

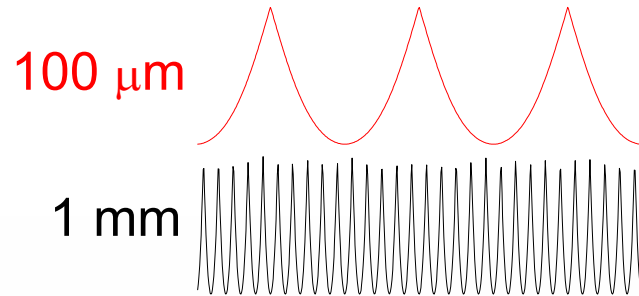
# Quantum Cascade Micro-Lasers with Two-dimensional Photonic Crystal Reflectors

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



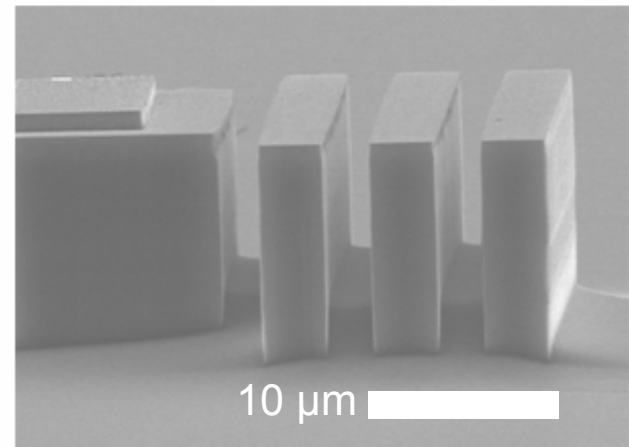
Single-mode: reduction of resonator length  
→ increased mode spacing  
→ increased mirror losses



→ Highly reflective mirrors required

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

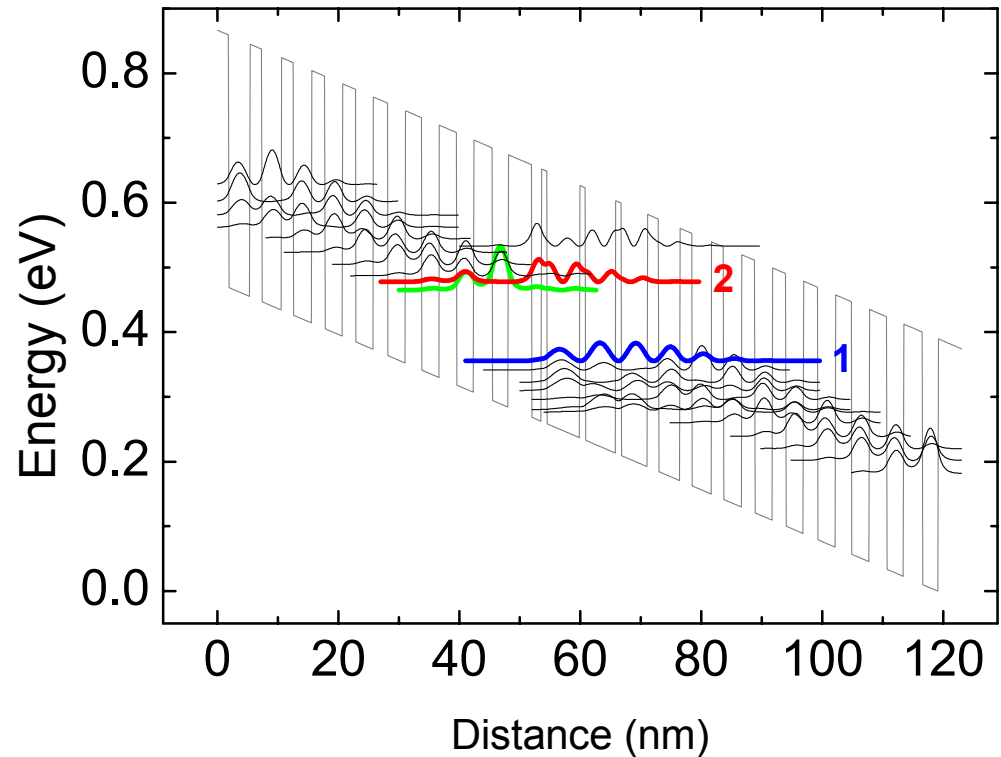
Dunbar et al., Opt. Exp. 13,  
no. 13, pp. 8960, 2005



