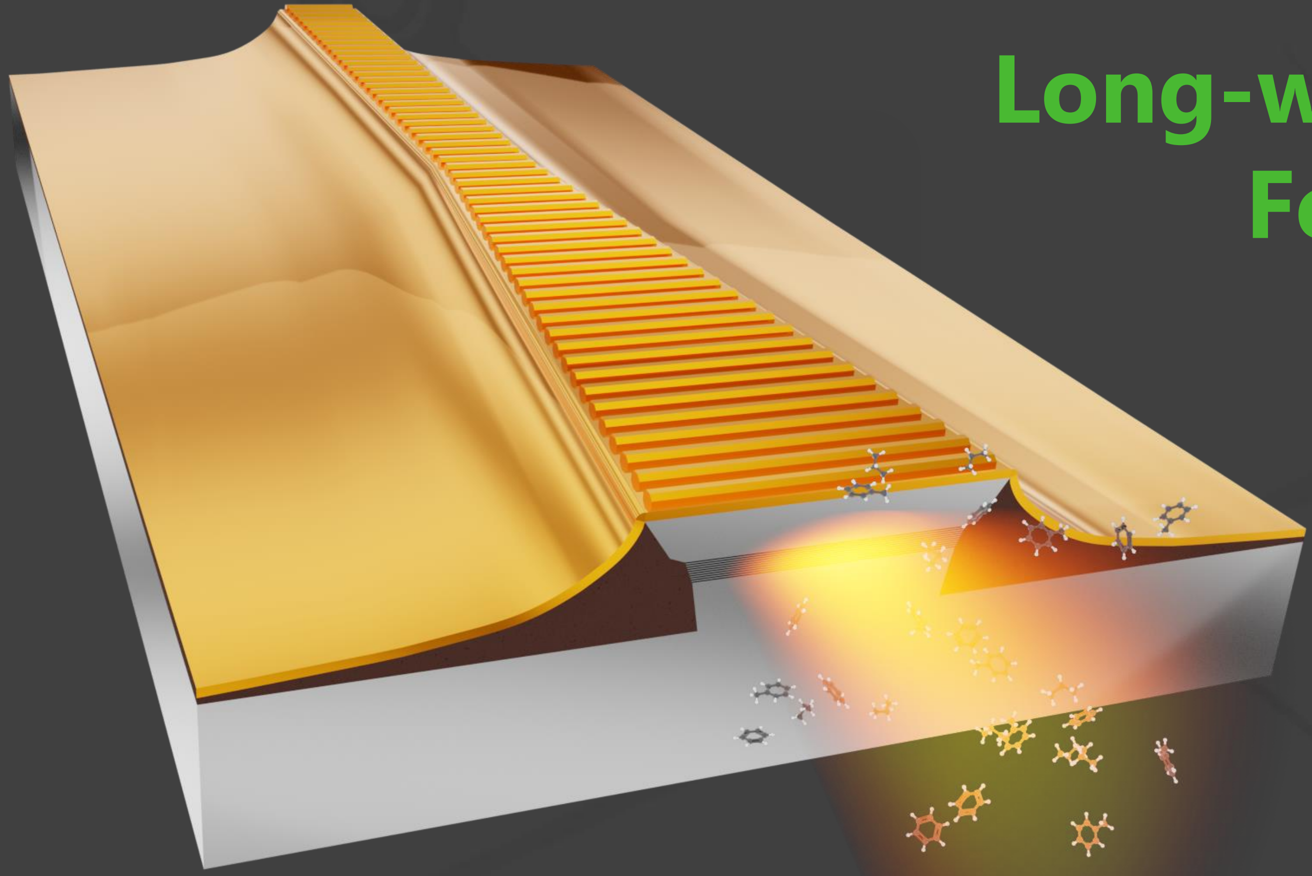
OPTAPHI — Optical Sensing using Advanced Photo-Induced Effects — A European Double Doctorate Training Network

C-PASS — Conference on Photonics for Advanced Spectroscopy and Sensing

*European Double Doctorate Training Network*



# Long-wavelength Distributed Feedback Tapered QCLs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*3-8 September 2023*

*C-Pass: Conference on Photonics for Advanced Spectroscopy and Sensing*


*OPTAPHI has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 860808*


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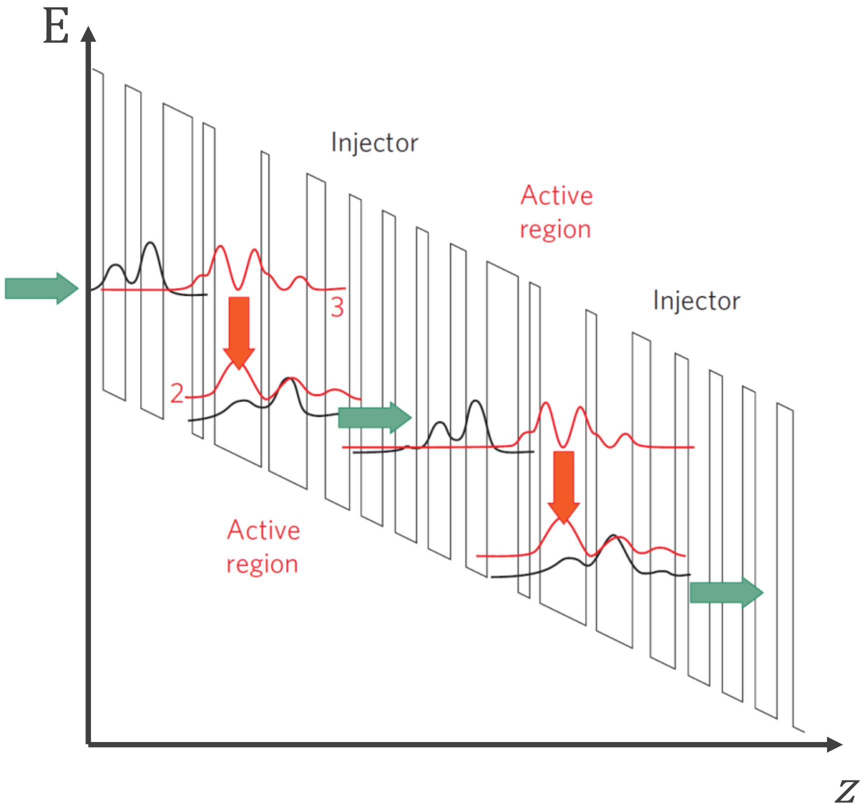
# Quantum cascade lasers (QCLs)




Yao, Y., Hoffman, A.J., Gmachl, C.F., 2012. Nature Photonics 6, 432–439.

## QCL'S MAIN CHARACTERISTICS

- "Artificial semiconductor" obtained as a repetition of quantum wells and barriers
- Photon are emitted by intersubband transition in a multistage-cascaded geometry
- Emission in the Mid-Infrared region: λ = 2 μm – 24 μm



