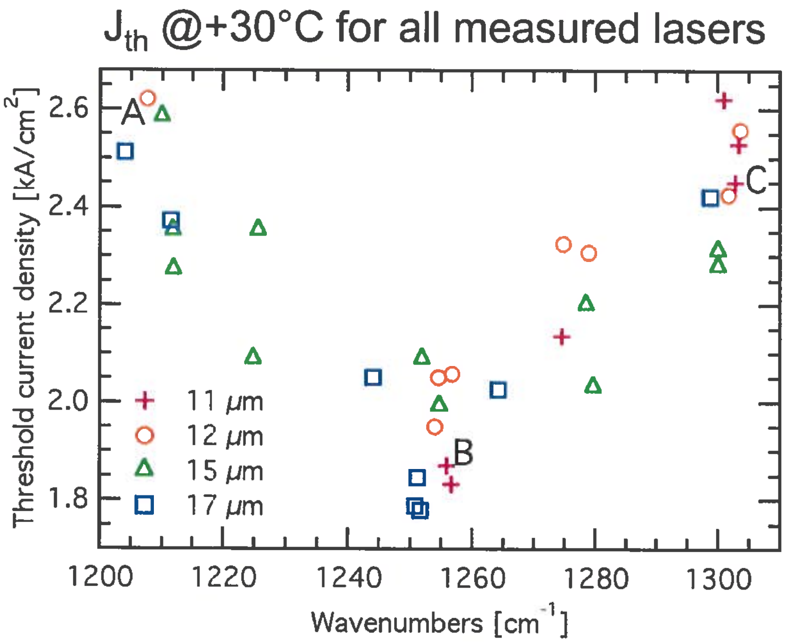
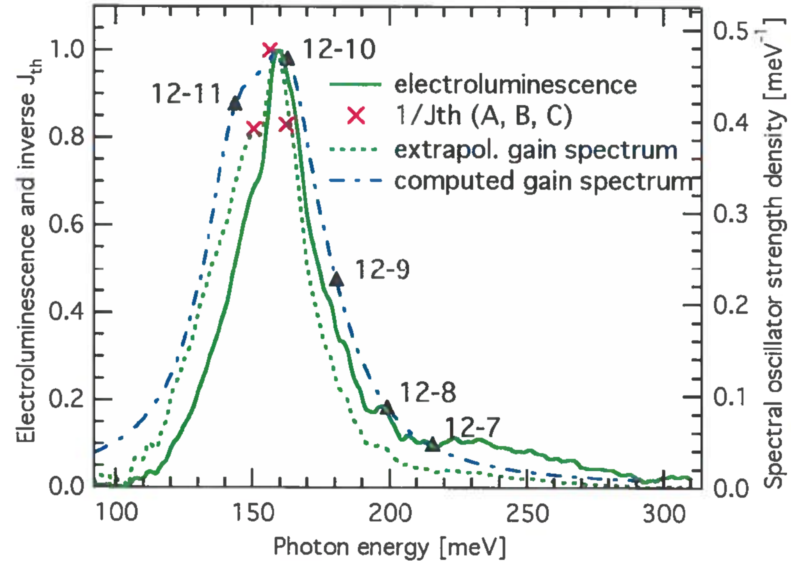
Gain versus threshold current density





- Lowest threshold current density at gain center
- No trend with ridge width

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A QCL on Mars ...

Jet Propulsion Laboratory
California Institute of Technology

Take-off in ~ 2010

QCL for Tunable Laser Spectrometer integrated in the Sample Analysis at Mars Instrument Suite (SAM), a component of the Mars Science Laboratory.

MSL goal: chemical composition of different gases present at the surface of Mars
-> *"suitable information to determine if the conditions of life have been previously assembled on the planet"*

QCL mission: measurements of isotopic ratio at 7.79 µm

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QC Laser module specifications

Wavelength	1283.6 cm^{-1} (7.79 μm)
Tuning range	1 cm^{-1} (1283.1 - 1284.1 cm^{-1})
Spectral linewidth	< 20 MHz (RT-CW)
Heatsink temperature	305 K
Laser temperature	20-25°C
Max. laser I / V	600 mA / 10 V (6 W max.)
Output power	> 2 mW
Max. cooler I / V	2.1 A / 4.5 V (9.45 W max.)

Shall survive the trip!

-> MIL specifications:

5000 hours of operation, radiation, heating, thermal cycles (-40 to +85°C), mechanical shocks, acceleration (up to 20 G),…

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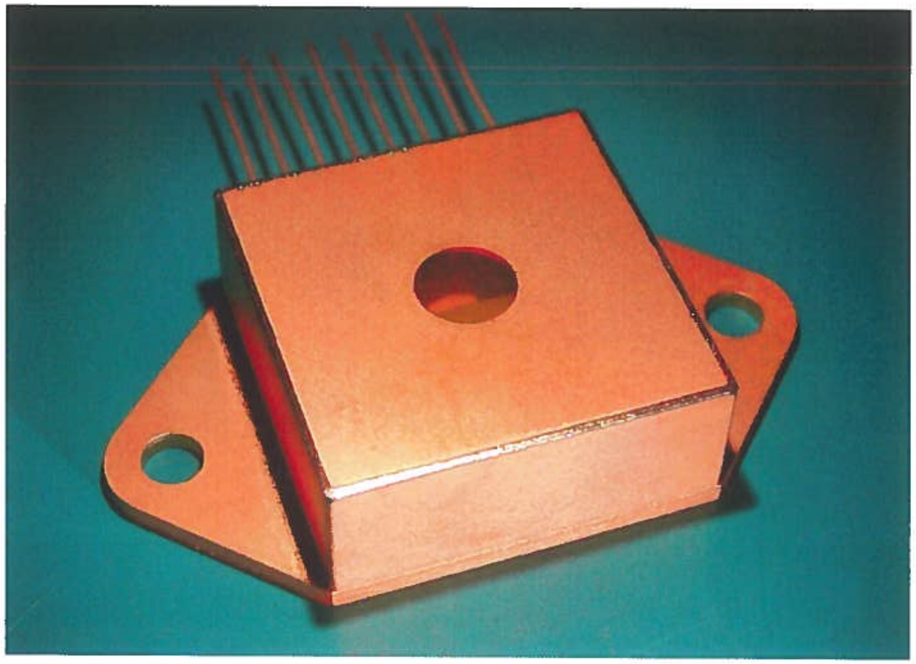
Final QCL Module



Size: 47.2 x 25.4 x 11.2 mm

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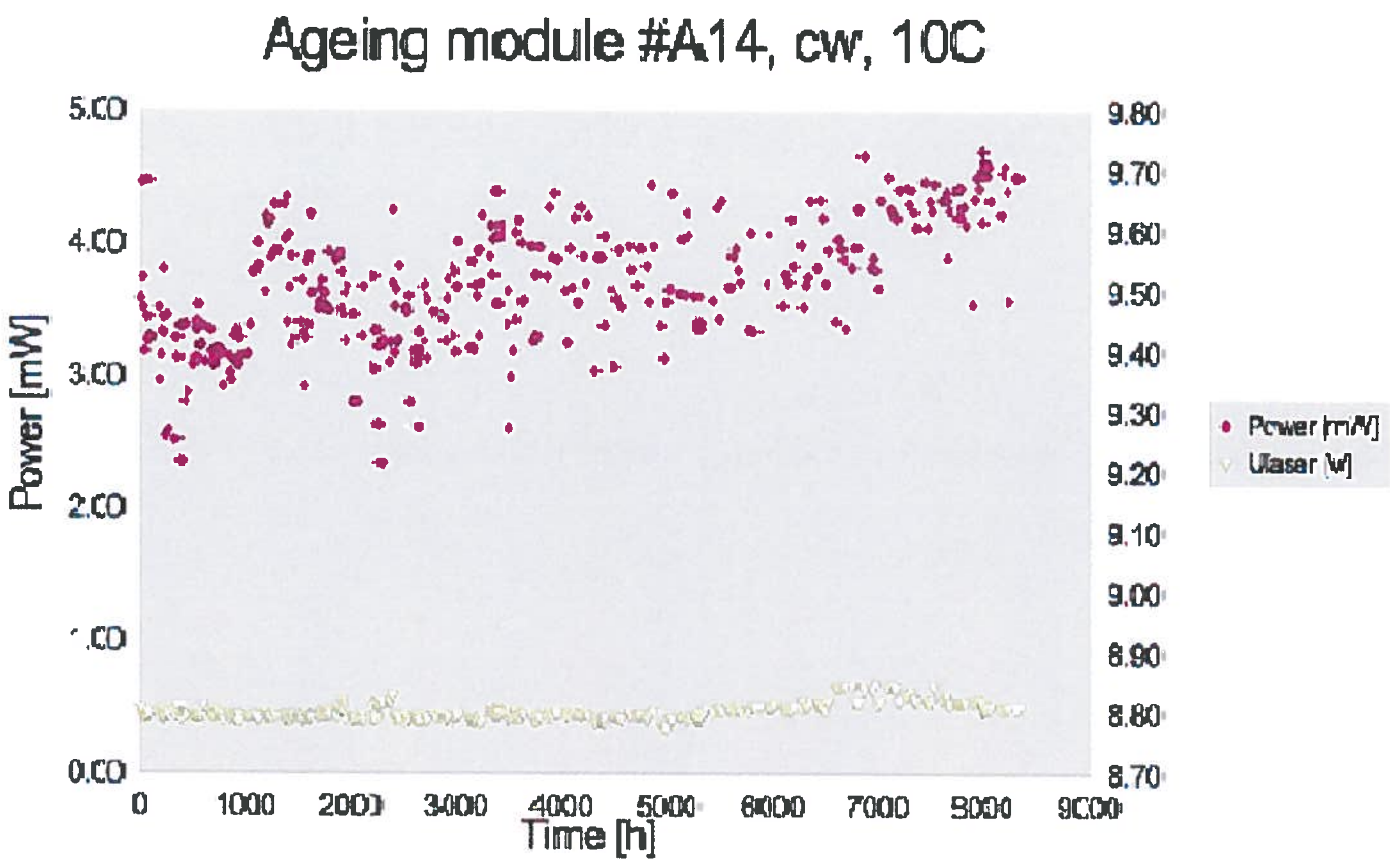
Lifetime measurements



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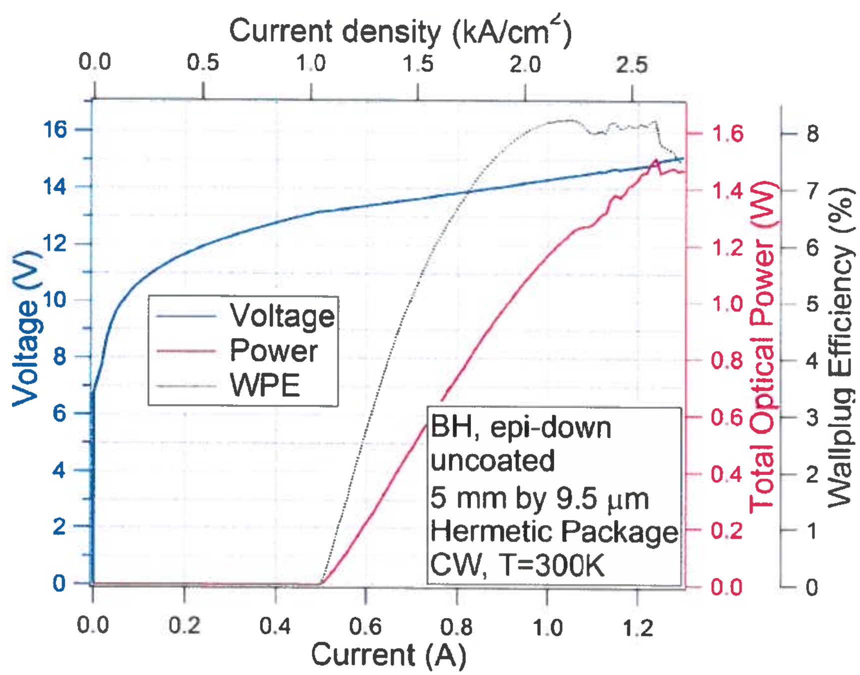
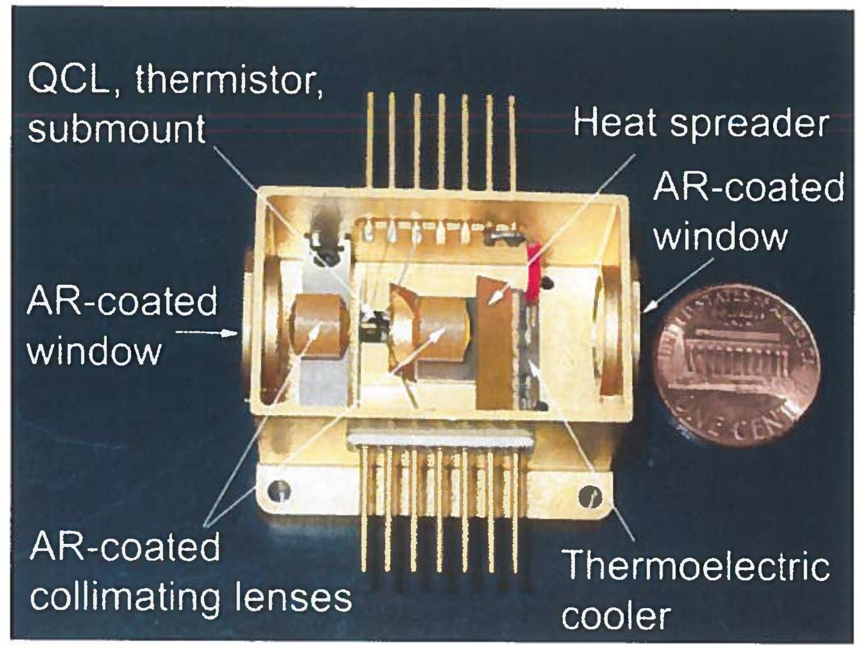
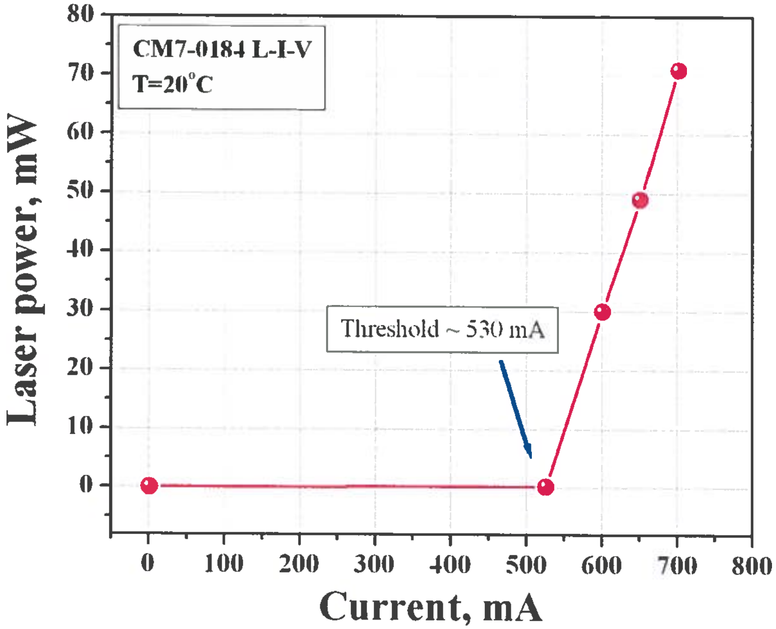
High Performance 4.6 μm CW, RT QC Laser - 2008