Bound-to-continuum  
GaAs/ $\text{Al}_{0.45}\text{Ga}_{0.55}\text{As}$   
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

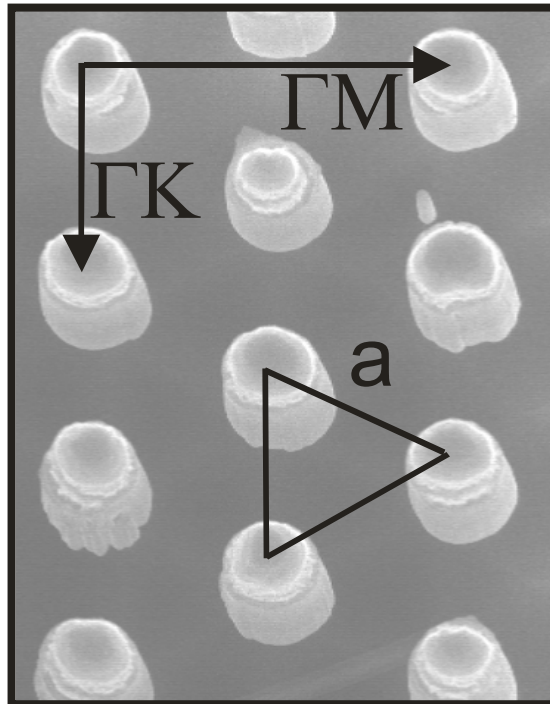


**Trigonal PhC lattice with high index pillars used as reflector**

Lattice constant  $a = 3.5 \mu\text{m}$

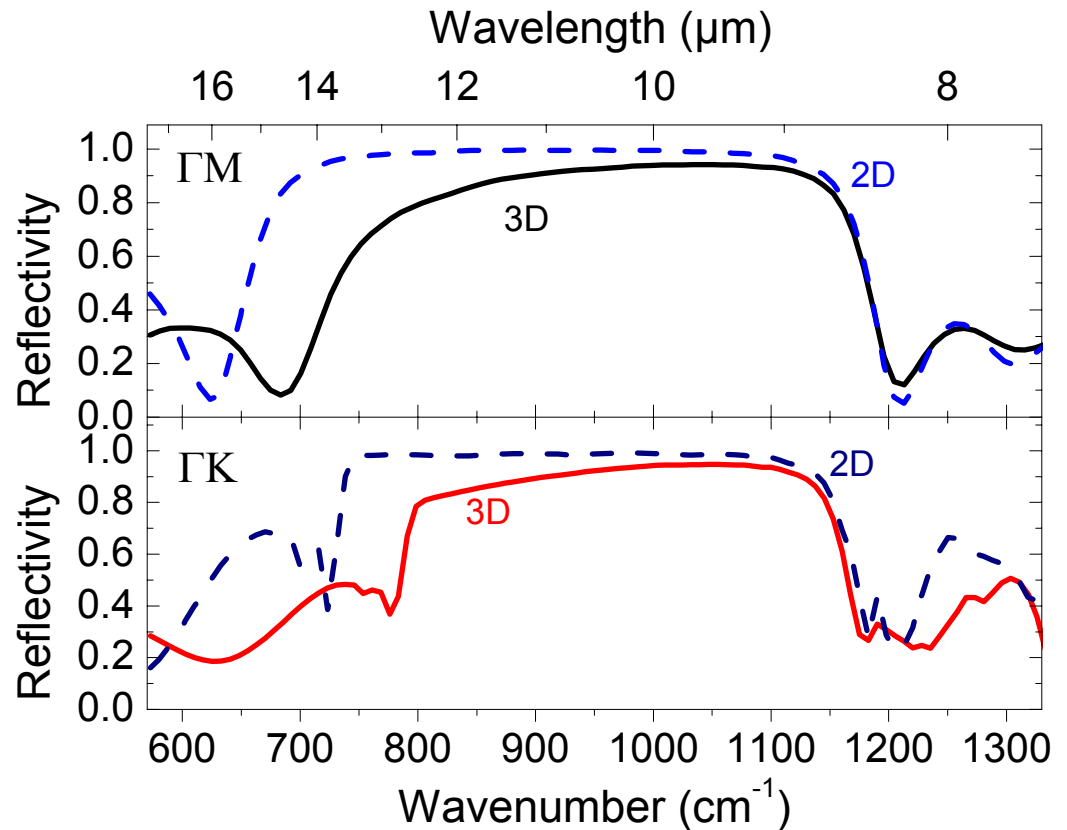
Pillar diameter  $d = 1.7 \mu\text{m}$