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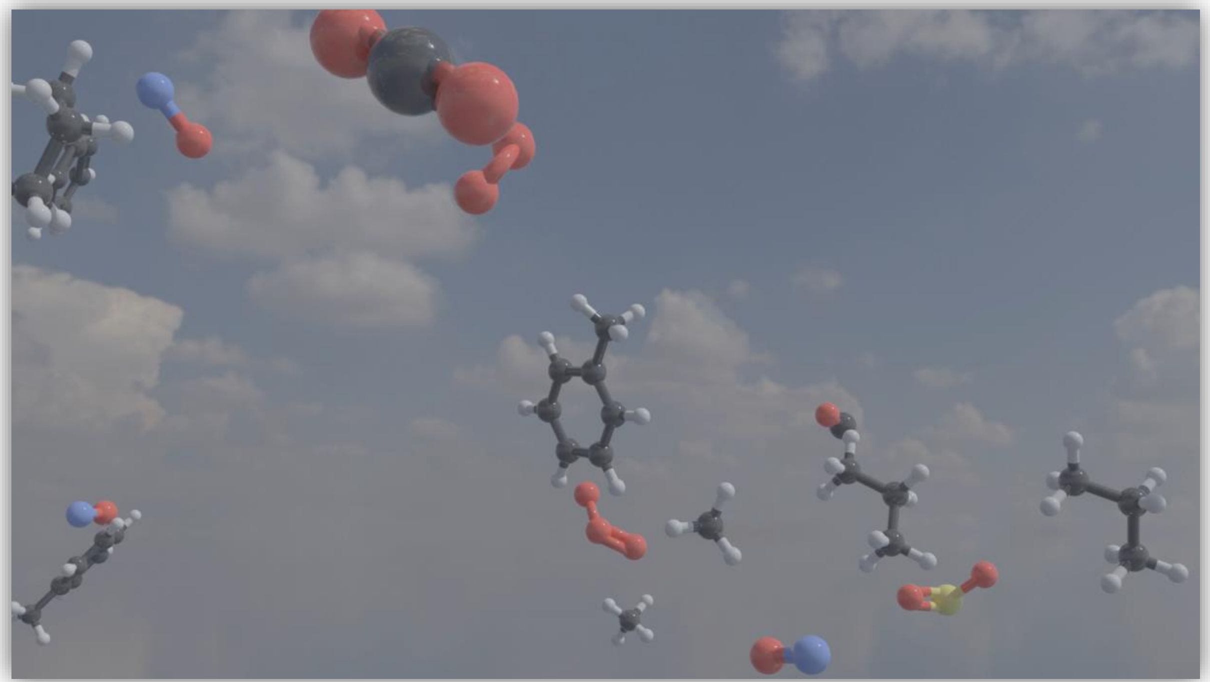
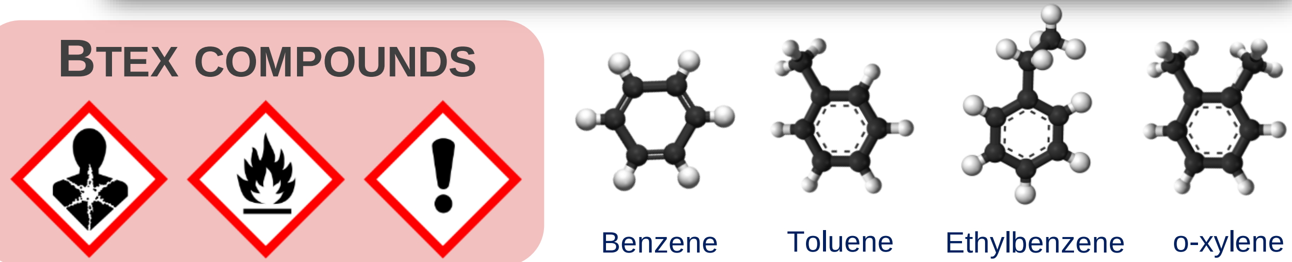
# QCLs applications: spectroscopy

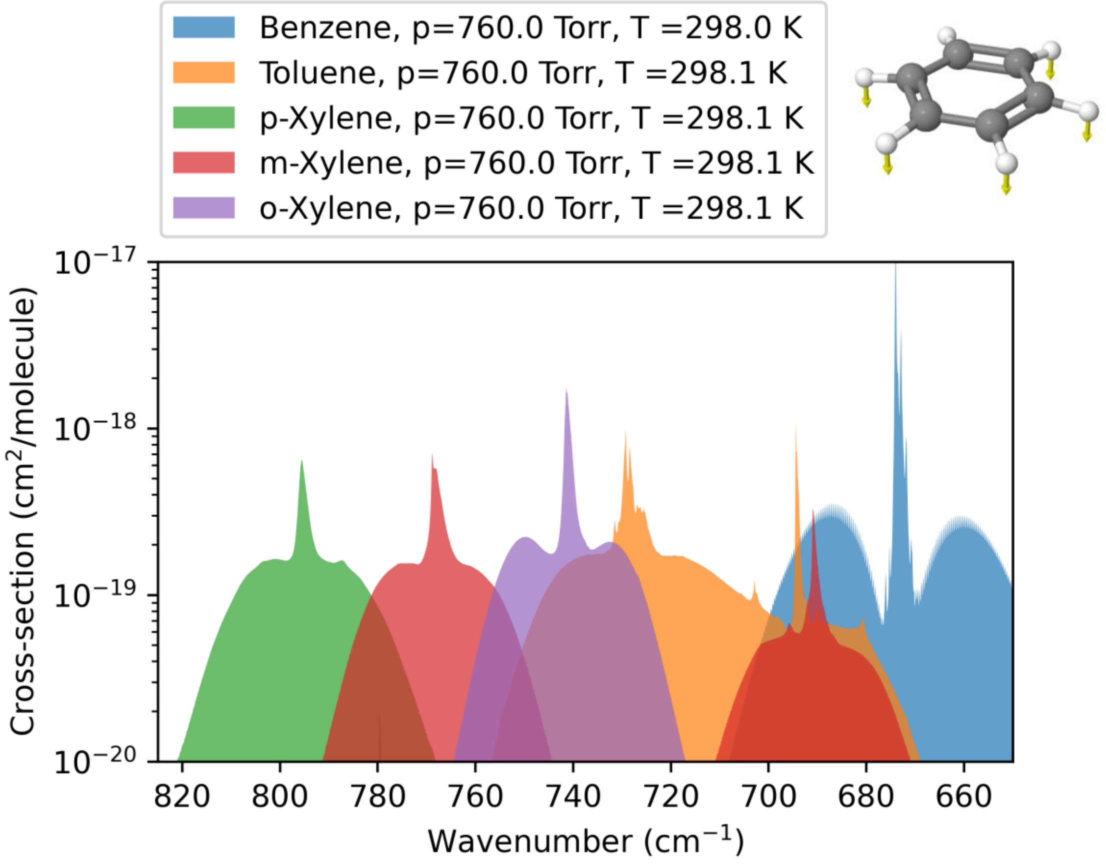


## Chemical sensing (Environmental Monitoring, Health & Life Science)



**BTEX compounds**



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# The Long-wavelength Challenge – InAs material system

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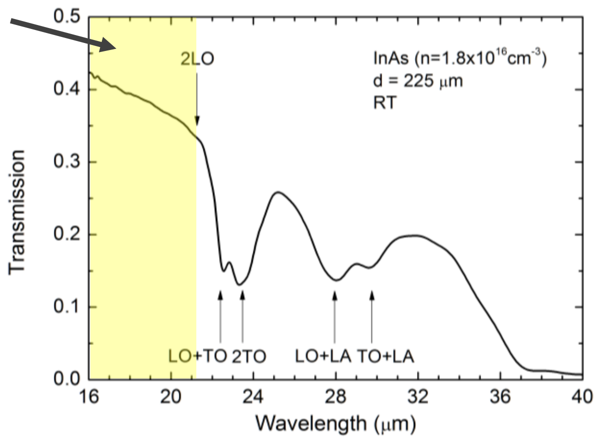
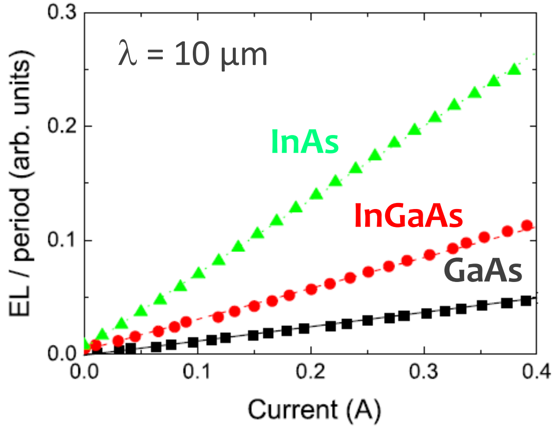
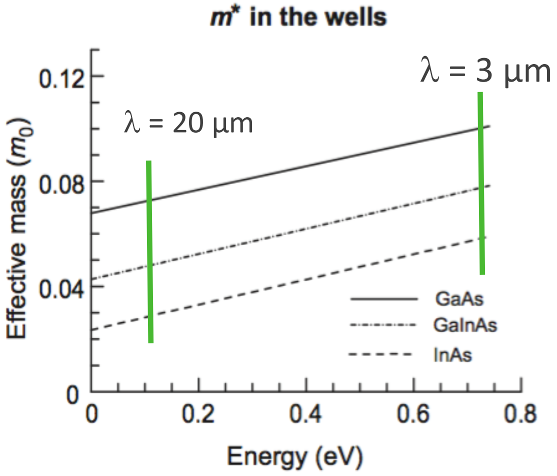
## FACING THE LIMITATIONS:

