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Quantum Cascade Micro-Lasers with Two-dimensional Photonic Crystal Reflectors

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- Introduction
- Design and Fabrication
- Results and Discussion
- Summary

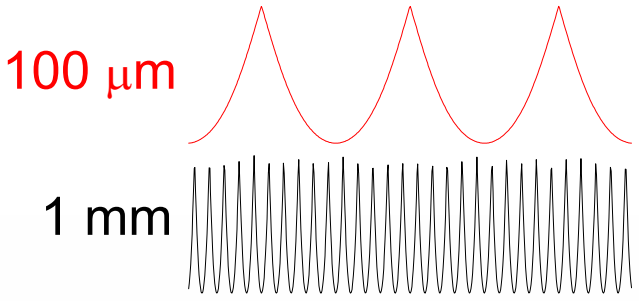
Technical Physics

Introduction

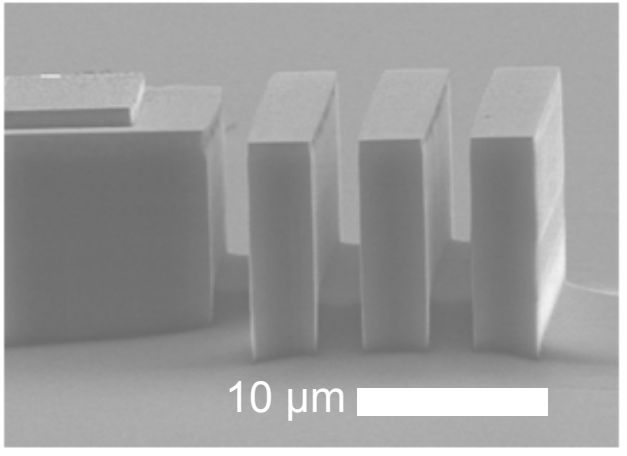
Single-mode: reduction of resonator length

→ íncreased mode spacing

→ increased mirror losses



→ Highly reflective mirrors required



2D PhCs: Colombelli et al., Science 302, pp. 1374, 2003

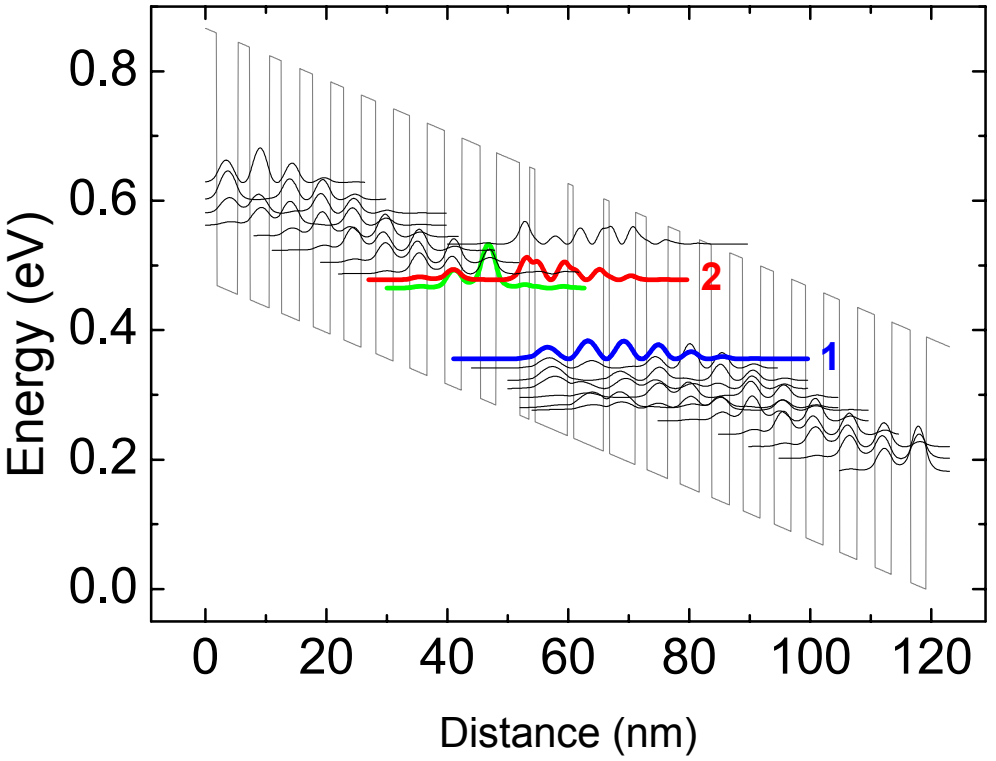
Dunbar et al., Opt. Exp. 13, no. 13, pp. 8960, 2005