→ **Photonic band gap at the emission wavelength ( $\sim 11 \mu\text{m}$ )**

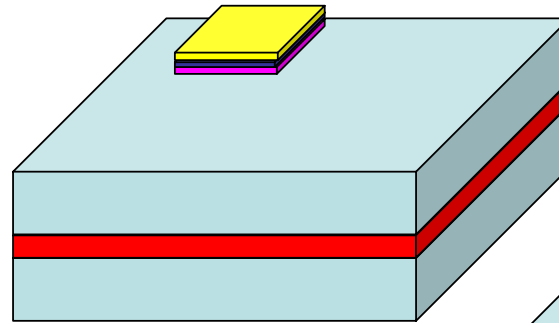


FDTD simulations  
for 1.5 period  
(3 column rows)

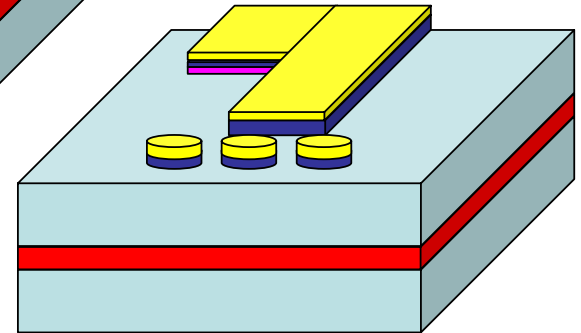
- **Broad stop band**
- **Diffraction losses limit max. reflectivity**
- **> 80 % reflectivity (3D)**



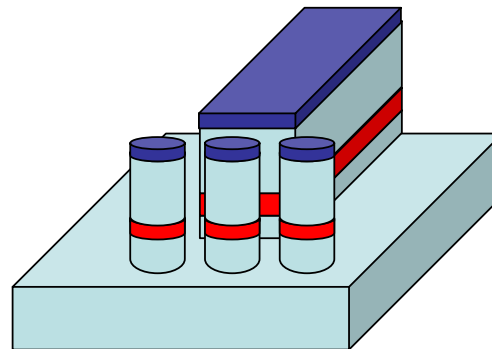
**(1) Definition of contact pad**  
(optical lithography + lift-off)



