



THz photonic crystal resonators

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Photonic crystal (PhC) resonators

- THz QCLs with double-metal waveguide
- PhC with full gap for TM-modes used as reflectors
- Further reduction of facet losses
- High-Q cavities
- Modes shifted to bandgap of PhC
- Outside bandgap increased losses

Photonic crystals \leftrightarrow THz QCLs

- THz quantum-cascade lasers (QCLs) have reached a high grade of maturity ¹
 - Low frequencies 0.83 THz ²
 - Lasing up to 164 K ³
 - Peak output powers of 248 mW ⁴
- Compact sources of THz radiation
- Light guiding solutions
- Photonic circuits

¹ R. Köhler et al., Nature **417**, 156 (2002)

² G. Scalari et al, ITQW 2007

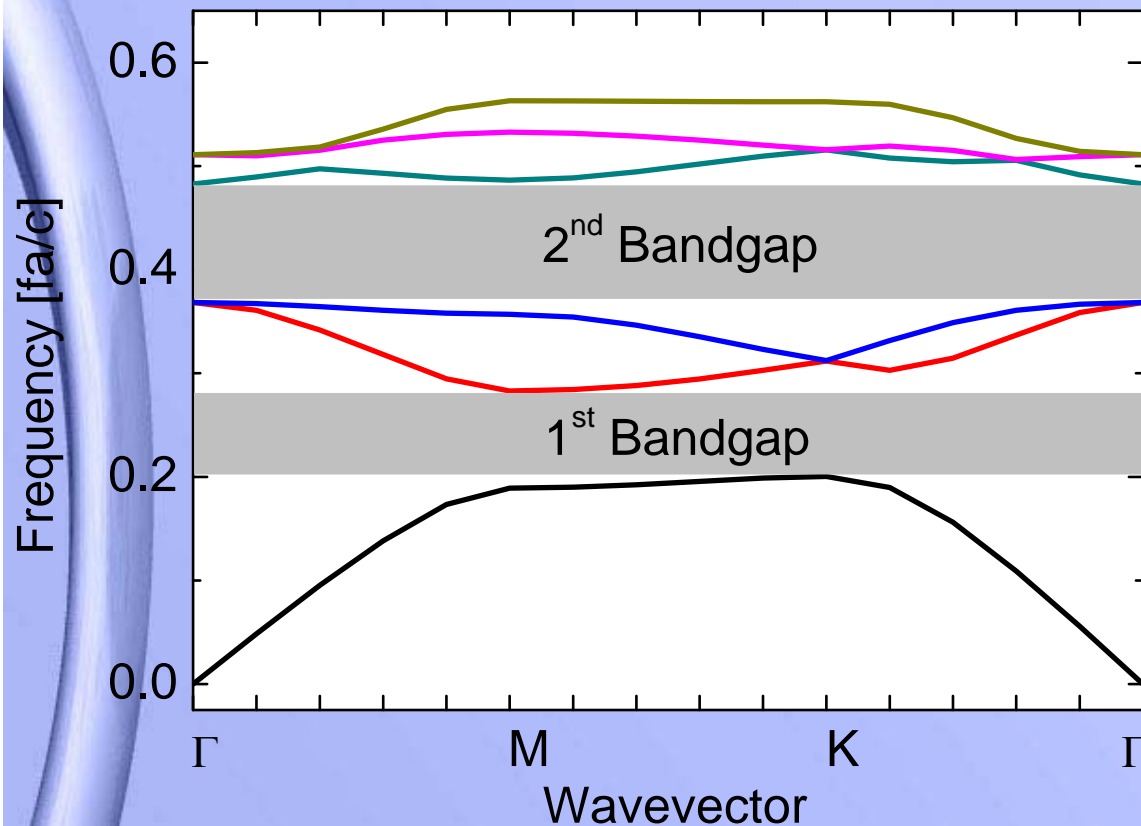
³ B. S. Williams et al., Opt. Exp. **13**, 3331 (2004)

⁴ B. S. Williams et al., Elec. Lett. **42**, 89 (2006)

THz photonic crystals (PhC)