Transparency region in InAs




1. Smaller upper lifetimes (energy close to LO-phonon energy)
2. Free carrier scattering losses $\propto \lambda^2$
3. Material absorption (proximity to Reststrahlen band)




*E. Benveniste et al., Appl. Phys. Lett.* ***93****, 131108 (2008) - MPQ*

## THE SOLUTION: HIGH GAIN MATERIAL

$$g = \frac{e\hbar}{\varepsilon_0 c m_0}\frac{1}{2\gamma_{32} n L_p} f_{32}\tau_3\left(1-\frac{\tau_2}{\tau_{32}}\right) \sim \frac{1}{(m^*)^{3/2}}$$

- At larger wavelengths the non-parabolicity of the bands can be neglected
- Lower m* in InAs than in other materials
- First long-wavelength QCLs demonstrated at **Université de Montpellier**, since 2013

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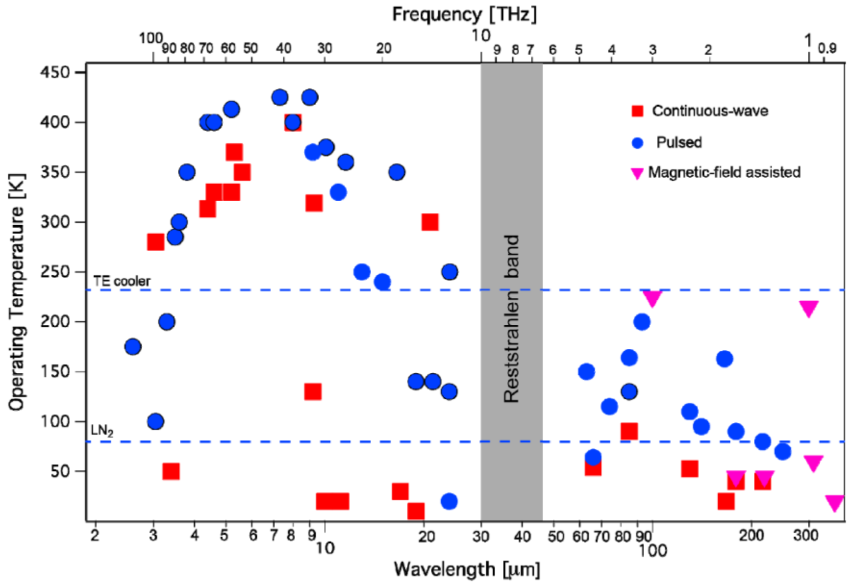
# The strive toward higher optical power






*Quantum Cascade Lasers: 20 years of challenges, Opt. Exp. 2015*

- Thermally activated processes (such as backfilling) reduce the laser performance at higher λ;
- The material system and heat extraction technology also play a fundamental role for CW-operation;
- Reduced optical power:

$$P_{opt} = F_{ph}\hbar\omega \propto \frac{1}{\lambda}$$

**NEED OF A STRATEGY TO IMPROVE AVAILABLE POWER!**



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# The strive toward higher optical power

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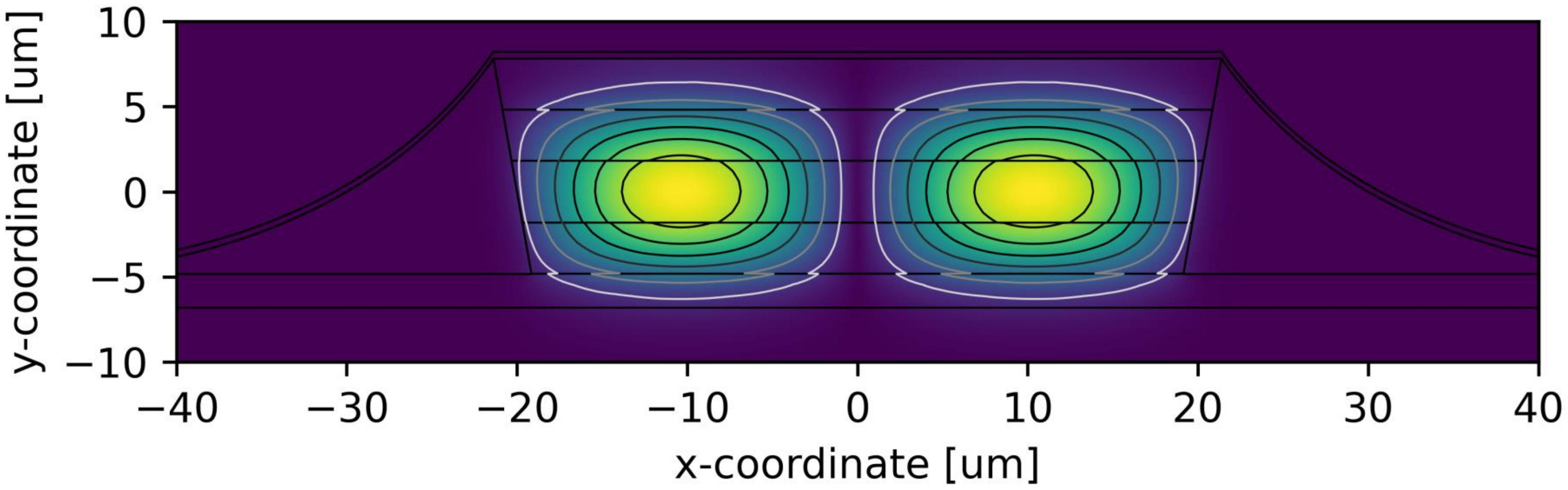


## BEAM QUALITY FACTOR

$$M_{x,y}^2 = \frac{4\pi\sigma_{0(x,y)}\sigma_{\theta(x,y)}}{\lambda}$$

**NARROW RIDGE WIDTH** → diffraction limited beam quality ($M^2 \approx 1$)

**WIDE RIDGE WIDTH** → waveguide supports higher order modes ($M^2 \gg 1$)



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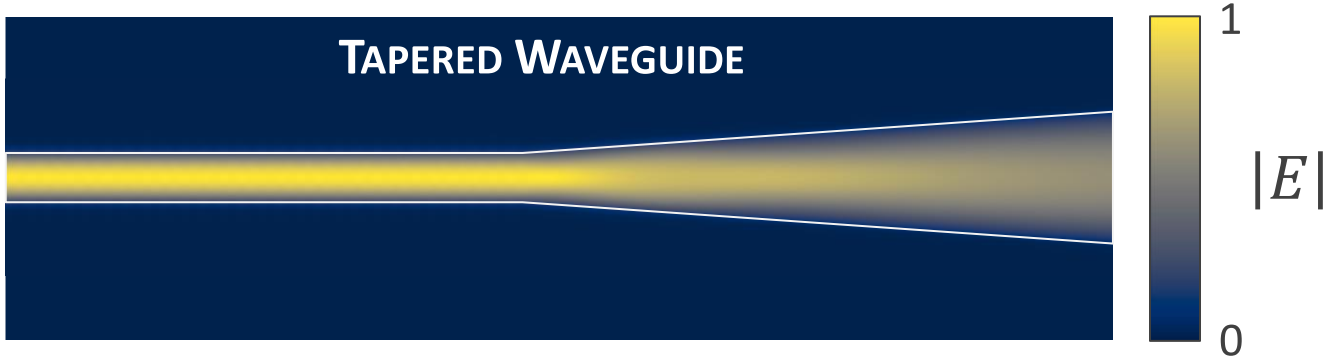
# MOPAs & Tapered lasers




