# (Al,In)GaN laser diodes in spectral, spatial, and time domain: near-field measurements and basic simulations

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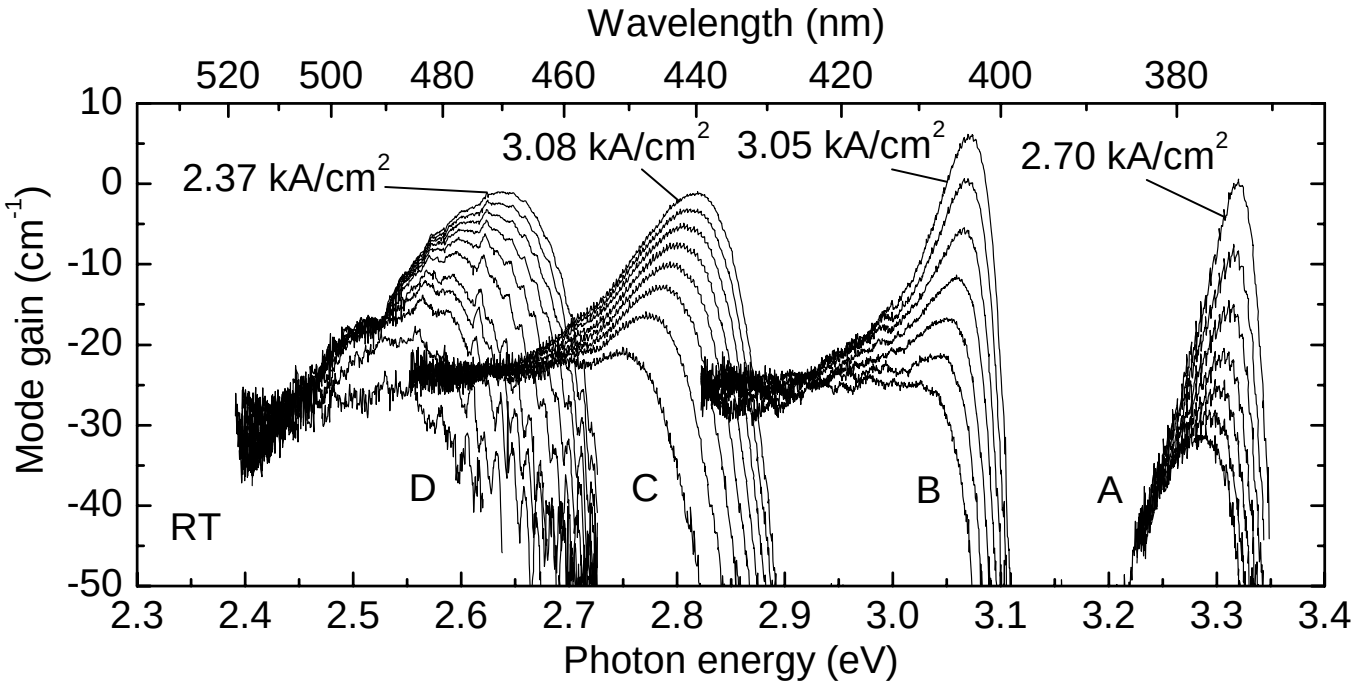
**Regensburg University**

- **Optical gain spectra**
- **Above threshold spectra**
- **Filaments / lateral dynamics**

# 375 nm to 470 nm set of gain spectra



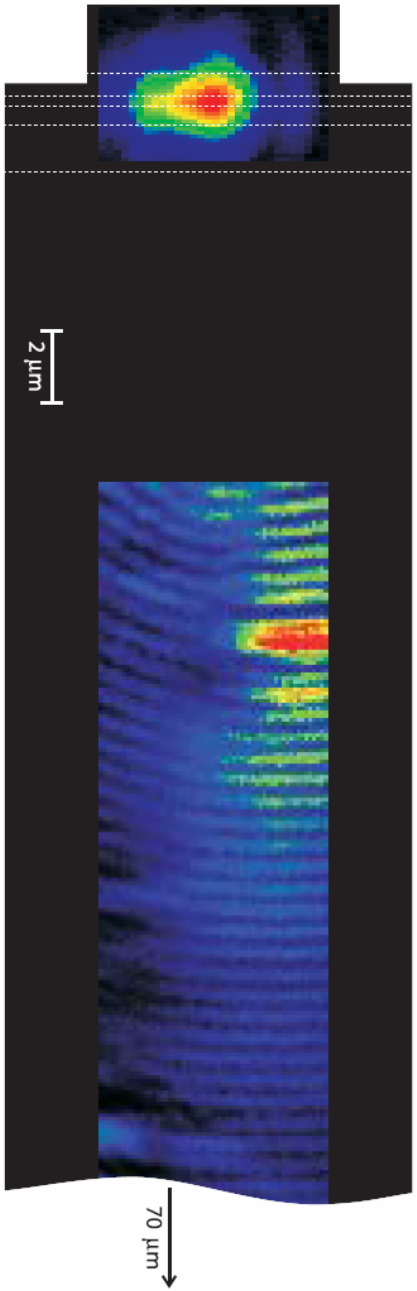

Hakki-Paoli method

Nichia LDs
@ 470 nm, 440 nm,
405 nm, and 375 nm.

- Impact of band-tail states on optical gain spectra
- Const. carrier density vs. const. Fermi level gain model
- Gain insensitive to inhomogeneous broadening at ~ 1000 $cm^{-1}$ level

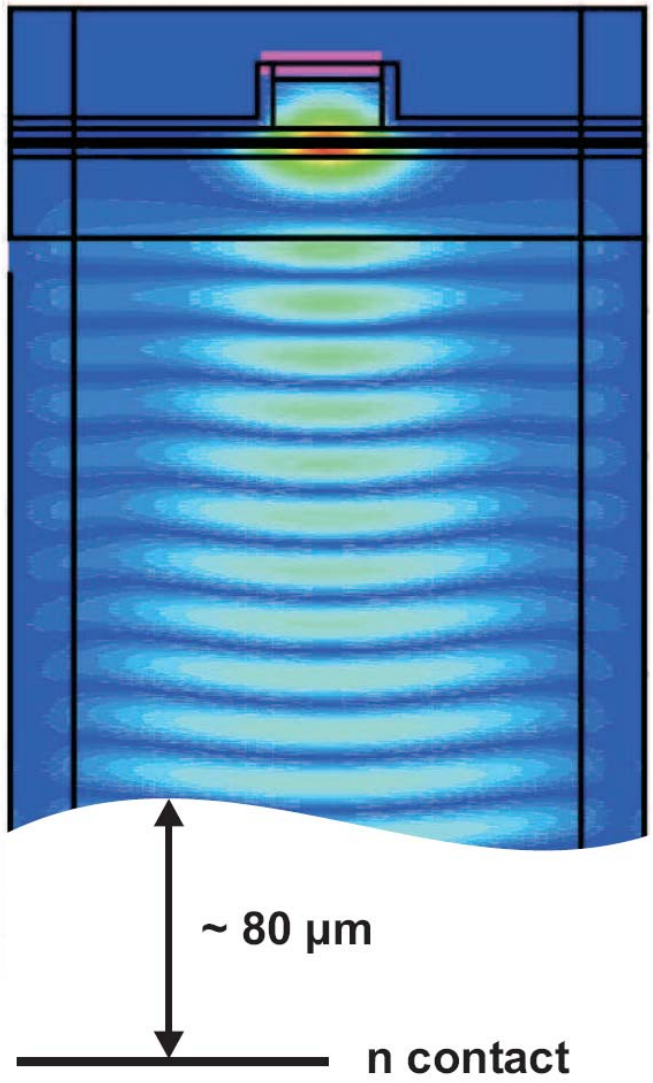

K. Kojima *et al.*, Optics Express **15**, 7730 (2007),
B. Witzigmann *et al.*, IEEE J. Quantum Electronics **44**, 144 (2008).

# Substrate Modes



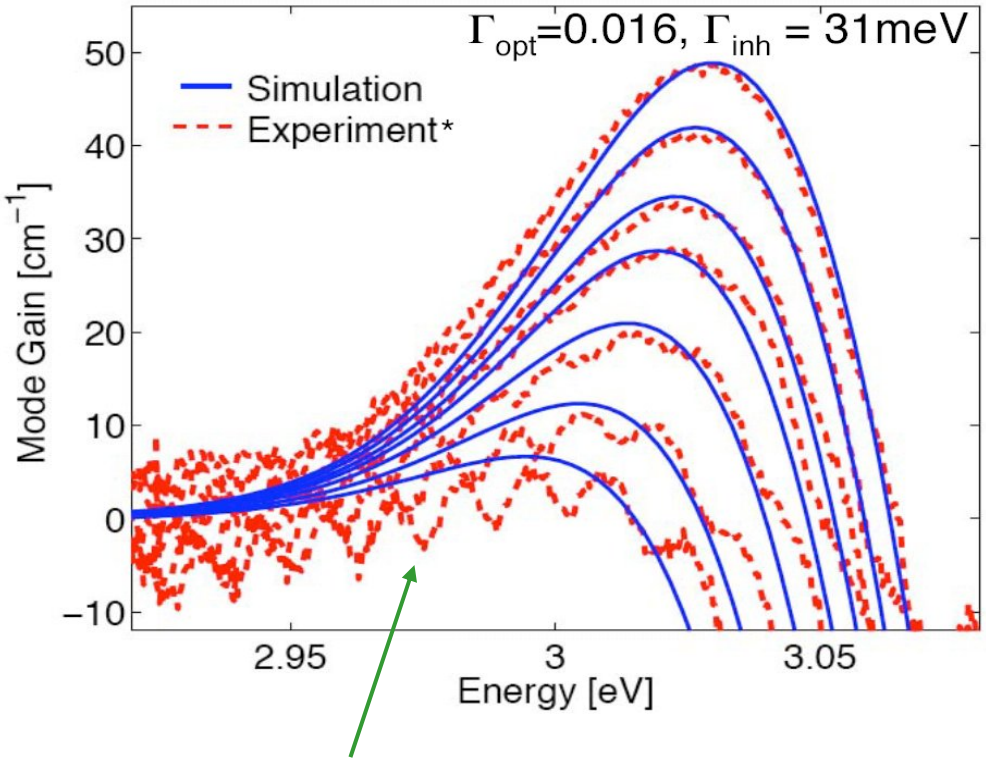

Simulation →

← Experiment




V. Laino, et al., IEEE J. Quantum Electronics **43**, 16 (2007).

# Microscopic analysis of gain spectra




Bernd Witzigmann, ETH Zürich

- Quantum-kinetic Maxwell-Bloch equations
- Many-body effects (Coulomb, exciton, bandgap renormalization), 6 band kp
- Self-consistent treatment of piezoelectric fields
- Homogeneous broadening parameter free

