ICTP-SAIFR School on Nonlinear Optics and Nanophotonics, Dec 2-5, 2013

Broad-area lasers, laser solitons and patterns in optics

Thorsten Ackemann

SUPA and Department of Physics, University of Strathclyde, Glasgow, Scotland, UK

Agenda

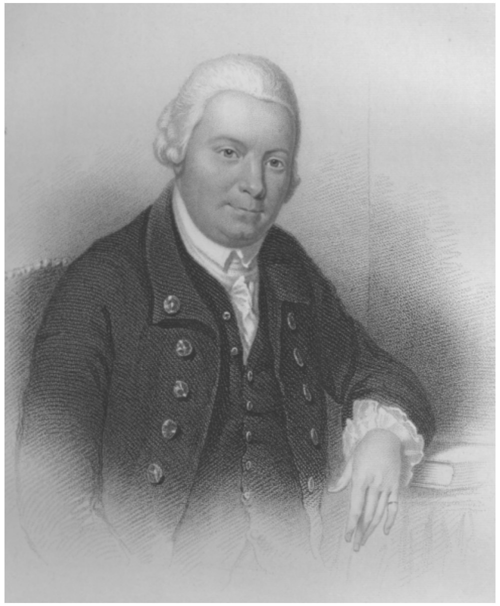
- Aim: Overview on and understanding of the formation and selection of spatial modes in nonlinear optical systems
  - in particular broad-area lasers
  - connections to nonlinear dynamics and complexity science
- Broad-area and high-power semiconductor lasers
  - Modal behaviour, beam quality and instabilities
- Exercise: Modulational instabilities in lasers and beam propagation
- Pattern in VCSELs
  - Pattern selection in lasers
  - quantum billiards
- Cavity soliton laser (VCSEL with feedback or saturable absorption)
  - optical control of self-localized microlasers
  - significance of disorder and phase-locking
  - high-order solitons and vortices
  - connection to dissipative solitons

Agenda II

- Other optical pattern forming systems
  - Single-mirror setup
  - Counterpropagating beams
- Spontaneous symmetry breaking and pattern selection
  - Hexagons as the “second harmonic generation” of transverse nonlinear optics
- One new direction: Optomechanical patterns

University of Strathclyde

situated at the heart of Glasgow, a thriving cultural city on the west coast of Scotland and only a short distance from the Scottish Highlands



John Anderson, Prof. of Natural Philosophy at Glasgow University (Jolly Jack Phosphorus), left instructions in his will for ***"a place of useful learning"***

→ Anderson's institution 1796 → ... →

→ Royal Charter for University of Strathclyde 1964

- still characterized by stimulating and engaging research and knowledge exchange culture
- 2012: UK University of the Year
- 2013: UK Entrepeneurial University of the Year

2012 THE AWARDS UK University of the Year

Department of Physics

- In John Anderson building
- Research divisions: Nanoscience, Plasmas, Optics
  - Computational Nonlinear and Quantum Optics Group
  - Photonics Group
    - Cold atoms and Bose-Einstein condensation
    - Quantum information (single atom imaging in optical lattices)
    - High precision (quantum) measurements
    - Mid-infrared sensing with quantum cascade lasers
    - Nonlinear photonics
- Part of the Scottish Universities Physics Alliance – SUPA
- Strathclyde leading centre for photonics innovation and photonics at the academic-industrial interface: Institute of Photonics, Centre for Biophotonics, Fraunhofer Institute for Applied Photonics

Computational Nonlinear & Quantum Optics Group

CNQO Group * Department of Physics * University of Strathclyde

Student opportunities

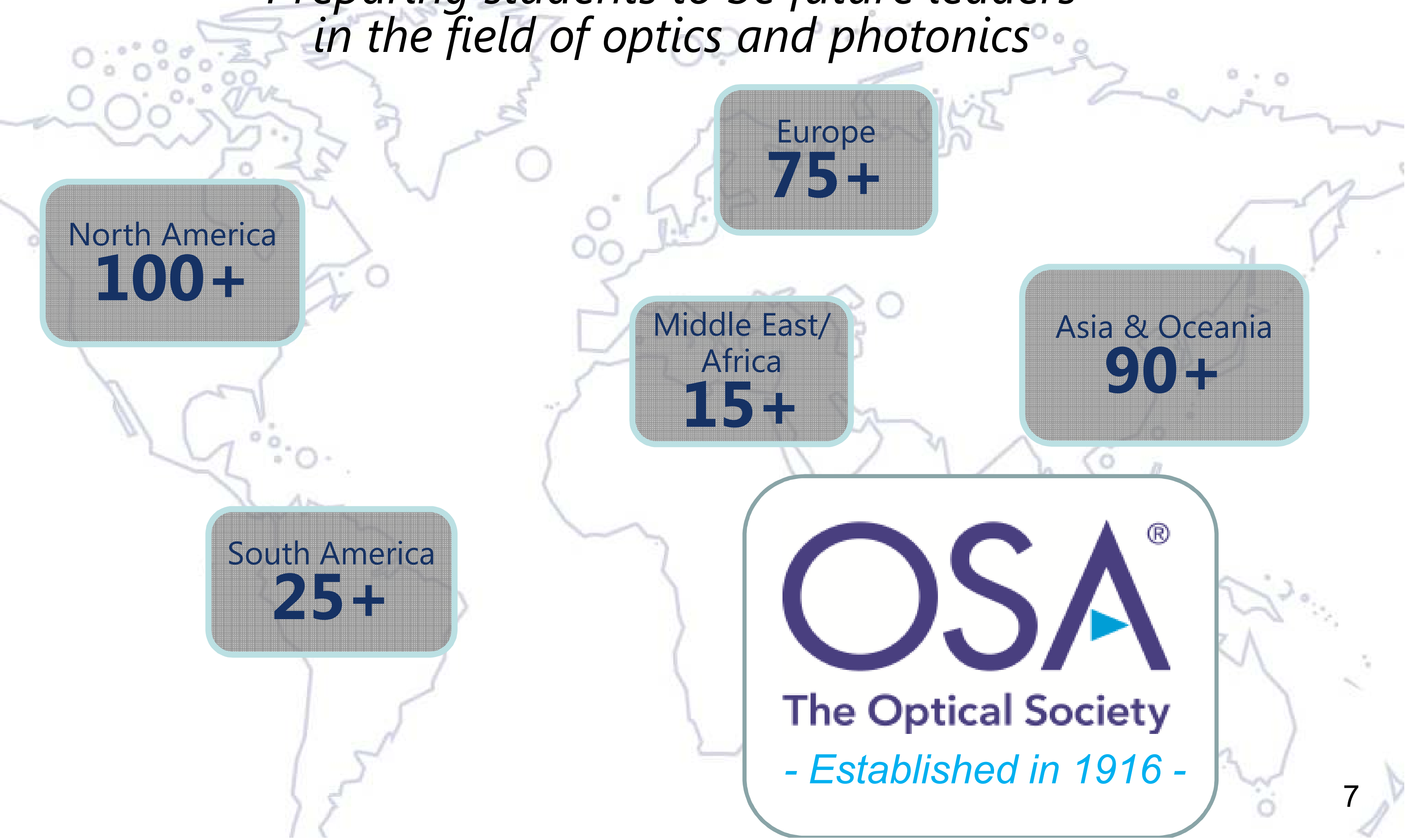
- > 350 undergraduate students
- > 110 **postgraduate students**

  PhD, MRes and MSc
- Taught **MSc degrees** in
  - **Nanoscience**
  - **Optical Technologies**
  - **Photonics and Microfabrication**
- **SCOPE:** OSA Student Chapter
  - Social and scientific networking
  - Company visits
  - Outreach work
  - International student conferences
  - OSA leadership conferences

SCOPE
student community
for optics & photonics
engineering

World-wide OSA student chapters

Preparing students to be future leaders in the field of optics and photonics



Europe
75+

North America
100+

Middle East/ Africa
15+

Asia & Oceania
90+

South America
25+

OSA®
The Optical Society
- Established in 1916 -

OSA student chapters

- ✓ $ 250 start-up funding
- ✓ education and activity grants
- ✓ traveling lecturer program
- ✓ participation at IONs conference (International OSA Network for Students) organized by students, for students
- ✓ Leadership conferences
- ✓ Information, networking, career service

  - ➢ Myself member since 1992 (first international conference)
  - ➢ Faculty adviser to SCOPE since 2009
  - ➢ IONS conference in Glasgow 2009
  - ➢ OSA fellow 2013
  - ➢ current visit thanks to travel grant from OSA Fellow Lecturer Program
  - ➢ contact me for any questions!

Nonlinear Photonics at Strathclyde

- Understand
- Control
- Utilize

nonlinearities and complexity in nonlinear optics,
especially semiconductor-based photonic devices
as vertical-cavity lasers (VCSEL)

Combine fundamental physics with applications and devices

- **Cavity soliton laser**
- **Polarization and spintronics in VCSELs**
  - ultrafast self-oscillations due to spin dynamics
  - broad-area VCSELs, coupling of spatial and polarization degrees of freedom: quantum chaos, optical spin-orbit coupling
  - dynamics of telecommunication VCSELs
- **Self-organization** and opto-mechanical coupling in **cold atomic** vapors
- **Terahertz** generation by difference frequency mixing (heat sinking)
- Quantum dot devices (nonlinear optics, lasers, THz …)

Thanks

VCSEL patterns:

- Experiment: M. Schulz-Ruhtenberg (Muenster)
- Devices: K. F. Huang (National Chiao Tung University, Hsinchu)
- Theory: I. V. Babushkin (Minsk, now WIAS, Berlin), N. A. Loiko (Minsk)
- Funding: Deutsche Forschungsgemeinschaft, DAAD

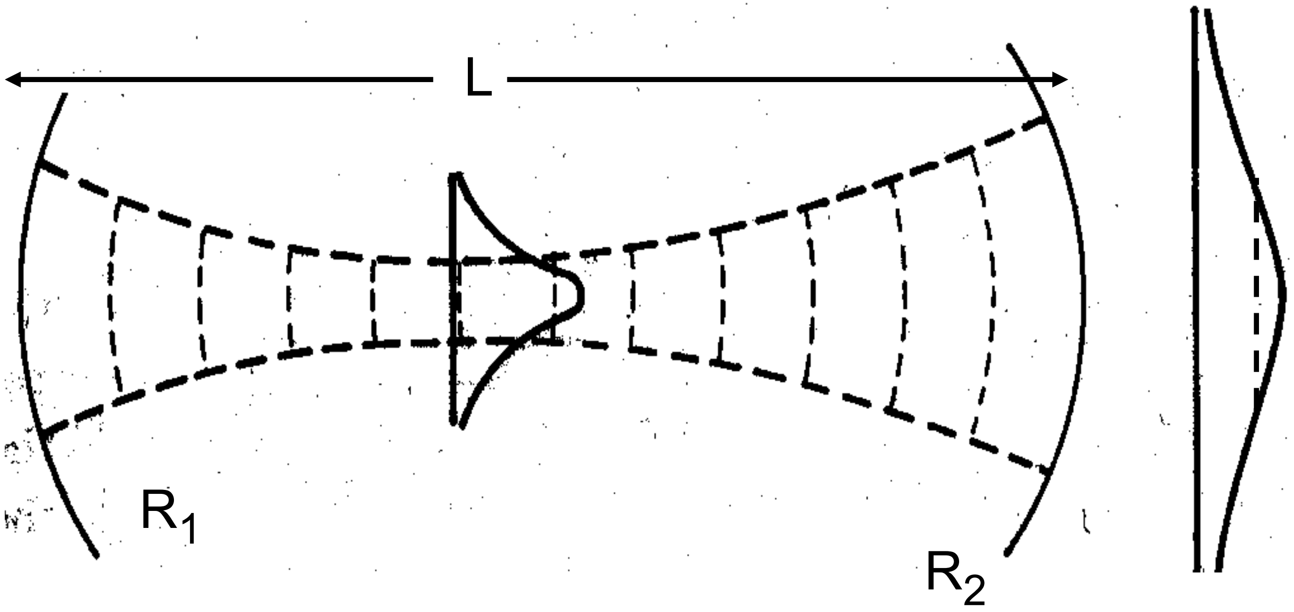
Cavity soliton laser:

- Experiment: Y. Noblet*, J. Jimenez**, N. Radwell*, Y. Tanguy
- Devices: R. Jaeger (Ulm Photonics)
- Theory: C. McIntyre*, W. J. Firth, G.-L. Oppo (Strathclyde), P. V. Paulau (Minsk, Strathclyde, Palma, now University of Oldenburg), D. Gomila, P. Colet (IFISC, Palma de Mallorca), N. A. Loiko (Minsk), N. N. Rosanov (St. Petersburg)
- Funding: *EPSRC DTA, ** Conayt, EU FP6 FunFACS, British Council, Royal Society, DAAD

Solitons and patterns in atomic vapors with feedback:

- Experiment, theory + devices: M. Schaepers, A. Aumann, W. Lange (Muenster)
- Funding: Deutsche Forschungsgemeinschaft, DAAD

Eigen modes of resonators



Typical laser resonators (solid-state, gas, semiconductor disk laser)

Refocusing by curved mirrors →

stable resonator

Parameter: $g_i = 1 - L / R_i$ for mirrors i=1,2

Eigen mode: „Gaussian beam“

Gaussian Amplitude profile

Parabolic Phase profile

$$u_0(x,y,z) \sim \frac{1}{w(z)} e^{i\psi(z)} \exp\left[-\frac{x^2+y^2}{w^2(z)} - ik\frac{x^2+y^2}{2R(z)}\right]$$

Source: Siegman, *Lasers* (1986)

Propagation and diffraction

Diffractive spreading

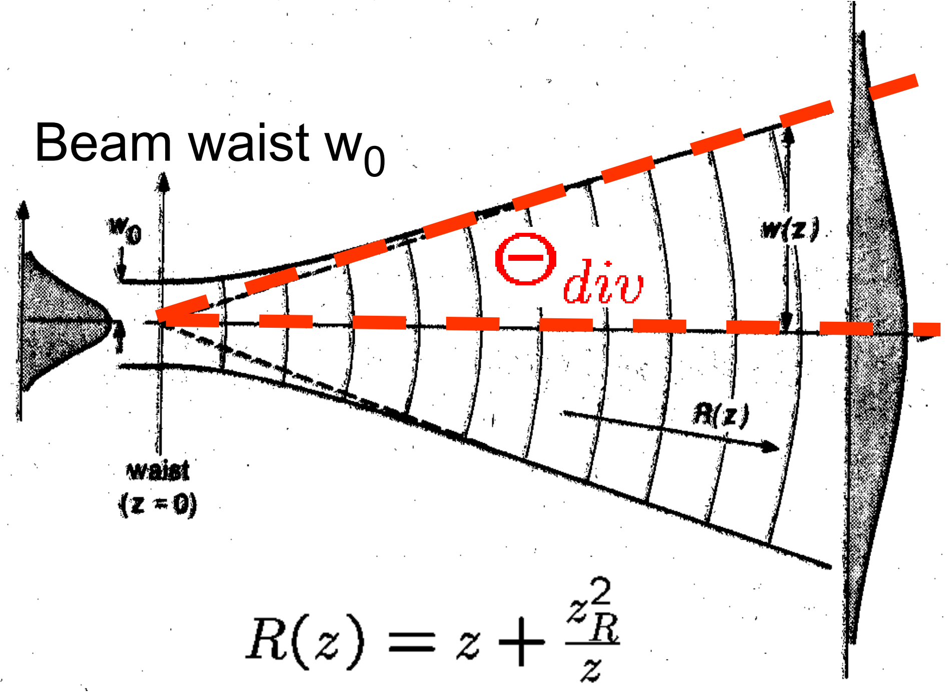
Rayleigh Length $z_R = \frac{\pi w_0^2}{\lambda}$

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \xrightarrow{z \to \pm\infty} w_0 \cdot \frac{1}{z_R} \cdot z$$

linear for large z

Diffraction angle: $\Theta_{div} = \frac{\lambda}{\pi w_0}$

Beam waist w_0

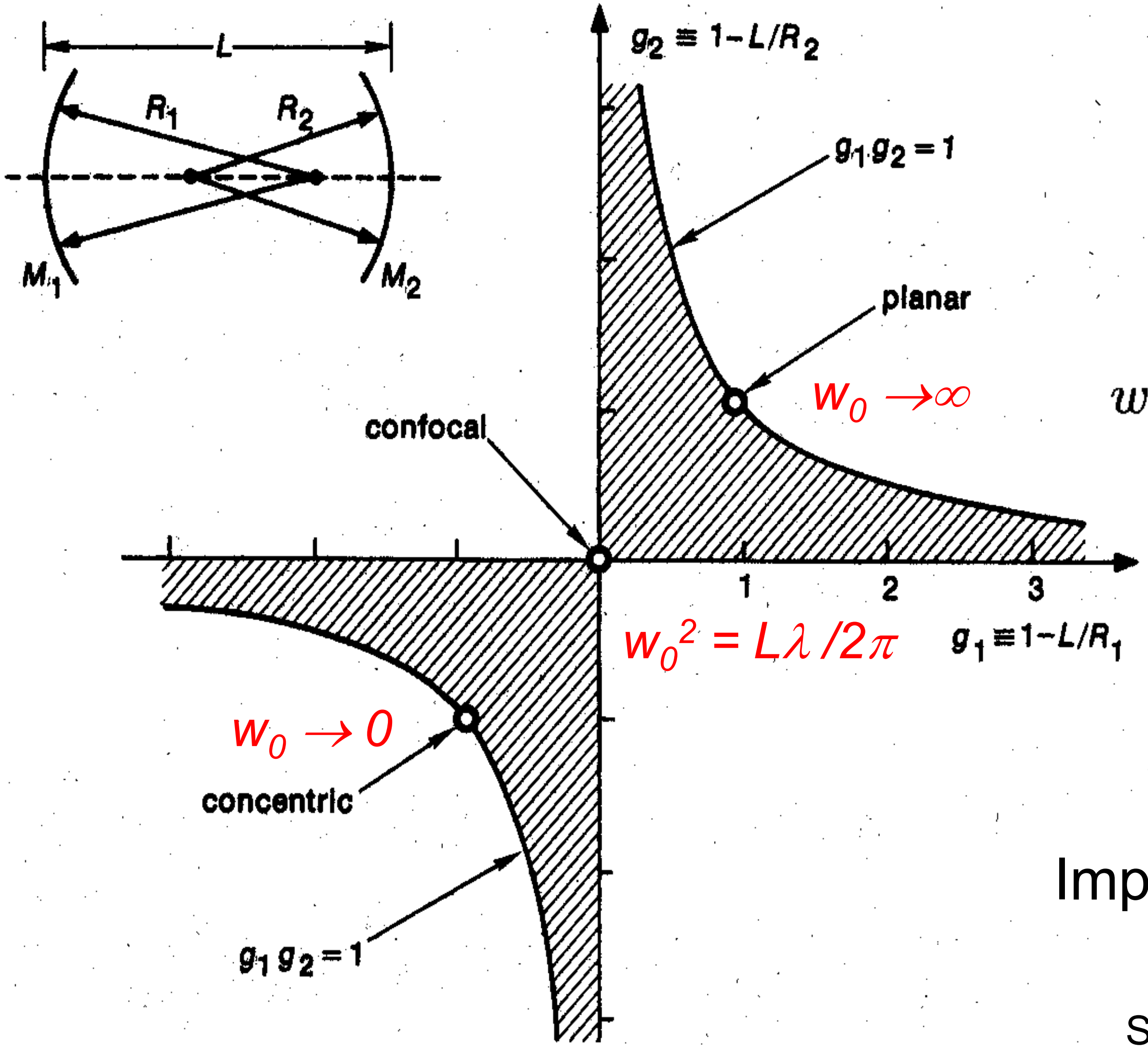


$$R(z) = z + \frac{z_R^2}{z}$$

Light in this cone is spatially coherent

Source: Siegman, *Lasers* (1986)

