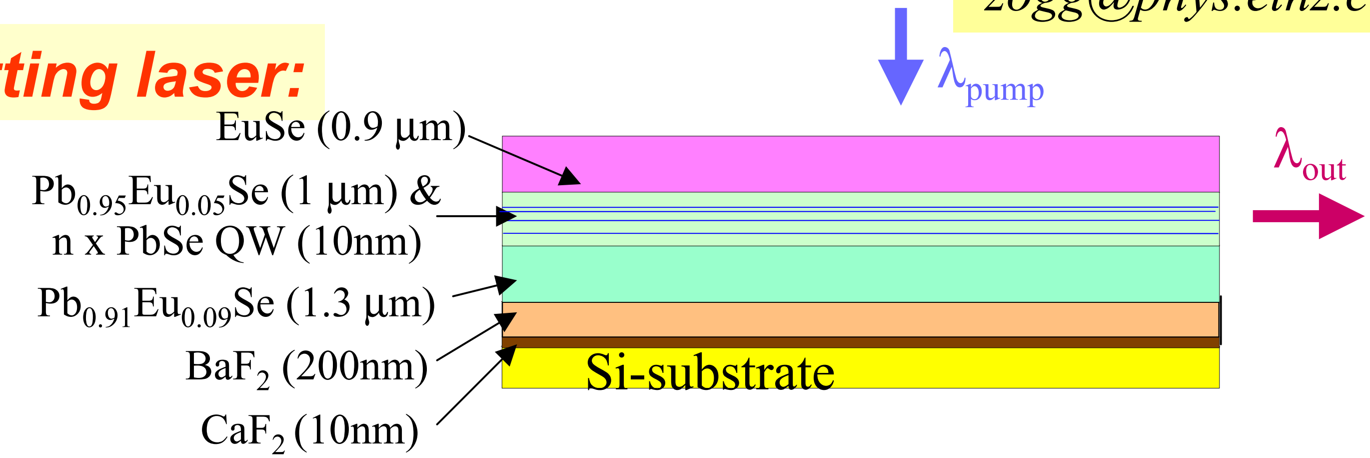
# Optically pumped lead-chalcogenide infrared-emitters on Si-substrates

***Klaus Kellermann, Karim Alchalabi, Dmitri Zimin, Hans Zogg***
Thin Film Physics Group, Swiss Federal Institute of Technology, Zurich

*http://www.tfp.ethz.ch*
*phone 01 445 1480*
*FAX 01 445 1499*
*zogg@phys.ethz.ch*

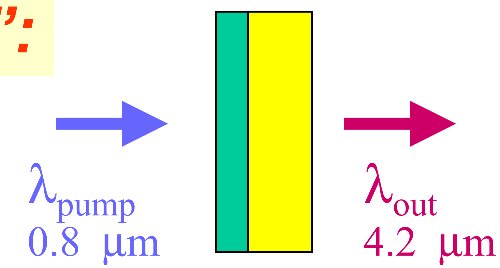
*low-cost mid-IR emitters:*
*pump optically with low cost 0.8 - 1.5 μm laser-diodes!*