B. Witzigmann, *et al.* APL **88**, 021104 (2006)
IEEE Phot. Tech. Lett. **18**, 1600 (2006)
*Nitride Semiconductor Devices*, edited by J. Piprek, Wiley-VCH 2007
IEEE J. Quantum Electronics **44**, 144 (2008)

# Parameter set

**Directly from gain spectra:**

| | |
|---|---|
| Internal losses | $\alpha_{int} = 25\ cm^{-1}$ |
| Linear gain | $a = 9.8 \times 10^{-13}\ m^3 s^{-1}$ |
| Antiguiding factor | $\alpha = 3.5$ |
| Mode shift with I | $3.5 \times 10^{-3}$ nm/mA |
| Gain shift with I | $2.3 \times 10^{-2}$ nm/mA |
| Gain dispersion | $1.25 \times 10^{42}\ m^4 s^{-1}$ |
| Gain fluctuations | $5 \times 10^{-4}$ |

**From microscopic simulations of gain spectra:**

| | |
|---|---|
| Radiative | $\tau_s = 4.5$ ns |
| Nonratidative | $\tau_{nr} = 9$ ns |
| Intraband relax. | $\tau_{in} = 25$ fs |
| Dipole moment | $R_{cv}^2 = 2.8 \times 10^{-57}\ C^2 m^2$ |

**Other:**

| | |
|---|---|
| Cavity length | L = 600 µm |
| Mirror reflectivities | 17% & 98 % |
| Threshold current | $I_{th} = 50$ mA |
| Confinement factor | 0.017 |
| Group ref. index | 3.59 |
| Eff. ref. index | 2.53 |

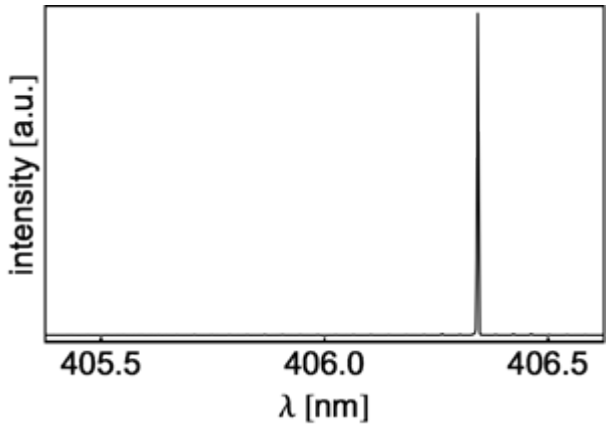
T. Meyer, *et al.,* Optics Express **16**, 6833 (2008).
D. Scholz, *et al.,* Optics Express **16**, 6846 (2008).

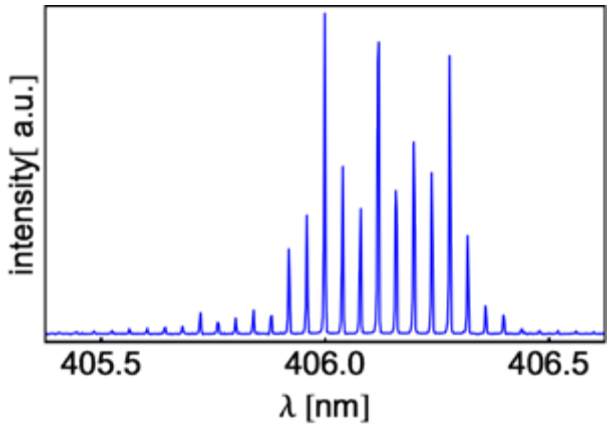
# Spectra of LD on SiC and GaN substrates

Same epitaxial structure!

Epitaxy on **SiC** substrate

Epitaxy on **GaN** substrate



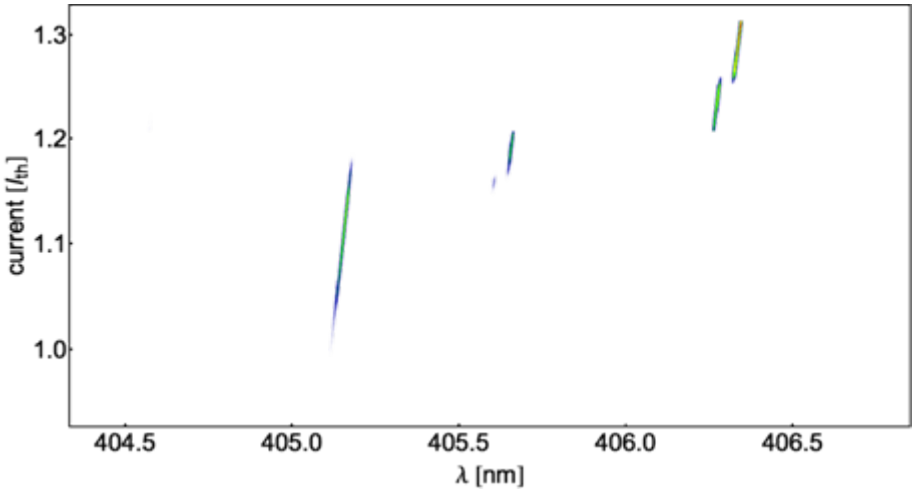

SiC: **single** longitudinal mode

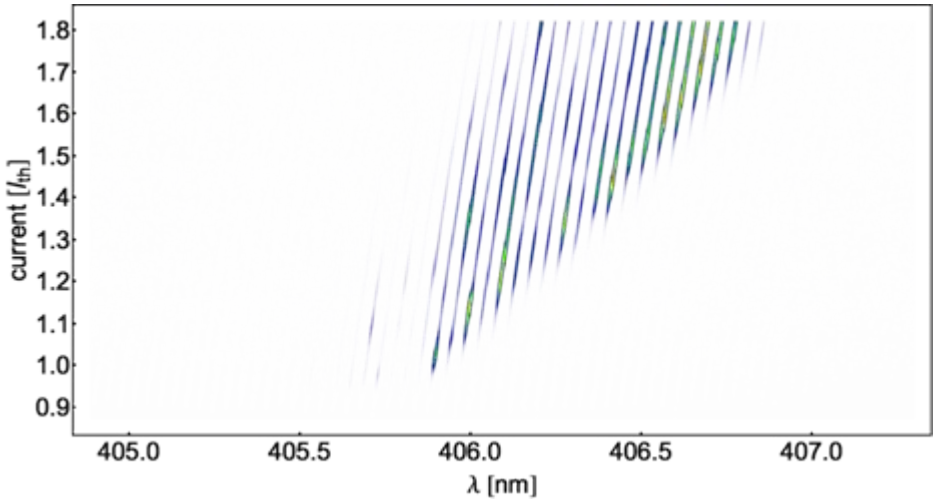
GaN: **~ 15** longitudinal modes

# Spectra of LD on SiC and GaN substrates

Epitaxy on **SiC** substrate

Epitaxy on **GaN** substrate




SiC: Mode hopping between single modes

GaN: broad, asymmetric spectrum

# Multimode rate equation model

Rate equation for electrons

$$\frac{dN}{dt} = \eta_{\mathrm{inj}} \frac{I_{\mathrm{inj}}}{q_{\mathrm{e}}} - \frac{N}{\tau_{\mathrm{s}}} - \sum_p \zeta_p A_p S_p$$

Rate equations for photons

Consideration of several longitudinal modes *p*

$$\frac{dS_p}{dt} = \left(\tilde{g}_p - \tilde{g}_{\mathrm{th}}\right) S_p + \beta_p \frac{N}{\tau_{\mathrm{r}}}$$

