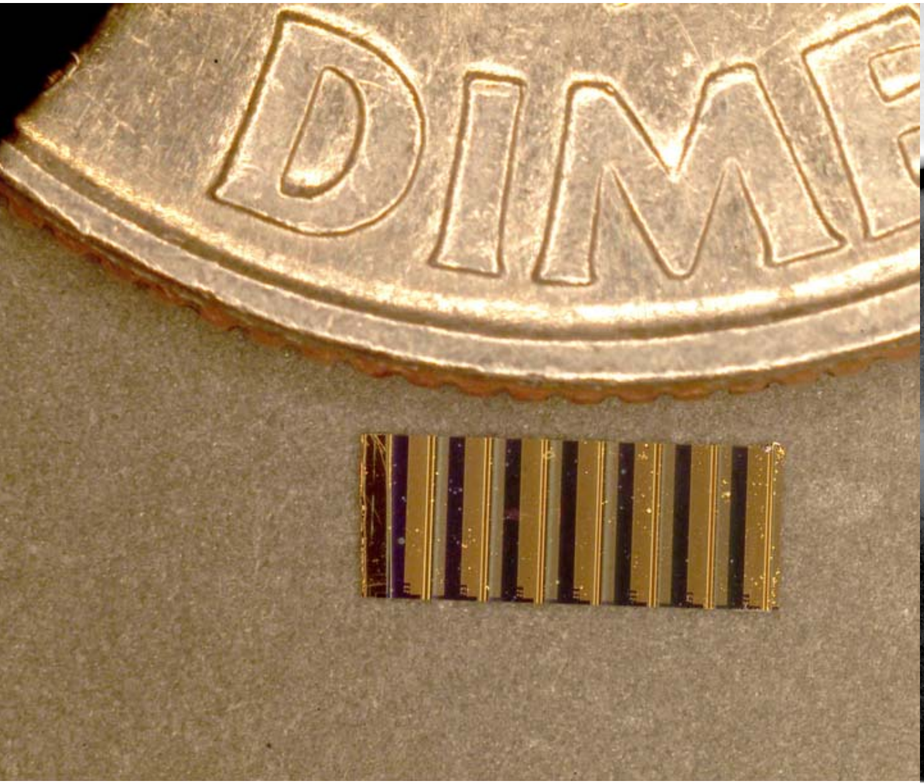
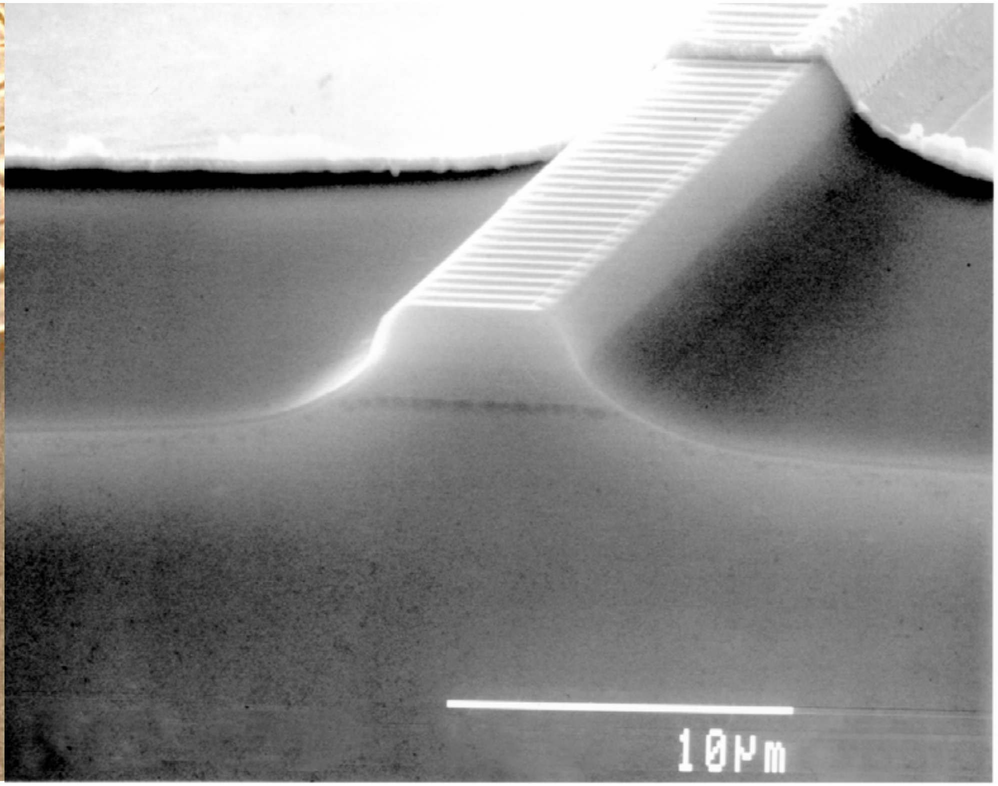
Development of mid-IR lasers for Laser Remote Sensing

Alexander Soibel, Kamjou Mansour, Gary Spiers and Siamak Forouhar

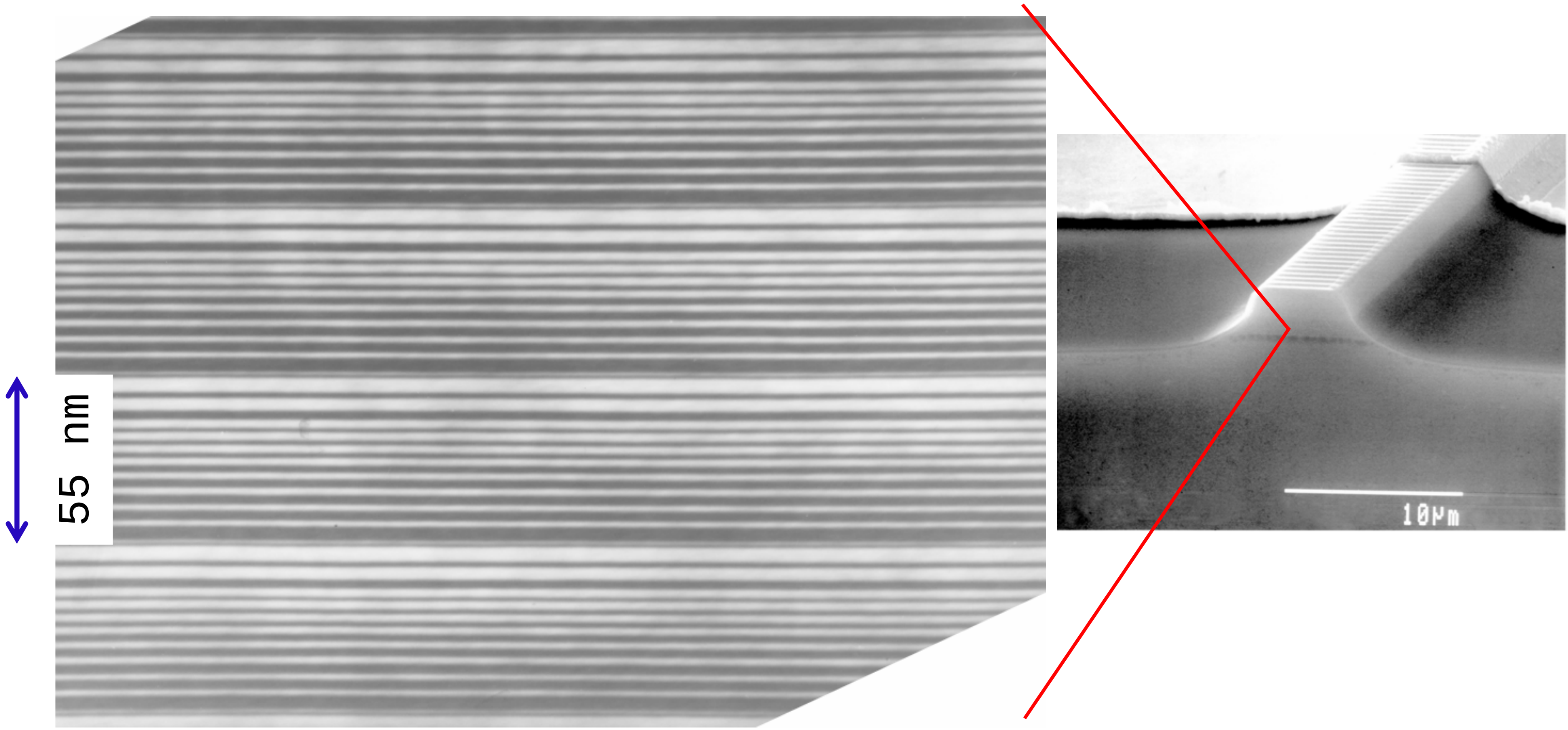
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr, Pasadena, CA 91109

The QC-laser is a semiconductor injection laser …





TEM / SEM image

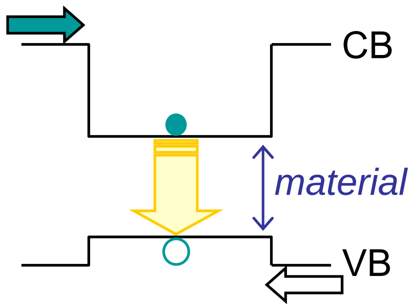


Intersubband Quantum Cascade Lasers

Intersubband QCL are semiconductor lasers but they are **very different** from the conventional semiconductor lasers

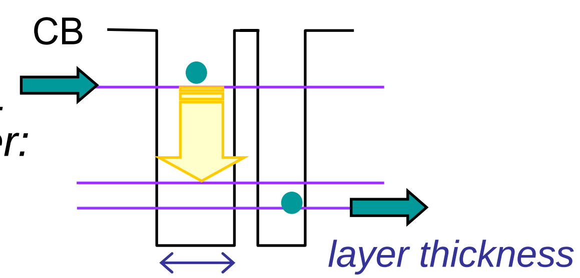
- **Quantum cascade lasers (QCL) are based** on the optical transition between the energy states in the conduction band of III-V semiconductors rather than transition between the conduction and valence bands as in conventional diode laser

diode laser:



Conventional semiconductor laser:
Light is generated across material's band-gap, at electron transition between the *conduction* and *valence* bands

QC-laser:

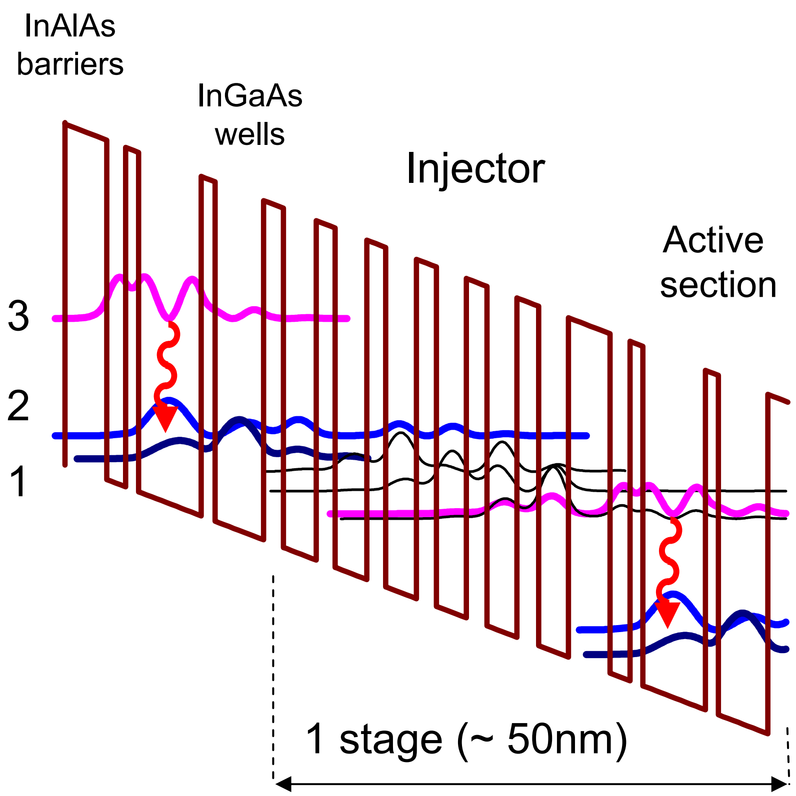


QC-laser:
Light is generated across designed energy gap, at electrons transition between the *engineered quantum states in the conduction band*

QC Laser Design

Energy levels of the electrons in QCL and the resulting operational characteristics of the lasers such as wavelength are engineered by the choice of semiconductor material thickness

