Vertical cavity lasers for applied spectroscopy

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Outline

- **Laser spectroscopy for sensing:**
- Fiber-Bragg sensors;
- Tunable laser diode absorption spectroscopy;
- Resonant Photoacousltic gas sensors;
- **1500-2000 nm Vertical Cavity Lasers with fundamental mode emission of 1-6 mW;**
- **2 W difraction limited Vertical External Cavity Lasers in the 1500 nm band.**

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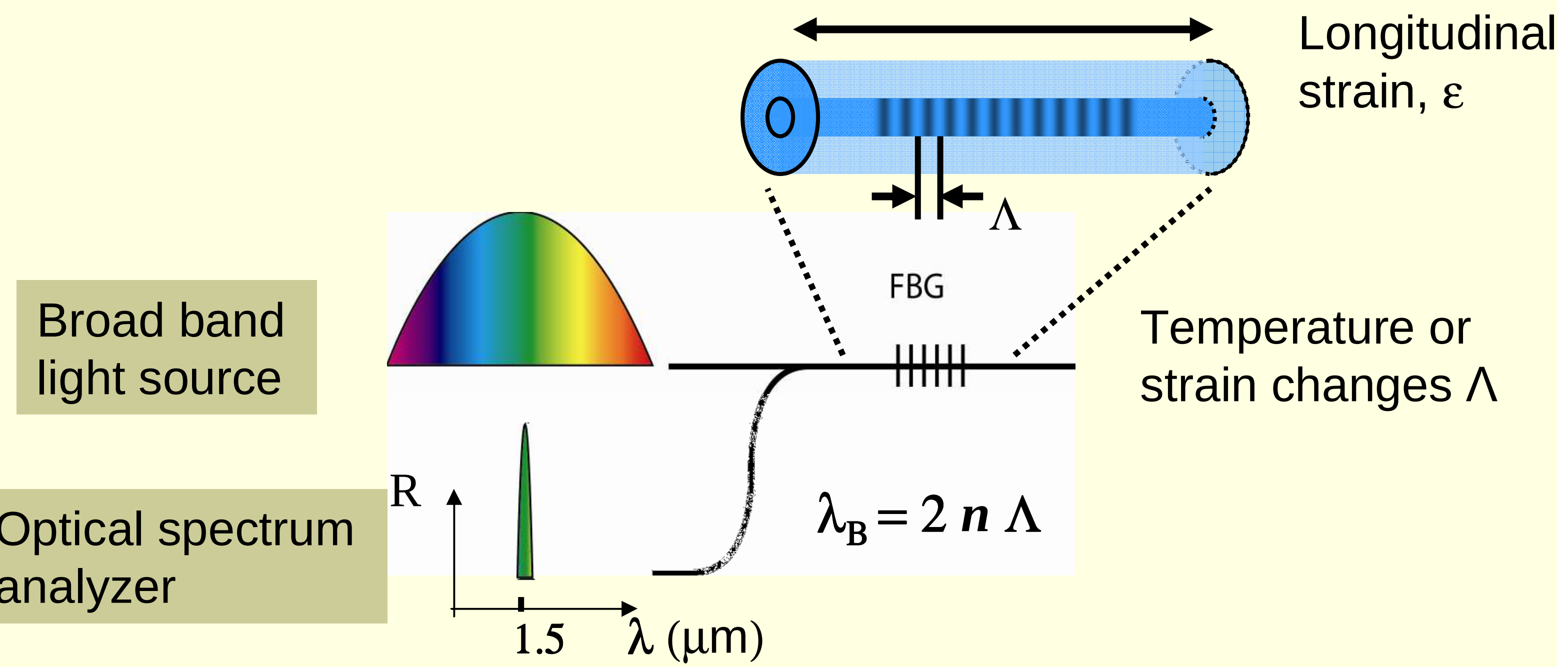
FBG – sensor spectroscopy

The Bragg condition - determines resonance wavelength.

Fiber Bragg grating - couples forward to backward propagating modes.



The resonance peak position depends on temperature and longitudinal strain.

FBG sensors in CH structures (EMPA)

- **Stay cable bridge, Winterthur**
- **Power dam of Luzzone**

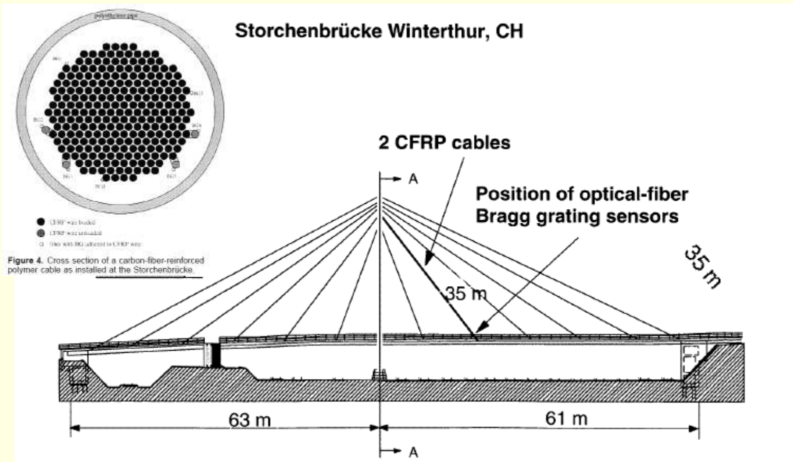


Figure 3. Schematic view of the bridge (Storchenbrücke in Winterthur), crossing 17 railway tracks.

SMS 7, 1998, Brönnimann et al.

Figur 4: Bogen-Staumauer Luzzone während der Erhöhung

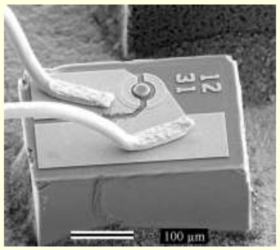
SPIE 3407, 1998, Brönnimann et al.

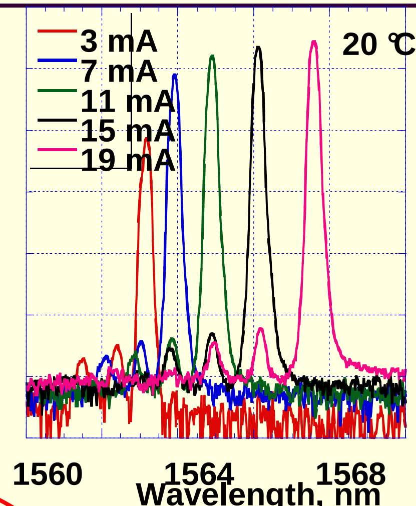
Surveillance using FBG is **performed periodically** since each time **expensive** FBG interrogation equipment has to be shipped in the field and installed.

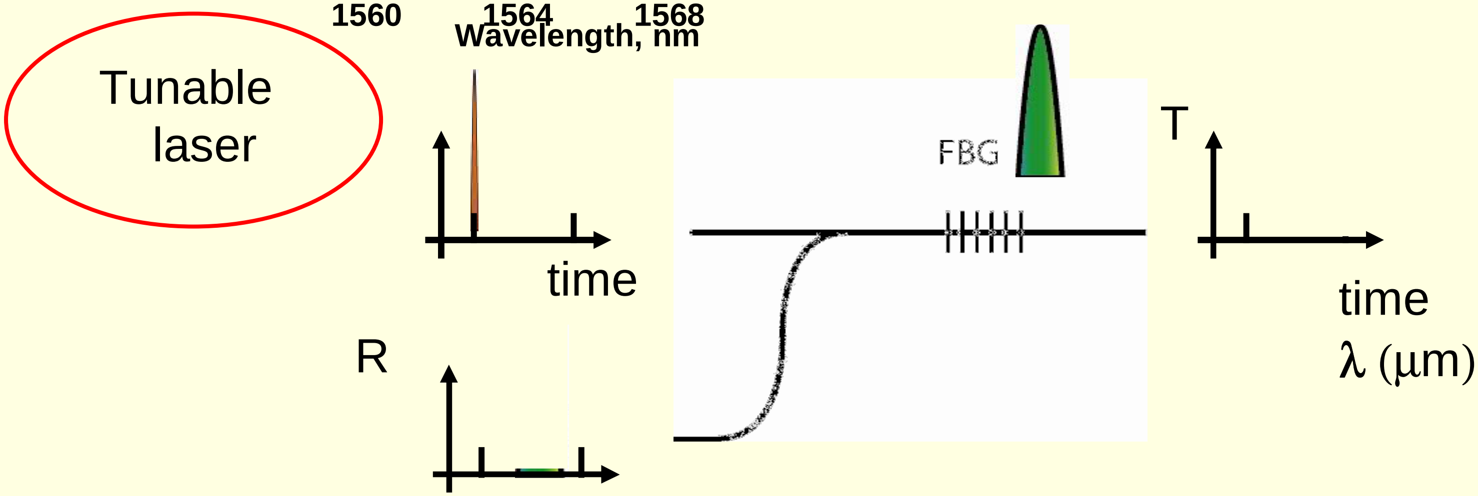
Needs for in-situ,light-weight structural monitoring

In-situ longitudinal strain monitoring

FBG-VCSEL sensor system







VCSEL requirements for portable, in-situ FBG sensing systems

- Wavelength inventory in the 1550 nm band;
- ~1-5 mW fundamental mode emission;
- Wavelength sweep frequency ~ 1 kHz;
- Tuning range ~ 10 nm;
- Line-width ~5 MHz.

Spesifications developed in collaboration with Dr. Hans G. Limberger, APL, IMT, EPFL, in the frame of Nanotera Proposal 20NAN1_123588, 2008

VCSEL based FBG systems:

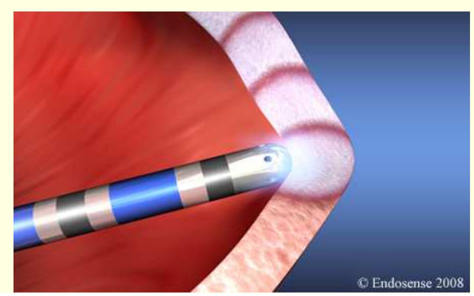
- **light weight** fiber grating interrogation system based on WDM technology;
- **Dynamic in-situ measurements** of temperature and strain during curing of composite materials;
- portable systems for continuous monitoring of **terrestrial, airborne and space** structures.