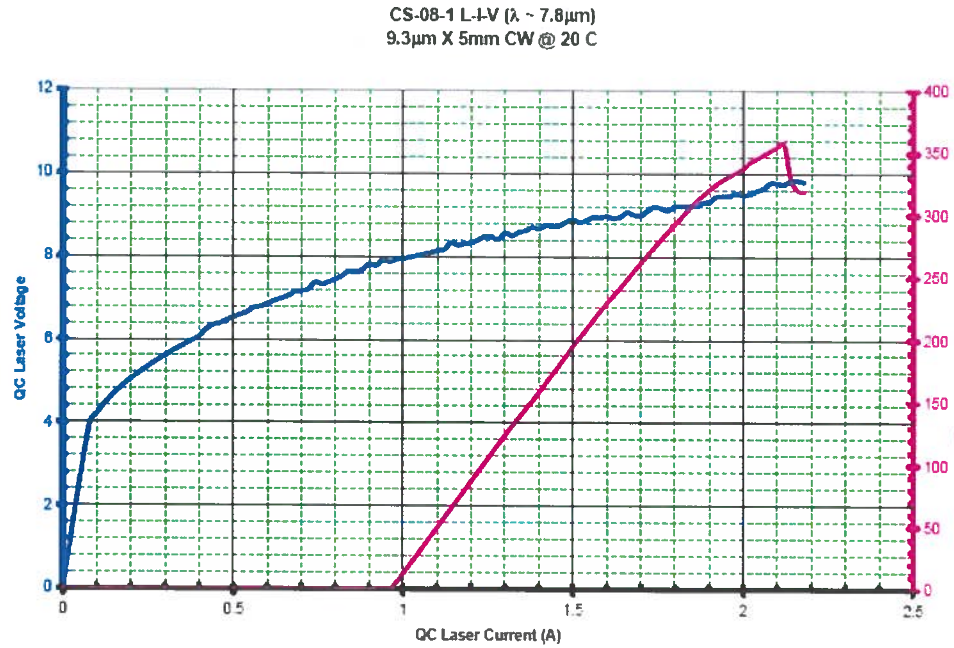


A. Lyakh et al., Pranalytica, Harvard, Adtech, Applied Physics Letters 92, 111110, 2008

Performance of Adtech – Princeton MIRTHE CW RT FP QC Lasers



June 23, 2008

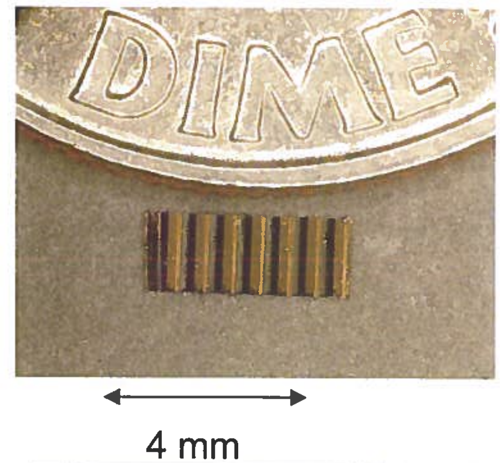


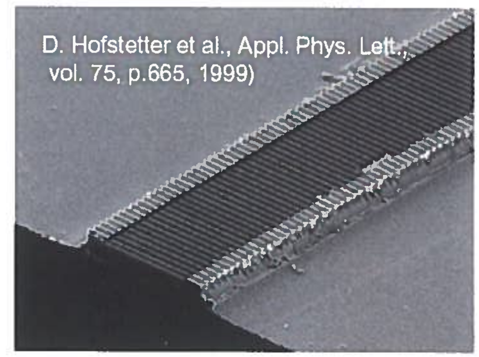
October 30, 2008

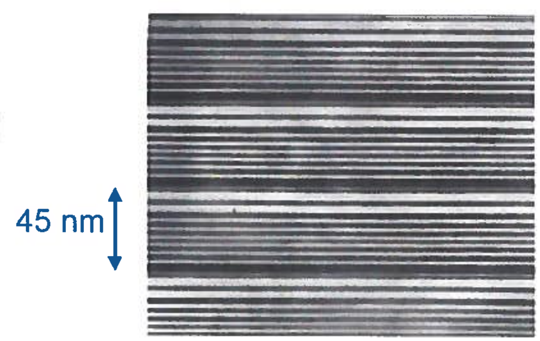
Key Characteristics of mid-IR QCLs and ICL Sources-2008

- **Band – structure engineered devices**
  (emission wavelength is determined by layer thickness – MBE or MOCVD); mid-infrared <u>QCLs operate from 3 to 24 µm (AlInAs/GaInAs)</u>
- Compact, reliable, stable, long lifetime, and commercial availability
- Fabry-Perot (FP), single mode (DFB) and multi-wavelength
- <u>**Spectral tuning range in the mid-IR**</u>
  (4-24 µm for QCLs and 3-5 µm for ICLs)
  - 1.5 cm^{-1} using injection current control
  - 10-20 cm^{-1} using temperature control
  - > 200 cm^{-1} using an external grating element and heterogeneous cascade active region design; also QC laser array (Harvard)
- <u>**Narrow spectral linewidth**</u>
  - CW: 0.1 - 3 MHz & <10Khz with frequency stabilization (0.0004 cm^{-1})
  - Pulsed: ~ 300 MHz (chirp from heating)
- <u>**High pulsed and cw powers of QCLs at TEC/RT temperatures**</u>
  - Pulsed and CW powers of ~ 1.5 W; high temperature operation ~300
  - >50 mW, TEC CW DFB @ 5 and 10 µm
  - > 600 mW (CW FP) @ RT & wall plug efficiency of ~12.% at 4.6 to µm ; Princeton, Harvard, Northwestern, and commercialization by Hamamatsu, Adtech Optics, Pranalytica, Alpes, DLS, Alcatel-Thales, Nanoplus, Laser Components,Maxion, Corning.

China, ETH
Fraunhofer.
Vienna
Montpellier.

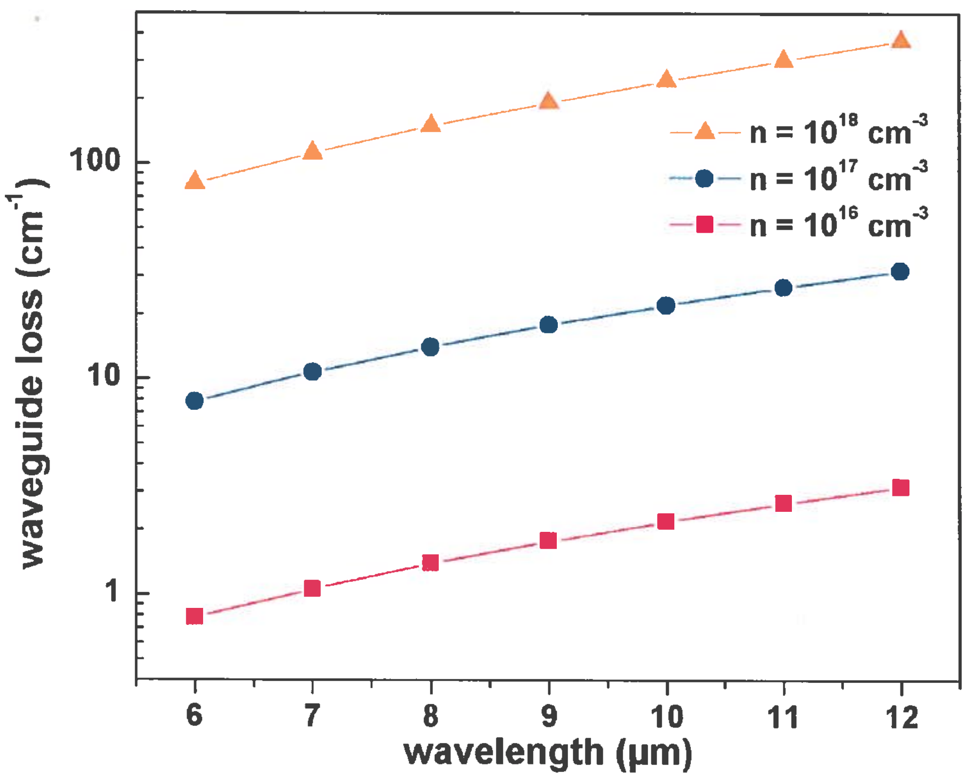


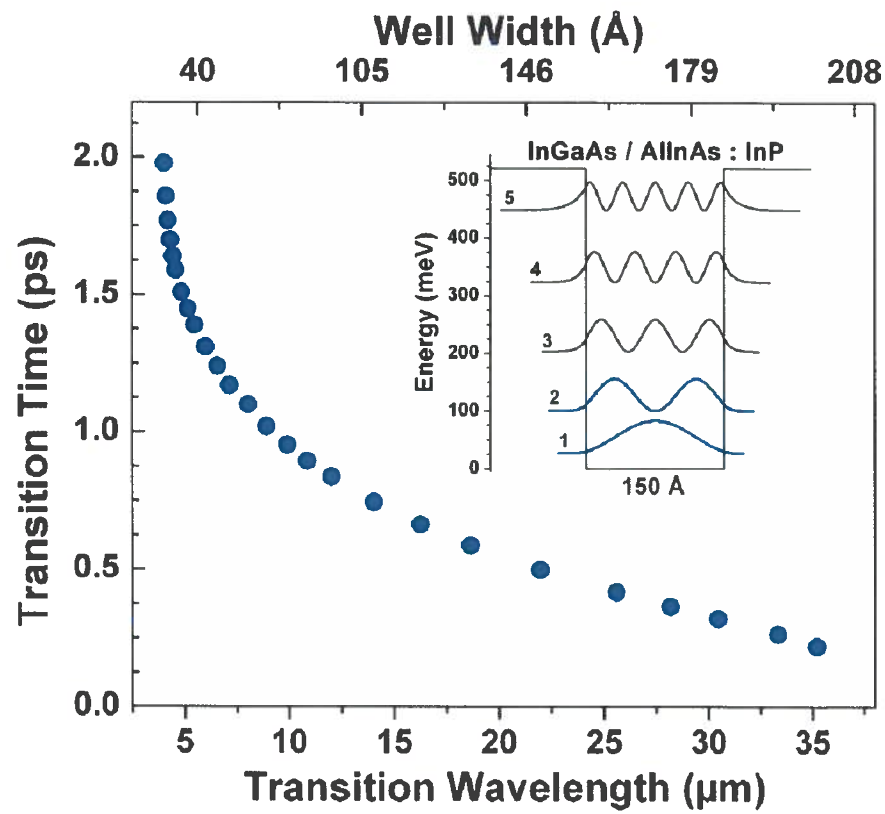




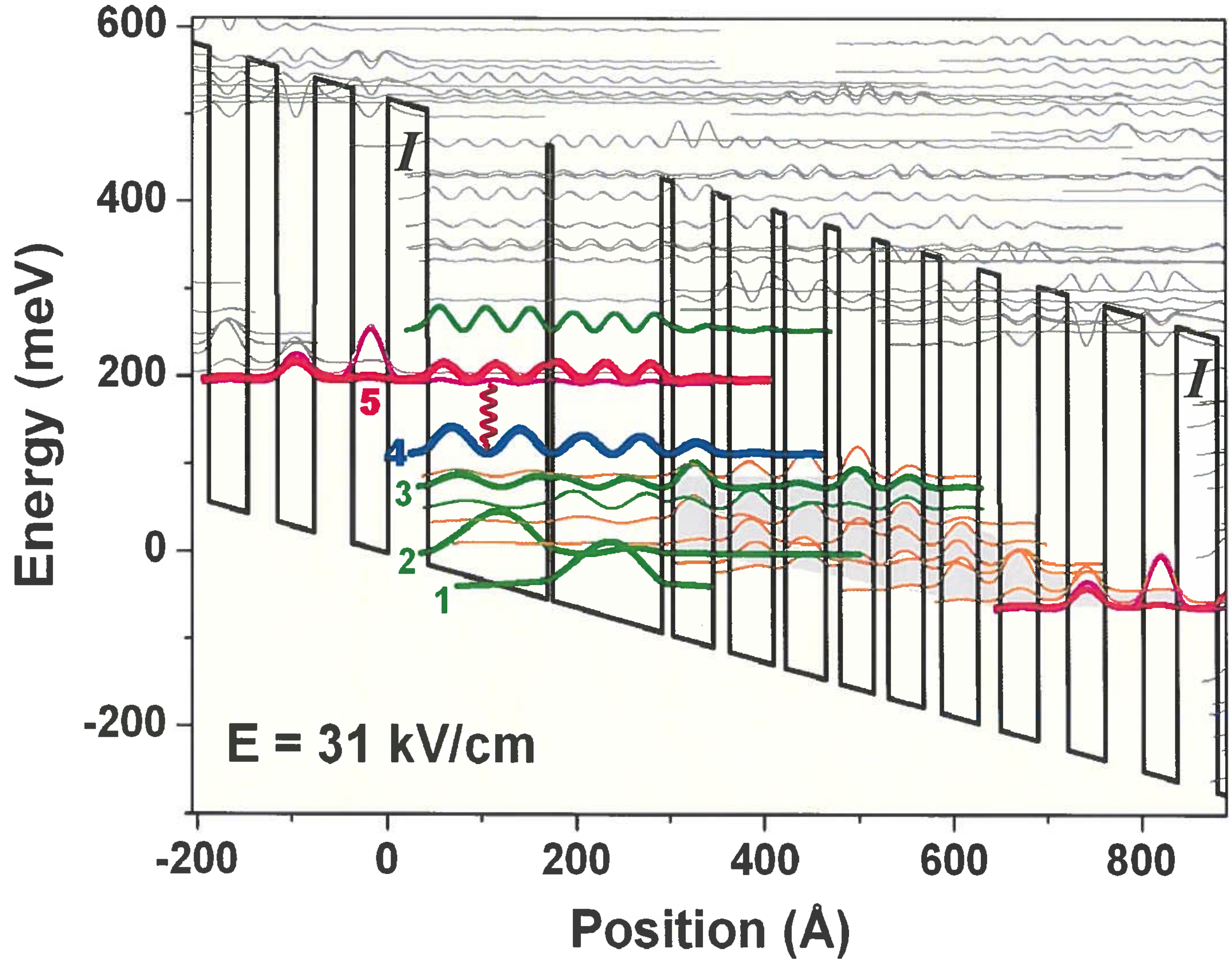
Why are long wavelength QCLs challenging?

- Optical absorption increases with wavelength
- Upper laser level lifetime >lower state lifetime





15 μm excited state QC laser

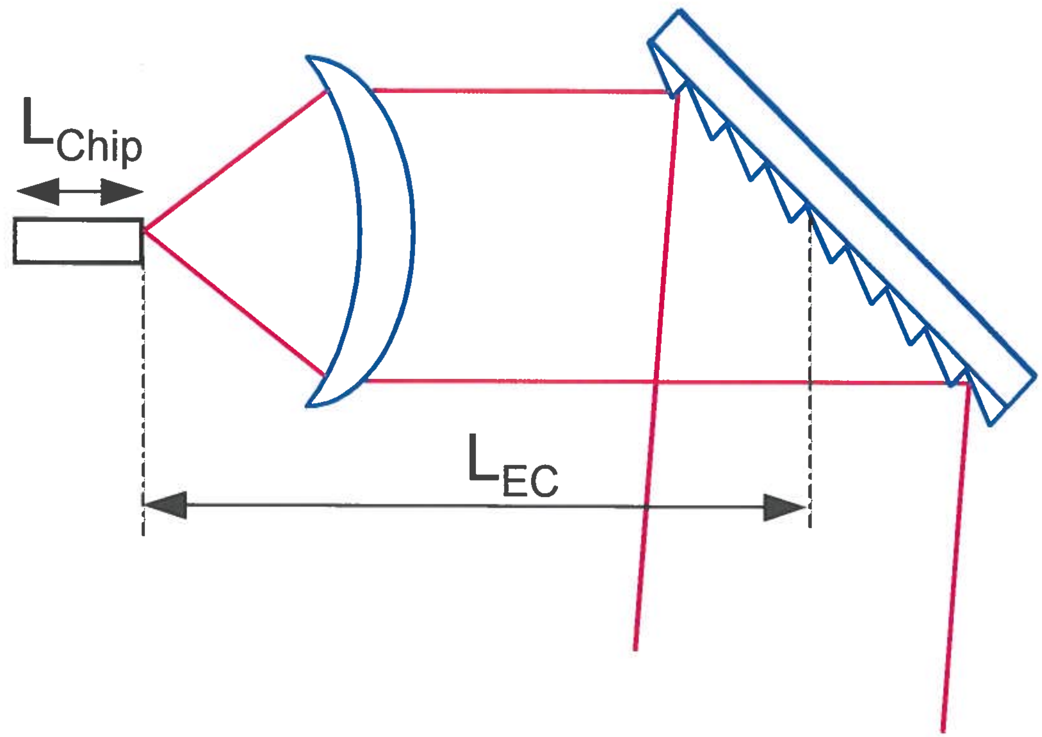


- $E_{ul} = 83.6$ meV
- $z_{ul} = 50.3$ Å
- $\tau_5 = 0.586$ ps
- $\tau_4 = 0.215$ ps
- $\tau_{54} = 1.9$ ps
- FoM = 1313 ps Å^2
- $z^2\tau_5 = 1483$ ps Å^2
- $z^2\tau_5 E = \mathbf{124}$ ps Å^2 eV

