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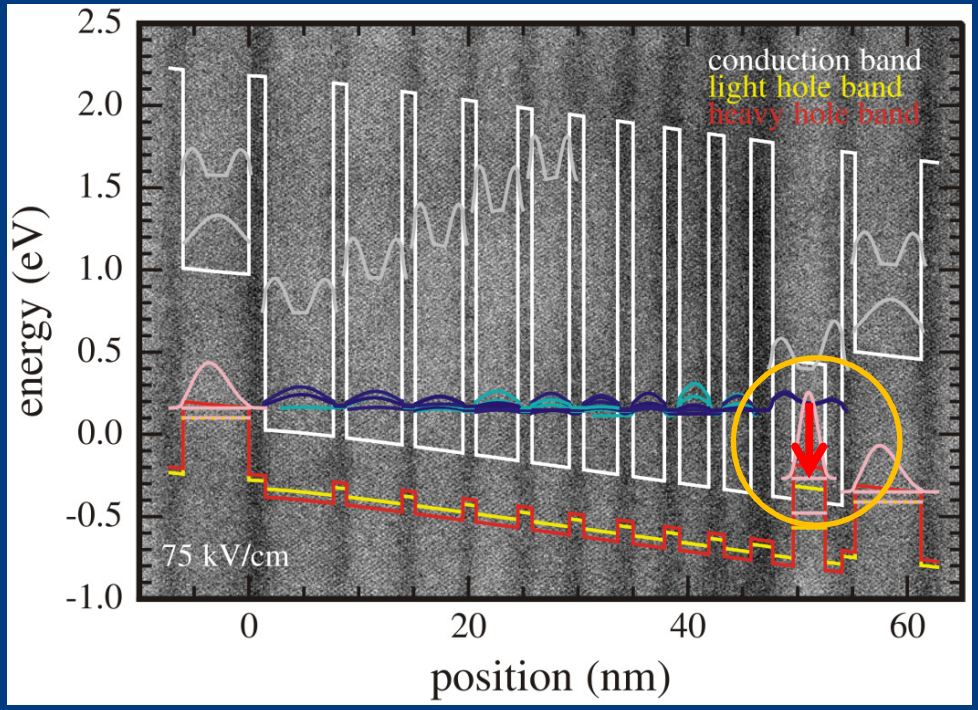
Julius-Maximilians-
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Mid-Infrared Interband Cascade Lasers

S. Höfling*, R. Weih, M. Dallner, M. Kamp

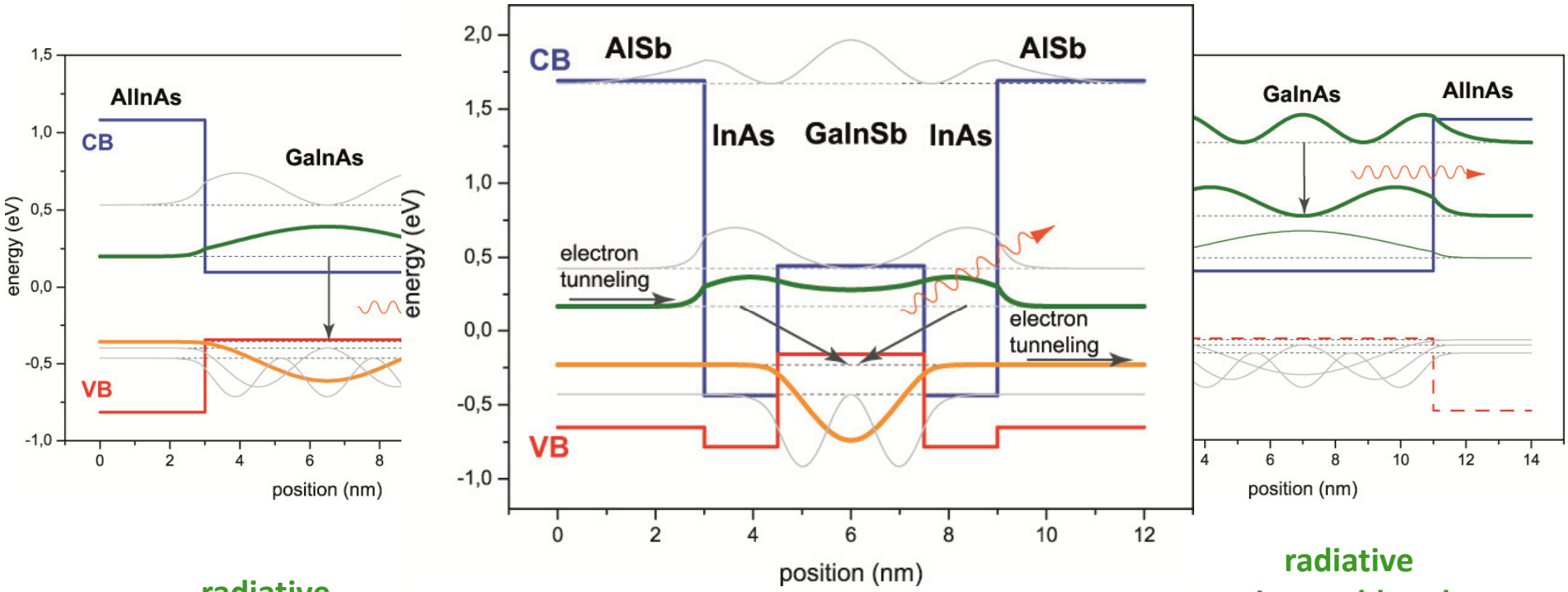
Technische Physik, University of Würzburg, Würzburg, Germany
*** University of St Andrews, St Andrews, United Kingdom**

- **Interband Cascade Lasers (ICLs)**
  - **Introduction**
  - Epitaxial layer performance
  - Single-mode emitters
  - Selected applications
- conclusion



semiconductor laser concepts

≈ 0.3 – 3.x µm	≈ 3 – 6µm	≈ 3.x – 16 µm
Bipolar interband diode laser	**Interband Cascade laser**	**Quantum Cascade Laser**

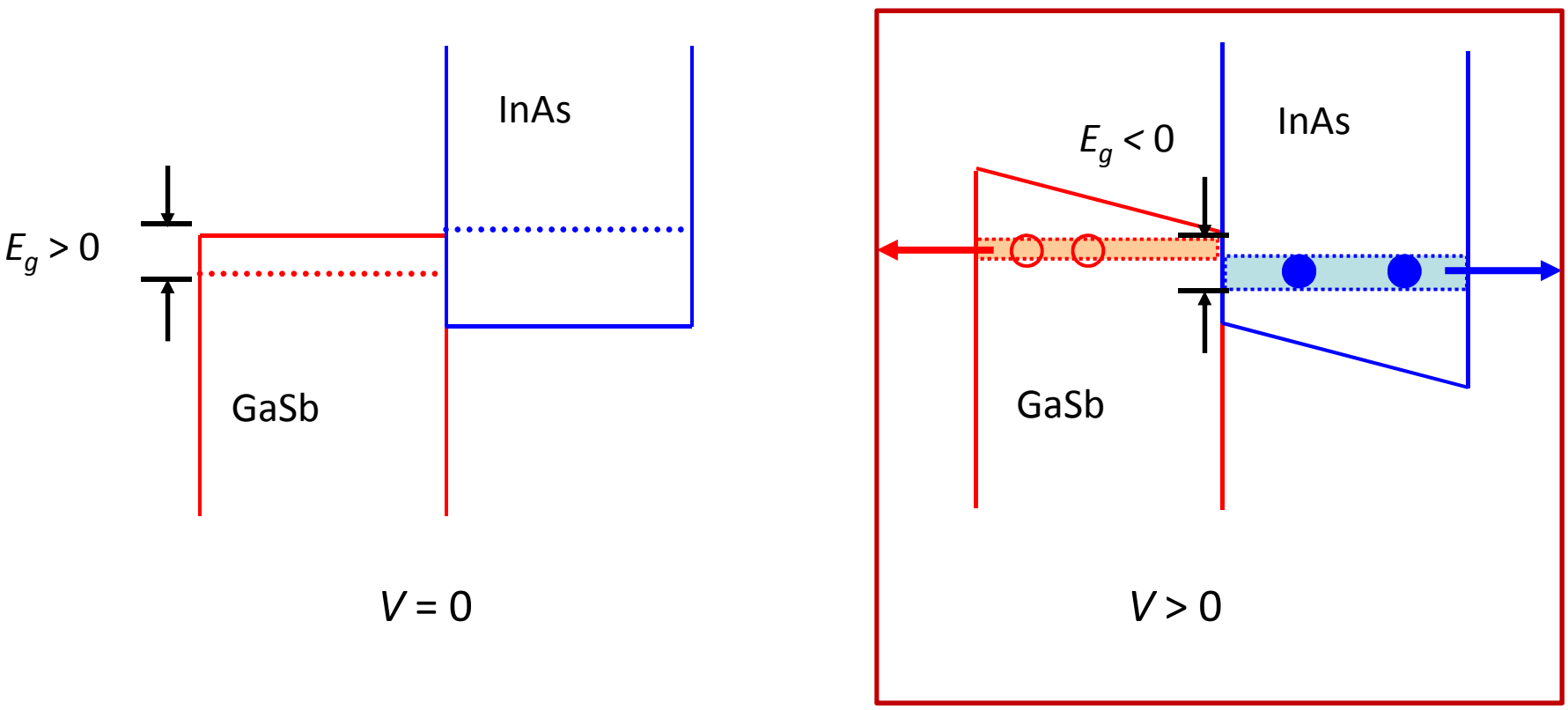


radiative recombination	enhanced overlap radiative recombination	radiative intersubband transition

Alferov, Rev. Mod. Phys. **73**, 767 (2001)	Yang, Superlattices Microstruct. **17**, 77 (1995)	Faist, Science **264**, 533 (1994)

see for instance Bauer et al , Semicond. Sci. Technol. 26, 014032_ (2011) for a comparative review

Electron-hole generation

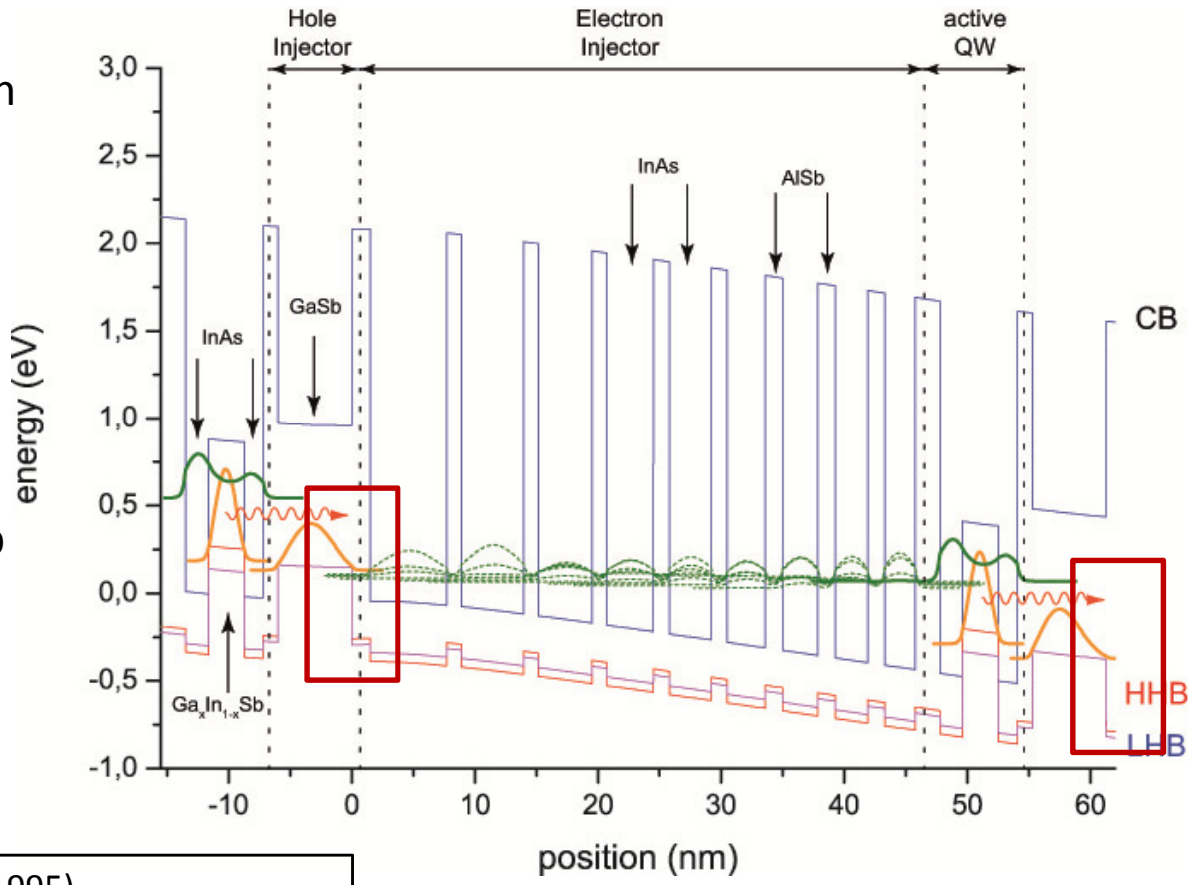


Cartoons from Meyer et al., Nature Comm. **DOI: 10.1038/ncomms1595**, (2011)