- Integration into bandgap laser suffers from increased surface recombination
- QCL doesn't show that effect, ideal for minituarization
- TM-polarization of QCL-modes
 - Emits in-plane
 - Planar processing technology
 - Results in 2D-PhC
- Large wavelength (60 to 350 μm) of THz-QCLs makes the fabrication easy
 - Period of the PhC in the order of the wavelength

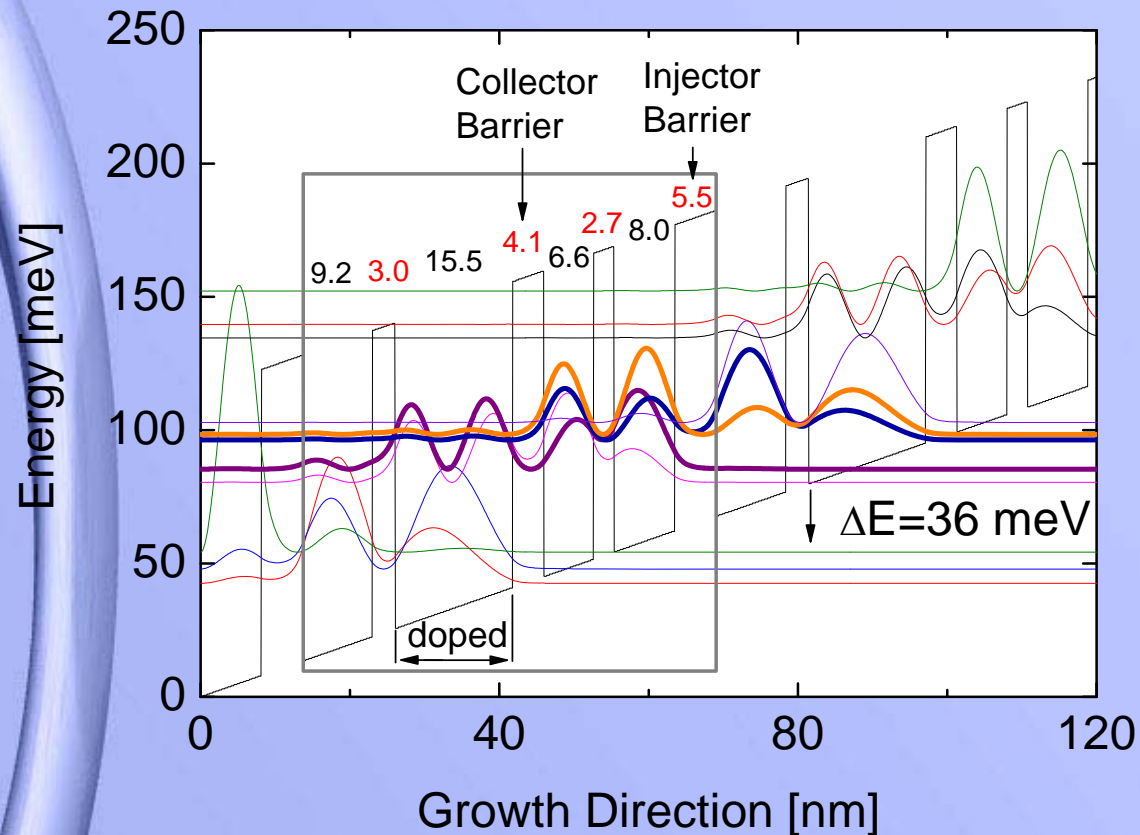
PhC band structure



- 2D-model used ¹
- Dielectric rods surrounded by air
- Rods are infinitely high
- $n_{\text{eff}}=3.9$
- Bandgaps for TM:
 - 1st: .2 to .28
 - 2nd: .37 to .48

¹ S.G. Johnson et al., Opt. Exp. 8 173 (2001)