## Advantages of Tapered Waveguide:

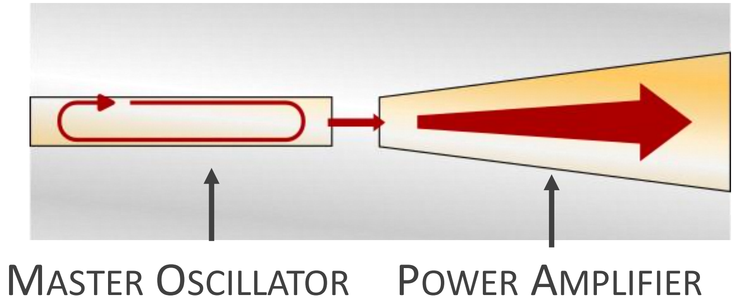
1. Larger active zone
2. Good Beam quality
3. Reduced in-plane divergence

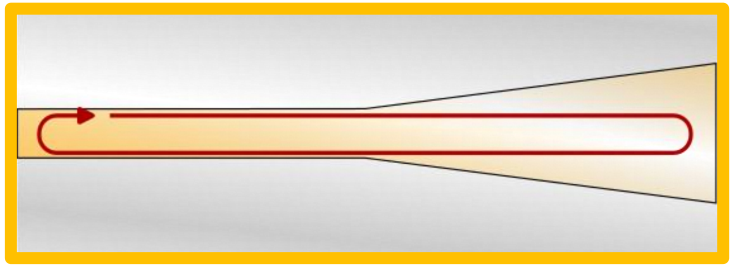
## Master Oscillator Power Amplifier:

- PA is driven below self-lasing current density
- Individual components optimization
- Adds complexity

## Tapered laser:

- the tapered waveguide acts as a (unstable) laser cavity
- Monolithic device





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# Fabrication of LW-Tapered QCLs

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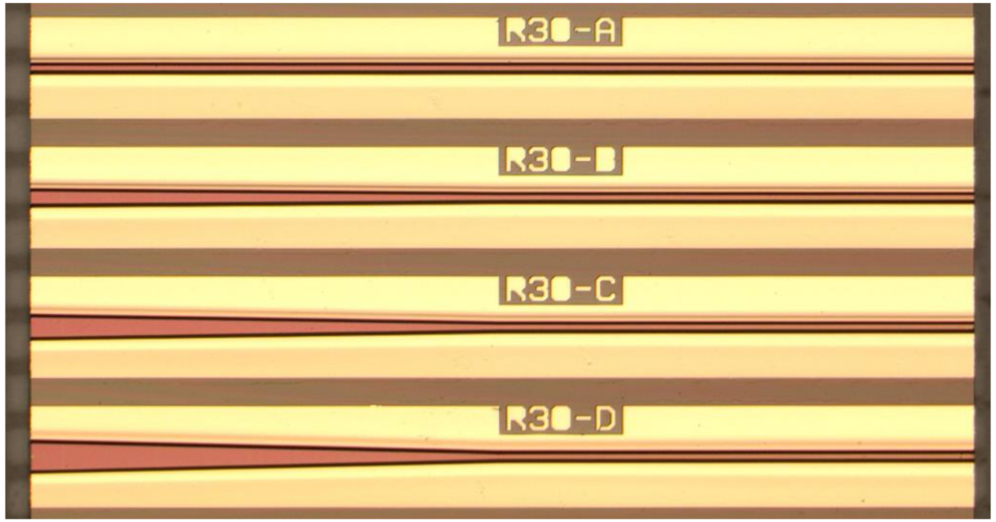
## TAPERED GEOMETRY:

- 3.6 mm long laser bars
- Taper (full-)angles between 0° – 3°
- Linear taper geometry
- ½ Taper section
  ½ Ridge section




| Laser | Taper angle |
|---|---|
| A | 0° |
| B | 1° |
| C | 2° |
| D | 3° |

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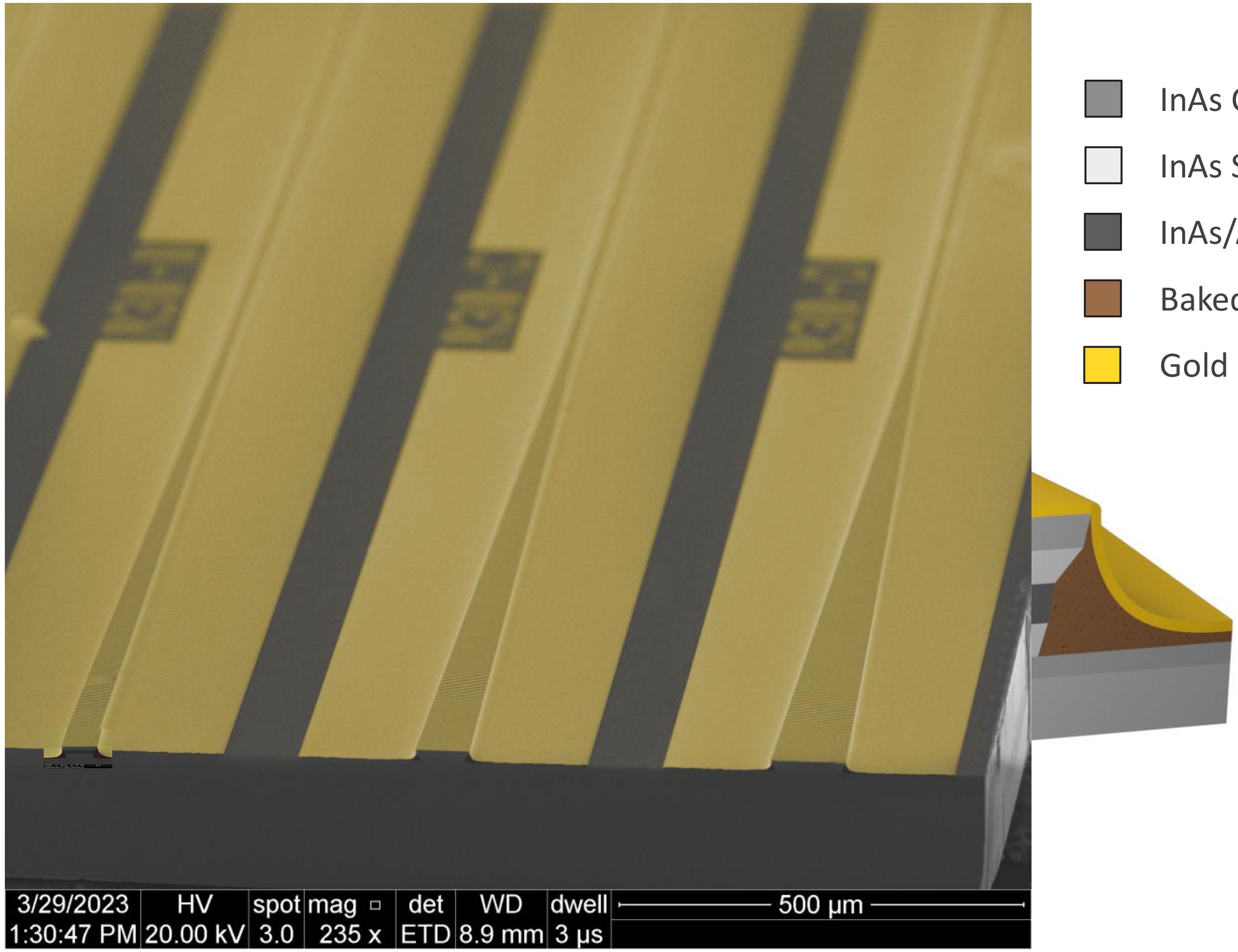
# Fabrication of LW-Tapered QCLs



0. Grating fabrication via electron-beam lithography
1. Deep wet MESA etching
2. Insulation via resist hard-bake
3. Top contact metalization




- InAs Cladding (doped)
- InAs Spacer (undoped)
- InAs/AlSb active zone
- Baked resist
- Gold metalization



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# Fabrication of LW-Tapered QCLs