→ external bias applied to type-II InAs/GaSb interface induces semi-metallic band alignment causing the generation of electron and holes that are available for radiative recombination

Interband Cascade Lasers

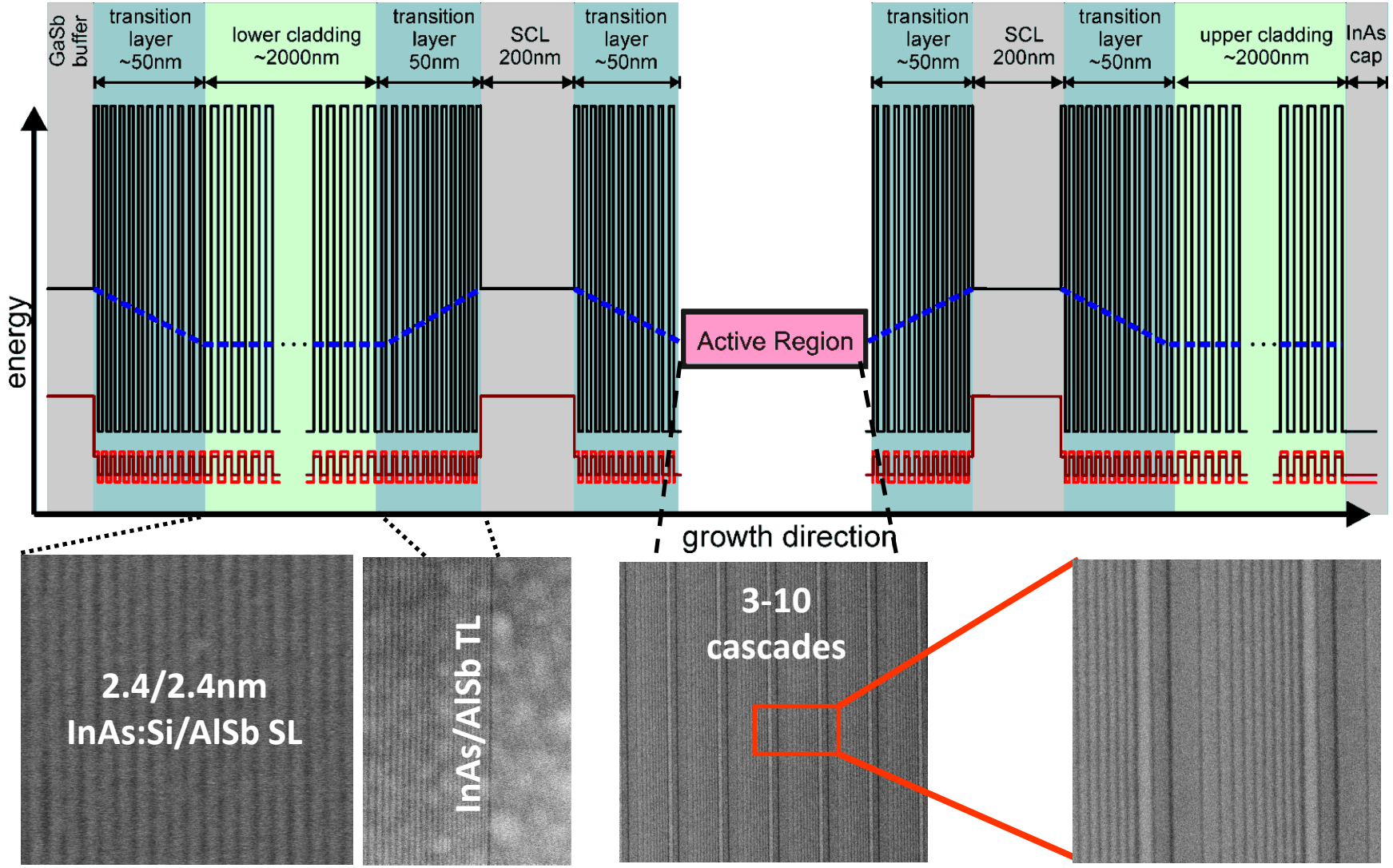
- first proposed by Yang et al. in 1995 [1]
- cascaded design but optical transitions between conduction and valence band
  - quantum efficiencies > 100% possible
- wavelength easliy adjustable [2]
- emission from about 3.0 µm up to 5.6 µm in RT cw operation [3] and up to 10.4 µm in pulsed regime [4] already covered



Bauer, Opt. Eng. **49**, 111117 (2010)

[1] Yang et al., Superlatt. Microstruct. **17,** 77 (1995)
[2] Bauer et al., Appl. Phys. Lett. **95**, 251103 (2009)
[3] Bewley et al., Opt. Express **20**, 3235-3240 (2012)
[4] Tian et al., Electron. Lett. **48**, 113-114 (2012)

ICLs – design and principle



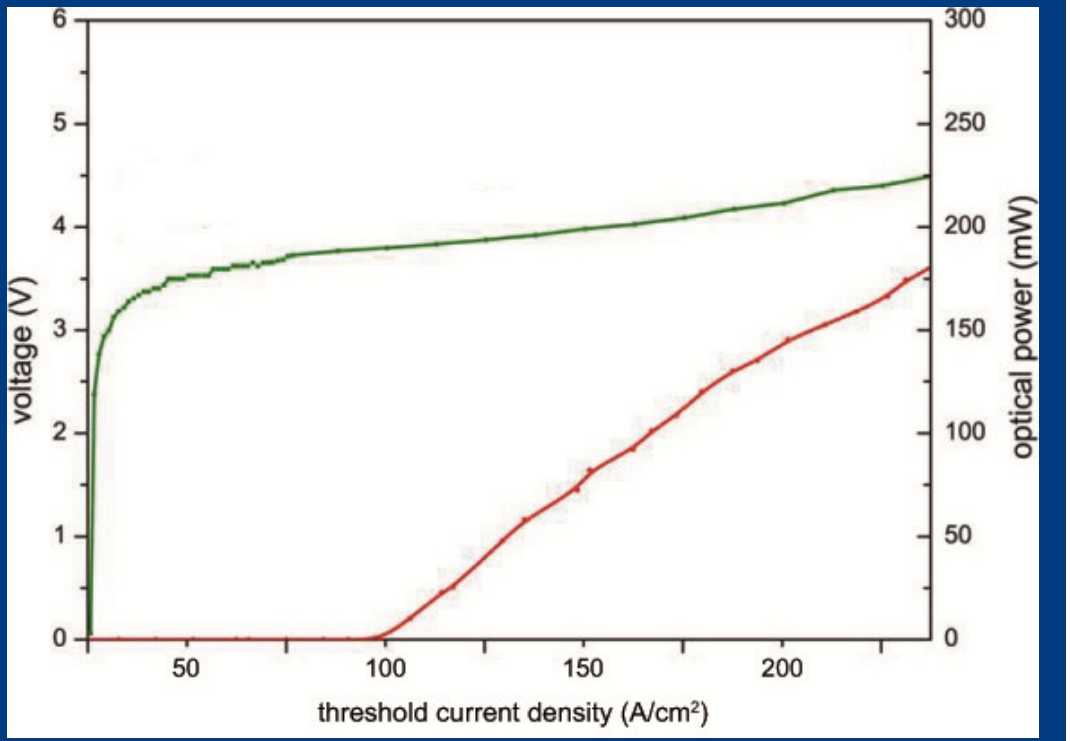
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Mid-Infrared Interband Cascade Lasers

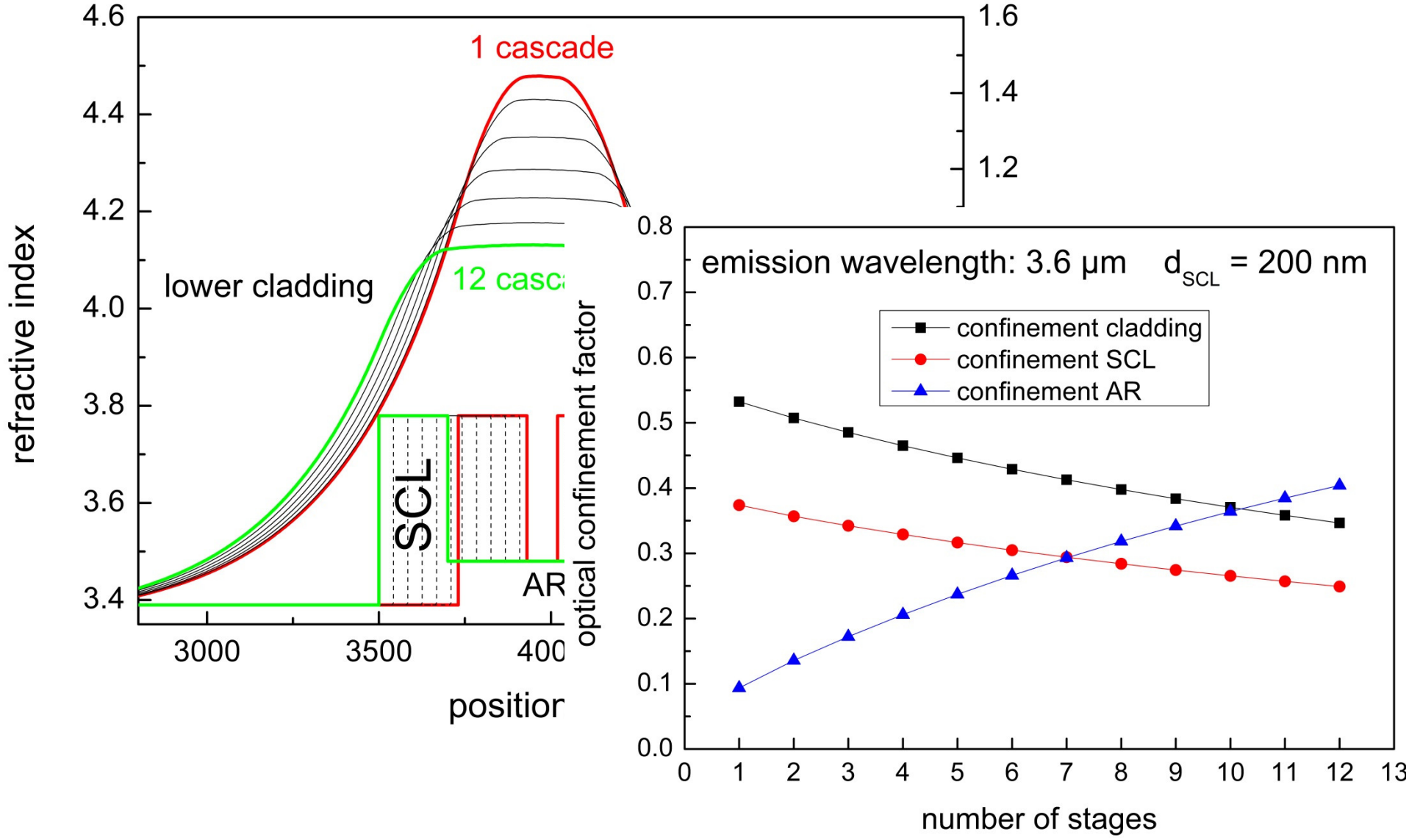
S. Höfling*, R. Weih, M. Dallner, M. Kamp