- QCL consists of multiple Quantum Wells (QW's) under external applied electric field
- Laser wavelength is set by the thicknesses of the QW
- Can be set at any wavelength in mid-IR **(4-30 mm)** and in far-IR **1.5-5 THz** (60-200 mm)
- Optical radiation is emitted by electron transition between levels 3 and 2
- 1 - 100 active regions/injectors
  - (typically ~ 30)
- layer thicknesses designed to provide population inversion $t_{32} >> t_2$
- designed for tunneling transport

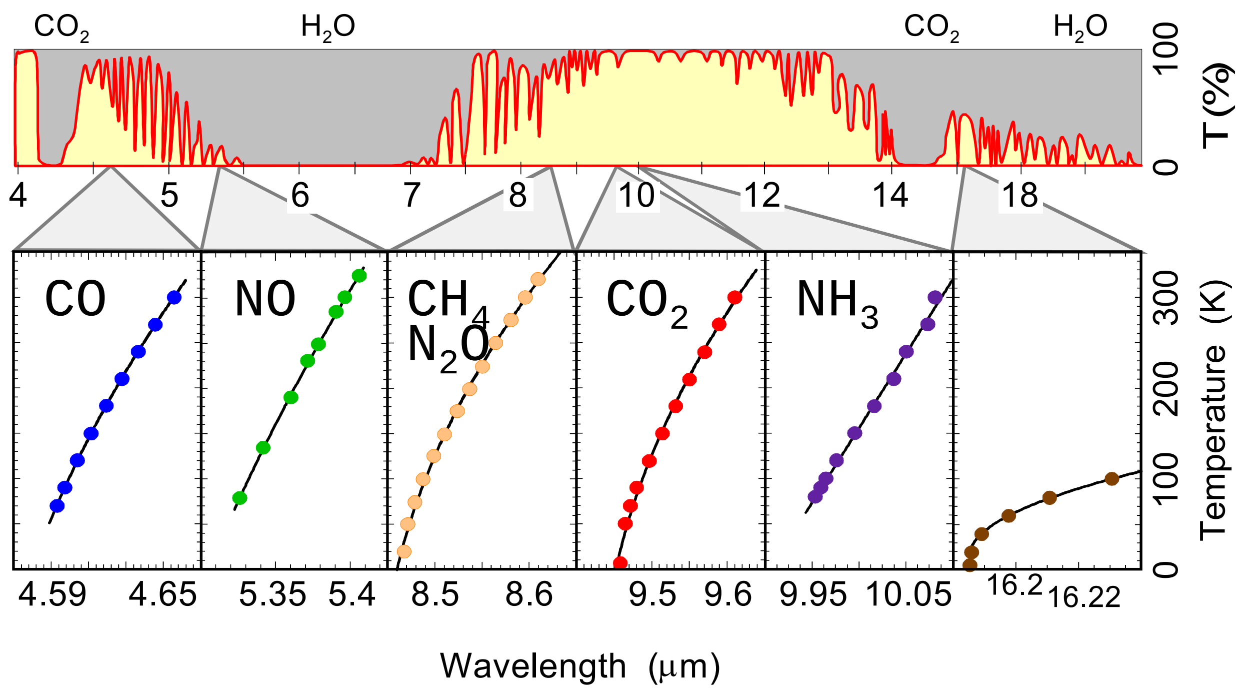


•Band structure of 8 micron QC laser

Mid-infrared trace-gas sensing applications with DFB QC lasers

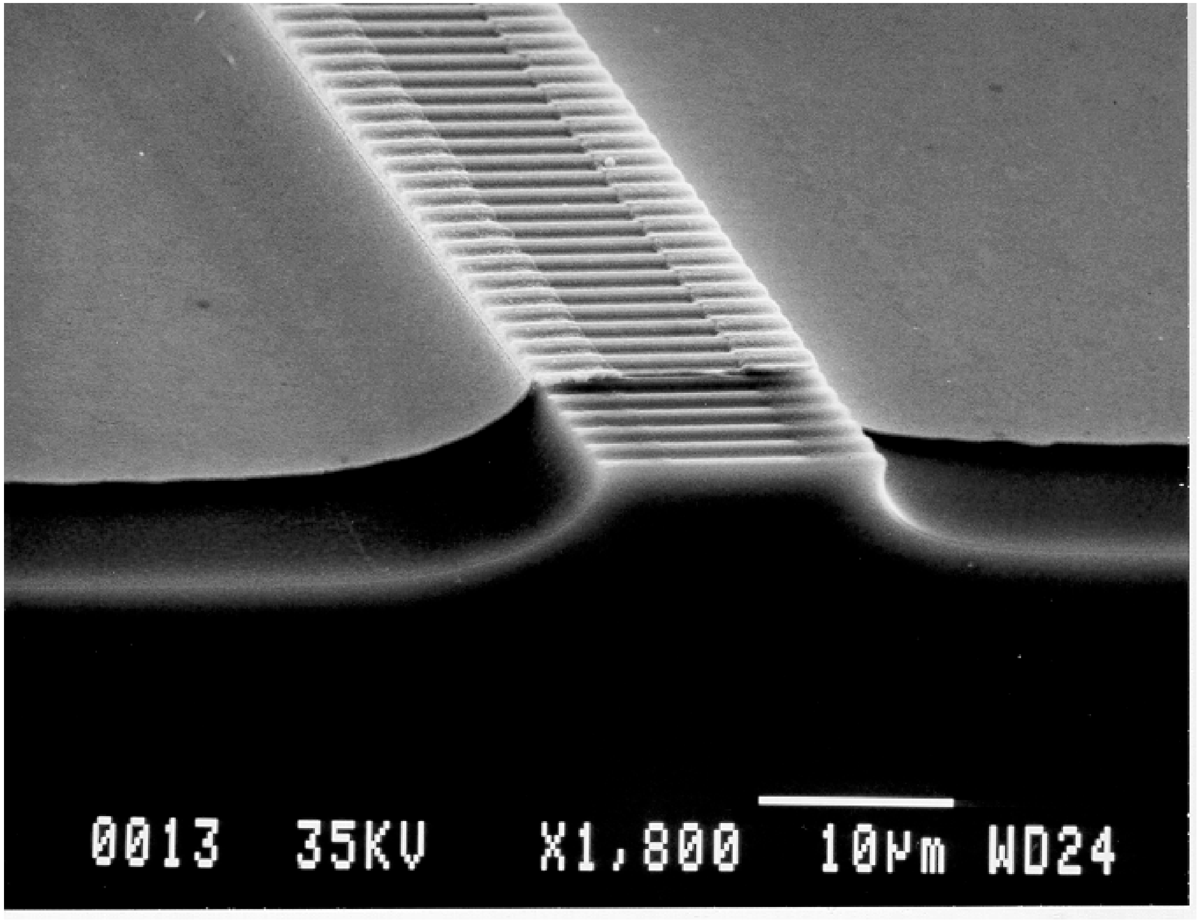
Intersubband QCL can be employed in many applications

- Chemical sensing and detection
- Remote sensing (aerosol distributions for example)
- Nonlinear Spectroscopy (multiphoton spectroscopy)
- Wireless telecommunication (during bad weather condition, dust, etc)
- Lidar and Ladar
- Mid-IR imaging (as optical source)
- Military application



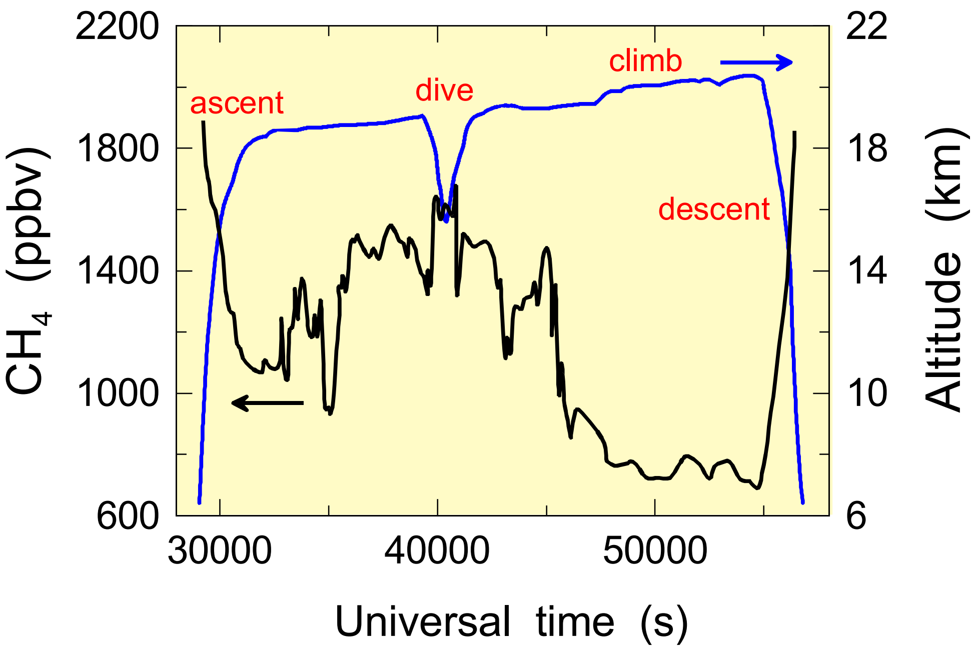
Absorption spectra of several gases in mid-IR spectral region

QC + Bragg grating = QC-DFB laser



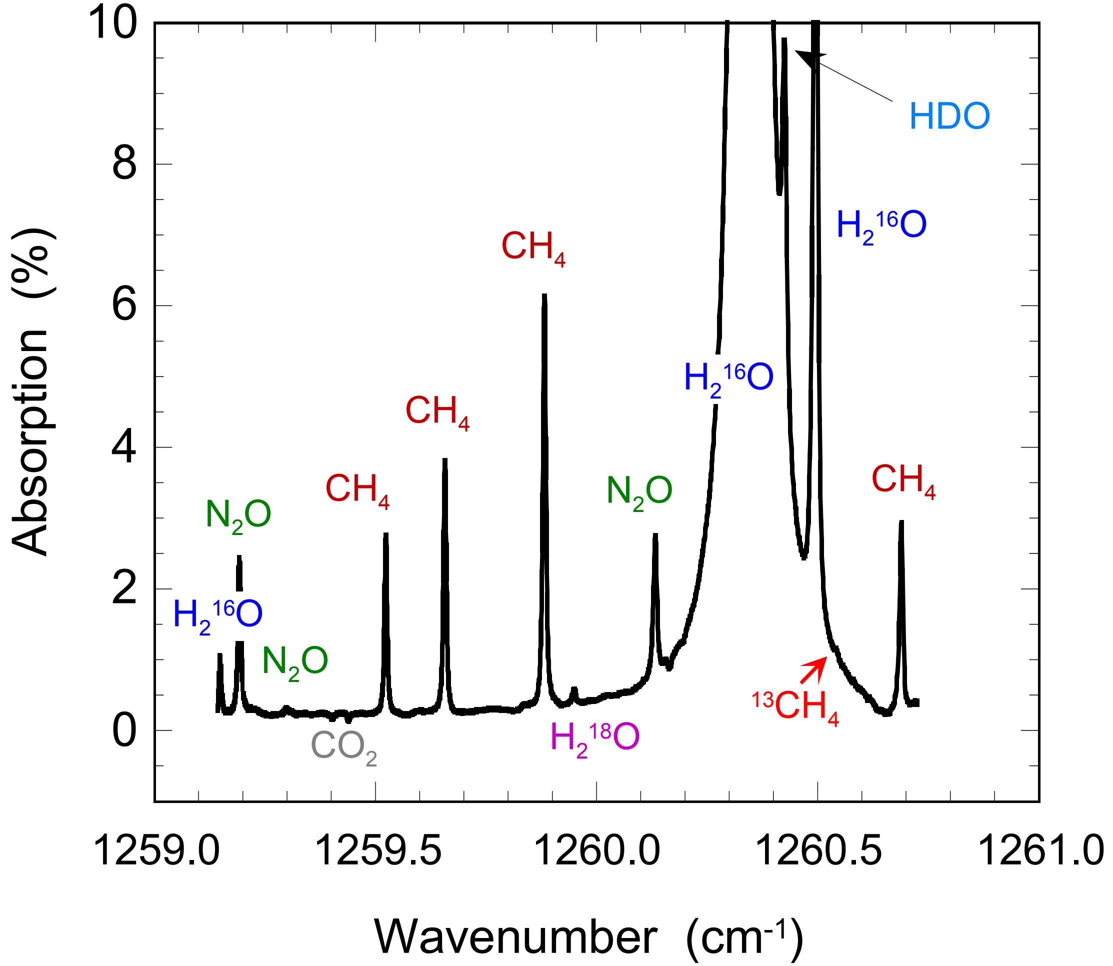
High sensitivity detection of stratospheric CH_4 and N_2O by wavelength modulation spectroscopy