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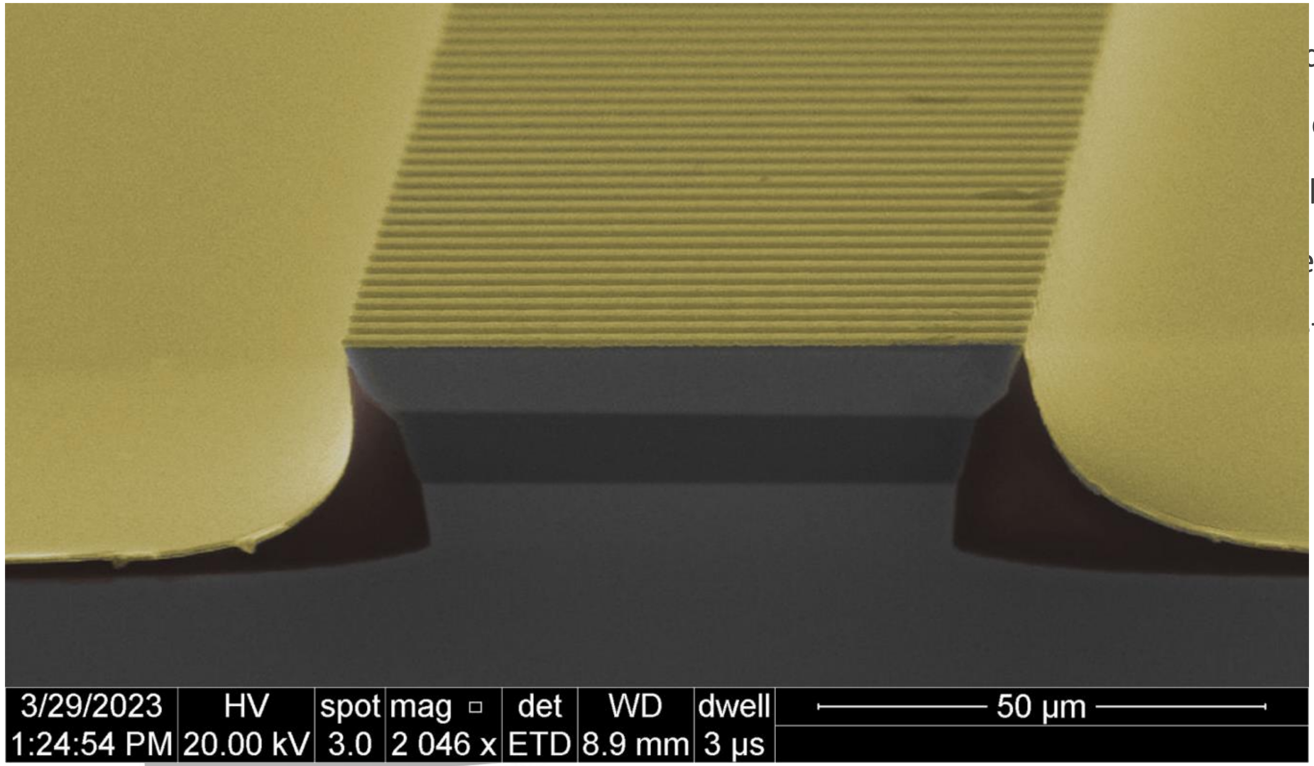
## FABRICATION PROCESS:

0. Grating fabrication via electron-beam lithography

1. Deep wet MESA etching

2. Insulation via resist hard-bake

3. Top contact metalization




dding (doped)

cer (undoped)

b active zone

esist

talization



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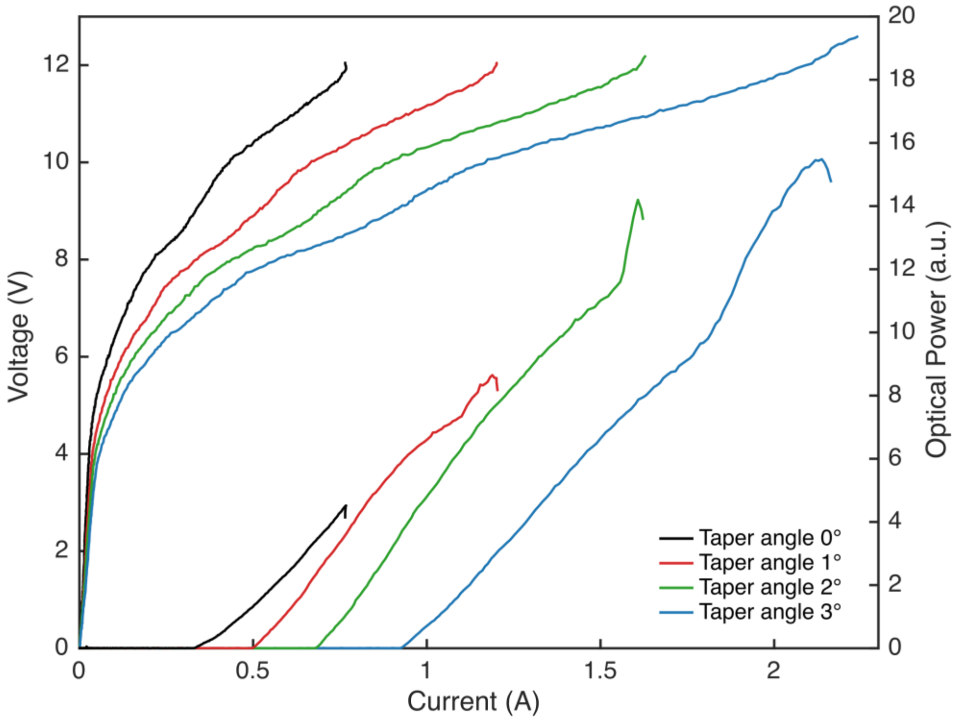
TU WIEN TECHNISCHE UNIVERSITÄT WIEN
UNIVERSITÉ DE MONTPELLIER

# Optical Power enhancement



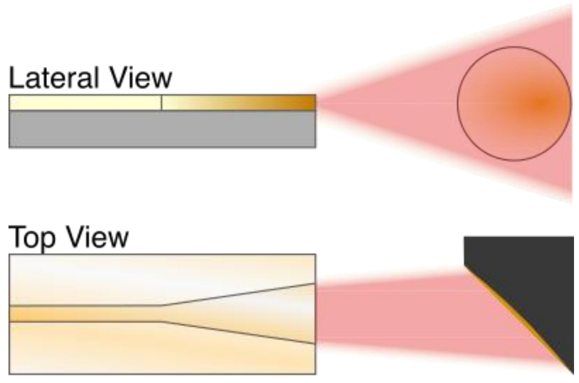
## LIV of Fabry-Pérot Tapered QCLs

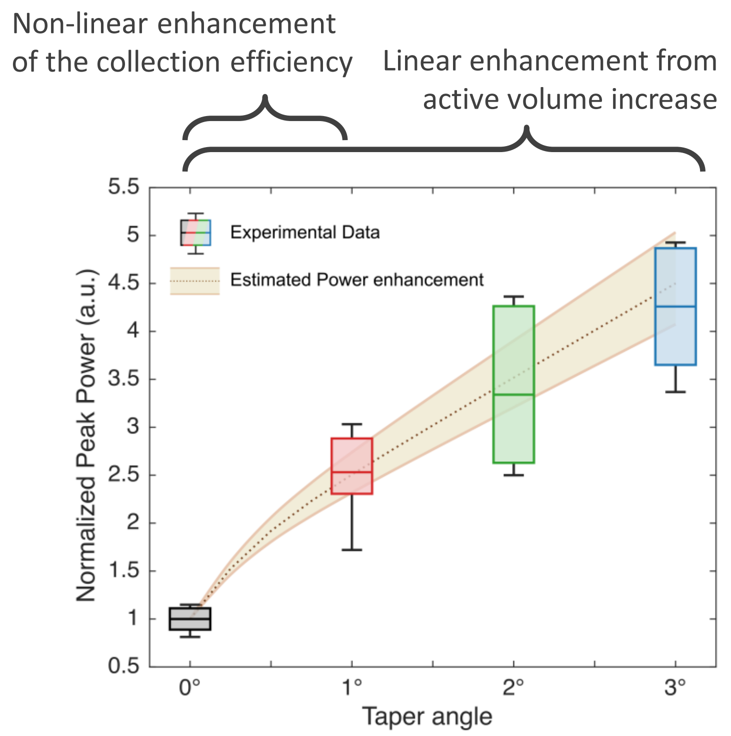
Pulsed Operation (PRR = 12 KHz, dt = 330 ns)
Room Temperature