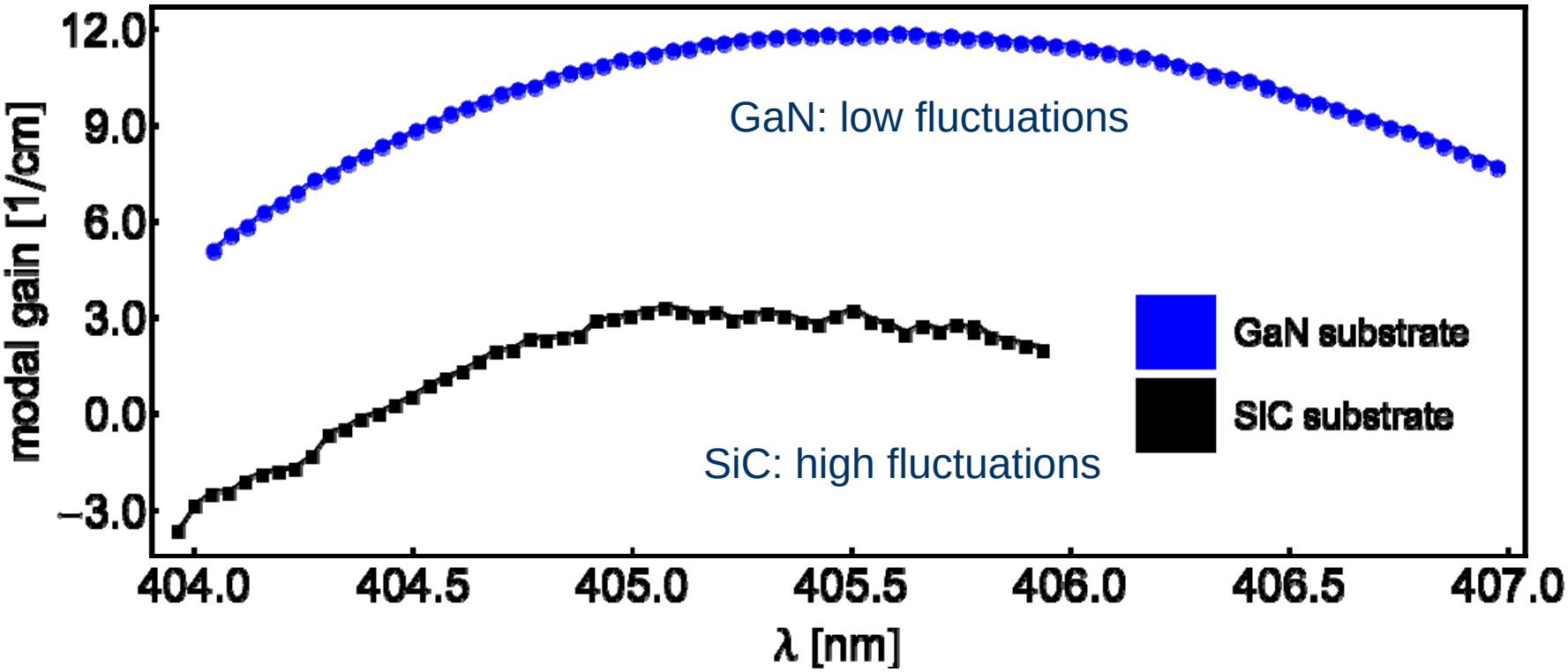
$$\tilde{g}_p = \zeta_p A_p - B S_p - \sum_{q \neq p} \left(D_{pq} + H_{pq}\right) S_q$$

Gain fluctuations

Linear gain

Gain saturation effects

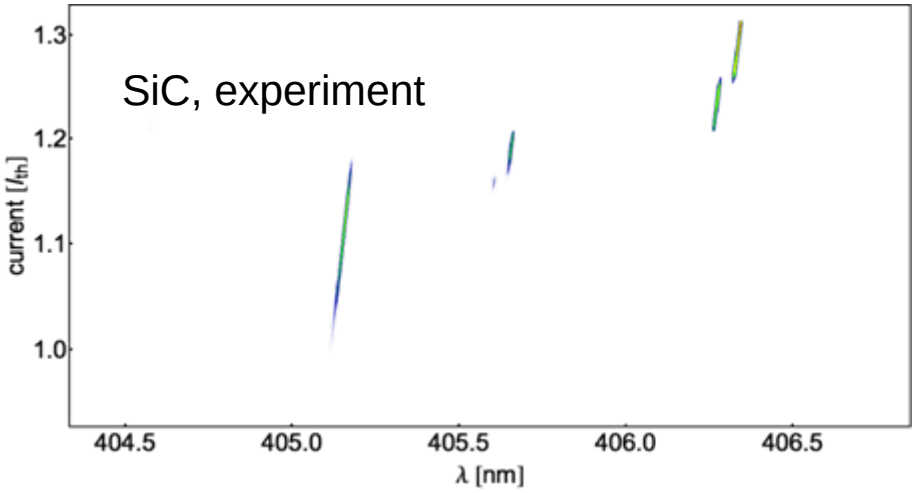
# Gain fluctuations below threshold

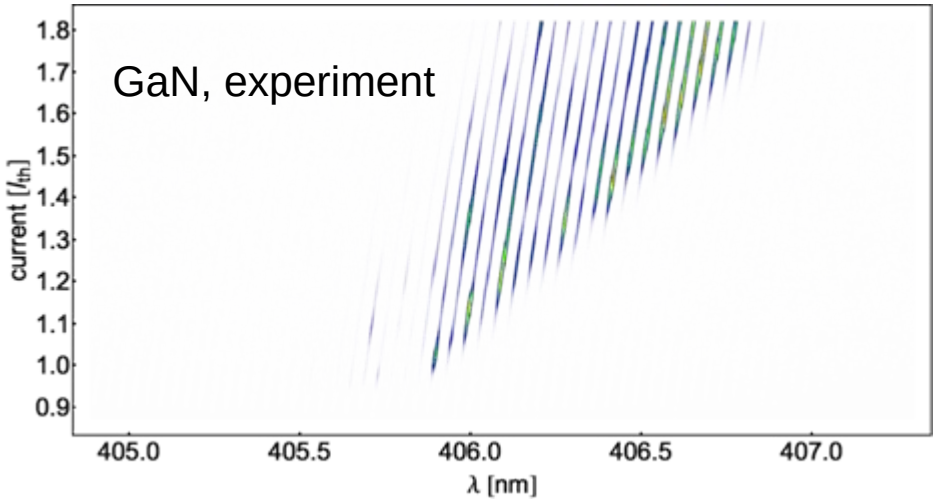


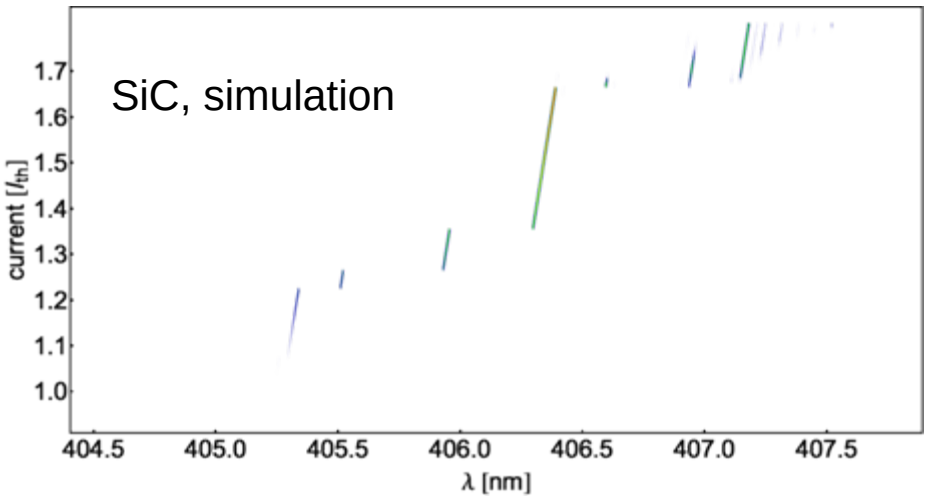

**Gain fluctuations: ~ 10 x higher for SiC compared to GaN**

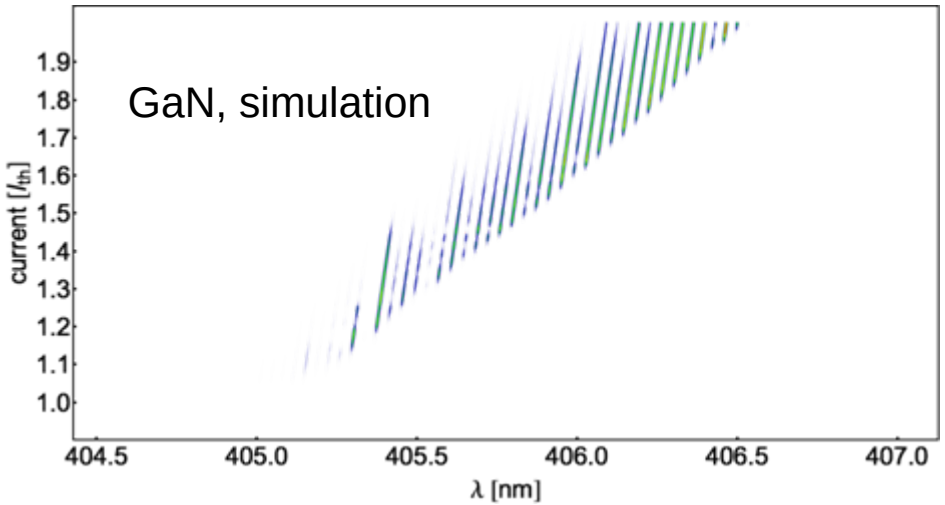
T. Meyer et al.,
Optics Express **16**, 6833 (2008)