Widely Tunable, CW, TEC
Quantum Cascade Lasers

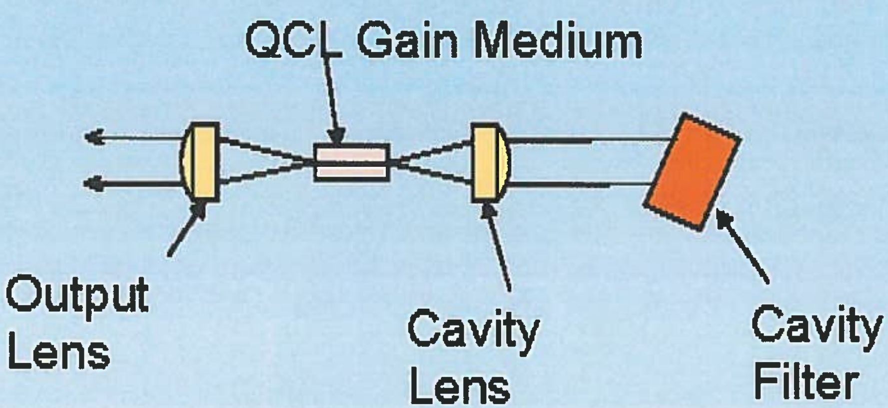
FP QCL suitability for an external cavity platform

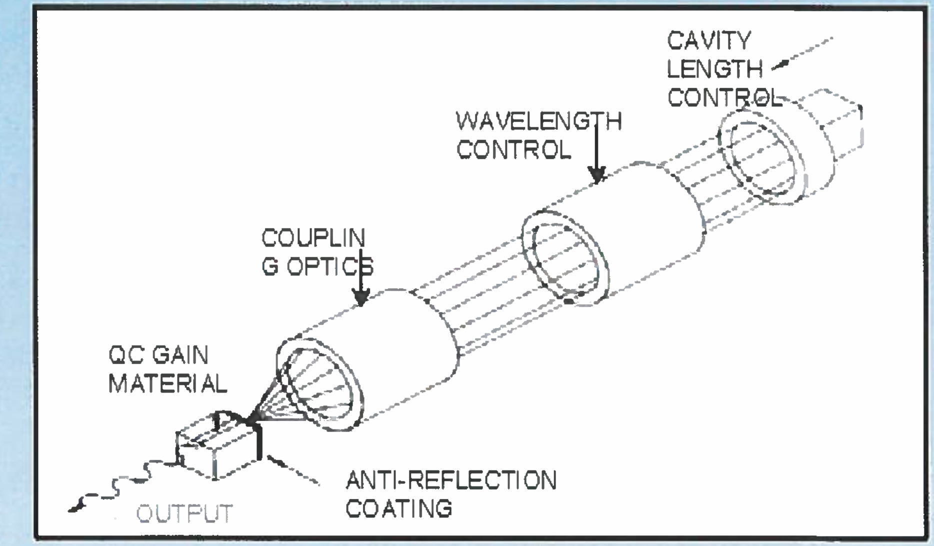
- **Power,**
- **CW operation,**
- **Broad gain,**
- **Far field pattern,**
- **Life-time,**



DAYLIGHT SOLUTIONS

ECQCL basics





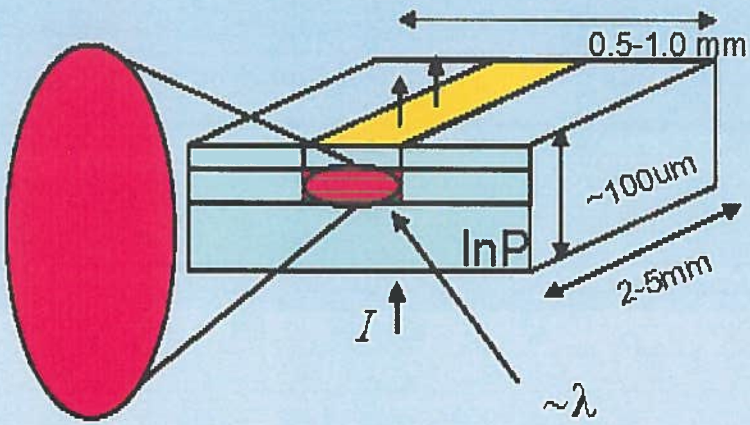
P. Zorabedian, "Tunable External Cavity Semiconductor Lasers"

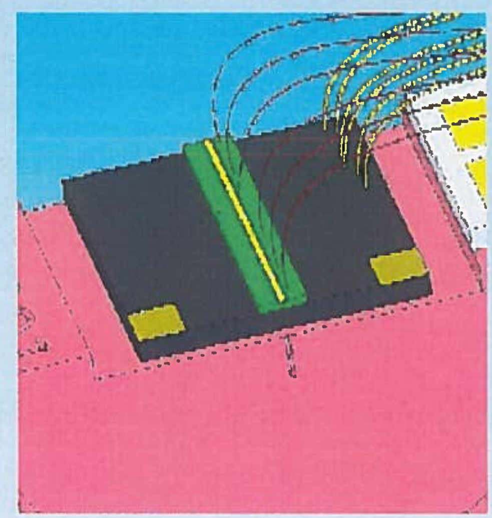
- Components need to be compatible with mid-IR radiation
- Micro-optic components required for compact lasers
- QC Gain Media needs to be AR coated and single mode
- QC attach needs to be robust and high thermal conductivity
- Filter tuning needs to be wavelength and phase controlled

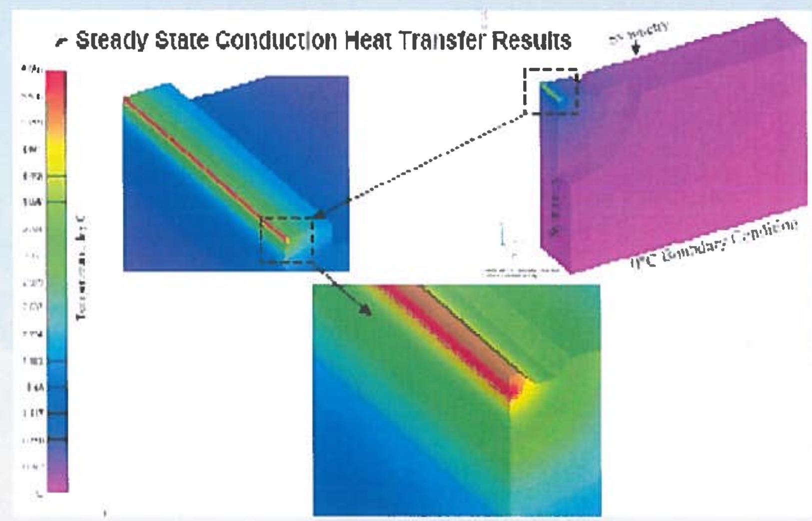
Key technology and components

- QC gain media
- AR coatings
- Micro-Optic lenses
- Wavelength tuning and filtering
- Instrument control

QC Gain Media







- EPI up or down can be accommodated
  - Buried Heterostructures or Ridges
  - EPI down mounting for most efficient heat removal
  - Solder attach for high temperature operation
- Multiple commercial suppliers
  - Adtech
  - Hamamatsu
  - Alpes
  - Maxion
  - Laser Components
  - Nanoplus
  - III-V Labs

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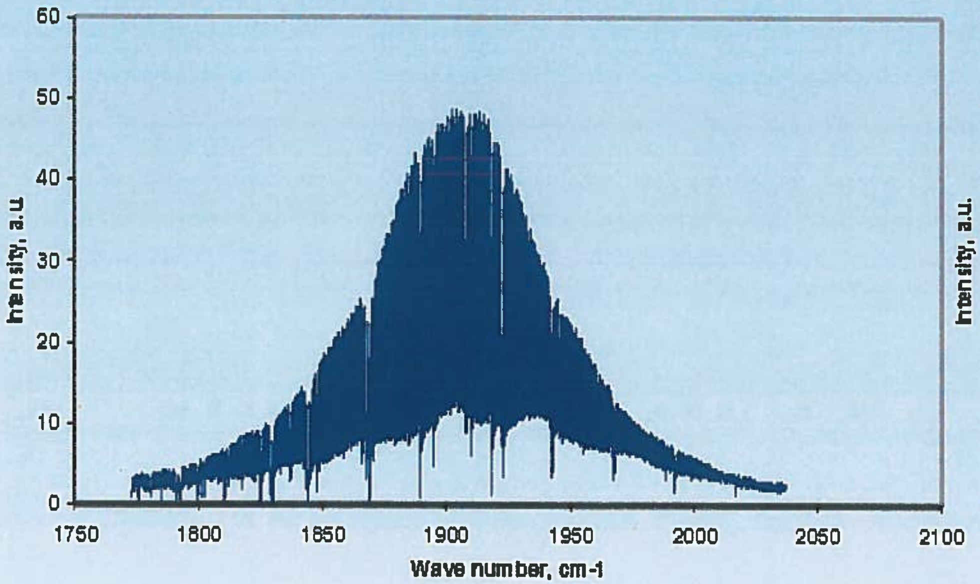
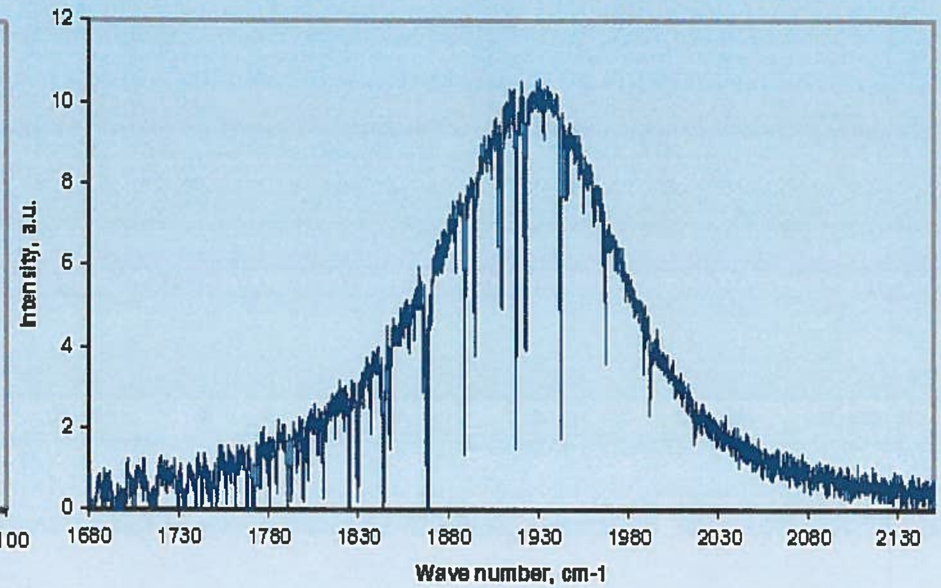
AR Coatings

FTIR spectrum of uncoated 5.2 um

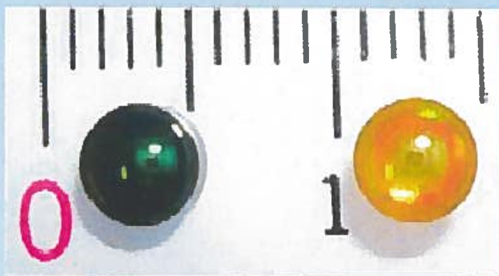


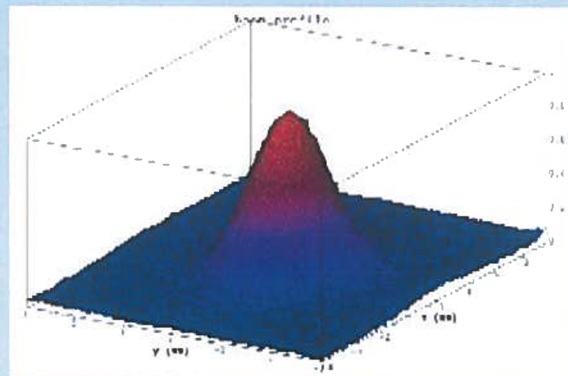
FTIR spectrum of 5.2 um after AR coating



- MID IR coating materials required
- Broad band performance required (thick coatings)
- Reflectivity's below 0.001 for optimum performance
- Long lifetime, high stress, high heat coatings

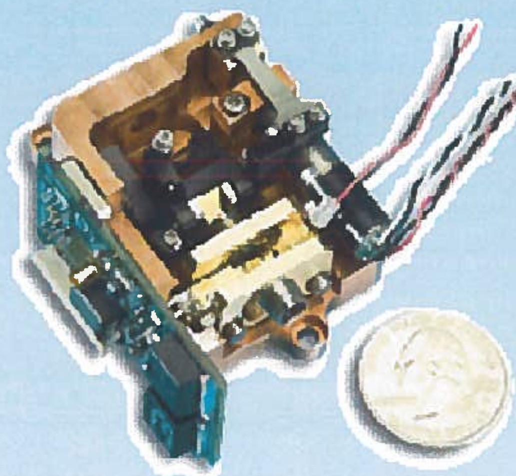
Micro-Optic Lenses





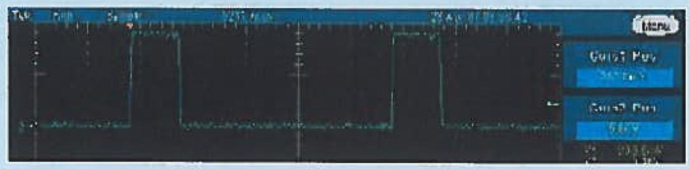
- Diffraction limited performance required
- High N.A. (>0.8)
- Low wave-front error manufacturing
- MID IR materials (ZnSe, Ge, Chacolgenide..)
- Aspheric surfaces required

Wavelength filter and filter tuning



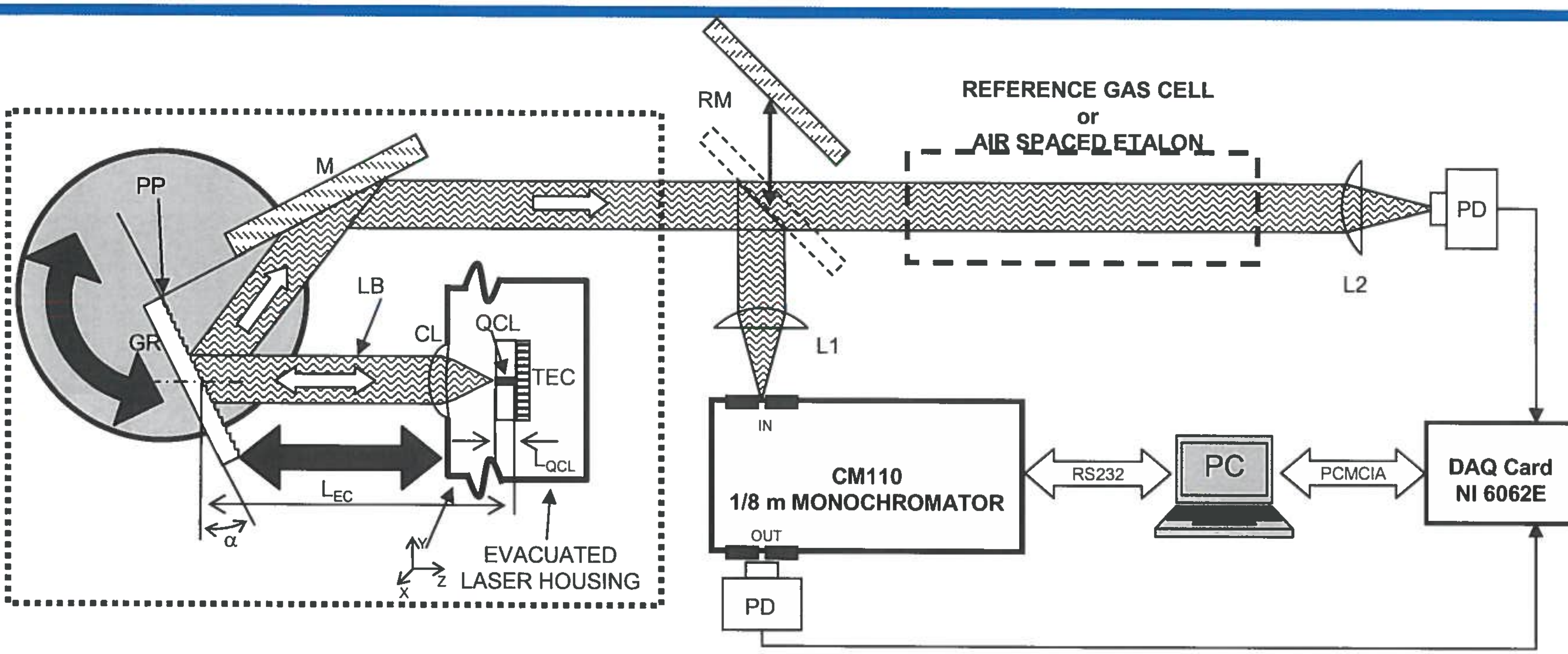
- Diffraction gratings provide high feedback (>80%)
- Disk drive or MEMS tuning are options
- Pulsed lasers do not need MHF (phase continuous) tuning
- High resolution tuning requires wavelength and phase control
- Digital encoders for wavelength readout