Quantum Cascade Laser (QCL)

Bound-to-continuum $GaAs/Al_{0.45}Ga_{0.55}As$ active region design

Pflügl et al. Appl. Phys. Lett. 83(23) (2003)

- Resonant tunneling between **lowest injector state** and **upper laser level 2**
- Fast depopulation of **lower laser level 1** by interminiband scattering processes



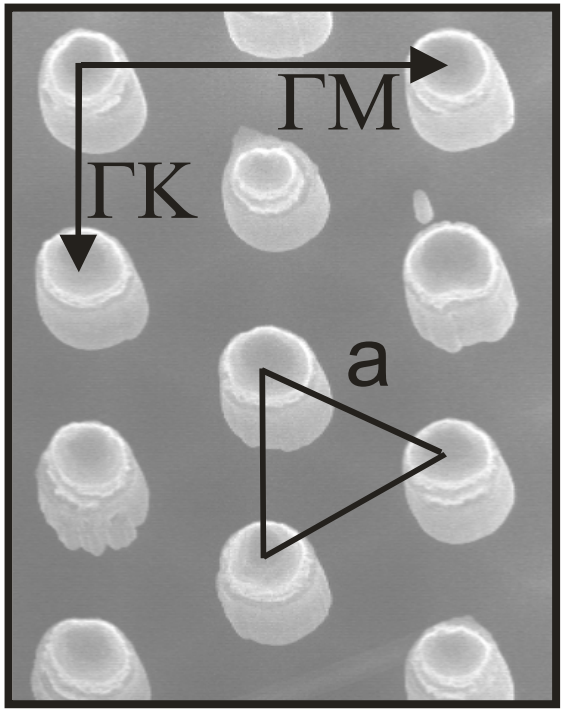
PhC Layout

Trigonal PhC lattice with high index pillars used as reflector

Lattice constant a = 3.5 µm

Pillar diameter d = 1.7 µm

→ **Photonic band gap at the emission wavelength (~11 µm)**



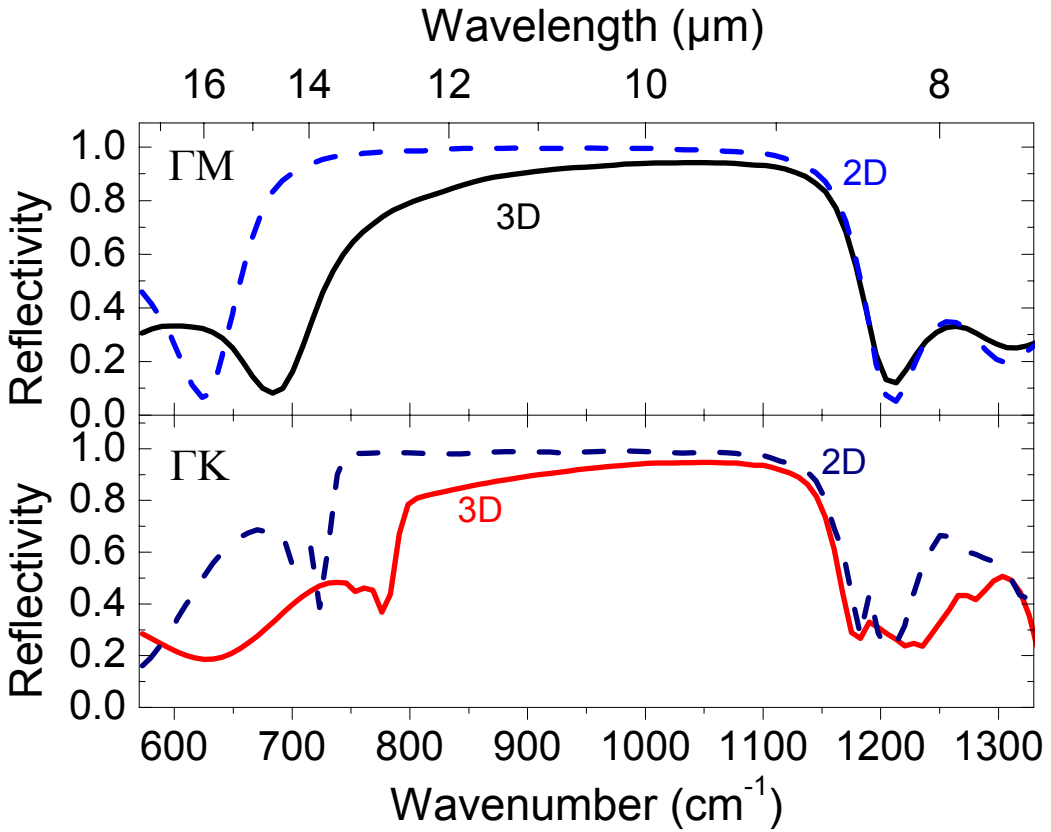
Reflectivity Calculations

FDTD simulations
for 1.5 period
(3 column rows)