## *a) 3-6 μm edge-emitting laser:*




## *b) 3-6 μm "wavelength transformer":*

***(VCSEL in sub-threshold)***




**TDLS E16, p.144**

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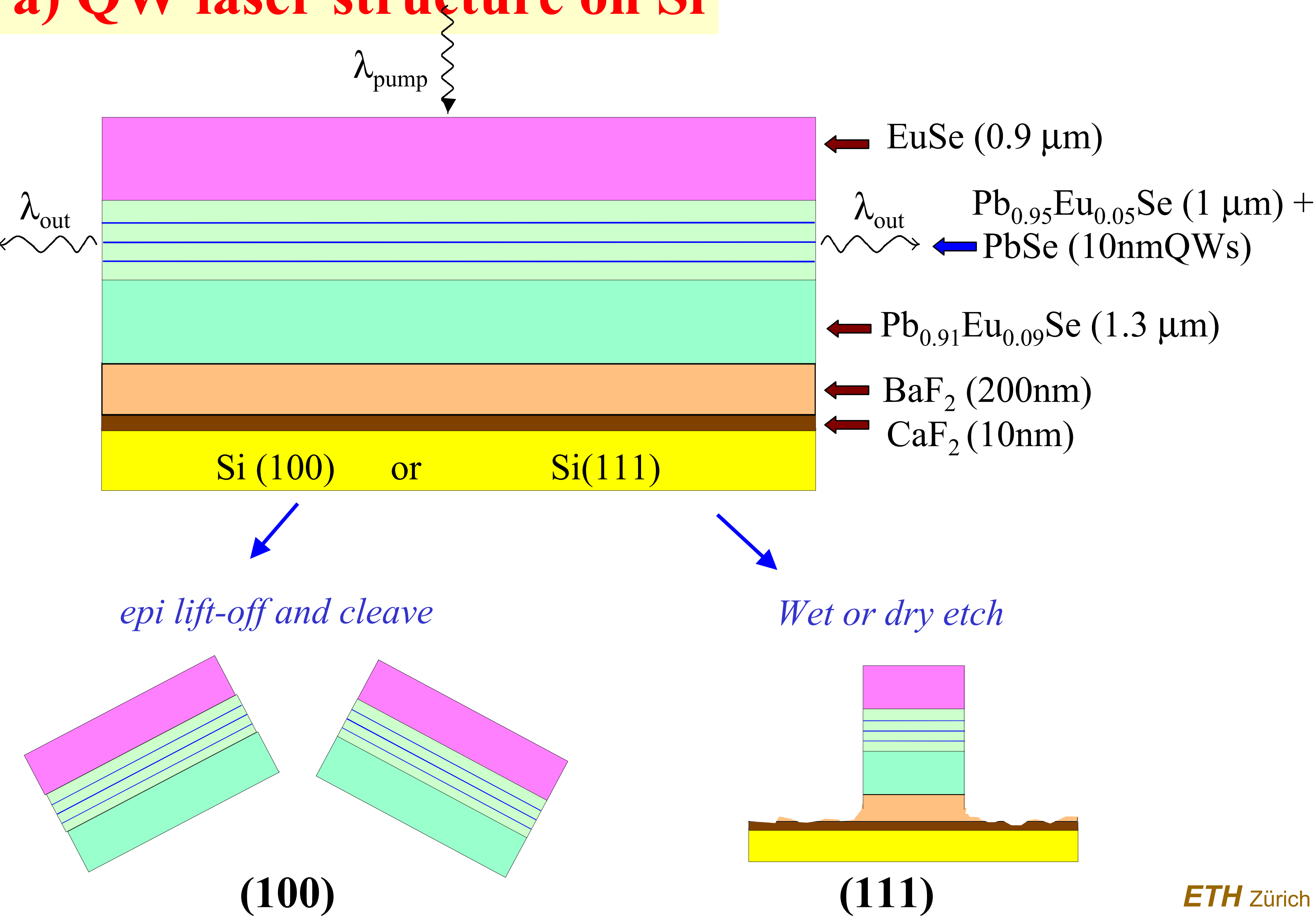
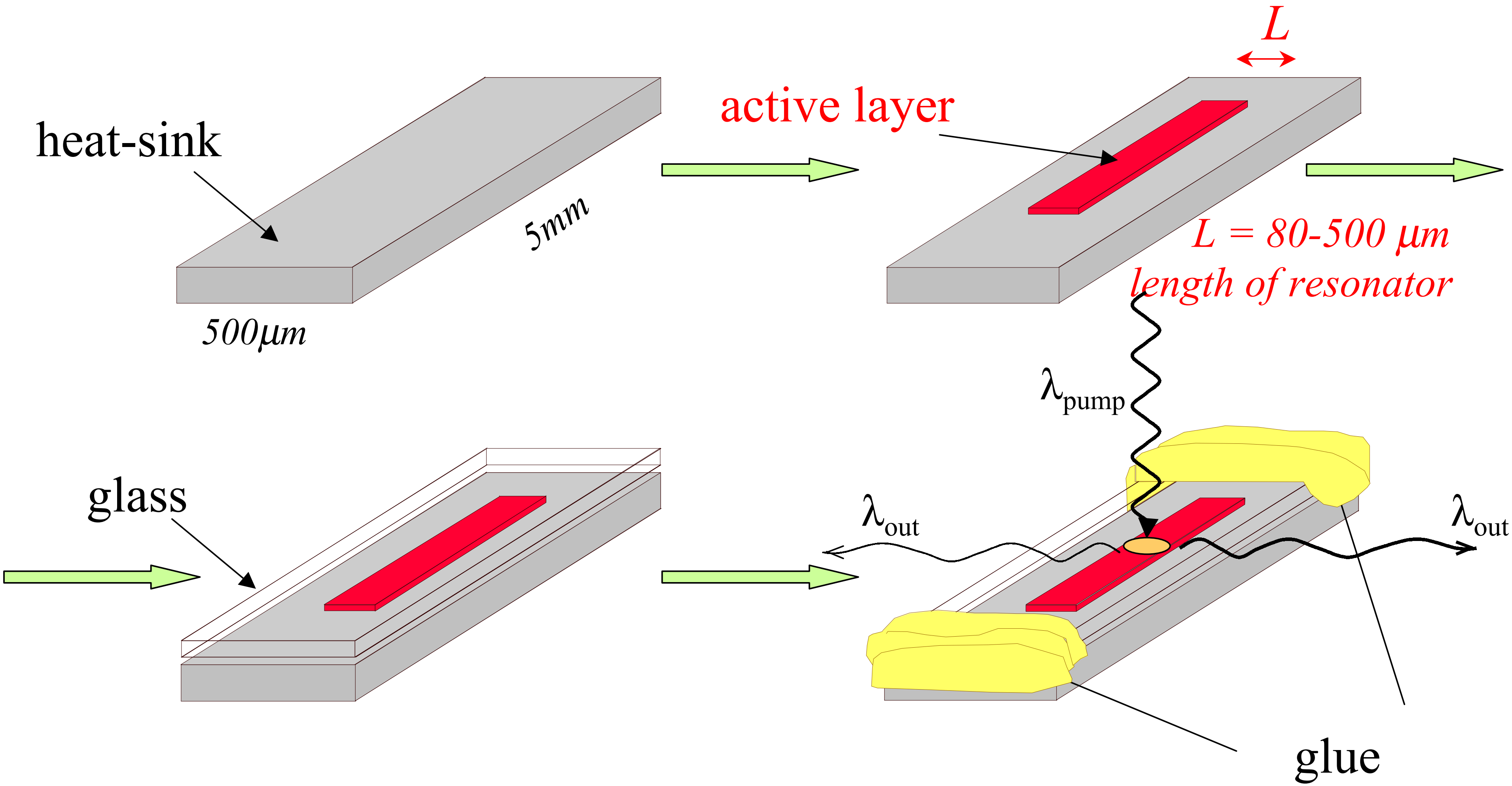
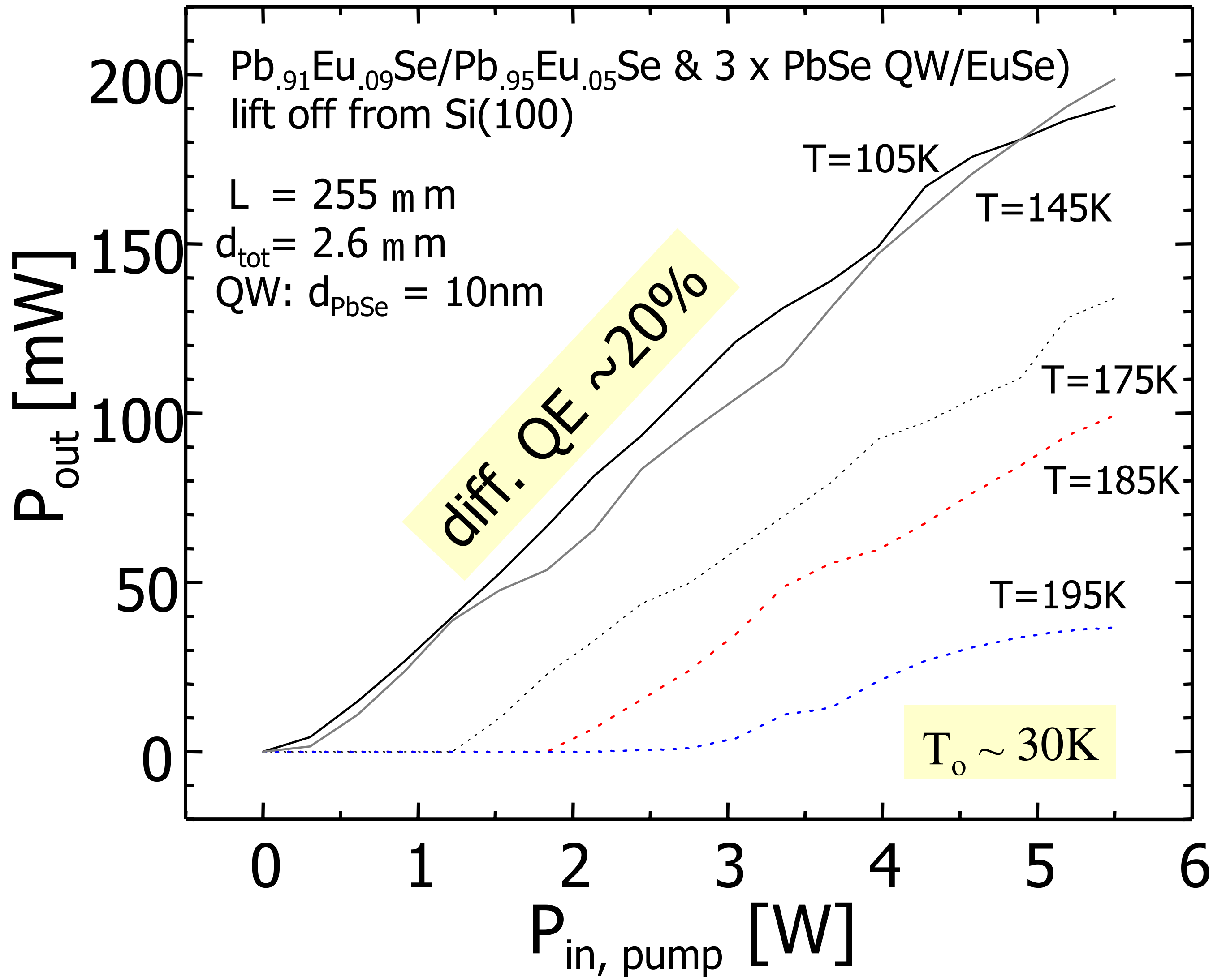
# a) QW laser structure on Si