The observed total output is a **combination** of:

1. larger **active area**
2. higher **collection efficiency**




*Ridge width= 14 um, Laser Length 3.6mm, Taper section 50%

| Taper angle | Active volume enhancement* | Collection efficiency* | Estimated power enhancement* |
|---|---|---|---|
| 0° | 1 | 1 | 1 |
| 1° | 1.56 | 1.48 | 2.3 |
| 2° | 2.12 | 1.51 | 3.2 |
| 3° | 2.68 | 1.52 | 4.1 |



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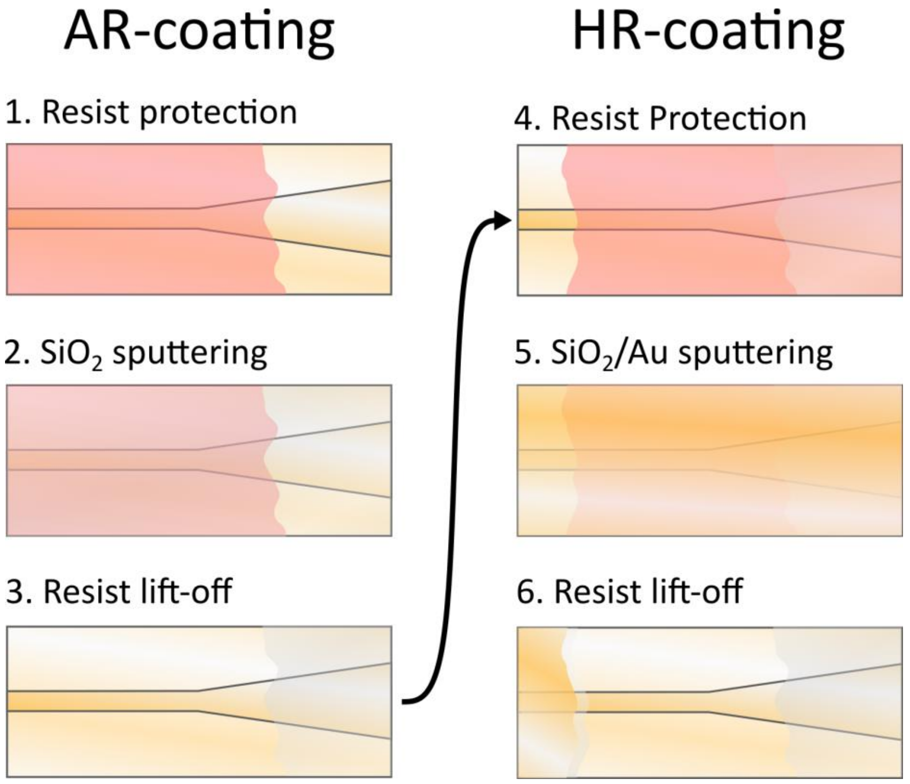
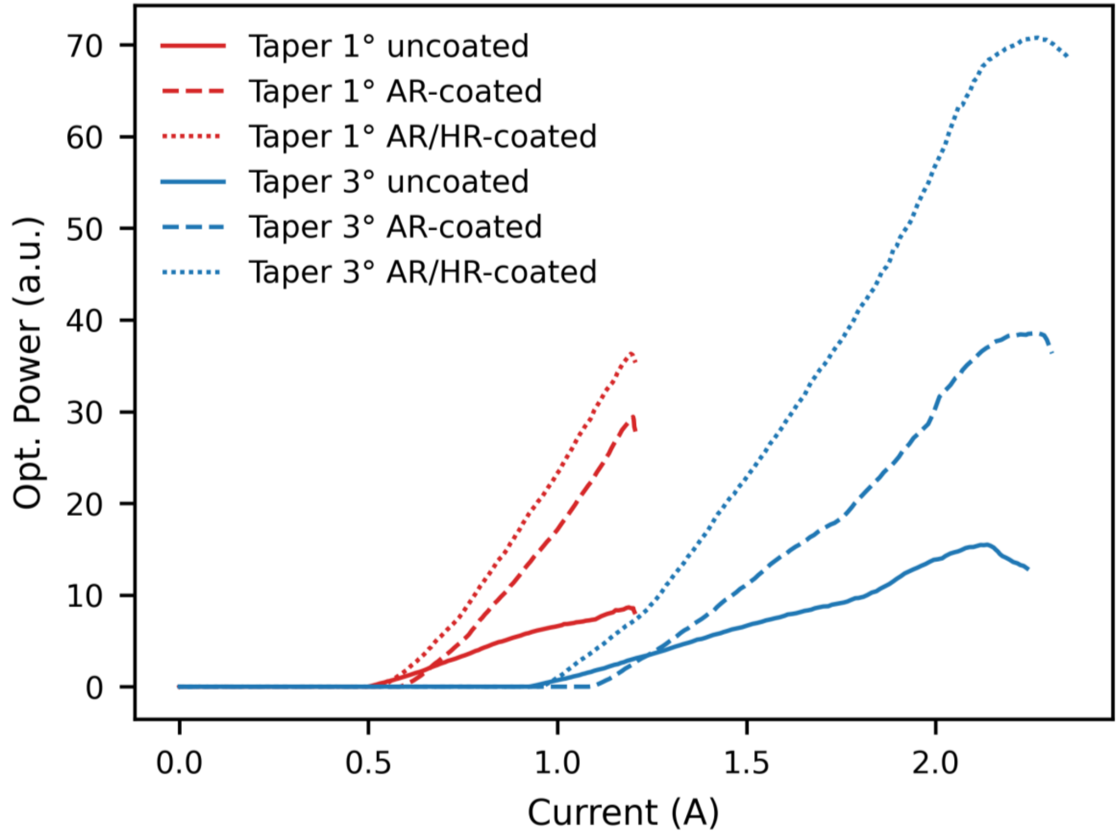
# Anti- & High-reflection Coatings