Chris Webster et al.
NASA, JPL, and Caltech
Bell Labs, Lucent Technologies



- stratosphere over the USA and Canada, Russia and
- reliable operation and detection over 23 days, 8 h/day - repeatedly
- detection limit: ~ 2ppbv

Detection of multiple trace gas species w/single QC-DFB laser

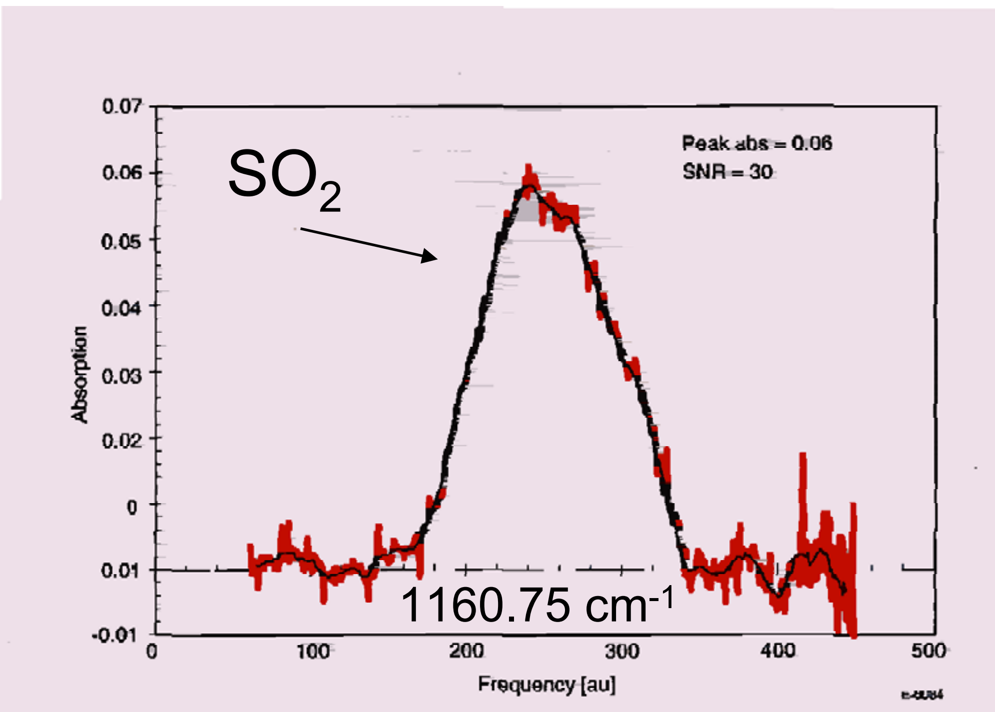


Claire Gmachl and
Federico Capasso
Bell Labs, Lucent Technologies

Anatoliy Kosterev and
Frank Tittel
Rice University, TX

QC-laser operated in cw mode at 77 K; gas sample in 100-m multipass cell

Detection of SO_x w/pulsed QC-DFB lasers



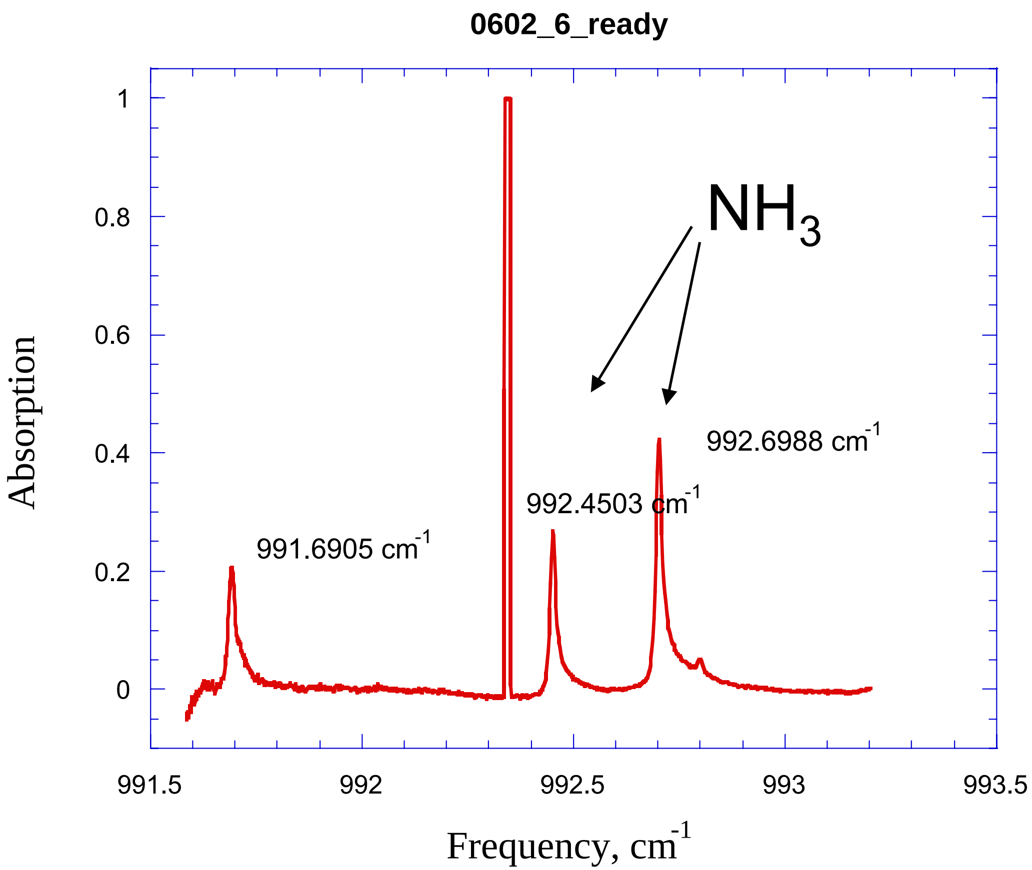
- Mission:

- SO_x emission from Jet engine exhaust;
- engine optimization and environmental impact,

Claire Gmachl and Federico Capasso
Bell Labs, Lucent Technologies

Mark Allen et al.
Physical Sciences Inc., MA

Detection of NH_3 w/pulsed QC-DFB lasers



- Mission:

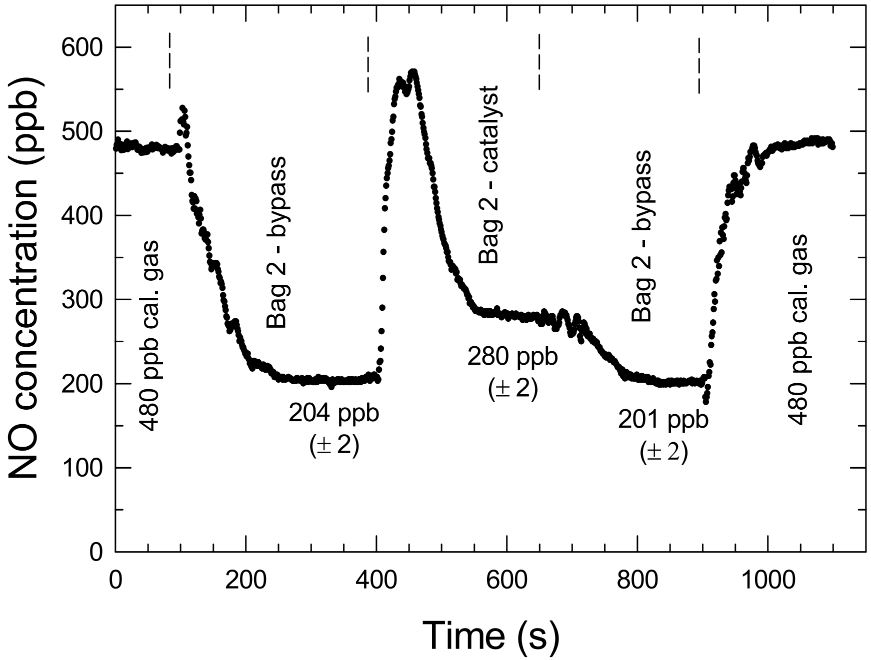
  Control of the environment on the international space station;

  NASA testbed, Houston, TX

Claire Gmachl and Federico Capasso
Bell Labs, Lucent Technologies

collaboration with
Anatoliy Kosterev and Frank Tittel Rice University, TX

W. H. Weber et al. "Using a Wavelength-Modulated Quantum Cascade Laser to Measure ***NO*** Concentrations in the Parts-per-Billion Range for Vehicle Emissions Certification" *Appl. Spectr.* **56** (6/2002)



Application:

NO concentrations at sub-ppm in vehicle exhaust certification of future ultra-low emission vehicles

Laser & Method:

QC-DFB cw at ~ 100 K, frequency modulated locked to the center of NO at ~ 1921 cm^{-1}

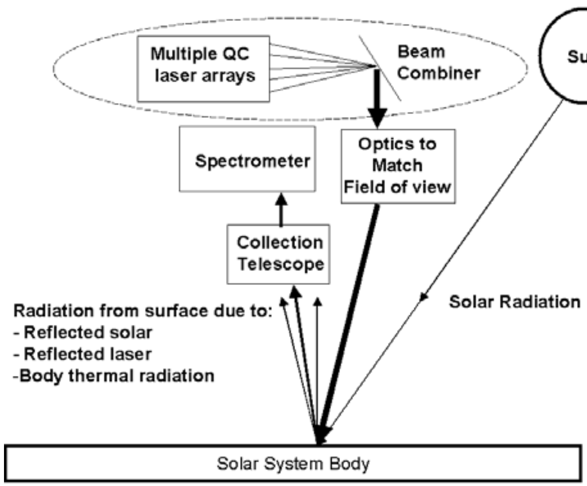
100 m path length multipass Herriott-type

Results:

demonstrated detection of NO in the few ppb range in diluted exhaust-gas bag samples collected in the vehicle certification process.

Application for High Capability Instruments

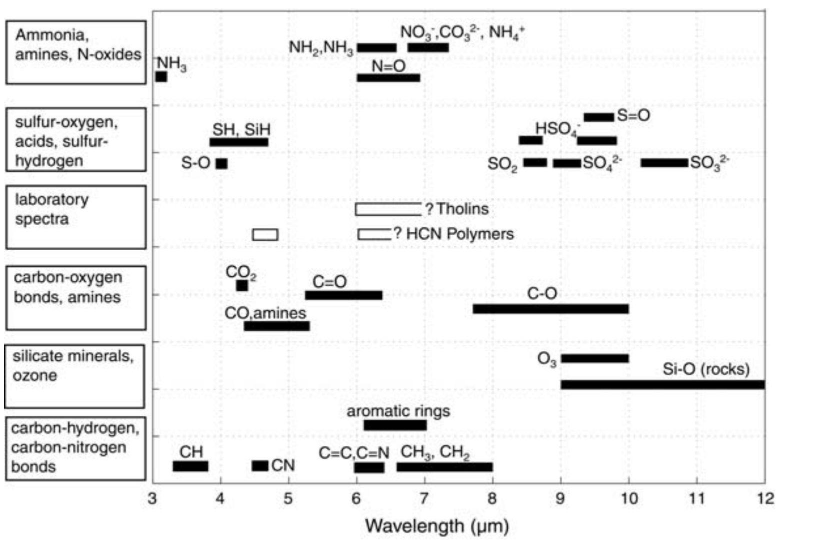
We build mid-infrared lasers that for the first time demonstrate a capability to act as the illumination source for conducting active mid-IR reflectance spectroscopy of solid-surfaced objects in the outer Solar System.