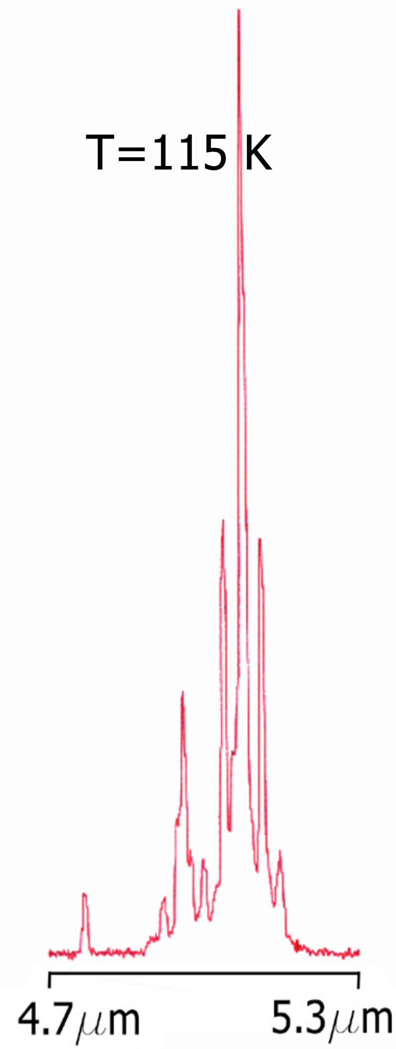


# a) on Si(100): Epi lift-off and cleave



# a) laser results on Si(100), cleaved mirrors



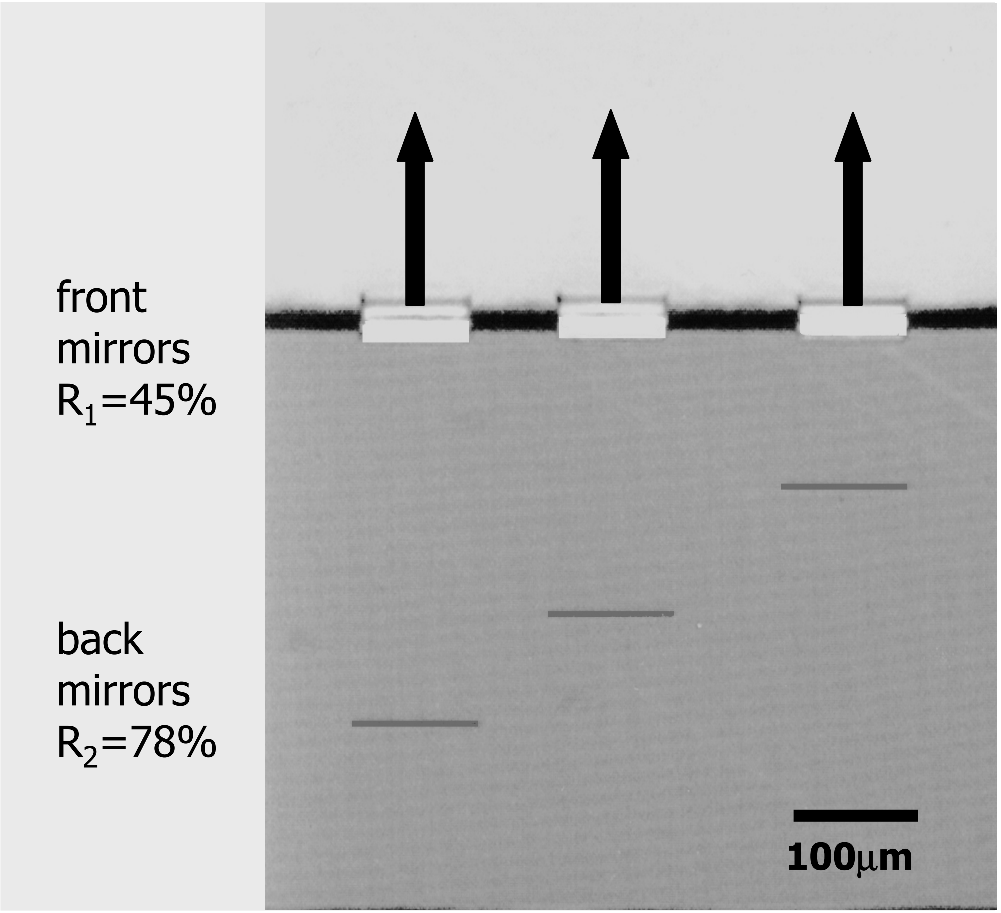




limited power of pump-diode: lasing up to 250 K

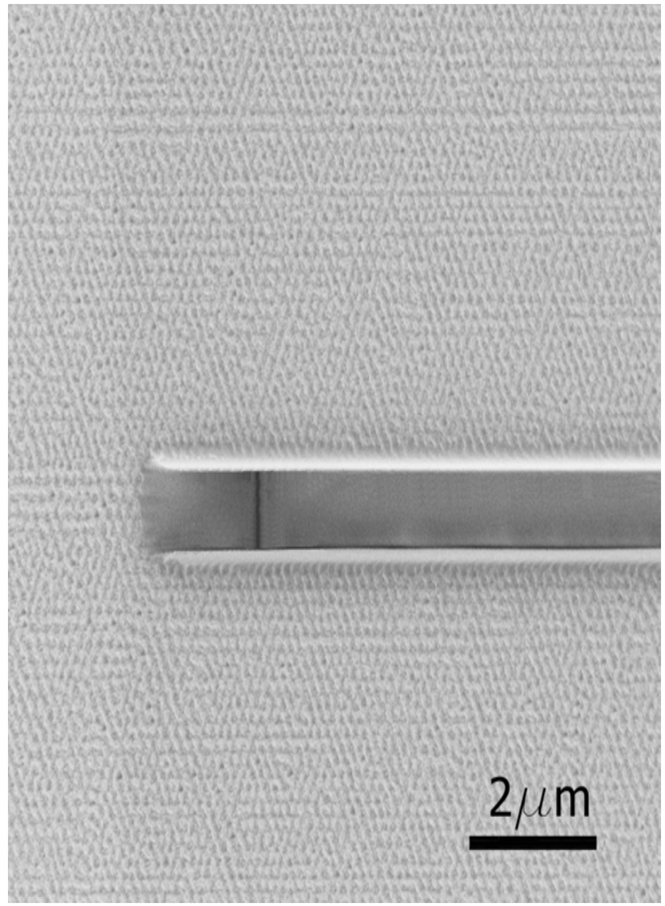
# a) on Si(111): no cleaved mirrors

## dry-etched mirrors for PbSe-based DH & QW laser structures on Si(111)

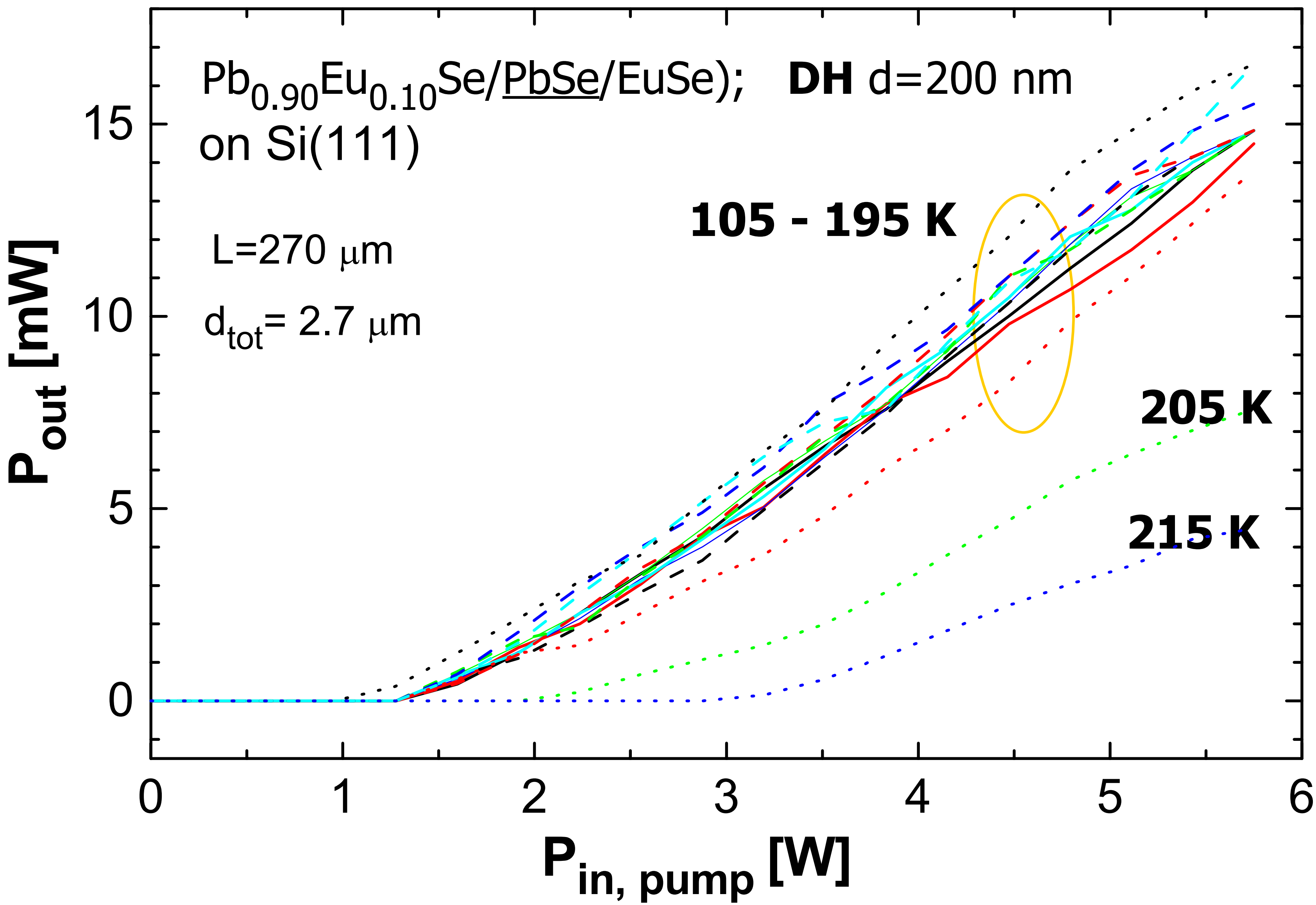
