Broad-area lasers, laser solitons and patterns in optics

Part I: Broad-area lasers

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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 Entrepreneurial 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
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
World-wide OSA student chapters

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

North America 100+
South America 25+
Europe 75+
Middle East/ Africa 15+
Asia & Oceania 90+

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

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
Eigen modes of resonators

Parameter: \( g_i = 1 - L / R_i \) for mirrors \( i=1,2 \)

Typical laser resonators (solid-state, gas, semiconductor disk laser)
Refocusing by curved mirrors \( \rightarrow \) stable resonator

Eigen mode: "Gaussian beam"

Propagation and diffraction

Diffractive spreading

\[ w(z) = w_0 \sqrt{1 + \left( \frac{z}{z_R} \right)^2} \quad \text{as } z \to \pm \infty \quad w_0 \cdot \frac{1}{z_R} \cdot z \]

Rayleigh Length \[ z_R = \frac{\pi w_0^2}{\lambda} \]
linear for large \( z \)

Diffraction angle:

\[ \Theta_{\text{div}} = \frac{\lambda}{\pi w_0} \]

Beam waist \( w_0 \)

Light in this cone is spatially coherent

Stability diagram

Solution only for \(0 < g_1g_2 < 1\)

\[
w_0^2 = \frac{L\lambda}{\pi} \sqrt{\frac{g_1g_2(1-g_1g_2)}{(g_1+g_2-2g_1g_2)^2}}
\]

\(w_0 \rightarrow \infty\)

\(w_0 \rightarrow 0\)

Important design tool

Source: Siegman, Lasers (1986)
High order spatial modes

Hermite-Gaussian Mode

\[ u_{mn}(x, y, z) \sim \frac{1}{w(z)} e^{i\psi(z)} \exp \left[ -\frac{x^2 + y^2}{w^2(z)} - i\kappa \frac{x^2 + y^2}{2R(z)} \right] \cdot e^{i(m+n)\psi(z)} H_m \left( \frac{\sqrt{2}x}{w(z)} \right) \cdot H_n \left( \frac{\sqrt{2}y}{w(z)} \right) \]

Field

Modal size \( x_m/w_0 \)

Transverse size:
\[ w_{\text{eff}} \approx \sqrt{n} \cdot w_0 \]

Source: Siegman, Lasers (1986)

Intensity

Mode order m
For the quality of a laser beam not only initial size $w_0$, but also the divergence $\Theta$ is important!

Divergence of high order modes $\sim \sqrt{m} \Theta_0$

**Brightness** $B = \frac{\text{power}}{(\text{mode area} \times \text{emission angle})}$

$= \frac{P}{(\pi w_0^2 \times \pi \Theta^2)}$  \[\text{W cm}^{-2} \text{ str}^{-1}\]

Relevance for applications

(micromachining, medical, nonlinear optics …)

*Focused spot size $\sim \Theta f$; 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!)*
M²-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/e²)

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

Half divergence angle (1/e²)

- for fundamental, TEM₀₀₀ mode
  \( \Theta_0 = \frac{\lambda}{\pi w_0} \)
  \( \rightarrow M^2 = 1 \)

- for high-order, TEMₘ₀₀ mode
  apparent size ~ \( \sqrt{m} w_0 \)
  divergence ~ \( \sqrt{m} \Theta_0 \)
  \( \rightarrow M^2 \approx m \)
  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

\[ L = d_2 - d_1 \]
Schematics of a semiconductor laser

Inversion possible, if external voltage > band edge

Vertical waveguide < 0.5 µm core

Active layers quantum wells ~ 10 nm

Easy to drive: some V!

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

<table>
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<th>Specification for engineering samples</th>
<th>DATE: 10th Jun. 2008</th>
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</table>

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

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<tr>
<th>Parameters</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
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<td></td>
<td>W</td>
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<td>Central wavelength</td>
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<td>Wavelength temperature tunability</td>
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<td>nm/°C</td>
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<td>Spectral width (FWHM)</td>
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<td></td>
<td>nm</td>
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<td>Operating current</td>
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<td>A</td>
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<td>Threshold current</td>
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<td></td>
<td>A</td>
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<tr>
<td>Forward voltage</td>
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<td>1.5</td>
<td></td>
<td>V</td>
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<td>Aperture size</td>
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<td>μm²</td>
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<td>Divergence parallel to p-n junction (FWHM)</td>
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<td>13</td>
<td>Deg.</td>
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<tr>
<td>Divergence perpendicular to p-n junction (FWHM)</td>
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<td>37</td>
<td>40</td>
<td>Deg.</td>
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Best lasers
- 980 nm
- 11 W out of 90 μm stripes
- $M^2 \approx 20$

$M^2 \approx 30-40$
Two types of semiconductor lasers

- **edge – emitting (conventional)**
  - direction of emission *orthogonal* to epitaxial growth
  - elliptical beam
  - macroscopic cavity length
  - large gain

- **surface – emitting VCSEL = vertical-cavity surface emitting laser**
  - direction of emission *parallel* to epitaxial growth
  - *circular* beam
  - superior fiber coupling
  - short, small
  - single longitudinal mode

VCSEL = vertical-cavity surface emitting laser
Vertical-cavity surface-emitting lasers