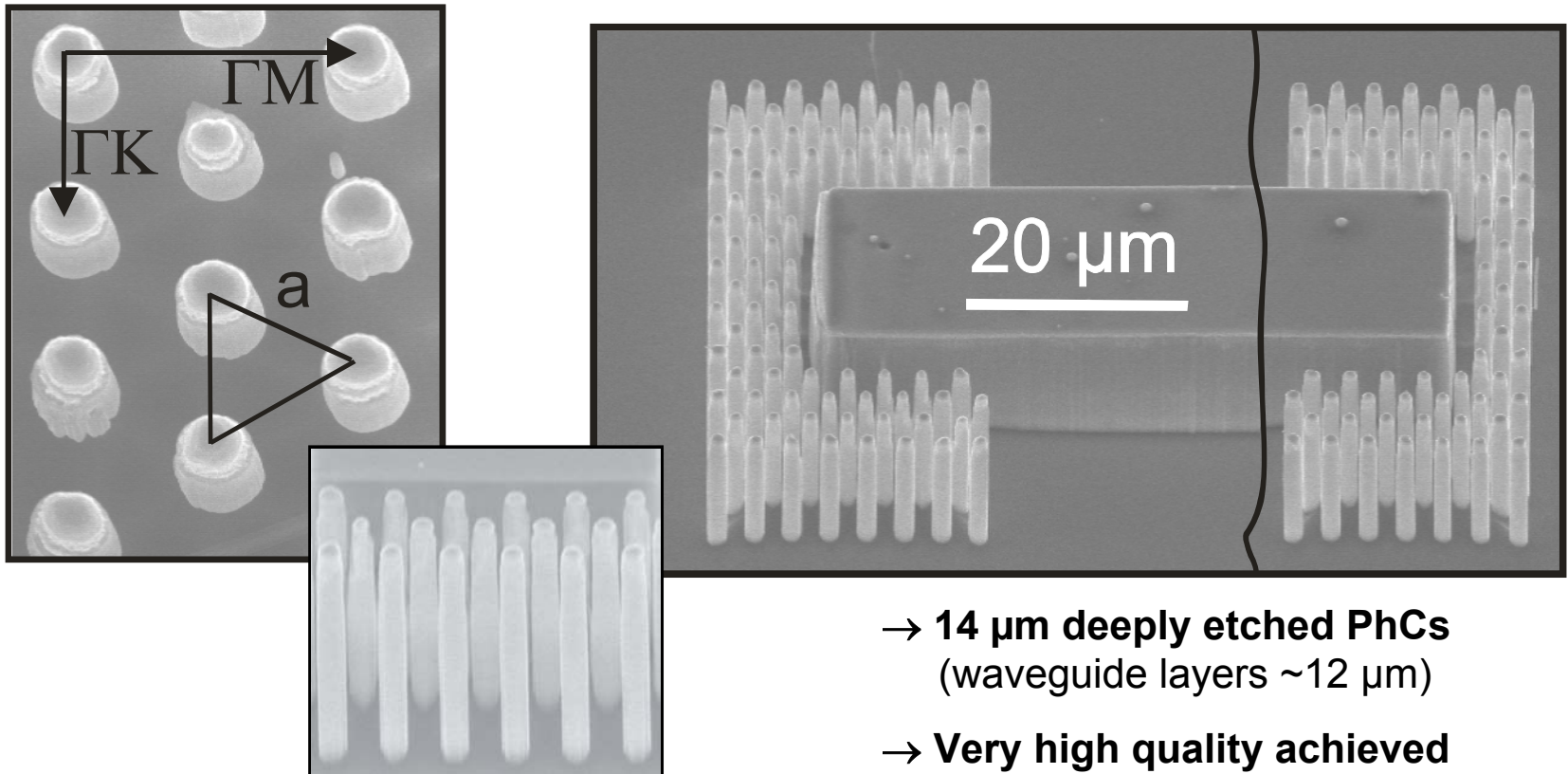
**(2) RWG and PhC mirror definition**  
(e-beam lithography + lift-off)



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



→ **Fabrication in  
single etch step**



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

600  $\mu\text{m}$  PhCs  $\alpha_m = 1.4 \text{ cm}^{-1}$

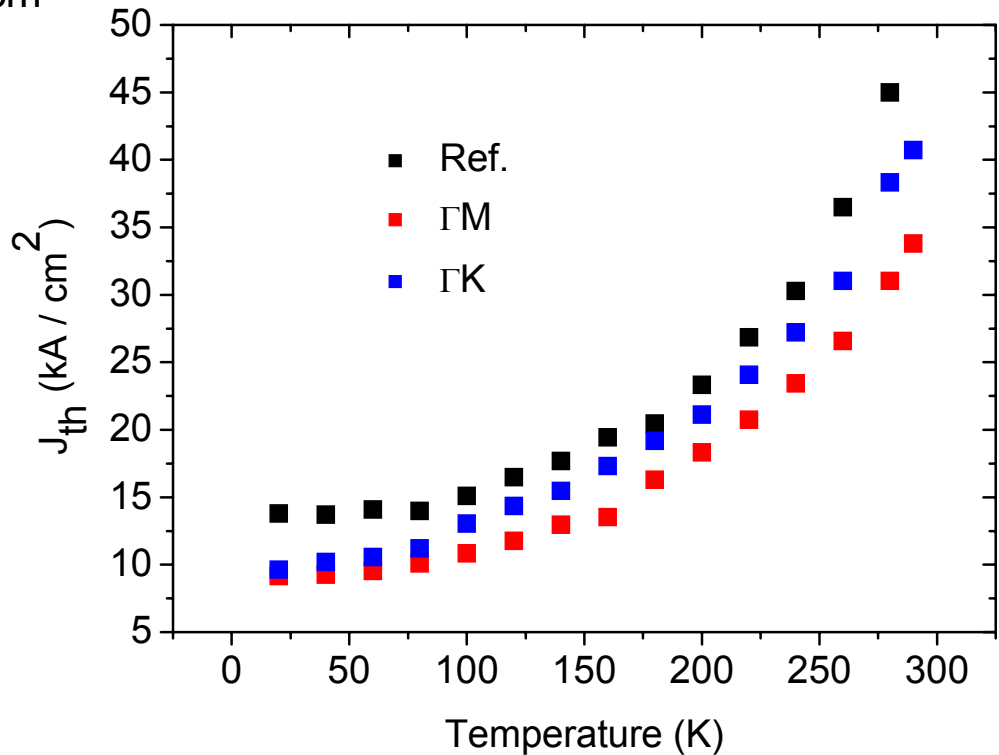
**600  $\mu\text{m}$  PhC QCLs show  
reduced thresholds**