# Spectra of LD on SiC and GaN substrates



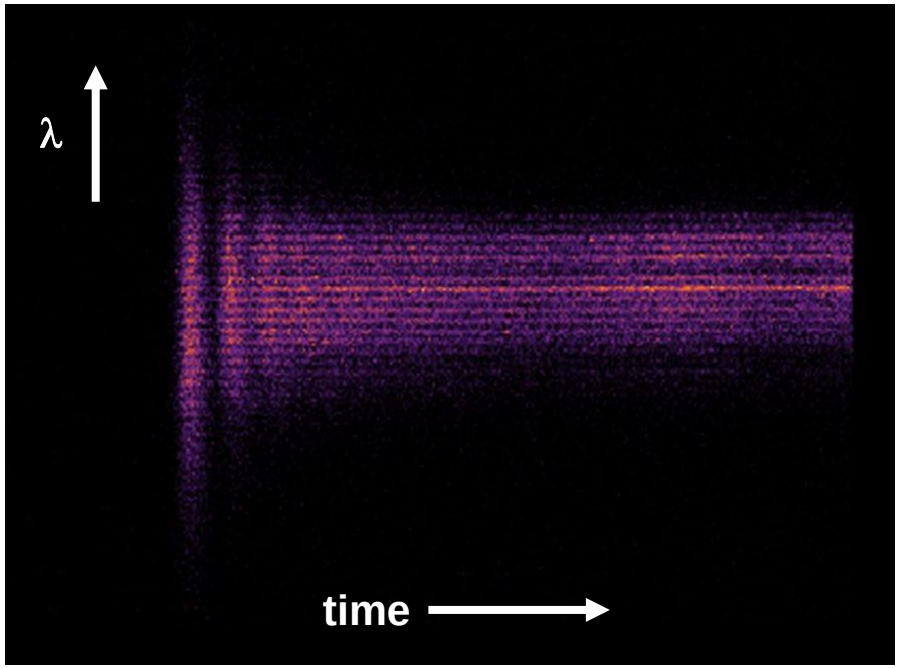



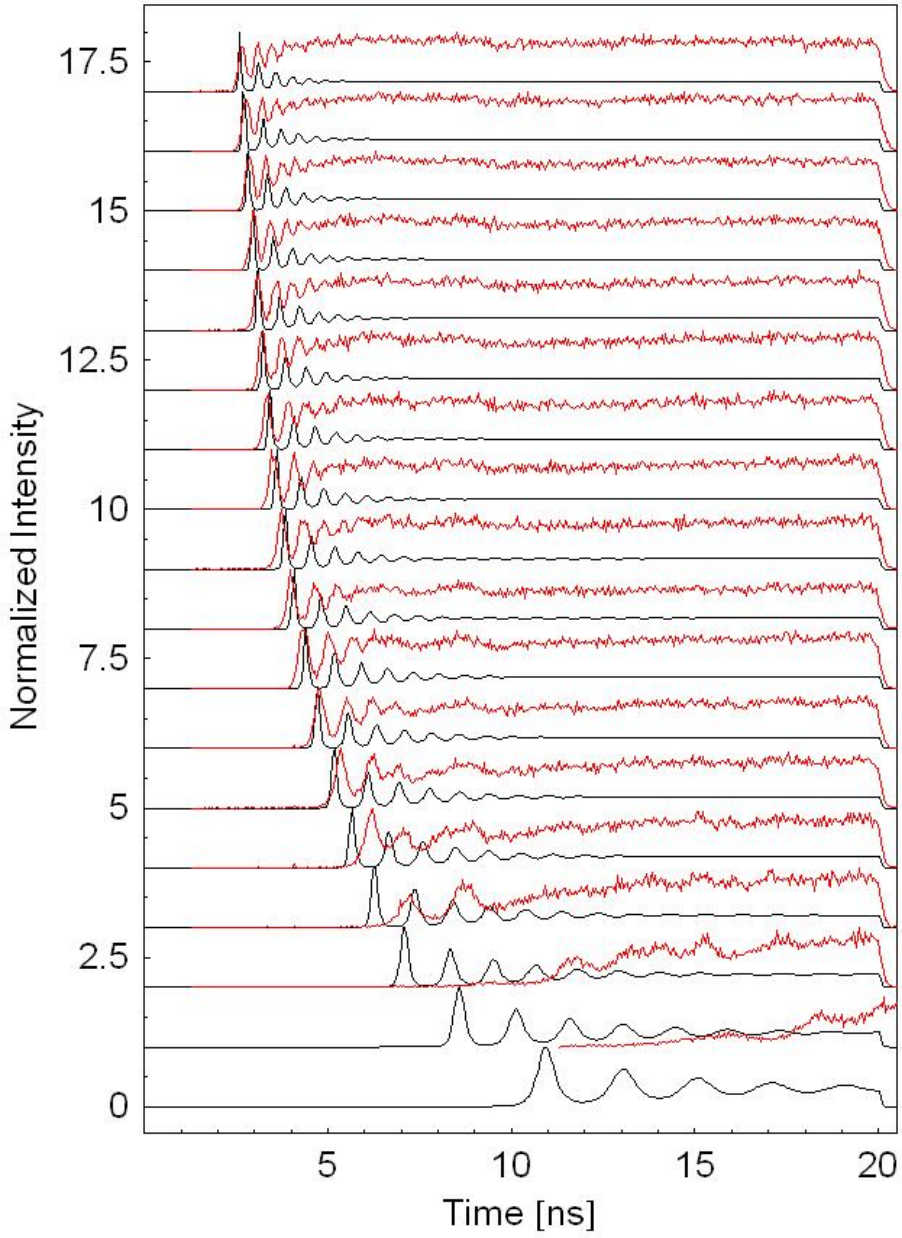
# Relaxation Oscillations

Red: experiment
Black: simulation

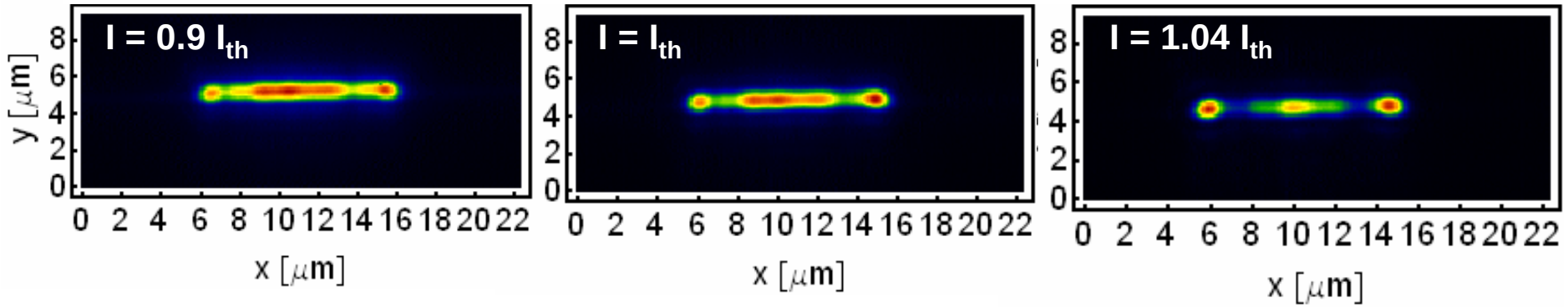
Comparison with simple
rate equation model.

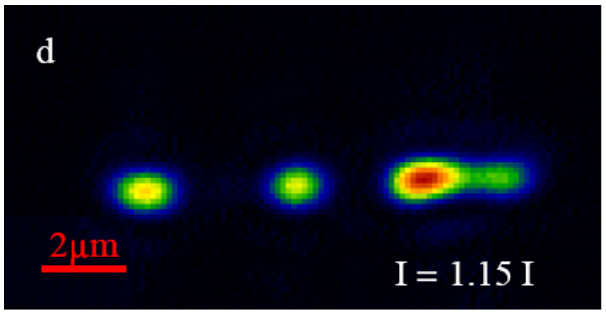
Same set of parameters
as used for simulation of spectra.