→ **Broad stop band**

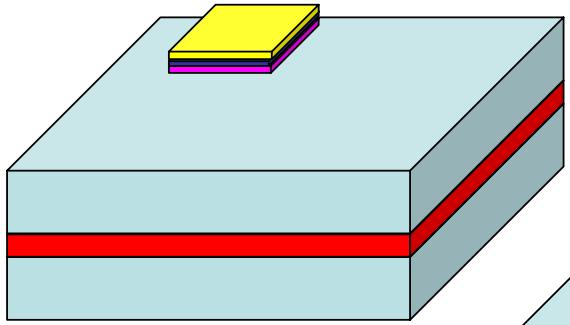
→ **Diffraction losses limit max. reflectivity**

→ **> 80 % reflectivity (3D)**

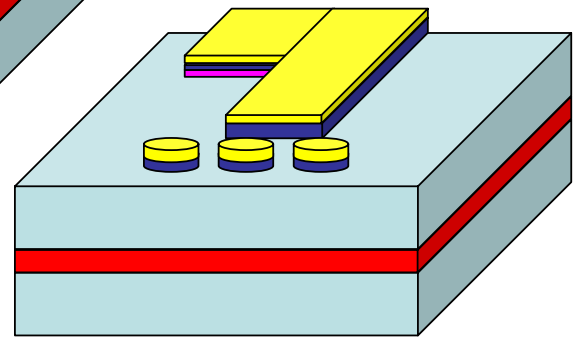


Device Fabrication

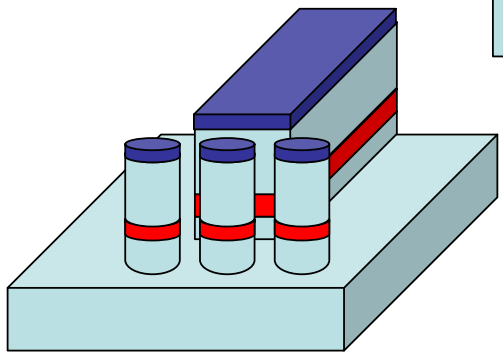
(1) Definition of contact pad
(optical lithography + lift-off)



(2) RWG and PhC mirror definition
(e-beam lithography + lift-off)