$\Gamma\text{M}$ : 34 % @ 20 K

$\Gamma\text{K}$ : 30 % @ 20 K

theo. estim.: 38 %

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





Mode spacing:

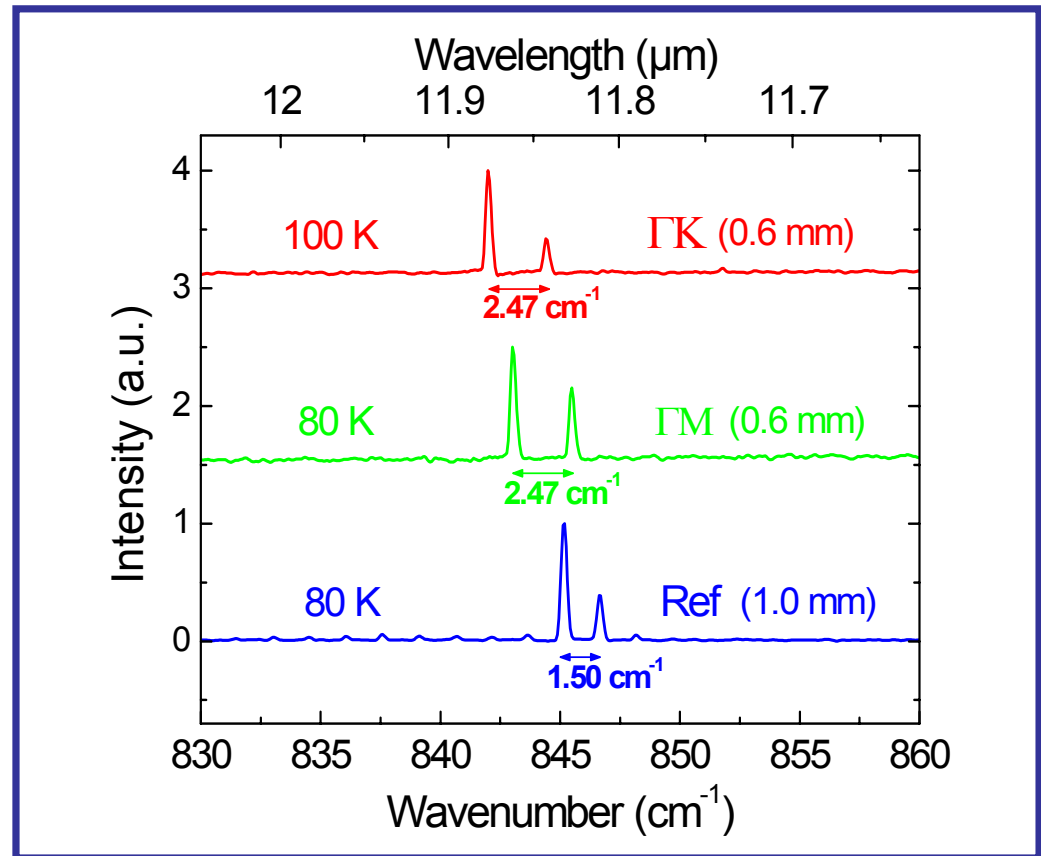
- $2.47 \text{ cm}^{-1}$  (600  $\mu\text{m}$  PhC)
- $1.50 \text{ cm}^{-1}$  (1 mm Ref.)