Letters of support from

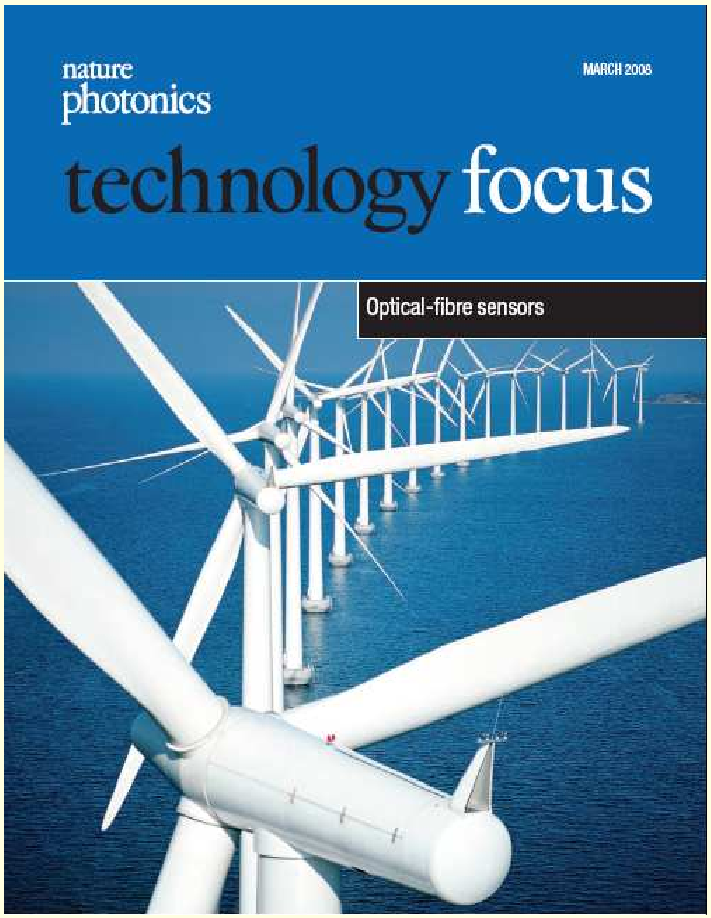
- Alinghi
  http://www.alinghi.com/en/

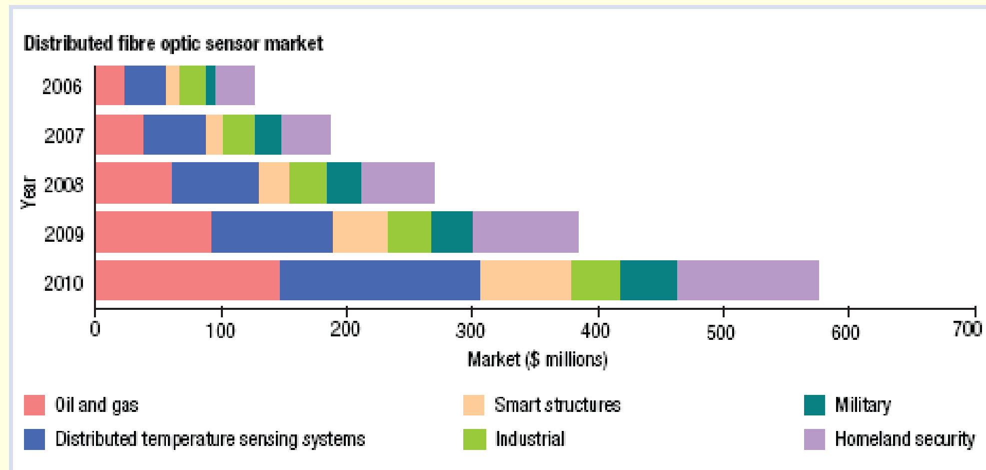
- Oerlikon space
  http://www.oerlikon.com/space/

- Endosense
  http://www.endosense.com



Technology focus on fiber optic sensors





Distributed fiber optic market estimations:

- Optoelectronics Industry Development Association (OIDA): $550 million by 2010.
- Global Industry Analysts: > $650 million by 2010.

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Tunable laser diode spectroscopy in the 1500-2000 nm range

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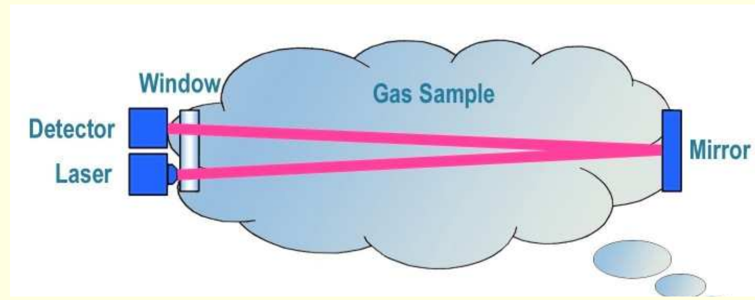
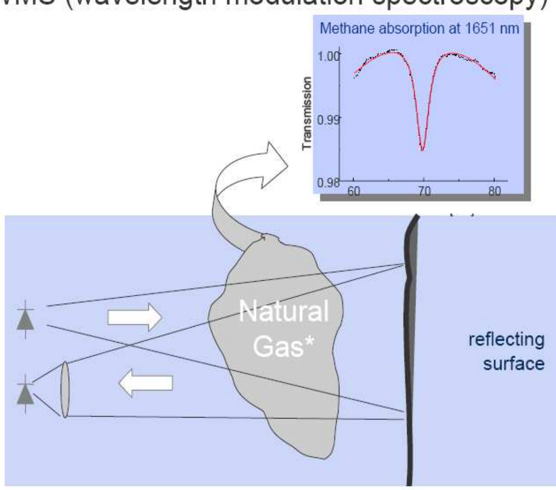
Gas	Symbol	Absorption line, nm
Methane	CH_4	1650
Ammonia	NH_3	1512
Carbon Monoxide	CO	1570
Carbon Dioxide	CO_2	2004, 1953
Water	H_2O	2003
Ethylene	C_2H_4	1617
Hydrochloride	HCl	1740

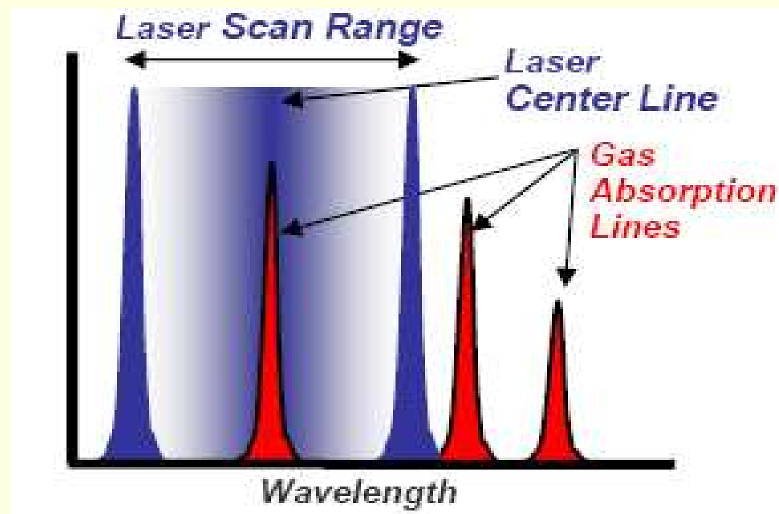
Local gas-cell sensing



Remote sensing of CH4

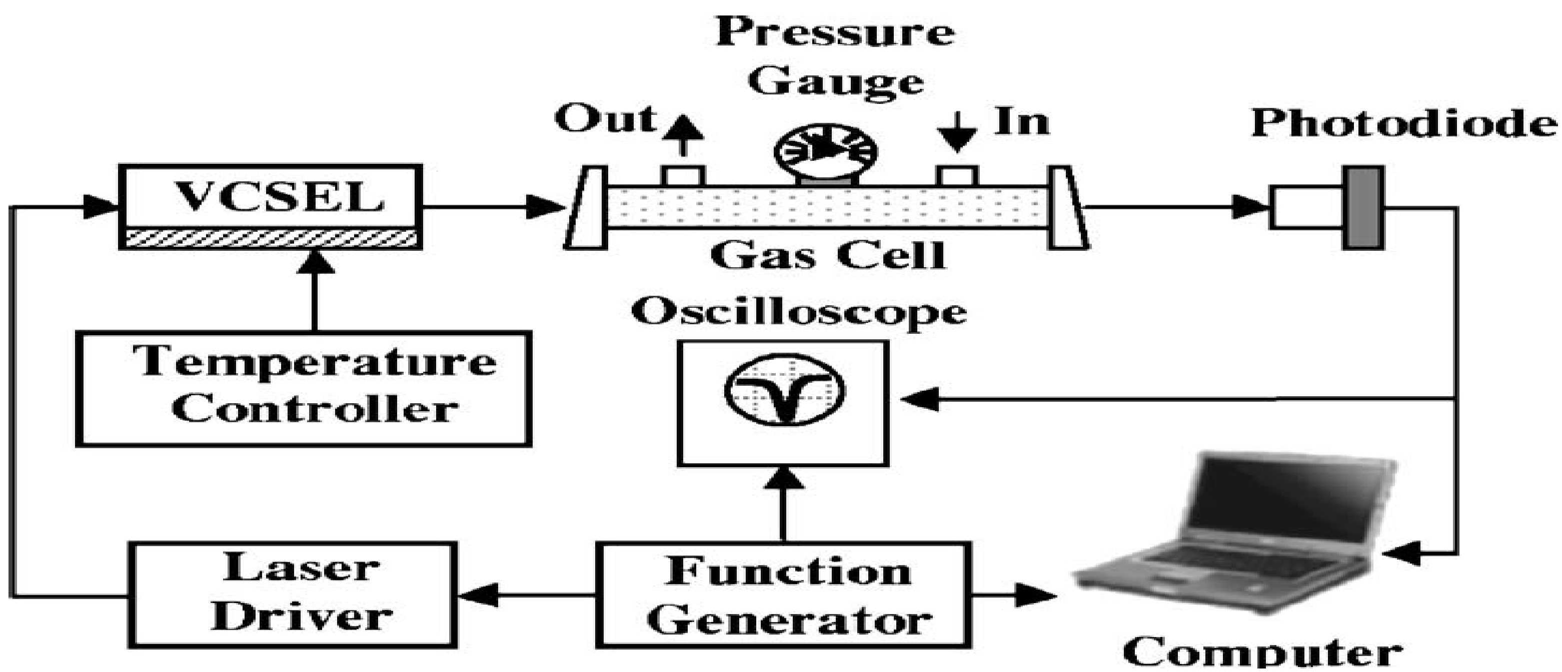
Application – WMS (wavelength modulation spectroscopy)





The fine structure of the gas absorption peak consists of single absorption lines.

Example of VCSEL based absorption spectroscopy set-up

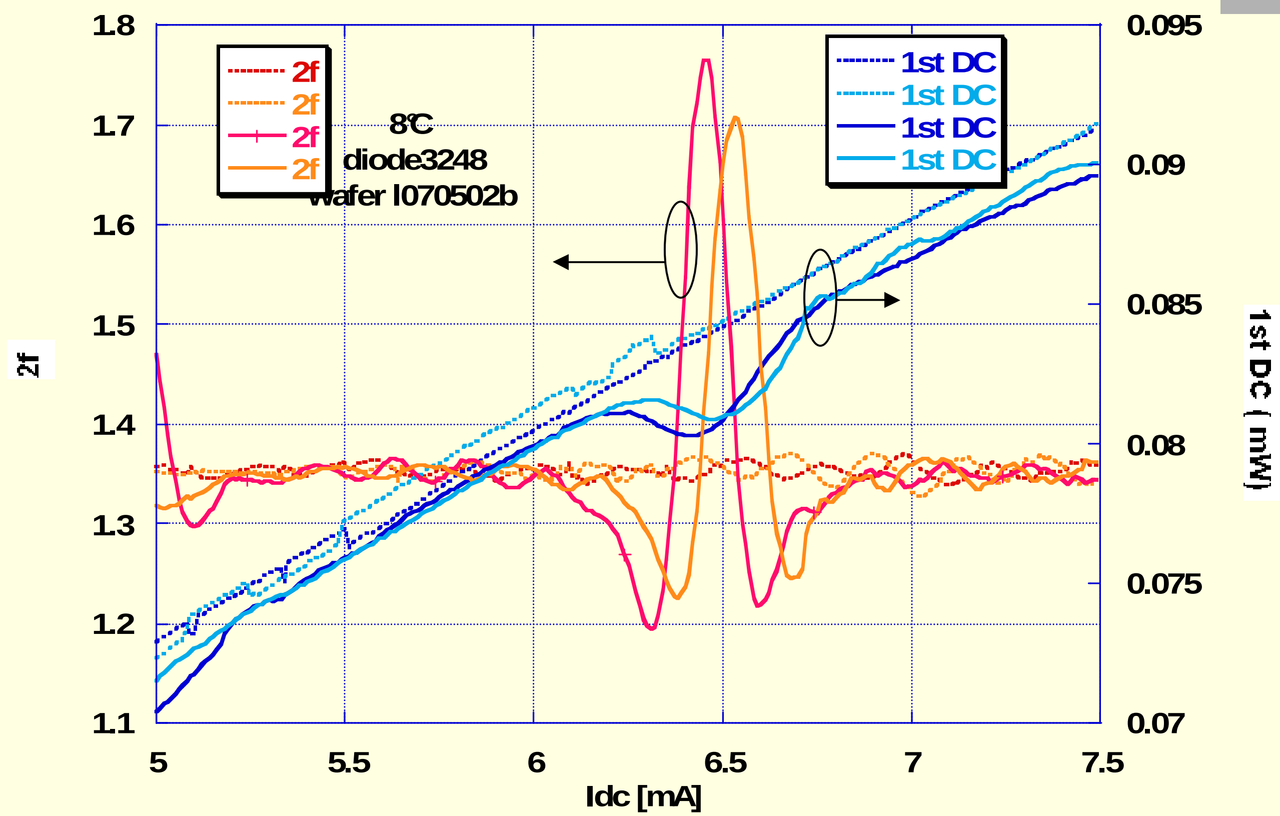


Temperature and injection current are controlled to 0.01℃ and 1μA

A modulation current is superimposed on the VCSEL drive current for increasing detection sensitivity;

Gas pressure is controlled in the range 1 mbar- 1 bar.