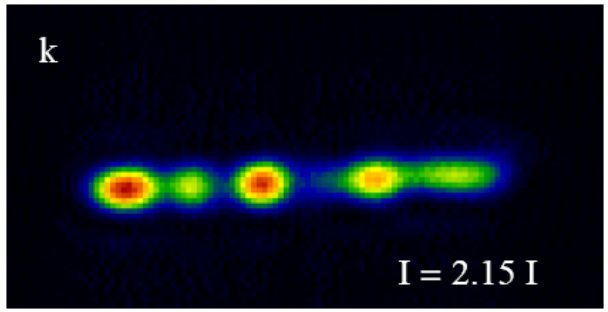


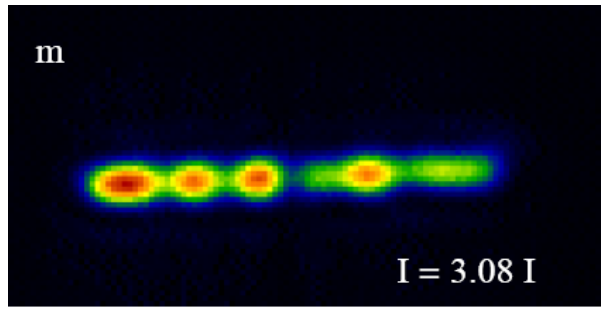



# Filaments in a 10 µm wide, blue LD



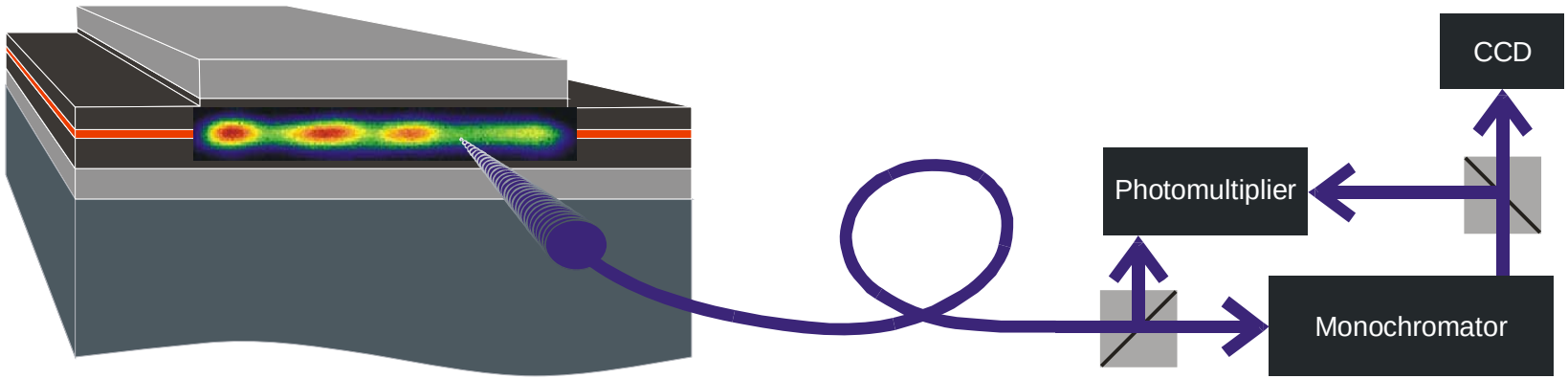



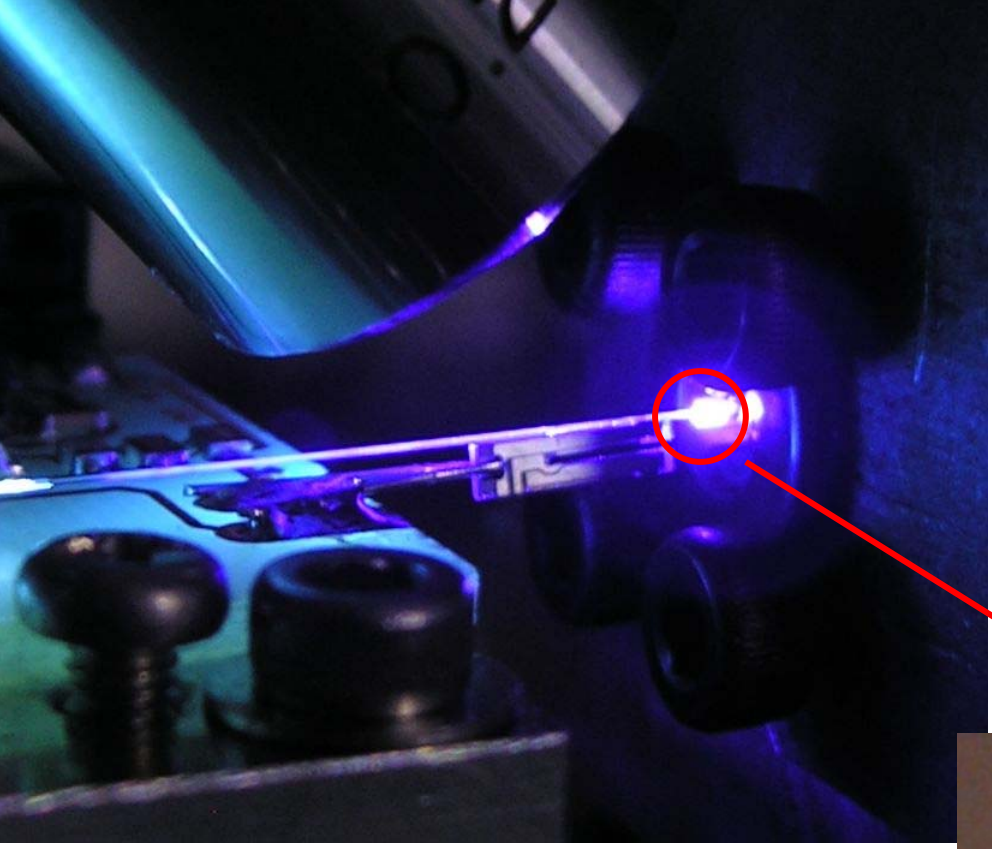
# Laser diode dynamics measurement

4-dimensional data hyper-cube: x – y – t – λ




Scanning near-field microscope (SNOM)
Or: imaging with high NA aspheric lense

PMT or Monochromator & PMT or CCD
or: monochromator & streak camera

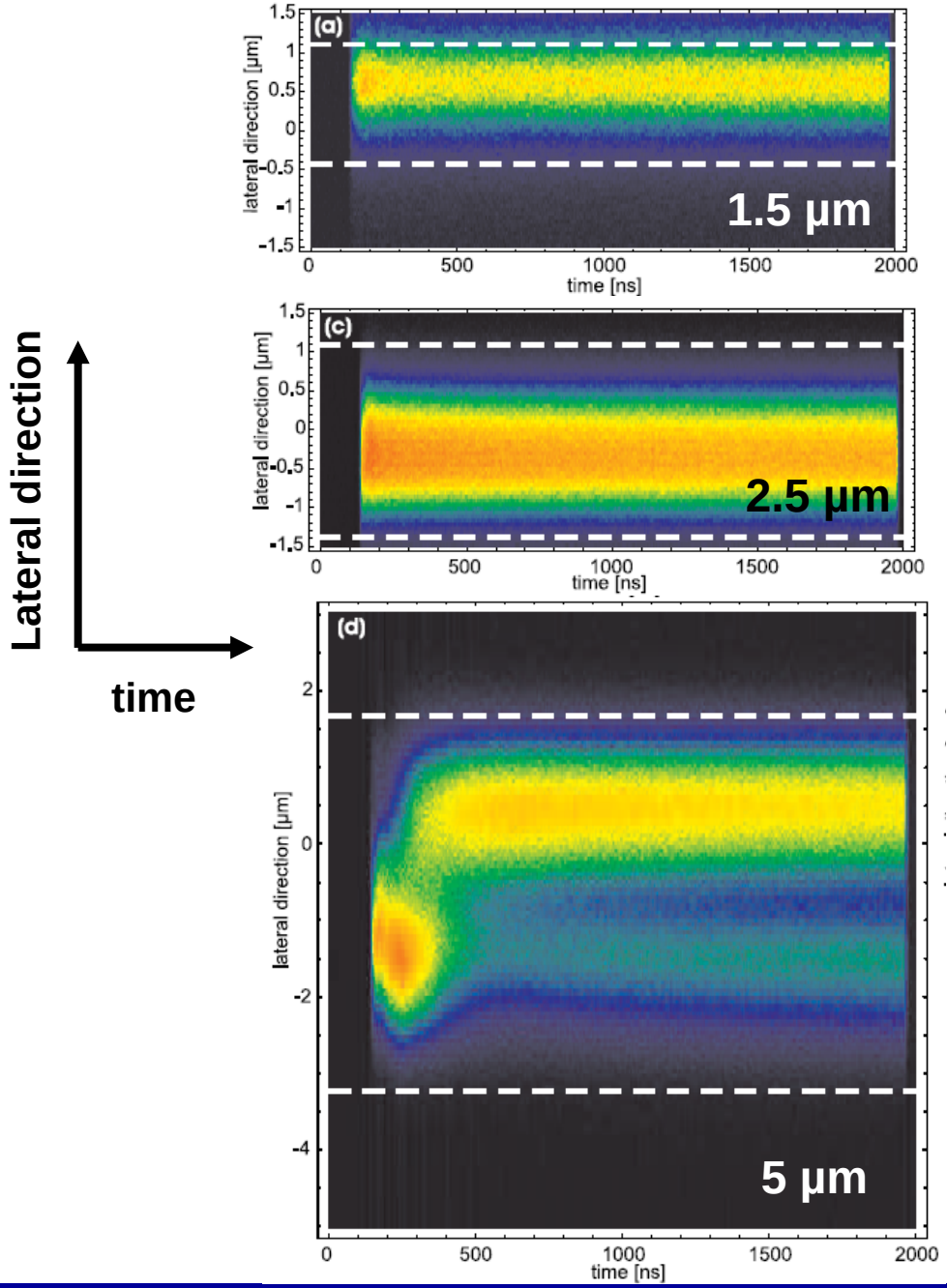


HP 8114A or HP8131A
pulse generator

Detection with
Hamamatsu
streak camera

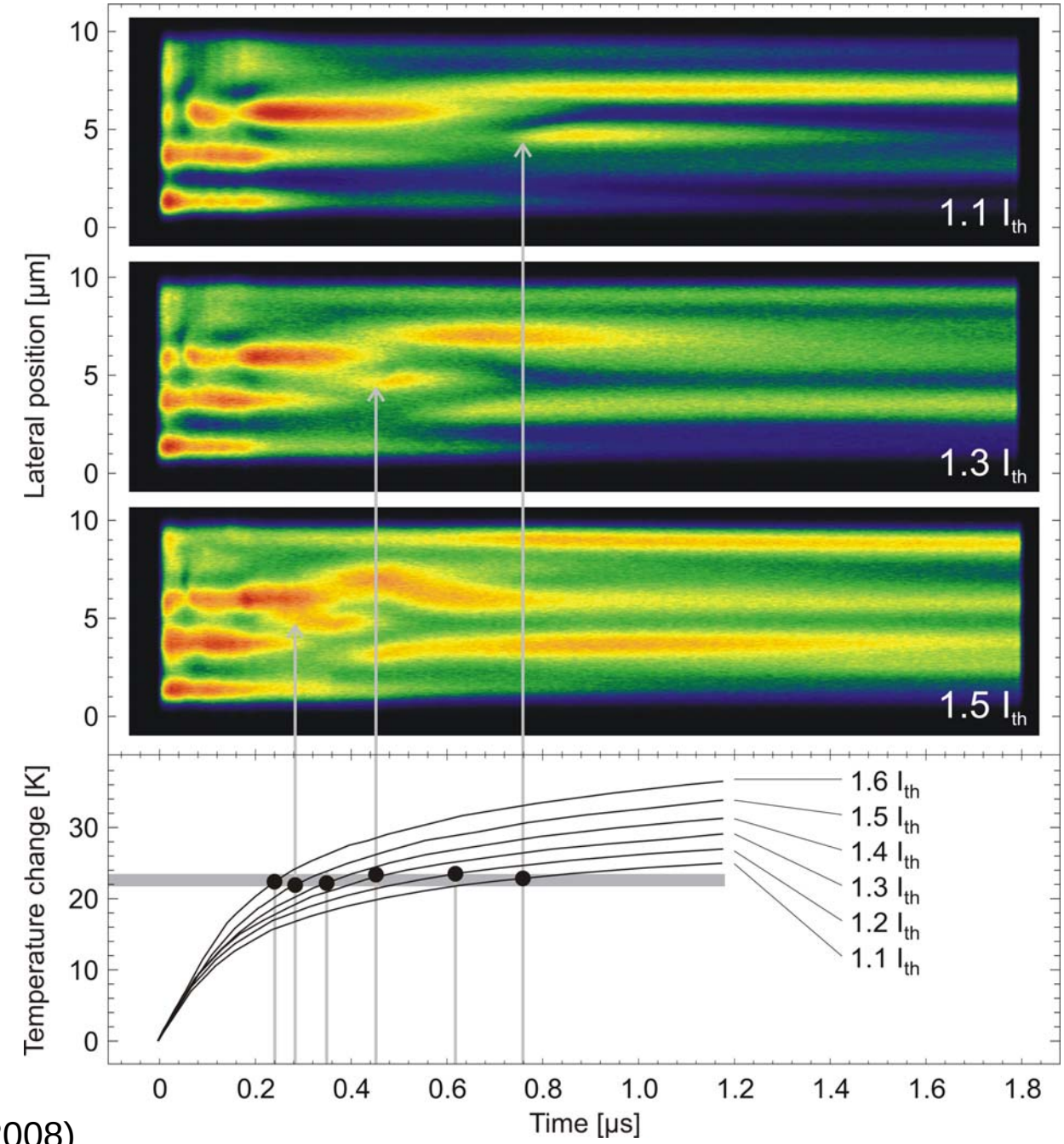
Fiber tip

# Filaments in ridge waveguide LDs

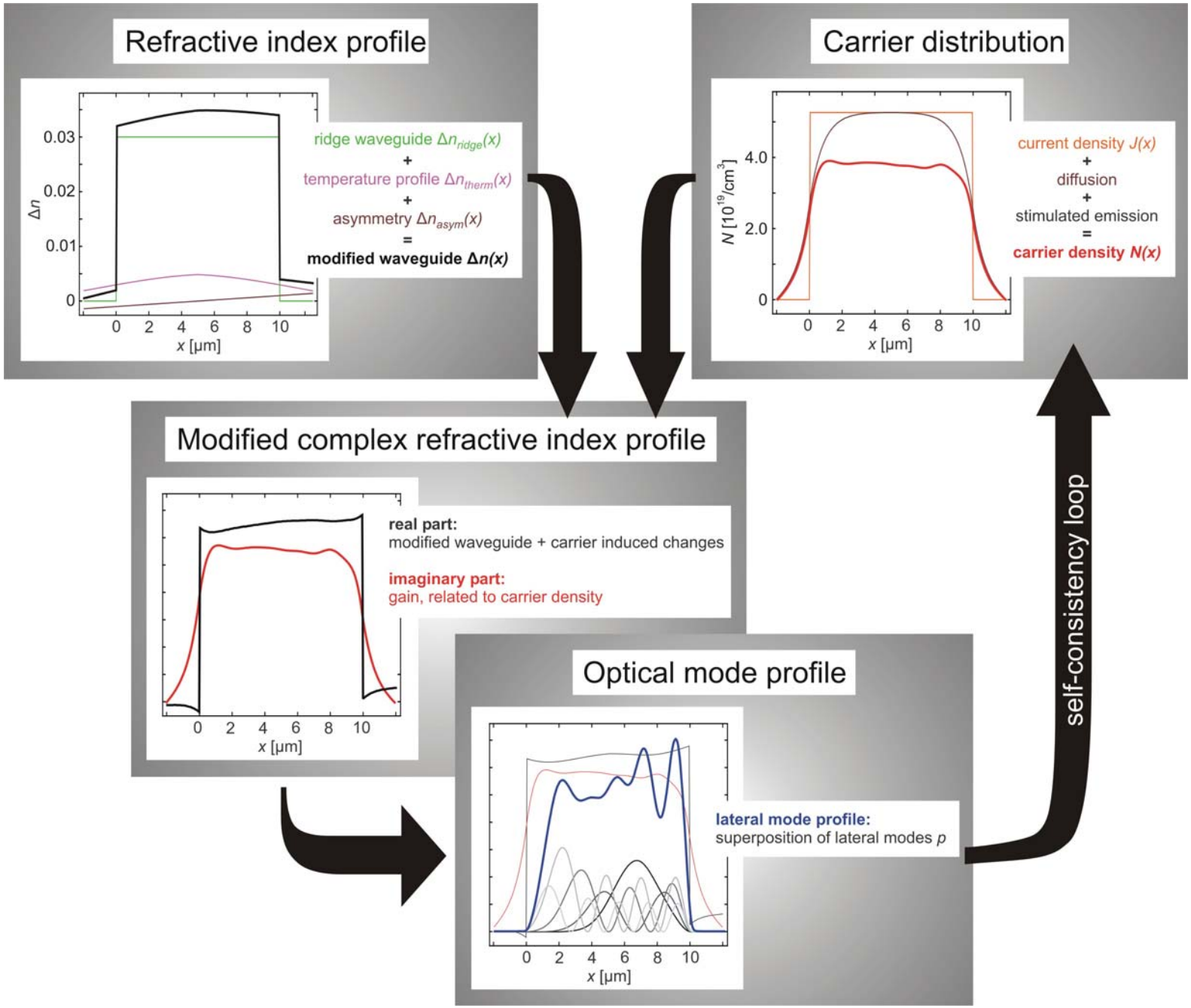