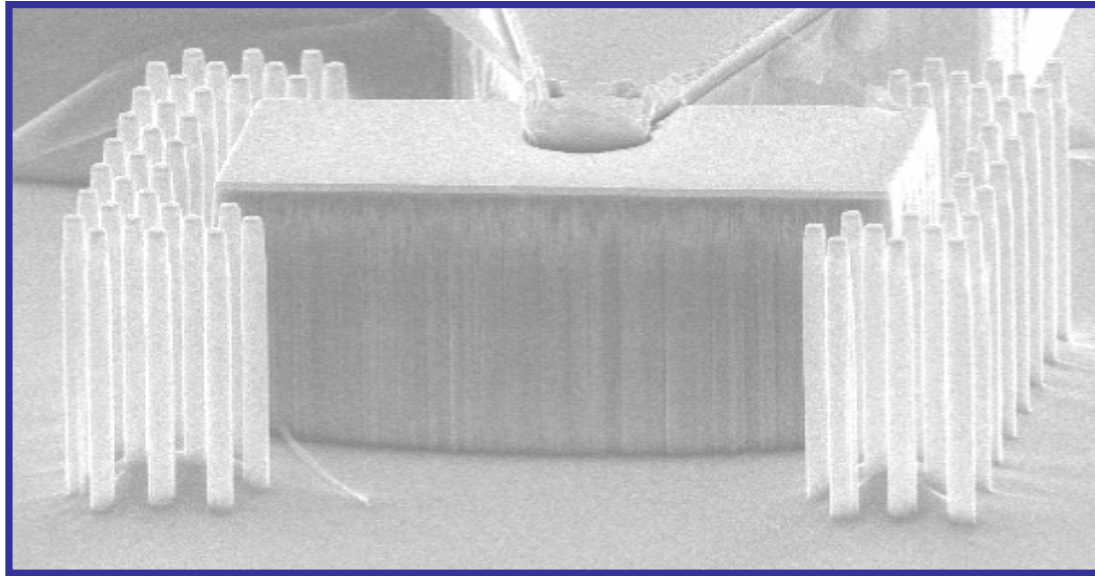
$$\rightarrow n_{\text{eff}} = 3.35$$

Spontaneous emission:  
FWHM  $32 \text{ cm}^{-1}$

$$\Delta\nu \sim 15 \text{ cm}^{-1}$$

$$\rightarrow L_{\text{res}} \sim 100 \mu\text{m}$$





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