Stability diagram



Solution only for
$0 < g_1 g_2 < 1$

$$w_0^2 = \frac{L\lambda}{\pi}\sqrt{\frac{g_1 g_2(1-g_1 g_2)}{(g_1+g_2-2g_1 g_2)^2}}$$

Important design tool

Source: Siegman, *Lasers* (1986)

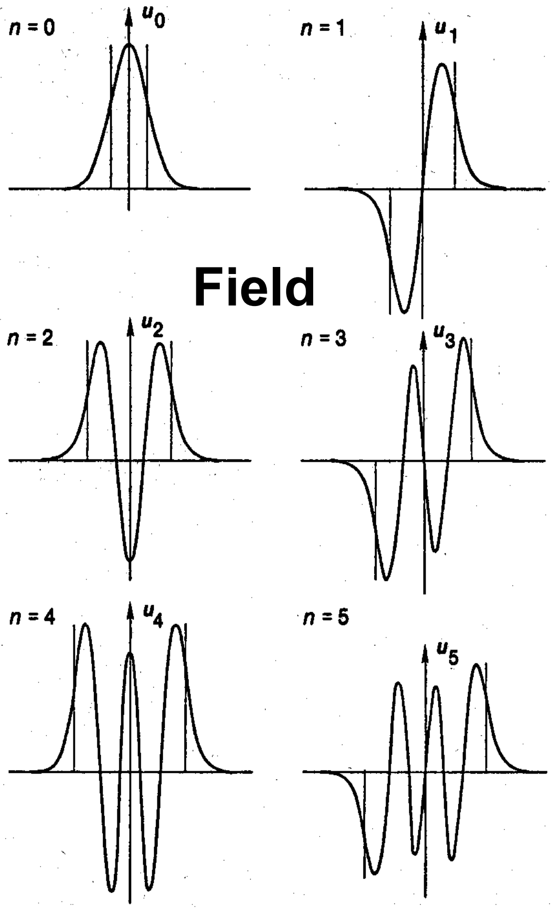
High order spatial modes

Hermite-Gaussian Moden

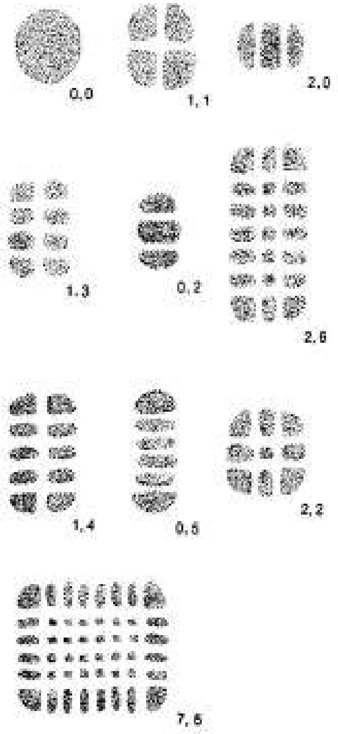
$$u_{mn}(x,y,z) \sim \frac{1}{w(z)} e^{i\psi(z)} \exp\left[-\frac{x^2+y^2}{w^2(z)} - ik\frac{x^2+y^2}{2R(z)}\right]$$

$$\cdot e^{i(m+n)\psi(z)} H_m\left(\frac{\sqrt{2}x}{w(z)}\right) \cdot H_n\left(\frac{\sqrt{2}y}{w(z)}\right)$$

Hermite polynomial of order m,n

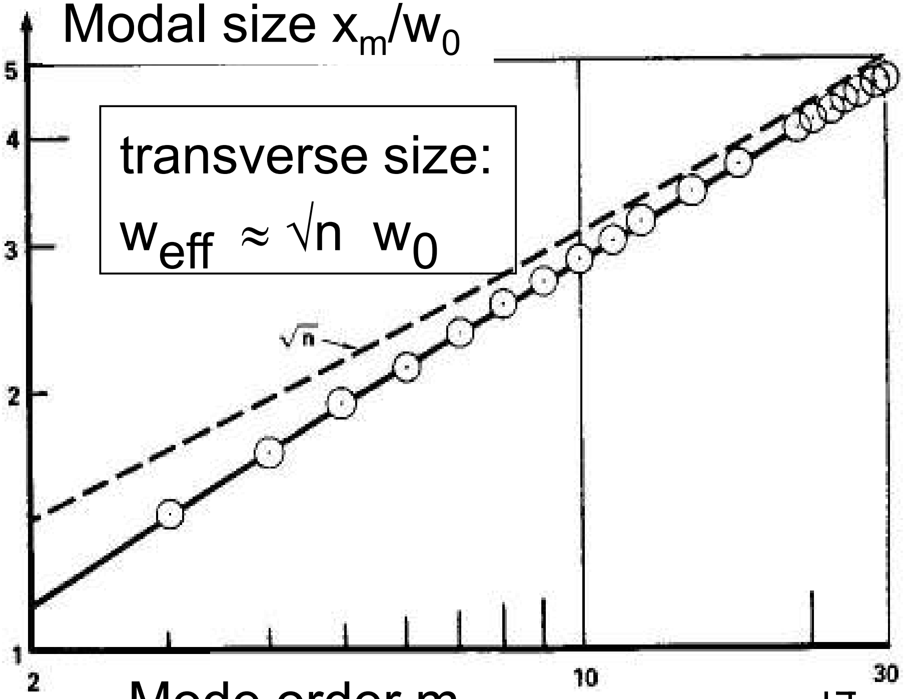


Field



intensity

Modal size x_m/w_0



transverse size:

$w_{eff} \approx \sqrt{n}\ w_0$

Mode order m

Source: Siegman, *Lasers* (1986)

Divergence and brightness

- For the quality of a laser beam not only initial size w_0, but also the ***divergence*** Θ is important!
- Divergence of high order modes ~ $\sqrt{m}\,\Theta_0$
- ***Brightness*** B = power / (mode area × emission angle)

  $= P /(\pi\, w_0^2 \times \pi\, \Theta^2)$ $[\mathrm{W\ cm^{-2}\ str^{-1}}]$
- Relevance for applications

  (micromachining, medical, nonlinear optics …)

  Focused spot size ~ Θ f; need low divergence to focus tightly
- Product $w_0 \times \Theta$ can't decrease in passive homogeneous or lens-like optical systems

  if you got it wrong at the start, you can't improve brightness any more

  → *get it right at the start (in the laser!)*

M^2-factor and divergence

Engineers/applied physicist use **beam quality factor M^2**

beam size – divergence product normalized to the one of an ideal beam

Minimal size (radius, $1/e^2$)

$$M^2 = \frac{\pi \cdot w_0 \cdot \theta_0}{\lambda}$$

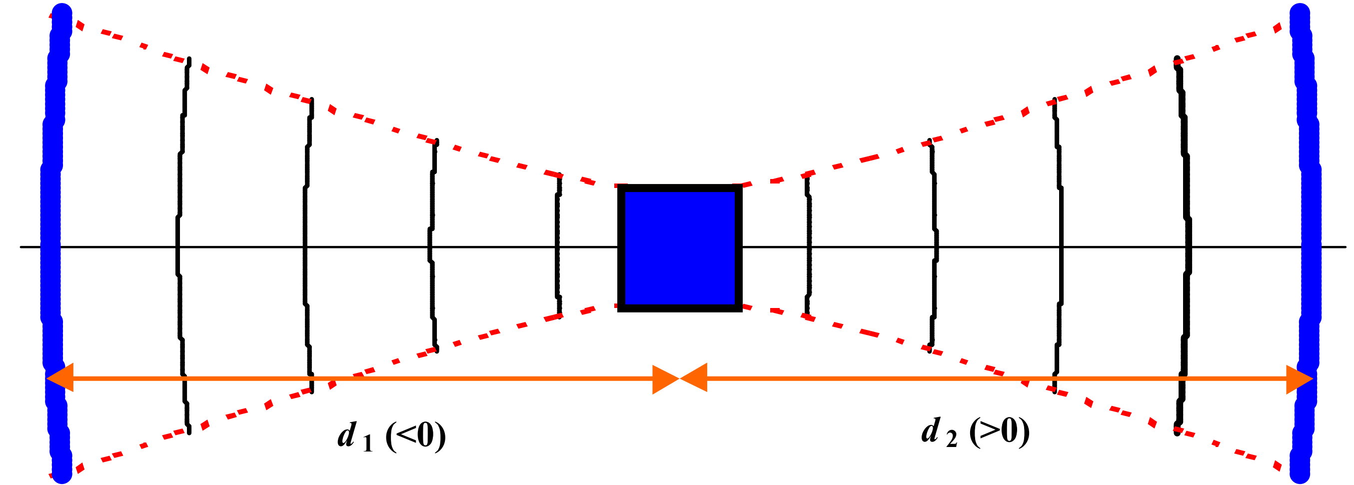
Half divergence angle ($1/e^2$)

- for fundamental, TEM_{00}, mode
  $\Theta_0 = \lambda /(\pi w_0)$
  $\rightarrow M^2 = 1$

- for high-order, TEM_{m0}, mode
  apparent size $\sim \sqrt{m}\, w_0$
  divergence $\sim \sqrt{m}\, \Theta_0$
  $\rightarrow M^2 \approx m$
  highest mode order

Cavities for high power lasers

- Engineers and most other people do not like high order modes
- Design for fundamental mode operation by matching mode area to active gain area
- Not easy, but possible by using the **degrees of freedom of stability diagram** often possible (in reality in multi-mirror resonators)
- You can get solid-state (e.g. Nd:YAG) and semiconductor disk lasers with **> 10 W of single spatial mode power**



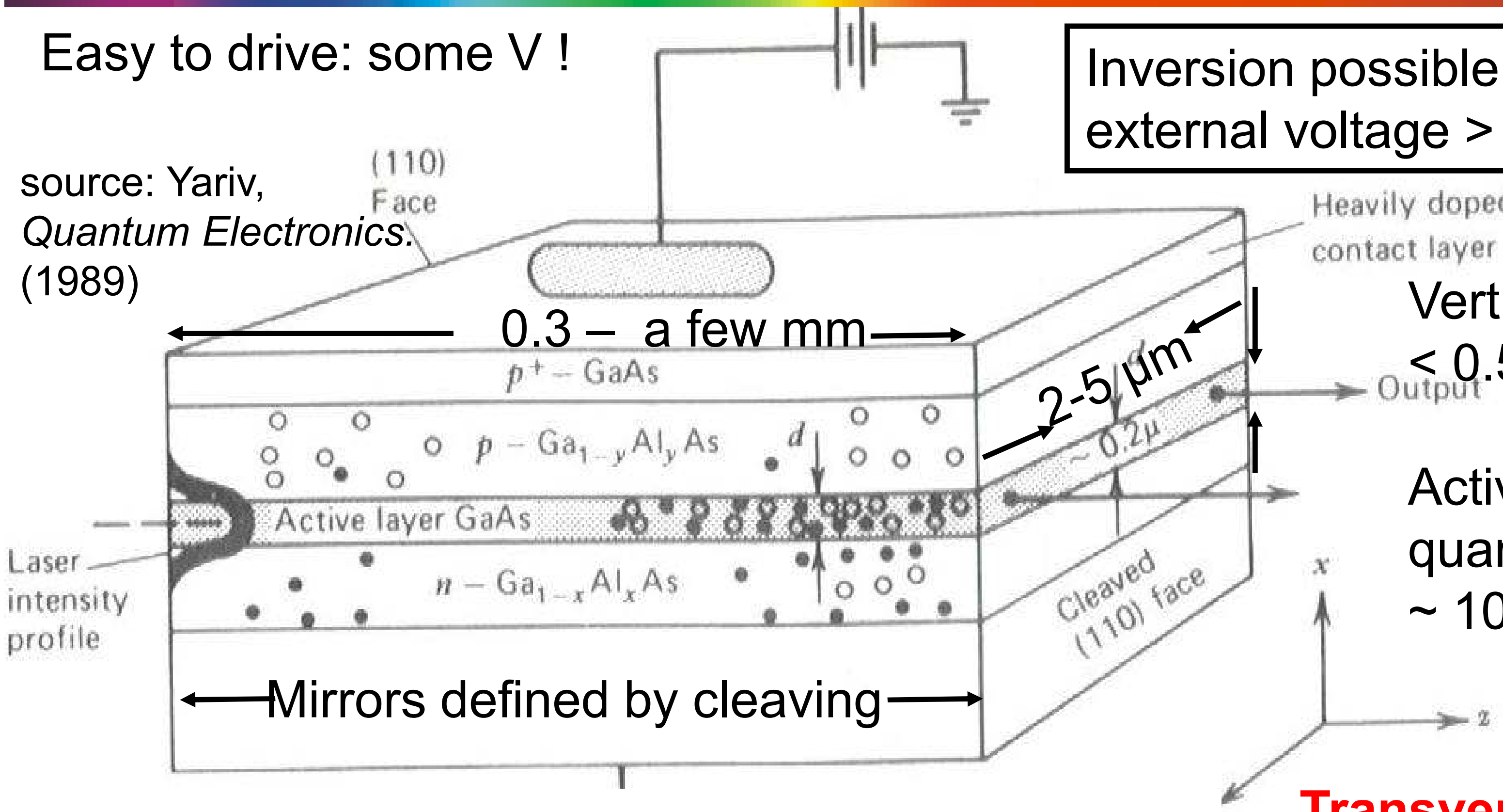
total cavity length $L = d_2 - d_1$

Schematics of a semiconductor laser

Easy to drive: some V !

Inversion possible, if
external voltage > band edge

source: Yariv,
Quantum Electronics
(1989)



0.3 – a few mm

2-5 µm

Mirrors defined by cleaving

Vertical waveguide
< 0.5 µm core

Active layers
quantum wells
~ 10 nm

- monolithic, robust
- inexpensive to value for money
- energy efficient (up to 68% wall plug efficiency)

Transverse size 2-5 µm
for single mode
Max. Power ≈ 1 W

But no way to **engineer modal size independently from active size**!

Broad-area edge-emitting lasers (BAL)

LD-1210-BA-8W

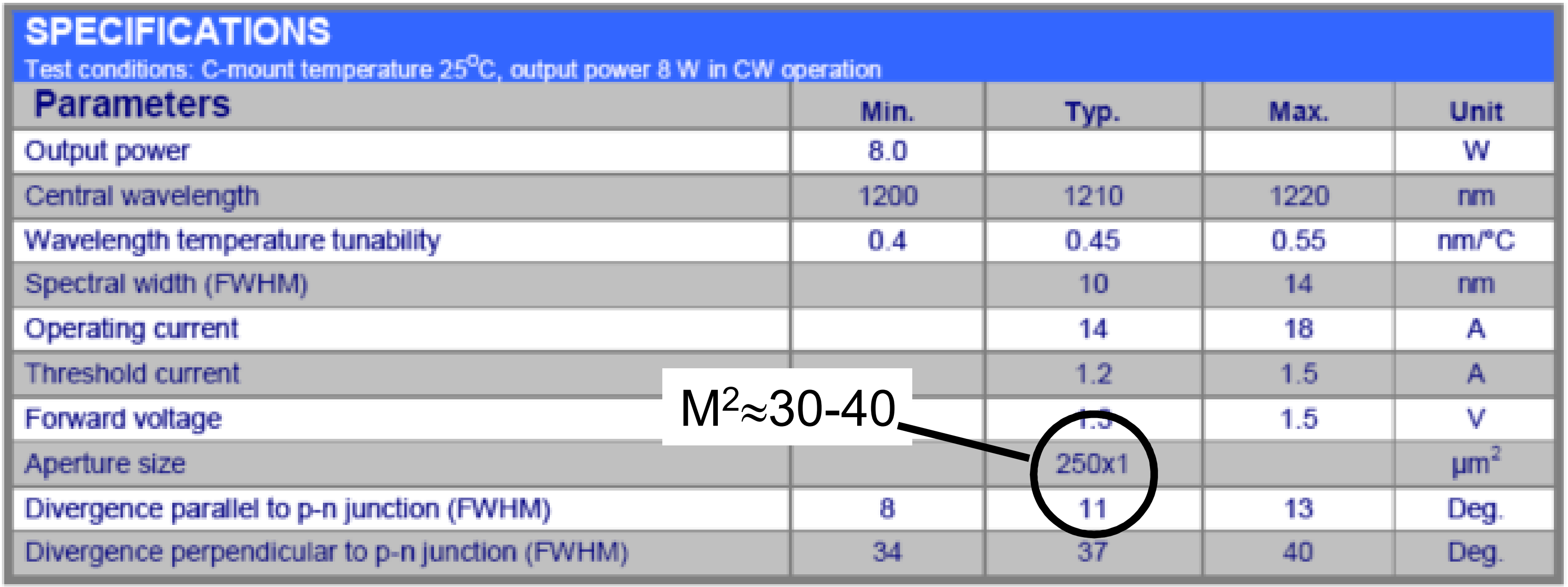
High Power Diode Laser – 8W @ 1210nm

Features:
- InAs/GaAs Quantum Dot based diode laser
- CW operation
- C-mount open heatsink

Applications:
- Medical
- Direct materials processing

Specification
for engineering samples

DATE: 10th Jun. 2008



SPECIFICATIONS

Test conditions: C-mount temperature 25°C, output power 8 W in CW operation

Parameters	Min.	Typ.	Max.	Unit
Output power	8.0			W
Central wavelength	1200	1210	1220	nm
Wavelength temperature tunability	0.4	0.45	0.55	nm/°C
Spectral width (FWHM)		10	14	nm
Operating current		14	18	A
Threshold current		1.2	1.5	A
Forward voltage		1.3	1.5	V
Aperture size		250x1		μm^2
Divergence parallel to p-n junction (FWHM)	8	11	13	Deg.
Divergence perpendicular to p-n junction (FWHM)	34	37	40	Deg.

