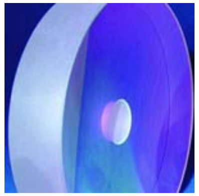
Spectroscopic Laser Diodes and Accessories, 1.2 – 150 µm:



Selected Recent Developments

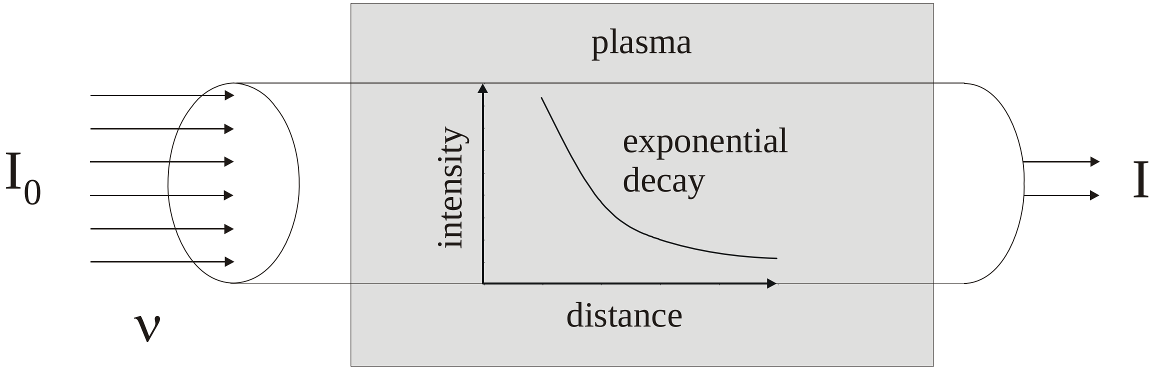
www.lasercomponents.com

Content

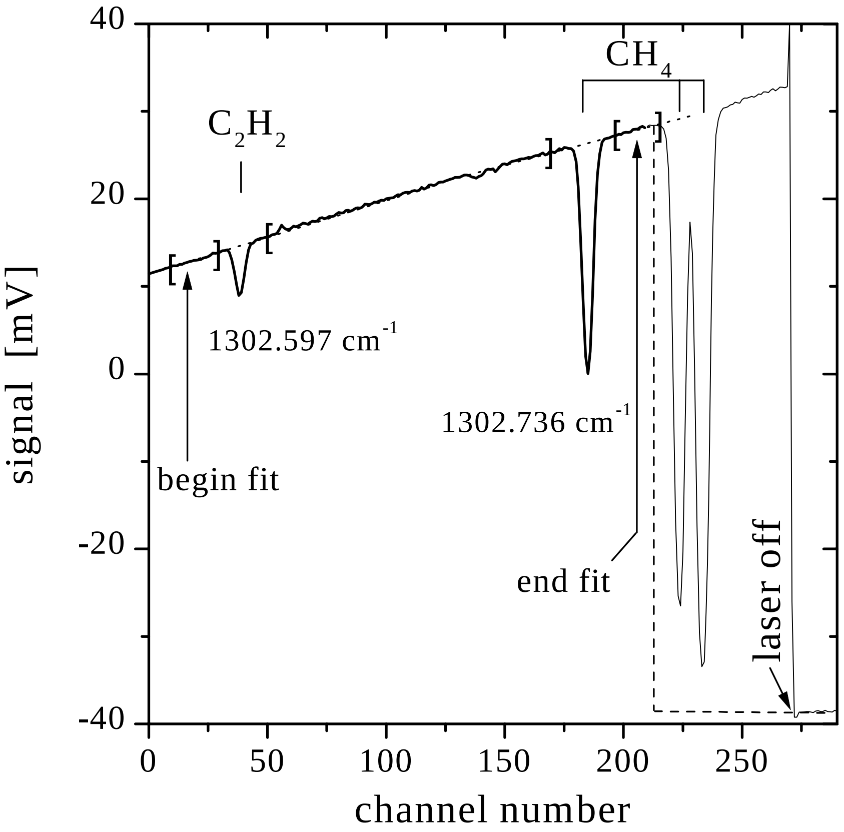
1. Universal Working Principle:
Basics of Tunable Diode Laser Absorption Spectroscopy