3 lasers with different cavity lengths etched in one substrate




detail of a back Bragg mirror with two λ/4 grooves for very high reflectivity



# a) laser results on Si(111), etched mirrors

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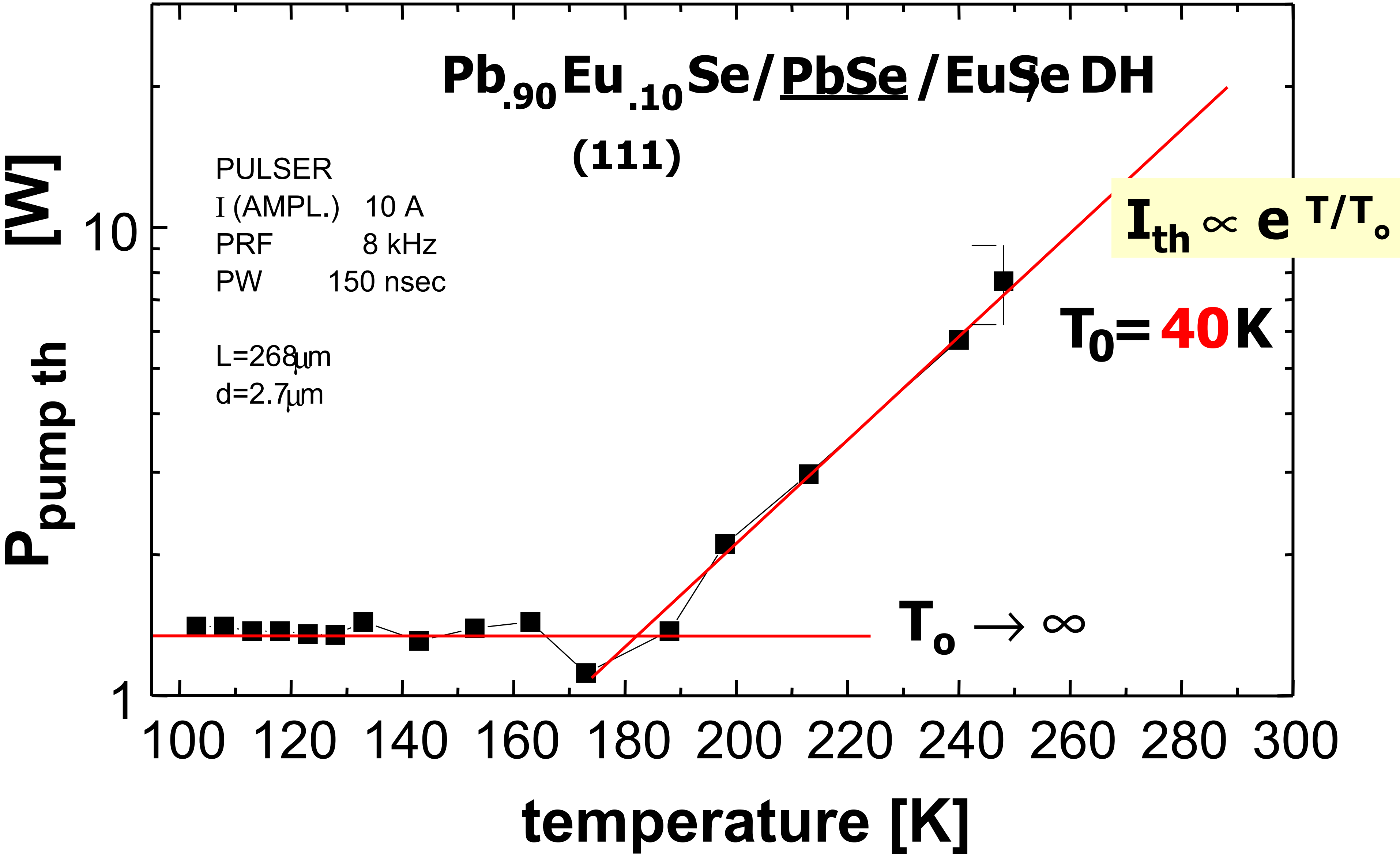
# a) DH-structure on Si(111), etched mirrors