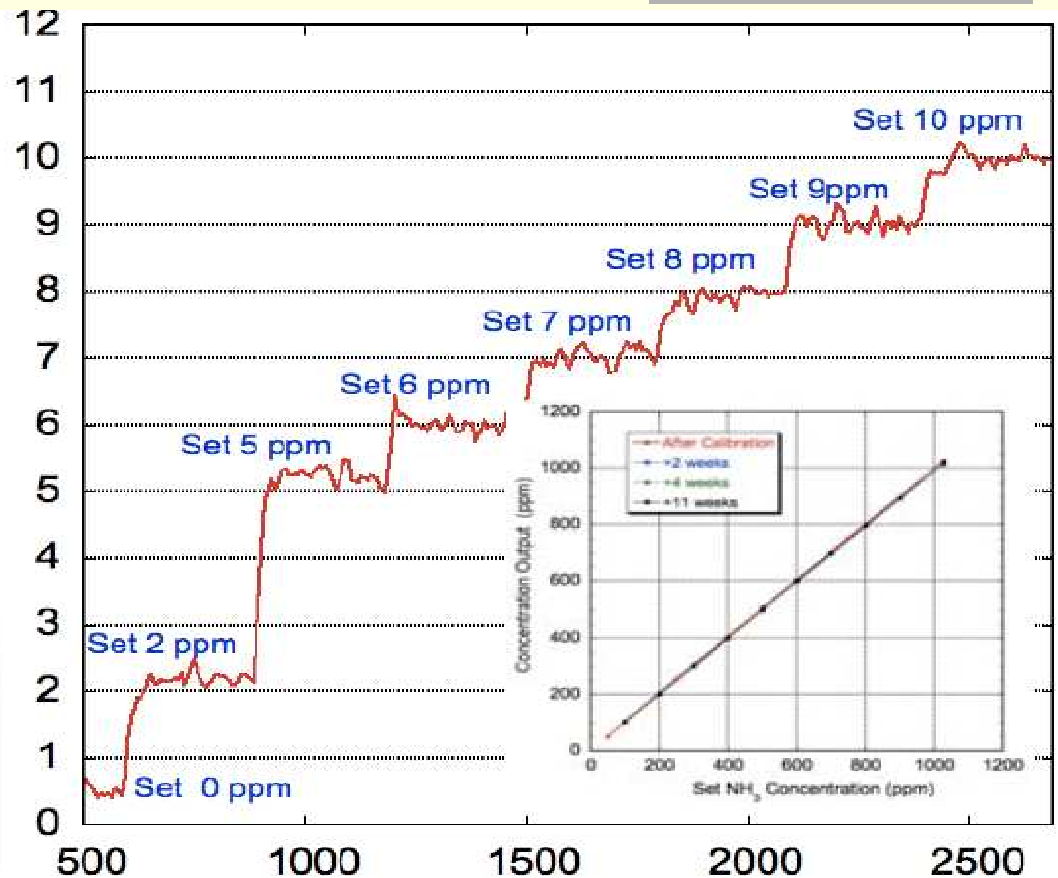
CO_2 detection with LPN/BX VCSEL



V.Iakovlev, Internal report

Dashed lines– ordinary room air
Solid lines– 10 mbar CO_2
Optical path length - 10 cm

Detection limit of micro- Laser Gas Detectors



B. Willing, IRM/Leister, PSE, EPFL

Laser power ~ 1 mW. Detection limit ~ 0.3 ppm

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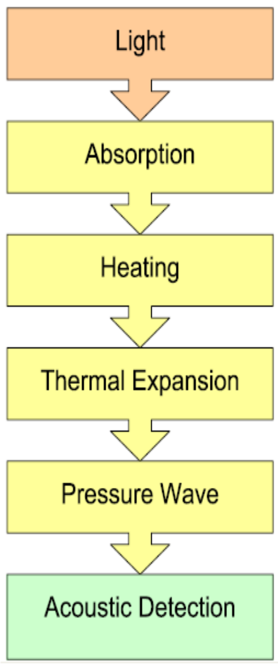
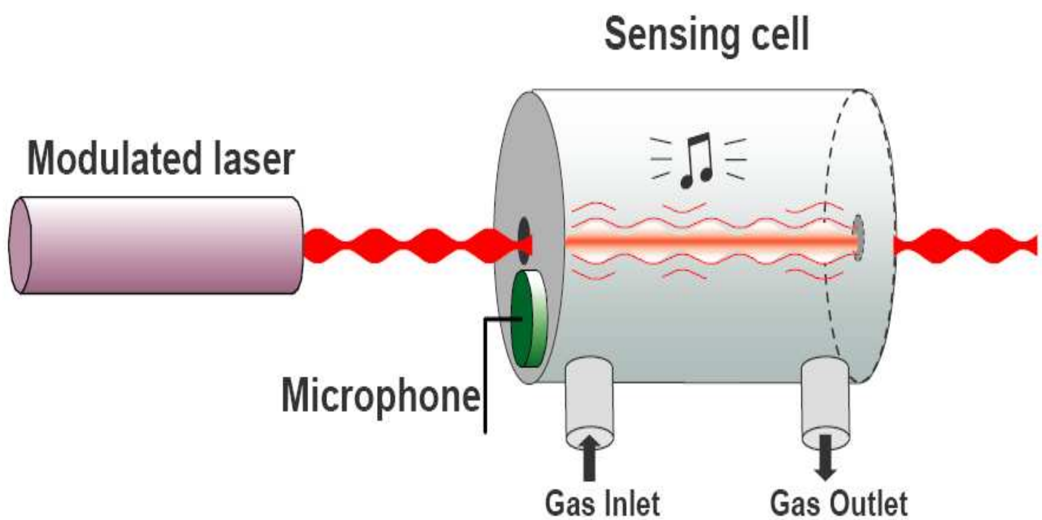
Resonant photo-acoustic spectroscopy





- Modulated light is absorbed by gas molecules and results in a temperature increase and a local pressure raise.

-The sensing cell (~25x15 cm) acts as an acoustic resonator amplifying the signal by more that 500 times.

-Required laser power level 0.5-1 W!

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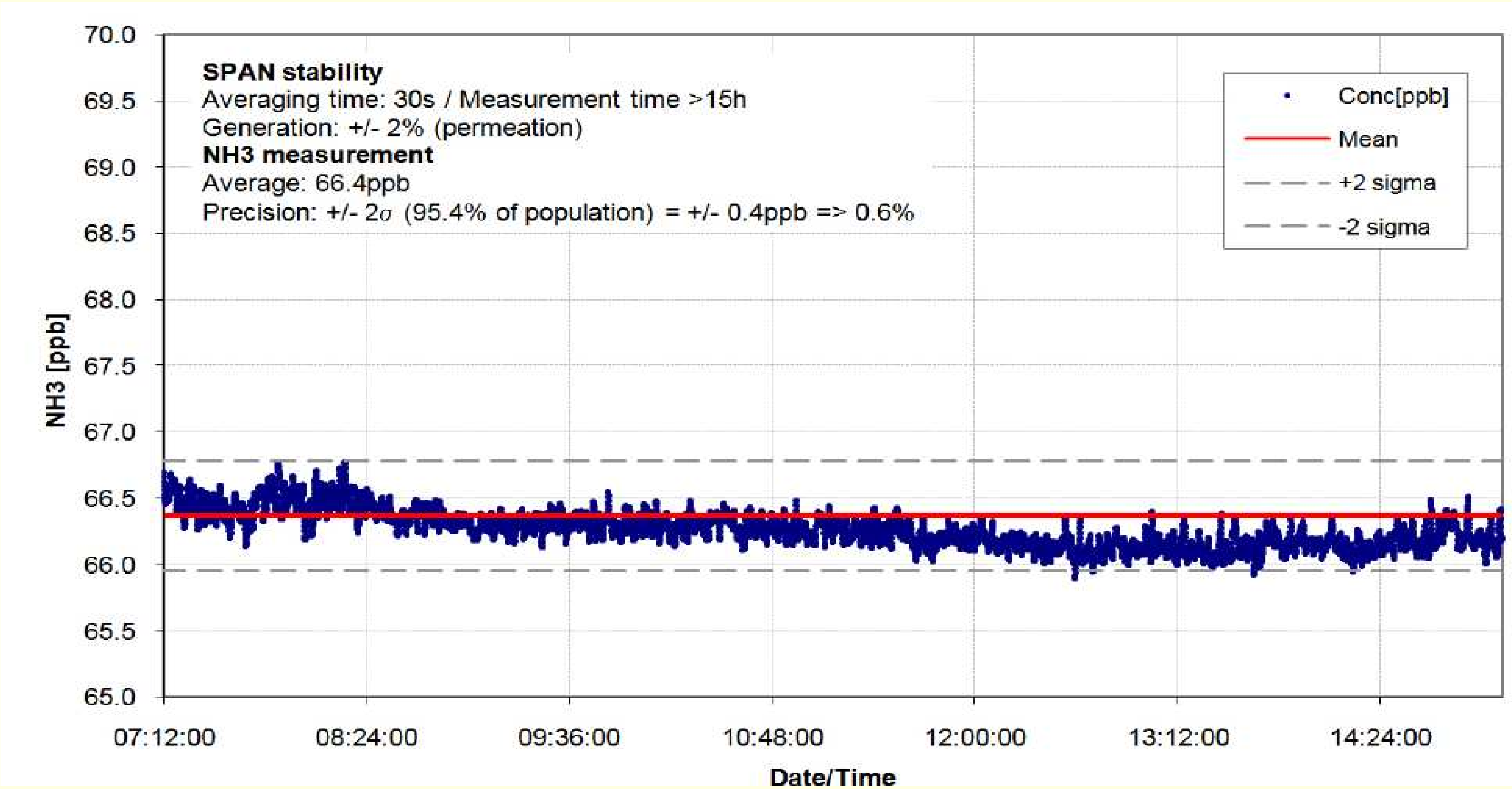
Detection limit, ammonia at 2500 nm



Dr. Etienne Rochat, Omnisens S.A., Morges, VD

Precision ~ ±0.4 ppb

NH3 Photoacoustic sensor aparatus produced by Omnisens S.A. in Morges

The system is based on a CO_2 laser.

Challenge:

To replace the CO_2 laser by 1512 nm and 1740 nm VECSELs with ~1W diffraction limited output for both NH_3 and HCl trace gas detection

Detection limit 0.1 ppb of NH_3. Application: trace-gas detection in clean-rooms.

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Sensing VCSELs important parameters:

- Broadband precise wavelength control;
- High output of several mW;
- Narrow line-width of ~ 5MHz;
- Continuous tuning of ~ 10 nm.