- Lambert-Beer absorption law
- Universal applicable (works at all temperatures)
- Calibratable
- Multipass: Increased absorption length

$$I(\nu) = I_0(\nu) \exp(-k(\nu)\, l\, n)$$



1. How does it work?



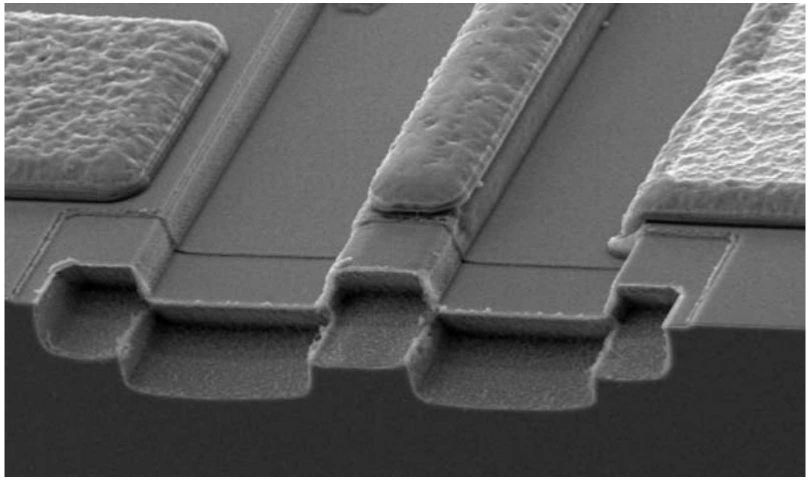
- Electrical Pulse: Switches laserdiode on. Laser warms up and changes emission wavelength. Scans over absorption.
- Look at Mid-Infrared (MIR) Fingerprint or Near Infrared (NIR) Overtone on the molecule.
- Example Ethane: Detection limit < 100 ppt (1 second)

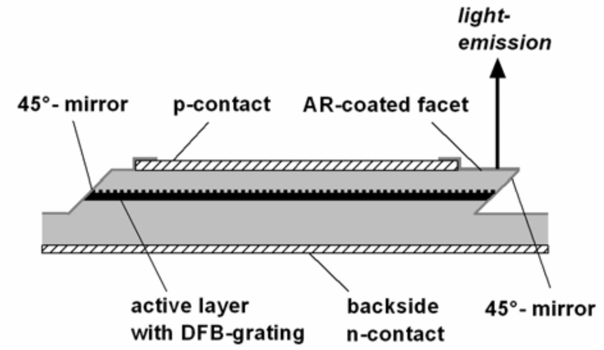
1. Commercial Importance

- Established method in NIR
- History: Breakthrough reported 2004 at 4th OPTAM conference
- MIR: so far systems for specific applications at low level
- Total number of system sales until 2003: 2,000 pcs. (estimated)
- Annual number of system sales 2006: aapr. 5,000 pcs. (estimated)

2. NIR Laserdiodes (1.2 – 1.85 µm)

- Idea: Combine the output power of a DFB with on-wafer test capability of a VCSEL
- Therefore: Price advantage
- Works well.
  Commercially available from 1.2 to 1.65 µm.
  Samples @ 1.3 µm

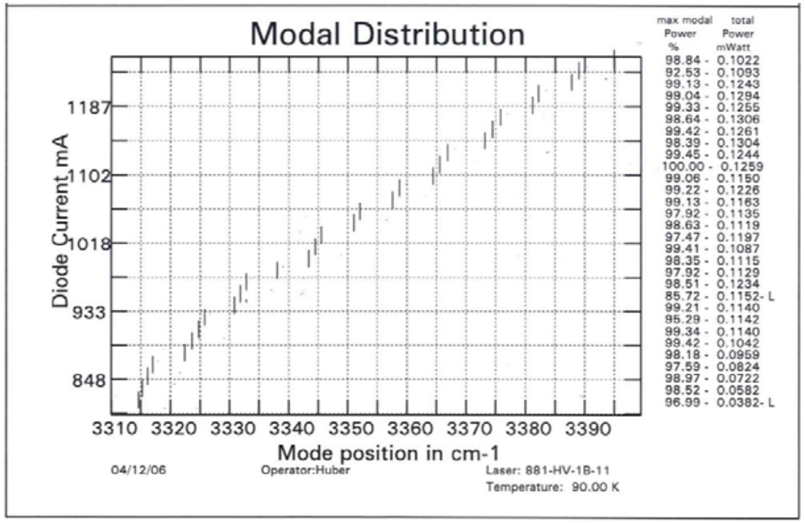




FhI HHI Berlin, M. Möhrle et al. (2006)