# a) Specifications: optically pumped IV-VI mid-IR lasers (preliminary):

**Material:** PbX/PbEuX (X = Se, Te), grown by MBE on Si-substrate

**Structure:** Edge emitter, length of resonator e.g. 300 µm (matched to width of pump-source)
Width of resonator: given by pump source (no lateral delineation needed)

**Crystallographic orientation, Resonant mirrors and mount:**
grown on Si(100): (100)-orientation, epitaxial lift-off, cleaved mirrors, mount on heat-sink
grown on Si(111): (111)-orientation, etched mirrors, heat-sink=Si-substrate

**Wavelength range:** with PbSe QWs: ca. 3 - 6 µm
given by design (width of the QWs) and temperature.
longer wavelengths up to 30 µm: with PbSnSe QWs (in preparation)

**wavelength tuning:**

*- by temperature*
ca. $2 \times 10^{-3}$ /K (change of band-gap with T), ca. $3 \times 10^{-4}$/K (for fixed mode, mainly T-dependence of refractive index)

*- by mechanical movement:*
move laser bar with slightly varying thickness of QWs with respect to pump laser

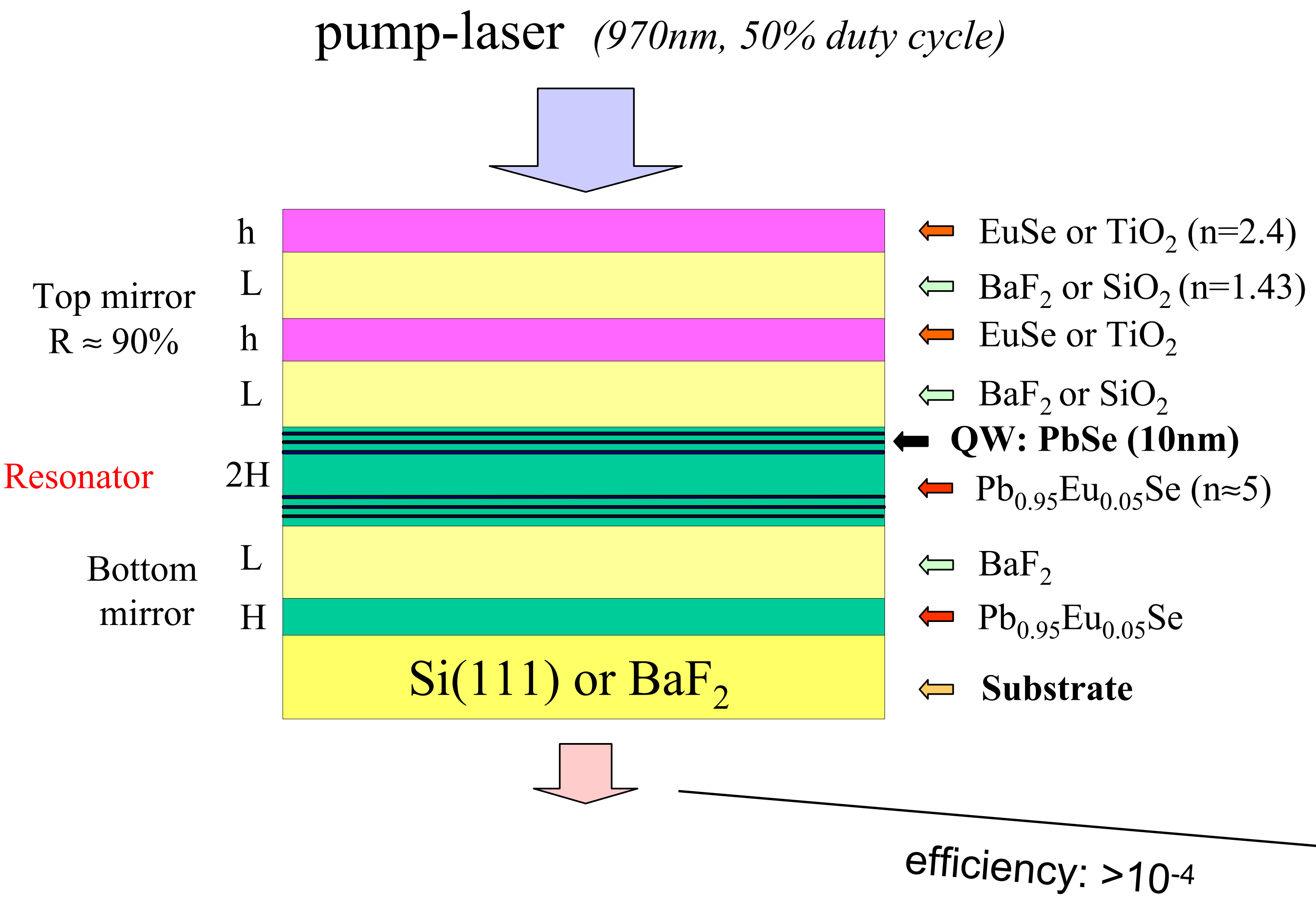
**Excitation:** low cost laser-diode with e.g. 870 nm wavelength
(focusing: Use a lens, or just place the IV-VI laser structure near (within e.g. 30 µm) the pump laser exit face.

