Broad-area lasers, laser solitons and patterns in optics
Part II: Laser solitons

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“I was observing the motion of a boat which was rapidly drawn along a narrow channel by a pair of horses, when the boat suddenly stopped—not so the mass of water in the channel which it had put in motion; ..., assuming the form of a large solitary elevation, a rounded, smooth and well-defined heap of water, which continued its course along the channel apparently without change of form or diminution of speed. I followed it on horseback, and overtook it still rolling on at a rate of some eight or nine miles an hour [14 km/h], preserving its original figure some thirty feet [9 m] long and a foot to a foot and a half [300–450 mm] in height. Its height gradually diminished, and after a chase of one or two miles [2–3 km] I lost it in the windings of the channel. ... Singular and beautiful phenomenon which I have called the Wave of translation.

Published: 1845
Report of the fourteenth meeting of the British Association for the Advancement of Science, York, September 1844.

Impact: 1960s
computers, plasmas, ...

Fibre optics: 1970s
http://www.ma.hw.ac.uk/solitons
Solitons started in Scotland

John Scott Russell

http://www.ma.hw.ac.uk/solitons

1834: “... large solitary elevation, .... without change of form or diminution of speed.”

Wave propagation includes dispersion and nonlinearities. Solitons are wave packets propagating with constant shape. Pulse broadening and steepening, shocks, and new frequencies are balanced. A soliton is a wave packet localized in the direction of propagation, leading to temporal solitons and longitudinal solitons, meaning self-localized in the direction of propagation.
Optical transverse soliton (propagation)

Nonlinear Schroedinger equation (NLS) for propagation in $z$

$$\frac{\partial}{\partial z} \psi = -i \left[ \frac{1}{2k_\perp} \nabla^2 \psi + k_l n_2 |\psi|^2 \psi \right]$$

conservative

diffraction and self-focusing might compensate ($n_2 > 0$)

spatial soliton

Length scale selected by nonlinearity

$r_0 \sim 1/\sqrt{n_2 I}$

Family of solutions
Experiment

side view of a cell containing sodium vapor
mounting straps

propagation direction →

Na (Bjorkholm and Ashkin 1974)

- linear propagation (top): diffractive spreading
- nonlinear propagation (bottom): self-guiding, spatial soliton
- pure $\chi(3)$ Kerr nonlinearity $\rightarrow$ collapse in 2D
  (need to stabilize by high-order terms,
   e.g. in Na, two-level atom saturable nonlinearity, “saturable Kerr”)

- in a propagation experiment you will never know whether your soliton
  is long-term stable because you run out of material
Cavity solitons

- Put medium in a cavity
  → propagation replaced by time evolution

- Dissipation: light leaks out of the mirrors
  → compensate by driving

- Second balance condition:
  → family collapses to single solution
  "attractor"

First approach to cavity solitons:

„soliton in a box“

What is a dissipative soliton?

- imagine **bistability** between two states: e.g. low and high amplitude

- in a spatially extended system different spatial regions might be in different states \(\rightarrow\) in between there will be a **front**!
- this front can **move** \(\rightarrow\) one state invades the other and the system becomes homogenous again
- fronts can **lock** and leave an island of one state in the other
  \(\rightarrow\) **localized state, localized structure, or dissipative soliton**

In optics: Rosanov group
Many aspects of VCSEL patterns and solitons are universal for self-organizing spatially extended systems driven out of thermodynamic equilibrium

- nonlinear optics
- hydrodynamics
- gas discharges
- chemistry
- biology
- nature

Not only structured, but self-localized
Cavity soliton laser needs bistability

But normal laser has a continuous turn-on from threshold: no cavity solitons.

Bistable laser schemes

Laser with injected signal

Laser with frequency-selective feedback

Laser with saturable absorber

Gain

Filter

Gain

SA

Truly free running laser with phase invariance


Genevet et al., PRL 101, 123905 (2008)

First semiconductor based CSL: Tanguy et al., PRL 100, 013907 (2008)

Still slaving by external phase reference

First CSL using photorefractories, dyes: Bazhenov et al. (1992); Saffman et al. (1994); Taranenko et al. (1997)

Go for this!
Thanks

Cavity soliton laser:

- 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
Our devices: High power VCSELs

- three InGaAs/GaAs quantum wells
  (gain maximum $\approx 980$ nm)
- oxide layer
  $\rightarrow$ current and optical confinement
- Emission through substrate

Grabherr et al., IEEE STQE 5, 495 (1999)

Miller et al., IEEE Sel. Top. QE 7, 210 (2001)
Technology and mounting

Grabherr et al., IEEE STQE 5, 495 (1999)

- for wavelength > 880 nm: emission through transparent substrate → **bottom emitter**
- heat sinking from top
- much more homogeneous

A **disk**, not a tube!
Setup with volume Bragg grating

**Volume Bragg grating** VBG:
Compact frequency-selective element

Radwell+Ackeman, IEEE QE 45, 1388 (2009)

Detection Branch:

- **Self-imaging**
- External cavity length $L \approx 7.6\text{cm}$
- Maintains high Fresnel number of VCSEL
Experiment: Current ramp
LI-curve of whole device

✓ local bistability
✓ global multistability

Radwell+Ackeman, IEEE-QE 45, 1388 (2009);
Current sweeps detuning, not gain

Switching threshold of first soliton

Switch-on
\[ \frac{dI}{dT} \approx -19.6 \pm 0.4 \text{ mA/K} \]

Switch-off
\[ \frac{dI}{dT} \approx -17.9 \pm 0.4 \text{ mA/K} \]

From other measurements:

- Shift of cavity resonance with temperature
  \[ \frac{d\lambda}{dT} \approx 0.066 \text{ nm/K} \]