3. MIR Laserdiodes (3-25 µm)
3.1 Lead Salt (3-25 µm)

- LASER COMPONENTS shifted available range slightly towards shorter wavelength (down to 2.95 µm)
- Earlier: active zone made by binary PbSe
- Recently: active zone made by ternary PbSrSe

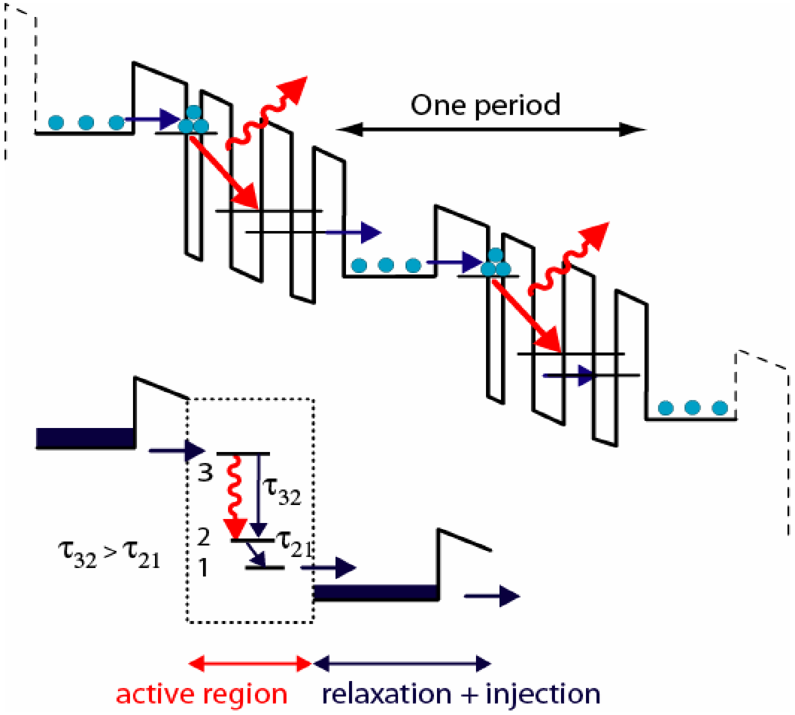


04/12/06 Operator:Huber Laser: 881-HV-1B-11 Temperature: 90.00 K

max modal Power %	total Power mWatt
98.84 -	0.1022
92.53 -	0.1093
99.13 -	0.1243
99.04 -	0.1294
99.33 -	0.1255
98.64 -	0.1306
99.42 -	0.1261
98.39 -	0.1304
99.45 -	0.1244
100.00 -	0.1259
99.06 -	0.1150
99.22 -	0.1226
99.13 -	0.1163
97.92 -	0.1135
98.63 -	0.1119
97.47 -	0.1197
99.41 -	0.1087
98.35 -	0.1115
97.92 -	0.1129
98.51 -	0.1234
85.72 -	0.1152- L
99.21 -	0.1140
95.29 -	0.1142
99.34 -	0.1140
99.42 -	0.1042
98.18 -	0.0959
97.59 -	0.0824
98.97 -	0.0722
98.52 -	0.0582
96.99 -	0.0382- L

- Spectral emission of lead salt @ 3350 cm^{-1} (2.985 µm)
- Hydroxyl radical @ 2.960 µm becomes available

3.2 MIR-QCL (3.3-16 µm)



- Intersubband transitions in semiconductor heterostructures
- Wavelength determined by design, not by bandgap
- Low inversion due to ps lifetime in upper laser level results in low gain
- Therefore CASCADE of several stages
- Faist et at. (1994)

Improvement directions:

- ☐ Thermal and optical losses
- ☐ Faster depopulation of lower laser level

3.2 MIR-QCL:
Motivations to use them in Trace Gas Monitoring

Theory

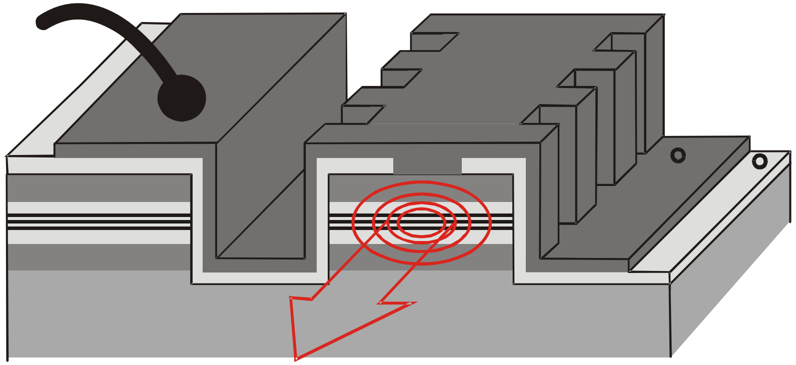
- Room temperature operation
- Instruments with higher resolution than lead salt laser based instruments due to narrow linewidth (kHz range compared to MHz at cw-operation)

Results

- Completely achieved at pulsed operation and widely at cw operation, but in commercial reality limited to bestsellers
- 7000 hours cw room temperature operation demonstrated for MARS mission
- Pulsed system performance similar to lead salt performance
- 5 times improvement at cw operation recently reported (Mc Manus et al, 2006). Detector limited?

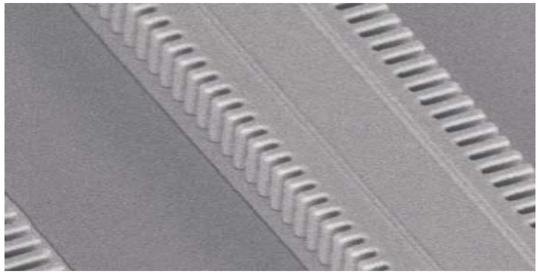
3.2 MIR-QCL: Thermal Design

- Basic Challenge: Phonon interaction with ps relaxation is used, i.e. heat is created
- Heat Conductivity: 15-20 times less in growth direction compared to lateral direction, appr. 500 layers



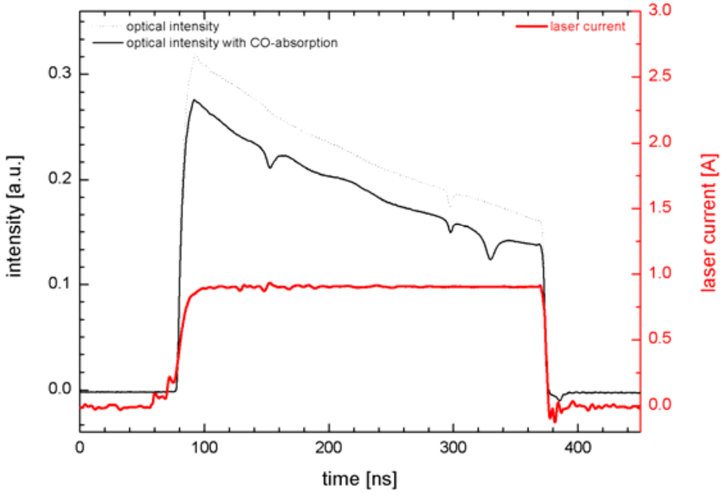
Practical ways

- Basic is hard to change
- Proven concepts applied:
  - ☐ Upside down mounting (heat sink close to active zone)
  - ☐ Overgrowth after processing, i.e. buried heterostructures (larger thermal contact area to heat sink)
  - ☐ Image: Lateral coupling (S. Golka et al)



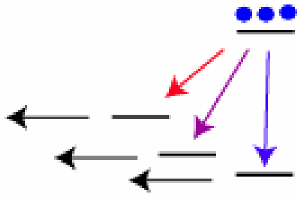
3.2 MIR-QCL: Materials

- Traditional:
  - GaInAs/AlInAs on InP
  - GaAs/AlGaAs on GaAs
- Recently:
  - AlAsSb barriers on InP (modification of traditional), especially at short wavelength (see CO-DFB)
- Theoretically:
  - GaN, Si/Ge