$M^2 \approx 30\text{-}40$

Best lasers
980 nm
11 W out of
90 µm stripes
$M^2 \approx 20$

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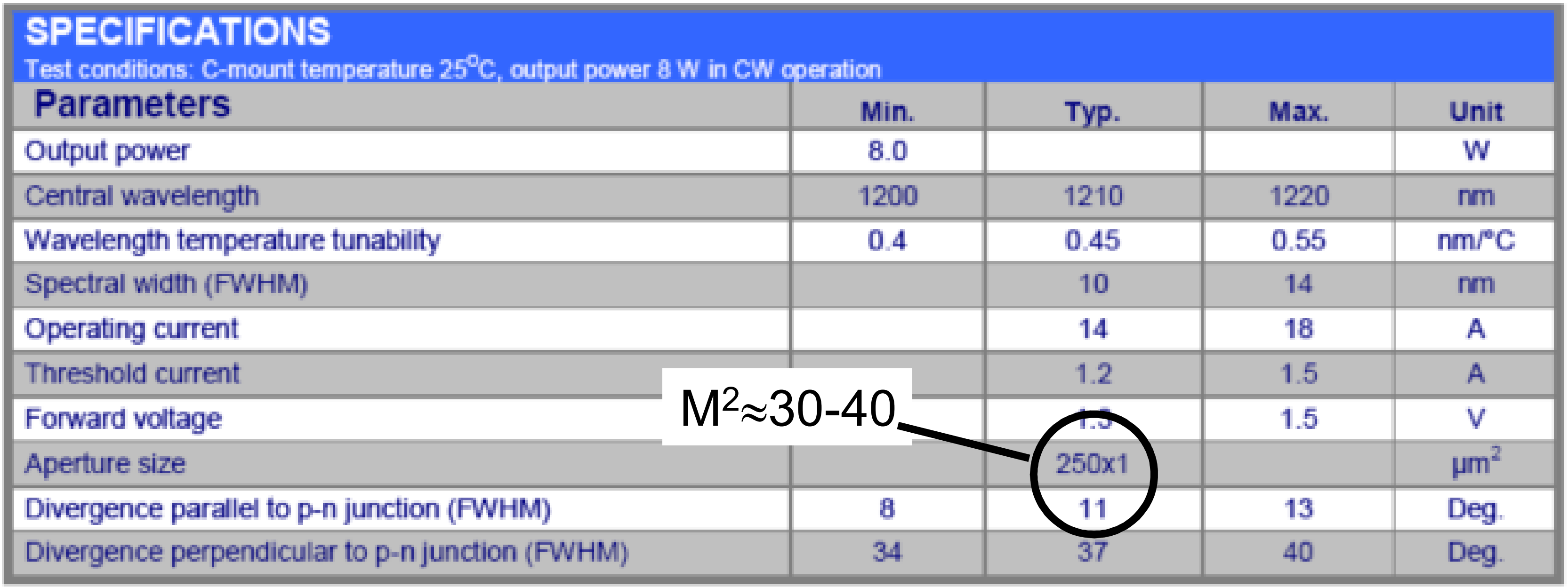

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Two types of semiconductor lasers

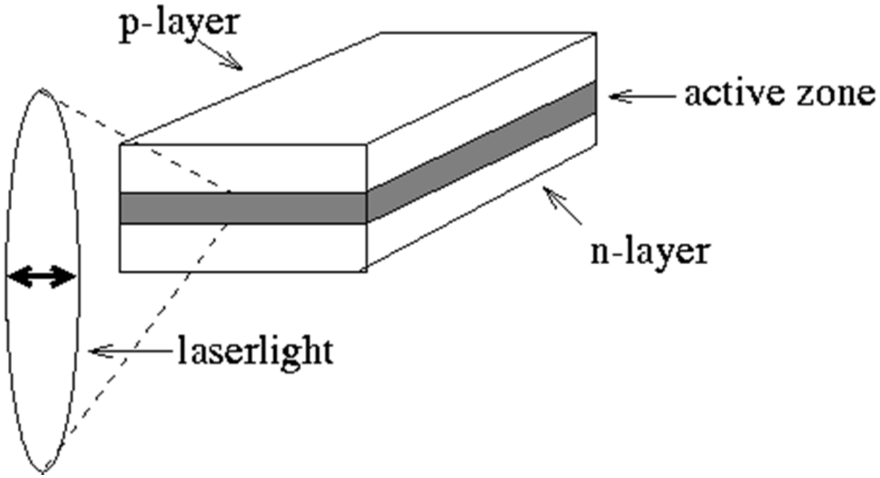
University of Strathclyde Science

edge – emitting (conventional)

surface – emitting
VCSEL = vertical-cavity surface emitting laser

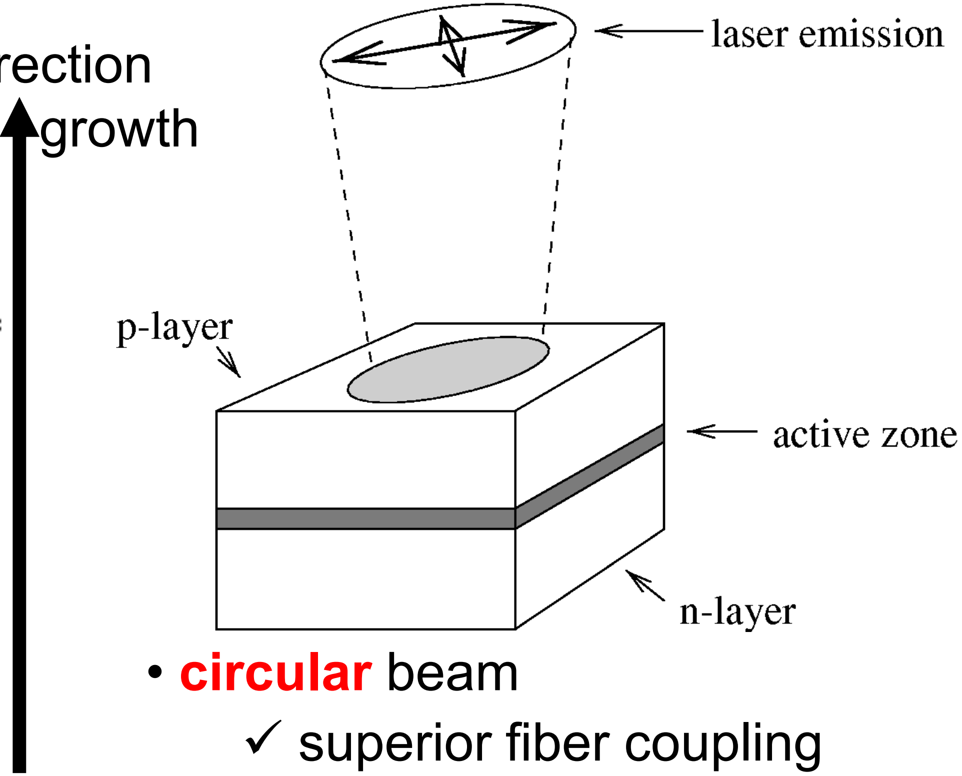
direction of emission **orthogonal** to epitaxial growth

direction of emission **parallel** to epitaxial growth



- **elliptical** beam
- macroscopic cavity length
- large gain

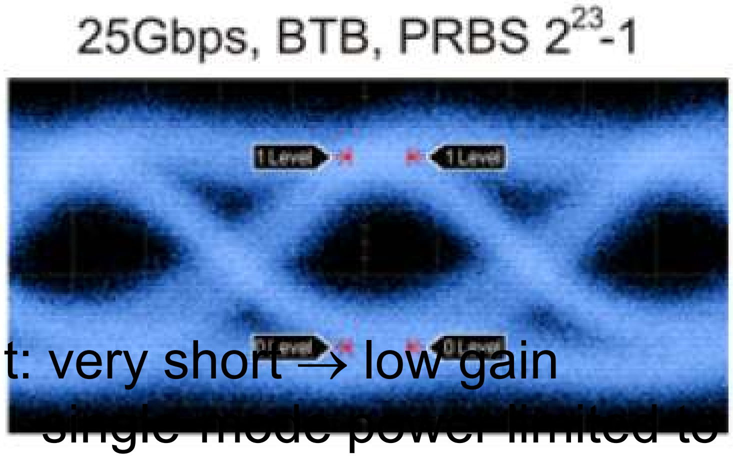
direction of growth



- **circular** beam
  - ✓ superior fiber coupling
- short, small
  - ✓ single longitudinal mode

Vertical-cavity surface-emitting lasers

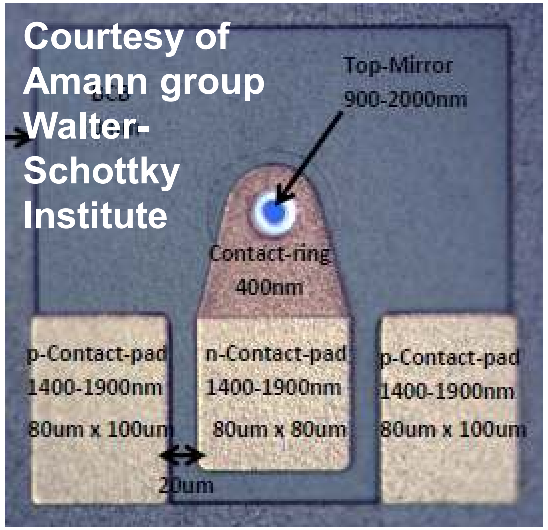
- short-haul data-communication (LAN, Ethernet etc.)
- optical mice
- single-mode long-wavelength VCSELs in development for telecommunications



But: very short → low gain

single-mode power limited to 0.5 -2 mW

→ ***Make devices wider than 2-3 μm!***

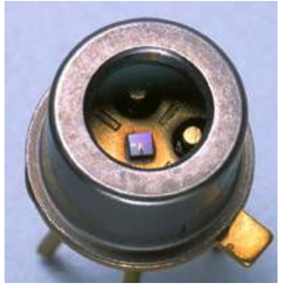


Courtesy of Amann group Walter-Schottky Institute

Packaged

Honeywell VCSEL
© Honeywell

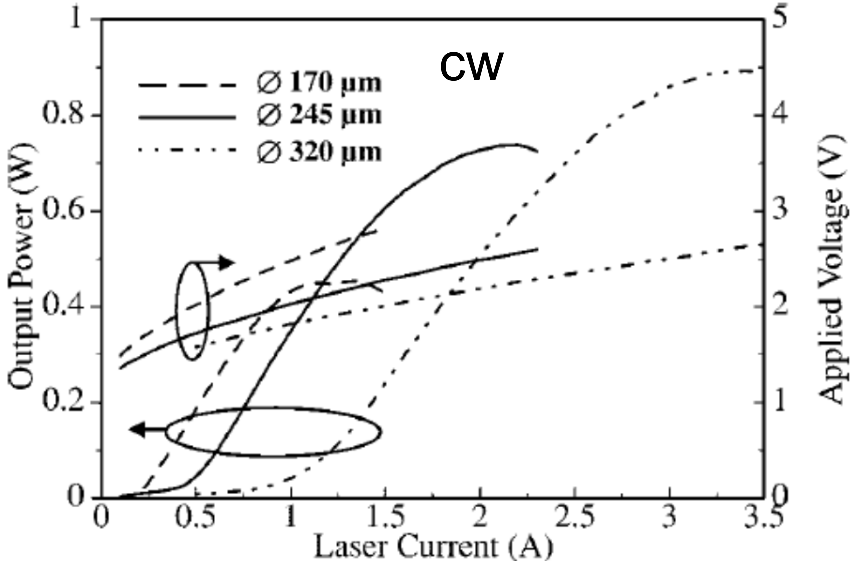
http://people.ee.duke.edu/

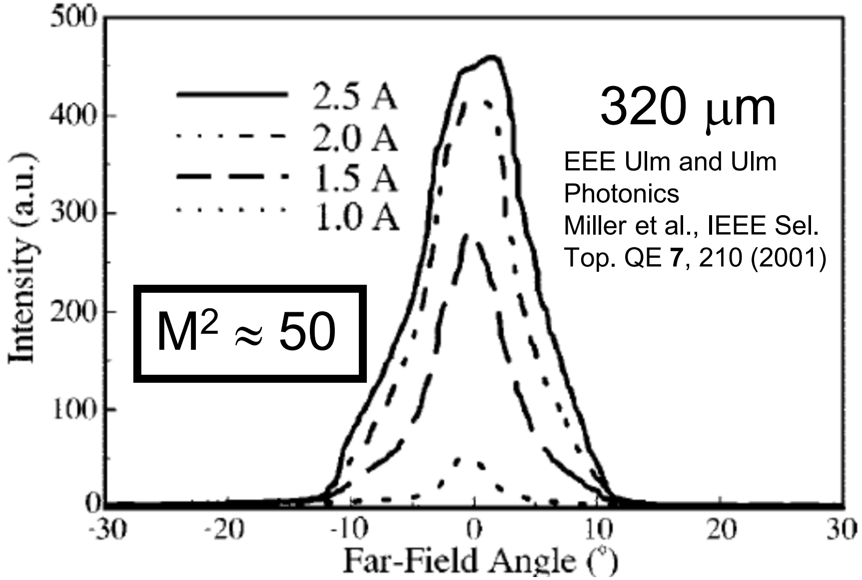


Final

Ulm Photonics

Very large area devices ("commercial")





320 μm

$M^2 \approx 50$

EEE Ulm and Ulm Photonics
Miller et al., IEEE Sel. Top. QE **7**, 210 (2001)

VCSEL arrays offer a robust and economic solution for many new applications with moderate brightness requirements as illustrated in Figure 3. Thanks to the good emission properties

Moench et al., CLEO Europe CB.P.19 (2011)

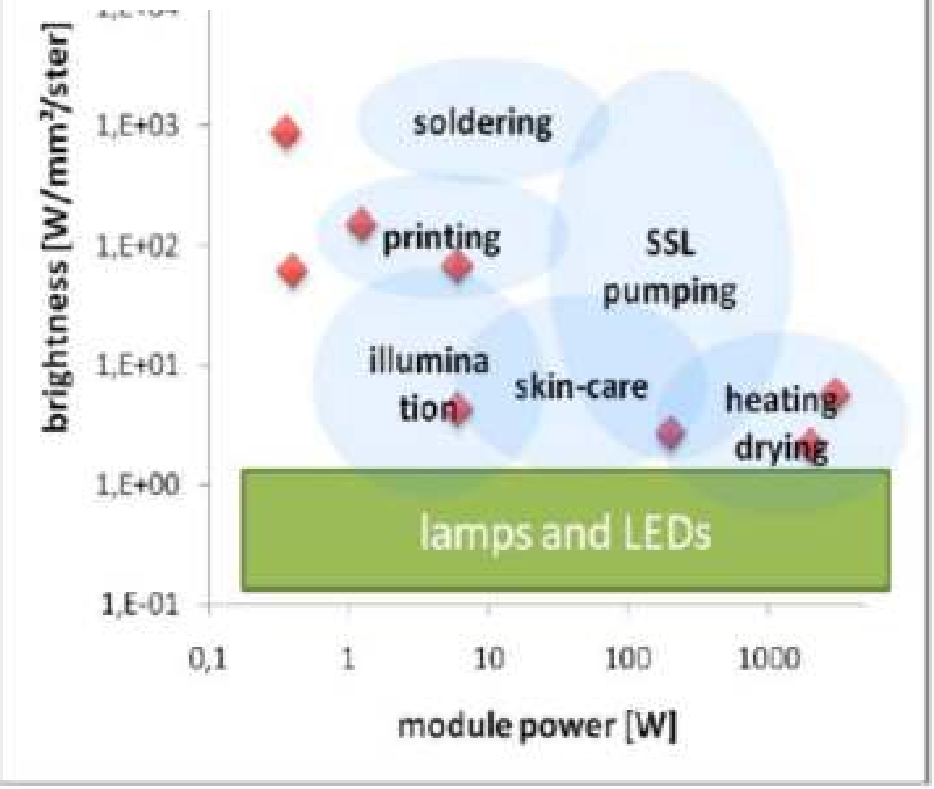


Figure 3 : Brightness vs. power map for examplatory VCSEL modules (symbols) and the requirements of several applications.