Technische Physik, University of Würzburg, Würzburg, Germany
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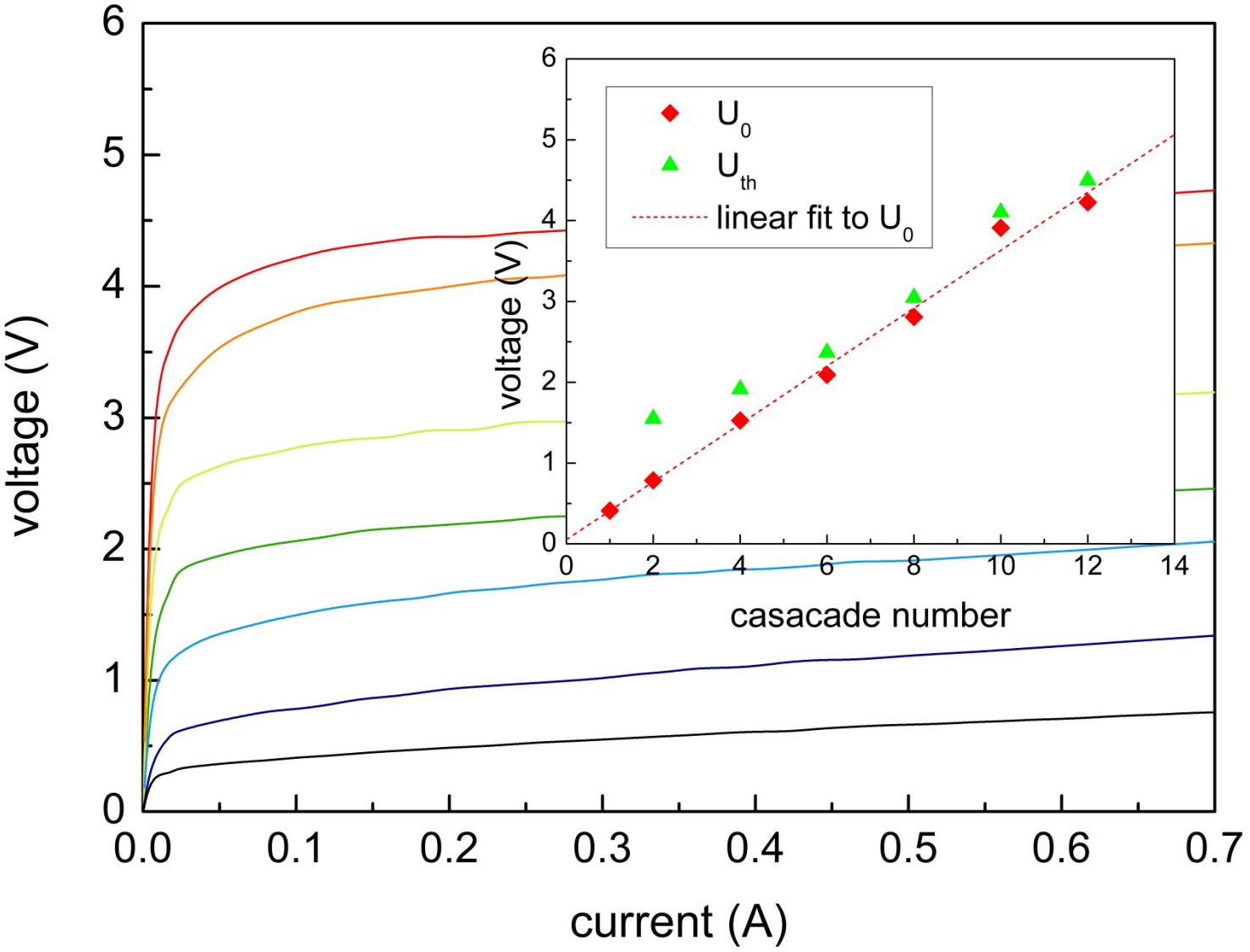
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Active Cascade Number Variation