Long-wavelength VCSELs: three main approaches

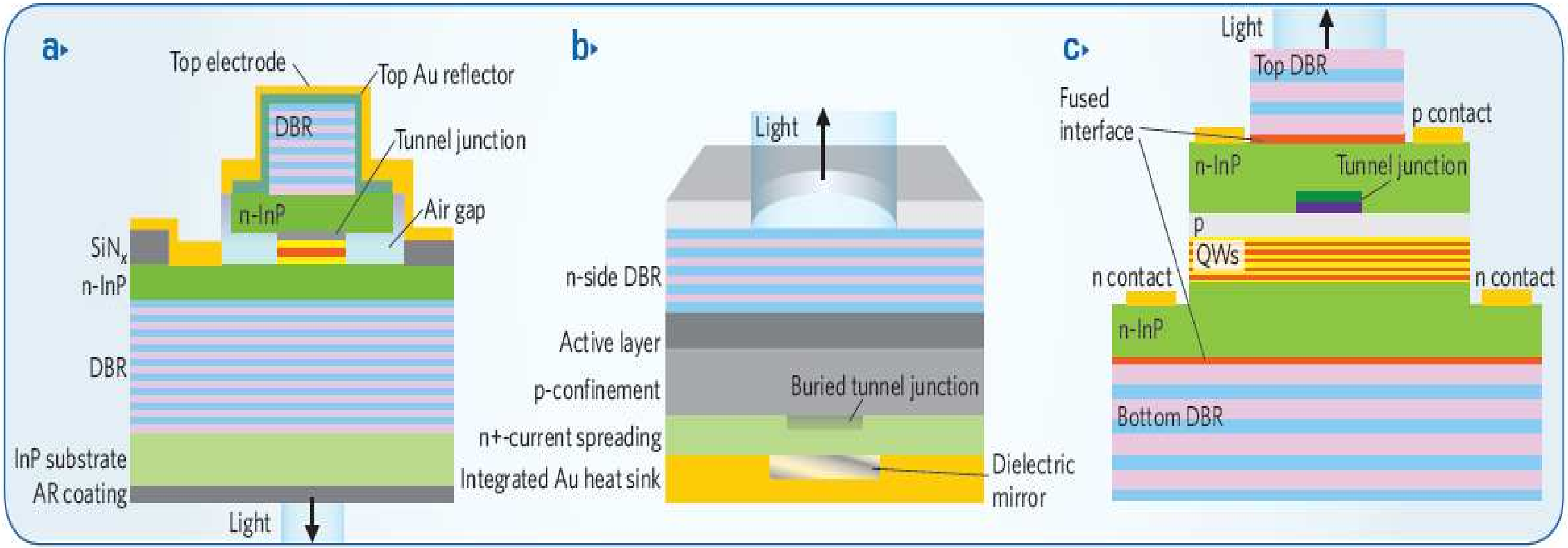


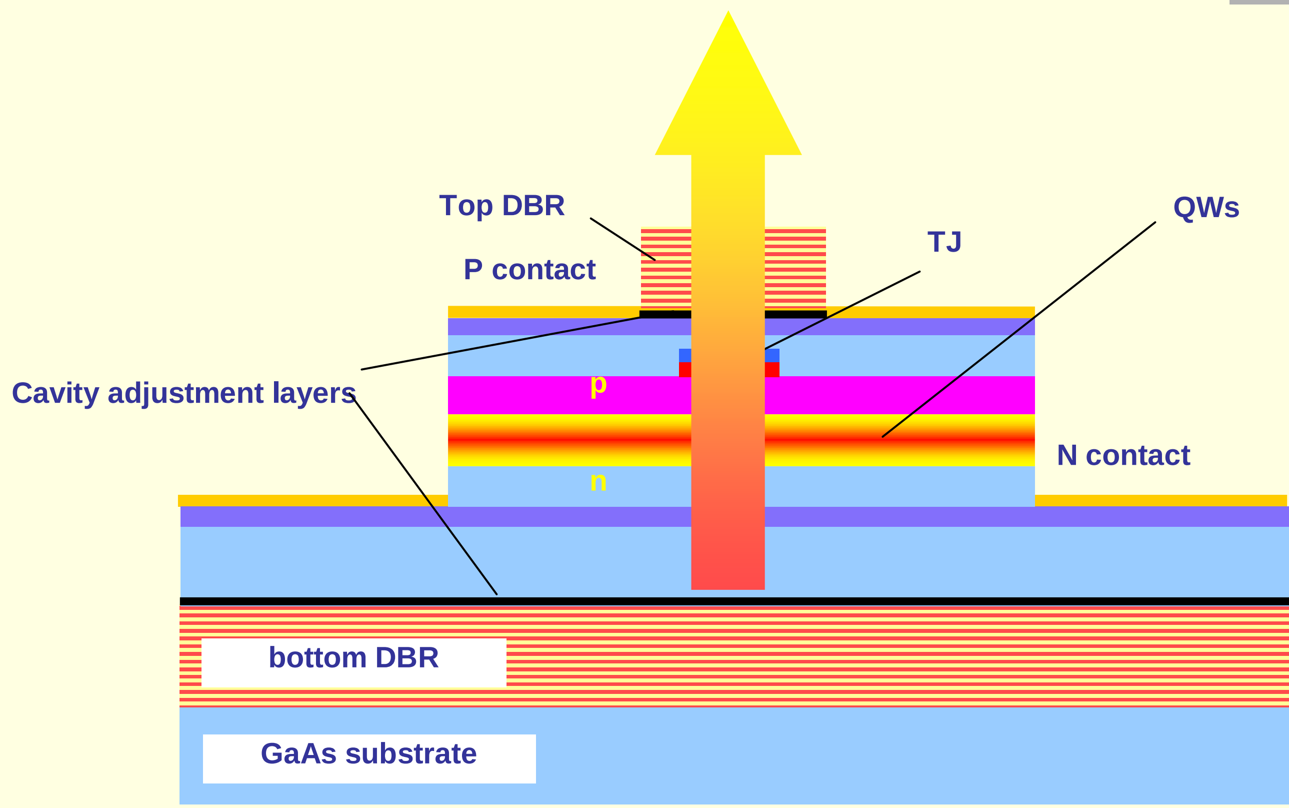
Table 1 | Current performance of LW-VCSELs

Aperture type	Mirror design	SM P_{max}, 20 °C	SM P_{max}, 80 °C
Undercut QWs	Top and bottom as-grown DBRs: InAlGaAs/InAlAs, or AlGaAsSb	1.6 mW	0.5 mW @ 70 °C
Buried TJ	One as-grown InAlGaAs /InAlAs DBR; one dielectric DBR	4.3 mW	1.4 mW
Regrown TJ	Both wafer-fused AlGaAs/GaAs DBRs	6 mW	2.5 mW

SM P_{max} 20 °C (80 °C), single-mode maximum power output at 20 °C (80 °C); TJ, tunnel junction.; QW, quantum well

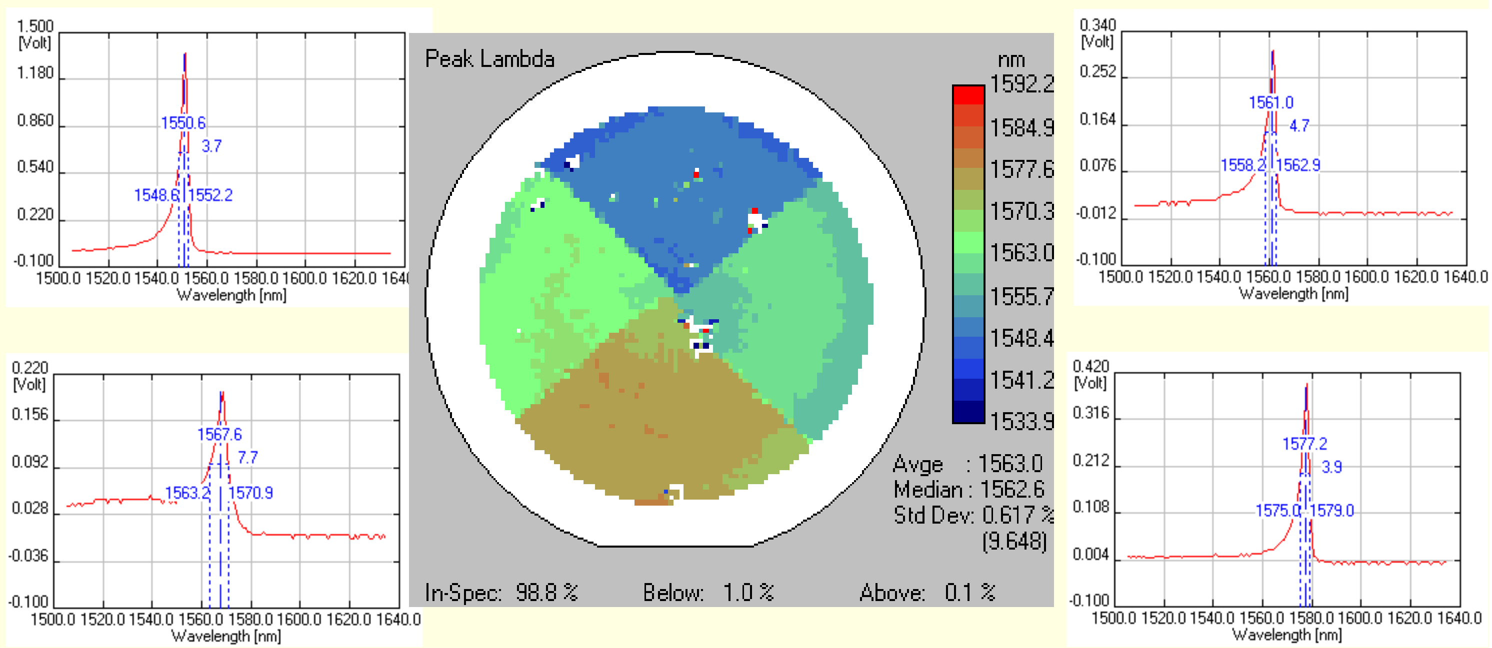
E.Kapon, A. Sirbu, Nature photonics, Technology focus, pp.27-29, 2009

1500 nm-2000 nm VCSEL design



4 regions on the wafer with different emission wavelengths

Cavity Mapping of double-fused wafer

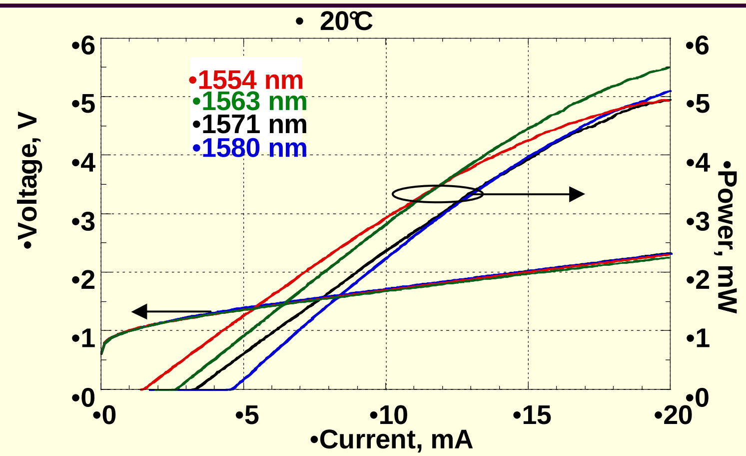


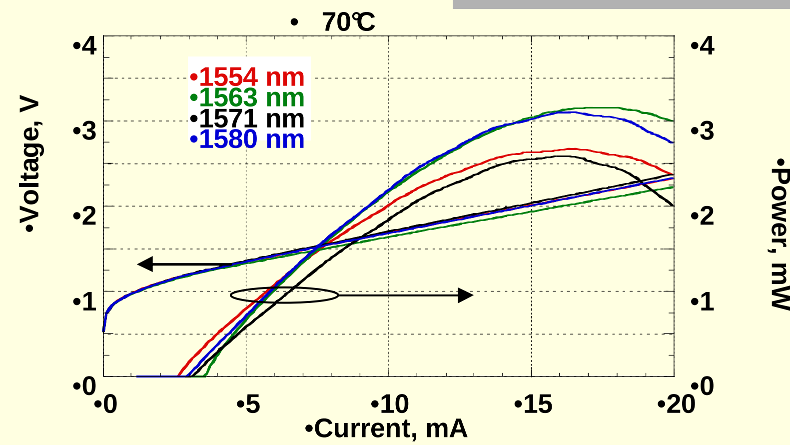
Emission at 1550 nm, 1560 nm, 1570 nm, 1580 nm