QCL band structure

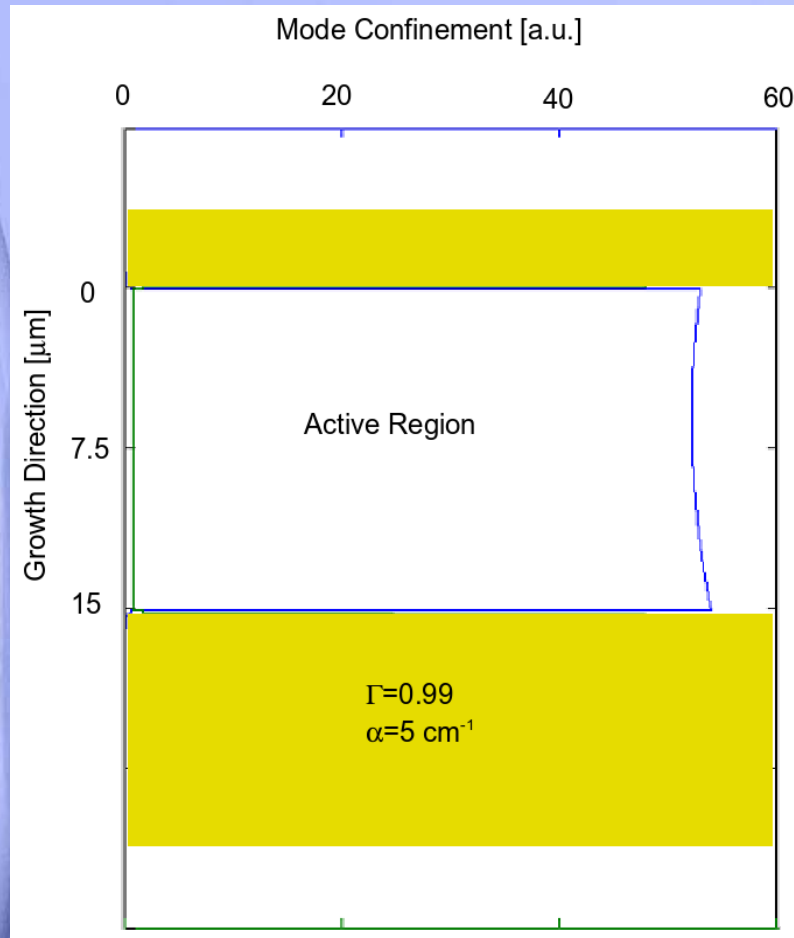


- LO-phonon depopulation design ¹
- Transition energy 12 meV
- 15 μm active region
- Two different samples used ²:
 - (a) 2.8 THz
 - (b) 2.5 THz

¹ S. Kumar et al., Appl. Phys. Lett. **84**, 2494 (2004)

² A. Benz et al., Appl. Phys. Lett. **90**, 101107 (2007)

Double-metal wave guide



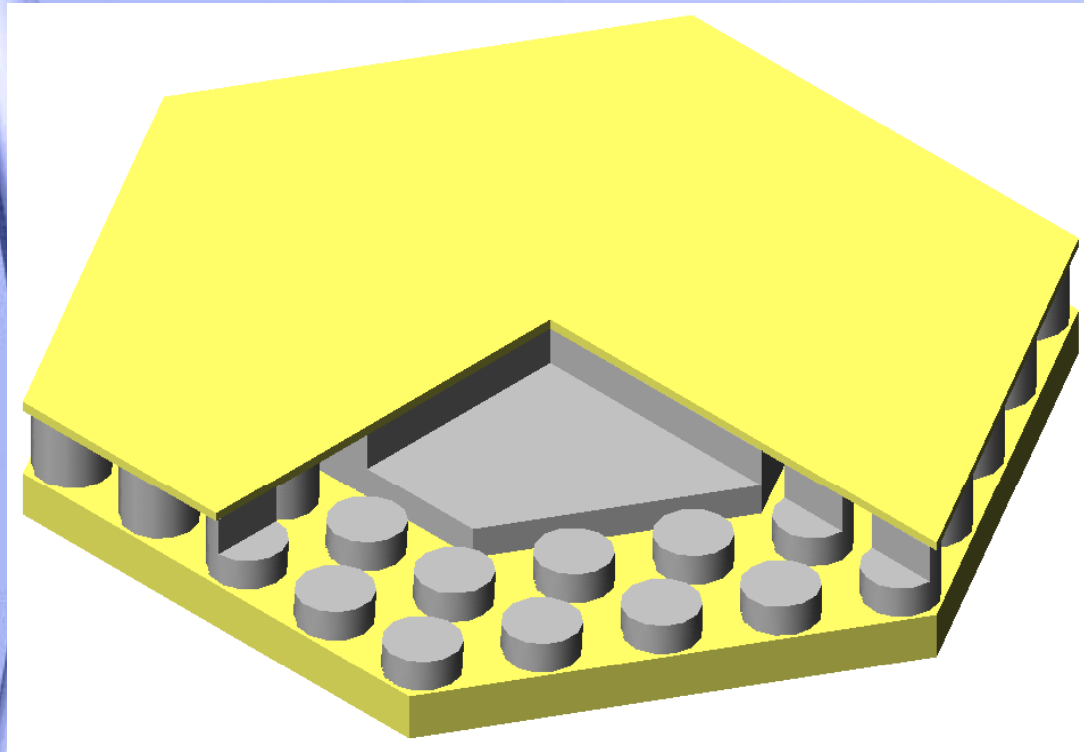
- Confinement near unity
- Low losses, $\alpha=5 \text{ cm}^{-1}$
- Only 1st order mode in vertical direction can propagate
- No out-of plane scattering
- Proven to be excellent wave guide for THz-QCLs ^{1, 2, 3}
 - Resonators with sub-wave length dimensions