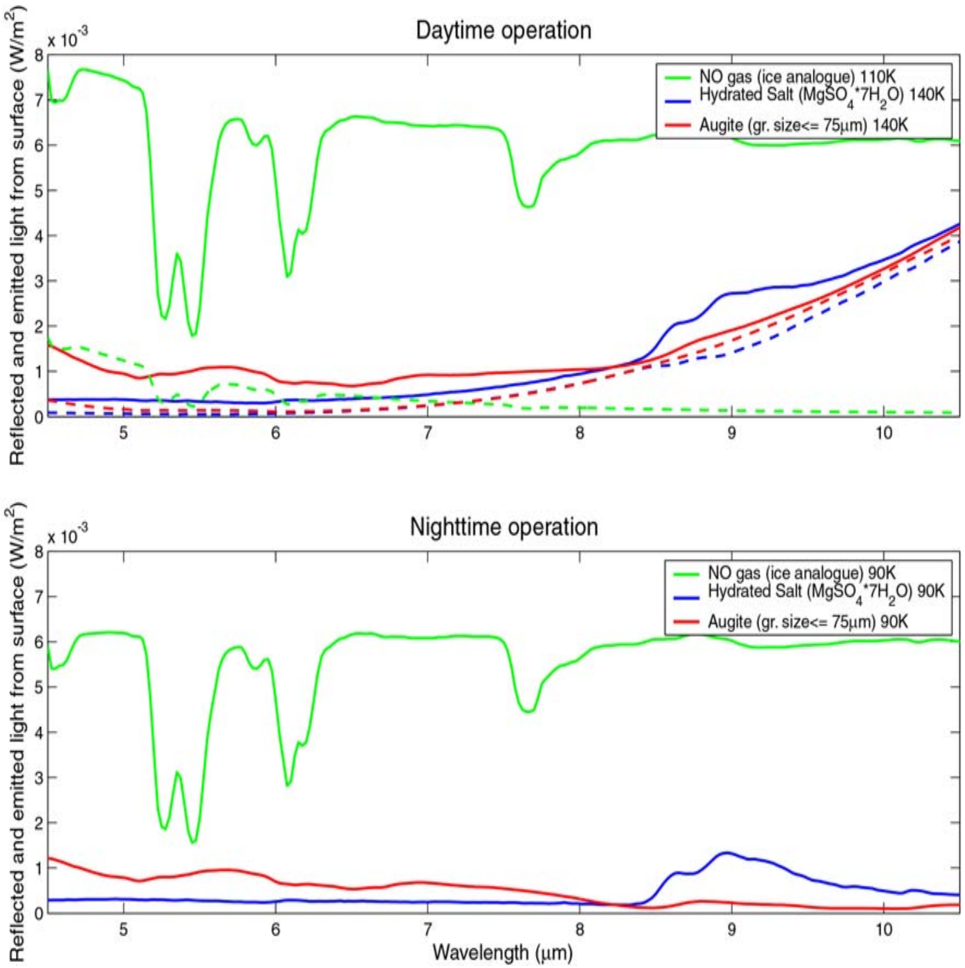
- Could be used from on-orbit, aircraft or rover
- Supplements/replaces solar illumination

- Wavelength availability has been the Achilles' heel of laser sensing. The use of QC lasers enables the entire IR region (4- 12 microns) to be covered and overcomes this limitation

- Spectral observations in this region, made possible with active illumination, will better enable one to determine the silicate and oxide mineralogy, ice composition, and the composition of organic materials on outer solar system surfaces by being able to observe fundamental absorption bands.



Laser Requirements – JIMO class instrument



Estimated radiance for possible Galilean Satellite surface materials illuminated with a 2 watt, 25 nm bandpass CW laser (at each wavelength) from a 100 km orbit. Dashed lines are radiance without laser illumination.

Wavelength (μm)	4.5 – 10
No. of wavelengths	51
Optical power/wavelength (W)	>2
No. of lasers/wavelength	~10+
Optical power/laser (W)	~0.2
Laser bandwidth (nm)	< 25
Total optical power (W)	> 102
Est. electrical power (kW)	~ 1+

Graphic courtesy of Karl Hibbets, PSI

Free-space transmission in the mid-infrared

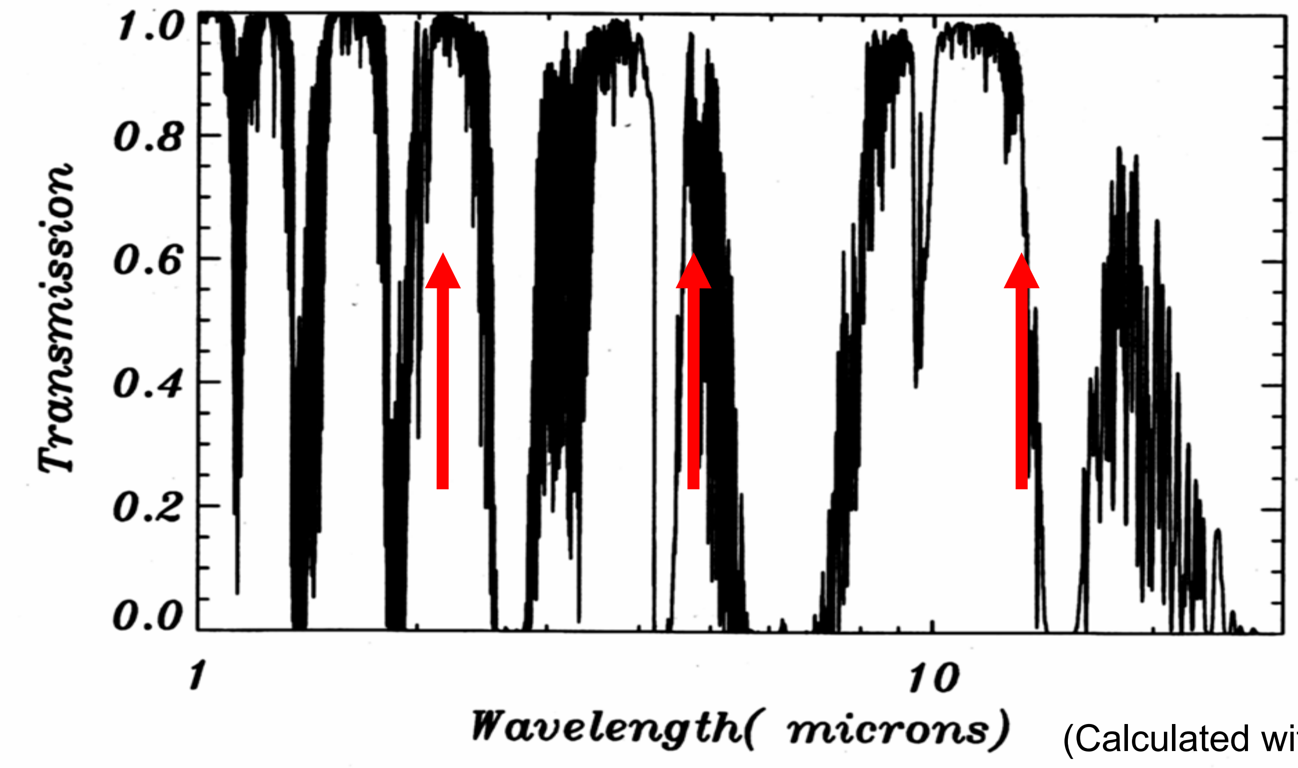
Long range transmission through Atmosphere in mid-IR

Range and quality of a free space optical (FSO) transmission link limited by extinction losses:

- Losses due to transmission
  - Absorption
  - Scattering
  - Scintillation
- Losses due to system
  - Beam spreading
  - Transmitter & Receiver Losses

Atmospheric windows

Molecular absorption at sea level:
→ three “equal” transparent windows



(Calculated with Hitran96)

Rayleigh scattering   particle r < wavelength λ

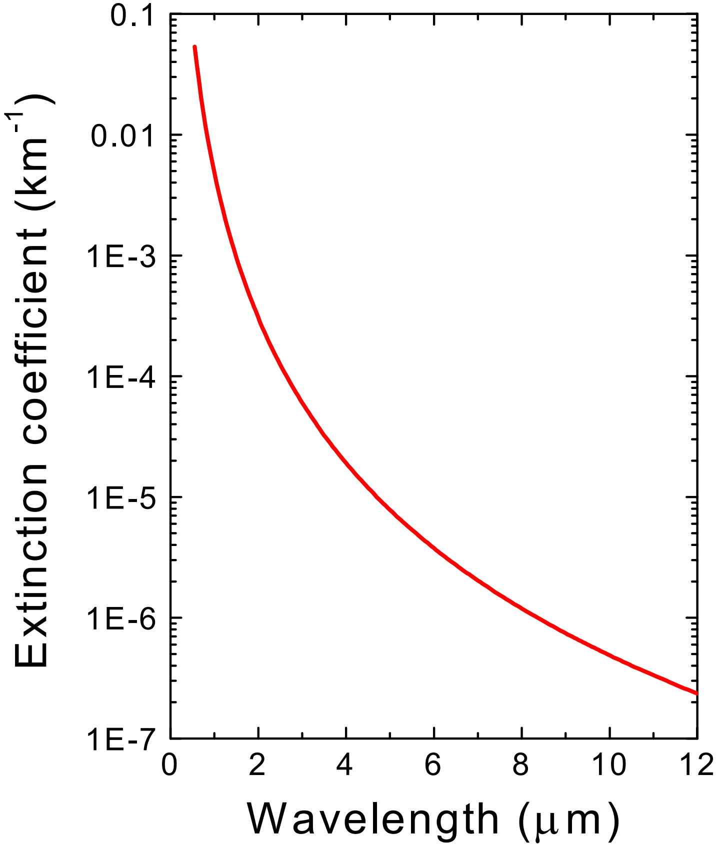
Extinction coefficient has strong λ^{-4}-dependence

- favors longer wavelengths with less extinction.

Comparison to 1.5µm to

5µm : **~ 100x lower losses**

8µm : **~ 1000x lower losses**

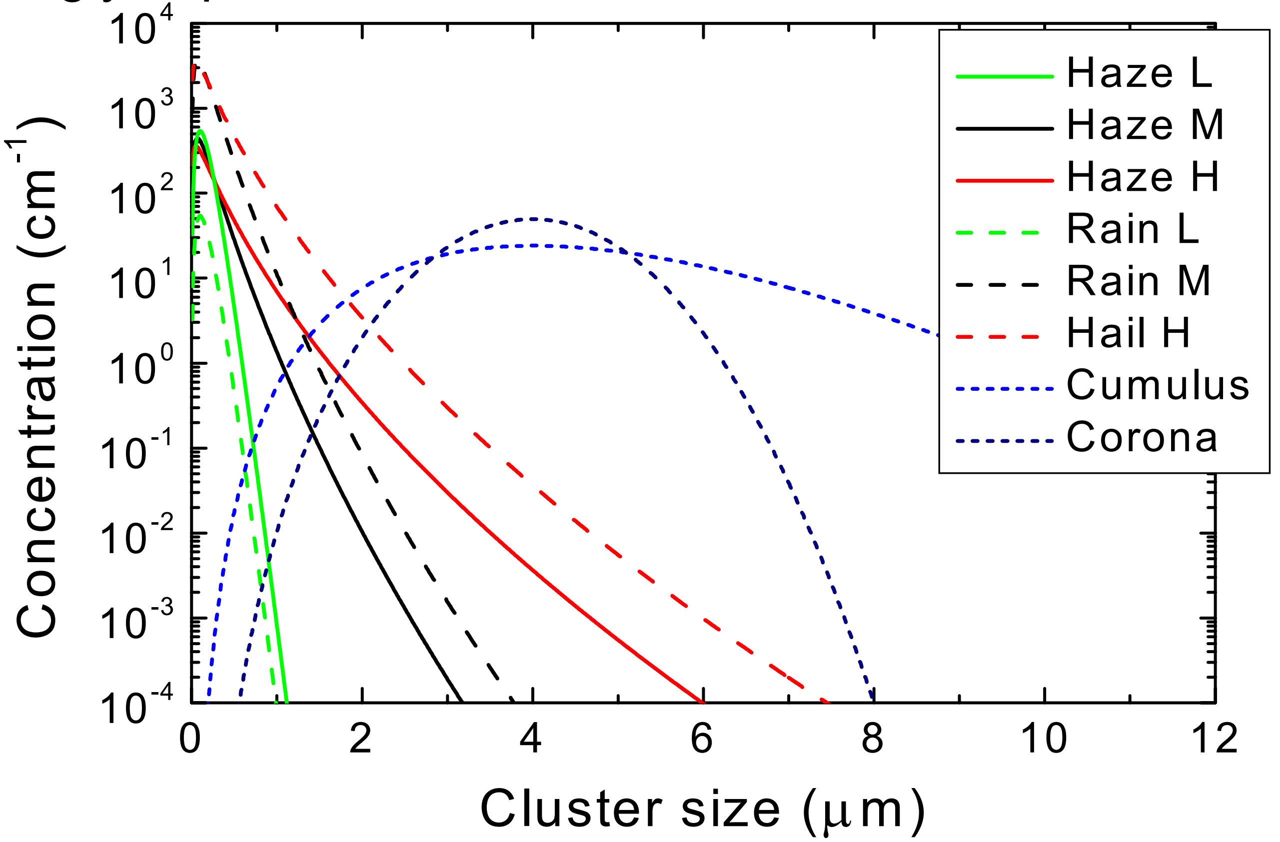


Mie scattering I

particle ***r*** ~ wavelength λ

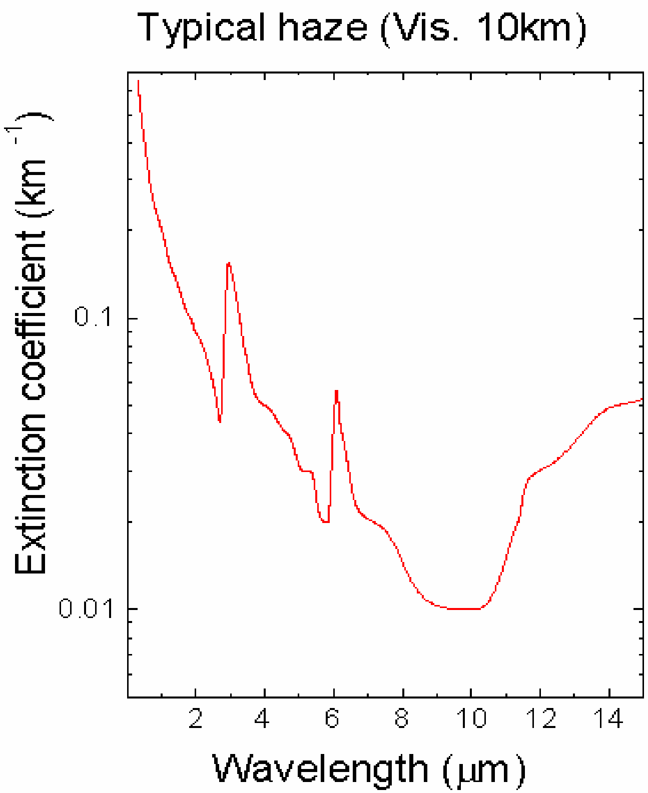
Concentration of cluster size determines wavelength dependence