CO-DFB Laser,
FhG IAF / LASER COMPONENTS

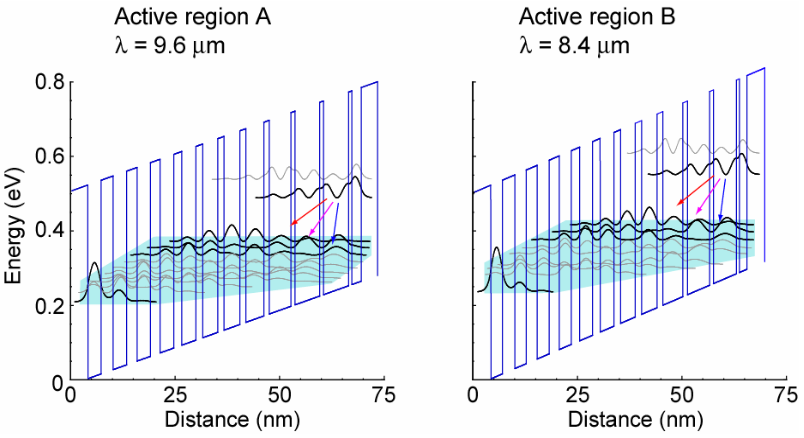
3.2 MIR-QCL: Depopulation Improvement

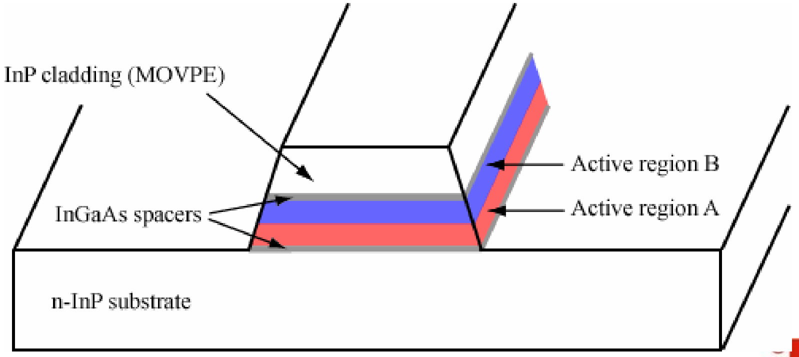


- Double phonon resonance:
  - 2 relaxation channels instead of 1 (4QW design, for CO-DFB shown before)
- Bound to continuum:
  - Transition to a miniband
  - Gain broadening (up to 300 cm-1 spontaneous emission FWHM @ 300 K)

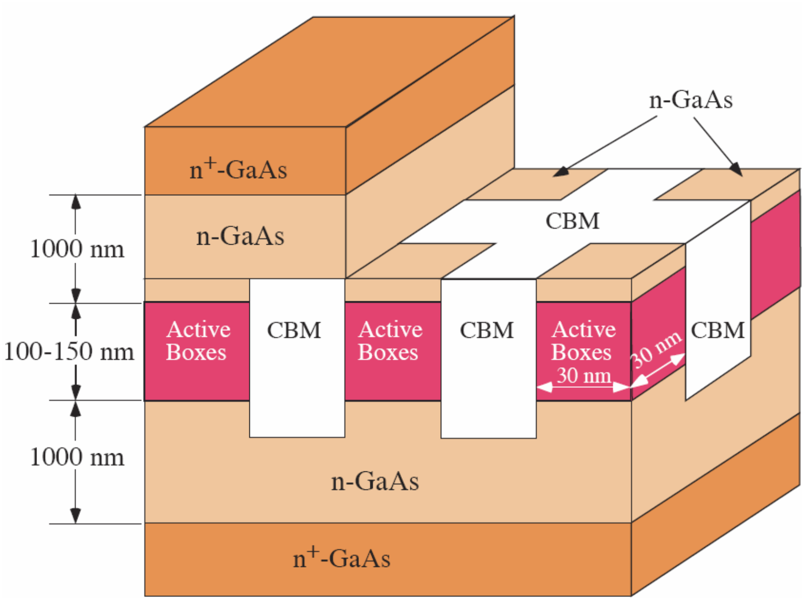
3.2 MIR-QCL: External Cavity

- Broad Gain Profile needed
  - Start with bound to continuum
  - Heterogenous cascade
  - Strong spectral overlap
- AR coating: 10^{-5} needed
- Result
  - Appr. 200 cm^{-1} tuning
  - 10^{-3} reflectivity
  - Maulini et al (2006)