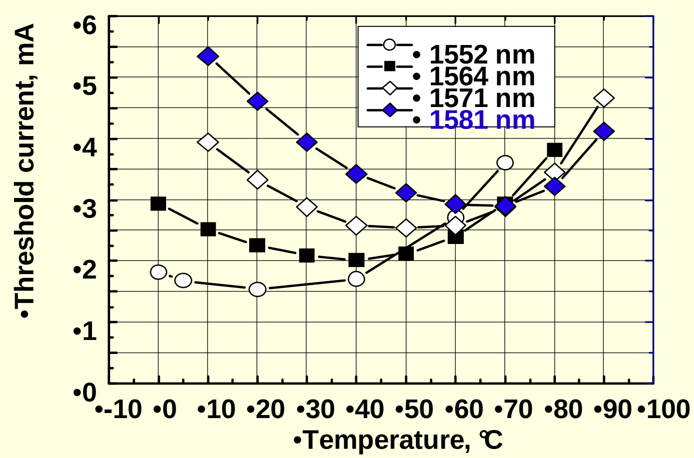
corresponds to off-sets of 30 nm, 40 nm 50 nm 60 nm

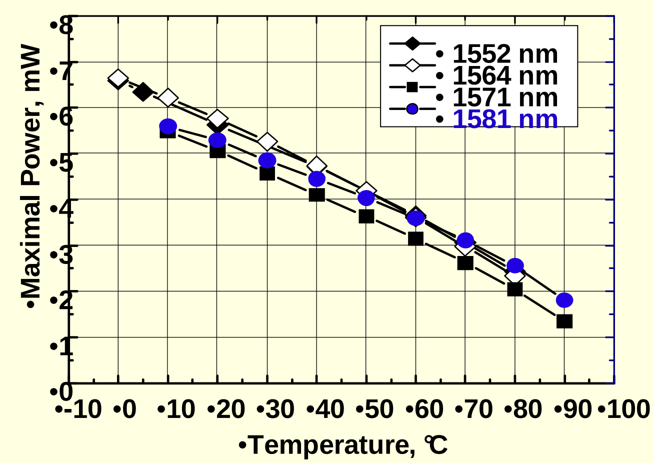
A. Sirbu, Invited talk AOE-08, A. Caliman, et al, ECOC-08

1550 nm LI and IV Characteristics (7 µm aperture)









- Max RT output: at 1560 nm (40 nm off-set);
- Max HT (90℃) output: at 1580 nm (60 nm off-set)

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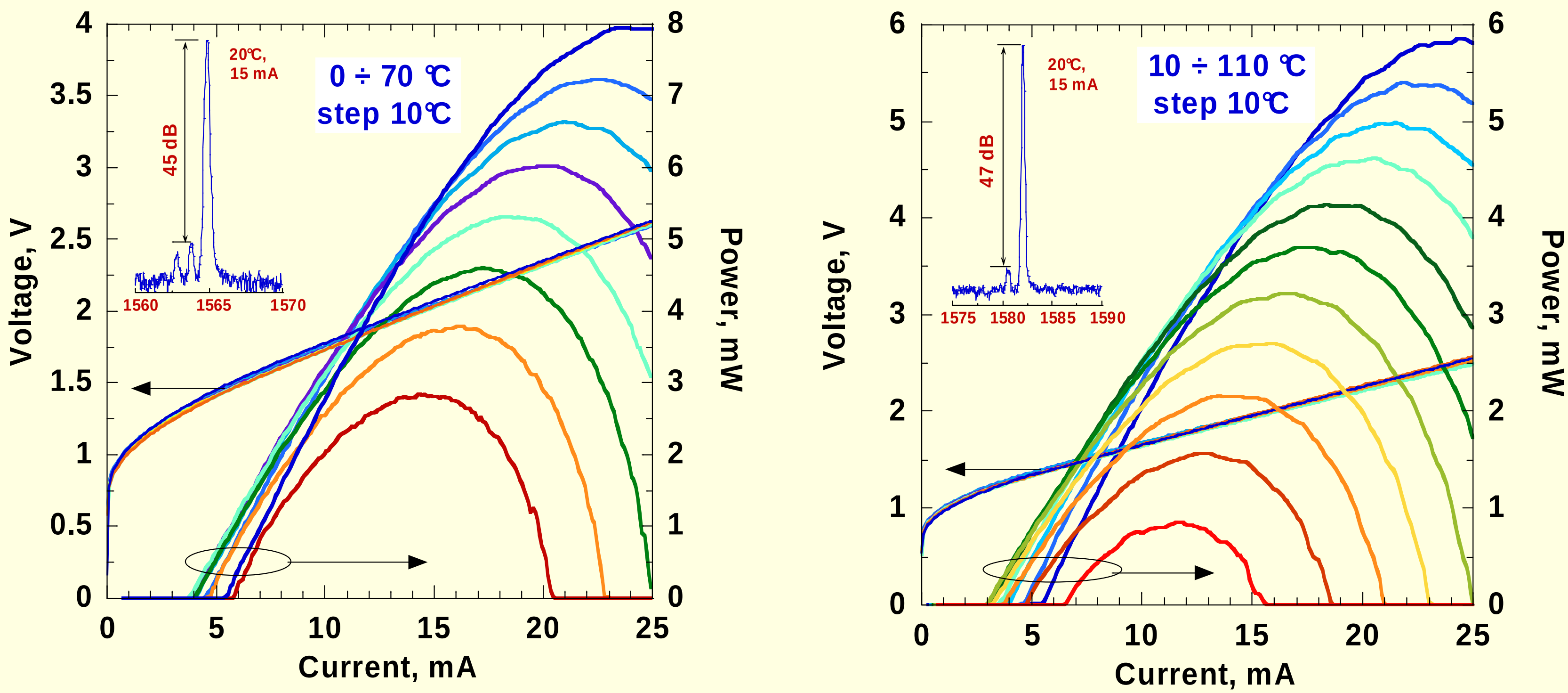
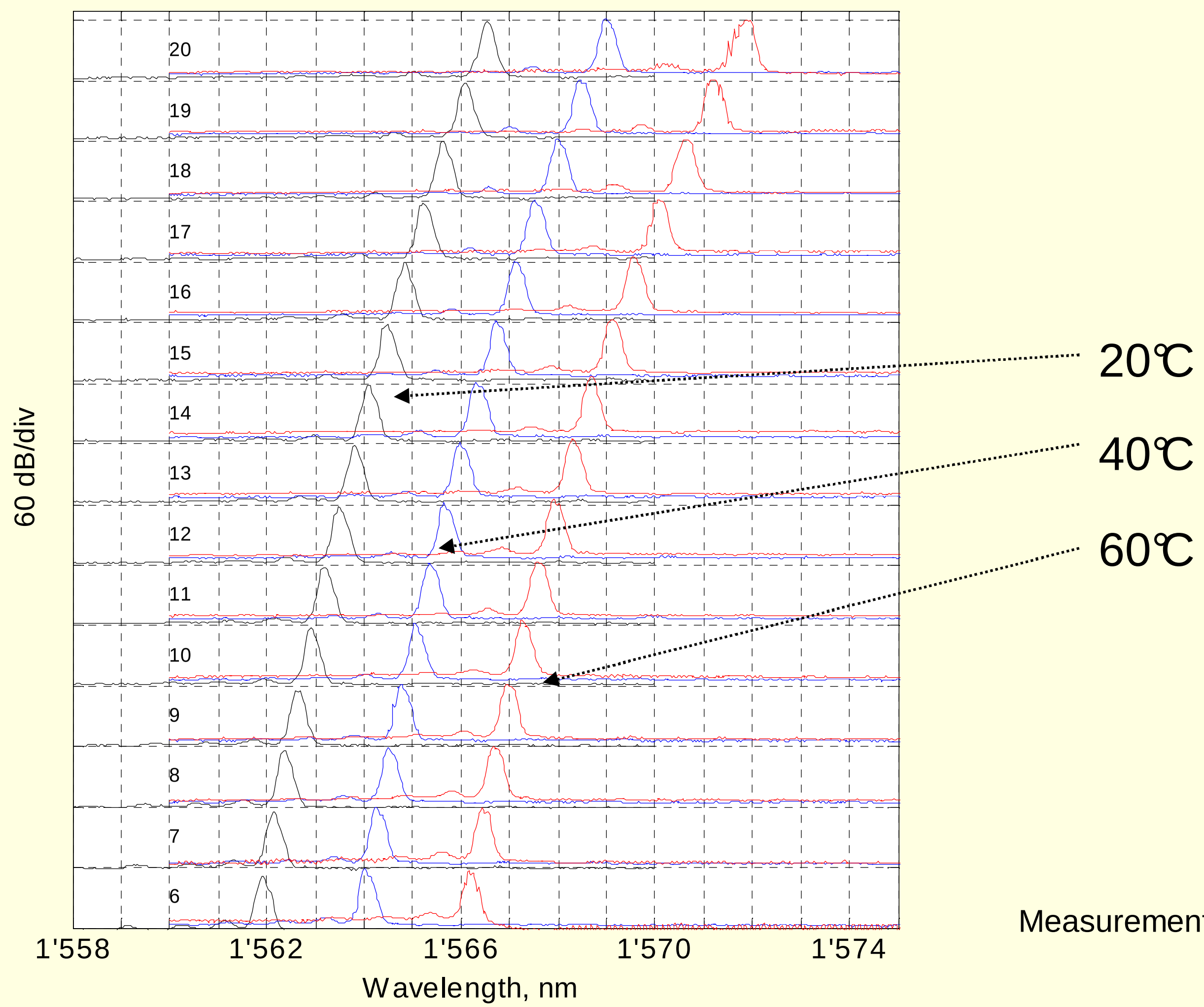
LIVs at different emission wavelengths



A. Caliman, To be presented at CLEO-09

Emission spectra vs current



Measurements by V. Iakovlev,

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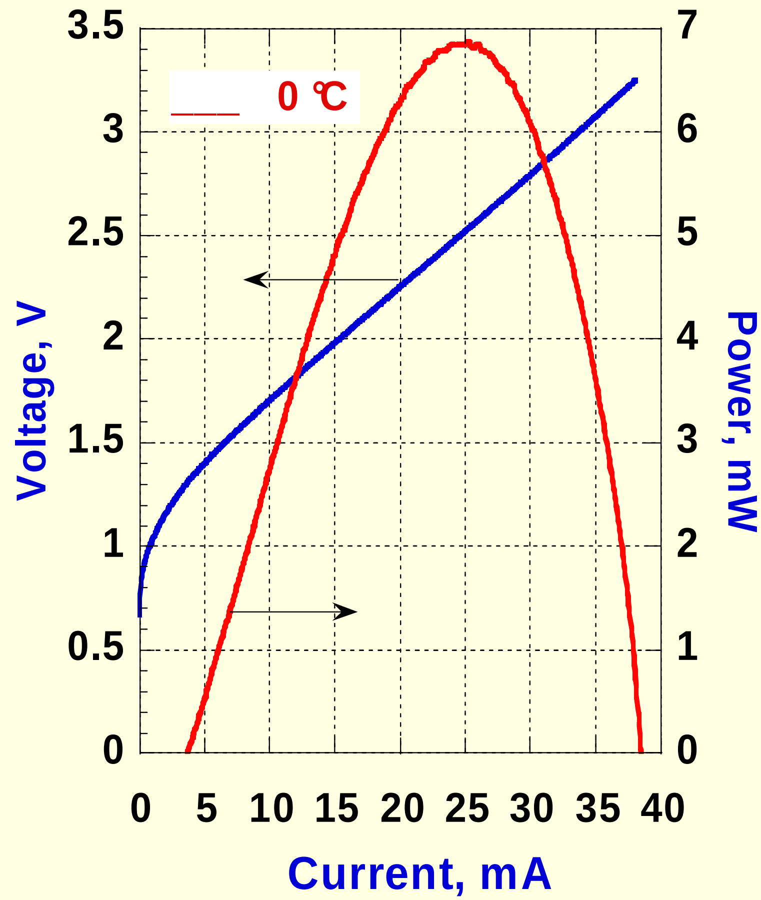
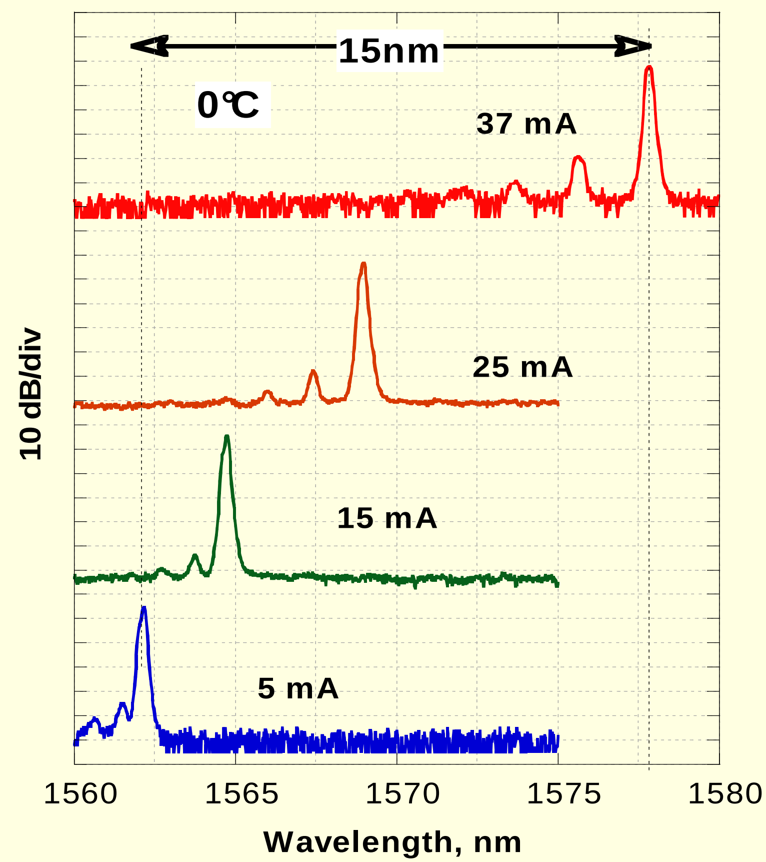
Tuning with current