100  $\mu\text{m}$  PhCs  $\alpha_m = 16.3 \text{ cm}^{-1}$

$\rightarrow \mathcal{Q}_m \sim \text{constant}$

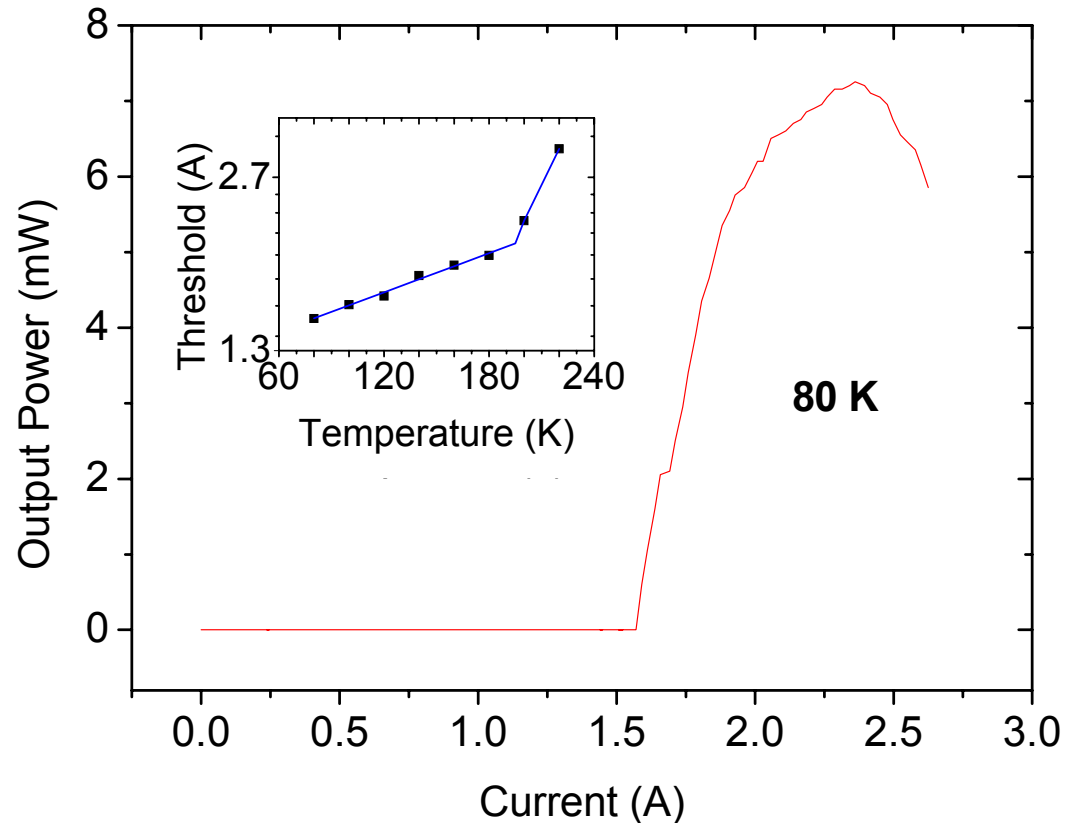
Accepted for PTL

**80 K**

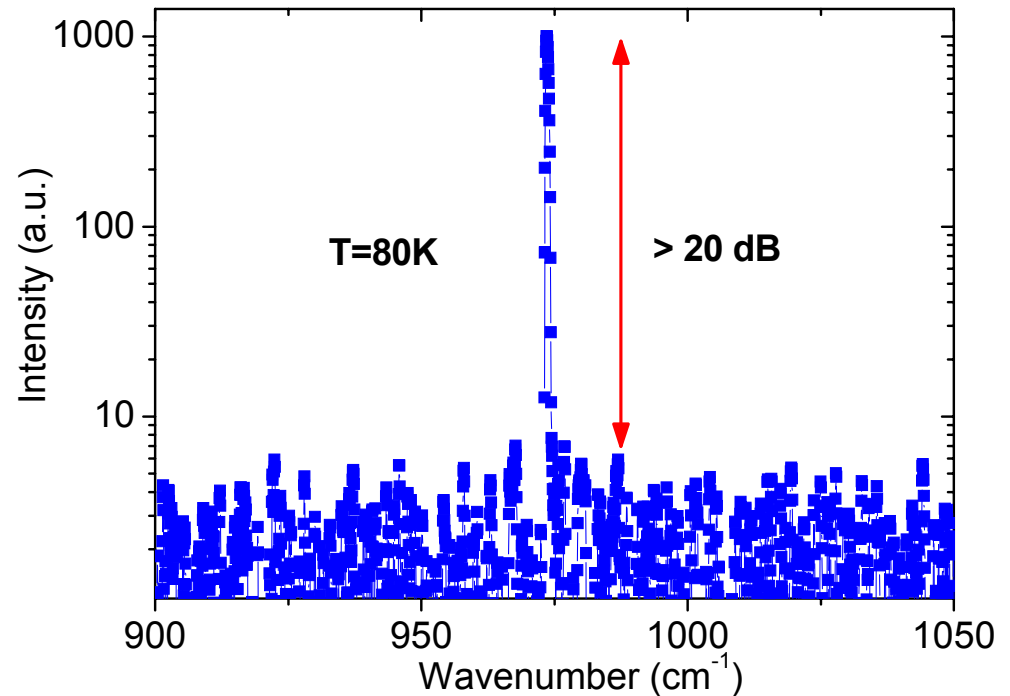
- $I_{th} = 1.6 \text{ A}$
- $I_{sat} = 2.4 \text{ A}$
- $P_{max} = 7.3 \text{ mW}$