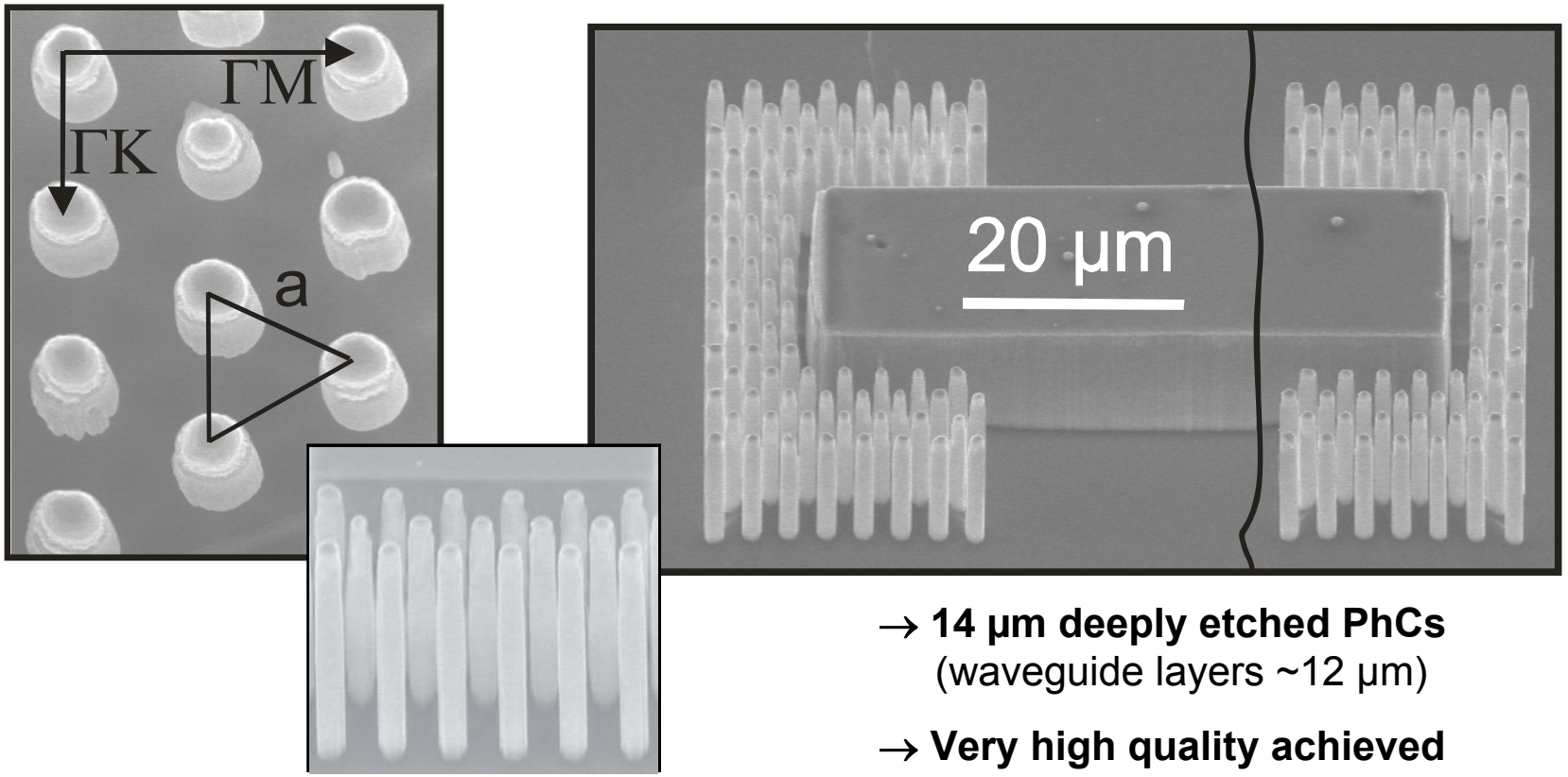


(3) Pattern transfer
(dry etching by ECR-RIE)



→ **Fabrication in single etch step**

PhC Devices



→ **14 µm deeply etched PhCs**
(waveguide layers ~12 µm)