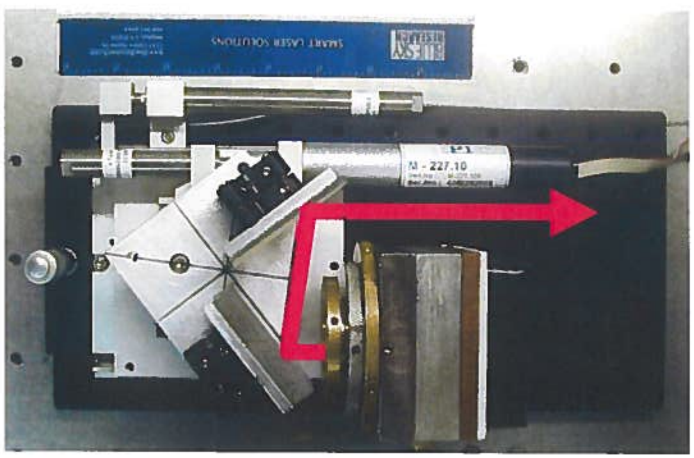
Instrument control



- Temperature control to 10mK
- Current control to ~2A
- High compliance voltages (up to 20V)
- Wavelength control to 1:10^5
- Pulsed and CW operation
- Computer interface

Tunable external cavity QCL based spectrometer





- Fine wavelength tuning
  - PZT controlled EC-length
  - PZT controlled grating angle
  - QCL current control
- Motorized coarse grating angle tuning
- Vacuum tight QCL enclosure with build-in 3D lens positioner (TEC laser cooling + optional chilled water cooling)

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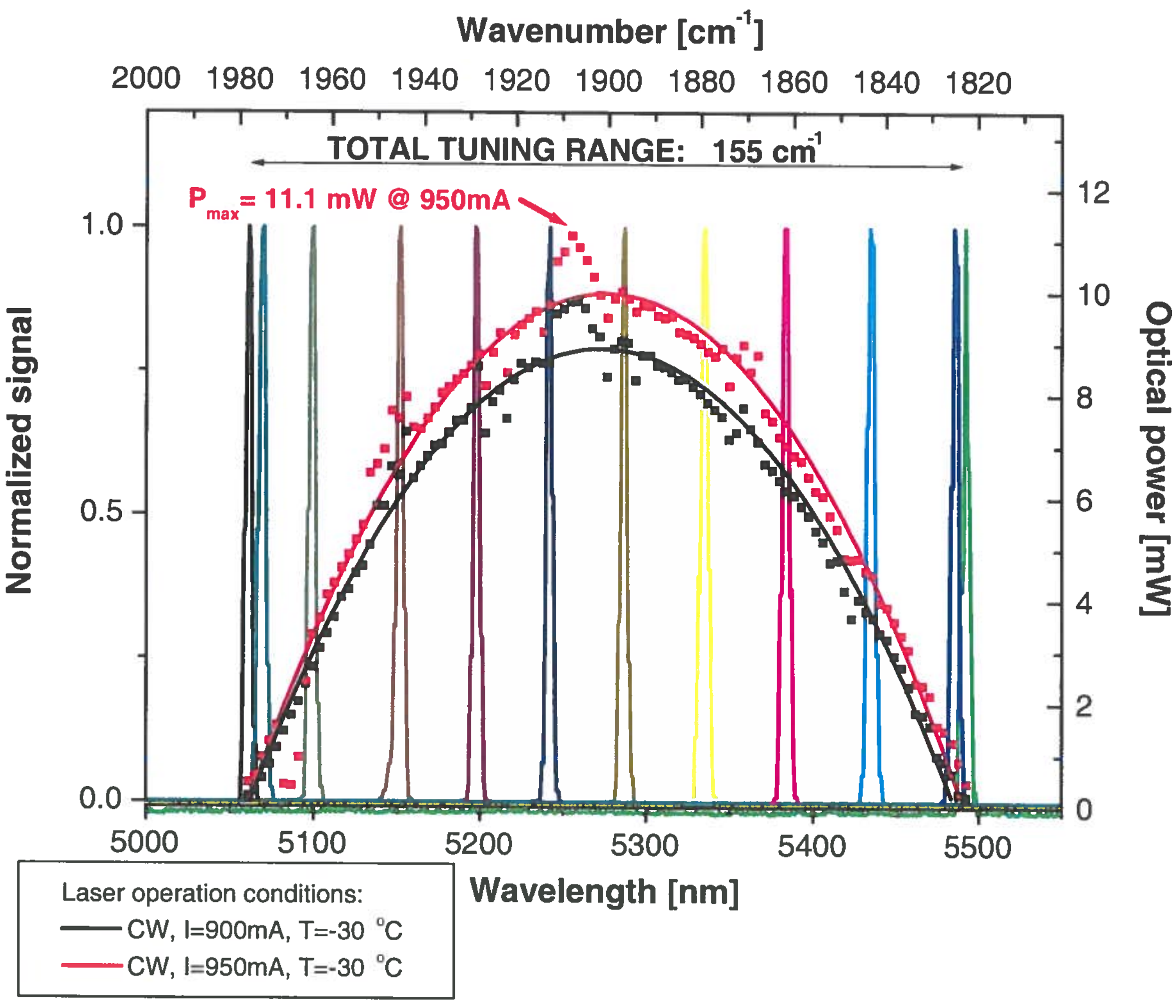
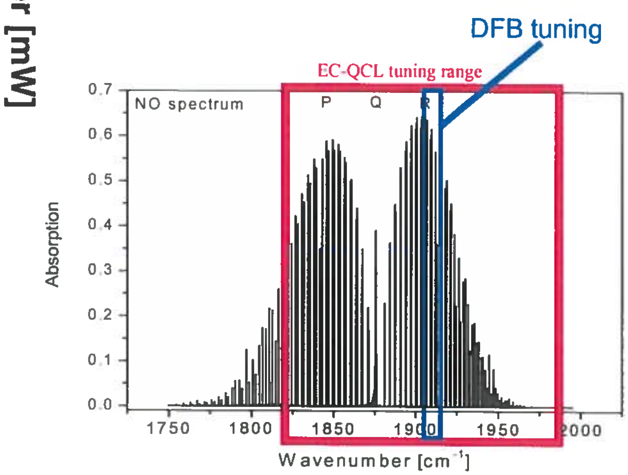
Wide Wavelength Tuning of a 5.3μm EC-QCL

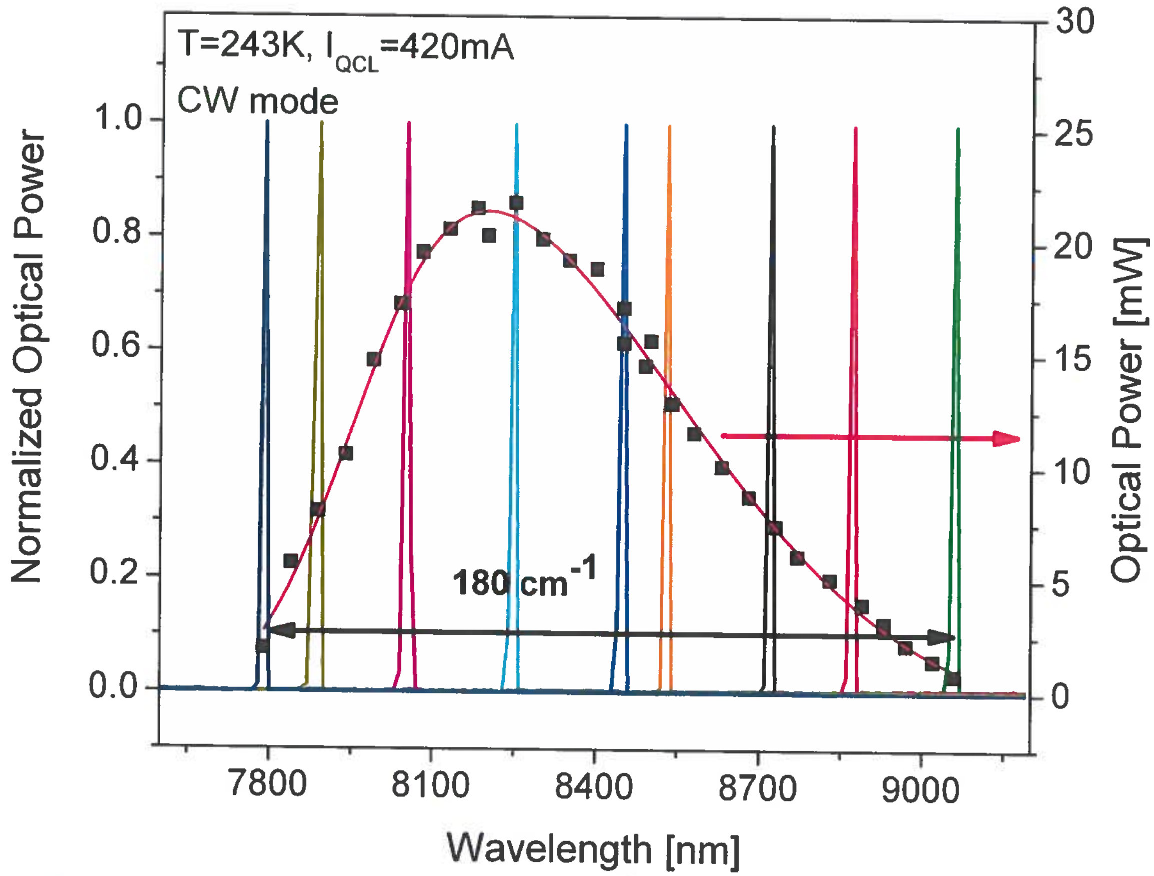


- Coarse wavelength tuning of **155 cm⁻¹** is performed by varying diffraction grating angle
- Power output is ~ **11mW**
- Access to Q(3/2) transition of NO at 1875.8 cm-1 for LMR spectroscopy



G.Wysocki et al. Applied Physics B, on line July 2008

Performance of 8.4 μm cw EC-QCL Spectroscopic Source



Tunability **182 cm^{-1}** @8.4 μm;(1100 to 1280 cm^{-1}); λ_c=15%

AR coating:
$R_{AR} \approx$ **2 × 10^{-4}**

$P_{EC\text{-}opt}$: ~ **50 mW @ -30 C, ; also ~100 mW & 201cm^{-1} @ 8.8 μm & 30 C with 2008 QCL technology**

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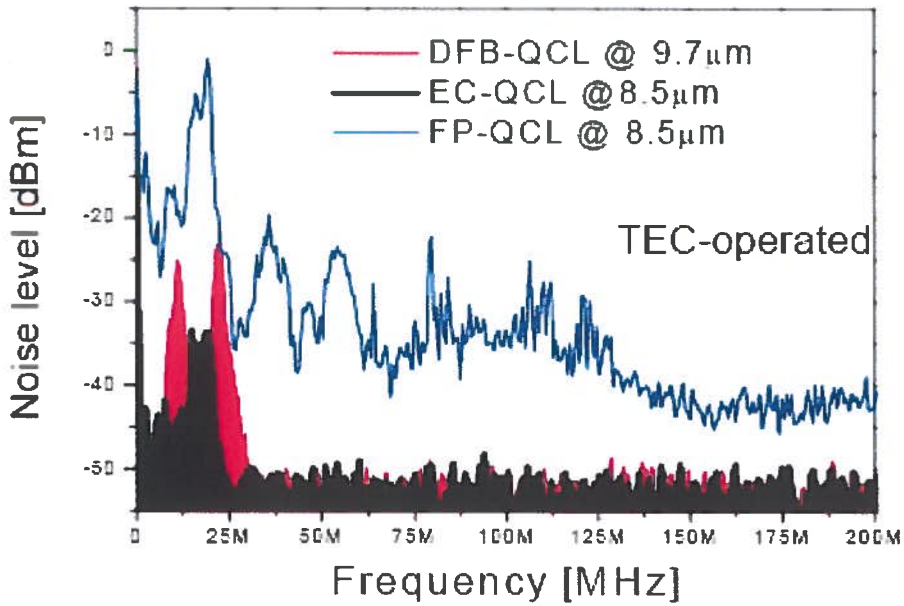
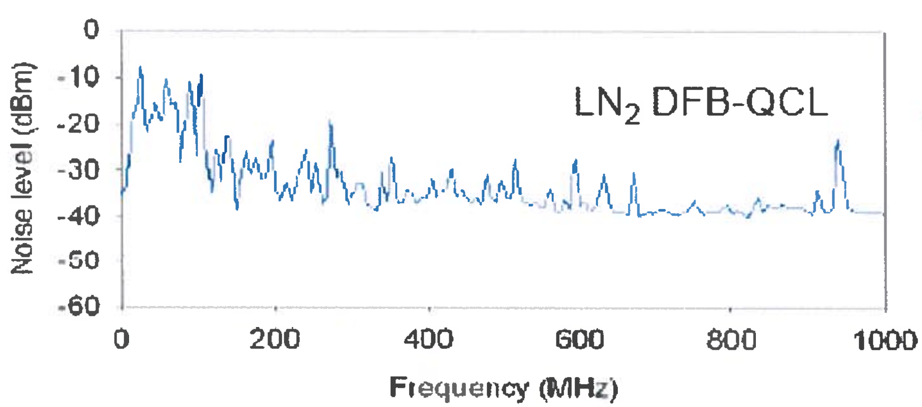
EC-QCL Noise





- EC-QCL outperforms DFB-QCLs in terms of RF noise figure
- EC feedback reduces laser excess noise
  - ~L_{QCL}/L_{EC} reduction of injection current fluctuations impact
  - Strong feedback gives >30dB SMSR
- The excess noise has direct Impact on QCL-based systems performance
- FP "close to threshold" is not the best way to obtain single-mode lasing

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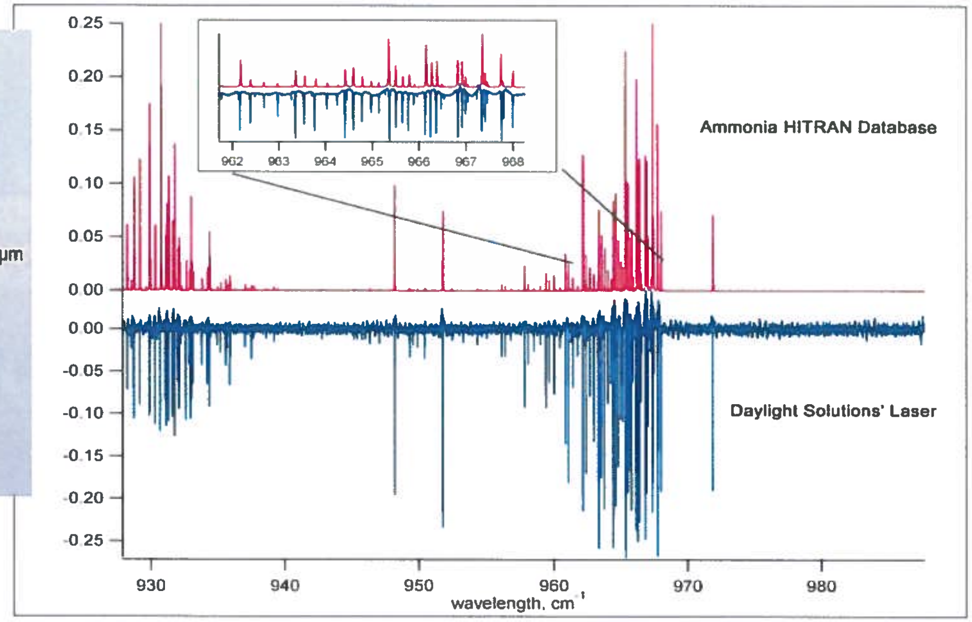
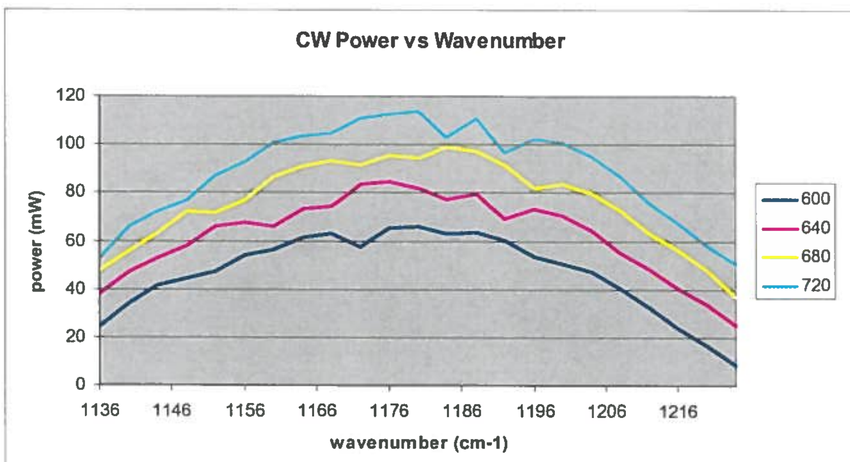
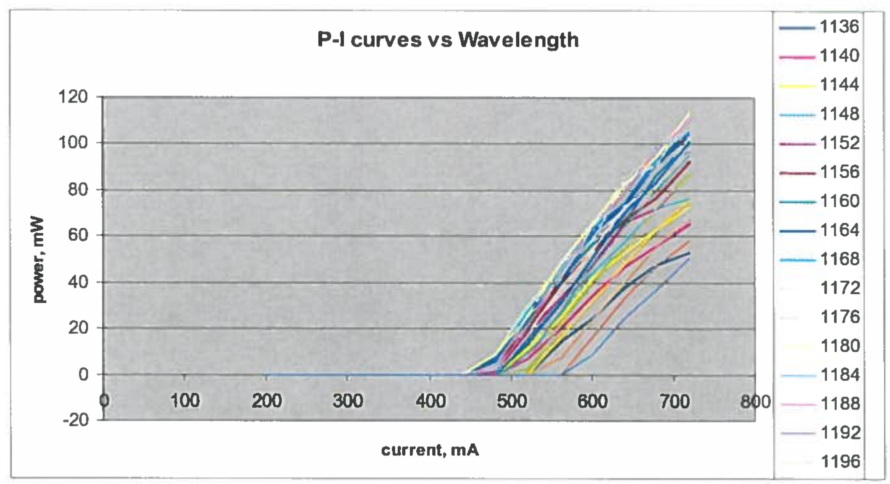
Commercial widely tunable CW EC-QCL