Performance limited due to

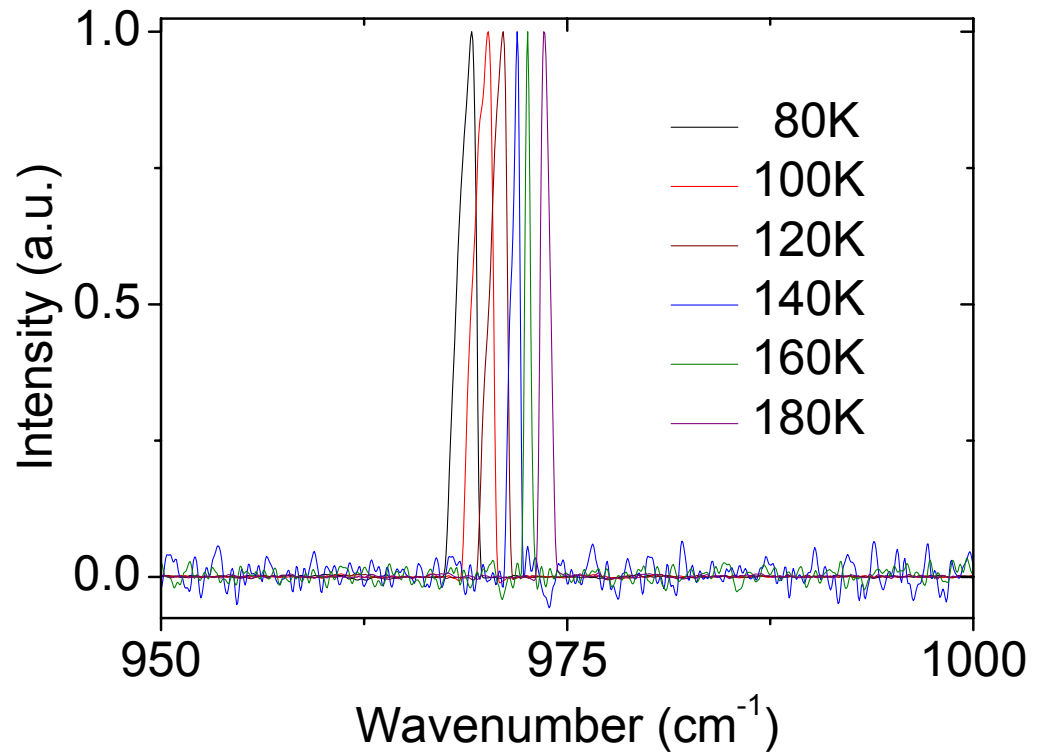
- High reflectivity of PhCs
- Current leakage
- Increased thermal resistance



- Limited gain bandwidth
  - Large mode spacing
- Only one mode excited



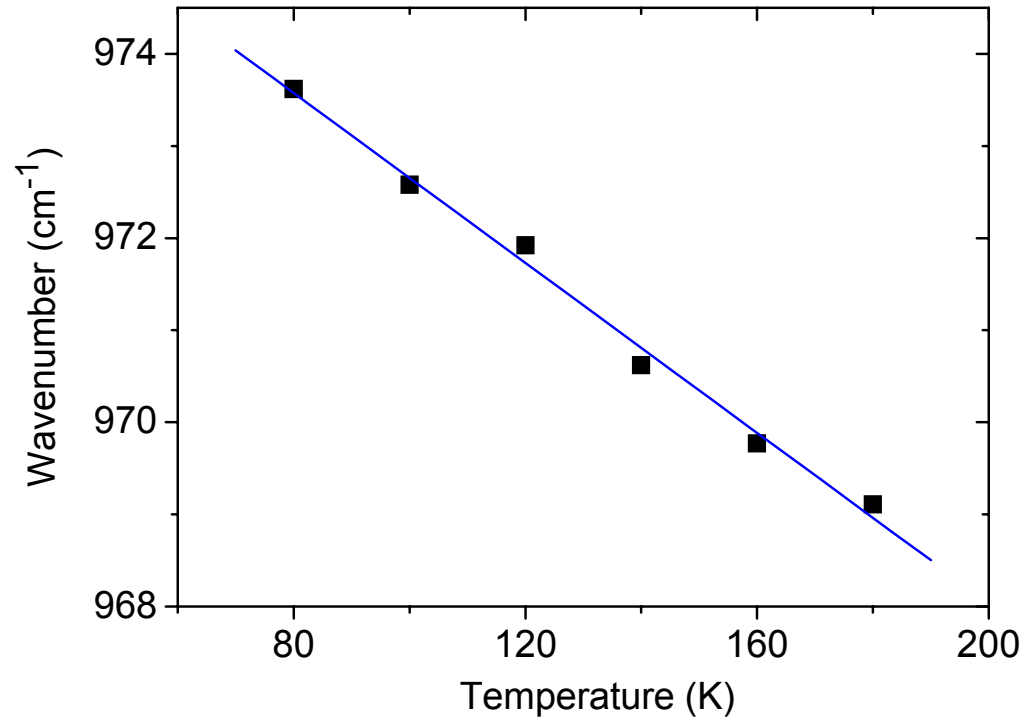
Stable single-mode  
emission up to  $T = 180$  K



Stable single-mode emission  
up to 180 K

→ enables single-mode tuning  
with temperature

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



- Fabrication of high quality PhCs with large etch depths ( $> 14 \mu\text{m}$ )
- 30% reduction of threshold current (20K) with  $600 \mu\text{m}$  long devices
- $100 \mu\text{m}$  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