→ **Very high quality achieved**

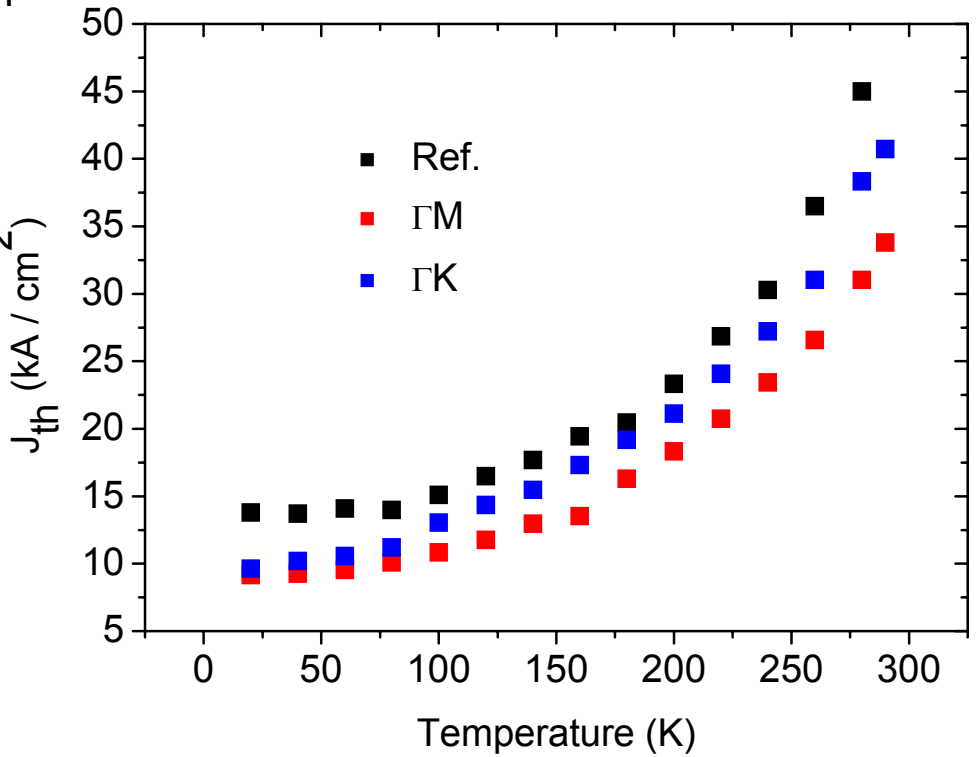
Threshold Characterisitics

1 mm (cleaved) $\alpha_m = 13.1\ cm^{-1}$

600 µm PhCs $\alpha_m = 1.4\ cm^{-1}$

600 µm PhC QCLs show reduced thresholds

ΓM: 34 % @ 20 K
ΓK: 30 % @ 20 K
theo. estim.: 38 %



S. Höfling et al. , *Appl. Phys. Lett.* 89, 191113, 2006.

Spectral Characteristics

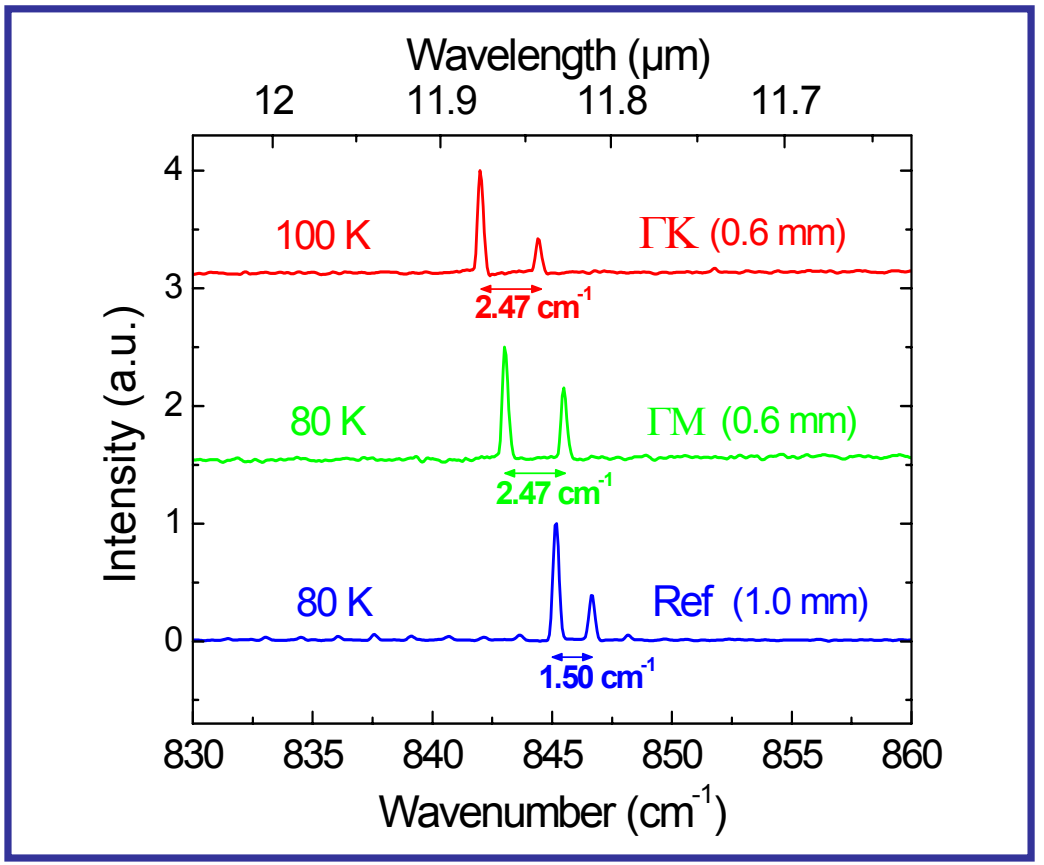
Mode spacing:

- 2.47 cm^{-1} (600 µm PhC)
- 1.50 cm^{-1} (1 mm Ref.)