3.2 MIR-QCL: Quantum-Box Lasers

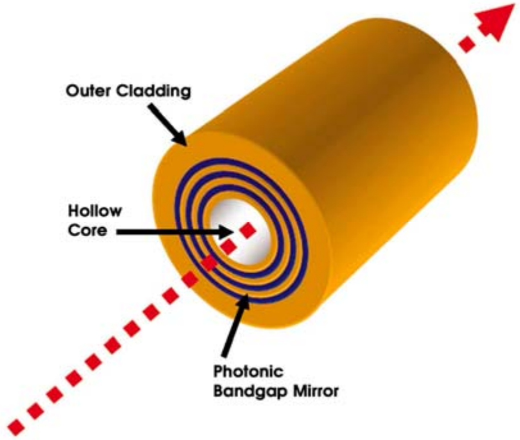


- Active region:
  2-D array of QB ministacks (2-3 QBs)
  → Wallplug efficiency can be increased to 50%
- CBM = Current-Blocking Material
  → etch-and-regrowth process
- No working device yet
- D. Botez et al (2006)

3.3 MIR Accessories: Infrared Single Mode Fibers

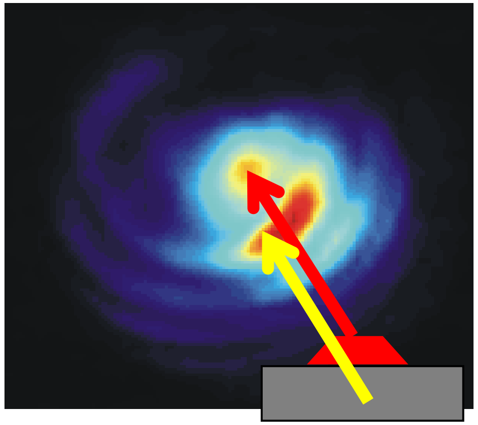
(From FTIR to QCL? - B. Mizaikoff et al (2006))

- Omnidirectional photonic bandgap refelctor enabled design of infrared SM fiber, 400 µm core
- Acts simultanously as wavelength selective waveguide and miniaturized gas cell
- Result: Detection of ethyl chloride (solved in liquid) at concentration levels of 30 ppb with response time of seconds probing a sample of 1.5 ml inside the fiber only
- Planar SM waveguides have also been demonstrated (also measurements in liquid phase)



4. THz-QCL: Basic Challenges

- Lower gain, therefore number of cascades doubled
- Waveguide design
- Farfield optimization