Origin of instabilities

- In a monolithic cavity, we can’t design mode volume and gain volume independently

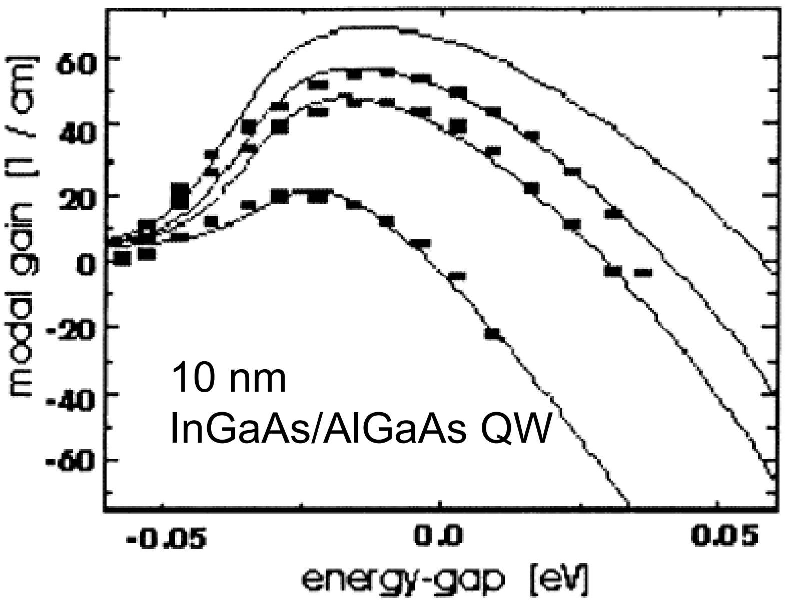
  → **high-order modes will overlap with gain distribution**
- Aggravated by **spatial hole burning**:

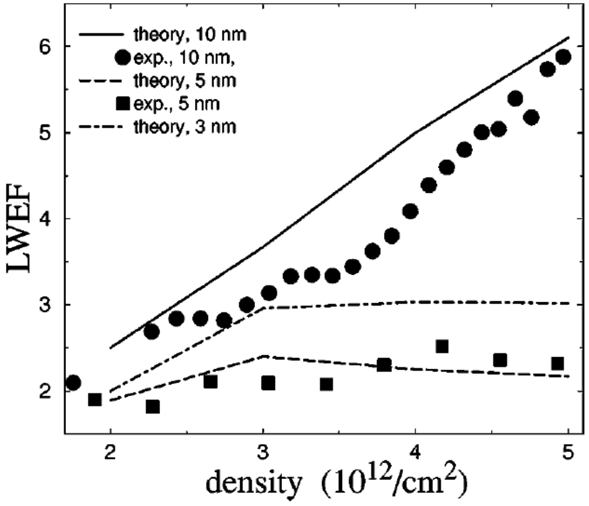
  even assuming that fundamental mode is lasing at threshold, carriers will **clamp** where fundamental mode is strong but not in regions close to device boundary

  → more gain for high order modes
- **nonlinear refractive index** → filamentation (next slides)
- in real devices augmented by a lot of other effects, in particular **thermal lensing**

Dominant nonlinearity with inversion

Hader et al., IEEE Sel. Top. QE 9, 688 (2003)





- ➢ Gain spectrum of a semiconductor is ***asymmetric!***
  → **refractive index contribution at gain maximum** (Kramers-Kronig)
- ➢ refractive index n depends on carrier density N → often used: Henry's α-factor

$n \sim \chi \sim (i + \alpha)\, N \quad \text{with } \alpha = 1.5\text{ -}7$

- ➢ n decreases with increasing N
- ➢ N decreases with increasing intensity
- ➢ n increases with increasing intensity

$n = n_b + n_2 I \text{ with } n_2 > 0$

- ➢ light is attracted to high n

self-focusing nonlinearity

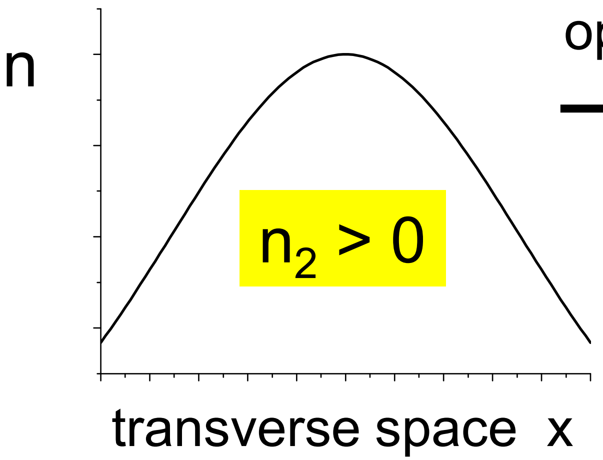
Self - focusing

Kerr medium

$$\begin{aligned} n &= n_0 + n_2 \,|\, E \,|^2 \\ &= n_0 + n_2 \, I \end{aligned}$$

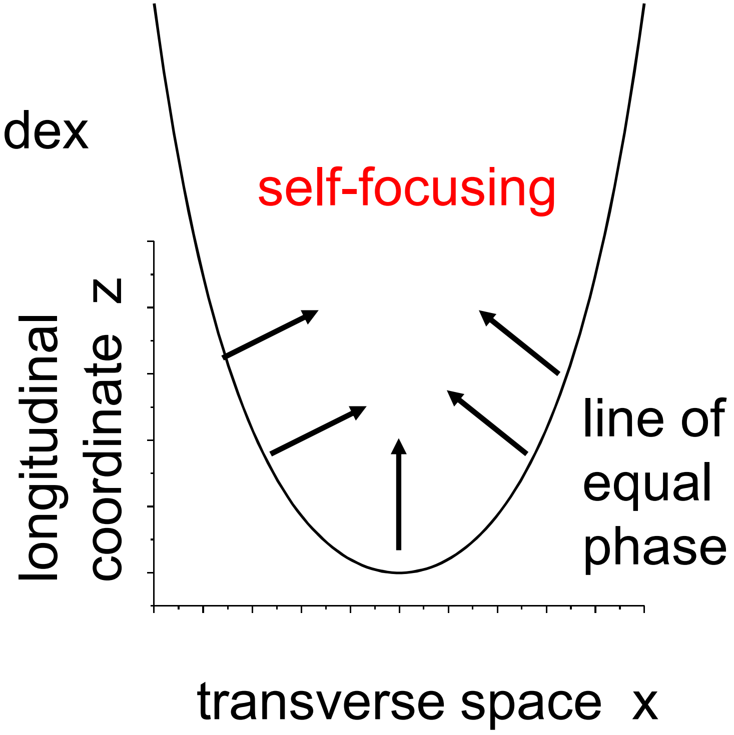
intensity dependent refractive index

in an inhomogeous beam, e.g. a Gaussian
→ transversally inhomogenous refractive index



optically thicker

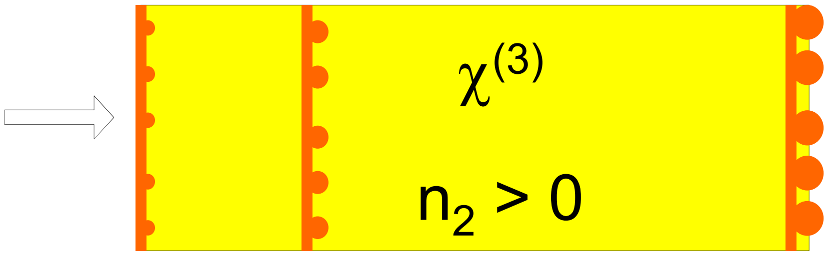
in centre

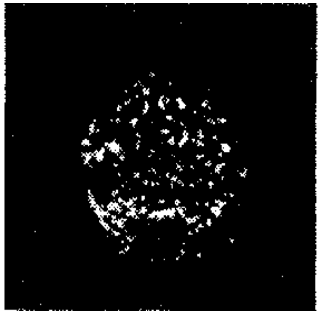


- an **optically induced lens**
- $n_2 > 0$ → self-focusing
- $n_2 < 0$ → self-defocusing

Modulational instability

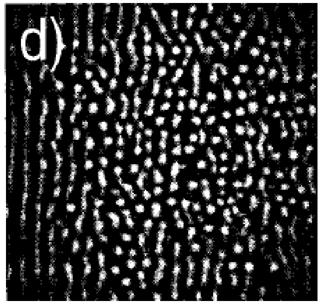
if your input beam is very broad, ideally a plane wave:





Abbi + Mahr 1971

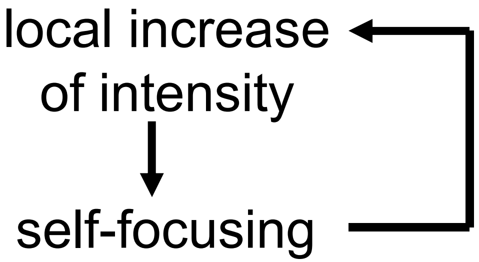
nitrobenzene



Mamev et al. 199

photorefractive crystal

every beam has some ripples “noise”:
modulations, ripples



local increase of intensity

self-focusing

positive feedback
→ *break-up* of beam

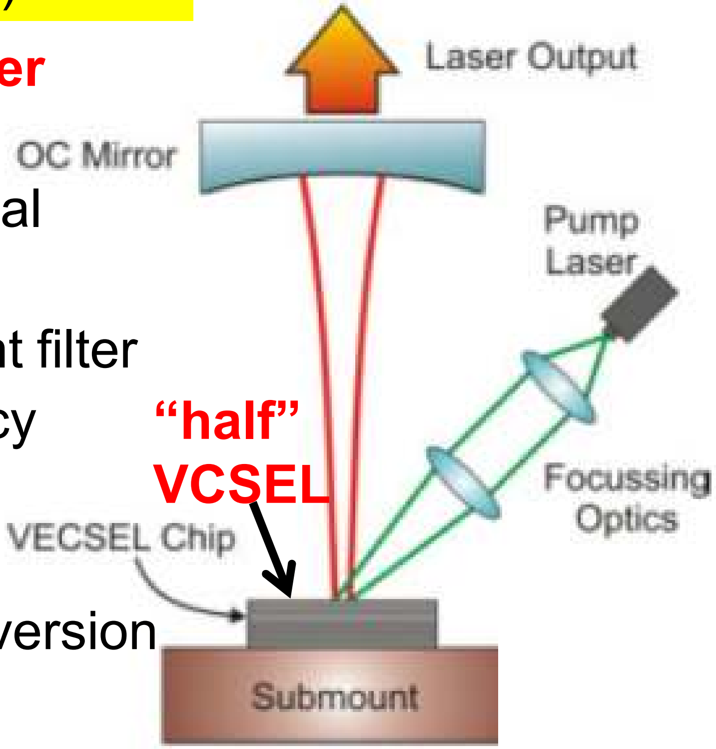
modulational instability, filamention, sometimes also
“small-scale self-focusing” (compared to “whole-beam self-focusing”)

- besides mode volume another driver for low beam quality in semiconductors

VECSEL: Marry advantages of

traditional (solid-state) lasers

- **Brightness converter**
  $M^2 < 1.1$
- space to put additional optical elements
  - etalon, birefringent filter
    → single-frequency tunability
  - nonlinear crystals
    → wavelength conversion
- power scalable
  (thin disk concept, A. Giesen, 1992)



semiconductor lasers

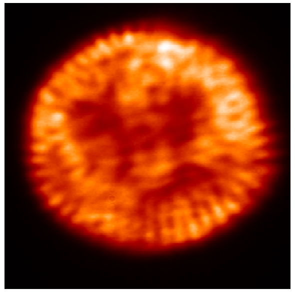
- broad wavelength coverage by bandgap engineering
- wafer scale processing
- lower noise
- record: 24 W with $M^2 =$ 1.5 out of 0.55 mm pump spot,
  Wang, IEEE PTL 22, 661 (2010)

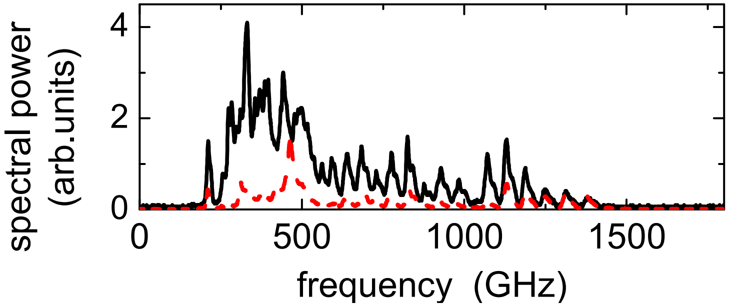
Drawbacks:
1. Less efficient
2. Not monolithic

- VECSEL = vertical-external-cavity surface-emitting laser
- OPSDL = optically pumped semiconductor disk laser

Intermediate summary

- broad-area, high power semiconductor lasers are great devices but suffer from **poor beam quality**
  - Large aperture, high Fresnel number → high order modes
  - nonlinear refractive index (amplitude-phase-coupling) → filamentation





- significant progress made by excellent engineering, but incremental (issues intrinsic to simple, monolithic design)

- but is there another, different approach to tame broad-area devices?
  - funnel instabilities in a **self-localized robust entity?** A **soliton?**
- Use as test bed for **fundamentals of self-organization and pattern formation**

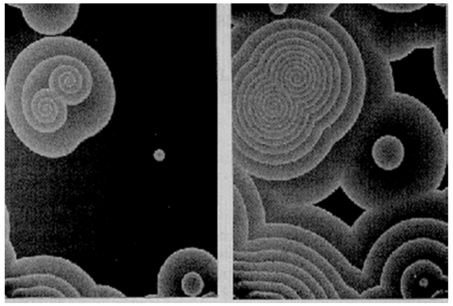
Self-organization and pattern formation

pattern formation is ubiqitious

chemistry

Koschmieder 1974

convection

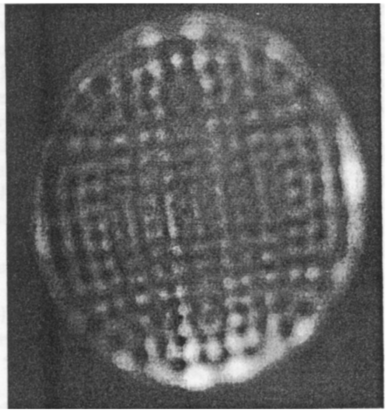


biology

Pomacanthus zonipectus
Kondo + Asai 1995

Many aspects are ***universal*** i.e. independent of specific nonlinearities and spatial coupling

want to avoid it?



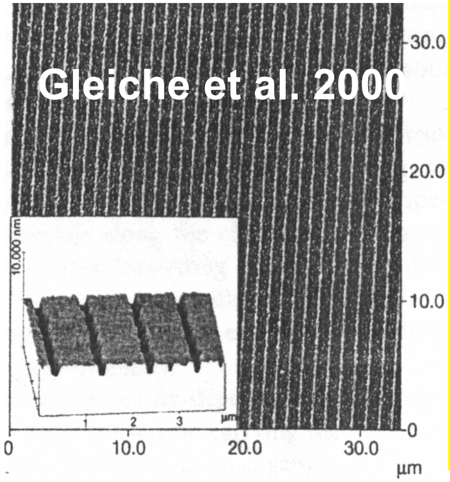
CO_2 laser

Dangoisse et al. 1992

want to apply it!

self-assembly

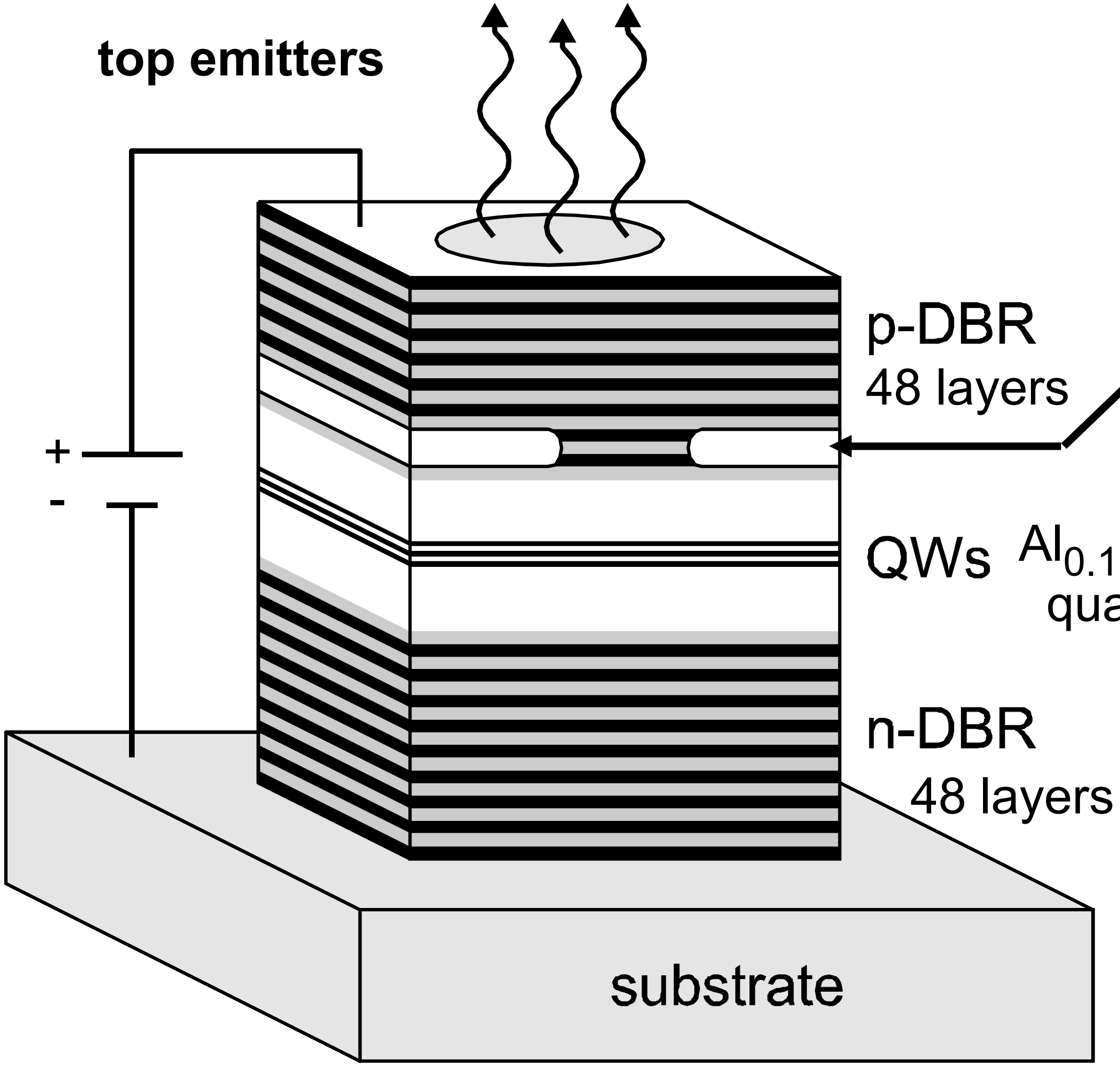
Langmuir-Blodgett film



Gleiche et al. 2000

Common feature: emergence of structures if system is driven far from equilibrium

Laser patterns and VCSEL: A closer look



Oxide aperture (Al_2O_3):