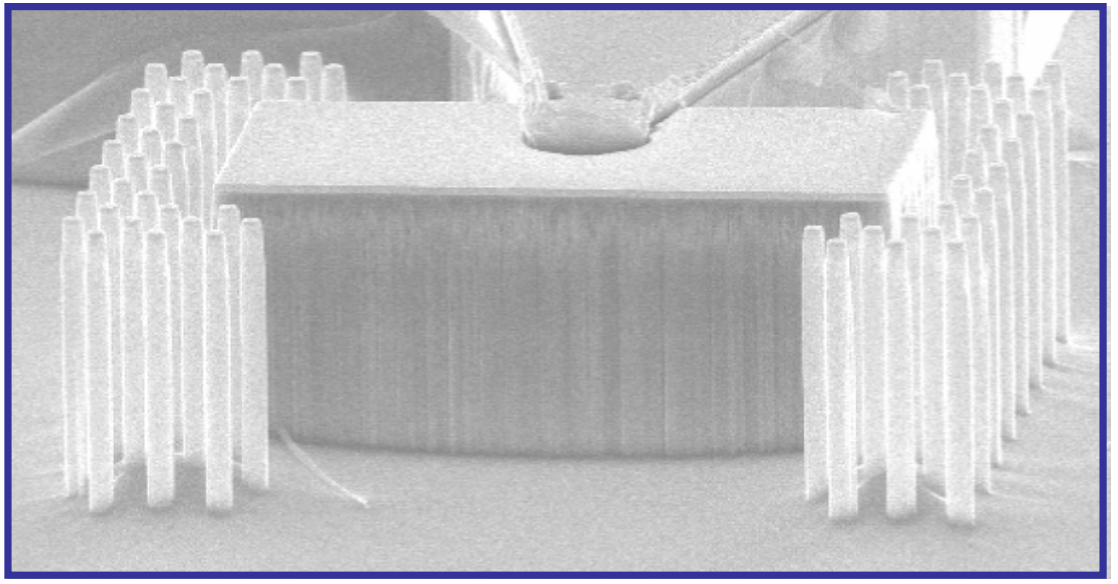
$\rightarrow n_{eff} = 3.35$

Spontaneous emission:
FWHM 32 cm^{-1}

$\Delta\nu \sim 15\ cm^{-1}$
$\rightarrow L_{res} \sim 100\ \mu m$



Micro-Laser with PhCs



1 mm (cleaved) $\alpha_m = 13.1\ cm^{-1}$

100 µm PhCs $\alpha_m = 16.3\ cm^{-1}$

Accepted for PTL

$\rightarrow \mathfrak{S}_m \sim$ constant