Active Cascade Number Variation



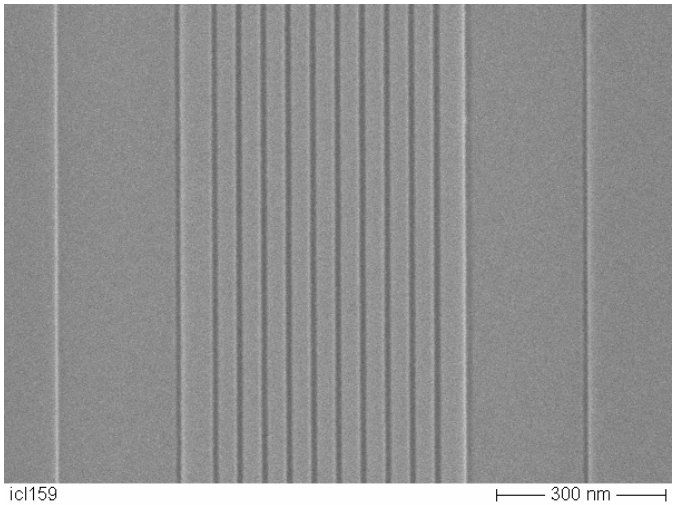
Low threshold current density

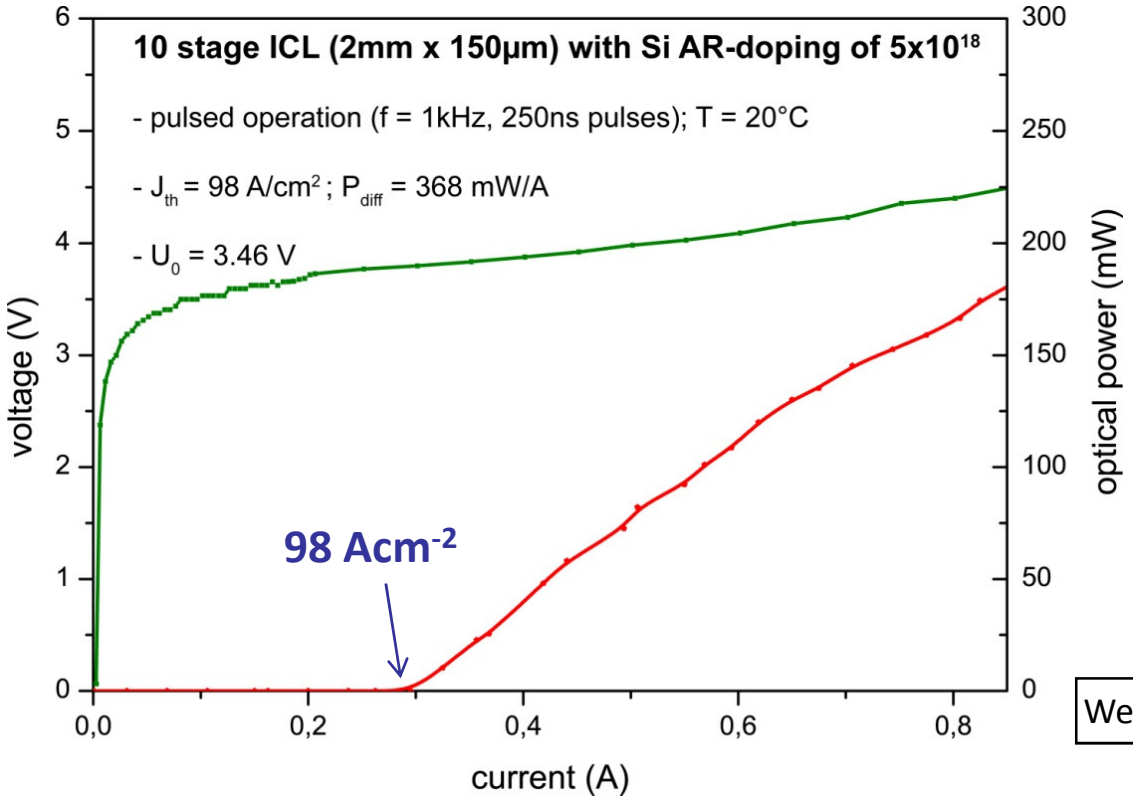
10 cascades

- **cascade number of 10**

→ threshold current density below **100 A/cm²** @ 20℃

→ **P_{th} = 372 W/cm²**

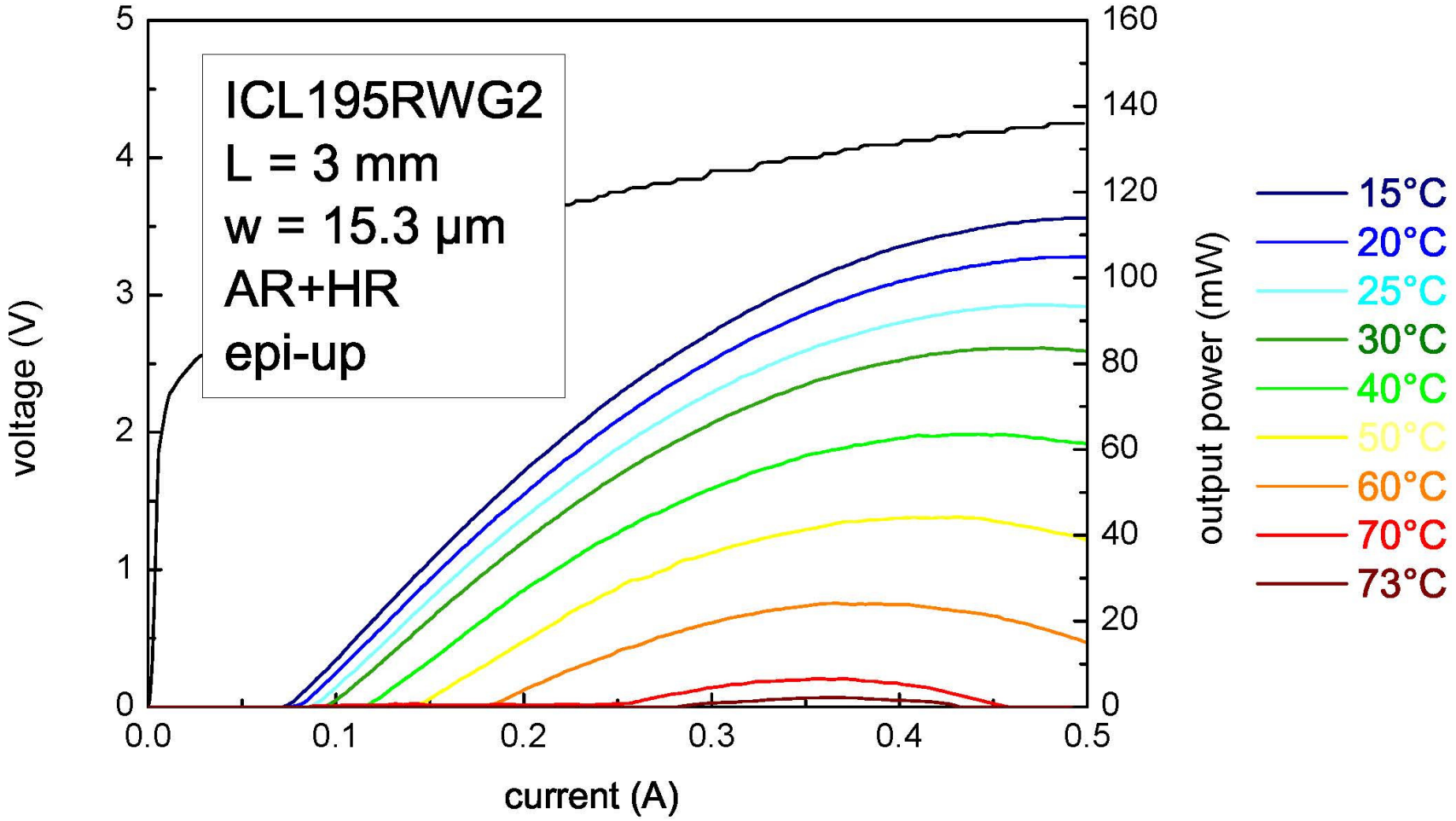




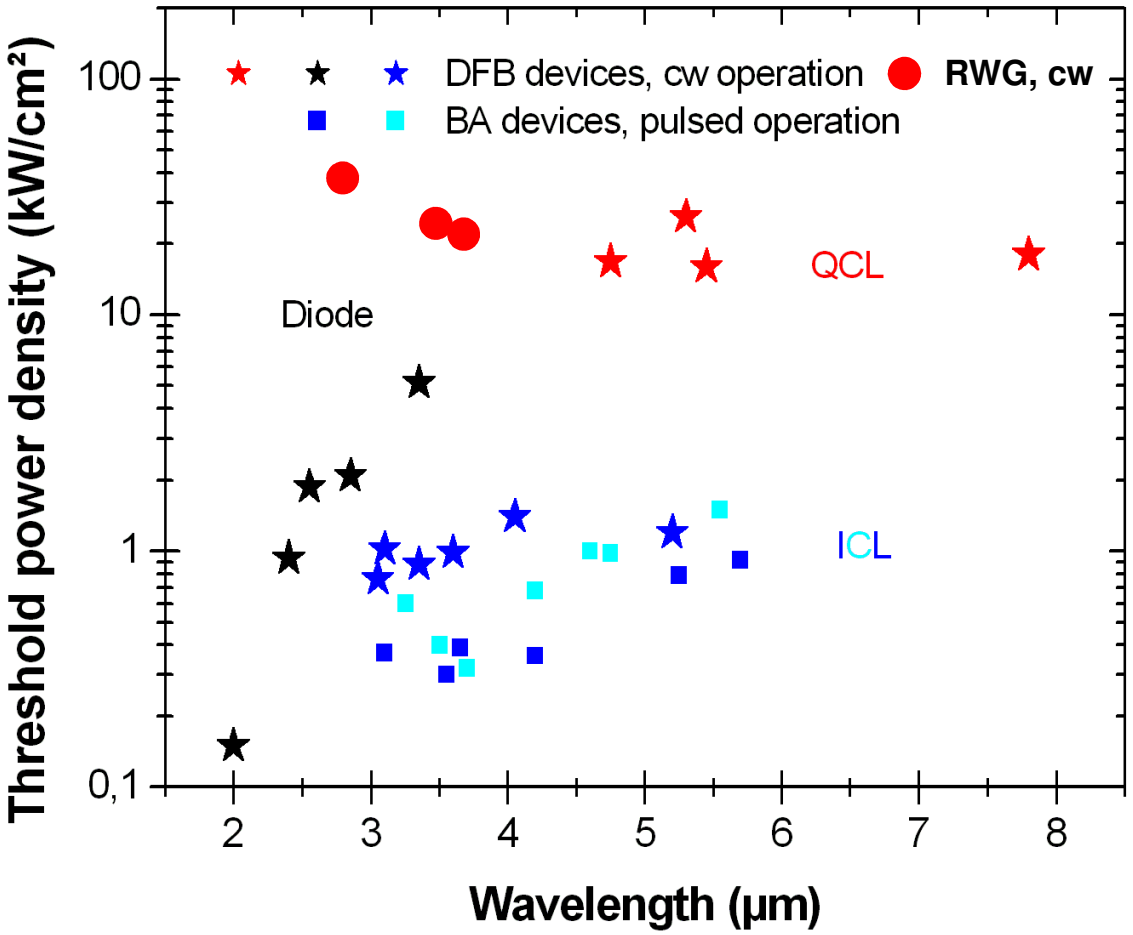
Weih et al., Appl. Phys. Lett. 102, 231123 (2013)

Ridge Waveguide ICLs

CW perfomrance (front side antireflection coated / rear facet highly reflective coating)



Threshold Power Densities



University Würzburg
nanoplus GmbH

Northwestern University
Alpes Lasers

Naval Research Lab

University Würzburg
nanoplus GmbH

Incomplete, but representative comparison

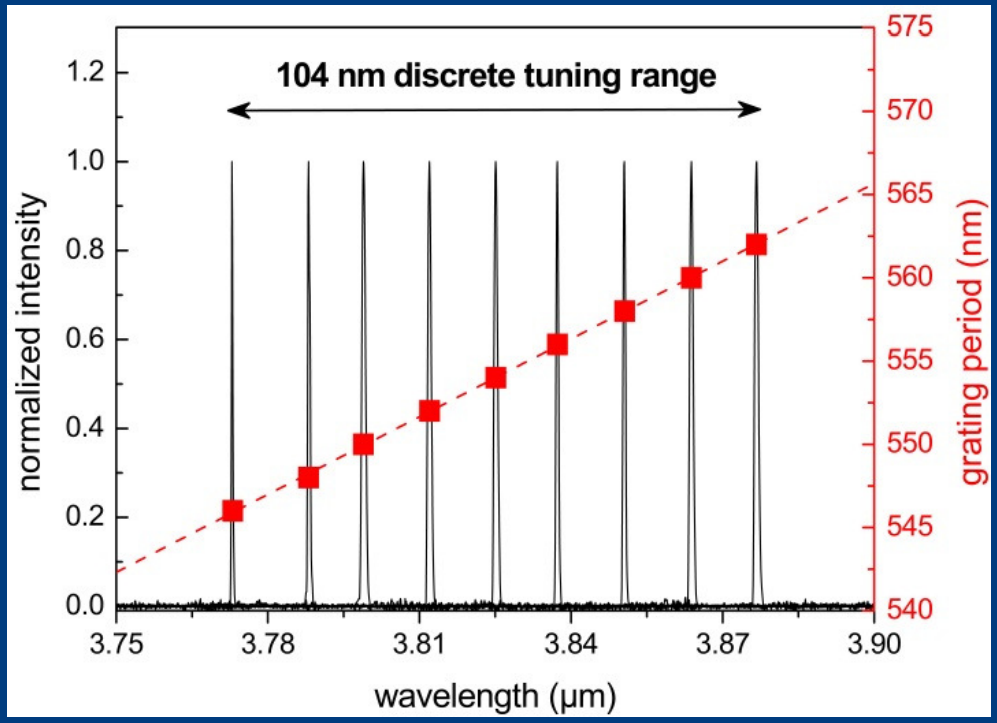
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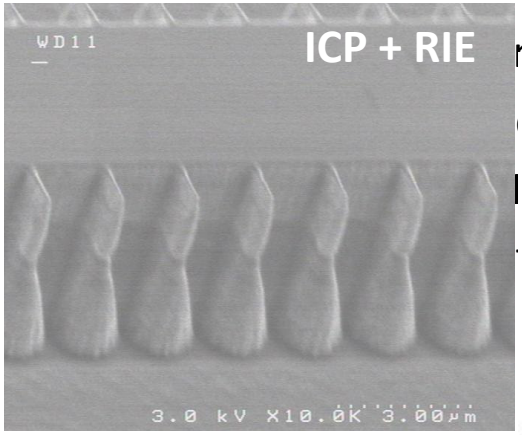
Technische Physik, University of Würzburg, Würzburg, Germany
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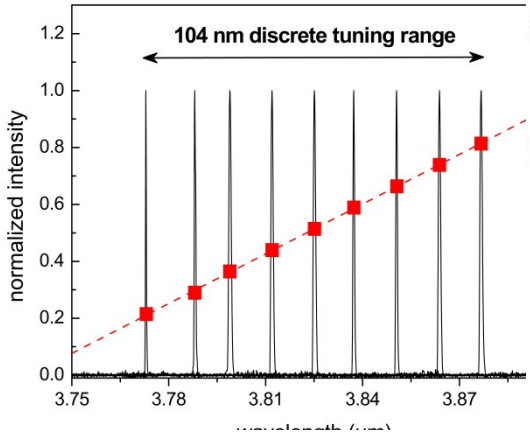
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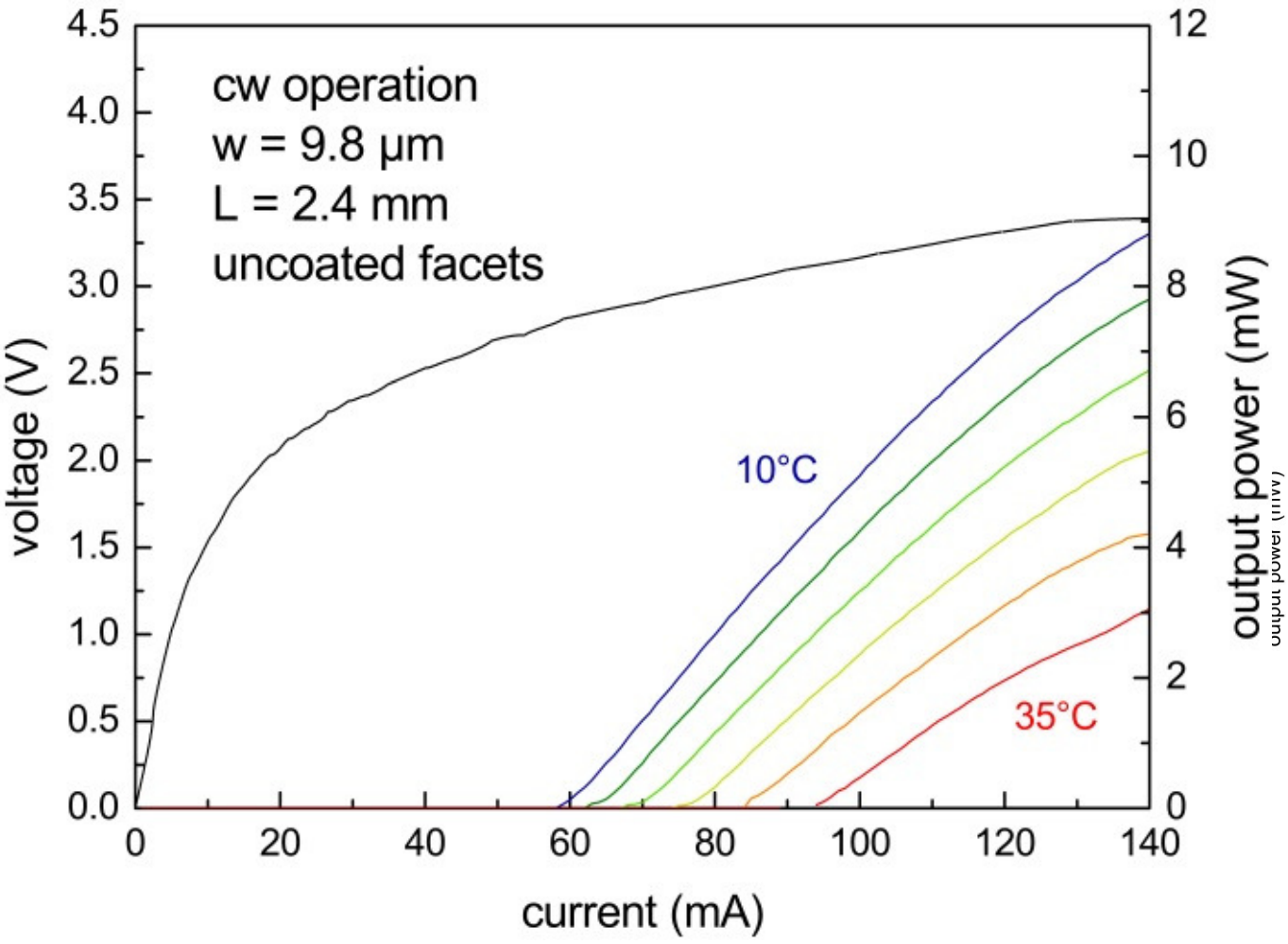