E. Kapon, Invited talk ISLC-08

1550 nm ar-field emission and line-width

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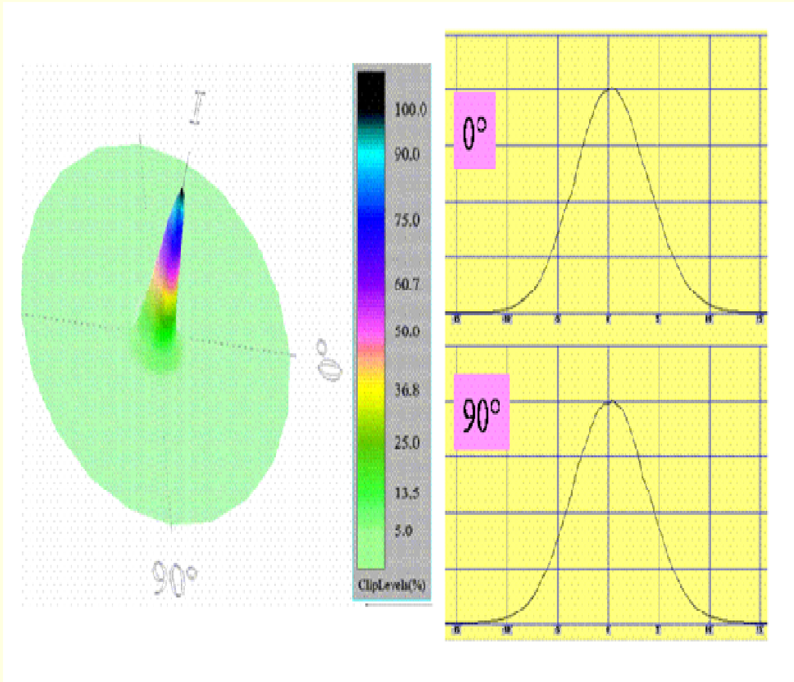
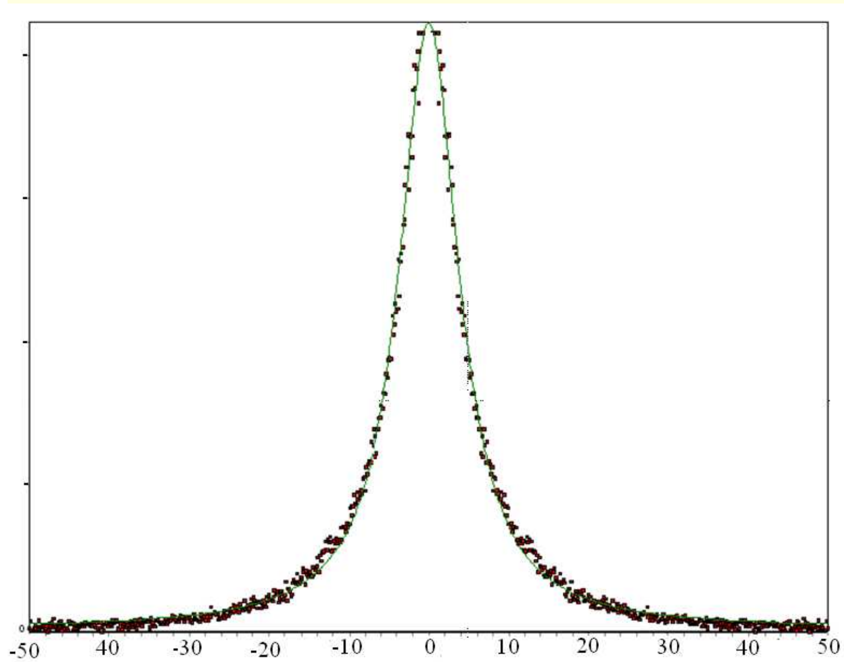
Far-field and line-width measurements performed at 2 mW output, RT





FWHM=9°

Lorentzian line-shape; $\Delta\nu$ = 4.5 MHz

Self-homodine line-width measurements performed by M.Grossenbacher, ED EPFL

Wavelength selection in the 2000 nm band

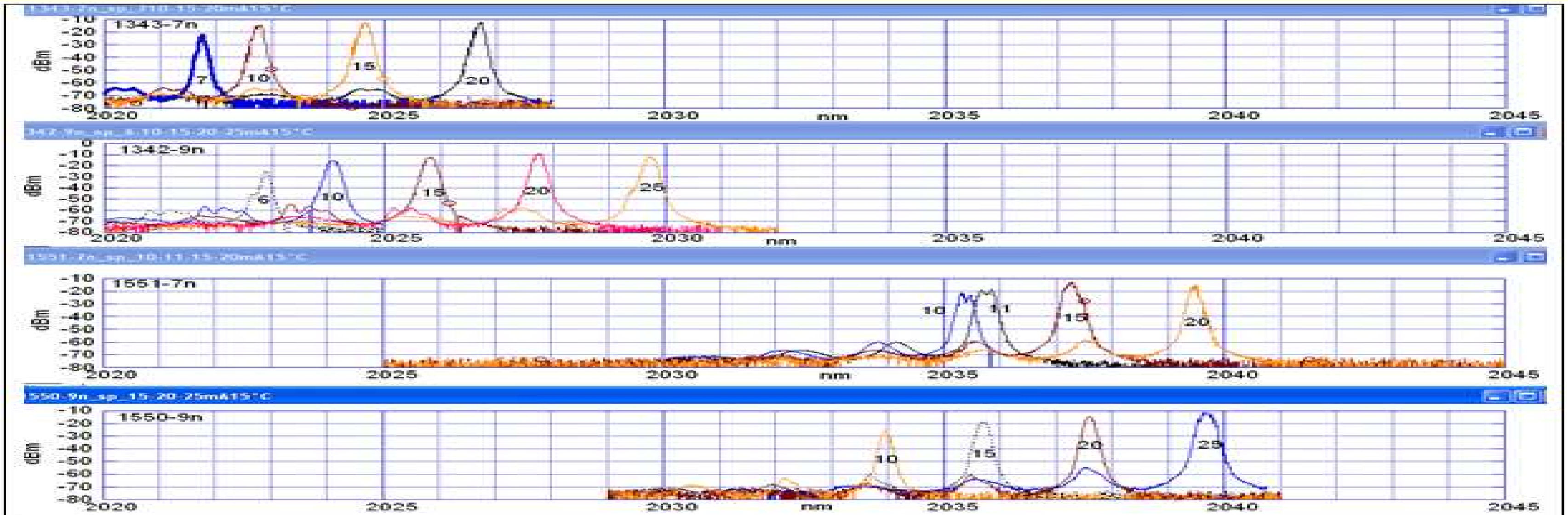


Figure 1 spectra

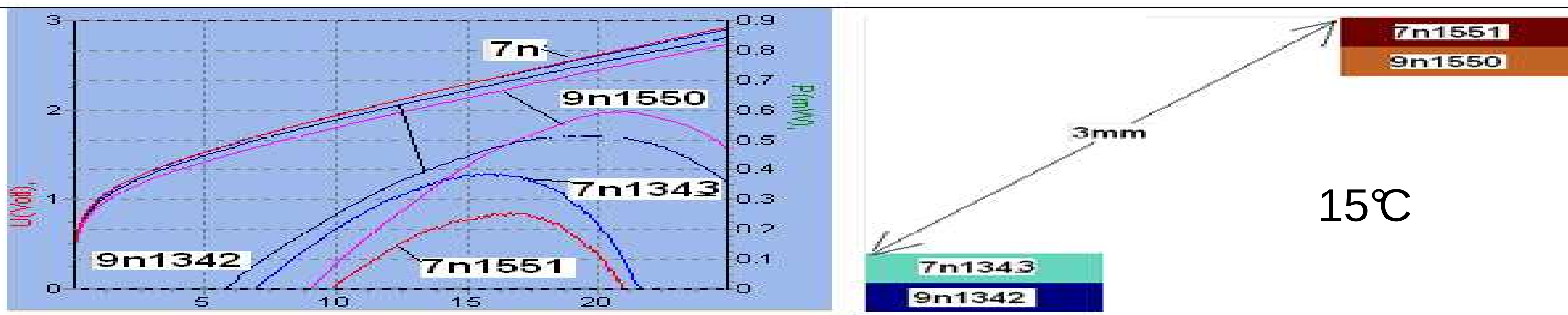
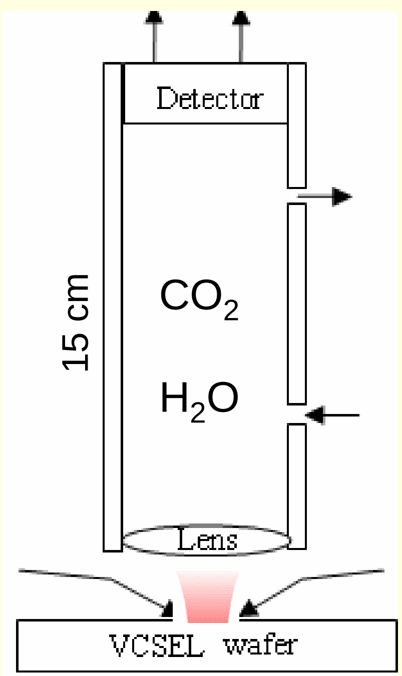
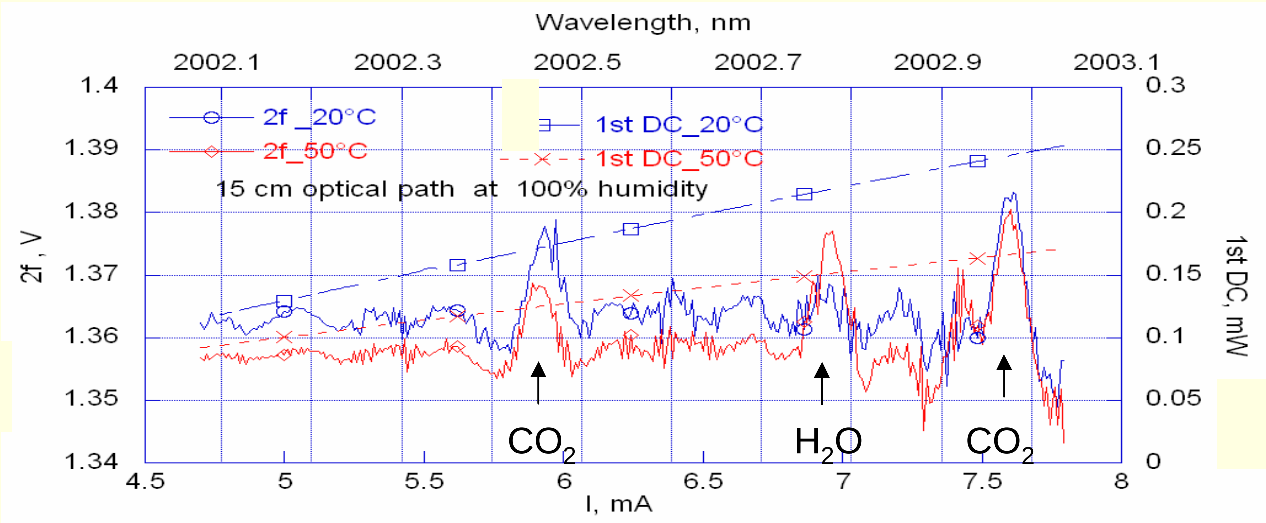