¹ G. Fasching et al., IEEE J. Quantum Elec. **43**, 687(2007)

² Y. Chassagneux et al., Appl. Phys. Lett. **90**, 091113 (2007)

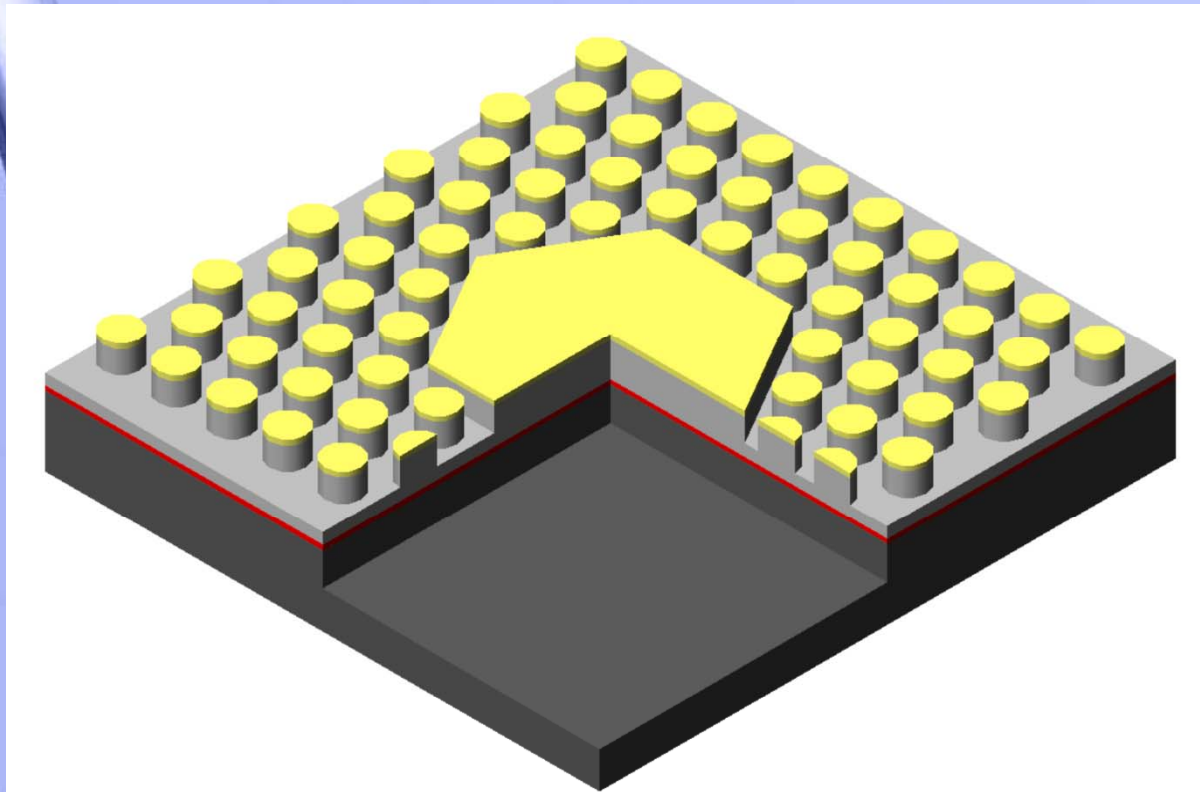
³ L. A. Dunbar et al., Appl. Phys. Lett. **90**, 141114 (2007)