Distributed feedback ICLs

- **Distributed feedback devices operating cw@RT**



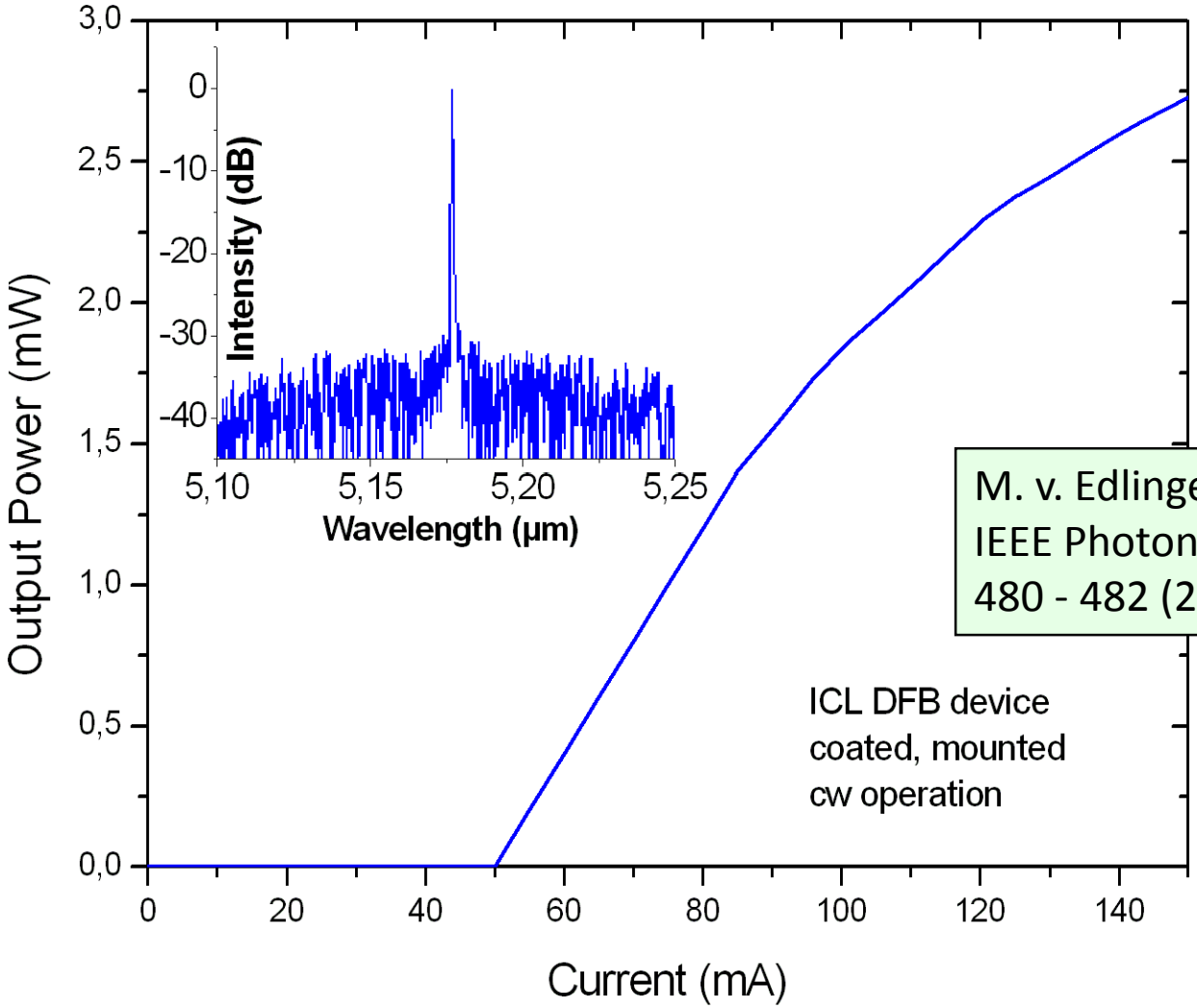




Nanosystems and Technologies GmbH
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Long wavelength single mode emission

Current long-wavelength record for single mode ICL sources

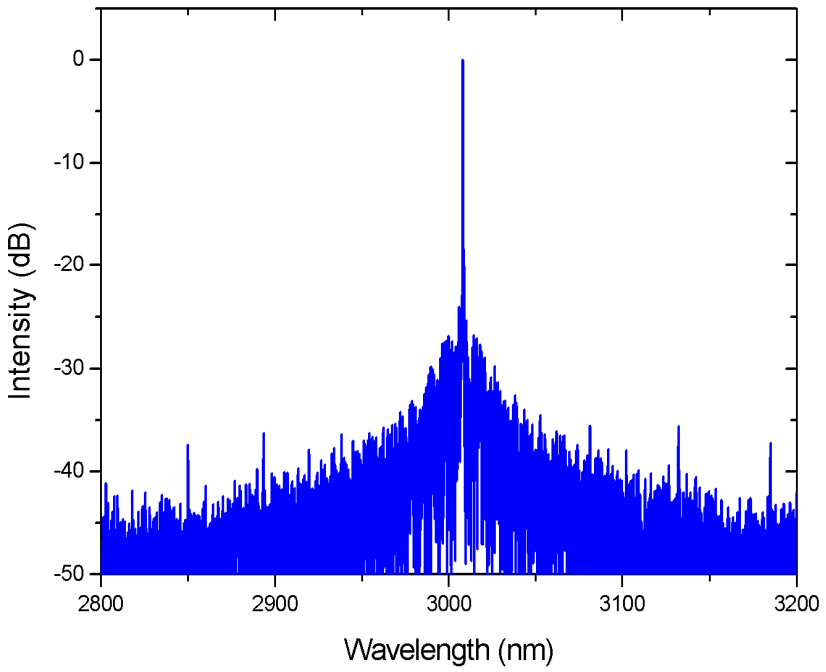


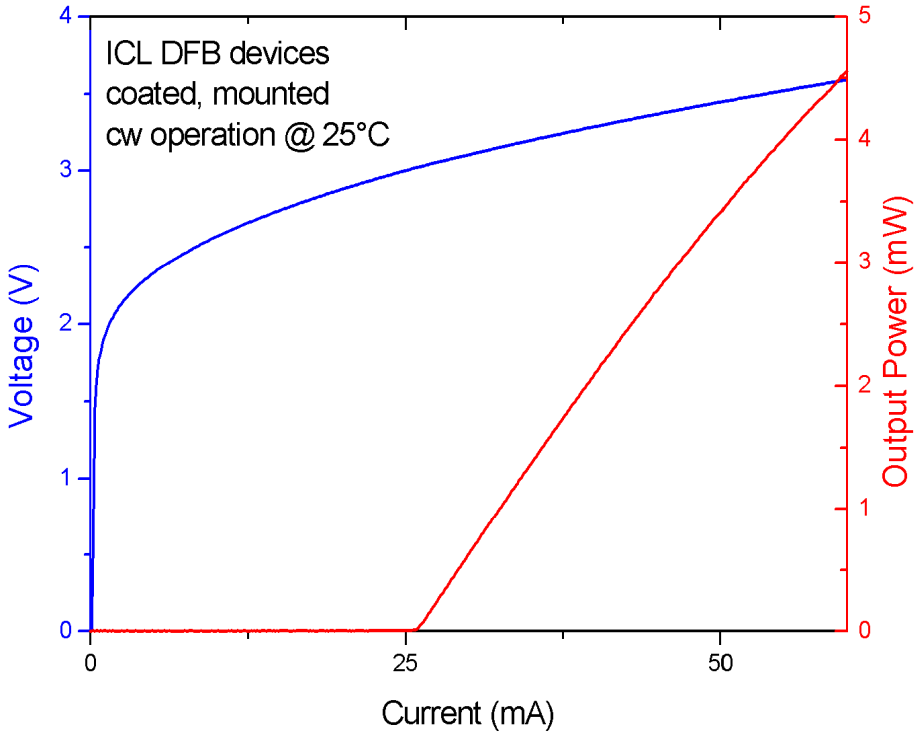
Nanosystems and Technologies GmbH
nanoplus

M. v. Edlinger et al.,
IEEE Photon. Technol. Lett. 26, pp. 480 - 482 (2014)

Short wavelength single mode emission

Current short wavelength record for single mode ICL

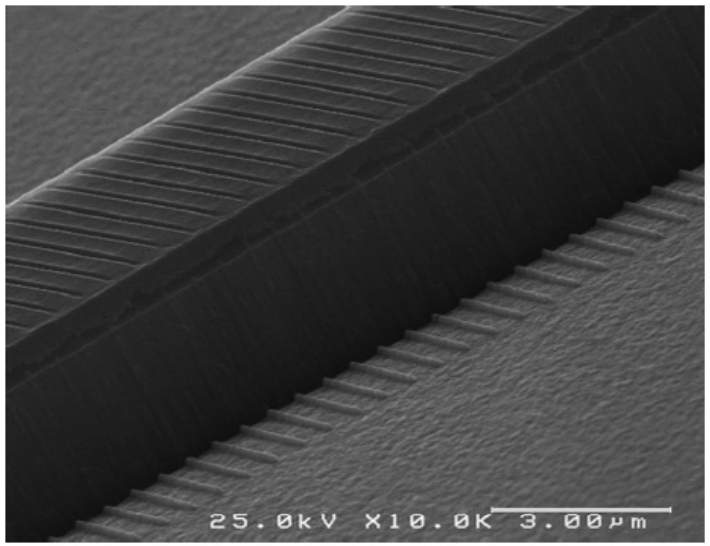




Threshold: 25 mA

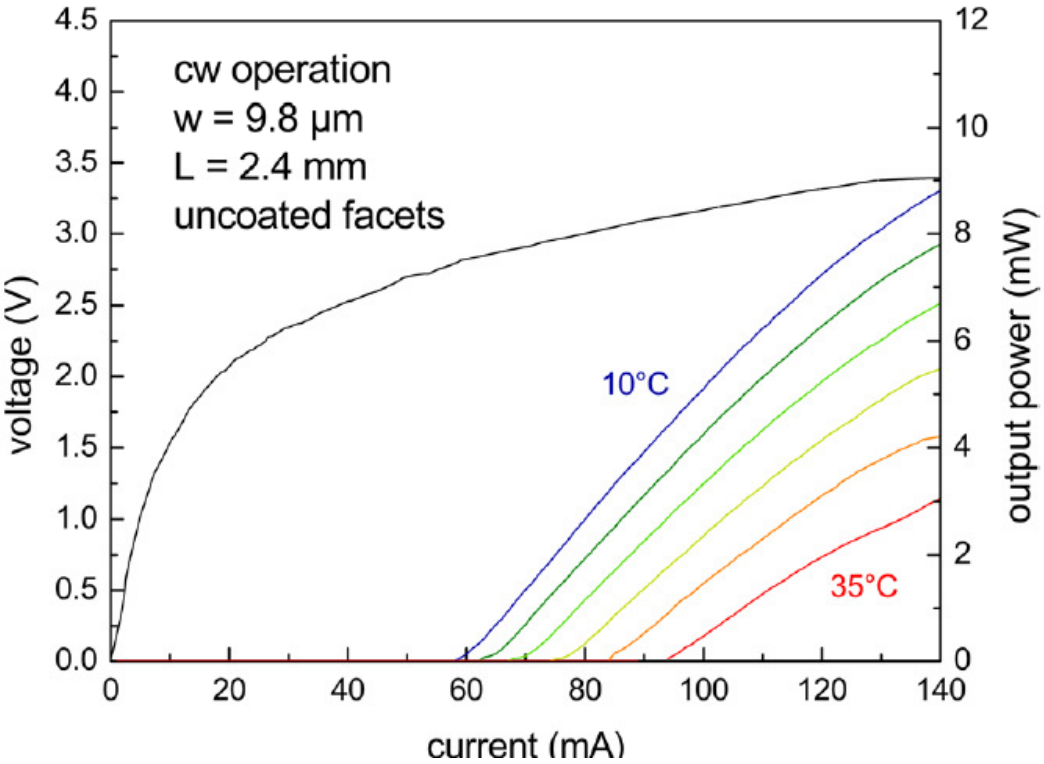
Output power > 4 mW

Lateral metal grating DFBs



Nanosystems and Technologies GmbH
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R. Weih et al.
Appl. Phys. Lett. 105, 071111 (2014)