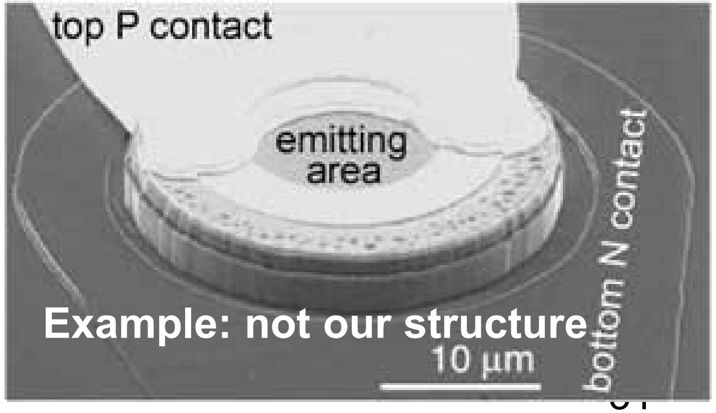
- ➢ current confinement
- ➢ **optical confinement**

  Δ n ≈ 3.6 -1.6 = 2

  (but only over 30 nm)
- ➢ here: square shape

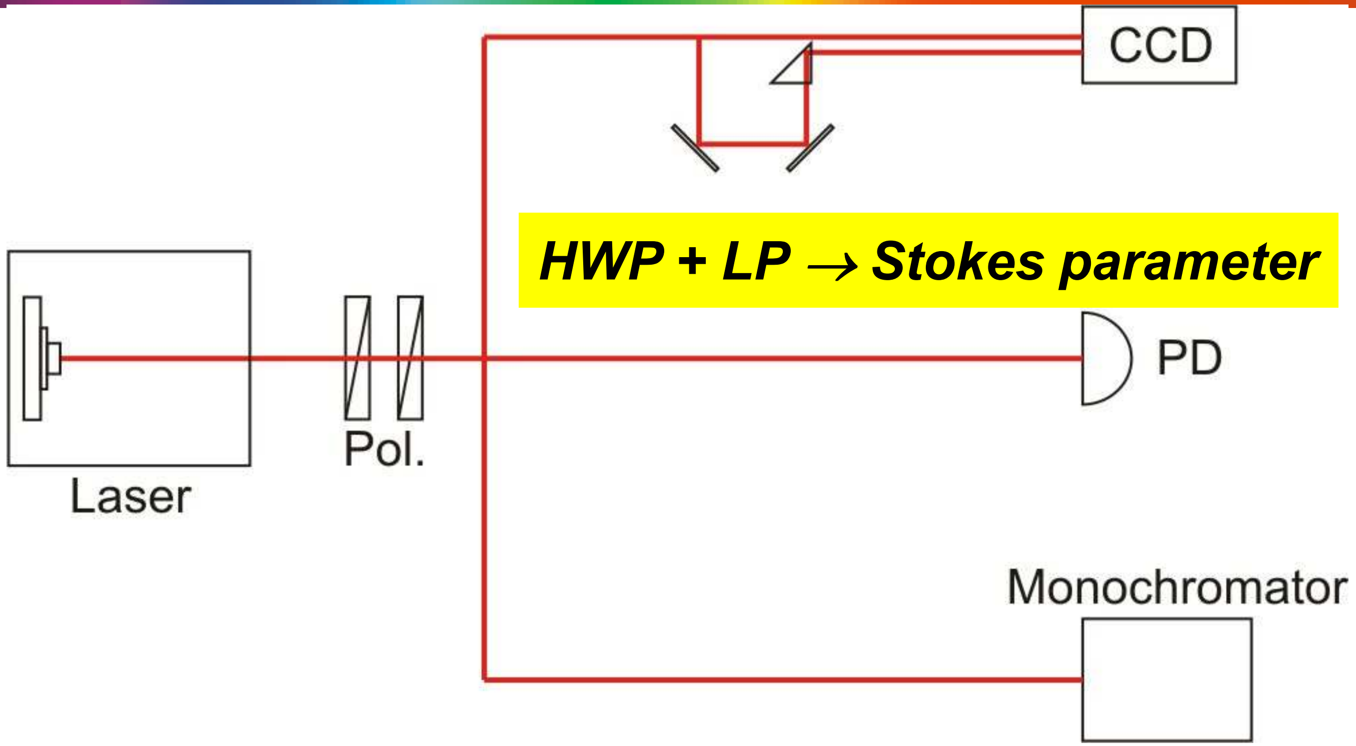
  30×30 and 40×40 μm

QWs $Al_{0.11}Ga_{0.89}As$/ $Al_{0.36}Ga_{0.64}As$ quantum wells ≈780 nm



Example: not our structure

Schematic setup



HWP + LP → Stokes parameter

Near field / far field

Output power

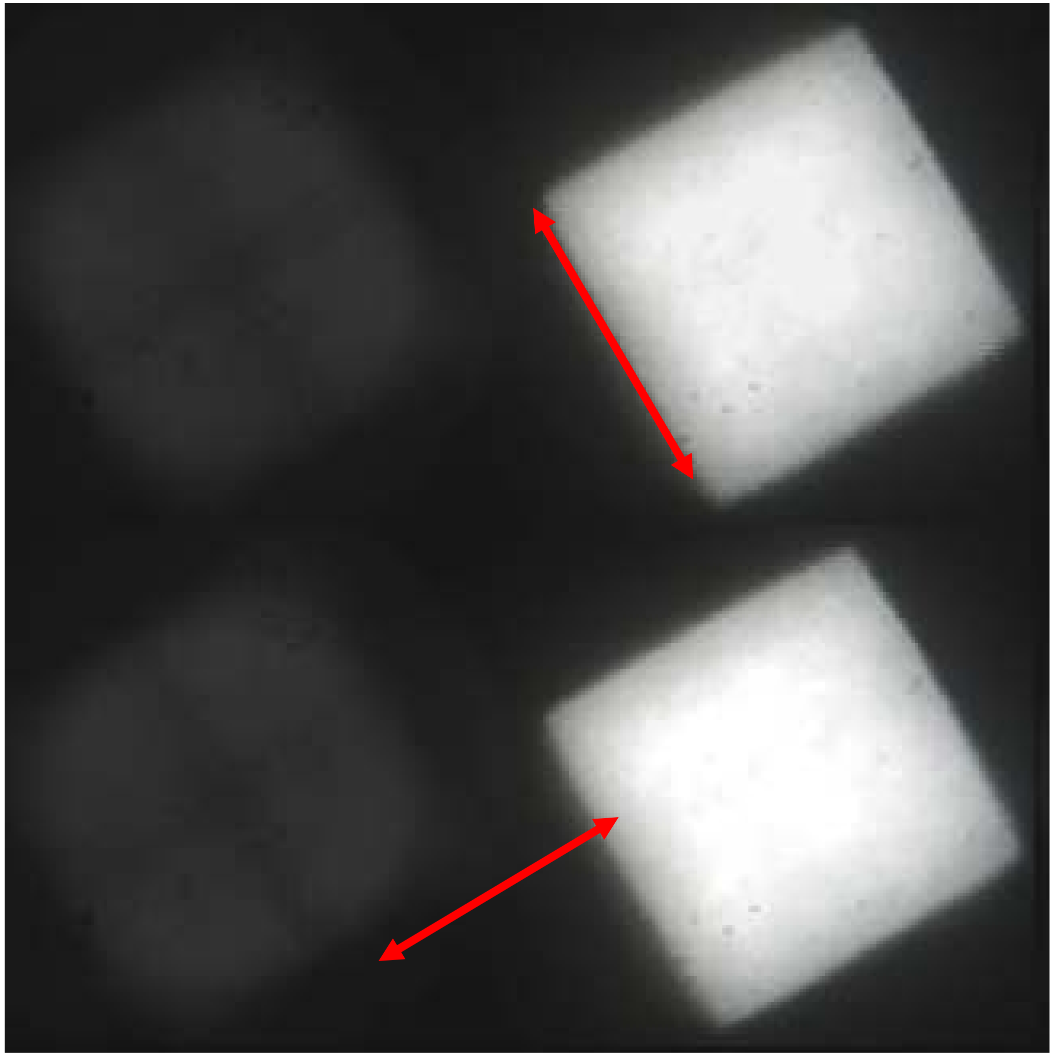
Spectra

- Laser put into air-tight box to avoid condensation water
- Temperature range at heat sink approx. 245-300K
- Spatially and wave number resolved Stokes parameters

Experiment: M. Schulz-Ruhtenberg (Muenster), TA Devices: K. F. Huang (National Chiao Tung University, Hsinchu, Taiwan)

Basic results vs. current

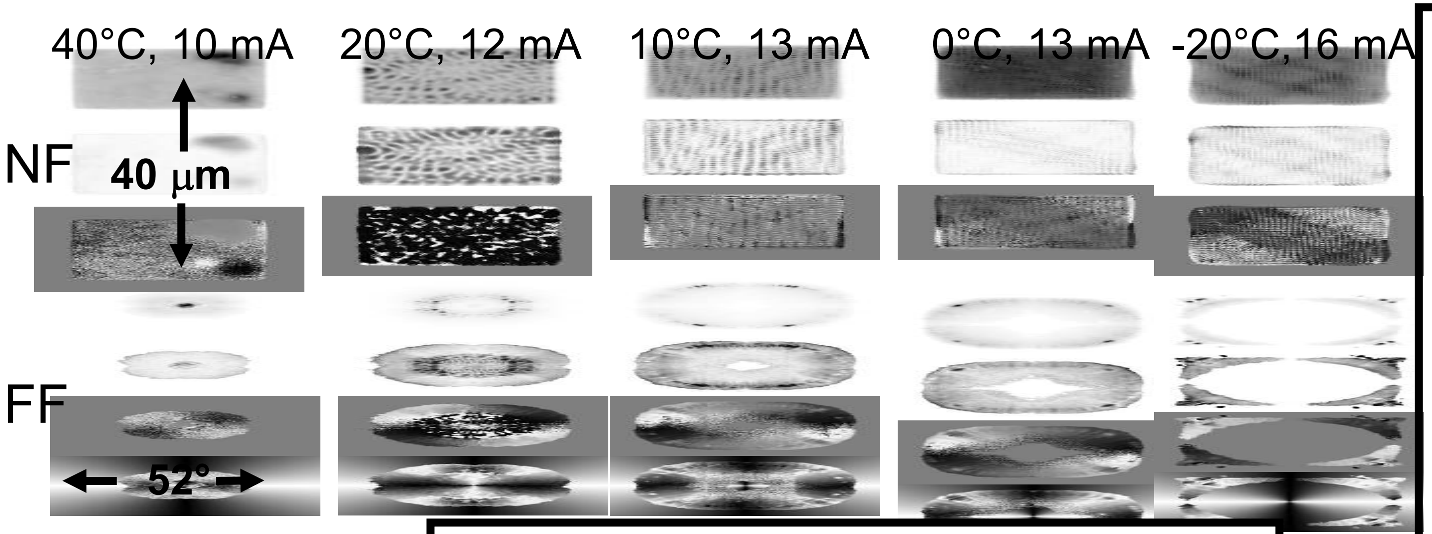
Far field Near field



- **off-axis wavevectors**
  - initially **ring** with **symmetry breaking**
  - then **broadening**
  - finally shift
- polarization „in tendency“ **orthogonal to wavevector**
- **coupling of *spatial* and *polarization* degrees of freedom**
- first observation: Cork group Hegarty et al., PRL 82, 1434 (1999)

Unpublished, see also
Babushkin et al., PRL **100**, 213901 (2008);
Schulz-Ruhtenberg et al. APB **81**, 945 (2005)

Temperature dependence: Structures



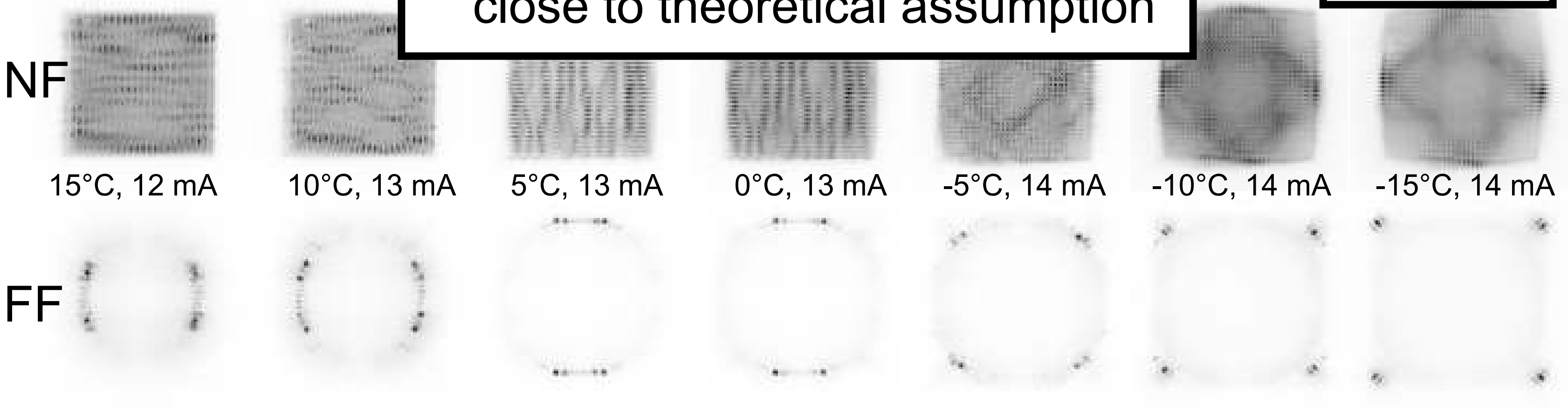
decreasing tem

increasing detu … nce

- ➢ very high order modes
- ➢ close to Fourier modes, i.e. close to theoretical assumption

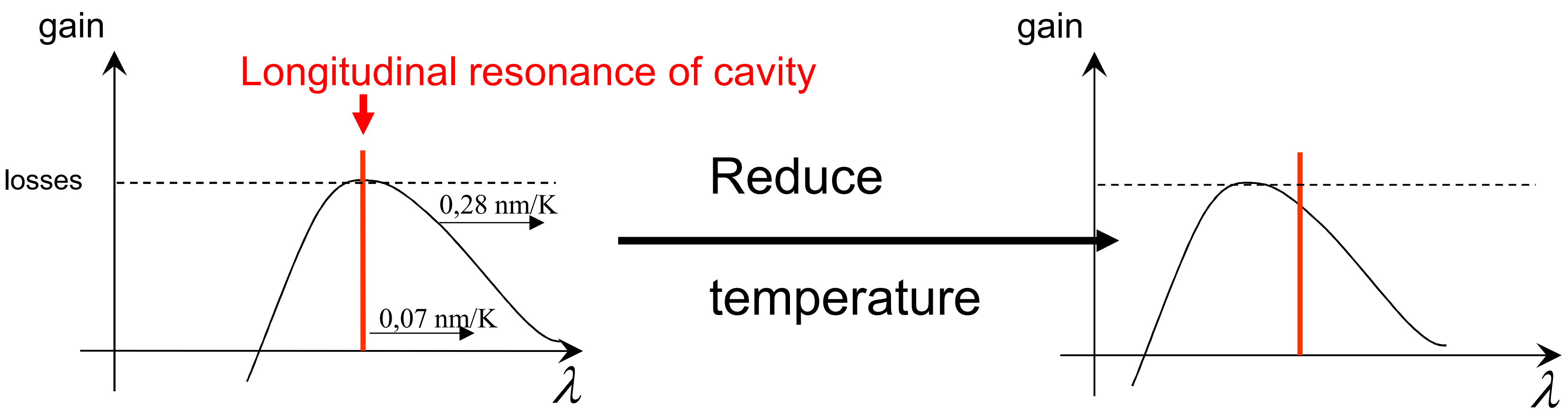
FF
on-axis
↓
off-axis
↓
off-axis on diagonal

NF
„spot“
↓
„stripes“
„waves“
↓
localized waves



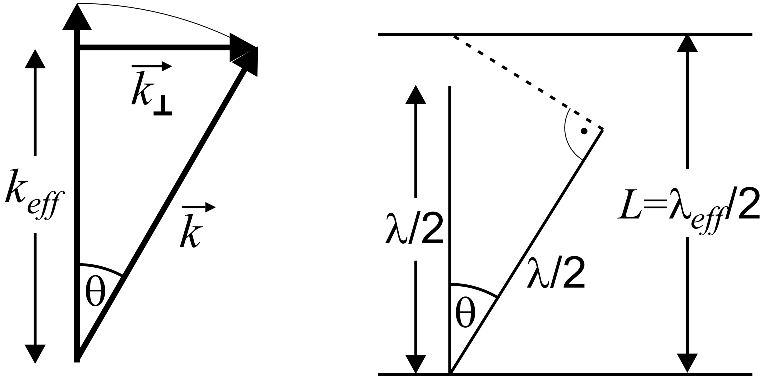
appears in several devices

Selection of wavenumber



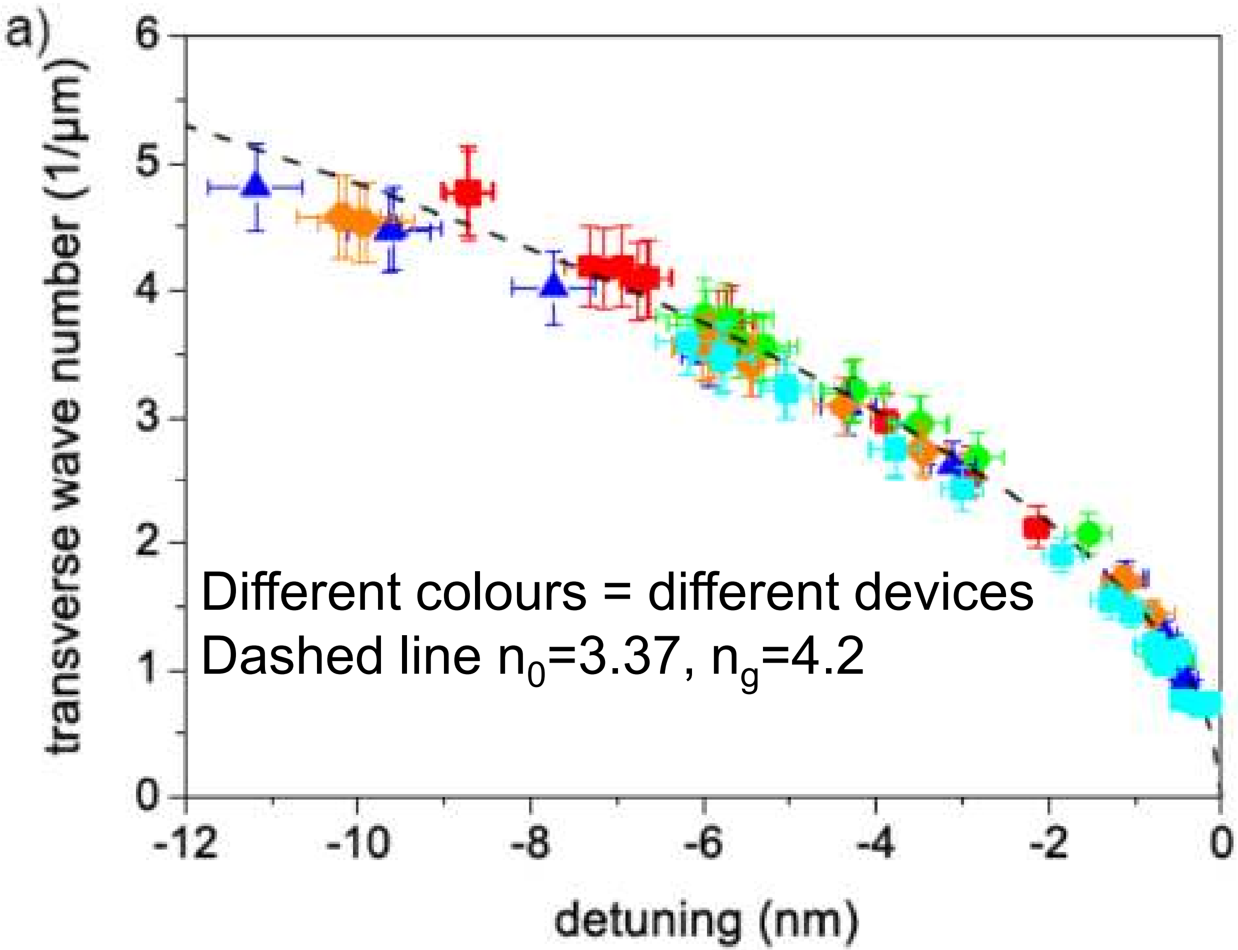
- Gain maximum = preferred emission wavelength shorter than resonance
- Laser can reestablish resonance by **tilting** emission

$$
\begin{aligned}
2\pi m &= k_{eff}2L = k\cos\theta \\
&= k2L - k2L\tfrac{1}{2}\theta^2 \\
&= k2L - k2L\,\frac{1}{2}\left(\frac{k_\perp}{k}\right)^2 \\
&= k2L - 2L\frac{k_\perp^2}{2k}
\end{aligned}
$$