- Strongly dependent from weather and environment condition



Mie scattering II

particle ***r*** ~ wavelength λ



Typical example for integrated extinction coefficient in haze (10 km vis)*

Comparison to 1.5μm to

5μm : **~ 3x lower losses**

8μm : **~ 10x lower losses**

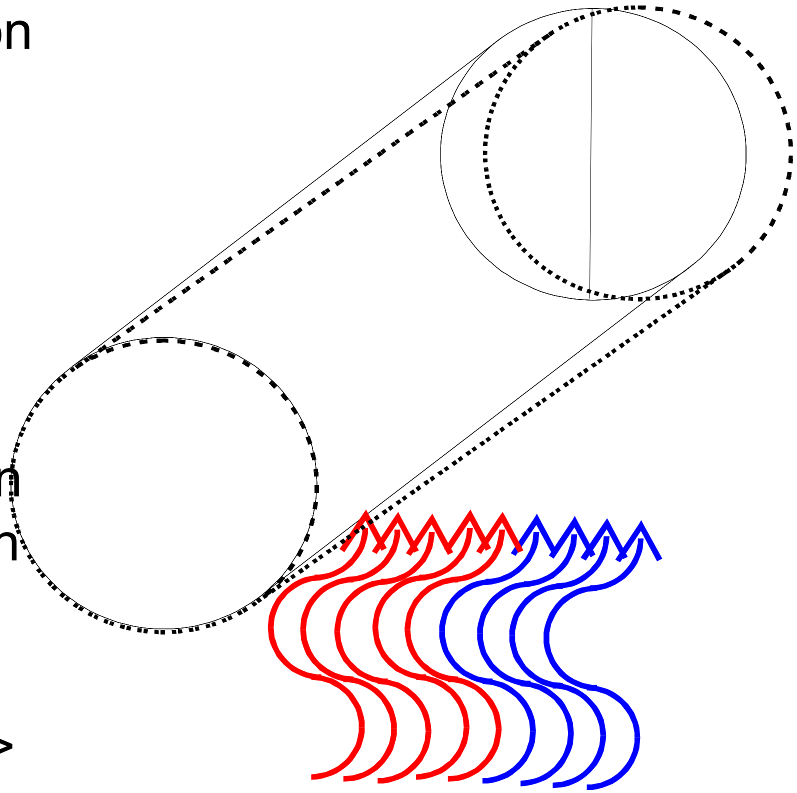
V.E. Zuev in "Laser Monitoring ..", Springer 1976

Scintillation effects

Fluctuation in the index of refraction over beam profile

- Causes:
  - beam wander
  - wavefront distortion

- Impact of given index fluctuation diminishes at longer wavelength
- Errors are typically non stochastic → hard to correct (Error burst with down times >> 1ms)



Temperature profile

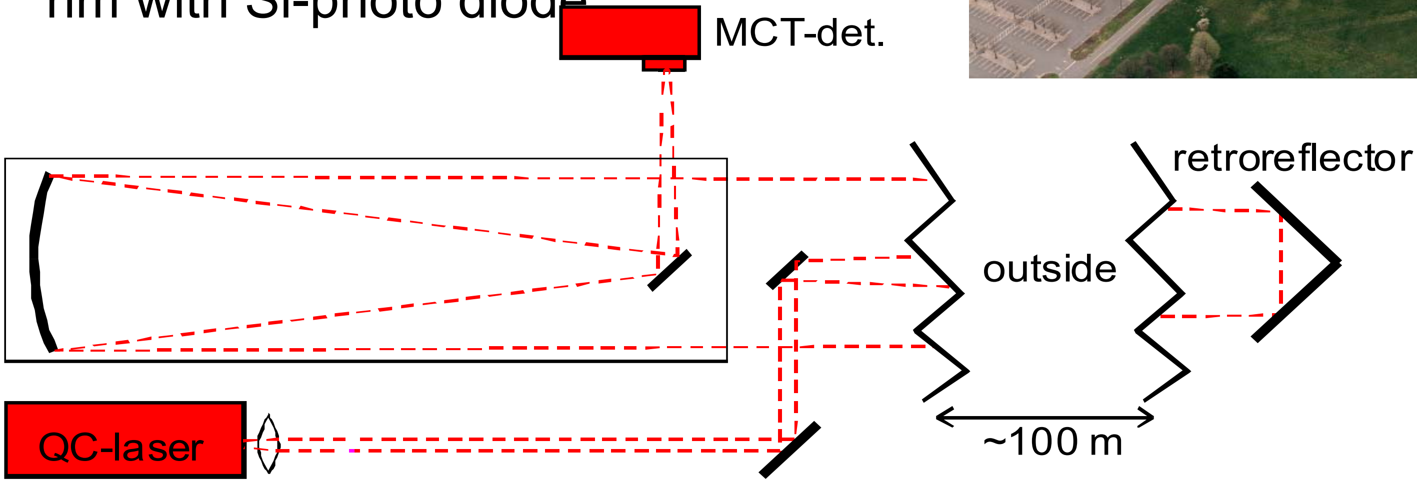
Advantages / Challenges of long wavelengths FSO

- Atmospheric transmission properties comparison 5-10μm to 1.5μm wavelength
  - Absorption — 1 (equal)
  - Rayleigh Scattering — 100 - 1000 x lower losses
  - Mie Scattering — 10 x lower losses
  - Scintillation — ~ 10 x lower losses
- Longer wavelength of QC-lasers allows more stable and reliable connection – especially in low-visibility areas

- maximum QC-lasers cw operating temperature ~ 200 K (rising ...,
  but not good enough yet for cheap, stand alone system)

QC laser link – optical setup

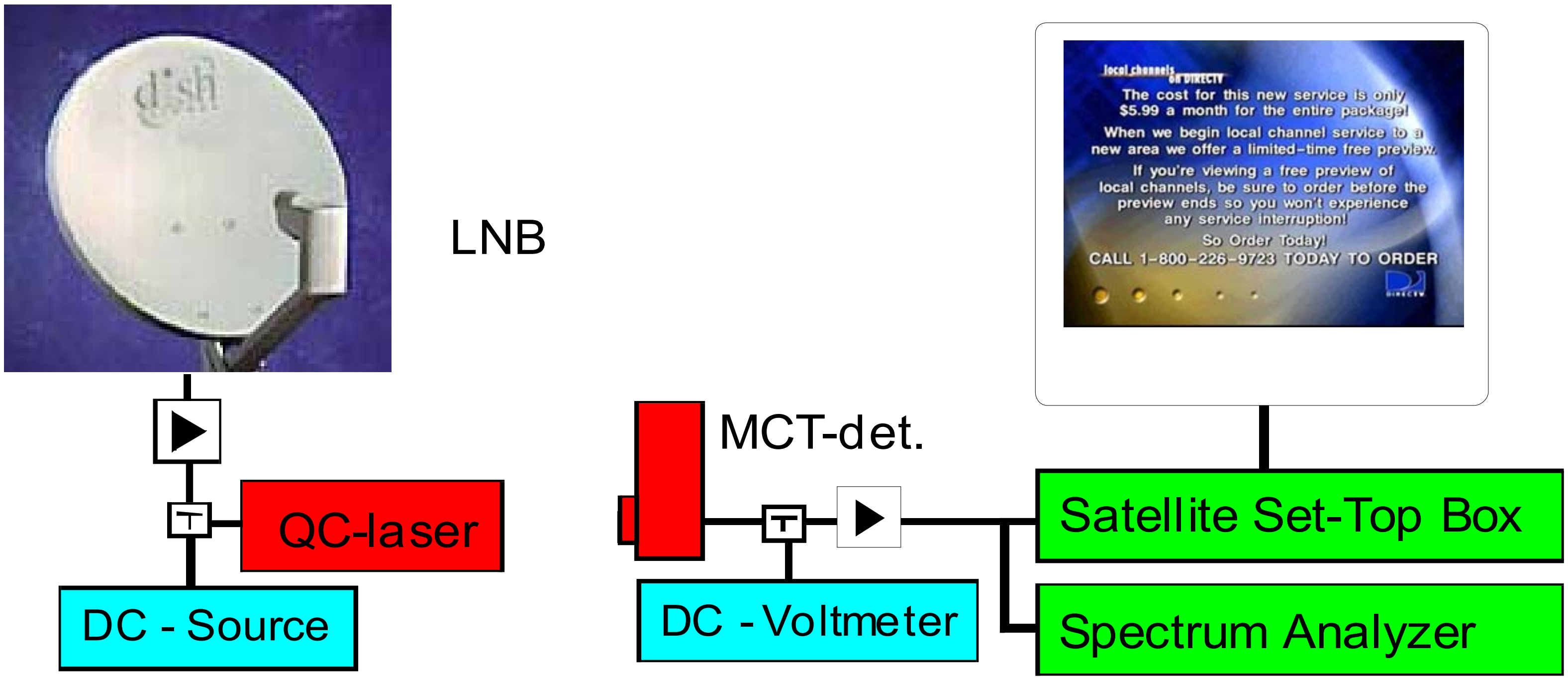
- Free space link over 200 m
- Laser output: 7 mW, λ = 8.1 μm
- Telescope: f/9, 76 mm aperture
- 10 dB optical losses during beam path
- Additional NIR link, 10 mW, λ = 850 nm with Si-photo diode



R. Martini, et. al., Stevens Institute of Technology and Bell Labs, Lucent Technologies

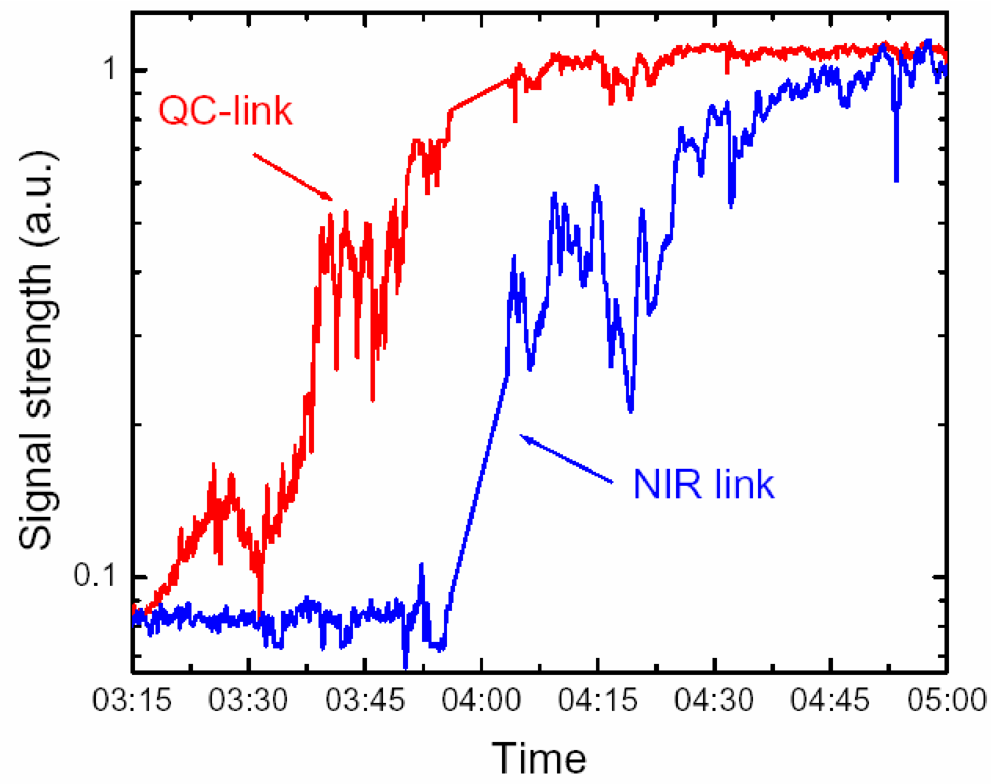
QC laser link - electrical setup

- Digital encoded satellite TV data with QPSK encoding
- Data distributed over 750 MHz – 1.45 GHz