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Interband Cascade Lasers for the Mid-Infrared Spectral Region

S. Höfling*, R. Weih, A. Bauer, A. M. Kamp

Technische Physik, University of Würzburg, Würzburg, Germany
*** University of St Andrews, St Andrews, United Kingdom**

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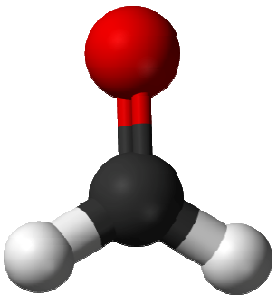
Monitoring of formaldehyde



- Wood products such as Oriented Strand Board are boards bonded using phenol formaldehyde



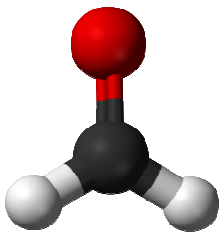
- California Air Resources Board regulations updated 2013 requires manufacturers to test board for formaldehyde emission, limit is 0.05 ppm

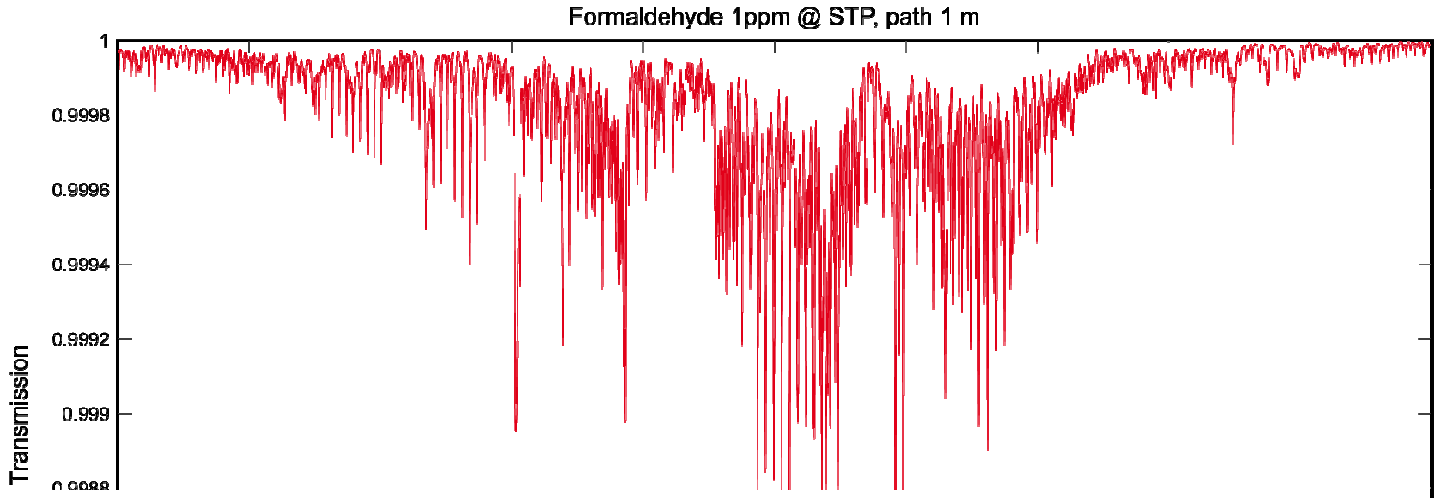


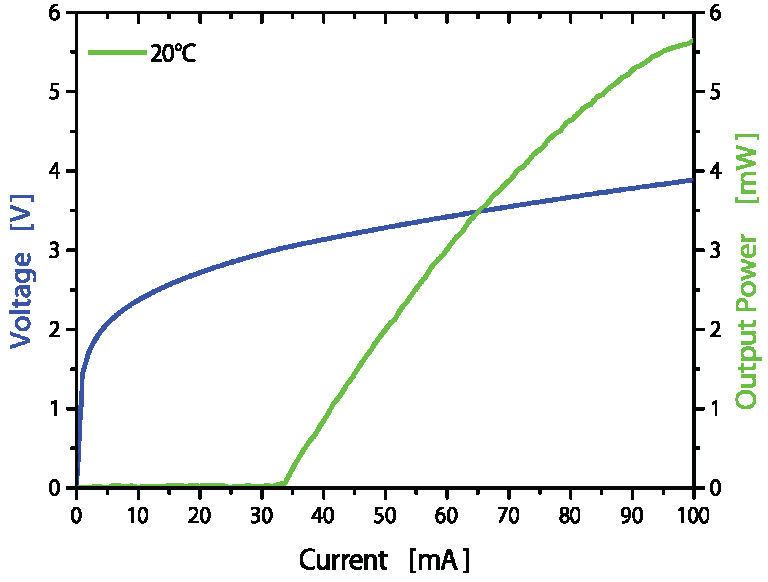
Airoptic

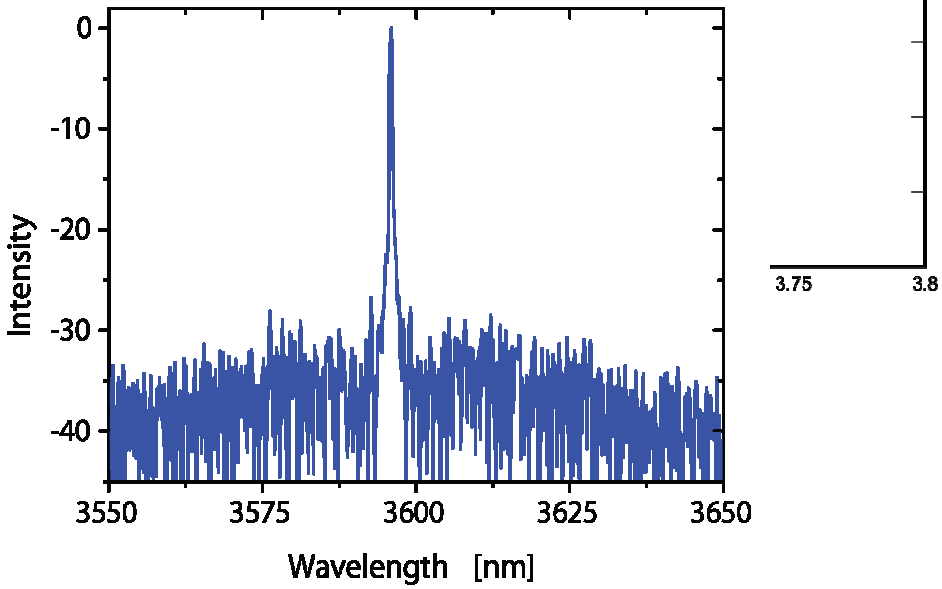
On-line CH_2O - monitoring

Formaldehyde spectrum around 3.5 µm









Airoptic gas detection device



acknowledgment

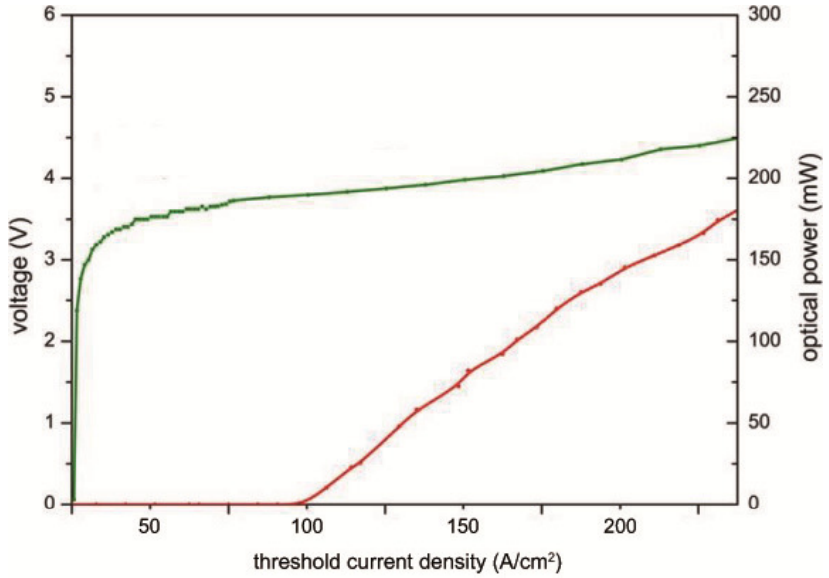
- funding by…
  - EU-project ‘WideLase’ of the 7th frame-work program (grant no. 318798) and SensHy
  - State of Bavaria

- expert technical assistance by…
  - A. Wolf
  - S. Kuhn
  - M. Wagenbrenner
  - S. Handel
  - T. Steinl

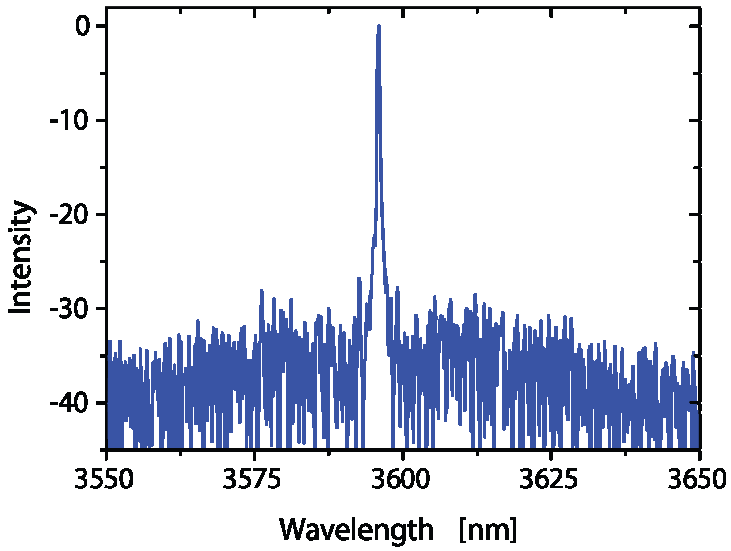
- Collaboration with …
  - L. Nähle
  - M. v. Edlinger
  - C. Zimmermann
  - M. Fischer
  - J. Koeth

…is gratefully acknowledged!

conclusion



Interband cascade laser with unprecedented threshold current densities below 100 Acm^{-2}