**TAPERED LASERS PROVIDED HIGHER OPTICAL POWER OUTPUT THAN RIDGE LASERS**



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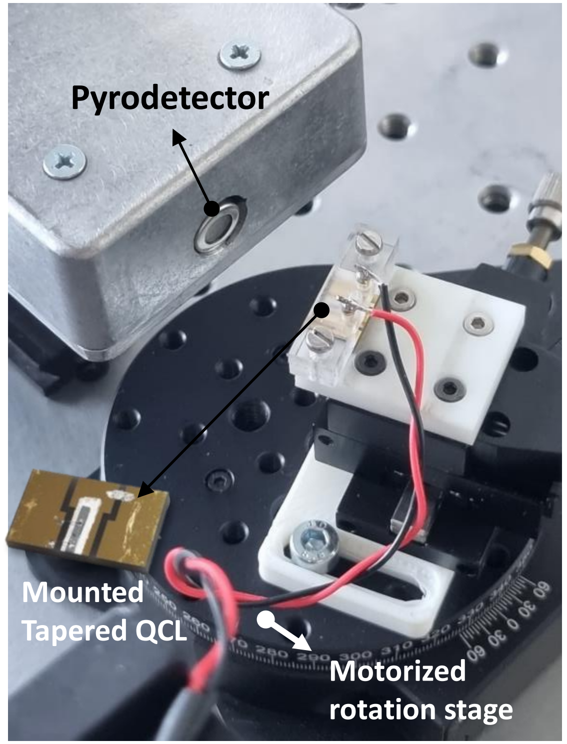
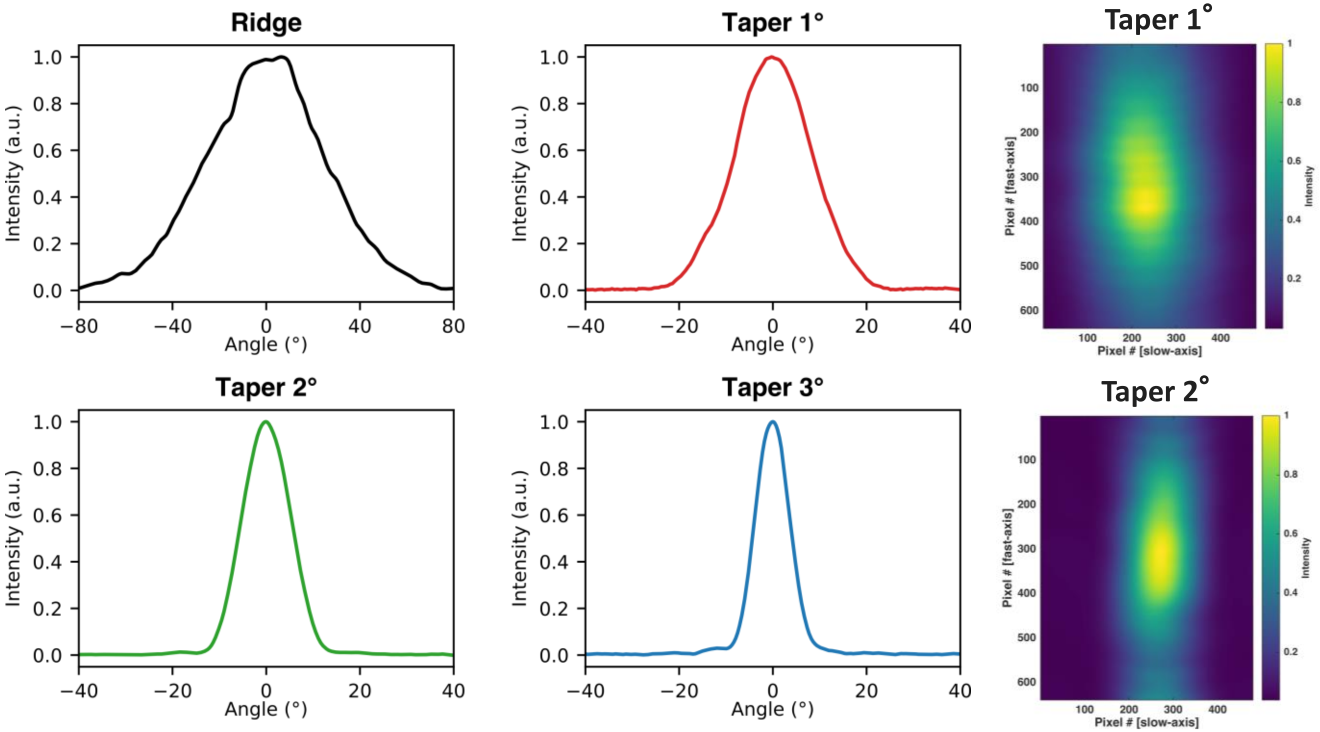
# Divergence angle and beam quality estimation

## Measurement Setup




## Divergence Angle Results




## Features

- **Narrower** slow-axis divergence for tapered devices
- **Single lobe** distributions
- **Absence** of higher-order modes also along **fast-axis**



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# Divergence angle and beam quality estimation

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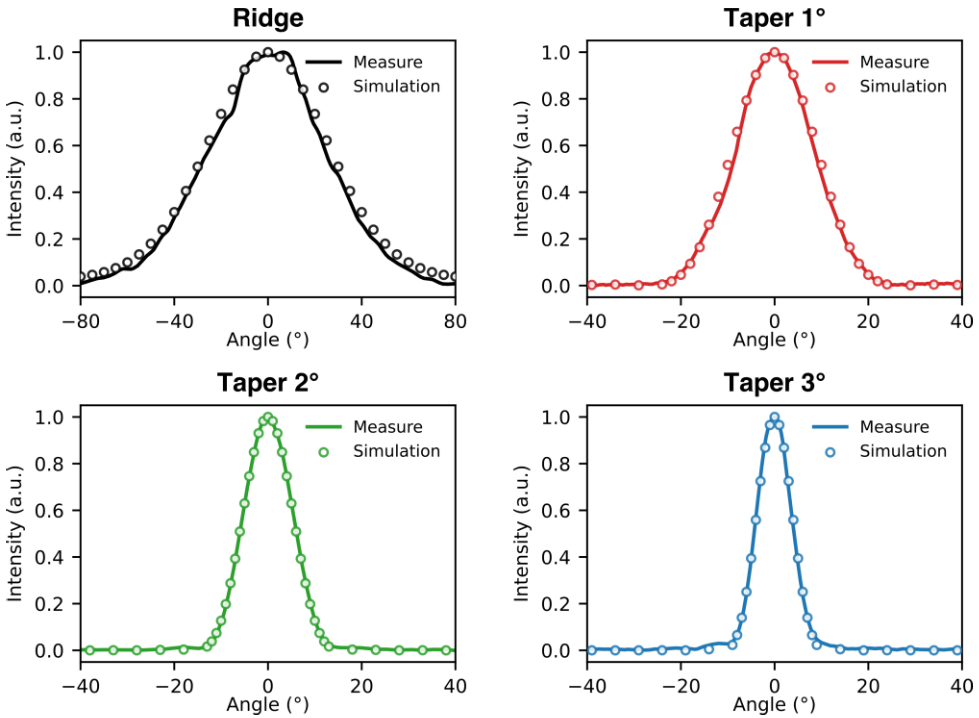
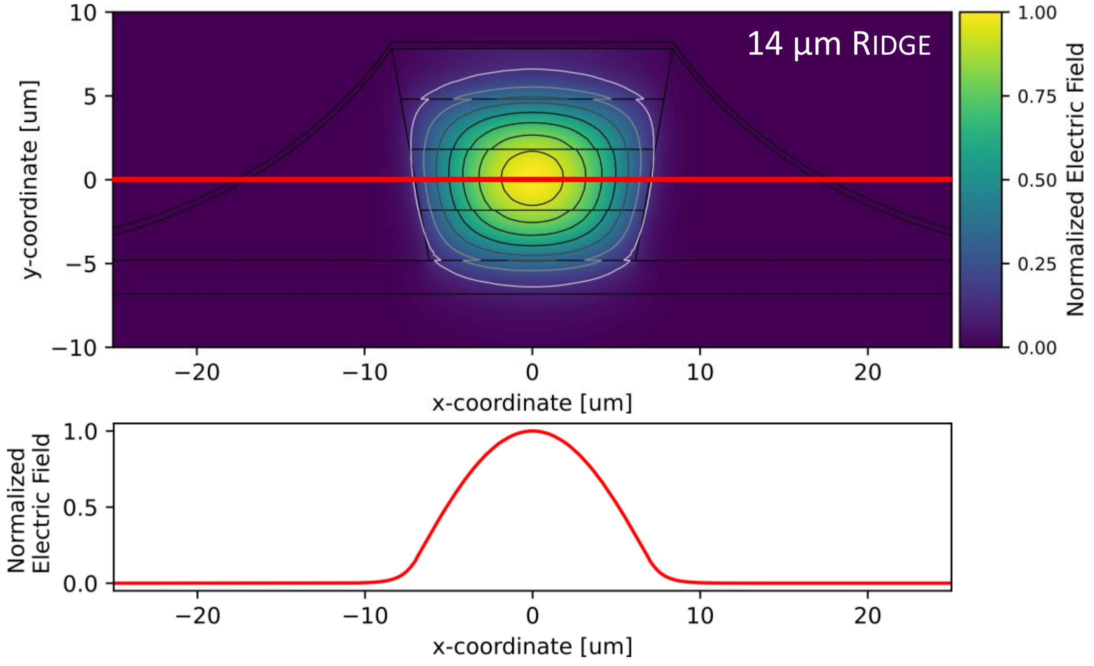
## Divergence Angle Results




## Mode Analysis




## Near-Field to Far-Field Distributions

$$P(k_x) = \int_{-\infty}^{+\infty} E(x) e^{i k_x x}\, dx \;\longrightarrow\; P^2(\theta) = \left| \int_{-\infty}^{+\infty} E(x) e^{i \frac{2\pi}{\lambda_0} \sin(\theta) x}\, dx \right|^2$$



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# Divergence angle and beam quality estimation