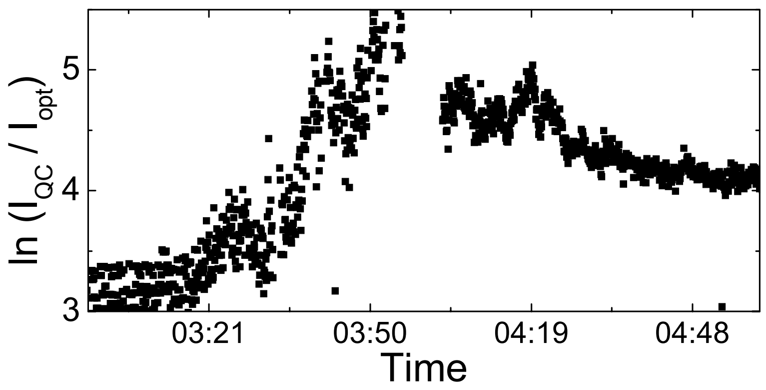


- Monitoring of signal strength and quality

Link results II



Ratio of signal strength:



- >250 stronger losses than for 10km haze
- QC-link much earlier stable

- Near-zero-visibility on 8/14/2001
  - Comparison of NIR / MIR link

Development of Intersubband QCL in JPL

Intersubband QCL have a tremendous potential for implementation in the applications and in instruments for a space research.

Goal of the current QCL R&TD work is an establishing of this laser technology in JPL; advancing of its to a level that these lasers can be reliably used in a space applications; and developing the QC laser with parameters tailored to the requirements of specific JPL and NASA mission.

Current work concentrate on several aspects of QC laser technology

- *Optimization of the QC laser and of the waveguide designs*
- *Improvement of the QC laser growth*
- *Establishing of reliable fabrication of QC lasers*
- *Improvement of the laser operational characteristics such as power, threshold current, maximal operational temperature, etc.*
- *Development and testing of the laser arrays*
- *Study of laser repeatability and reliability*

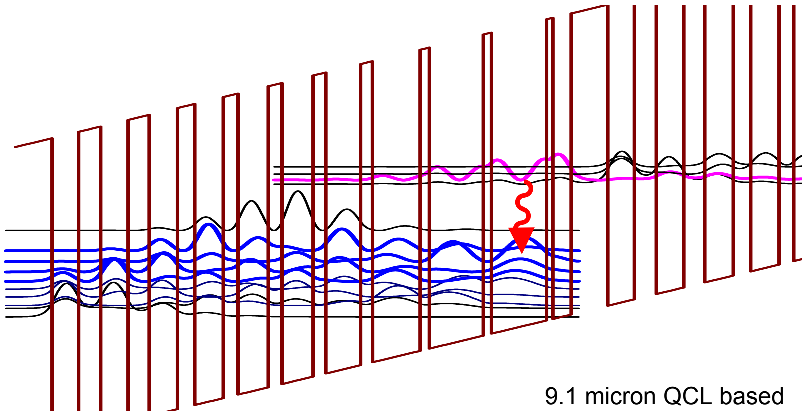
Current technical limitations of the Quantum Cascade Lasers

- **Limited output power**
- **Large electrical power consumption and thermal load**
- **CW operation typically requires cryogenic cooling**
- Exponential dependence of the threshold current on the temperature, $J_{th}=J^{0}_{th}\exp(T/T_0)$, where $T_0 \approx$ 100-150 K is a characteristic laser temperature
- Heat generation in the laser that increases the temperature in the laser cavity, $T=T_{sink}+G \times V \times J$, where G is thermal conductivity. For typical $W_{heat}= V x J \approx$ 5-20 Watt and $T_{gen} = G x V x J \approx$ 10-150 K

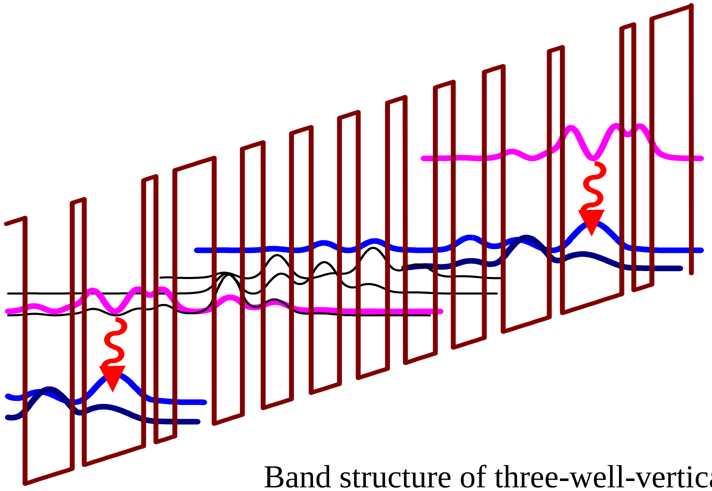
Development of QCL in JPL: Laser Design

Designs with different types of active regions such as three-well-vertical and bound-to-continuum designs

- Each of these designs has specific characteristics that set the operational parameters of the QC lasers, such as the maximal output power, threshold current, etc.
- A choice of the specific active region makes possible to determine the optimal design of the QC lasers for the application of interest.



9.1 micron QCL based
on bound-to-continuum design



Band structure of three-well-vertical
8 micron QC laser

Development of QCL in JPL: Lasers growth

High quality of QCL growth is essential to achieve ultimate parameters of the laser operation

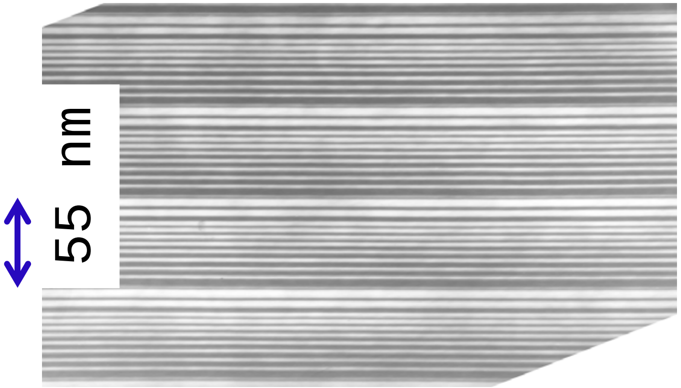
- QC lasers are grown by Molecular Beam Epitaxy (MBE)

- MBE growth of QC lasers is challenging and requires high accuracy and precise calibration of material composition, doping levels and thicknesses

- Growth of QC lasers is currently performed at Bell Labs, Lucent Technologies

i	GaInAs		40 Å
i	AlInAs		11 Å
n	GaInAs	2×10^{17} cm^{-3}	36 Å
n	AlInAs	2×10^{17} cm^{-3}	12 Å
n	GaInAs	2×10^{17} cm^{-3}	32 Å
i	AlInAs		12 Å
i	GaInAs		30 Å
i	AlInAs		16 Å
i	GaInAs		30 Å
i	AlInAs		38 Å
i	GaInAs		21 Å
i	AlInAs		12 Å
i	GaInAs		65 Å
i	AlInAs		12 Å
i	GaInAs		53 Å
i	AlInAs		23 Å

Growth sequence of one cascade of QC lasers. Typically, QC lasers have about 30 cascades



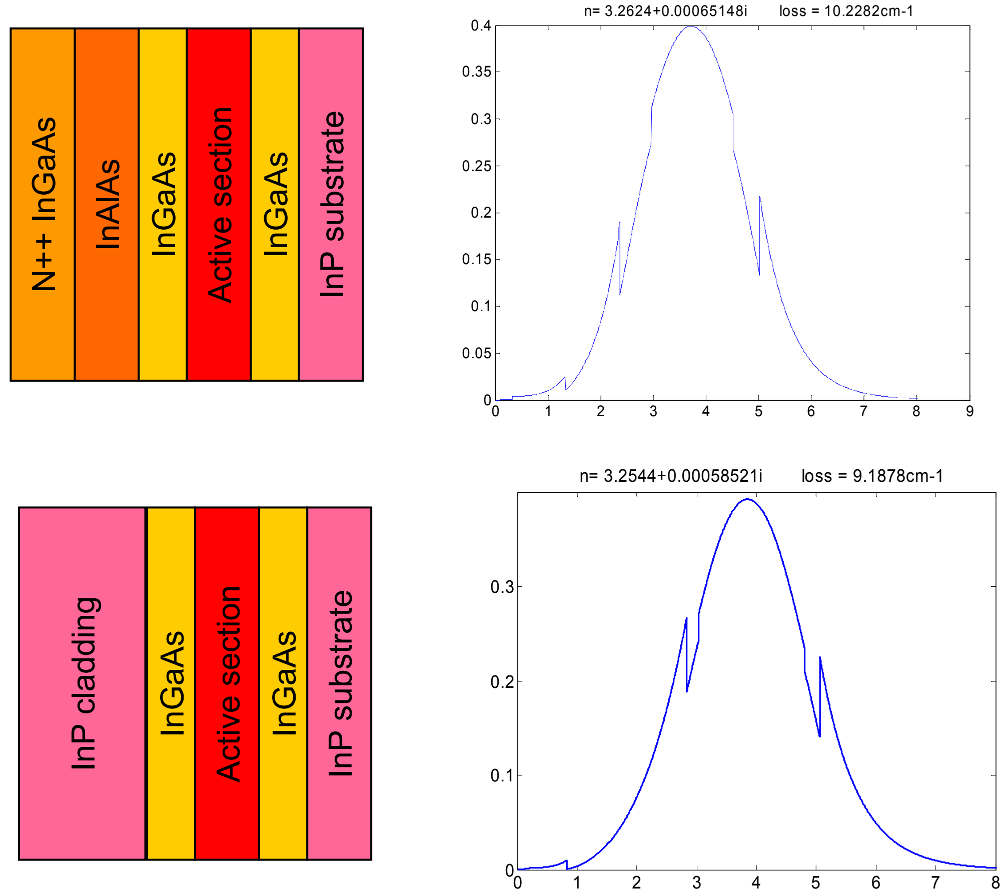
Transmission Electron microscope Image of QC laser

Development of QCL in JPL: Lasers growth with InP top cladding

We are currently developing a growth of the QC lasers with top InP cladding.

InP cladding provides a better heat removal from the active section of the QC lasers than a typical InGaAs/InAlAs cladding.

Consequently, this will result in higher optical output power and in higher operational temperatures in cw mode.