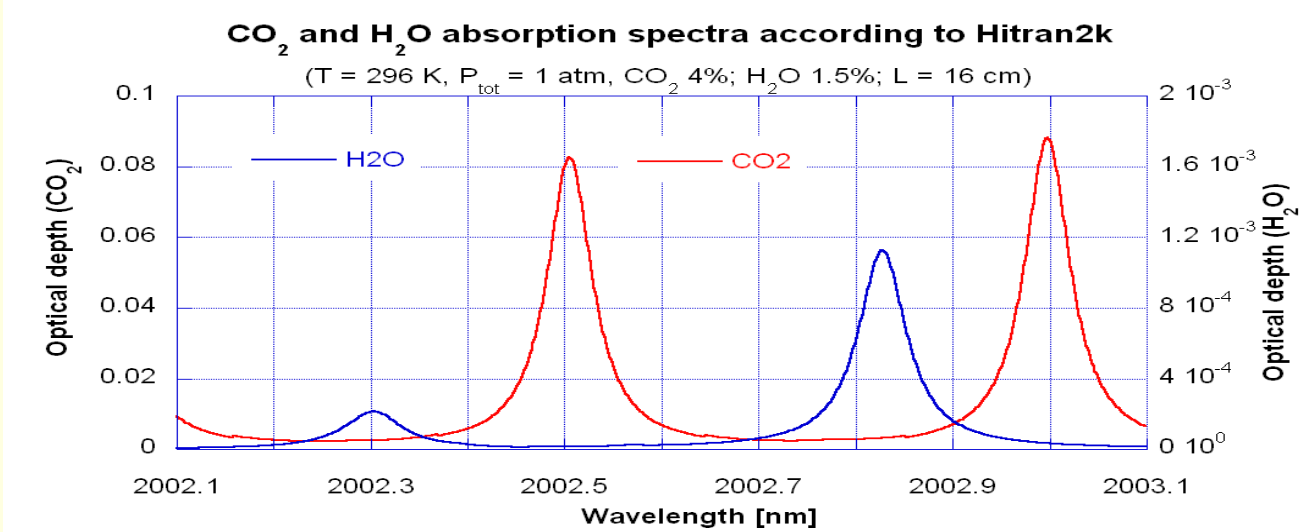
Figure 2. LIV of 4 devices

V. Iakovlev, Internal report

Two-species detection: CO_2 and H_2O

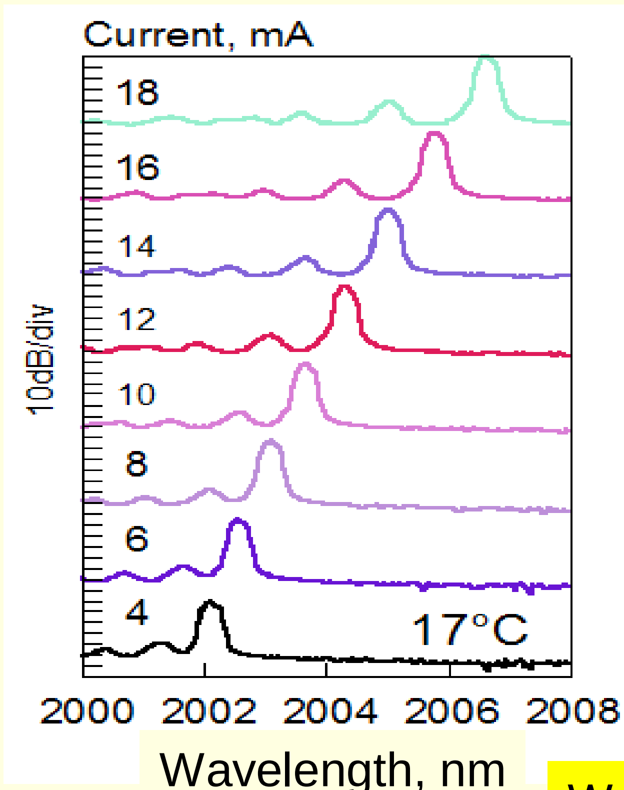


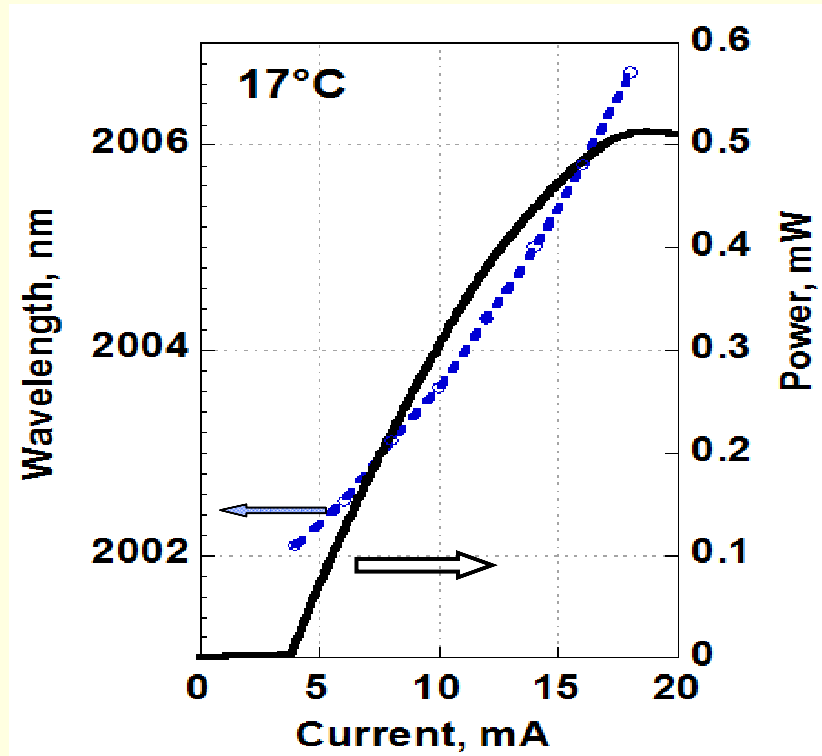




V. Iakovlev, Internal report

Wavelength tuning





Wavelength tuning range ~ 5 nm

Single mode emission in the 4-18 mA current range

Wavelength tuning rates:
– $\Delta\lambda/\Delta I \sim 0.31$ nm/mA
– $\Delta T/\Delta I \sim 0.14$ nm/℃

A. Mereuta et al. PTL 2008, IPRM-2008

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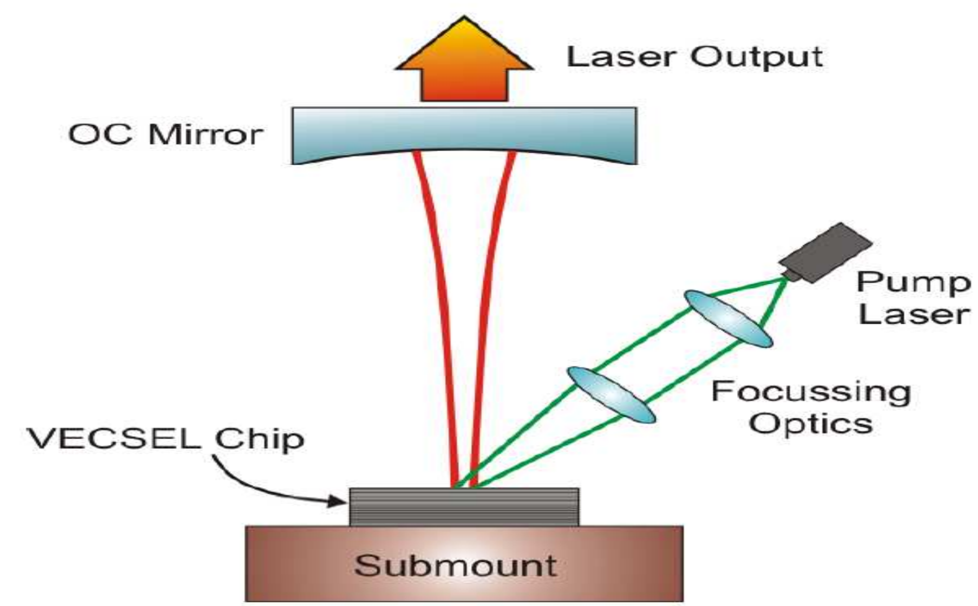
VECSEL scheme