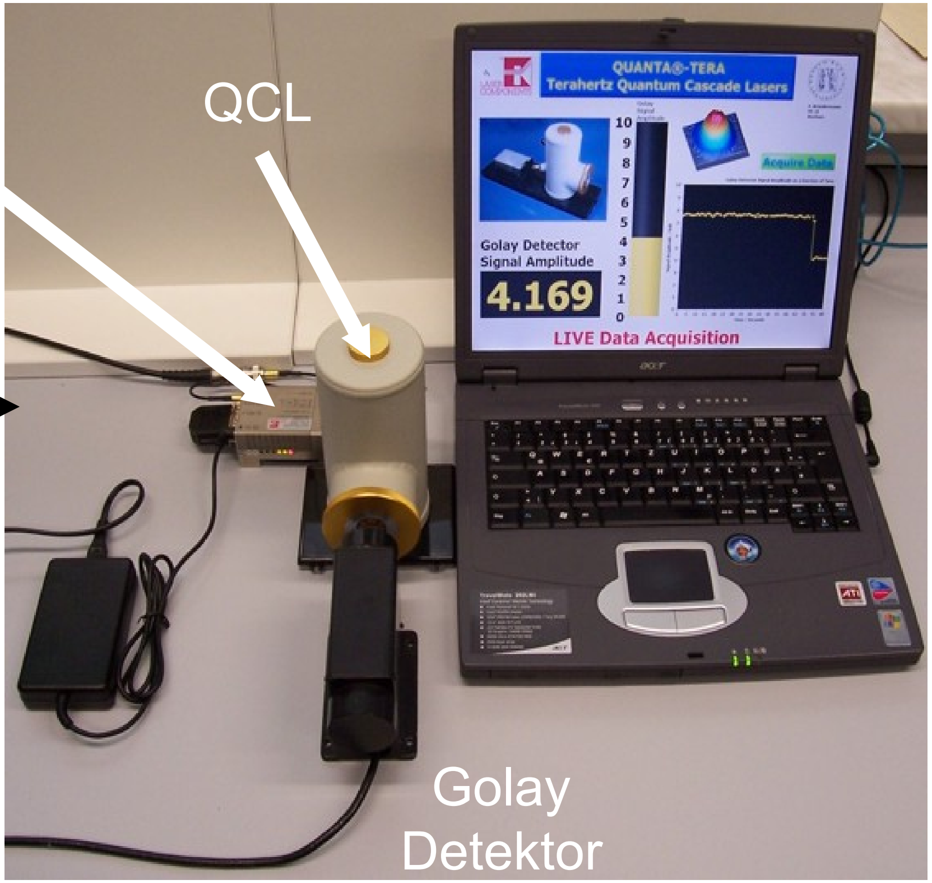


4. THz-QCL: Pros and Cons

- Direct and compact
- Reached threshold of usefulness for convenient imaging @ 10 K (33 mW) using FPA cameras (over 25 m distance demonstrated)
- Hope for parameter improvement
- Extremely low linewidth at cw (6 kHz measured)
- Can easiliy be moved over larger objects

- Limited tunability so far
- Limited availability so far (especially @ 77 K and high power)
- TDS: Spatial and spectral resolution, therefore QCL-applications must be developed