Switching of configuration
@ critical temperatures

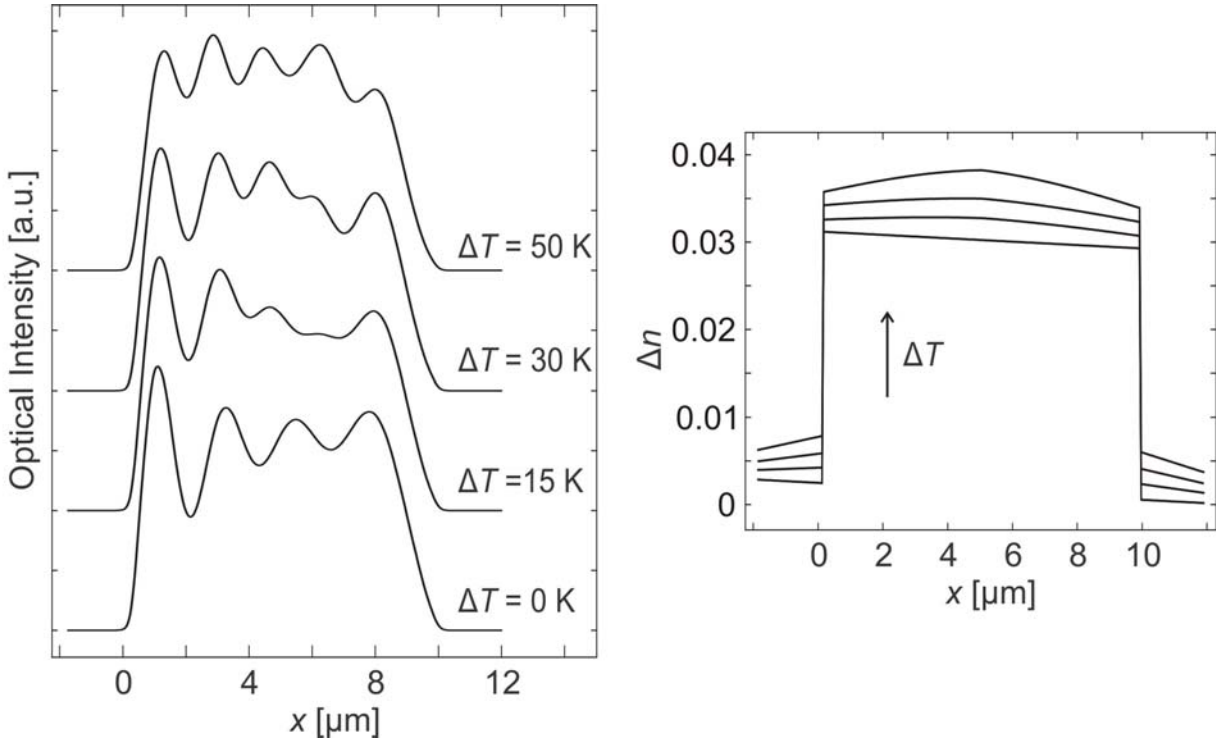
T(t) from
long. modes




D. Scholz et al.
Optics Express **16**, 6846 (2008)


Refractive index profile
0.03
0.02
0.01
0
Δn
0 2 4 6 8 10
x [μm]
ridge waveguide Δn_ridge(x)
+
temperature profile Δn_therm(x)
+
asymmetry Δn_asym(x)
=
modified waveguide Δn(x)
Carrier distribution
4.0
2.0
0
N [10^19/cm^3]
0 2 4 6 8 10
x [μm]
current density J(x)
+
diffusion
+
stimulated emission
=
carrier density N(x)
Modified complex refractive index profile
0 2 4 6 8 10
x [μm]
real part:
modified waveguide + carrier induced changes
imaginary part:
gain, related to carrier density