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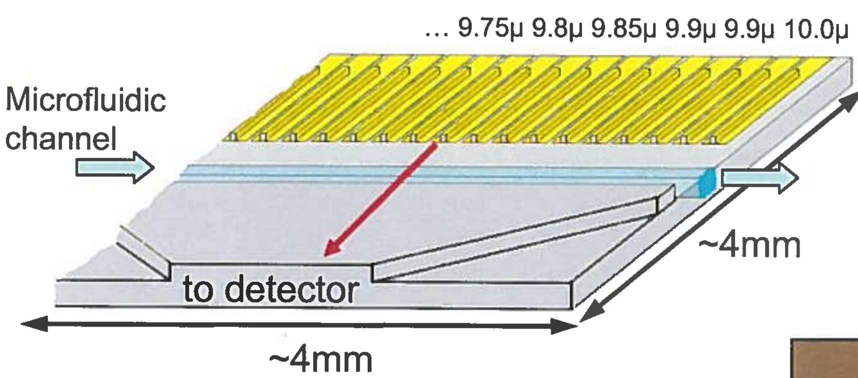
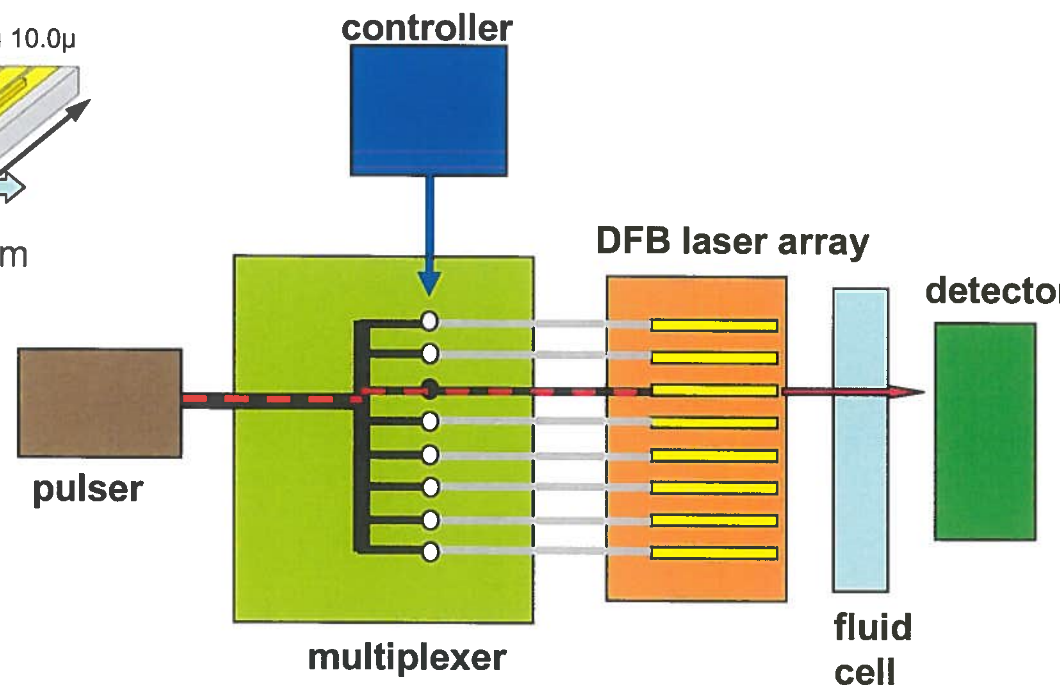
Broadband QCL Spectrometer on a Chip

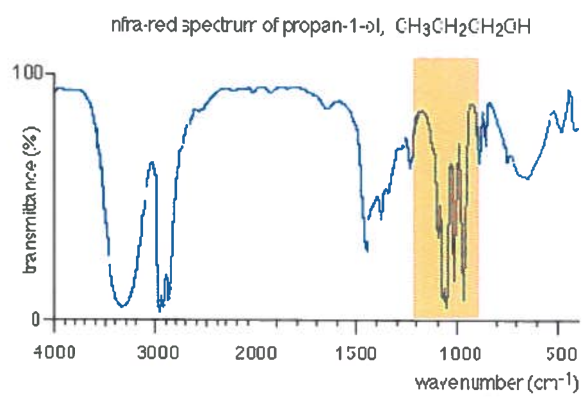
Schematics of QCL spectrometer





Technical Approach

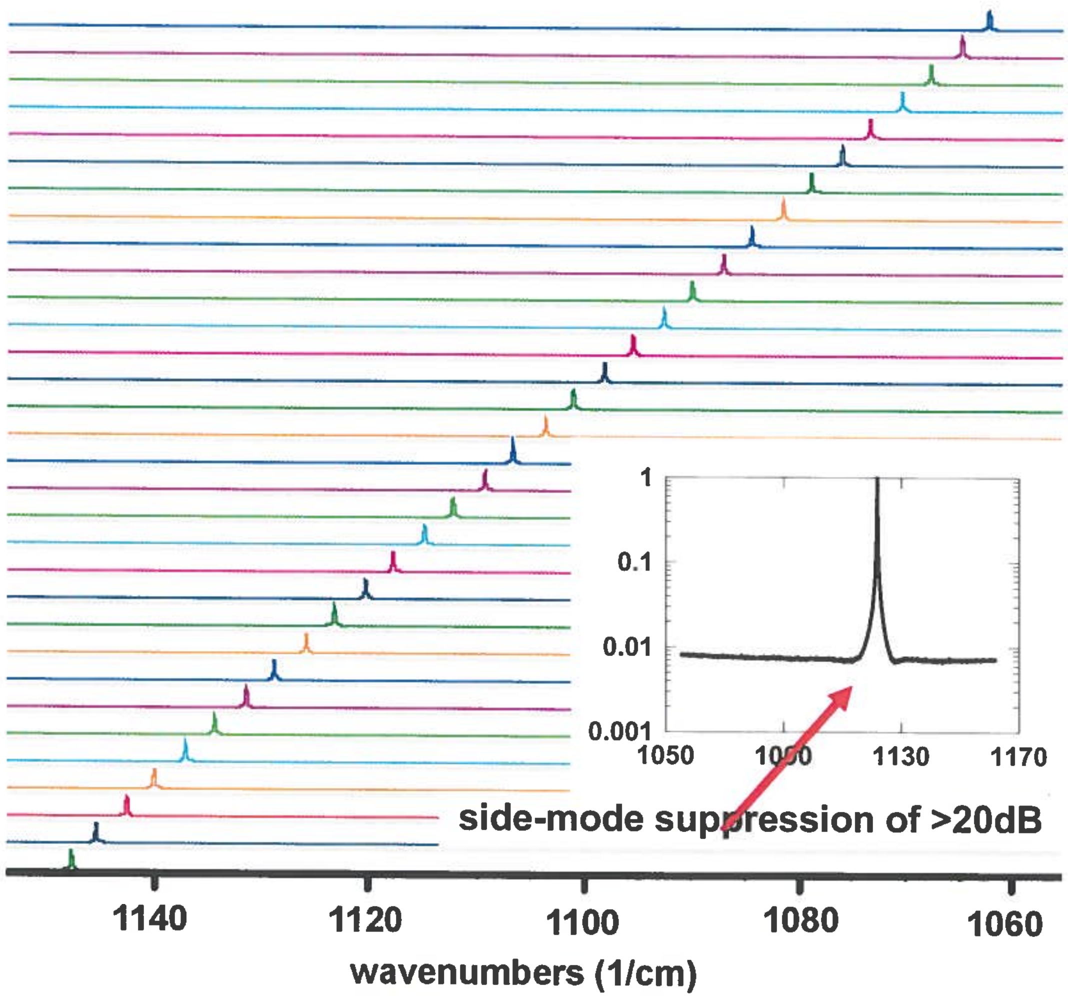
- ***Broadband mid-IR quantum cascade lasers***
- ***Distributed feedback (DFB) laser array with wavelengths spanning more than 250 cm^{-1}***
- ***Temperature tuning for continuous spectral coverage***
- ***Computer Control***

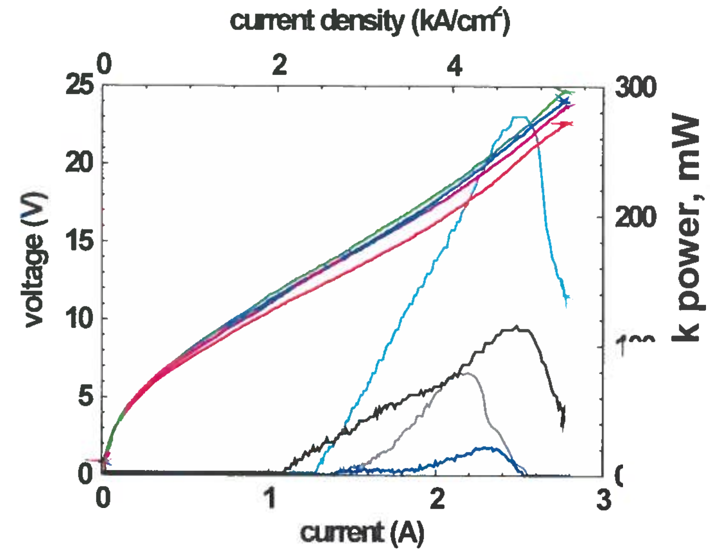


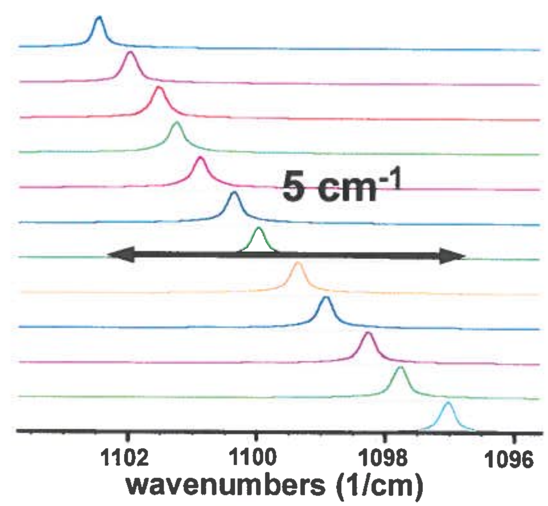
Lee et al. Appl Letters 91, 231101 (2007)

DFB QCL array performance

Emission spectrum of a 32 DFB-QCL array
Pulsed operation (80kHz, 50ns) at room temperature





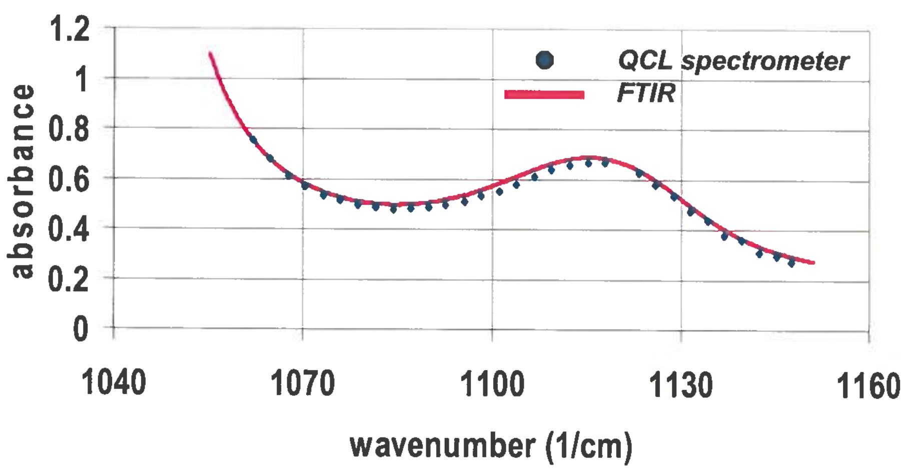


Temperature tuning by DC current

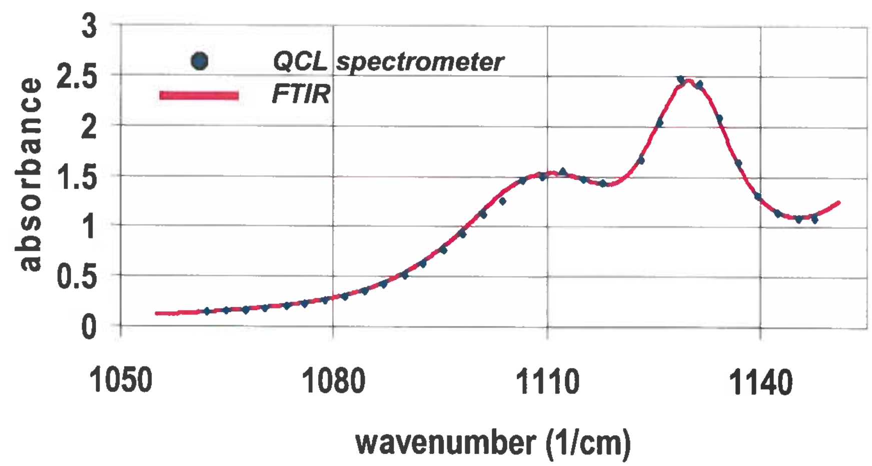
Lee, Belkin, et al., APL 2007

Absorption spectroscopy

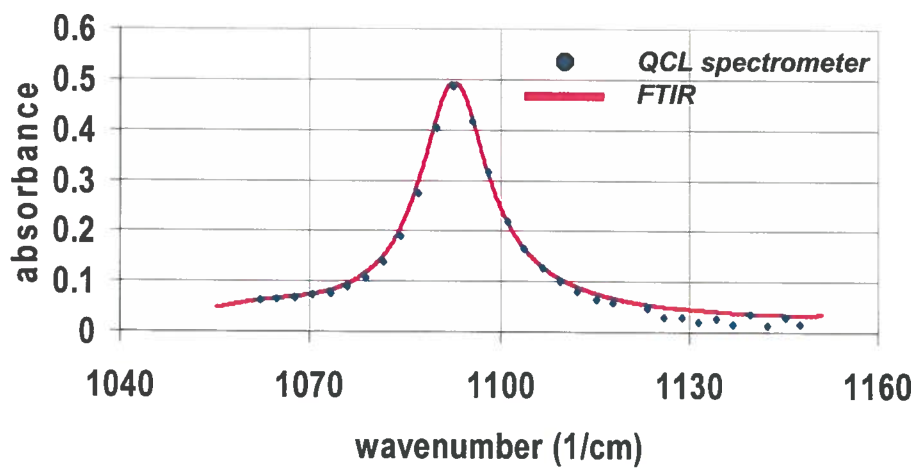
Methanol Absorption



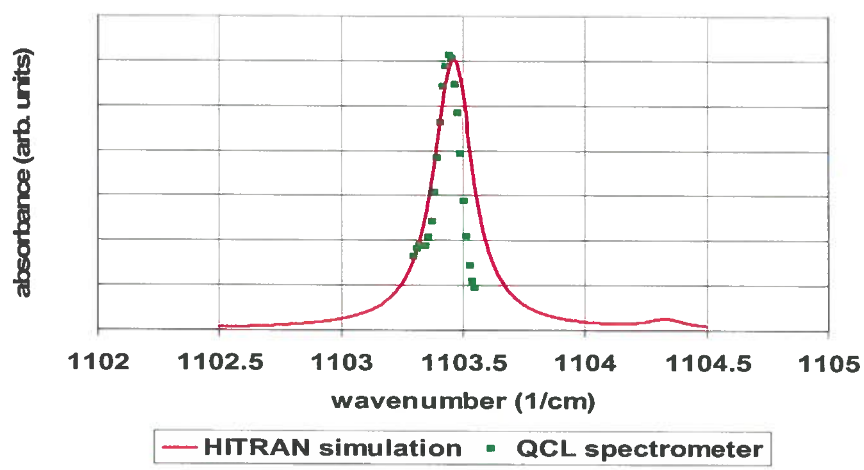
Isopropanol Absorption



Acetone Absorption



Ammonia Gas Absorption



Lee, Belkin, et al., APL (2007)