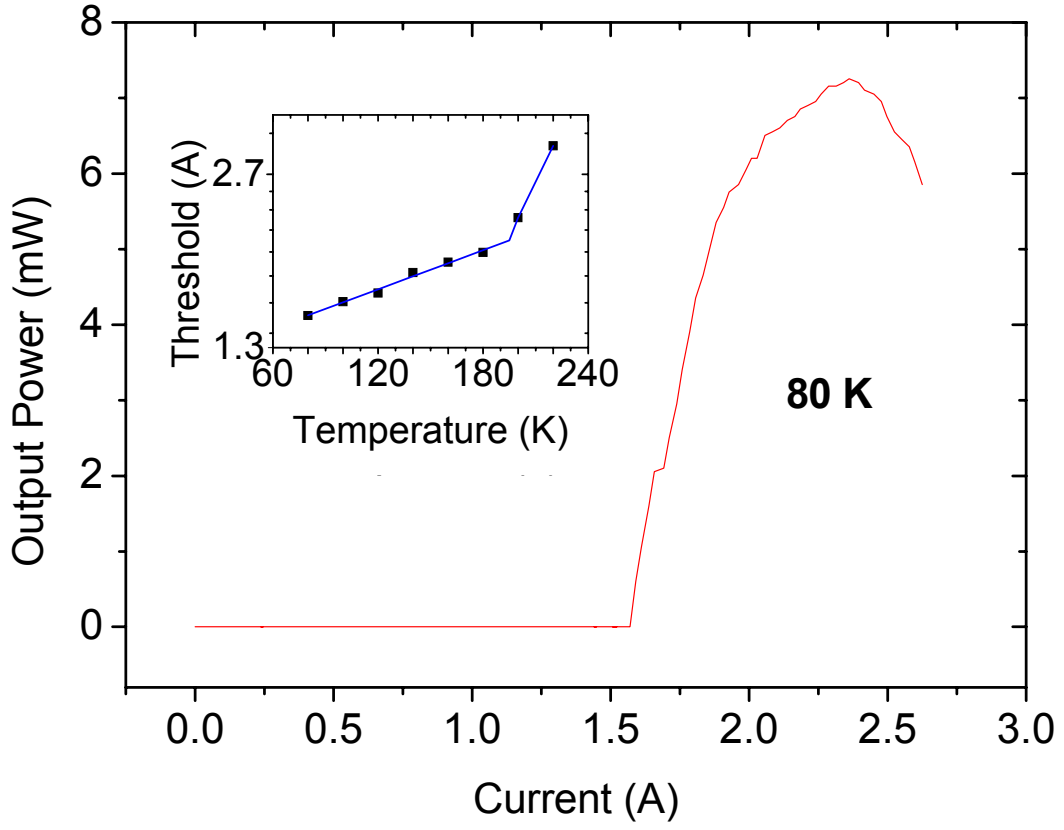
Performance of PhC micro-laser

80 K

- I_{th} = 1.6 A
- I_{sat} = 2.4 A
- P_{max} = 7.3 mW

Performance limited due to

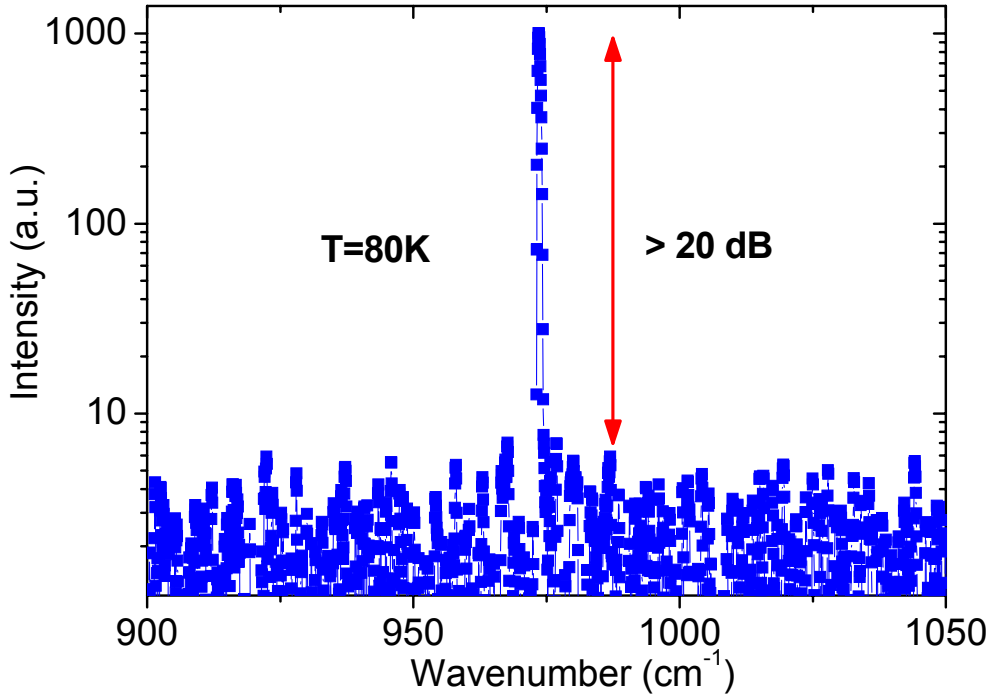
- High reflectivity of PhCs
- Current leakage
- Increased thermal resistance



Single-mode operation (1)