Optical mode profile
0 2 4 6 8 10
x [μm]
lateral mode profile:
superposition of lateral modes p
self-consistency loop

# Temperature as driving parameter for dynamics

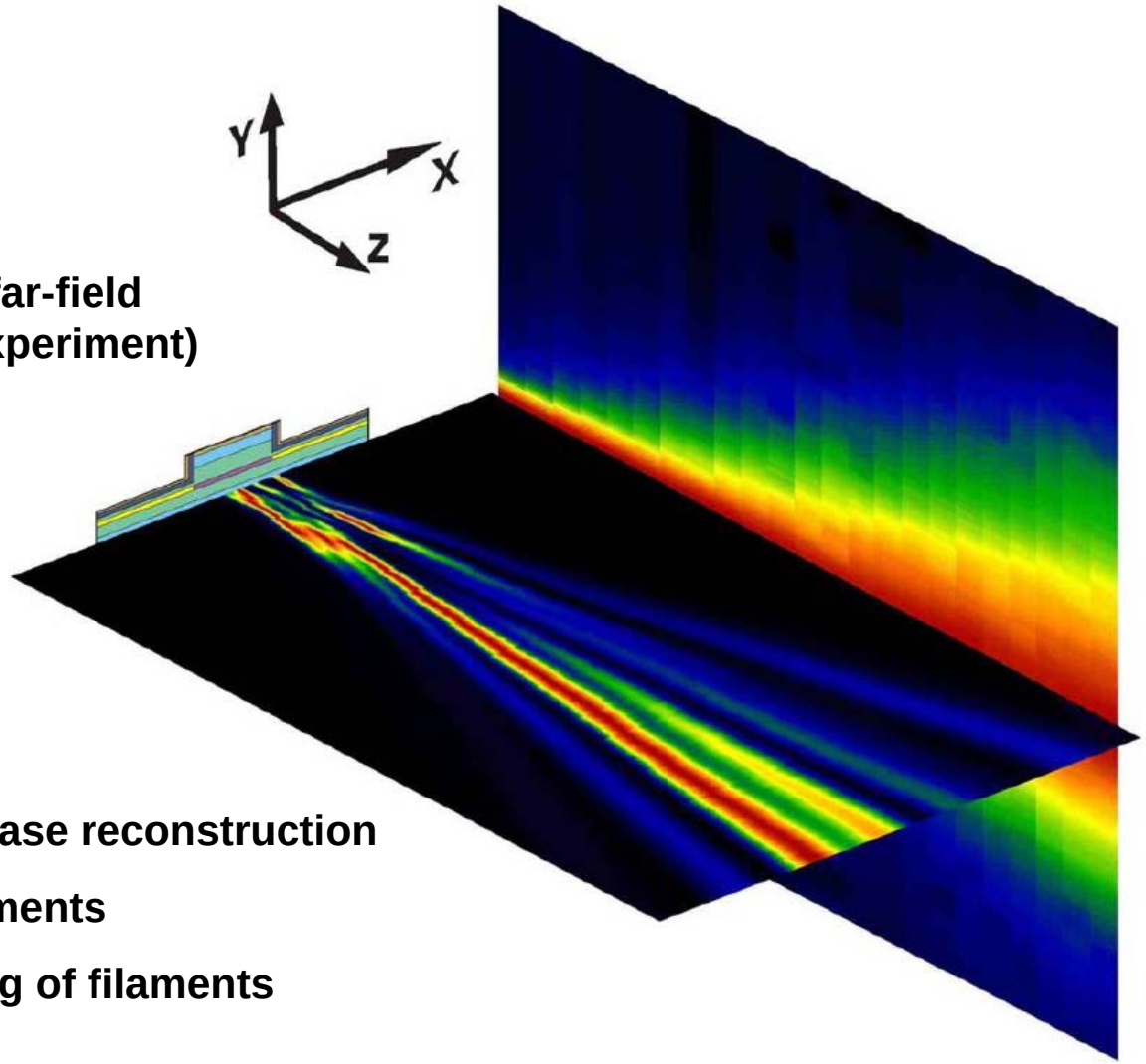



**Thermal induced ref. index profile determines filament configuration.**

- **width & number of filaments**
- **narrower filaments at edges**
- **evolution with time & temperature**

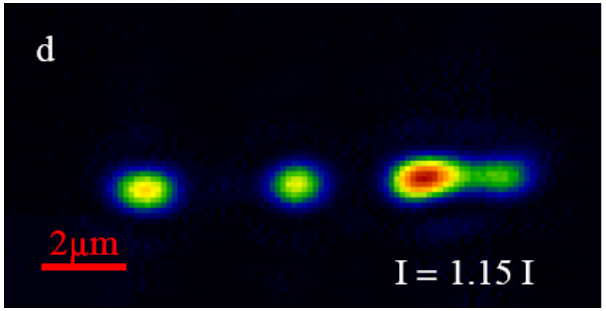
# Coherent / incoheren filaments

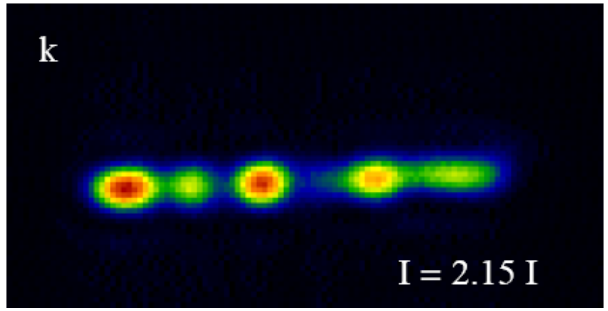
Near-field to far-field
Transition (experiment)

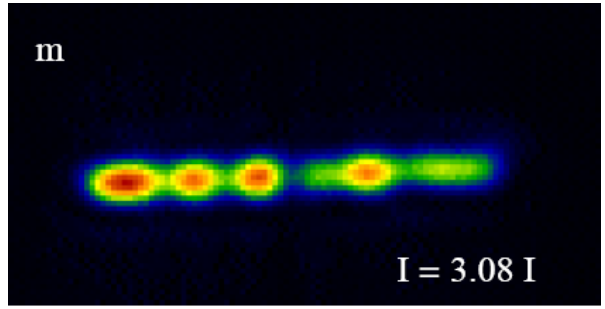



- Near-field phase reconstruction
- Modes / Filaments
- Phase locking of filaments