- tilt angle increases with detuning

Wavenumber: Quantitatively



Different colours = different devices
Dashed line n_0=3.37, n_g=4.2

$$q = \sqrt{8\pi^2 n_0 n_g \frac{\lambda_0 - \lambda}{\lambda_0^3}}$$

- ➢ good agreement
- ➢ these are essentially Fourier modes
- ➢ nothing mysterious: resonances of a plano-planar Fabry Perot in divergent light

Schulz-Ruhtenberg et al. APB **81**, 945 (2005)

Pattern selection

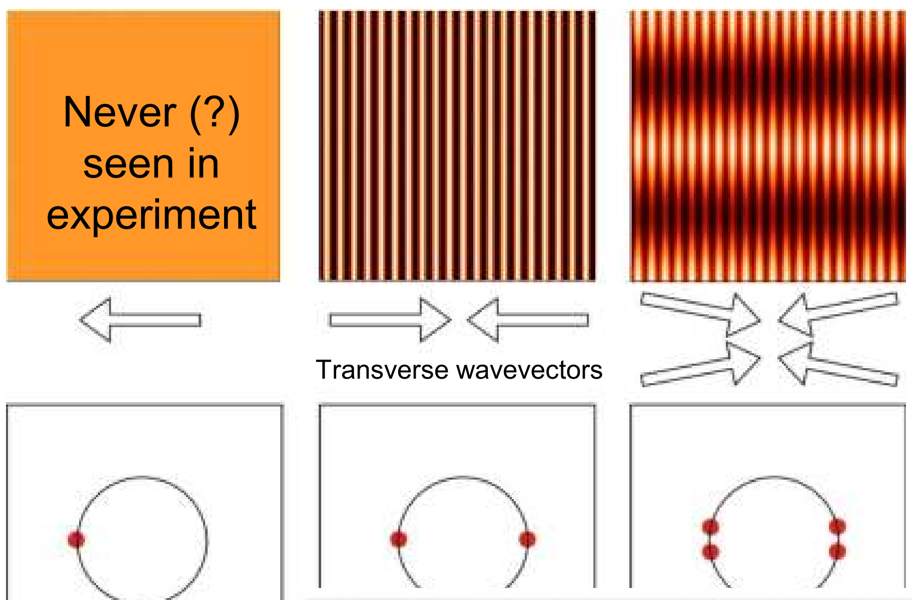
The linear resonance argument explains the wavenumber but not the symmetry

→ ***nonlinear pattern selection***

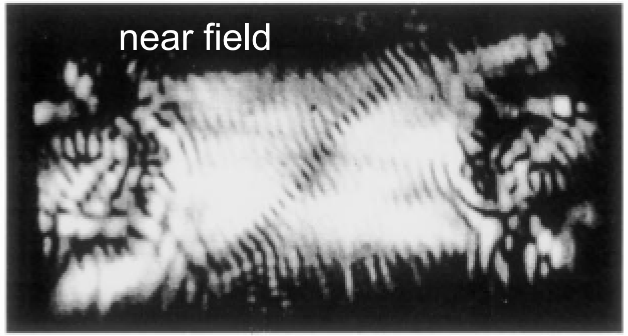
Nonlinear theory for infinite two-level laser
(Jakobsen et al. PRA 49, 4189, 1992)

→ **One** wavevector, **traveling wave**

Coordinate space (near-field)



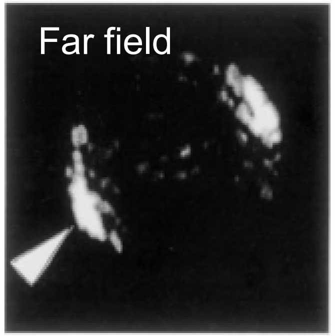
Fou



Possible in
Staliunas et al., PRL **79**, 2658 (1997)
Domains of traveling waves

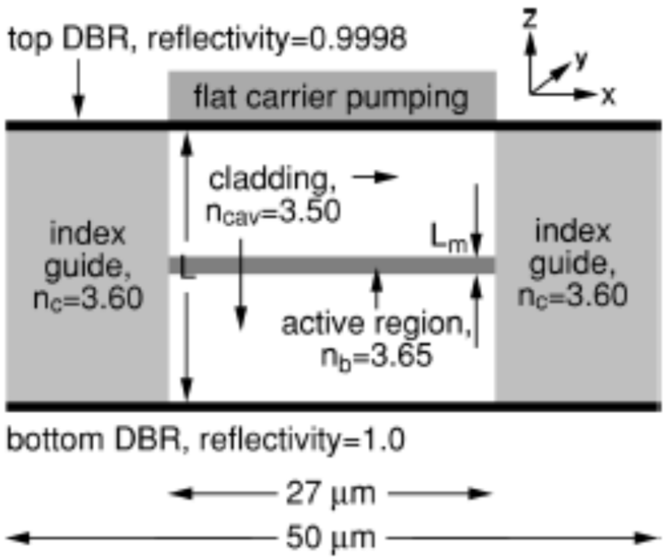
- Excitation of additional wave vector due to
  - secondary bifurcation
  - **reflection at boundaries**
- extreme position: K. F. Huang

(e)



s
n

Modelling



- ➢ Smear the 30 nm oxide out over cavity length
- ➢ Transverse waveguide
- ➢ Effective index method
- ➢ Δ n $\approx$ 2 $\rightarrow$ Δ n $\approx$ 0.01-0.03

$$\dot{E} = \frac{ic^2}{2\omega_c n_b n_g}\nabla_\perp^2 E - \kappa E + \xcancel{\frac{i\omega_c}{2\epsilon_0 n_b n_g}\beta\frac{L_m}{L}P}$$
$$+\frac{i\omega_c}{n_g}\left[\Delta n_b(x,y) + \xcancel{\frac{\partial n_b}{\partial T_j}(T_j - T_0)}\right]E.$$

Roessler et al., PRA 58, 3279 (1998) (Tuscon);
similar I. Babushkin, N. Loiko (Minsk), S. Balle (Palma)

Assume stationary state, gain balances losses, operating at resonance

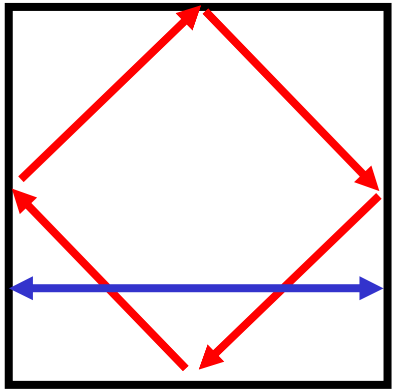
$\rightarrow$ Schroedinger/Helmholtz equation

For Δ n $\rightarrow \infty$ $\rightarrow$ hard boundaries, **2D (transverse) wave (quantum) billiard**

Wave and quantum billiards

Integrable billiards:

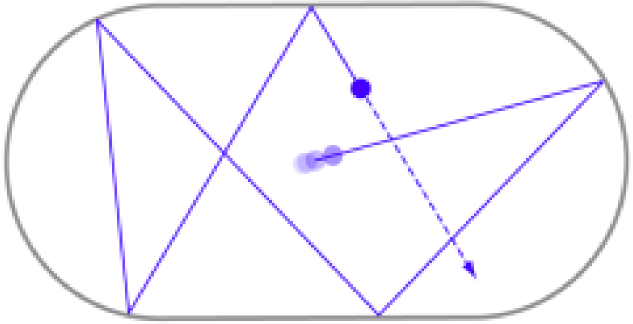
Closed periodic orbits



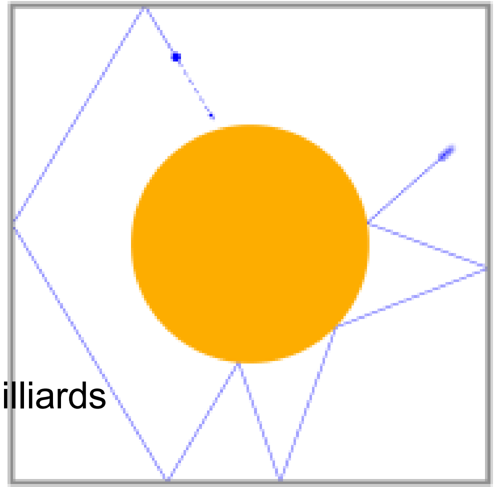
Chaotic billiards:

Periodic orbits
unstable, ergodocity

Bunimovich billiard



Sinai billiard



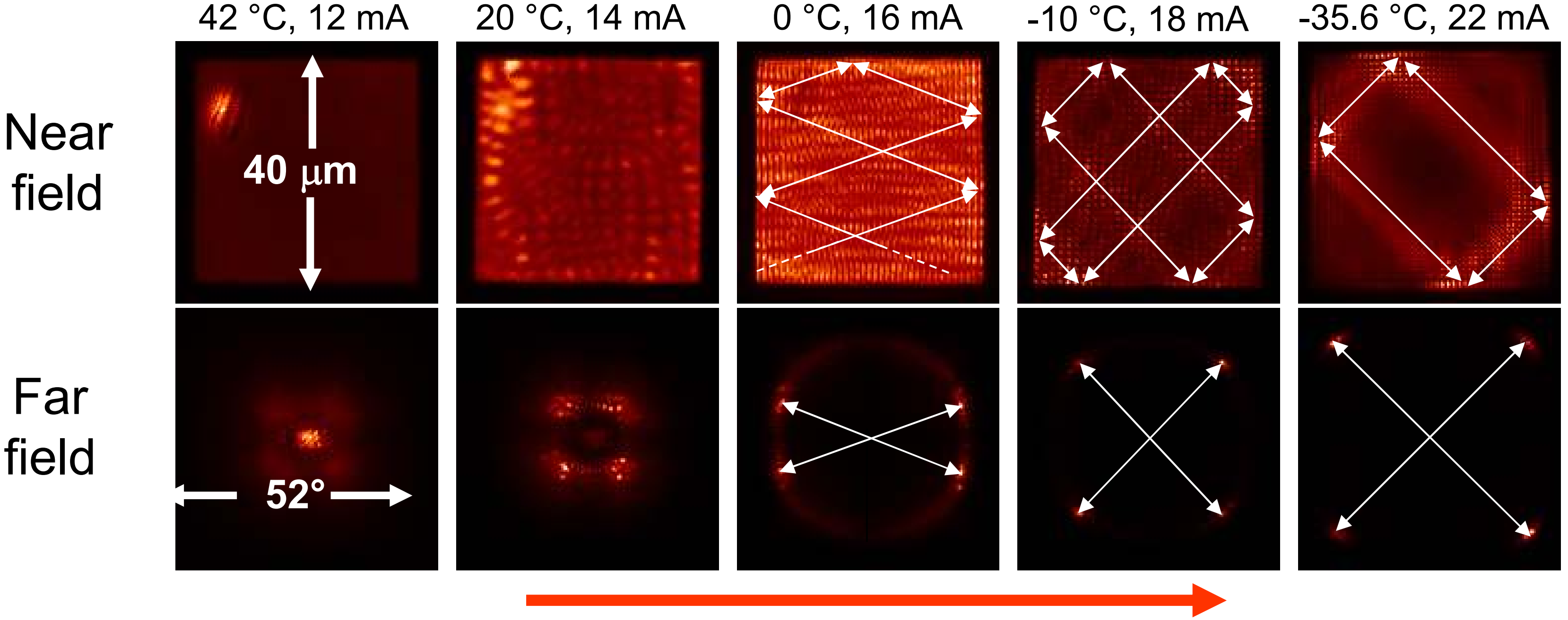
http://en.wikipedia.org/wiki/Dynamical_billiards

What happens after ***quantization***?

→ **Quantum or wave billiards**

Note: Quantum theory is linear and hence not chaotic →
what's fingerprint of chaos in quantum systems? → **quantum chaos**

Motivation: broad-area devices

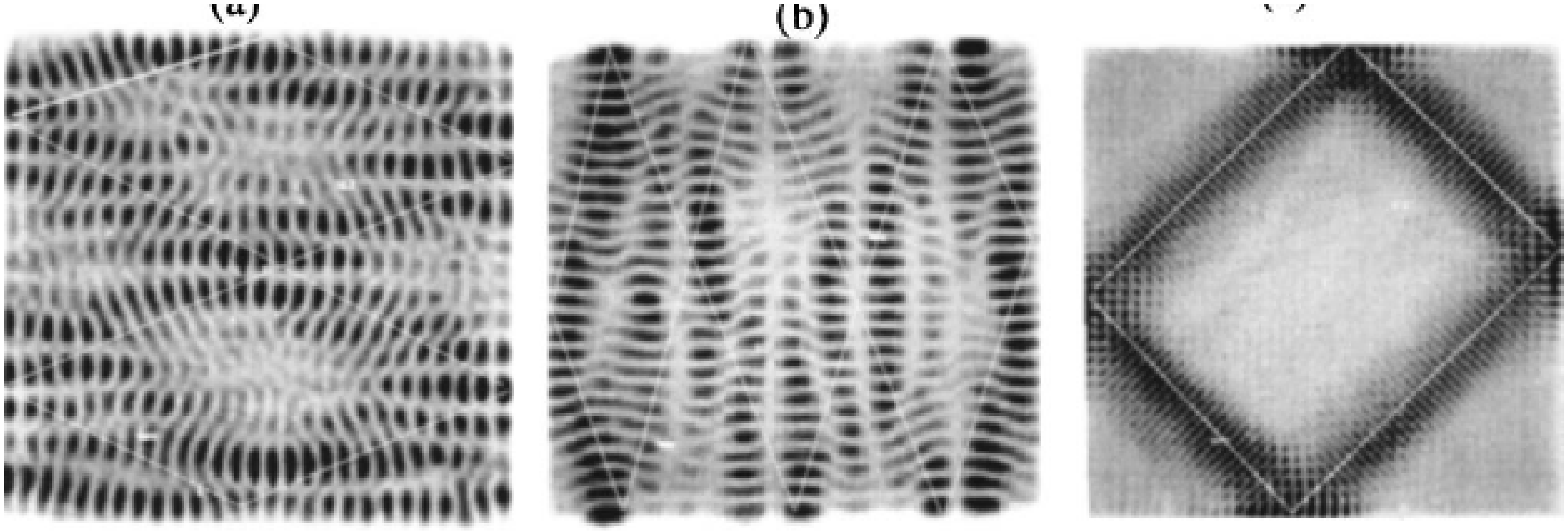


decreasing temperature ➔ increasing transverse wavenumber

- **Increasing mode-order, decreasing transverse wavelength**
- Quantum systems become **classical in the limit of low wavelengths**
- Wave functions seem to ***localize* along classical trajectories**
- You would not think that a laser wants to do this, because it does ***not*** fully use inversion then

Hegarty et al., PRL **82**, 1434 (1999); Huang et al. , PRL **89,** 224102 (2002); Chen et al. PRL **90**, 053904 (2003)

Quantum/wave billiard (Taiwan data)



- Localization along closed classical ray
- Note: we are dealing with the transverse part of the wavevector
- opposite to most billiard microcavity systems, you can actually observe the mode distribution

Huang et al. PRL 89, 224102 (2002); PRE 66, 046215 (2002); PRE 68, 026210 (2003)