Single mode operation cw @ RT



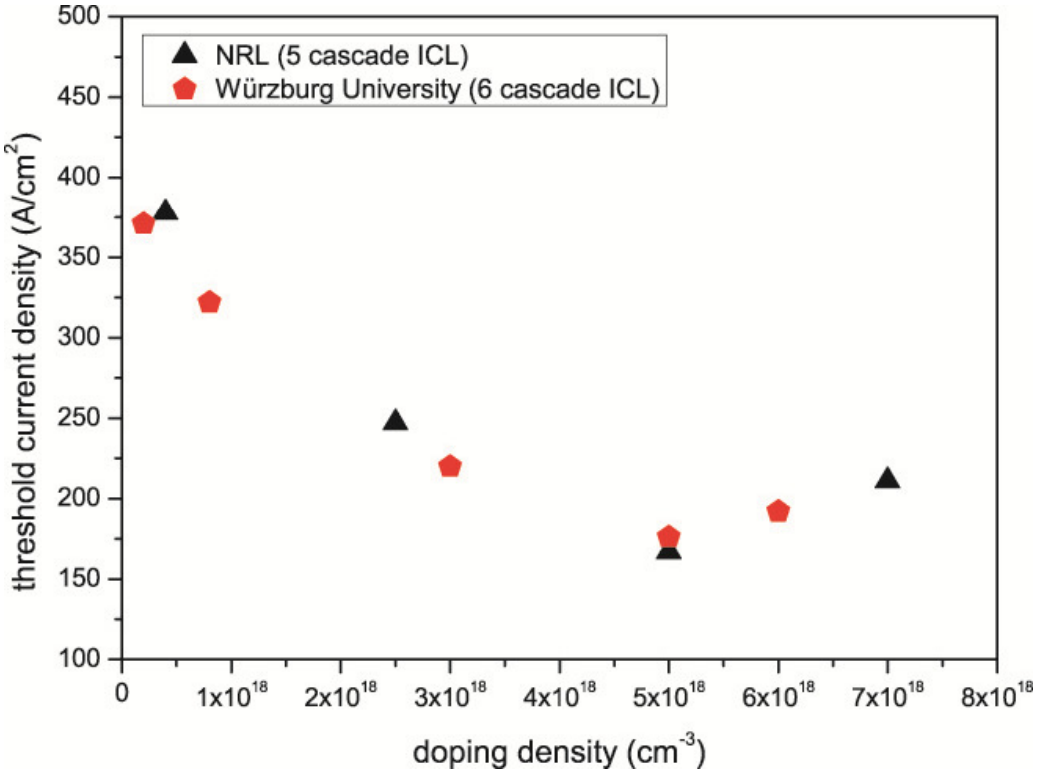
various green photonics applications

Carrier Rebalancing

→ Rebalancing of electron and hole carrier densities by increased n-doping

→ Jth minimum for this active region design seems around $5x10^{18}$ $1/cm^3$

→ results compare very well with the results obtained at Naval Research Lab



Deeply etched ridge waveguide devices

Naval Research Lab (NRL) results: see Vurgaftman et al. Nature Comm. **DOI: 10.1038/ncomms1595**, (2011)

Semiconductor laser concepts compared

- **comparison to other semiconductor laser concepts operating in the 3 to 4 µm spectral range at room temperature**

→ diode laser: @ 3.44 µm: **P_{th} = 1800 W/cm²; T_0 = 38 - 28 K; $P_{max/cw}$ = 20 mW**
(Belenky, Electronics Letters, Vol.46, No.21 (2010))
@ 3.73 µm: **P_{th} ~ 1900 W/cm²; T_0 = 38 - 16 K; -**
(Amann, SST-FT, Vol.27, 032001 (2012))

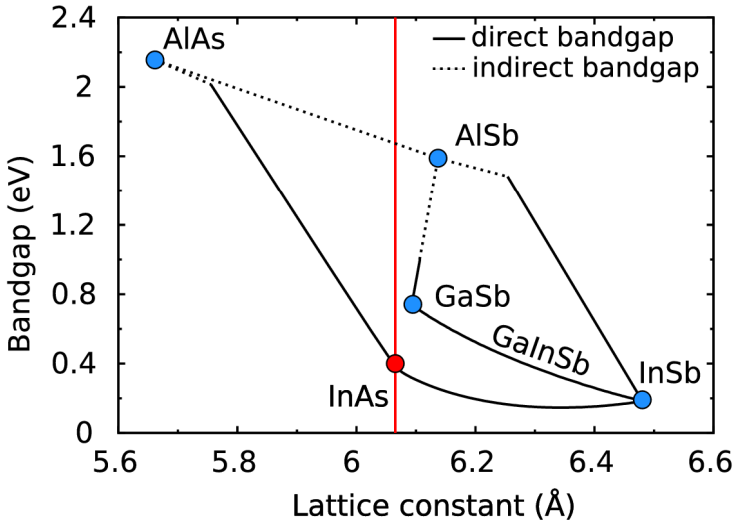
→ quantum cascade laser: @ 3.56 µm: **P_{th} = 15400 W/cm²; T_0 = 152 K; $P_{max/cw}$ = 437 mW**
@ 3.39 µm: **P_{th} = 21600 W/cm²; T_0 = 166 K; $P_{max/cw}$ = 403 mW**
(Razeghi, APL, Vol.100, 212104 (2012))
@ 3.20 µm: **P_{th} = 24900 W/cm²; T_0 = 108 K; $P_{max/cw}$ = 20 mW**
@ 3.00 µm: **P_{th} = 33490 W/cm²; T_0 = 102 K; $P_{max/cw}$ = 3 mW**
(Razeghi, APL, Vol.101, 241110 (2012))

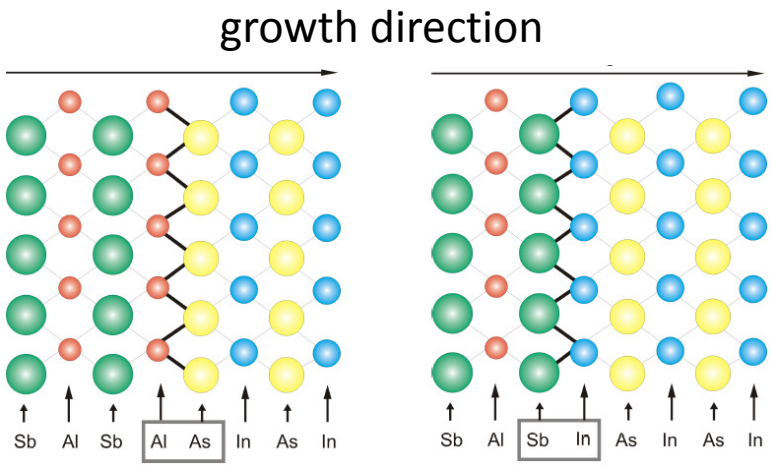
→ interband cascade laser: @ 3.62 µm: **P_{th} = 428 W/cm²; T_0 = 49 K** *(*10 stage *UWUERZ)*
$P_{max/cw}$ = 20 mW (6 stage)
@ 3.66 µm: **P_{th} = 315 W/cm²; T_0 = 55 K; $P_{max/cw}$ = 470 mW**
(5 stage, Meyer et al., Optics Express, Vol.20, 3235 (2012))

ICL active region growth I

Strain compensation in active region:

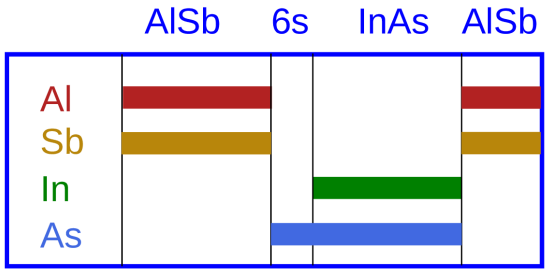
- Materials in active region: InAs, AlSb, GaSb, GaInSb
  - Only lattice matched or compressively strained layers relative to InAs substrate





- Forcing AlAs bonds at the interfaces by introducing As-soak
- 6s As soak after AlSb layers found sufficient for strain compensation

Shutter cylce:



Injector Doping Variation

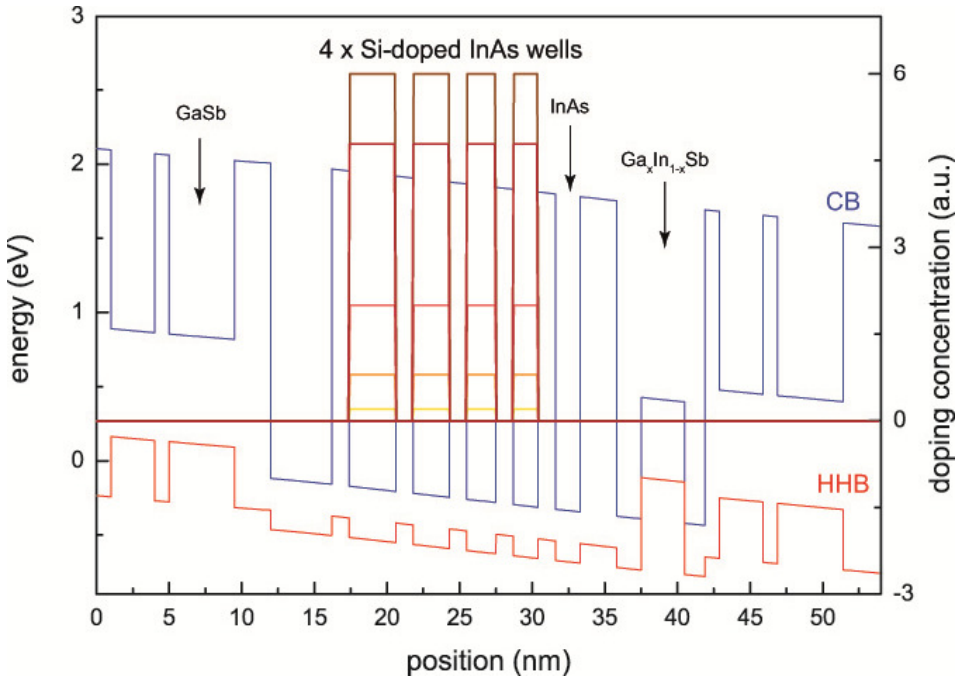
doping variation within the injector region: rebalancing of carriers

Vurgaftman et al. Nature Comm. **DOI: 10.1038/ncomms1595**, (2011)

- active region with 6 injector InAs wells
- 41 nm cascade length optimized for electric field strength of 90 kV/cm
- doping concentration of the 4 inner quantum wells varried in order to rebalance internally generated carriers

- Si-doping variation:

($2*10^{17}$/ $8*10^{17}$/ $3*10^{18}$/ $5*10^{18}$/ $6*10^{18}$)



Green Photonics

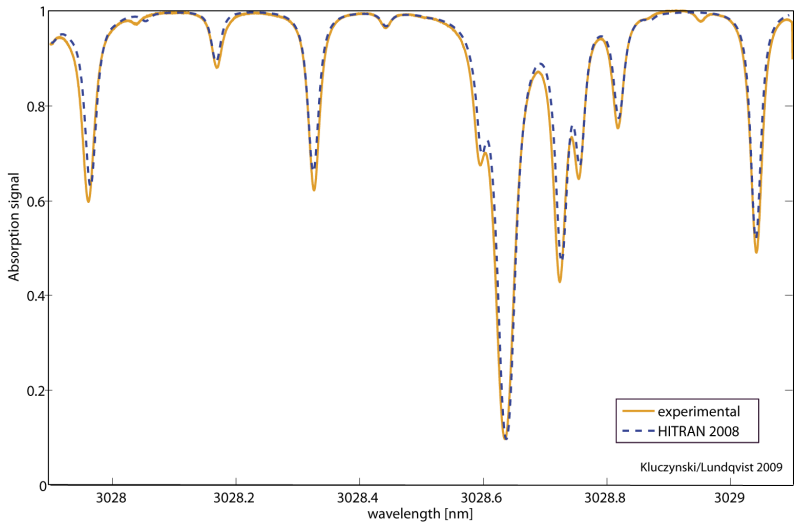
The developed laser sources are a key enabling technology for laser-assisted green manufacturing with low waste.

TLS for industrial process control in hydrocarbon manufacturing

Production of light olefins

- Ethylene is the largest volume industrially produced organic material
- Propylene is the world's second largest petrochemical commodity

For increased **energy efficiency**, improved product quality and **pollutant reduction**, it is important to monitor acetylene impurities in ethylene and propane impurities in propylene.