PhC resonator



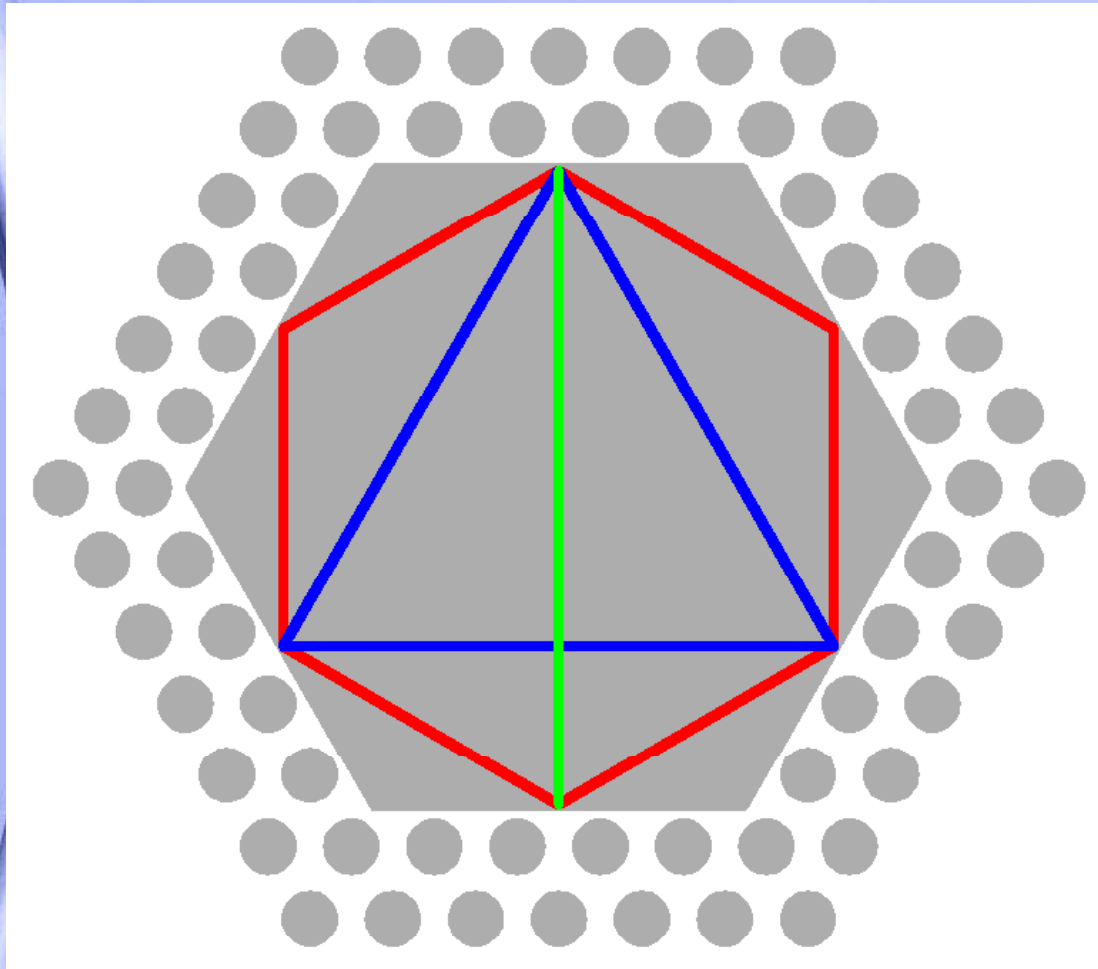
- Emission from facet
- Strong vertical confinement
- No mode leakage, problem for dielectric wave guides
- Lateral confinement by PhC
- Pillars are pumped but not supporting own modes