Interpretation as coherent states

SU(2) representation of coherent states

$$\Psi^{p,q}_{N,M}(x,y;A,\phi)=\frac{(2/a)}{\left[\sum_{K=K_0-J}^{K_0+J} C^N_K A^{2K}\sin^2(K\phi)\right]^{1/2}}$$

$$\times\sum_{K=K_0-J}^{K_0+J}\sqrt{C^N_K}A^K\sin(K\phi)$$

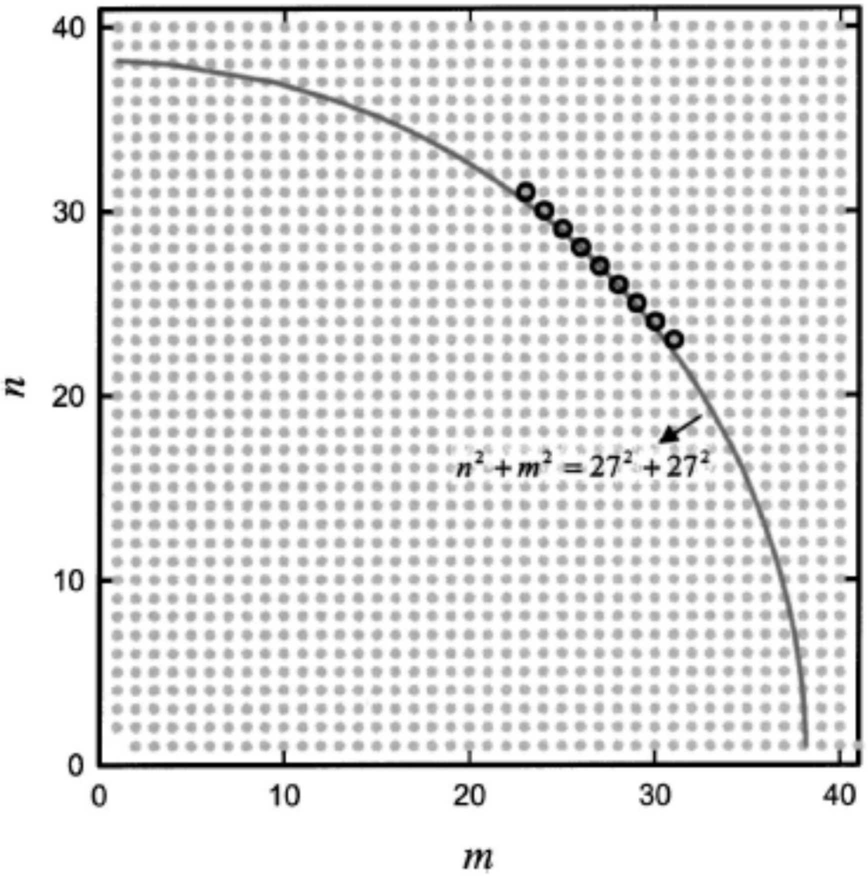
$$\times\sin\left[p(K+1)\frac{\pi x}{a}\right]$$

$$\times\sin\left[q(N-K+1)\frac{\pi y}{a}\right],$$

M=2J+1
number of
modes

Purely phenomenologically

Superposition of nearly degenerate Fourier modes

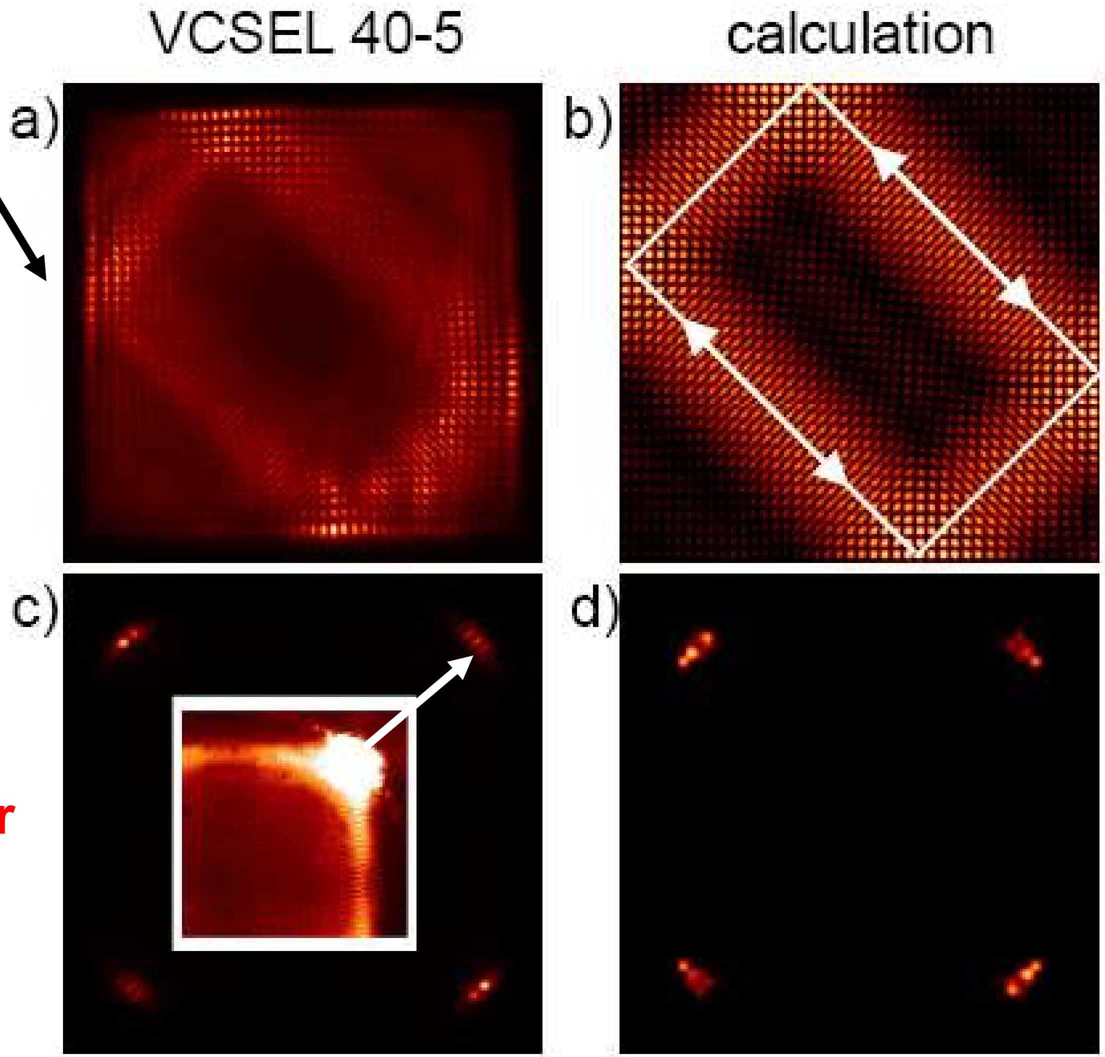


Huang et al. PRL 89, 224102 (2002); PRE 66, 046215 (2002); PRE 68, 026210 (2003)

Reconstruction

$K_0 = 80$, $M = 7$, $\phi = 0.63\ \pi$

Determines location at boundary



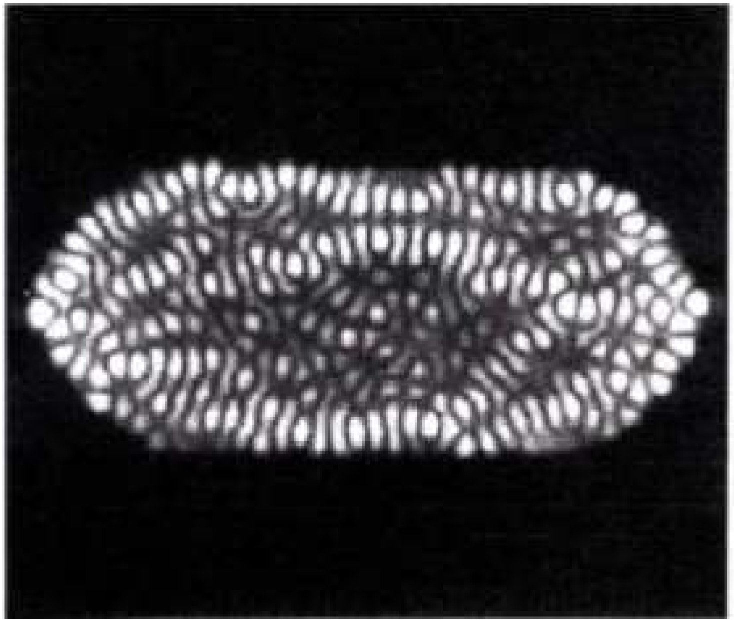
- ➢ phenomenologically!
- ➢ *A laser does not like not to use the available inversion!*
- ➢ Hence localization counterintuitive!
- ➢ only argument:

quantum states at high order / low wavelength become more classical

Schulz-Ruhtenberg, PhD thesis (2008) following PRE 68, 026210 (2003)

Some fun stuff

stadion



Huang et al. PRL 89, 224102 (2002)

triangle

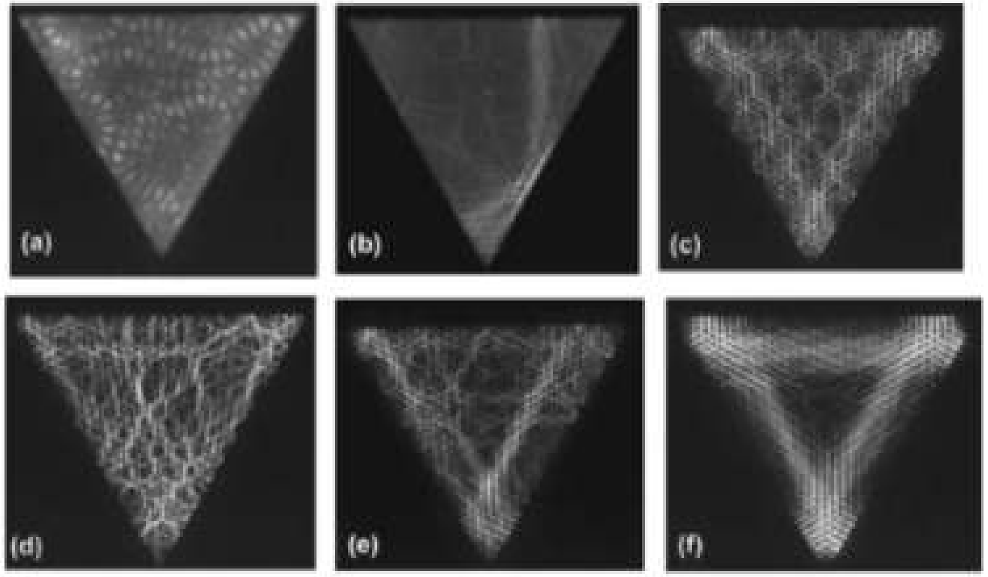
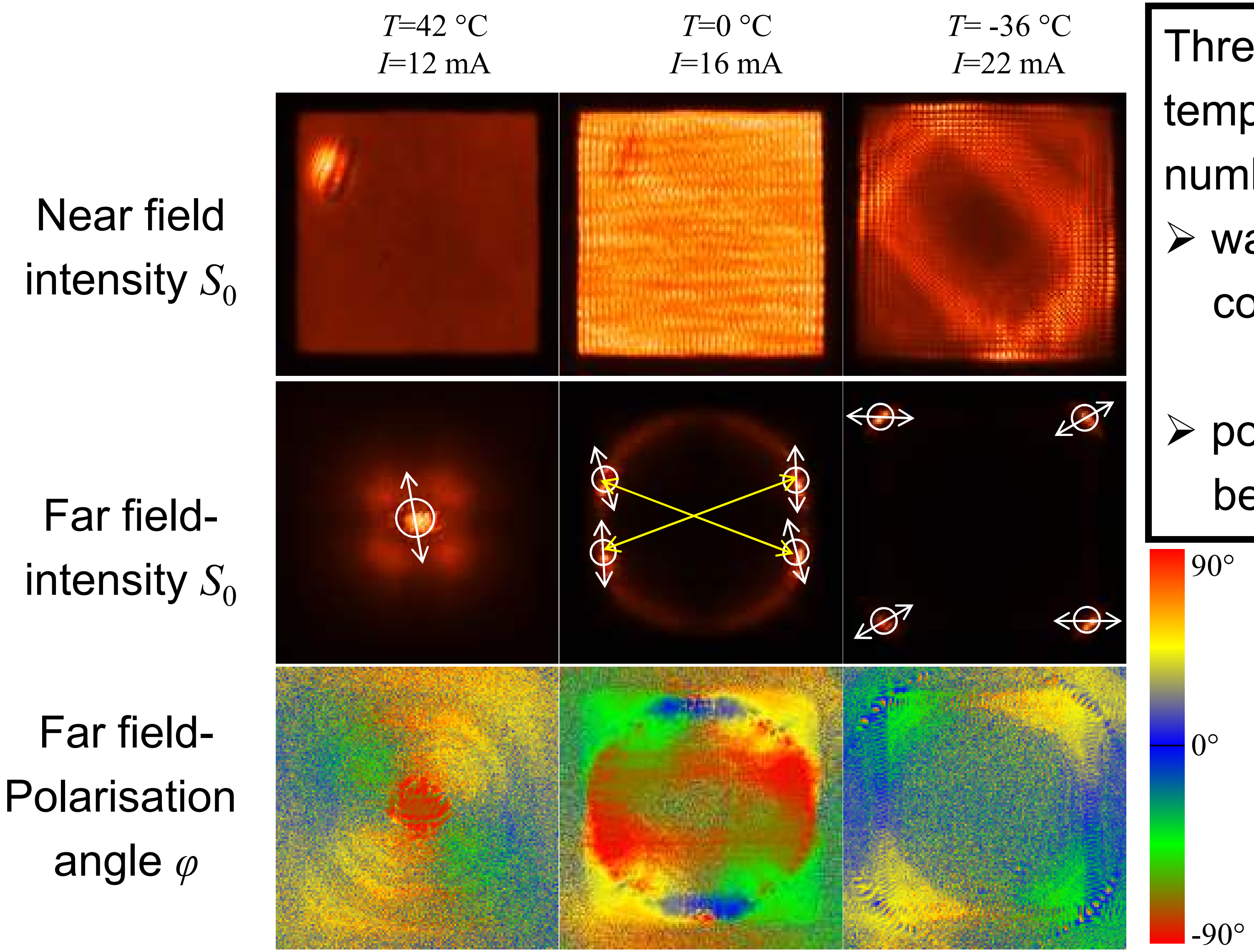


Fig. 2. Intensity patterns of transerse near-field patterns at temperatures of (a) 295 (room temperature), (b) 275, (c) 195, (d) 175, (e) 155, and (f) 125 K.

Chen et al., Opt. Lett. 33, 509 (2008)

Polarization: Principal observation



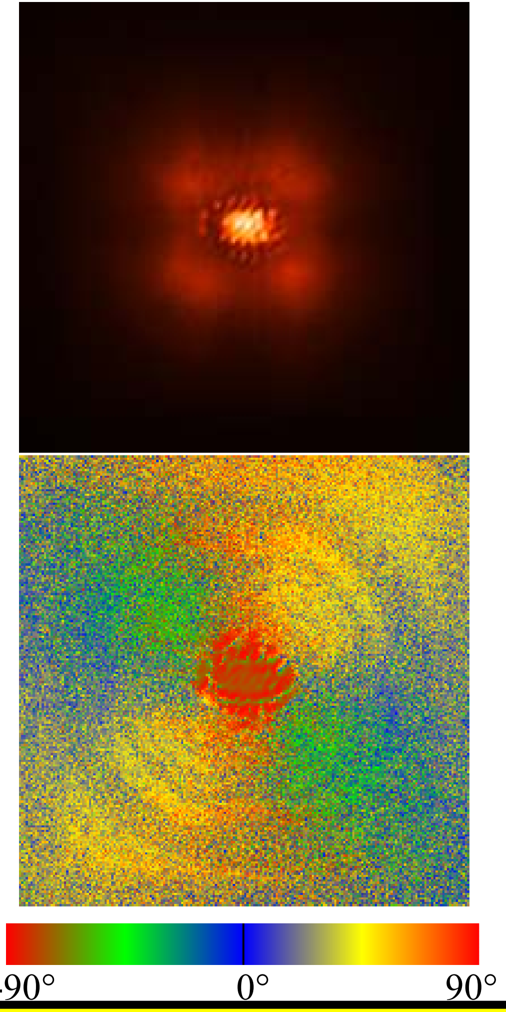
Three regimes in temperature / wave number with distinct

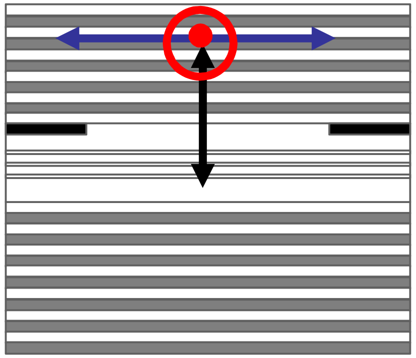
- ➢ wave vector configuration
- ➢ polarization behaviour

On-axis / small wave numbers

Far field

T=42 °C
I=12 mA





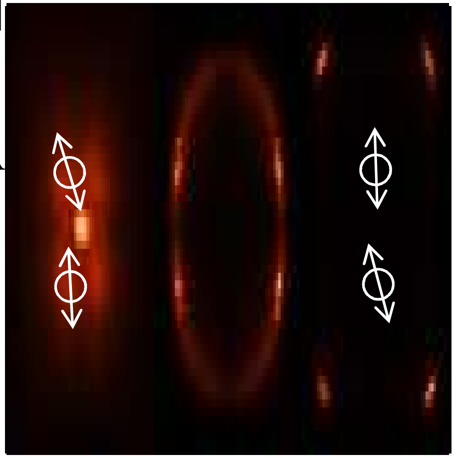
- VCSEL quasi isotropic for on-axis radiation
- No difference between s- and p-waves
- Situation essentially like in small-area lasers

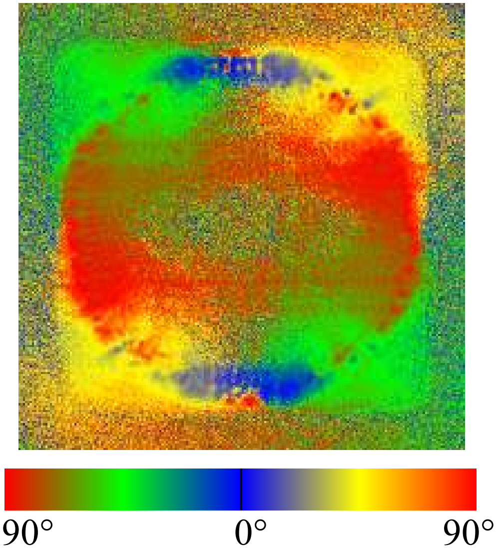
Polarization determined by uncontrolled material anisotropies