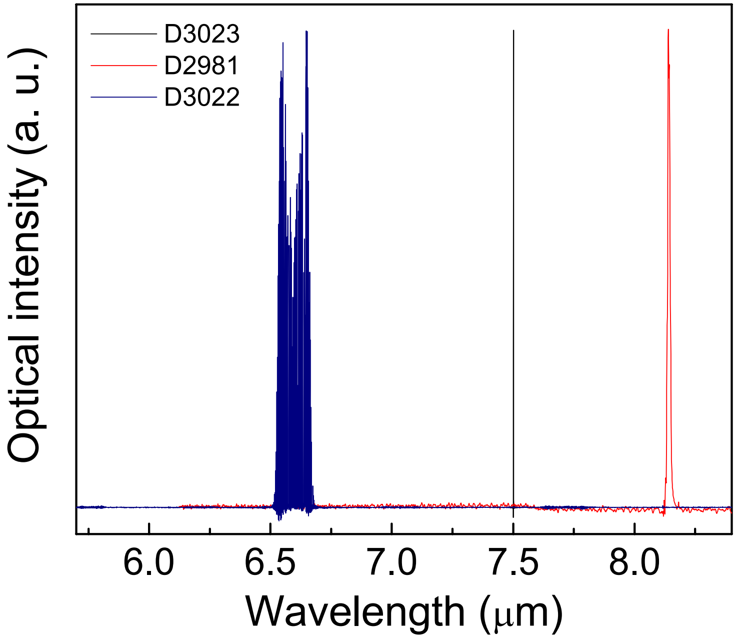


Designs of the InAlAs/InGaAs (top) and InP (bottom) QCL waveguide and calculated intensity distribution of an optical mode

Development of QCL in JPL: Current results

In our work we designed, fabricated and tested different QCL to develop lasers operating at pulsed and continuous mode

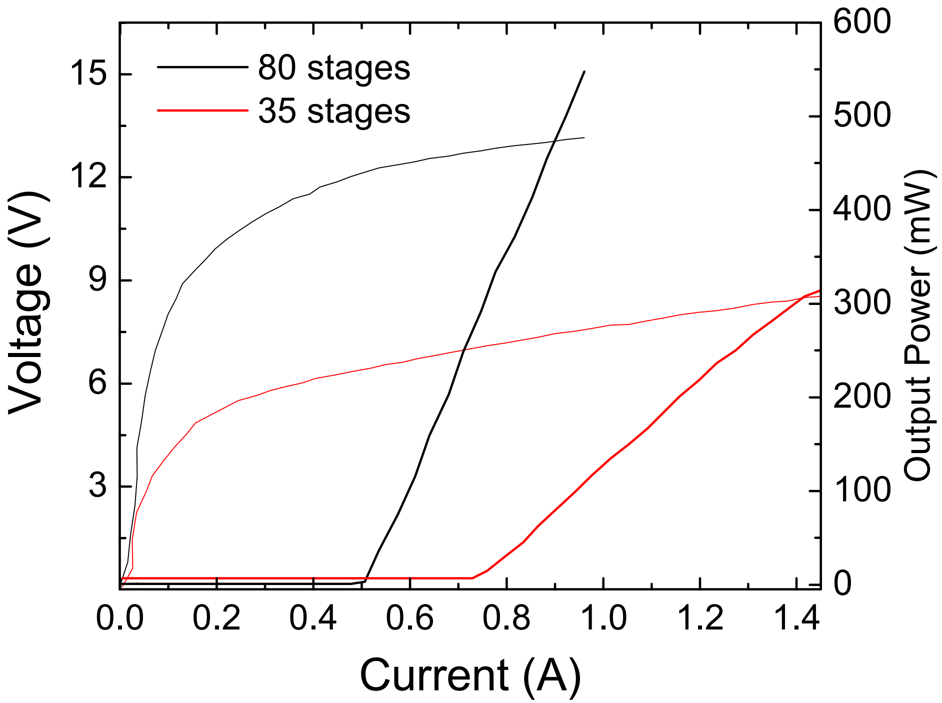
Initially, we have focused on the development of QC lasers designed to emit at several distinct wavelengths in the mid-IR spectral range (5-12 mm) that are of interest for future space instruments.



Optical spectra of three intersubband Quantum Cascade Lasers emitting at the different wavelengths. These lasers were designed with distinct types of active section to study their performance

Development of QCL in JPL: Current results

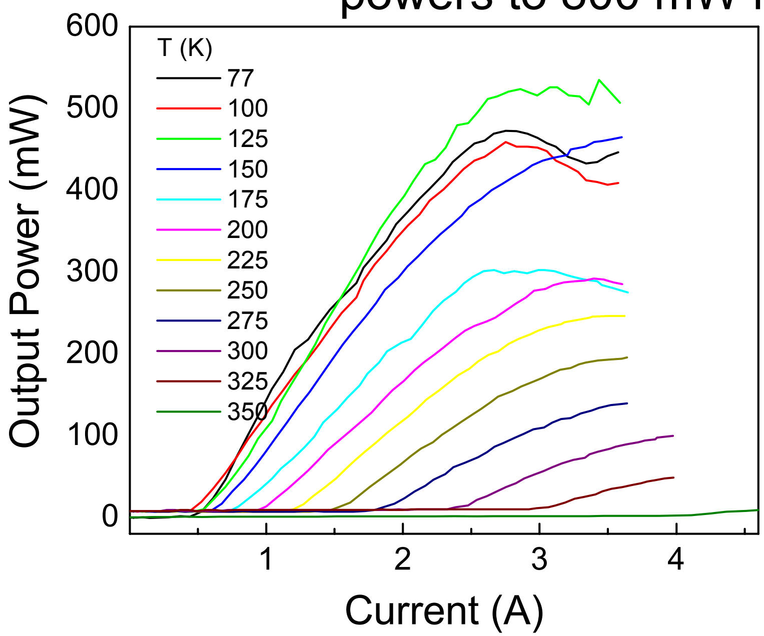
In our work we evaluated QCL with different design parameters such as number of stages, applied field, doping level, etc., in order to study and to improve the laser operation.



Voltage-Current Light-Current output characteristics of two intersubband Quantum Cascade lasers with different number of stages. The increase in number of stages decreased the threshold current and improved output power but also resulted in stronger laser heating. This heating prevented a laser operation at high currents

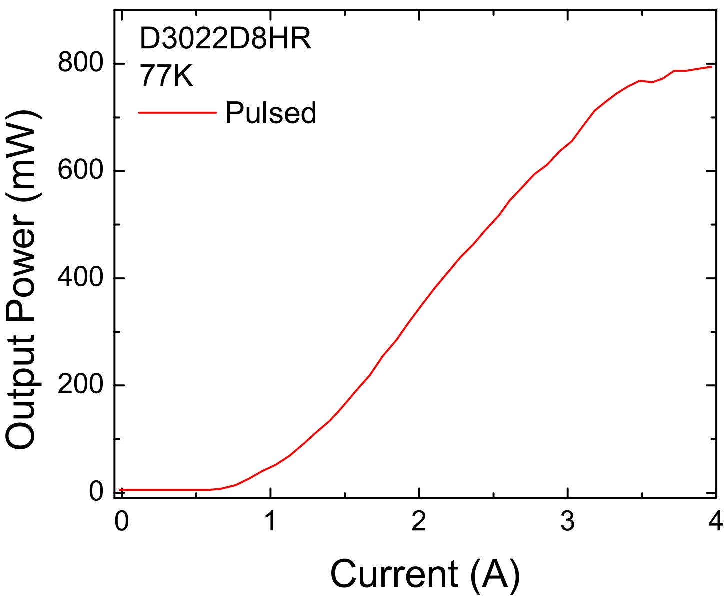
Development of QCL in JPL: Current results

We have optimized the design and epitaxial growth of the QC laser structures that enabled the laser pulsed operation up to T = 350 K (top) and increased output peak powers to 800 mW in the pulsed regime (bottom).



Light-Current output characteristics of intersubband Quantum Cascade lasers with improved design of the active section. New design increased laser characteristic temperature to T_0~ 150 and enabled the pulsed operation up to 350 K.

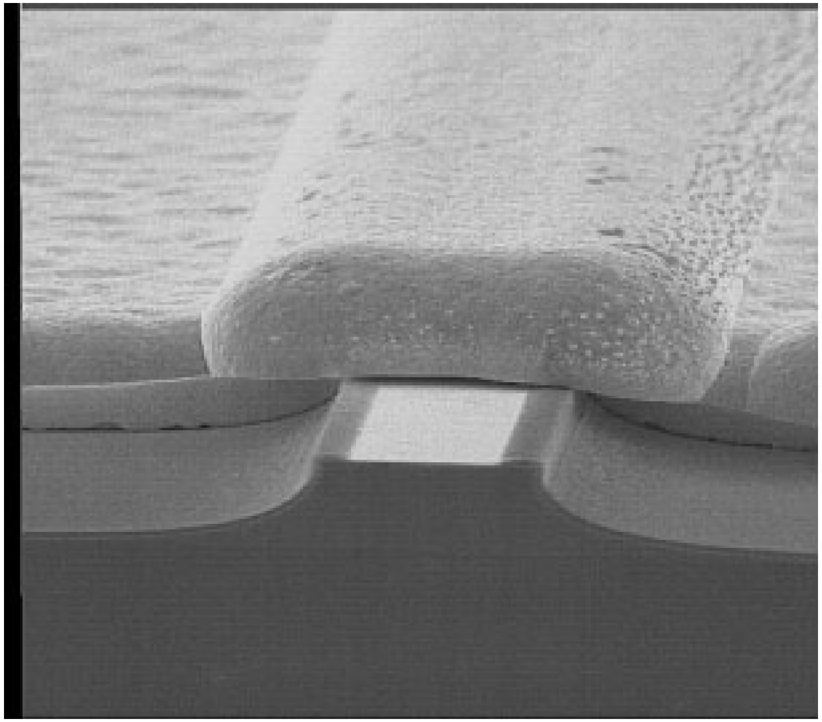
LI characteristics of QC laser operation in pulsed mode at T = 77 K

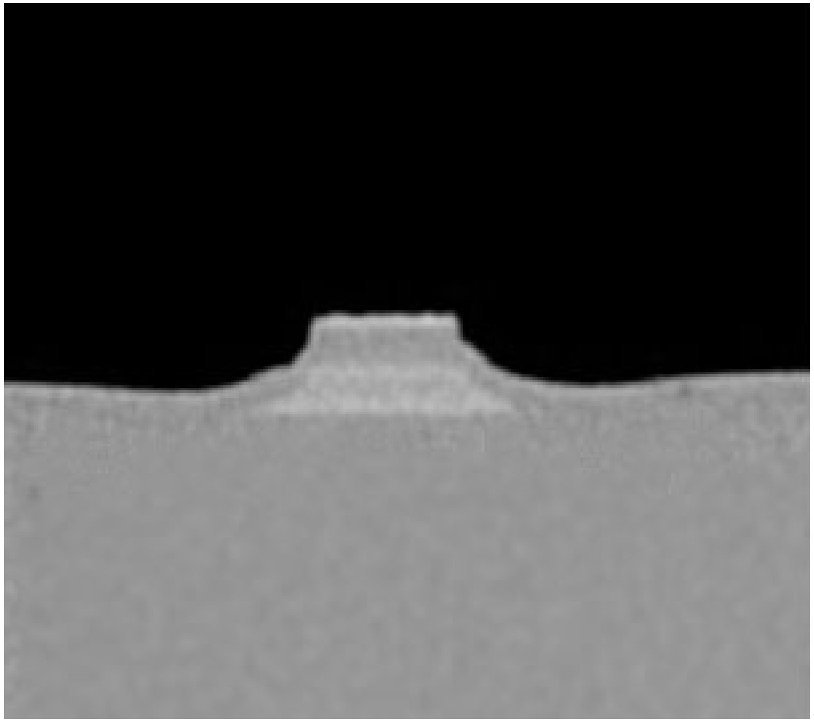


Development of QCL in JPL: Device fabrication

Developing of QCL fabrication technology is a crucial to improve the laser operation and to achieve the reliable and repeatable performance

Our fabrication and packaging process development concentrated on improvement of the heat transfer from the active section of the lasers.



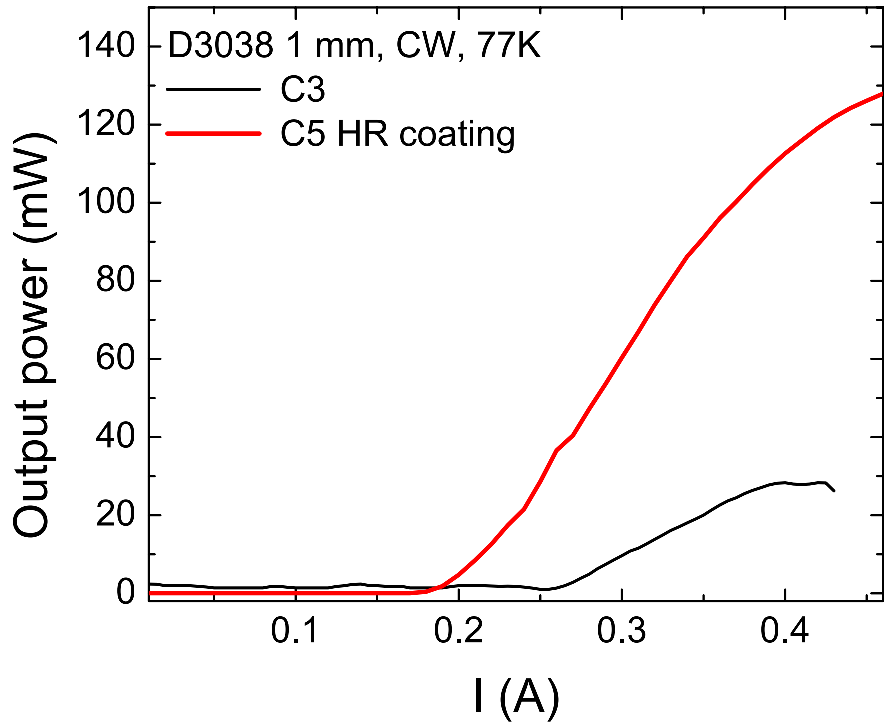


Scanning electron image of QC laser waveguide ridge laser with Au- electroplated coating (left) and an optical image of QC laser with InP over growth (right).