PhC processing



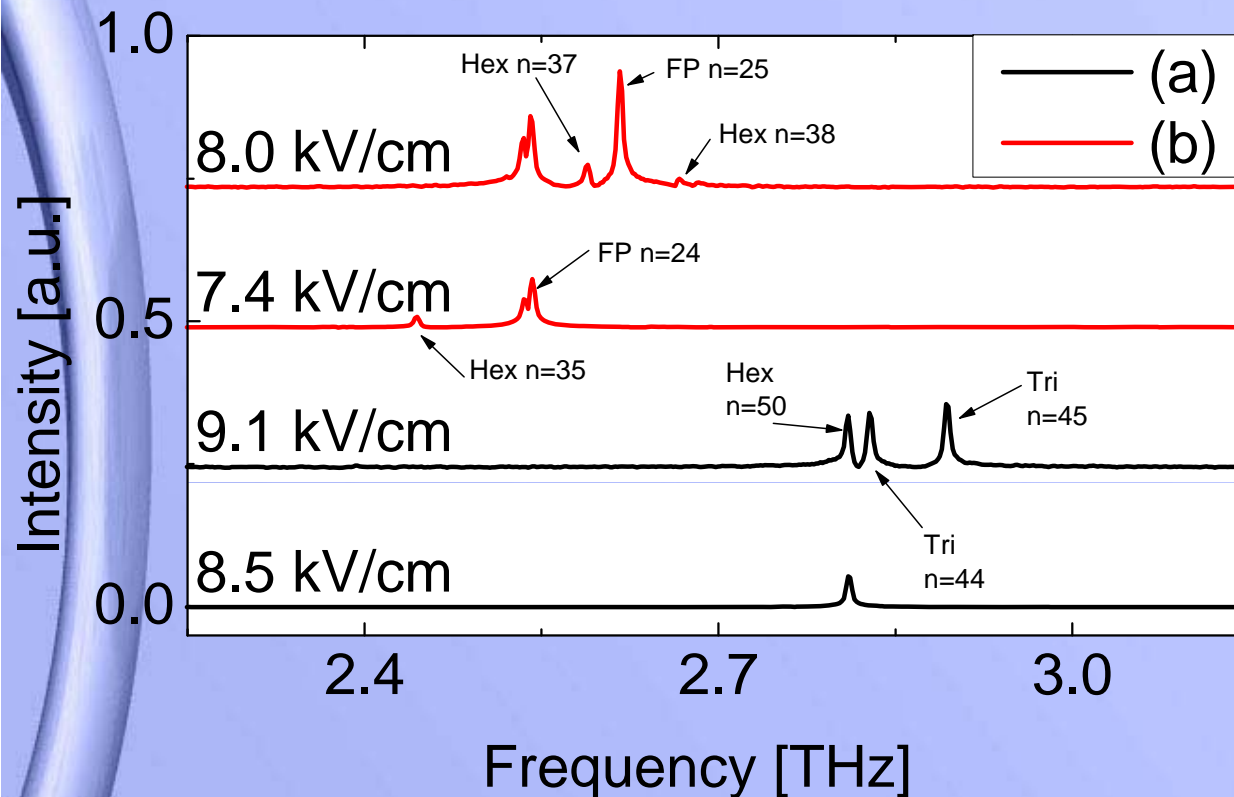
- Metal deposition, structure by opt. lithographie
- RIE etching
- Wafer bonding
- 2nd metal deposition step
- 2nd RIE etching step

Resonator modes



- Three dominant modes:
 - Fabry-Perot
 - Triangular
 - Hexagonal
- Different optical path leads to different mode spacing

Reference spectra



- Sample (a) emits between 2.8 and 2.9 THz
- Sample (b) emits between 2.45 and 2.7 THz
- Samples emit in the gain maximum of the active region

Summary

- PhC used as a frequency selective mirror
- Double-metal waveguide used
- Mode is forced to propagate through the PhC
- Emission shifted from the maximum gain to band gap of the PhC
- Mirror provides the lowest losses
- Modes identified as resonator modes of the hexagonally shaped core
- No single mode in general due to broad band gap

The background of the slide is a photograph of a city skyline at sunset. The sun is a bright, glowing orb on the left side, casting a warm orange and yellow light across the sky. The city buildings are silhouetted against the bright sky, appearing as dark shapes. The overall mood is serene and professional.

Thank you for your
attention!