SIEMENS

shown here: Measurement of acetylene by TLS

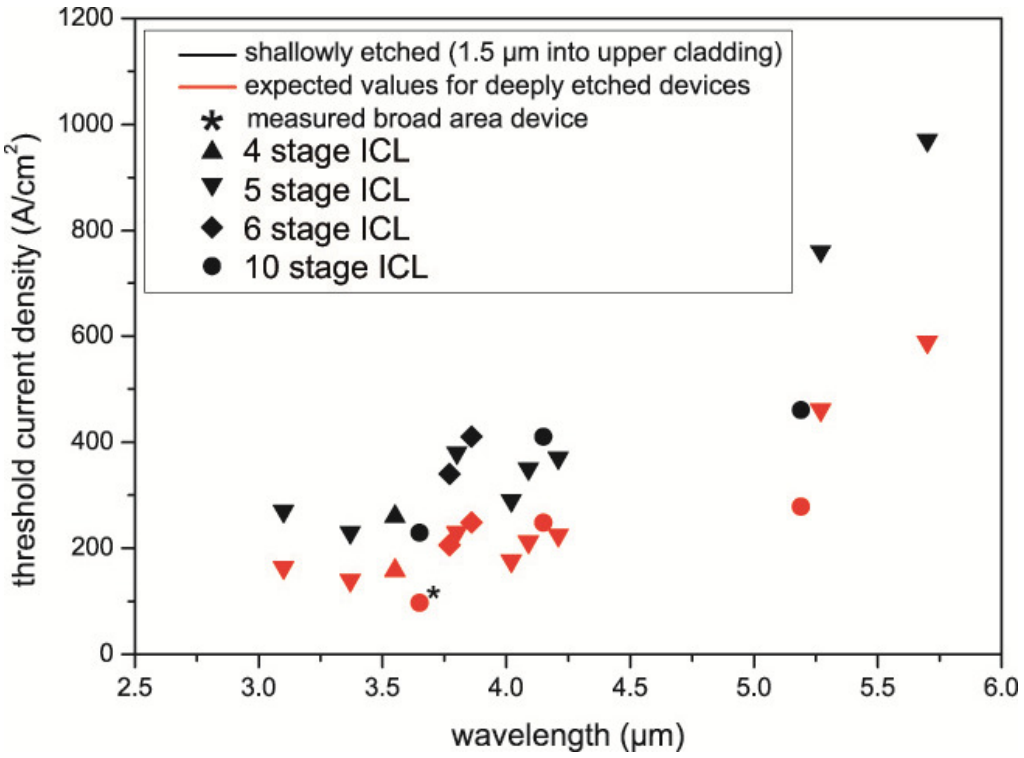
Kluczynski *et al.* published in *Optics Letters Vol.34, No.24*

SensHy expert sensing

wavelength coverage

- **wavelength window between 3 and 6 µm can be covered with RT-cw material**

→ higher stage numbers are of particular interest for long wavelength ICL material in order to reduce J_{th} and extend cw operation beyond 6 µm



→ Low threshold valued could be achieved over broad spectral range

acknowledgment

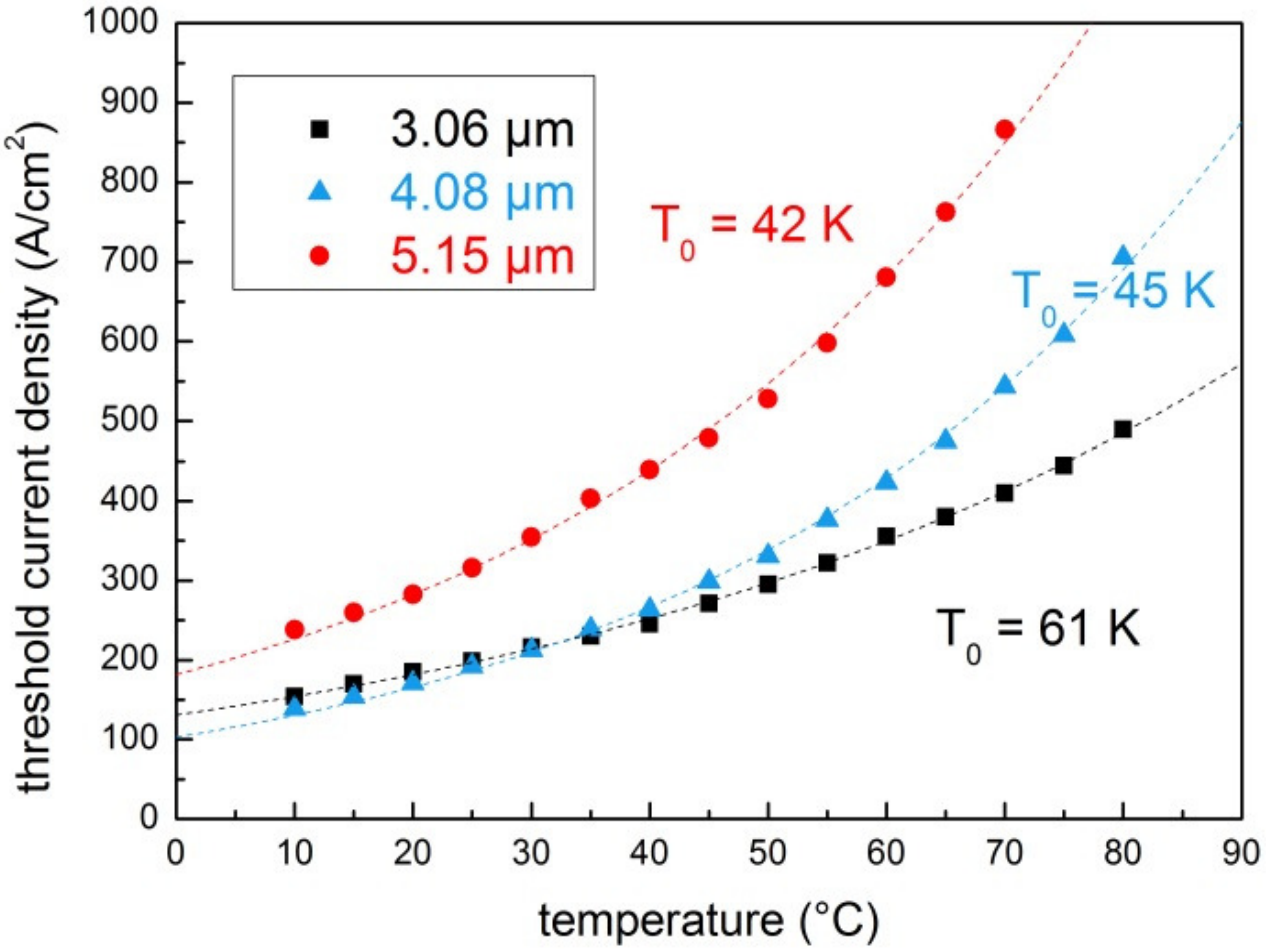
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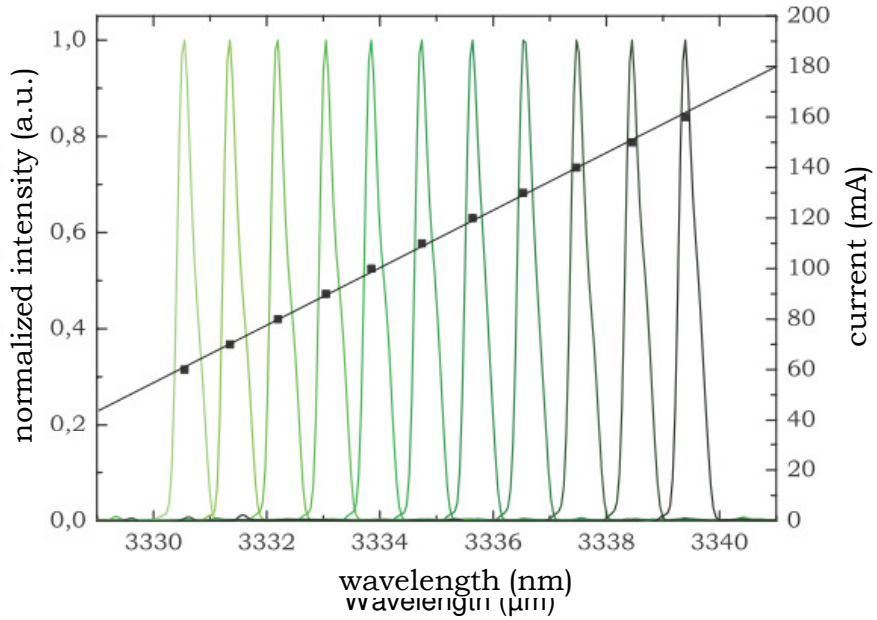
Wavelength dependence

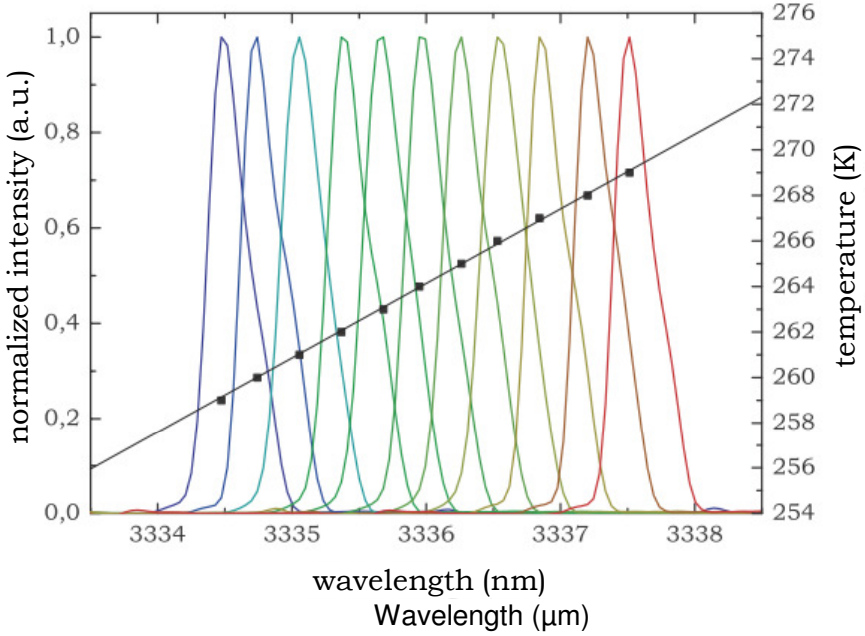


Threshold current densities below 300 A/cm² at RT in the 3-5 µm range

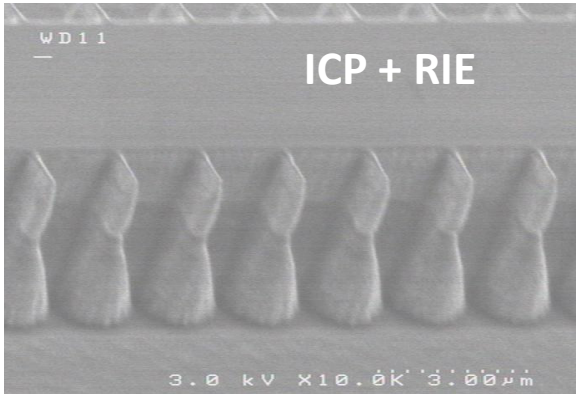
monomode emitters – vertical sidewall gratings

Mono mode emission was successfully realized using the concept of vertical sidewall gratings





- DFB operation in 3.3-3.4µm range under cw operation
- Spectral characterization shows excellent DFB coupling
- Effective refractive index n_{eff} ~ 3.48
- Current tuning values ~ 0.09nm/mA
- Temperature tuning values ~ 0.3nm/K
- SMSR around 25dB (pulsed) and 20dB (cw)



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