4. THz-QCL: Demo experiment

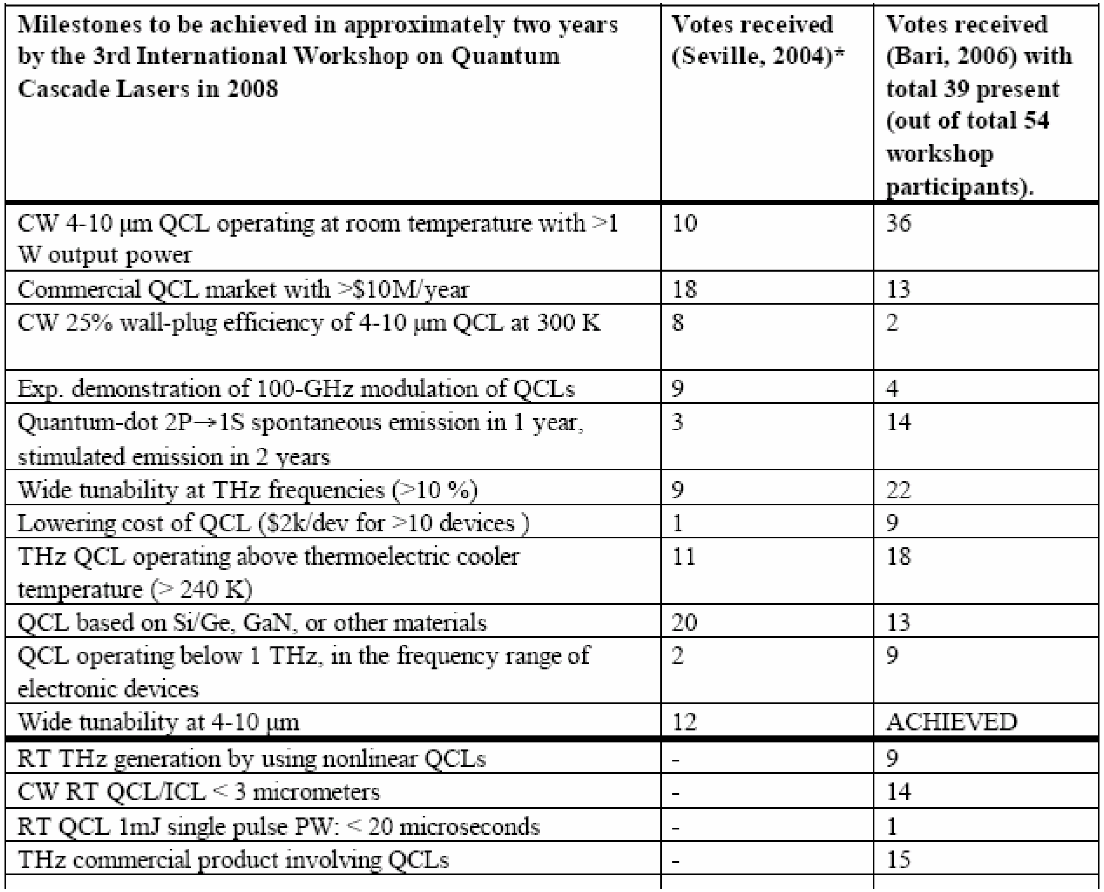


QUANTA®-OEM

external trigger

power supply

5. Wrap up @ 2nd QCL Workshop



Milestones to be achieved in approximately two years by the 3rd International Workshop on Quantum Cascade Lasers in 2008	Votes received (Seville, 2004)*	Votes received (Bari, 2006) with total 39 present (out of total 54 workshop participants).
CW 4-10 µm QCL operating at room temperature with >1 W output power	10	36
Commercial QCL market with >$10M/year	18	13
CW 25% wall-plug efficiency of 4-10 µm QCL at 300 K	8	2
Exp. demonstration of 100-GHz modulation of QCLs	9	4
Quantum-dot 2P→1S spontaneous emission in 1 year, stimulated emission in 2 years	3	14
Wide tunability at THz frequencies (>10 %)	9	22
Lowering cost of QCL ($2k/dev for >10 devices)	1	9
THz QCL operating above thermoelectric cooler temperature (> 240 K)	11	18
QCL based on Si/Ge, GaN, or other materials	20	13
QCL operating below 1 THz, in the frequency range of electronic devices	2	9
Wide tunability at 4-10 µm	12	ACHIEVED
RT THz generation by using nonlinear QCLs	-	9
CW RT QCL/ICL < 3 micrometers	-	14
RT QCL 1mJ single pulse PW: < 20 microseconds	-	1
THz commercial product involving QCLs	-	15

Closing remark

Much progress at sources,
but relative stagnation
at detectors and referring
optical components...

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THz-QCL: Technical Competition Part 1

THz	Room Temperature	Compact	Cheap	Tunable	Speed slow medium high	for User simple complex	S/N (typical f THz at good S/N)	Status Comm. Lab. Research
Lamp (FTS)	RT	sort of	THz-FTS components approx. 15T€	-	S (mechanics)	S (Golay D.)	0.1-10	C
Gas Lasers	RT	N	150 T€	hopping	S	C	(0.8-6.0)	C
Laser Diode Photomixer	RT	Y	May be	Y	M	C → S	0.01-4.0 (0.1-1.0)	L → C
TDS	RT	N	200T€	-	H (full spectra with ASOPS)	C (C → S fiber: P low)	0.1-4.0 (0.1-2.0 S/N: 10^3-10^4)	C
Pulse rectification (x*110 GHz)	RT	Y	ok (low f) pricy (high f)	Y (limited)	M	S (low f) C (high f)	0-2.5 (up to 1.0)	C
Smith-Purcell Emitters	RT	sort of	May be	Y	S (mechanics)	C → S	> 0.1	L → C
Bloch Oscillators	?	Y	May be	?	?	?	?	R
Germanium Lasers	quasi (cooler no liquids)	sort of (size limit cooler)	Y (but +cooler costs)	Y	M,H	S	(1-4, pulse: 1W)	L → C
QC Lasers	quasi (cooler no liquids)	sort of (size limit cooler)	Y (but +cooler costs)	Y (limited)	M,H	S	1-5 (some f, pulse: 10s mW)	L → C

THz-QCL: Technical Competition Part 2

	Problems **Advantages**
Lamp (FTS)	**P: S/N bad** **A: easy to maintain and cheap**
Gas Lasers	**P: gas handling (f coverage limited for gas phase samples)** **A: high power and multiple f with good coverage for liquid and solid samples**
Laser Diode Photomixer	**P: S/N roll off at high f (electronics)** **A: compact, easy handling, wide f coverage**
TDS	**P: S/N roll off at high f (electronics), expensive pump source: 100 T€** **A: wide f coverage at high speed with ASOPS, ps time resolution (chemical reactions)**
Multipliers (x * 110 GHz)	**P: S/N roll off at high f (electronics), limited tuning, complex for high f > 1THz** **A: compact, very stable, high power cw at f < 1 THz**
Smith-Purcell Emitters	**P: electron gun still too complex** **A: tunable from sub-THz to THz**
Bloch Oscillators	**P: still at research level** **A: potentiell for high temperature operation**
Germanium Lasers	**P: cooling required, He closed-cycle cooler and cryostat main investment: 80 T€** **A: high power and wide tuning range**
QC Lasers	**P: cooling required, limited tuning (low yield for user frequency)** **A: compact, may be cheap (with cheaper 80K coolers)**

CW operation: Typically needed only for applications in astronomy and atmospheric research (number of instruments may be 2 per satellite, rare cases of larger lots, mainly industry public relation and research level interest)

Pulsed operation: Higher power, therefore many applications conceivable **but** THz signatures of the application are needed and frequencies (if system not tunable) need to be tailored to each application!