Trace Gas Sensors Areas Explored at Rice

- Methods employed
  - Extended pathlengths (Multpass Gas Cells & Retroreflector)
  - Cavity Ringdown
  - Off-Axis Integrated Cavity Output Spectroscopy
  - Faraday Rotation Spectroscopy
  - Wavelength Modulation
  - Pulse-to-pulse fluctuation removal by comparing the same pulse on the same or another detector
  - Quartz Tuning fork based photoacoustic spectroscopy (QEPAS)
- 16 gases detected: NH_3, CH_4, H_2S, N_2O, CO_2, CO, NO, C_2H_2 H_2O, OCS, C_2H_4, SO_2, C_2H_5OH, C_2HF_5, H_2CO, C_2H_6, HCN and isotopic species of C, O and N
- Practical applications
  - Crew Health Maintenance & Life Support - H_2CO, NH_3
  - Fire and Post Fire Detection
  - Radioactive site remediation
  - Medical breath analysis - NO, NH_3, CO_2, CH_3COCH_3, OCS
  - Industry catalyst poison - CO
  - Urban air smog - H_2CO

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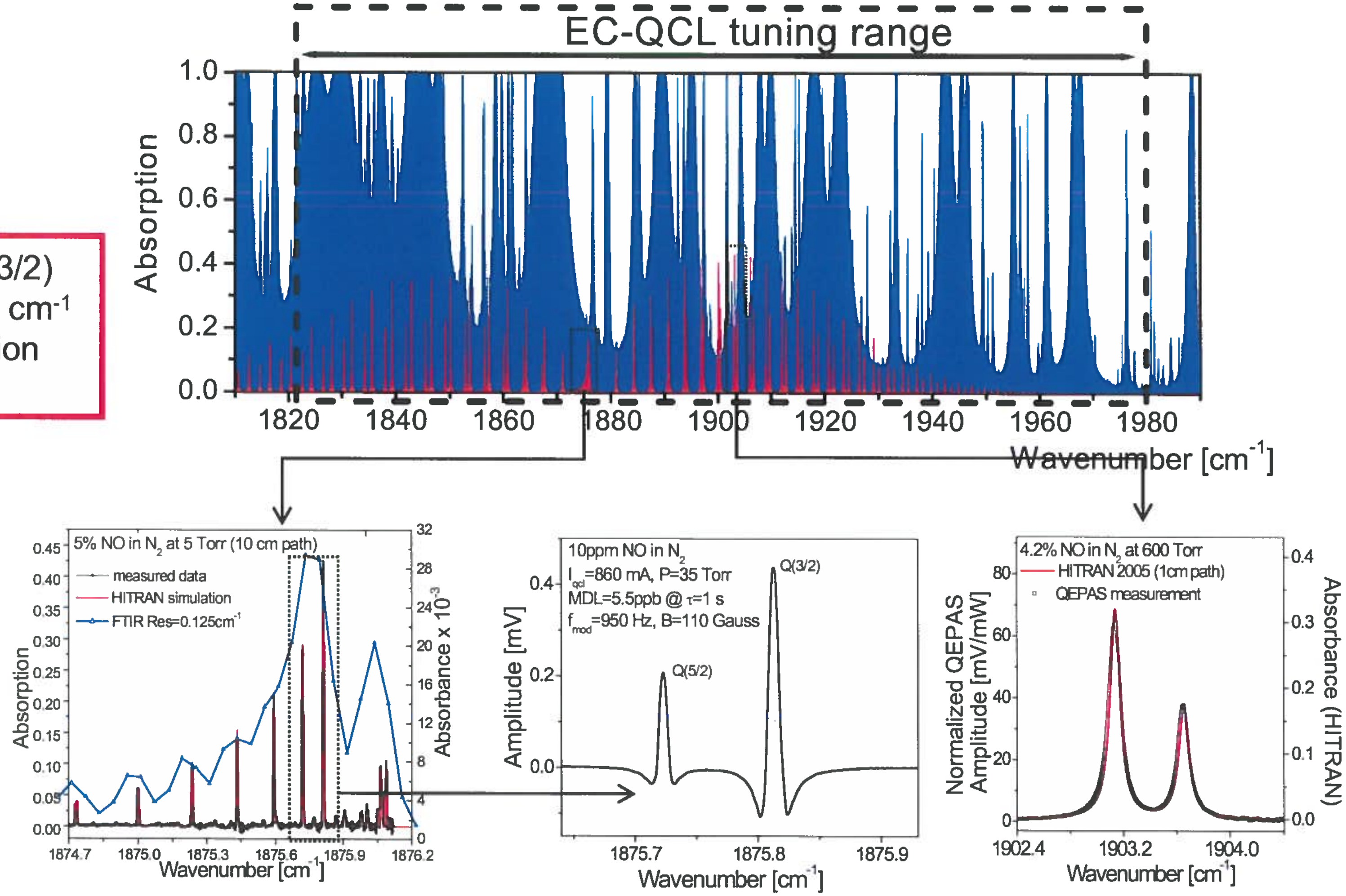
High resolution spectroscopy with a 5.3μm EC-QCL

Access to NO Q(3/2) transition at 1875.8 cm^{-1} for Faraday rotation spectroscopy

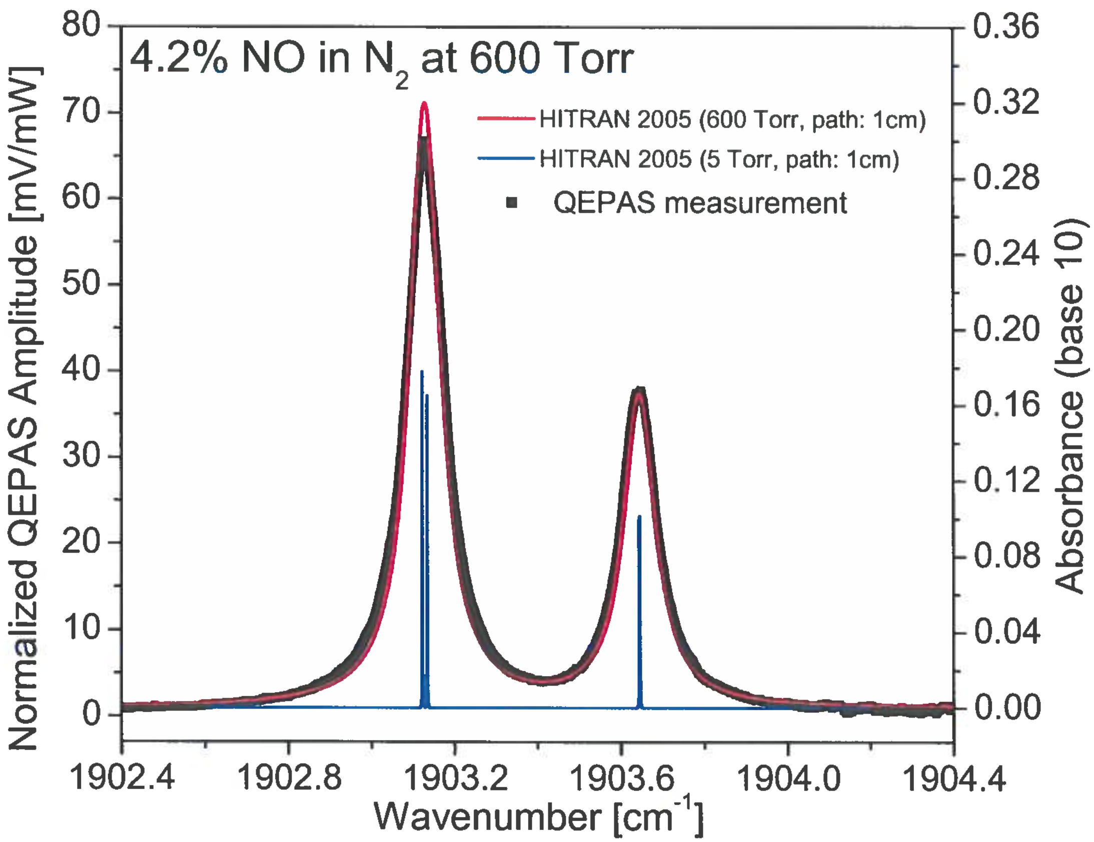


- Mode hop free scan of up to ~**2.5 cm^{-1}** with a resolution **<0.001cm^{-1}** (30MHz) can be performed anywhere within the tuning range

In collaboration with:

unine

High resolution EC-QCL based QEPAS



External Amplitude Modulation:

- QTF is used as a mechanical chopper at *f=~32kHz*
- No chirp associated with the laser current modulation
- High resolution mode-hop-free tuning is possible

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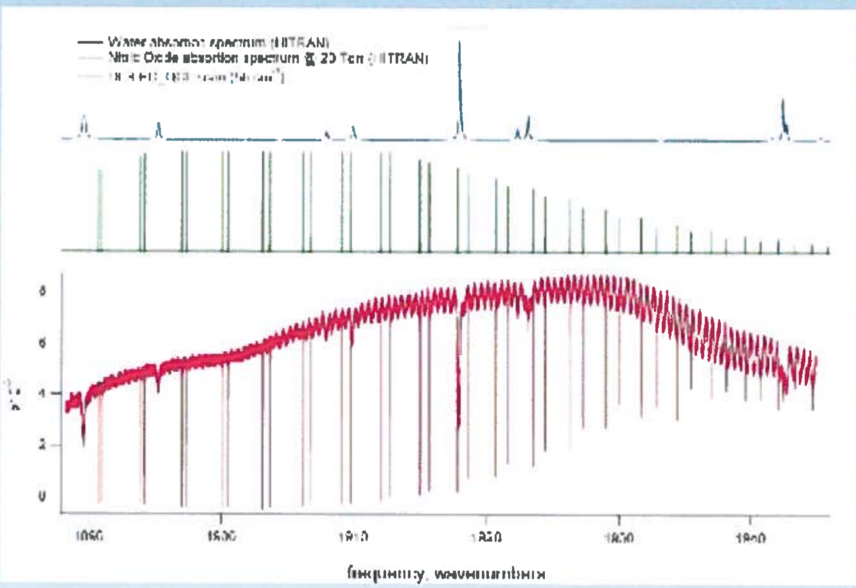
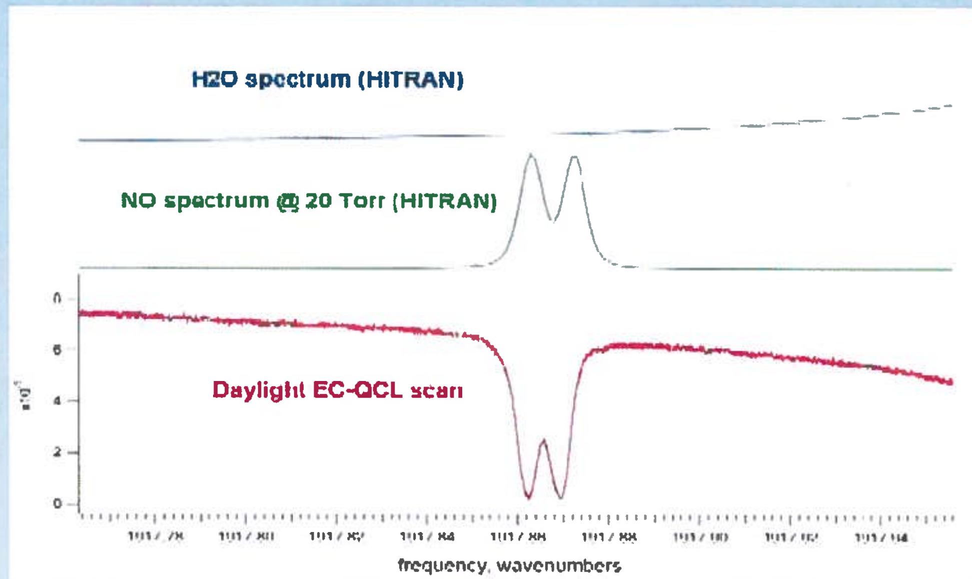
Applications

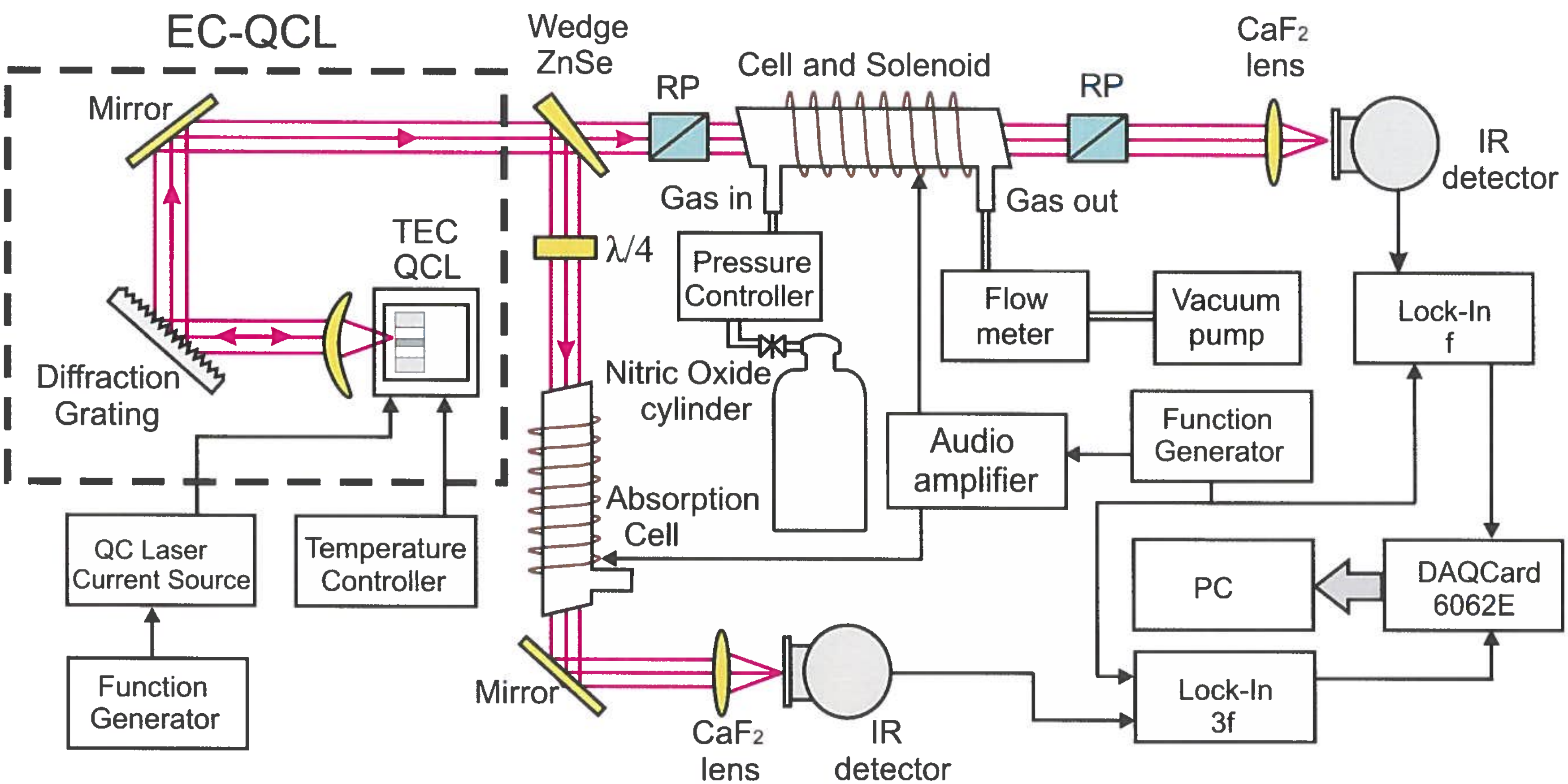
High Resolution Spectroscopy (NO)