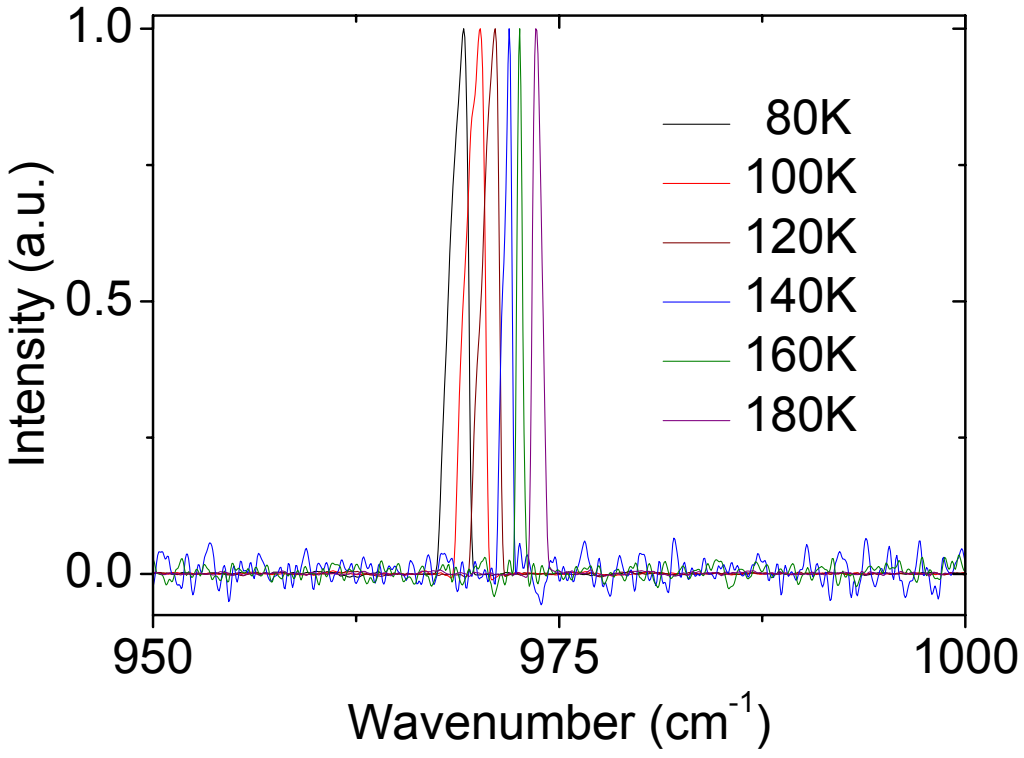
- Limited gain bandwidth
- Large mode spacing

→ Only one mode excited



Single-mode operation (2)

Stable single-mode emission up to T = 180 K

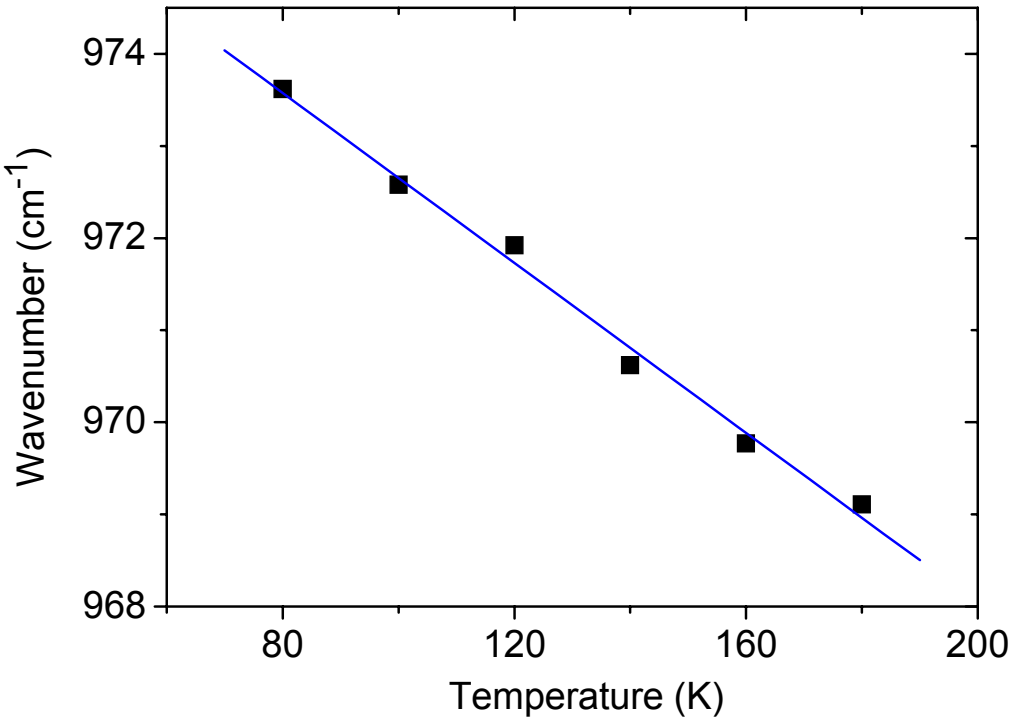


Tuning behaviour

Stable single-mode emission up to 180 K

→ enables single-mode tuning with temperature

Tuning rate of -0.046 cm^{-1} / K



Summary

- Fabrication of high quality PhCs with large etch depths (> 14 µm)
- 30% reduction of threshold current (20K) with 600 µm long devices
- 100 µm long micro-lasers: stable single-mode operation up to 180K
- Transfer to InP-based QCLs: possibility of room-temperature operation of PhC microlasers

Acknowledgement: M. Emmerling and A. Wolf