- short-haul data-communication (LAN, Ethernet etc.)
- optical mice

- single-mode long-wavelength VCSELs in development for telecommunications

25Gbps, BTB, PRBS $2^{23}-1$

But: very short $\rightarrow$ low gain

single mode power limited to 0.5 - 2 mW

$\rightarrow$ Make devices wider than 2-3 $\mu$m!
Very large area devices ("commercial")

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 exemplary 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
  \[\rightarrow \text{high-order modes will overlap with gain distribution}\]
- 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
  \[\rightarrow \text{more gain for high order modes}\]
- **nonlinear refractive index** \[\rightarrow \text{filamentation (next slides)}\]
- in real devices augmented by a lot of other effects, in particular **thermal lensing**
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 $\alpha$-factor

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

$n$ decreases with increasing $N$

$N$ decreases with increasing intensity

$n$ increases with increasing intensity

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

light is attracted to high $n$

self-focusing nonlinearity
Self-focusing

Kerr medium

\[ n = n_0 + n_2 |E|^2 \]
\[ = n_0 + n_2 I \]

in an inhomogeneous beam, e.g. a Gaussian
\[ \rightarrow \text{transversally inhomogenous refractive index} \]

- an **optically induced lens**
- \( n_2 > 0 \rightarrow \text{self-focusing} \)
- \( n_2 < 0 \rightarrow \text{self-defocusing} \)
Modulational instability

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

\[ \chi^{(3)} \]
\[ n_2 > 0 \]

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

local increase of intensity

self-focusing

positive feedback → break-up of beam

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

besides mode volume another driver for low beam quality in semiconductors

Abbi + Mahr 1971
nitrobenzene

Mamev et al. 1996
photorefractive crystal
VECSEL: Marry advantages of traditional (solid-state) lasers and semiconductor 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)

**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 ubiquitous in chemistry and biology. Many aspects are universal, i.e., independent of specific nonlinearities and spatial coupling.

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

Want to avoid it? Convection observed by Koschmieder 1974.

Want to apply it? Self-assembly demonstrated in CO$_2$ laser experiments by Dangoisse et al. 1992.


Laser patterns and VCSEL: A closer look

Oxide aperture ($\text{Al}_2\text{O}_3$):

- current confinement
- **optical confinement**

$$\Delta n \approx 3.6 - 1.6 = 2$$

(but only over 30 nm)

- here: square shape

30×30 and 40×40 µm

Example: not our structure
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

- **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 temperature, increasing detuning gain maximum
- Cavity resonance

- Very high order modes
- Close to Fourier modes, i.e., close to theoretical assumption

- FF on-axis
  - „Spot“
  - „Stripes“
  - „Waves“
  - Localized waves

- NF off-axis on diagonal

Images show structures at different temperatures and currents:
- 40°C, 10 mA
- 20°C, 12 mA
- 10°C, 13 mA
- 0°C, 13 mA
- -20°C, 16 mA

- 15°C, 12 mA
- 10°C, 13 mA
- 5°C, 13 mA
- 0°C, 13 mA
- -5°C, 14 mA
- -10°C, 14 mA
- -15°C, 14 mA

Images depict the appearance of various structures in several devices.
Selection of wavenumber

Gain maximum = preferred emission wavelength shorter than resonance

Laser can reestablish resonance by tilting emission

\[ 2\pi m = k_{\text{eff}} 2L = k \cos \theta \]

\[ = k2L - k2L \frac{1}{2} \theta^2 \]

\[ = k2L - k2L \frac{1}{2} \left( \frac{k_\perp}{k} \right)^2 \]

\[ = k2L - 2L \frac{k_\perp^2}{2k} \]

\[ \text{tilt angle increases with detuning} \]
Wavenumber: Quantitatively

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

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

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

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**

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
Modelling

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

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 $\Delta n \rightarrow \infty \rightarrow$ hard boundaries, 2D (transverse) wave (quantum) billiard
Wave and quantum billiards

**Integrable billiards:**
Closed periodic orbits

**Chaotic billiards:**
- Bunimovich billiard
- Sinai billiard

Periodic orbits unstable, ergodocity

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

- **Near field**
  - 40 μm

- **Far field**
  - 52°

Decreasing temperature $\rightarrow$ 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**

---

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

Superposition of nearly degenerate Fourier modes

\[
\Psi_{N,M}^{p,q}(x,y;A,\phi) = \frac{(2/a)}{\sqrt{\sum_{K=K_0-J}^{K_0+J} C_K^{N,M} 2^K \sin^2(K\phi)}} \times \sqrt{\sum_{K=K_0-J}^{K_0+J} C_K^{N,M} \sin(K\phi)}
\times \sin\left[p(K+1) \frac{\pi x}{a}\right] \times \sin\left[q(N-K+1) \frac{\pi y}{a}\right],
\]

M=2J+1 number of modes

Purely phenomenologically

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

Some fun stuff

Huang et al. PRL 89, 224102 (2002)

Three regimes in temperature / wave number with distinct

- wave vector configuration
- polarization behaviour
Far field

- $T = 42 \, ^\circ\text{C}$
- $I = 12 \, \text{mA}$

- 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

$T=0 \, ^\circ C$

$I=16 \, mA$

Anisotropic reflection: 

**s-wave favoured**

→ Higher Q


→ 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

$T = -36 \, ^\circ C$
$I = 22 \, mA$

Complex polarisation distribution $\rightarrow$ 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 $90^\circ$-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 vector

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.).