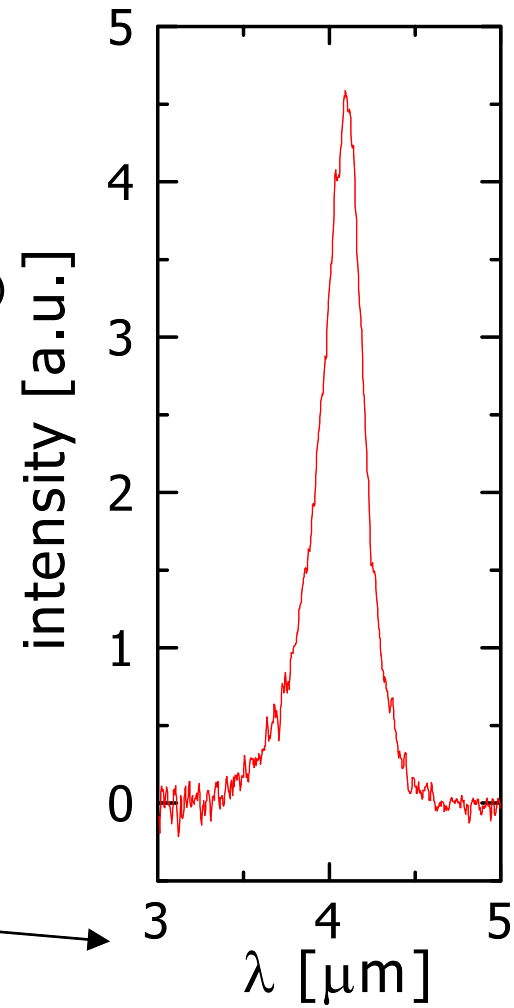
**Emission power: up to 200 $mW_p$** (tested at 4-5 µm wavelength)

**Operation temperature:**
Presently up to 250K (with pump power of 5 $W_p$), larger T with larger pump powers
In preparation: Optimising laser structure for lowest threshold near or at RT

# b) on Si(111): Resonant cavity mid-IR-source (at RT)

## = VCSEL operated in sub-threshold

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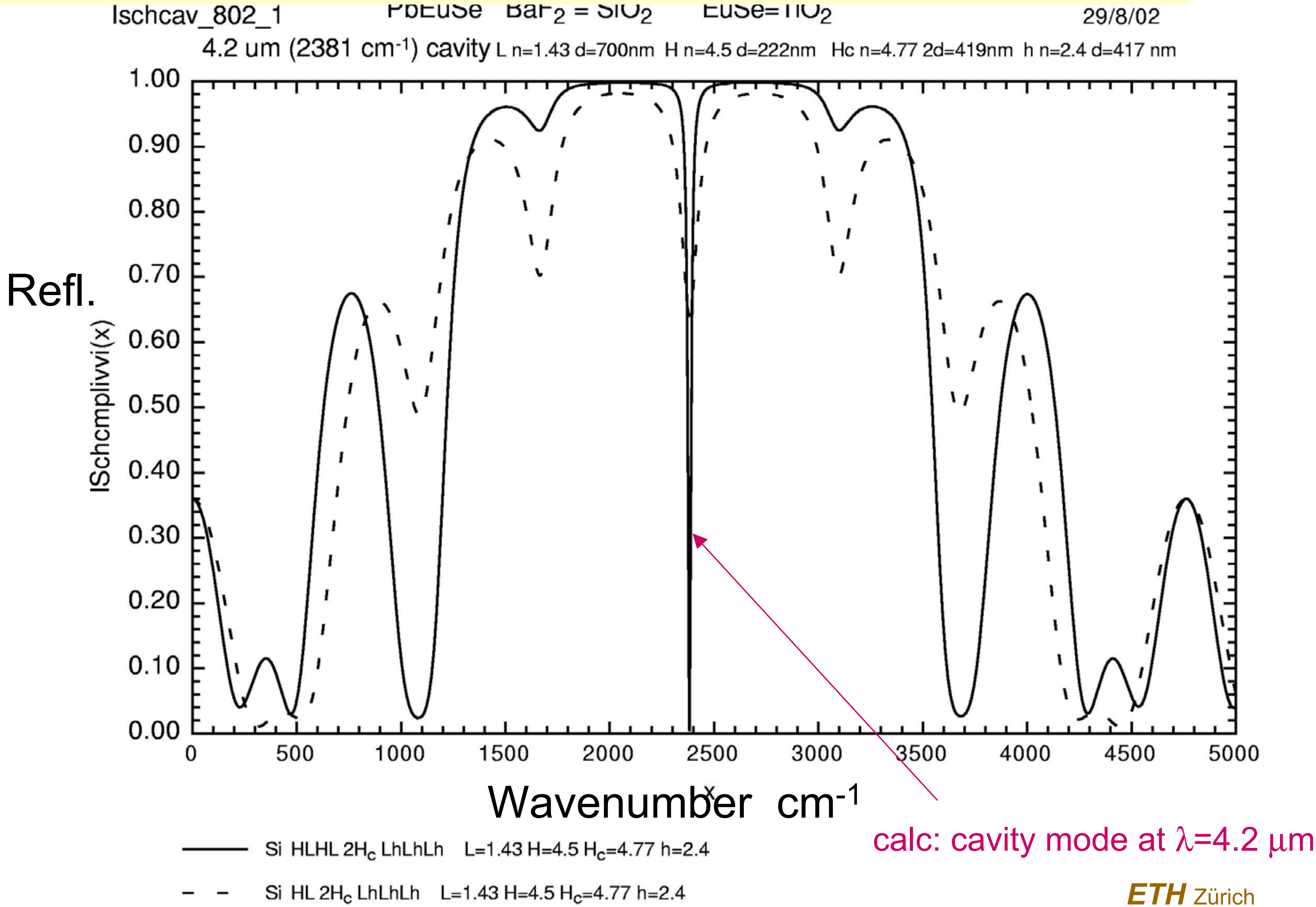
# b) narrow band IR-source: VCSEL-structure, ($I < I_{th}$, at RT)