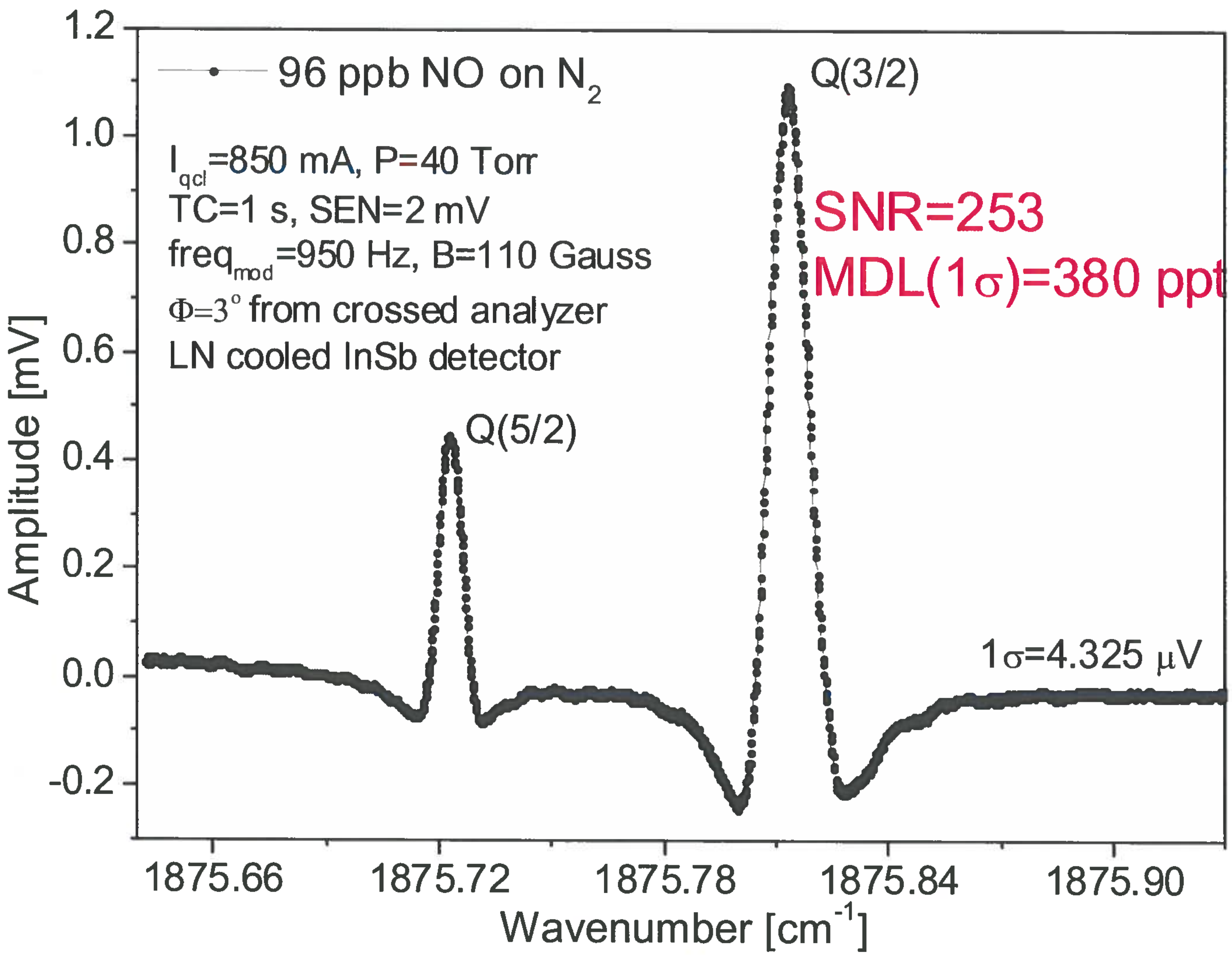


- Step control of center wavelength over full tuning range phase continuously
- Fine tuning with PZT to achieve inter-step continuous tuning
- Doublets can be easily resolved with laser linewidths below 10MHZ

EC-QCL based Magnetic Rotation Spectroscopy



Magnetic Rotation Spectroscopy of Nitric Oxide



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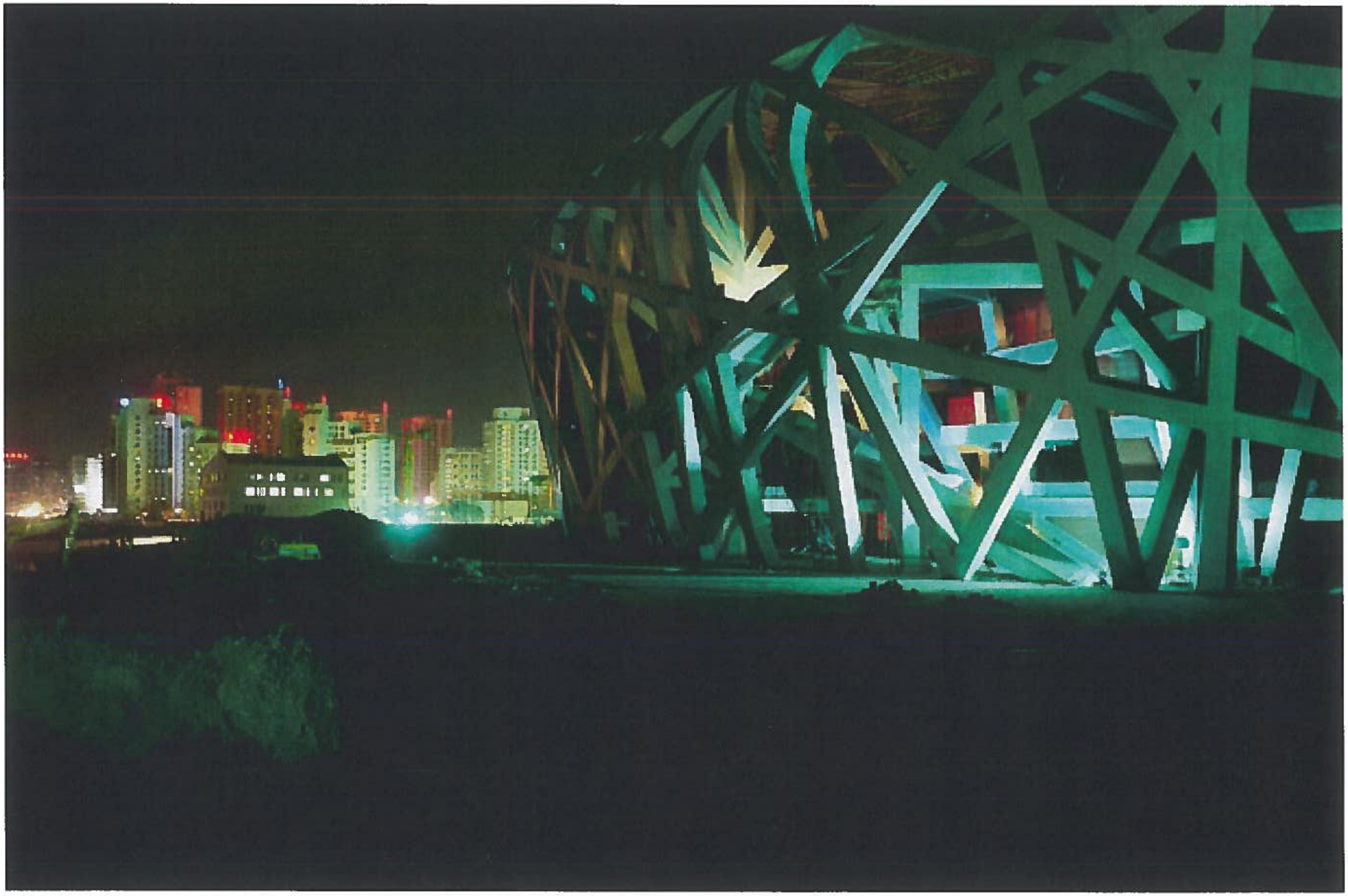
National Stadium, Beijing, July-Sept. 2008



Monitoring of broadband absorbers

- Freon 125 (C_2HF_5)
  - Refrigerant (leak detection)
  - Safe simulant for toxic chemicals, e.g. chemical warfare agents
- Acetone (CH_3COCH_3)
  - Recognized biomarker for diabetes
- TATP, Acetone Peroxide ($C_6H_{12}O_4$)
  - Highly Explosive

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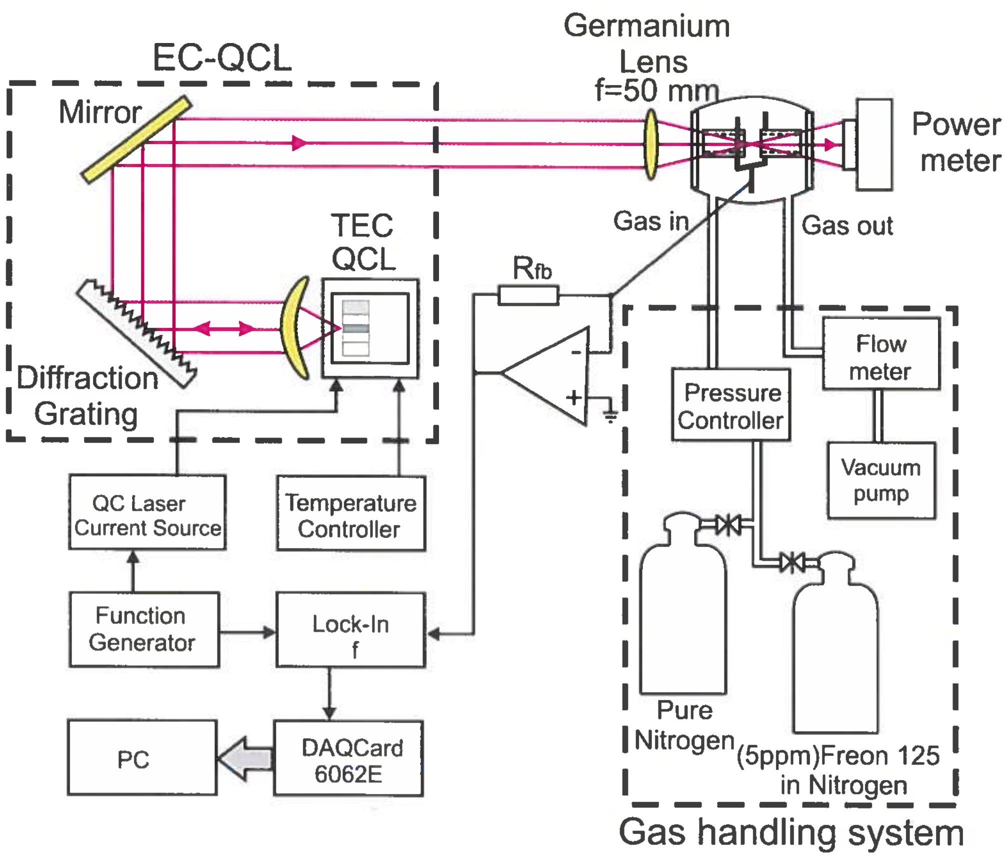
8.4 μm RT CW EC-QCL based QEPAS trace gas sensor



QEPAS Characteristics:

- High sensitivity (ppm to ppb)
- Excellent dynamic range
- Immune to environmental noise
- Ultra-small sample volume (< 1 mm^3)
- Sensitivity is limited by the fundamental thermal TF noise
- Compact, rugged and low cost
- Potential for trace gas sensor networks

R. Lewicki, G. Wysocki, A.A. Kosterev, F. K. Tittel "QEPAS based detection of broadband absorbing molecules using a widely tunable, cw quantum cascade laser at 8.5 μm", Optics Express, 7357-7366 (2007)

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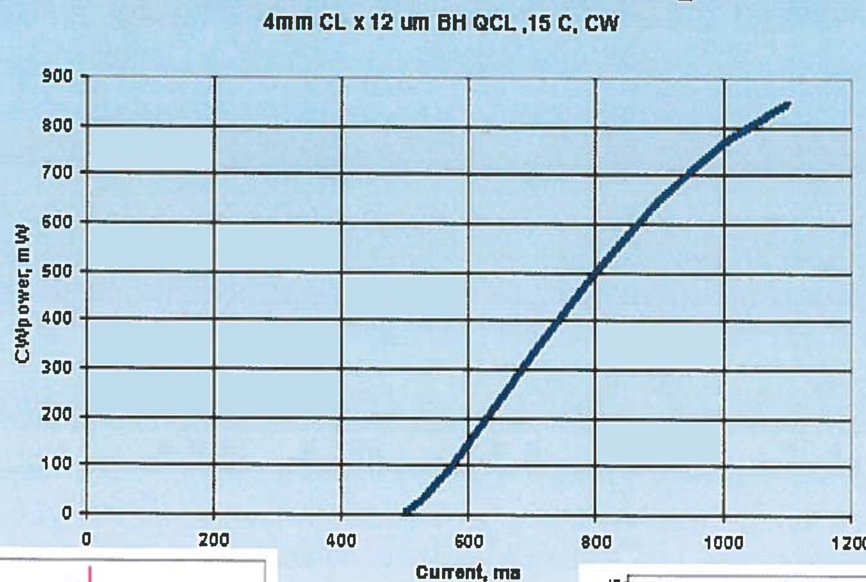
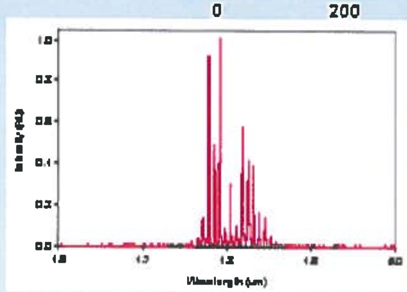
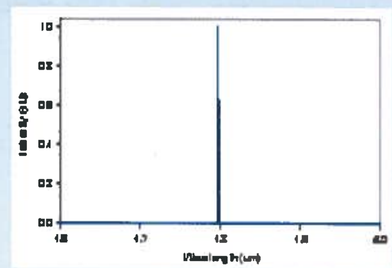
Next steps

Medium power : narrow linewidth : high volume packaging



Fabry-Perot





EC-QCL

- Single ended output powers > 0.85W at wavelengths of 4.5-5.5um and T > 15C
- Long lifetime, high reliability, robust packaging with high wavelength stability
- Linewidths < 0.01cm-1 using external cavity
- Manufacturable wavelength setting to 1:1000 Independent of temperature