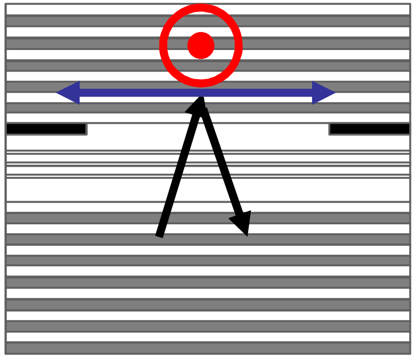
Intermediate wave numbers

Far field

T=0 °C
I=16 mA

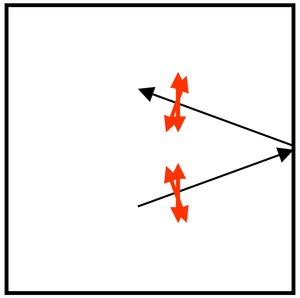






Anisotropic reflection:
s-wave favoured
→ Higher Q
Babushkin et al., J. Opt. B **3**, S100, 2001

➔polarisation orthogonal to wave vector ("90°-rule")

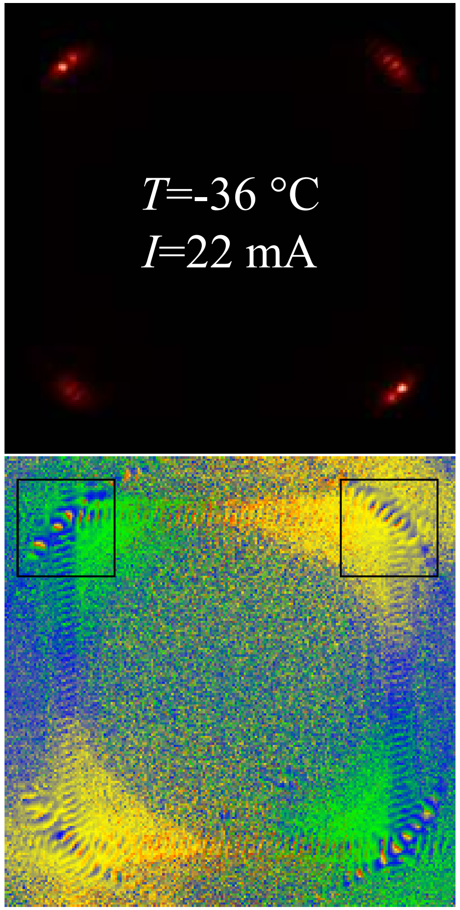


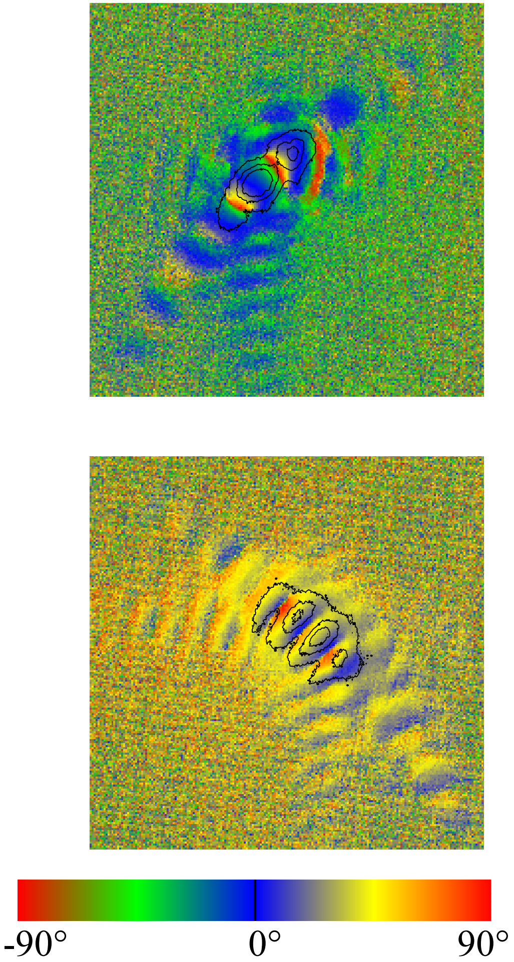
But: reflection at oxide aperture couples polarization of beam in ***linear order***;
Waveguide modes should have ***homogenous polarization***

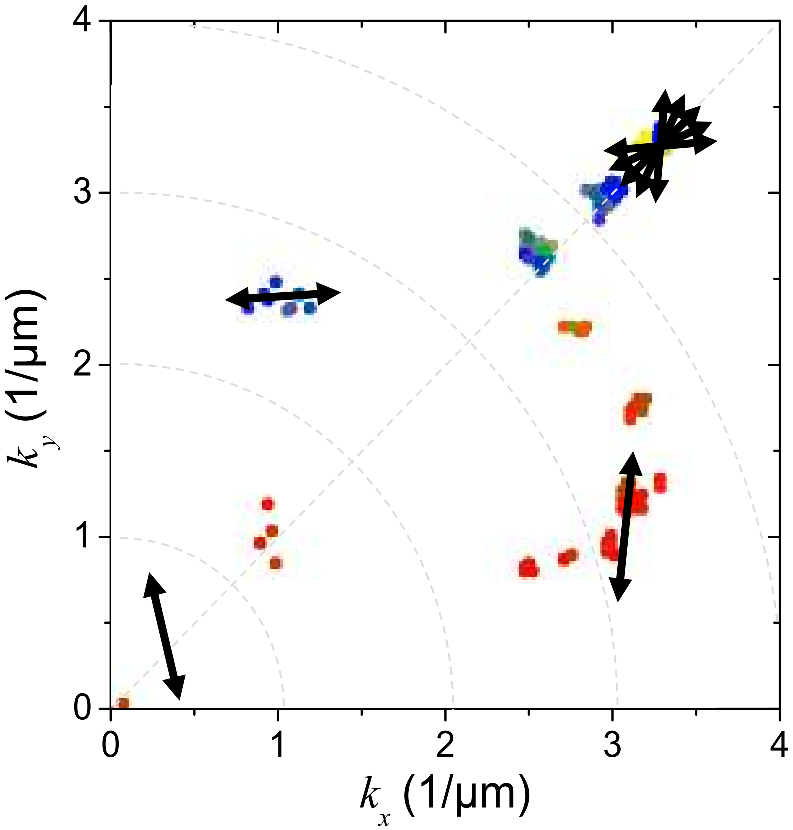
➔Polarisation in tendency parallel to boundary closest to 90°-rule

High wave numbers

Far field







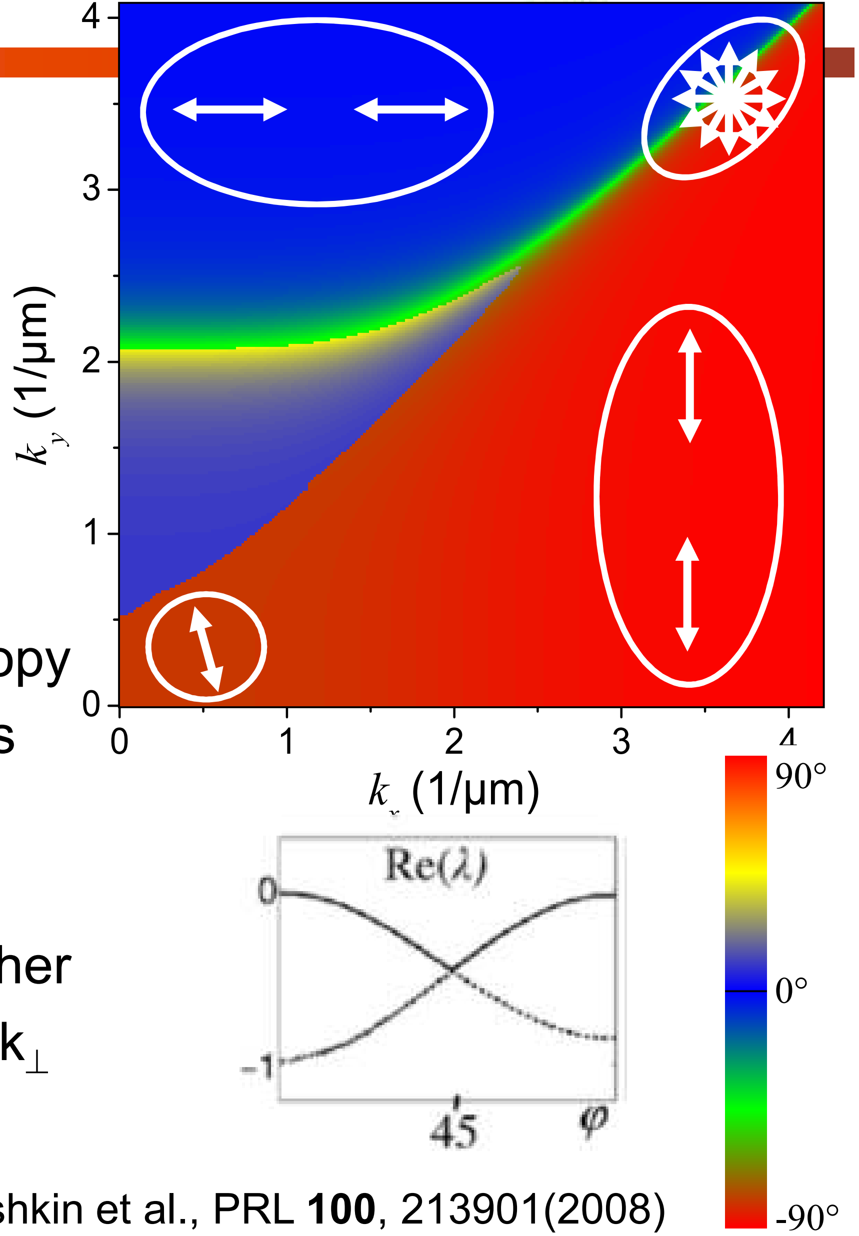
➔ Complex polarisation distribution → indication for degeneracy

Theoretical interpretation

- VCSEL at threshold (linearized eq.)
  - considers anisotropy of DBR
  - polarization of waveguide modes
  - material anisotropies put in by hand

Results for intra-cavity polarization:

- polarization at $k_\perp \approx 0$ from material anisotropy
- polarization at intermediate wave numbers determined by waveguide
- selects the one better fitted to 90°-rule
- non-matching components scattered to other wave numbers $\rightarrow$ justification for multiple $k_\perp$ and coherent states !?
- degeneracy at diagonal

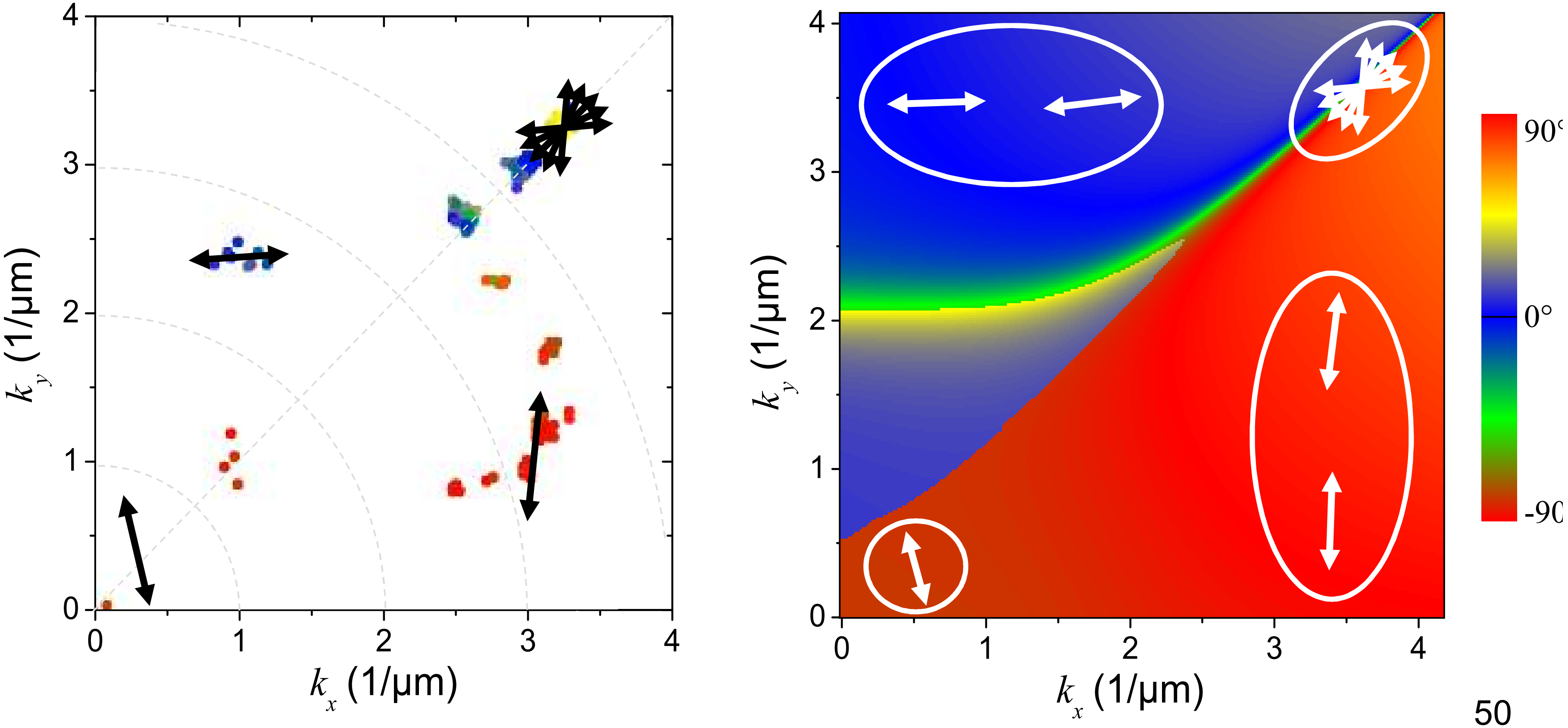


Babushkin et al., PRL **100**, 213901(2008)

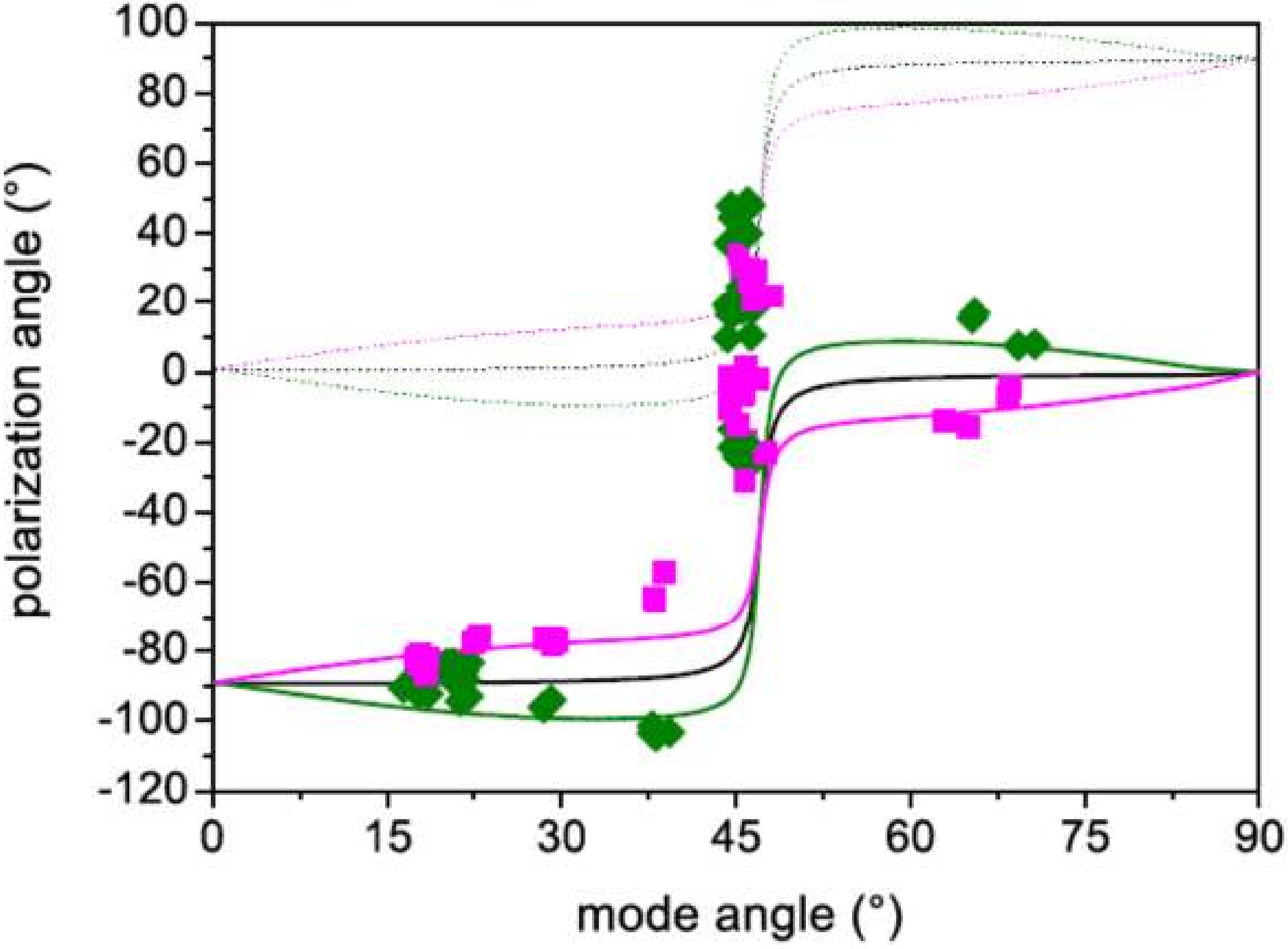
Extra-cavity polarization

In transmission: p-waves favoured → **polarization rotates towards wave vecto**

extra-cavity polarisation inhomogeneous within one mode



Detailed comparison: Extra-cavity



Lines:

Prediction

Points:

experiment

Summary: Laser patterns

- VCSELs show at and not too far beyond threshold patterns consisting of just a few Fourier modes
- The theoreticians love that!
- (some) edge-emitters do that actually also
- Interaction with device boundaries plays a strong role though
- Possibility to investigate quantum billiards
- Outlook:
    - Quantitative understanding of beyond threshold dynamics (daunting in semiconductor laser due to spread of time scales from 100 fs to ms)
    - Polarization
    - Quantum effects (correlations between beams etc.)
- Unfortunately, up to now no feedback into device design