VECSELs: circular difraction limed high power output

M.Kuznetsov, PTL, vol.9, pp.1063-1065, 1997

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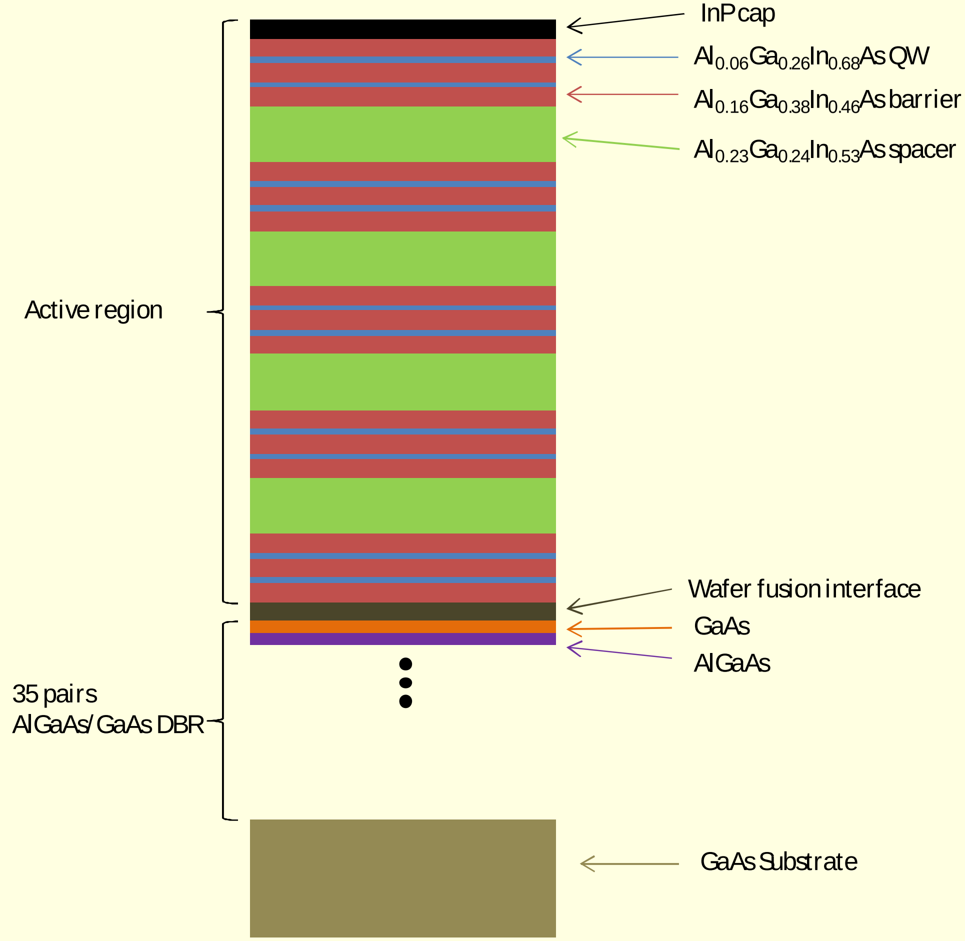
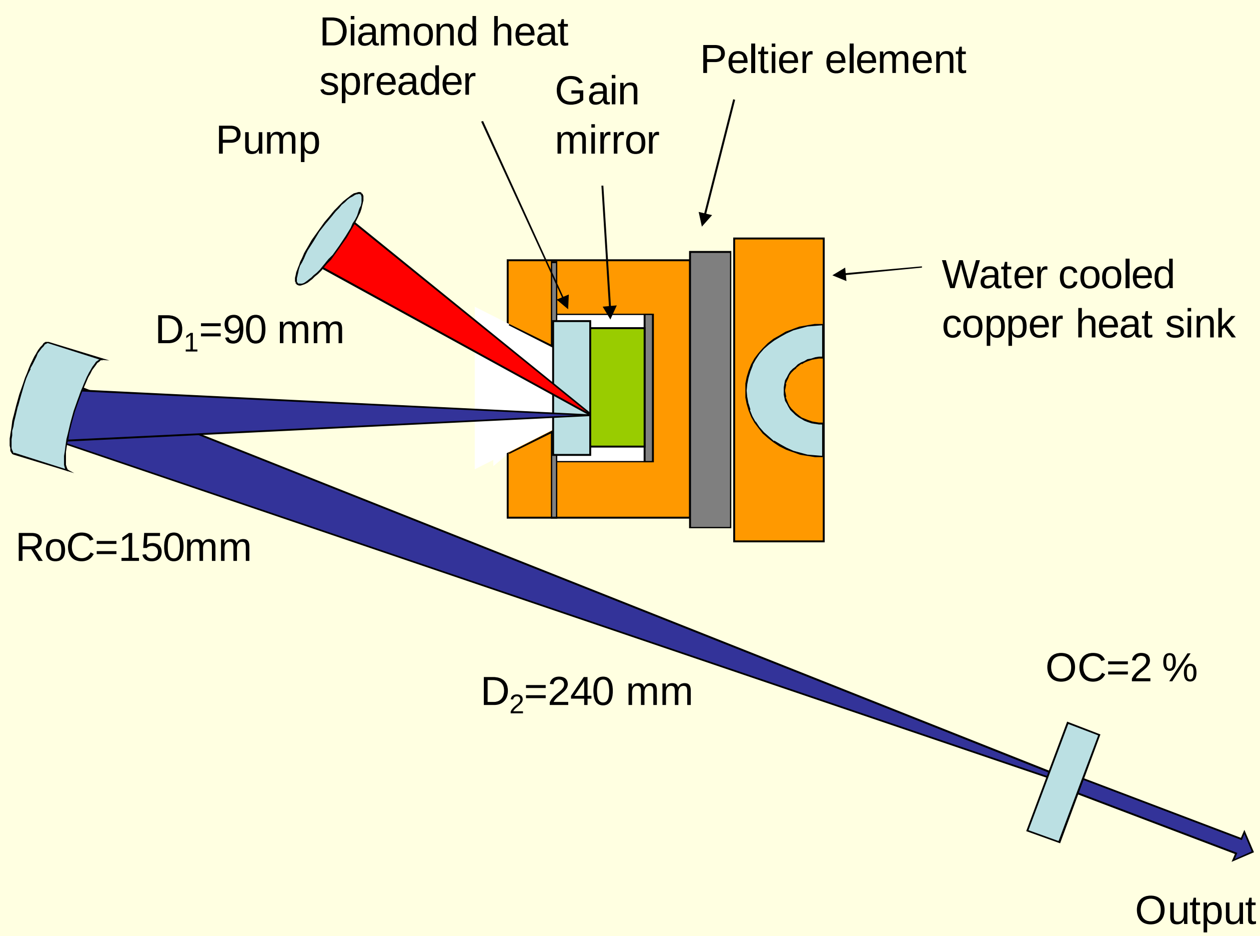
1550 nm VECSEL half-cavity

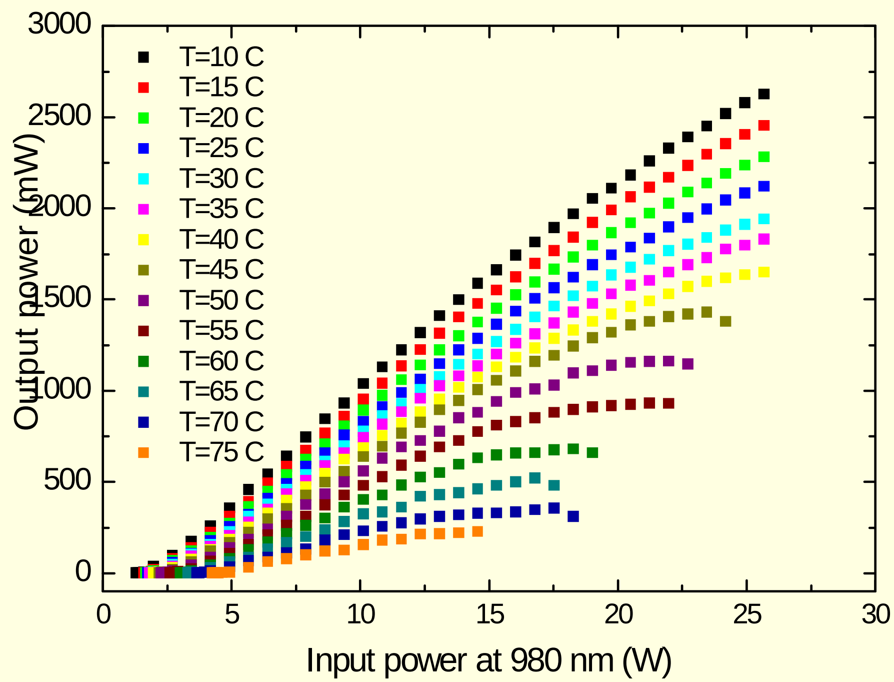


A.Sirbu et al., To be presented at OFC-09

1550 nm VECSEL pumping scheme



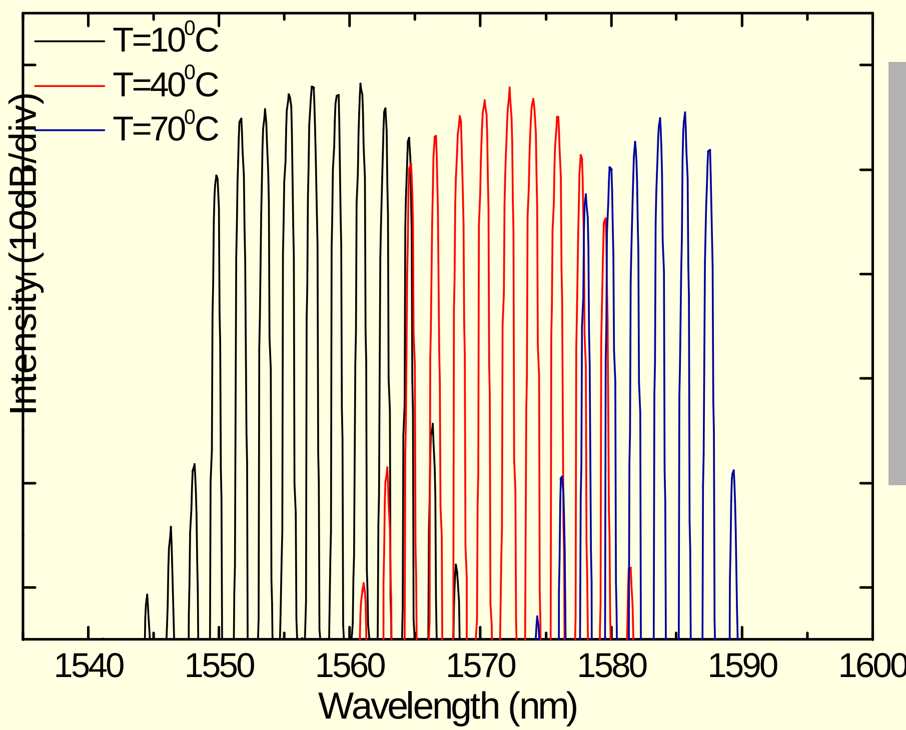
Output characteristics



J. Rauticainen, J. Lyytikainen, A. Sirbu, A. Mereuta, A. Caliman, E.Kapon, O.Okhotnicov, **Optics Express**, Dec. 2008

x 10 improvement compared with previous published results

Spectral characteristics



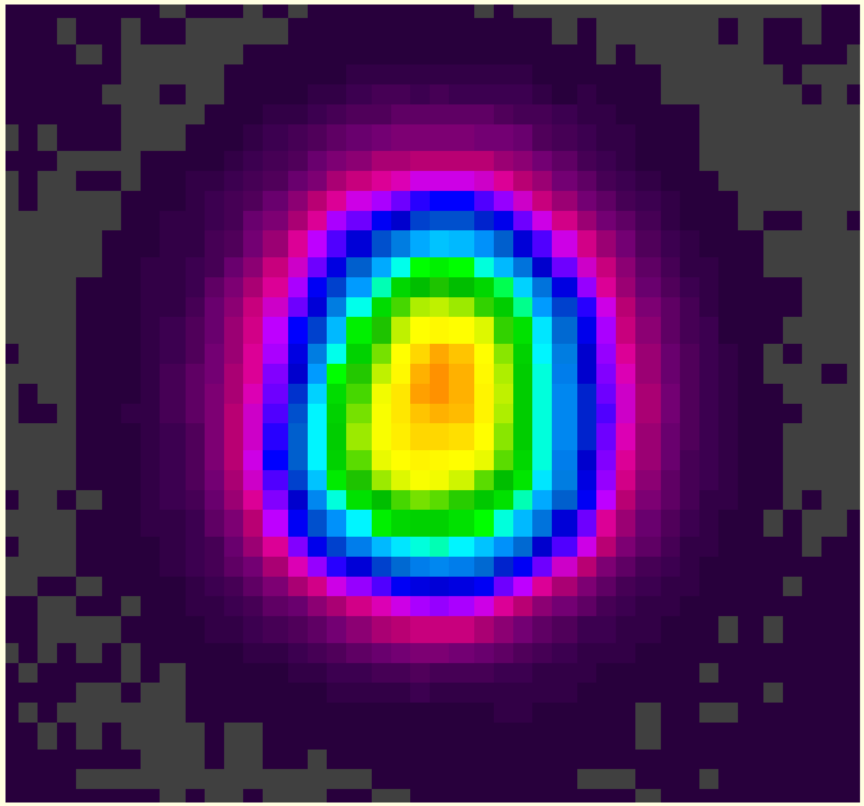
Spectra are taken at 10.9 W of 980 nm pump power.

Shift with temperature:

0.42 nm/℃

Wavelength combes: multiple reflections in the diamond heat-spreader

Far-field pattern



Far field pattern distribution measured with a pyrocamera

Summary

- Emerging spectroscopy developments in fiber-bragg sensors, tunable laser diode spectroscopy, and photo-acoustic sensors require laser sources with prescribed wavelengths, continuous tuning, narrow linewidth and high output power in the 1500 nm 2000 nm
- 1500 nm-2000 nm state of the art wafer fused VCSELs demonstrate fundamental mode output of 6+mW, excellent on-wafer wavelength control in the 50 nm band, narrow linewidth of below 5 MHz and continuous wavelength tuning of up to 15 nm. First gas sensing experiments have been successfully performed.
- High power of 2 W+ diffraction limited VECSELs in the 1550 band are demonstrated for the first time. Application in Ph. Application in acoustic sensing to be evaluated.

Thank you for your attention