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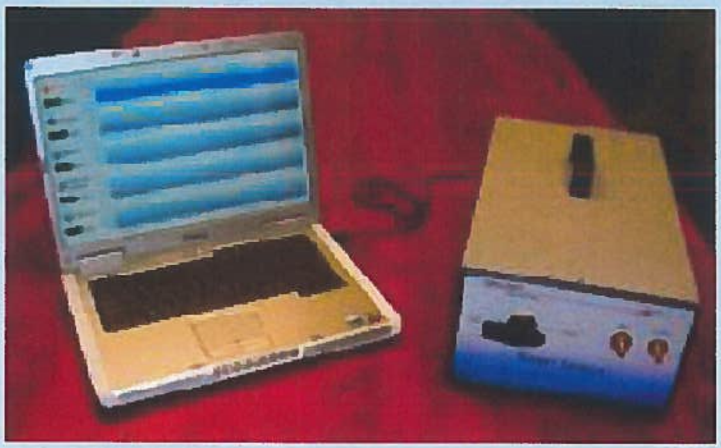
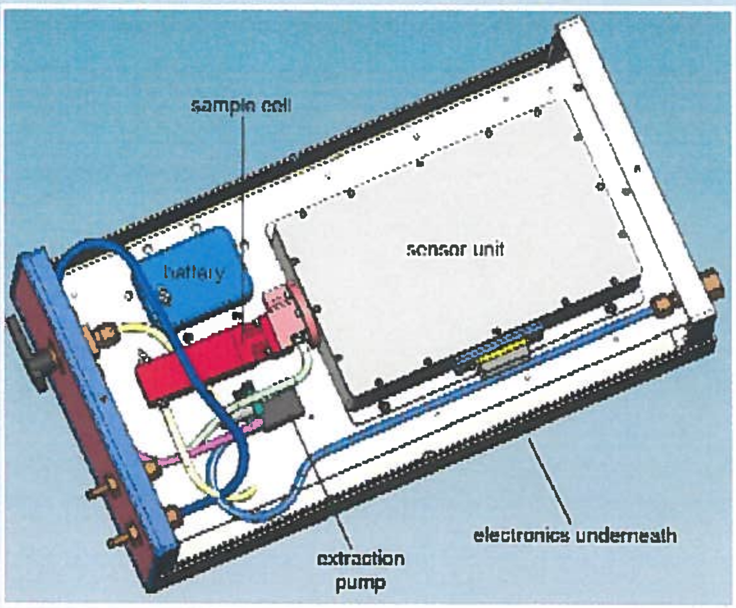
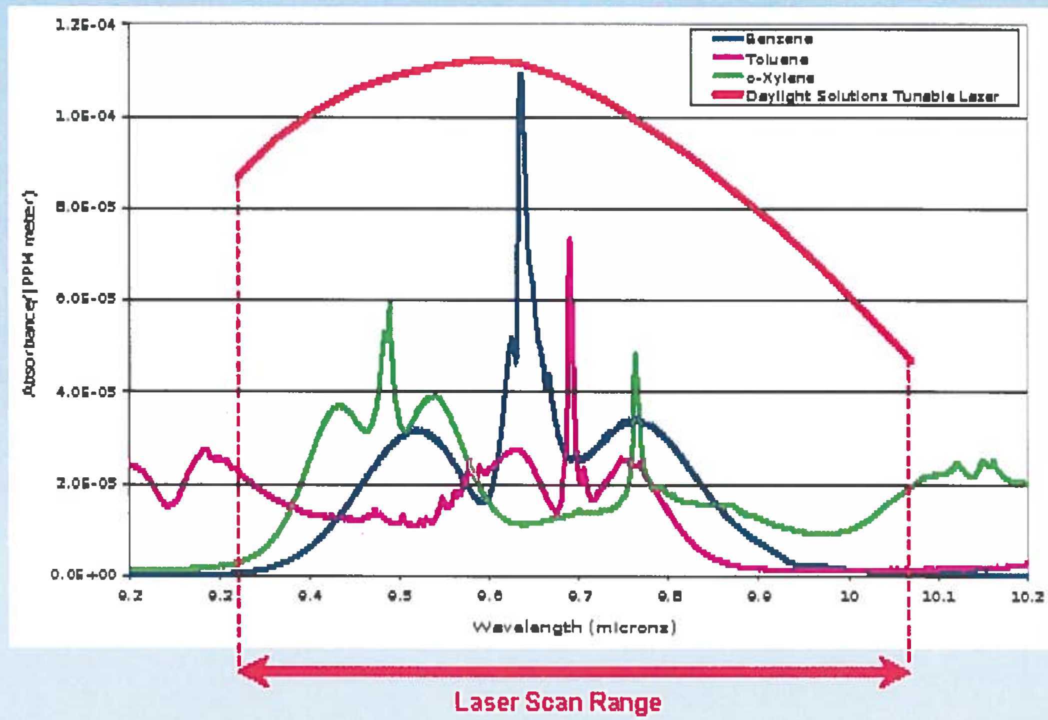
Applications

Integrated molecular detection subsystems

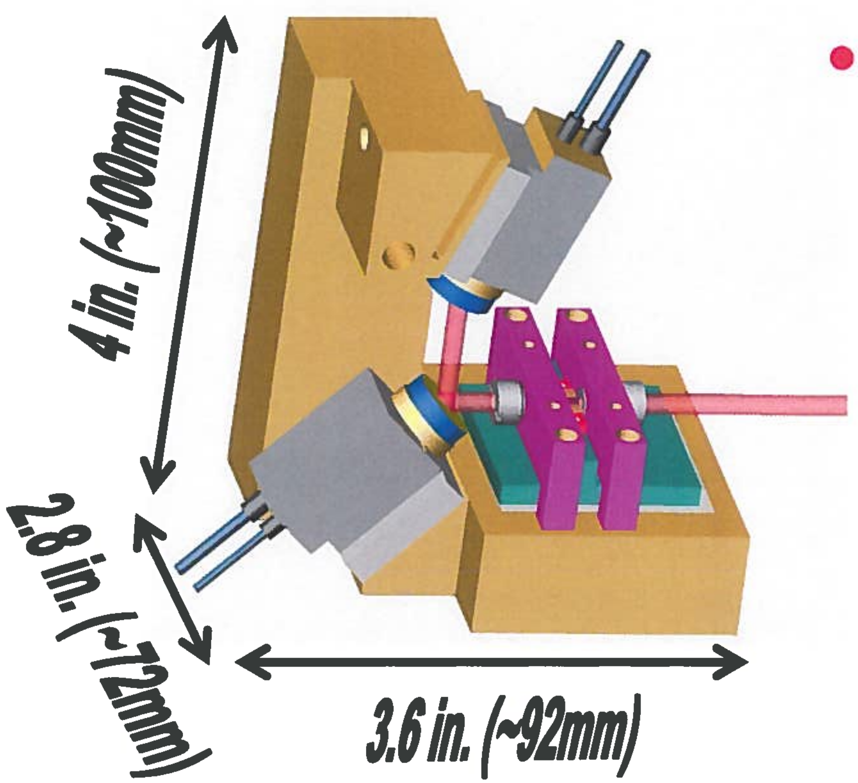






- Fully integrated microprocessor for spectral de-convolution
- Broad tuning ranges
- Multi-species identification

New design of fast broadly tunable EC-QCLs (2009)



- New optical configuration
  Folded cavity (configuration #1)
- Fast tuning capabilities:
  - Coarse Broadband Scanning
    (~*55 cm*$^{-1}$ @5μm) ***up to 5 KHz***
    (compared to available technologies ***<10Hz****)*
  - High resolution mode-hop free tuning (~*3.2 cm*$^{-1}$ @5μm)
    up to 5 KHz
    (compared to available technology ***100-200 Hz****)*

Patent pending, G. Wysocki, F. K. Tittel, 2007

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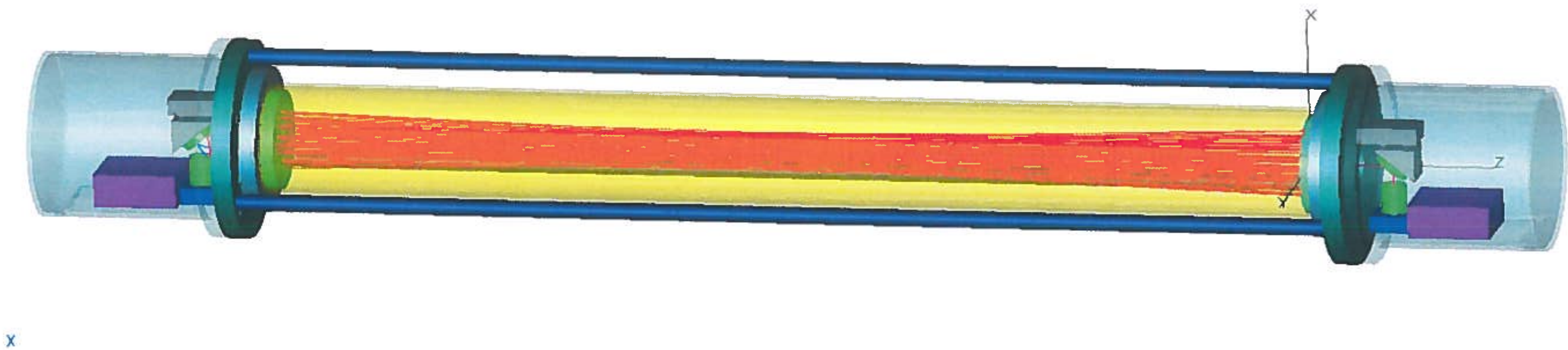
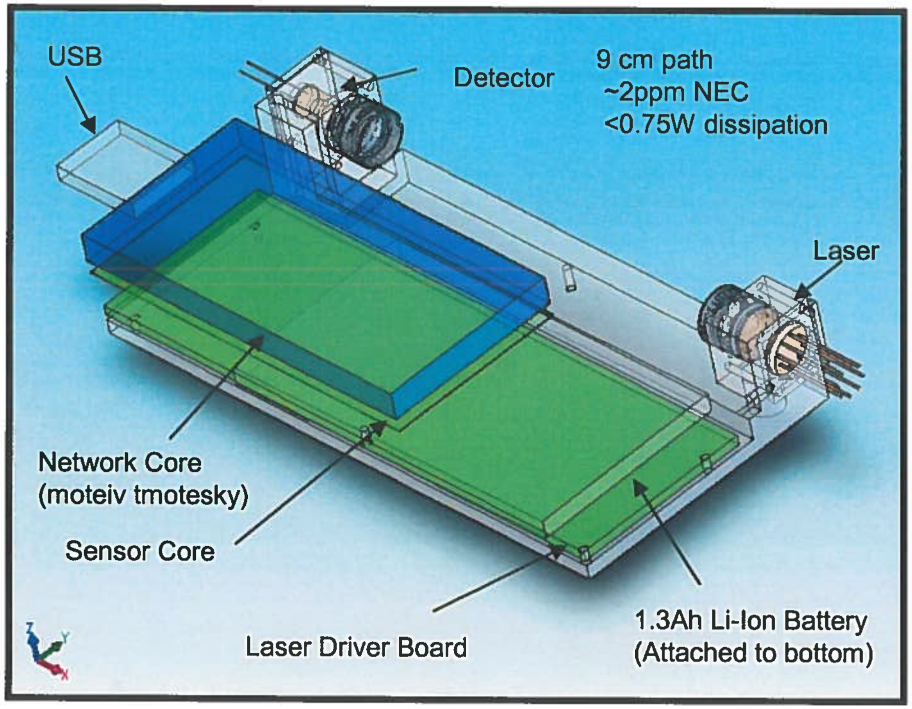
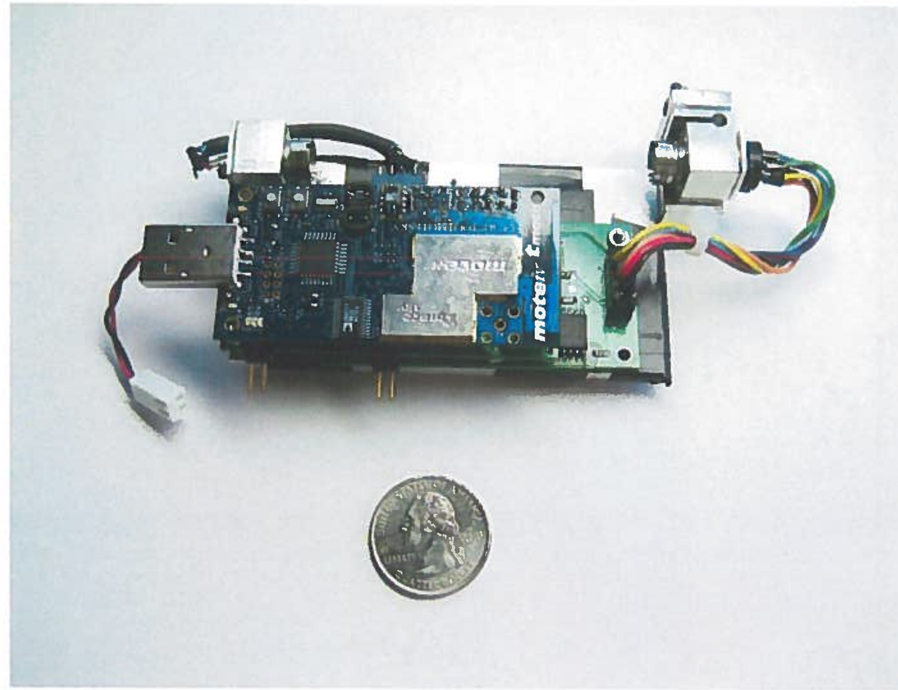
Conceptual Design of Ultra-compact QCL Trace Gas Sensor



Aerodyne, Inc, Barry McManus et al , 2008

PHOTONS v4.0 - 2.7μm CO2 Direct Absorption Based Sensor





- Small size
- Relatively low cost
- High efficiency switching power supplies
- PWM Peltier cooler driver
- 0.2W control system power consumption
- Detection sensitivity of CO_2 1 ppm with 1sec. lock-in time constant
- Over 100x improvement in sensitivity is possible @ 4.2μm

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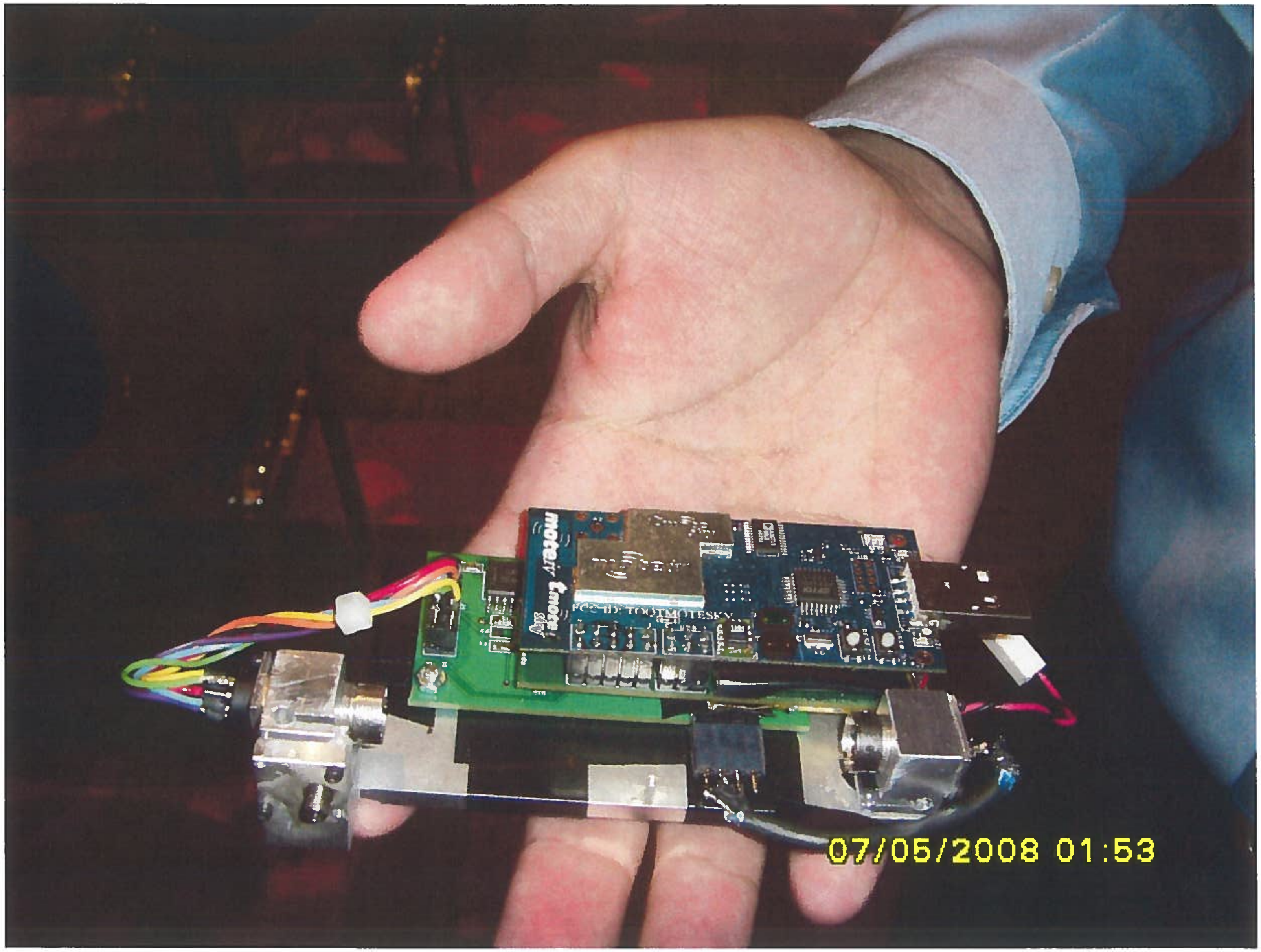
Ultra-compact Diode Laser based Trace Gas Sensor



Future Directions of Mid-IR Sensor Technology

- Major QCL improvements in areas such as wall plug efficiency, temperature performance, beam shape and price reduction
- Improvements of the existing sensing technologies using novel, thermoelectrically cooled, cw, high power, and broadly wavelength tunable mid-IR interband and intersubband quantum cascade lasers.
- New applications enabled by novel broadly wavelength tunable quantum cascade lasers (especially sensitive concentration measurements of broadband absorbers, <u>in particular VOCs and HCs)</u>
- Development of optically multiplexed gas sensor networks based on LAS or QEPAS
- Wearable sensors for medical & biomedical diagnostics (NO, CO, COS, CO_2, NH_3, C_2H_4)

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