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# b) Specifications: "Wavelength-transformer" (preliminary):

**Material:** PbX/PbEuX (X = Se, Te), grown by MBE on Si(111)-substrate

**Structure:** 8/2 cavity, Bragg mirror pairs n x (HL) bottom (exit side), m x (hL) top (entrance side)

**Excitation:** low cost laser-diode with wavelength at e.g. 870 nm

**Wavelength range:** with PbSe QWs: ca. 3 - 6 µm
determined by design (widths of the QW)
longer wavelengths up to 30 µm: with PbSnSe QW (in preparation)

**Operating temperature: RT**
**Temperature coefficient:** ca. 3 x $10^{-4}$/K

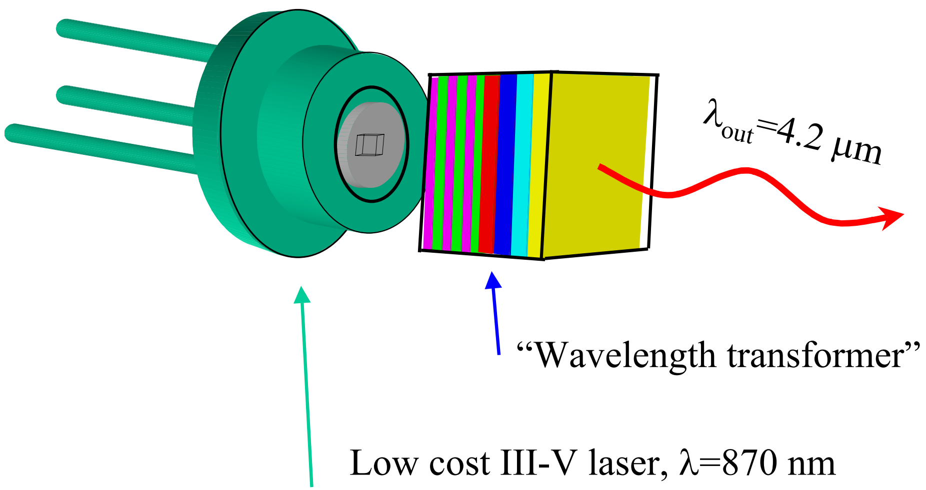
**Linewidth:** 0.2% to 7 % , depending on design (finesse of cavity)
**example:** HL 2H LhLh Structure (see slide): 5.5% (exp. and calc.)

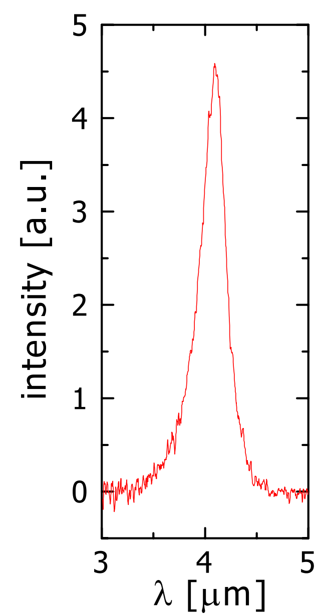
**Efficiency: ca. $10^{-4}$** (for HL 2H LhLh structure), exp.
higher values probable (by optimizing materials quality)

**Linewidths & efficiencies for differently designed Bragg mirrors** (with still higher reflections):

| Excit mirror number of HL-pairs | entrance mirror number of Lh-pairs | line-width | increase of efficiency |
|---|---|---|---|
| 1 | 2 | 5.5% | x 1 |
| 2 | 3 | 1.3% | |
| 2 | 4 | 1.0% | x 7 |
| 3 | 3 | 0.5% | |
| 3 | 4 | 0.2% | x 40 |

# b) Application: Resonant cavity mid-IR-source (at RT)




"wavelength transformer" 870 nm --> 3 - 5 µm

$\Delta\lambda / \lambda \sim 1 - 5\ \%$

for gas sensing: low cost mass production

$CO$ 4.6 µm
$CO_2$ 4.2 µm
$CH_4$ 3.4 µm
$H_2O$ 2.96 µm
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