Development of QCL in JPL: Device fabrication

Development of high quality high-reflectivity (HR) coating of the laser facets

- The HR coating of the laser facet decreases the total mirror loss and leads to reduction of the laser threshold current and increase of the optical output power.
- QC lasers with a metallic HR coating consisting of SiO2/Ti/Au thin film layers were fabricated

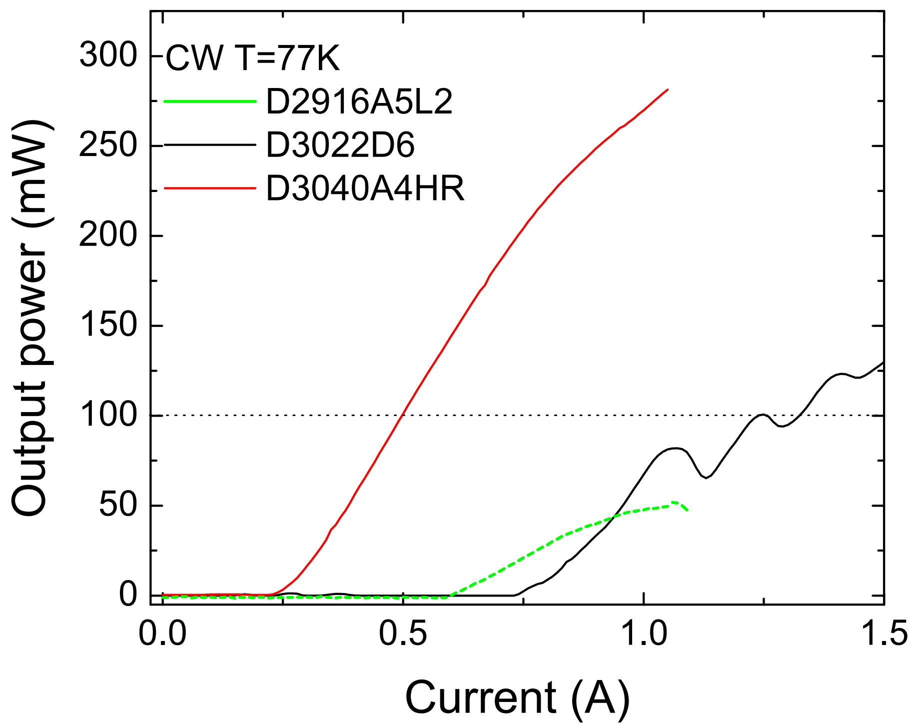


CW Operation of two identical 1 mm QC lasers with (C5) and without HR coating (C3)

Development of QCL in JPL: Current results

Improvement of CW operation

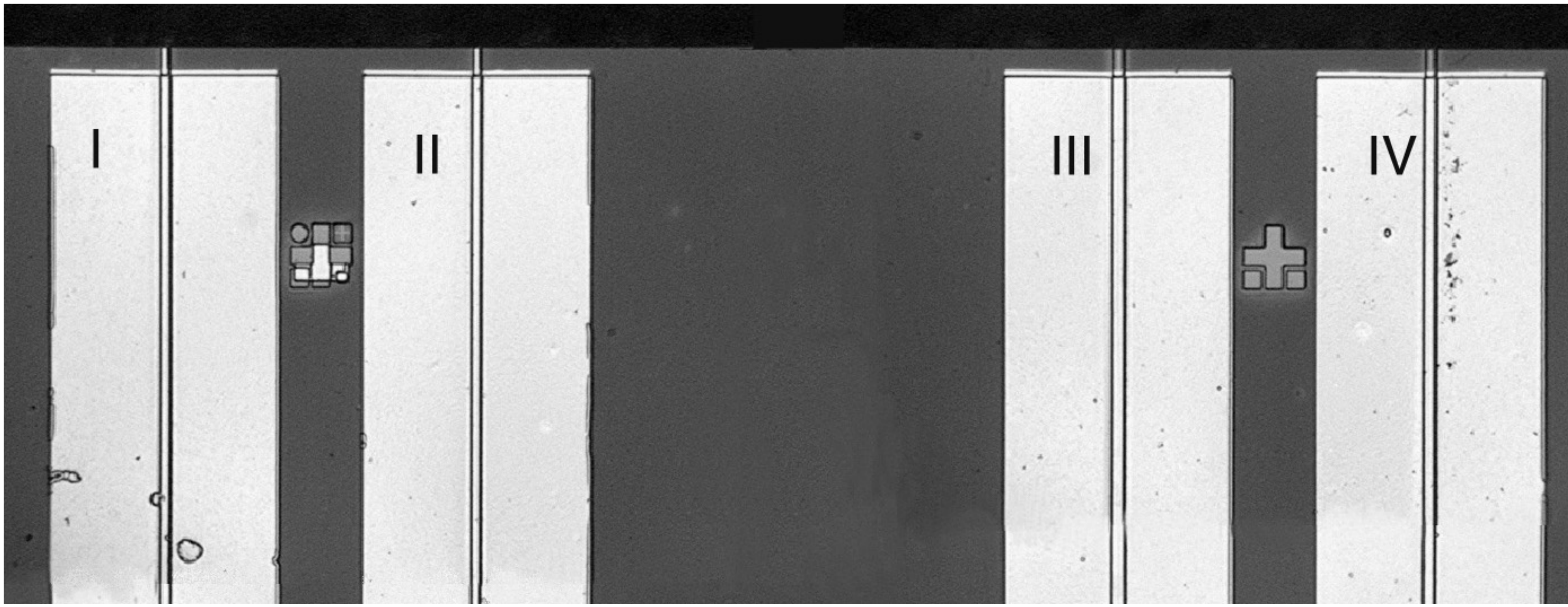
An enhancement of heat transfer from active section with Au-electroplating and utilization of HR coating of the laser facets has led to an increase in the laser cw output power from *P* = 50 mW (green dashed line, Figure 9) to about *P* = 300 mW (red line) at *T* = 77 K.
In addition, these optimization steps have significantly reduced the electrical power consumption and the thermal heating of the QC lasers operating in cw mode.



LI characteristics of several QC laser operating in cw at *T* = 77 K.

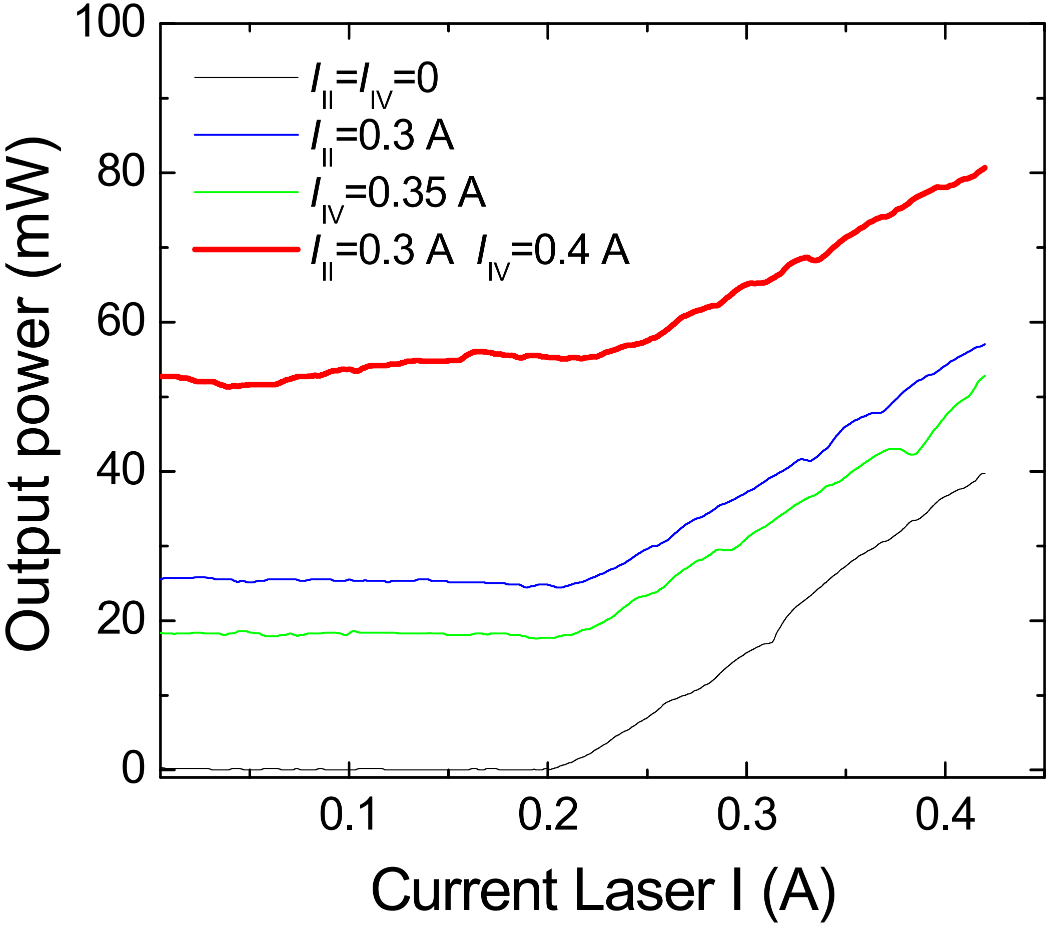
Development of QC laser arrays

Development of QCL in JPL: Laser arrays



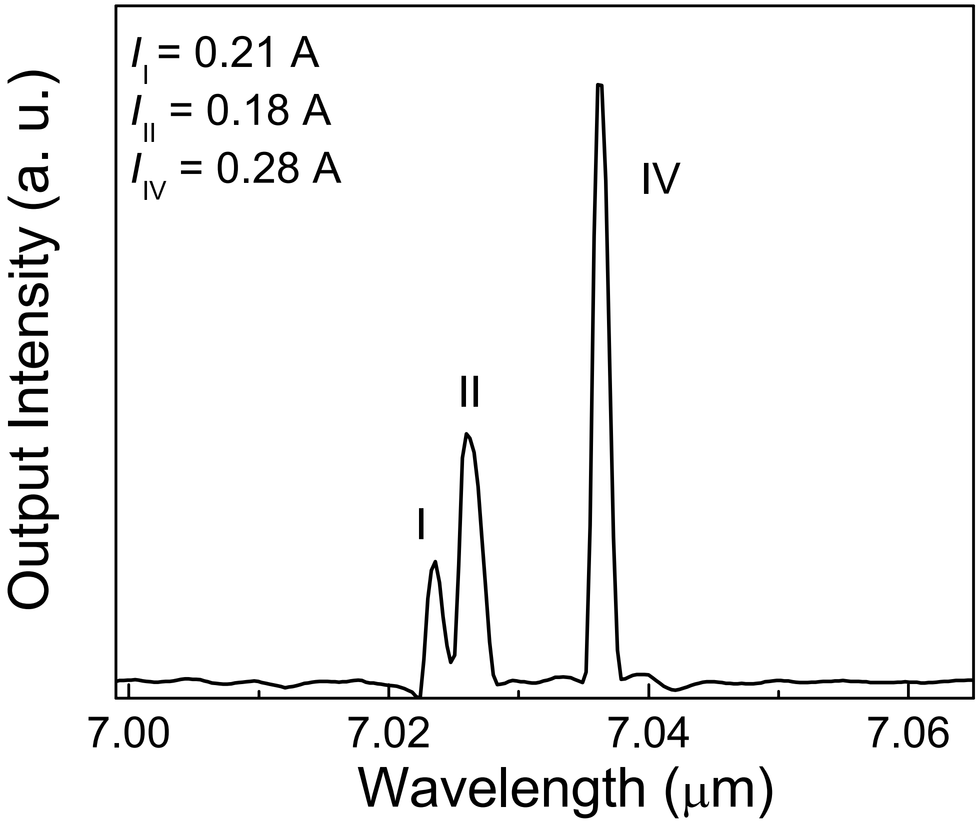
Top view image of the QC laser array. Individual lasers in QC laser array are labeled by I, II and IV in the picture.

Development of QCL in JPL: Laser arrays



Light-Current characteristics of the laser I operating in cw mode as a function of dc bias applied to the laser II and IV.

Development of QCL in JPL: Laser arrays



Continuous wave output spectra of the QC laser array for lasers I, II and IV operating simultaneously.