# Filaments in a 10 µm wide, blue LD

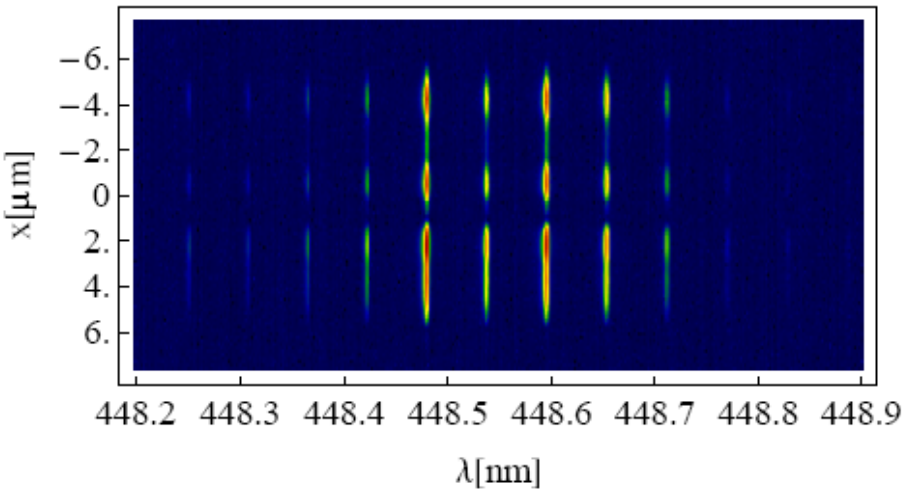


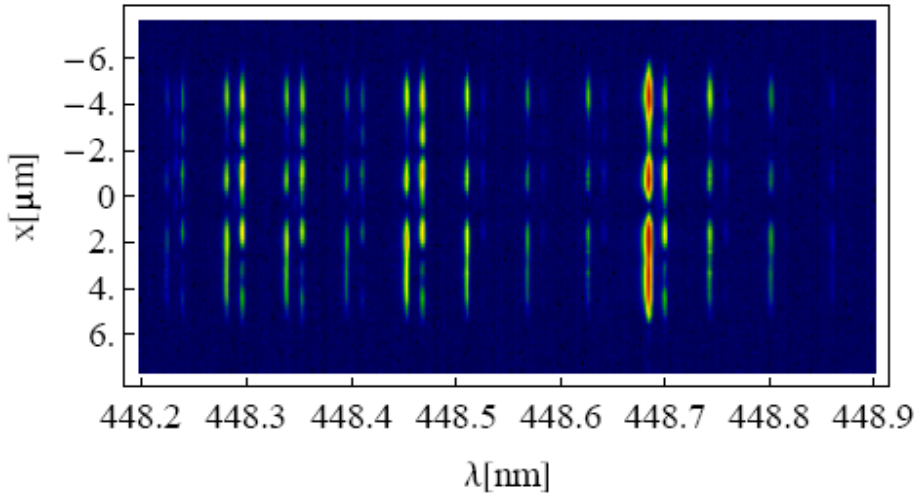




Phase-locked, coherent

incoherent

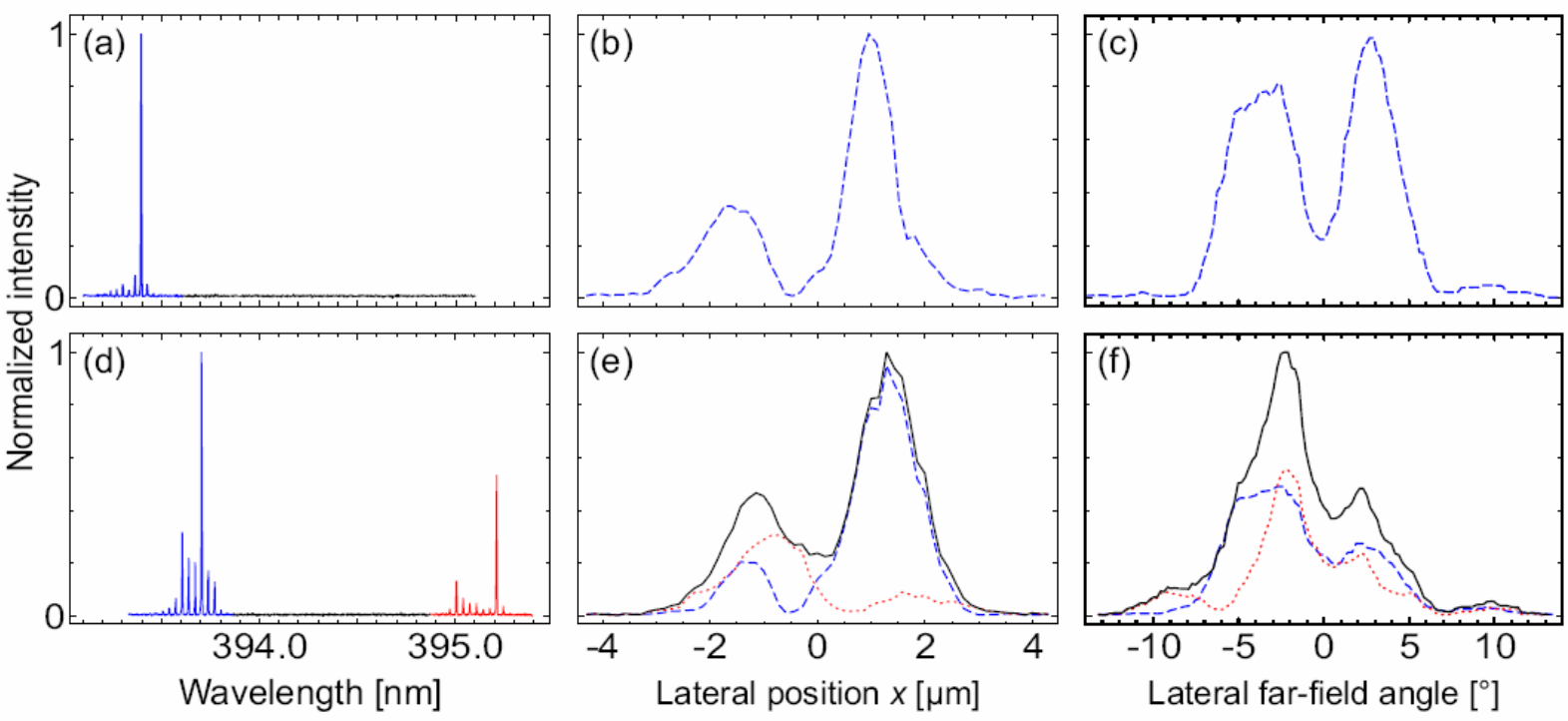



Single longitudinal mode comb




Multiple longitudinal mode combs

# Spectral separation of filaments



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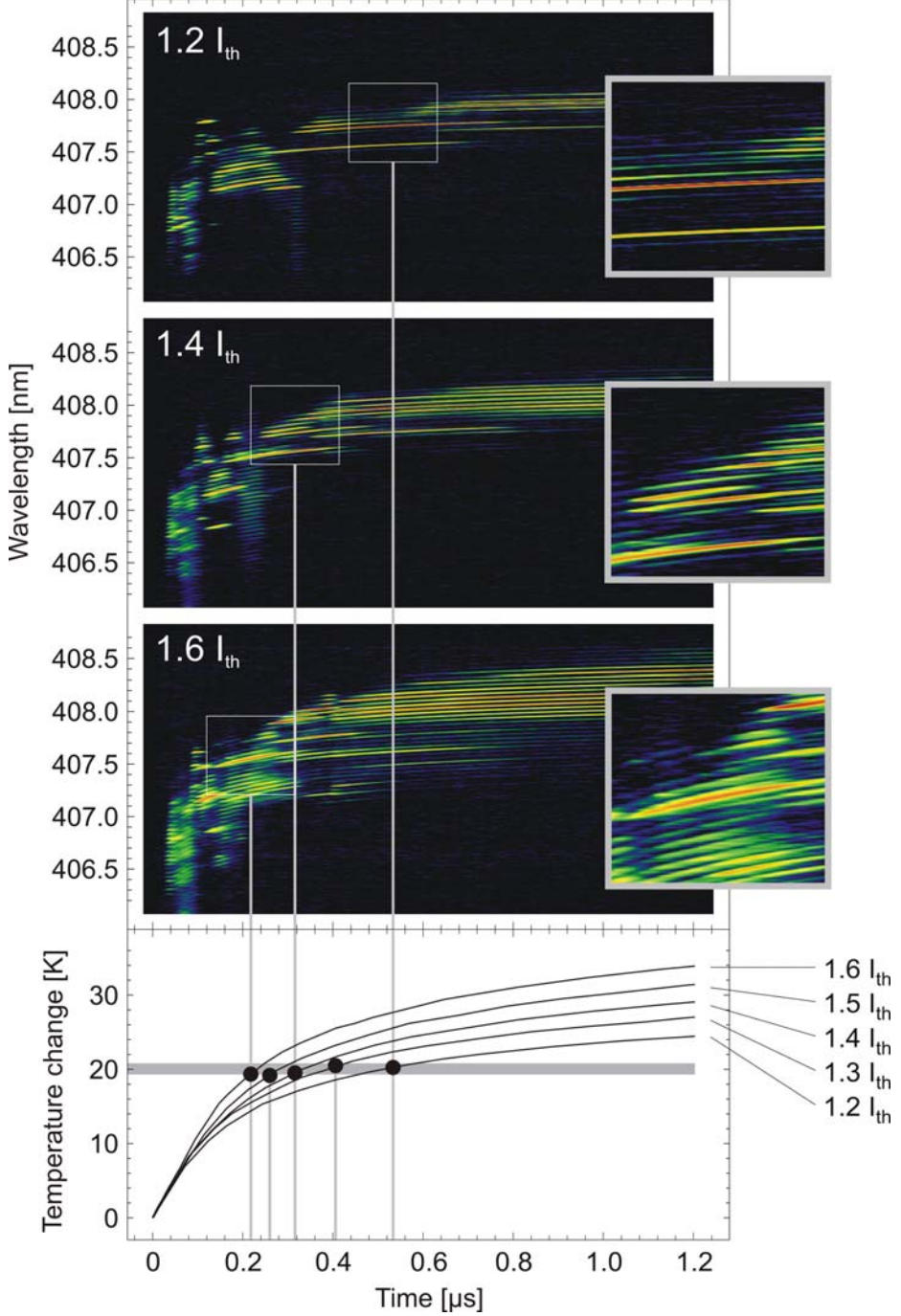
# Summary

- Simple models sufficient to model (w/o too much parameter bending)
- Advanced models necessary (microscopic, multi-dimensional)
- Experiments as input / for calibration
  - Optical gain spectra
  - Modal behavior above threshold
  - Relaxation oscillations, delay, decay, mode comp.
  - Filaments: static, dynamics, near-field and far-field

# Enjoy NUSOD 2008!

Similar picture for longitudinal modes:

Switching of mode combs
@ critical temperatures




H. Braun, et al.,
J. Appl. Phys. **103**, 073102 (2008).