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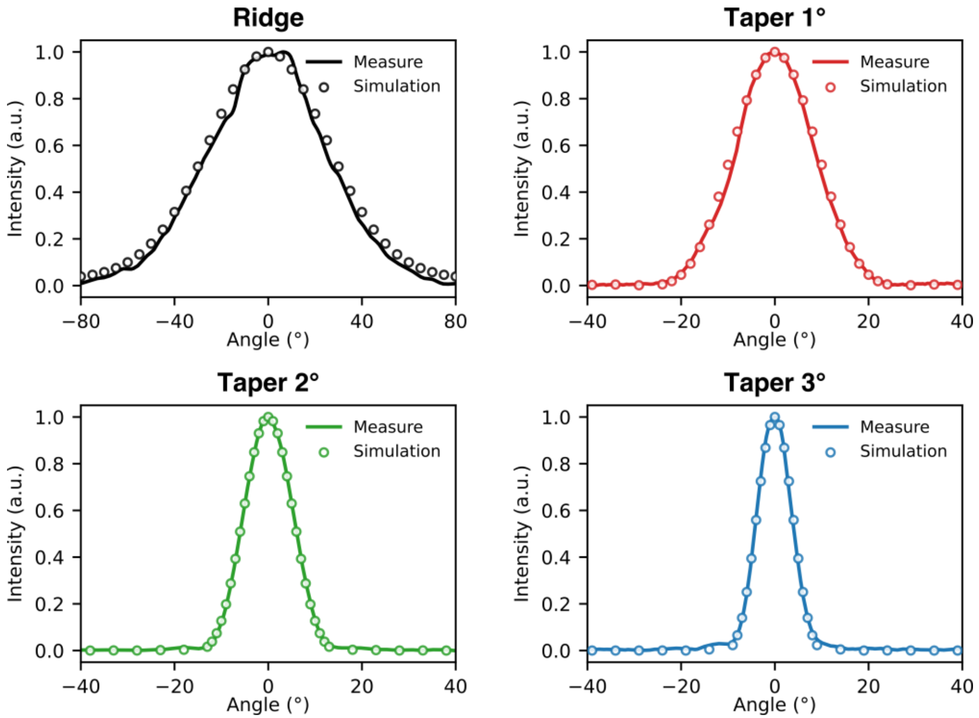
## Divergence Angle Results




## Beam Quality Factor

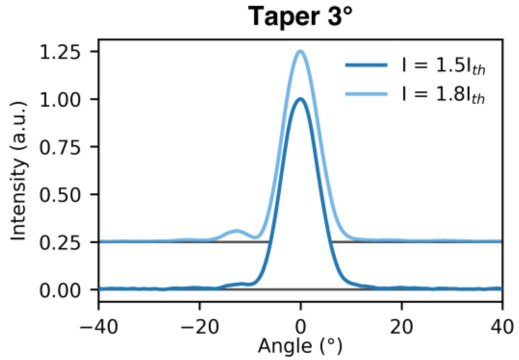
$$M^2 = \frac{4\pi\sigma_0\sigma_\theta}{\lambda}$$

## Second order momentum ($\sigma_0, \sigma_\theta$)

$$\sigma_\theta^2 = \frac{\int_{-\infty}^{+\infty}(\theta - \bar{\theta})^2 I(\theta)d\theta}{\int_{-\infty}^{+\infty} I(\theta)d\theta}$$

| Taper angle | $\sigma_\theta$ | $M^2$ |
|---|---|---|
| 0° | ~26° | ~1 |
| 1° | 8.03° | 1.02 |
| 2° | 5.06° → 5.13° | 1.07 → 1.08 |
| 3° | 4.23° → 4.80° | 1.29 → 1.46 |

(Low bias current → High bias current)




**Diffraction limited beam quality, aside from 3° tapers**



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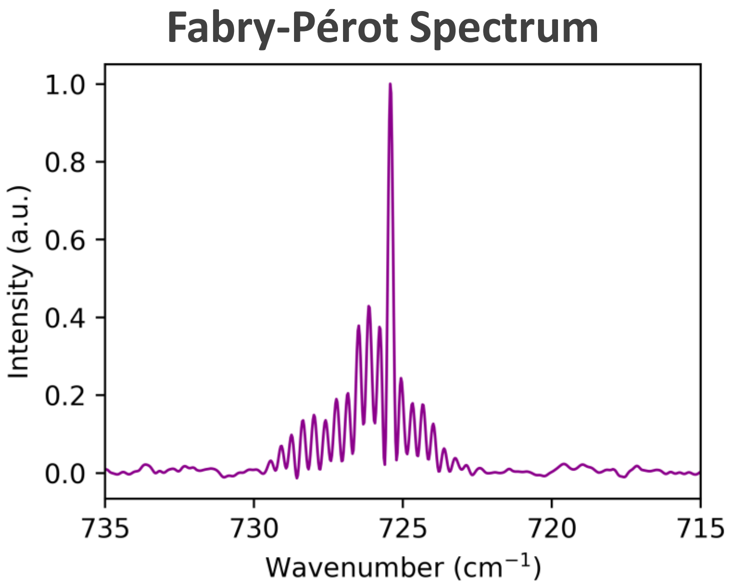
# Distributed Feedback Tapered QCLs





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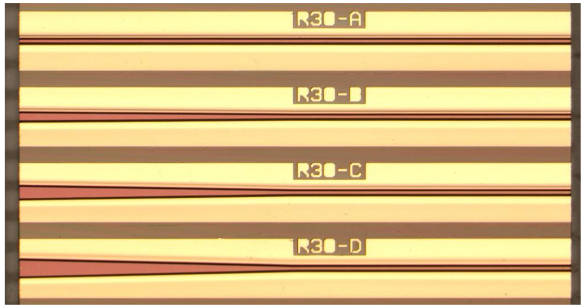
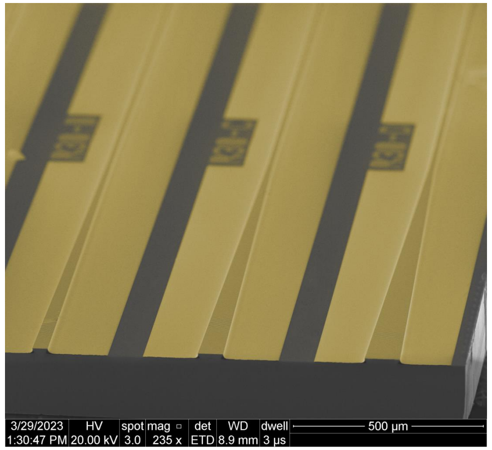
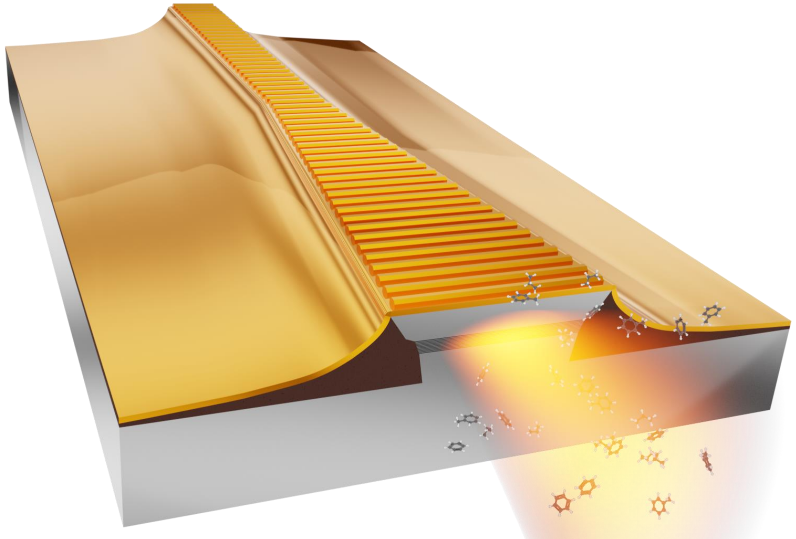
# Summarizing

## Conclusions

- First demonstration of DFB tapered lasers in the long-wavelength infrared region
- **Diffraction-limited beam quality** was achieved, together with **single-longitudinal mode operation**





## Outlooks

- Optimize taper geometry to achieve higher performances, especially for CW-operation
- Employment of the DFB-tapered lasers for spectroscopy of BTEX compounds



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# Thanks for your attention



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