- Ohmic heating induced shift
  \[ \frac{d\lambda}{dI} \approx 0.0035 \text{ nm/mA} \]

- Combined
  \[ \frac{1}{(dT/dI)} \approx 19 \text{ mA/K} \]

Main effect of current is red-shift of resonance until detuning between cavity and VBG so small that switching occurs via carrier nonlinearity
Bistability: Qualitative interpretation

**Low-amplitude state:** laser off, carrier density high, refractive index low

- Laser off, carrier density high, refractive index low
- Grating frequency
- Longitudinal cavity resonance
- Dispersion curve of high-order modes of VCSEL $q(\omega)$

**High-amplitude state:** laser on, carrier density low $\rightarrow$ refractive index high

- Laser on, carrier density low $\rightarrow$ refractive index high
- Soliton frequency $\rightarrow$ red-shift of effective cavity resonance
- Grating frequency
- $\omega_c = \frac{m c}{2 L n(N)}$

**Dispersive optical bistability**

Localized high-amplitude state stabilized by self-focusing
Coherent emitters

- Well defined, circularly symmetric spots with size of 4.8-5.8 μm (1/e²-radius of intensity)
- Angular width in far field: 57-69 mrad (centre on-axis within ≤ 18 mrad)
- Close to being diffraction-limited → high spatial coherence

- Linewidth in single-mode: ≈ 6 MHz → high temporal coherence
- these are coherent emitters → microlasers

Mutual coherence? -- Later
Spatial solitons: Switch-on/-off

Transverse plane (⊥ cavity axis) of broad-area VCSEL

- bright spots much smaller than pumped aperture
- stabilized by nonlinearities
- bistable

Demonstration of independent writing and erasure:
- all 8 possible configurations of 3 bits

→ solitonic character

→ Laser (cavity) solitons
Independence and mobility

- VBG isotropic → no preferred direction for switch-on/switch-off
- but symmetry broken by imperfections of device

- “Stir” LCS with cw writing beam
- WB attracts LCS and pulls them out of center of trap
- moves them from one trap to another
- pulls them where they can’t exist → mechanism for erasure
Frequency of solitons and disorder

- Different solitons have different threshold frequencies
- The most **reddish** solitons come first!
- Threshold increases with increasing detuning

“local” dispersion curves due to mirror roughness

- Switching will occur at locations with minimal gap
- **Explains why most reddish locations switch first!**

Power (Arb. Units)

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>981.05</td>
</tr>
<tr>
<td>981.1</td>
</tr>
<tr>
<td>981.15</td>
</tr>
</tbody>
</table>

Minimial gap

**ωg** **ωc** **ω**
Application in disorder mapping

Convert threshold value to detuning by wavelength shift 0.0035 nm/mA

- potentially useful to characterize disorder in VCSEL on relevant scales with fairly high resolution, Opt. Lett. 37, 1079 (2012)

- monolayer fluctuations
Theoretical model (class B)

Assume:
- perfect self-imaging
- feedback only dependent on frequency, not on wavevector

\[
\partial_t E = -(1 + i \theta)E + i \nabla^2 E - i \sigma (\alpha + i)(N - 1)E + \frac{2 \sqrt{T_1}}{T_1 + T_2} F
\]

\[
\partial_t N = -\gamma [N - J + |E|^2 (N - 1) + D \nabla^2 N]
\]

\[
F(t) = e^{-i \delta_f} \hat{G}(t - \tau_f / 2) [-r_1 F(t - \tau_f) + t_1 E(t - \tau_f)]
\]

\[
\hat{G}(t)[\cdot] = \frac{r_g}{2 \beta} \int_{t - 2 \beta}^{t} e^{i \Delta_g (t' - t)} [\cdot] \, dt'
\]

Note: Lang-Kobayashi: All round-trips

A. J. Scroggie, G.-L. Oppo, W. J. Firth, PRA 80, 013829 (2009)
Stationary LCS, single frequency, one external cavity mode
Width $\approx 8 \, \mu m$
Works also in 2D

- Good reproduction of experimental results
- Applies also to transient dynamics (Radwell et al., Eur. Phys. J. D 59, 121 (2010))
- Bifurcation structure and instabilities analyzed in simpler Ginzburg-Landau model plus linear filter (Paulau, Firth, ...)

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A simpler class A model

- Adiabatic elimination of carriers
  - same stationary states but stability properties might change
  - but note: carriers slower than field, loss of relaxation oscillations
- Take into account delay or not

\[
\frac{dE}{dt} = -\kappa E + \frac{\kappa\mu E}{1 + |E|^2} + \frac{i\alpha\kappa\mu E}{1 + |E|^2} - i\Delta E + F + i\omega_s E - i\alpha\kappa E.
\]

\[
\frac{dF}{dt} = -\lambda F + \sigma\lambda E(t - \tau)
\]

- Lorentzian filter
- Lang-Kobayashi for simplicity

Paulau et al.,PRE 78, 016212 (2008)
Filamentation vs. solitons

In **gap:** solitons with center on axis

Extended states with irregular spatio-temporal dynamics

Interpretation: filamentation, modulational instability
LCS branches start from homogeneous solution with infinite width, A, B merge in saddle-node bifurcation, C stable section:

- blue detuning to grating
- width 10-13 µm
- spontaneous motion: drift instability
Even simpler: Ginzburg-Landau model


Linear loss (gain) and frequency detuning

\[
\frac{\partial E}{\partial t} = g_0 E + g_2 |E|^2 E + i \Delta E + F
\]

Nonlinear gain (loss) and self focusing (defocusing)

\[
\frac{dF}{dt} = -\lambda F + \tilde{\sigma} E,
\]

Diffraction

Filtered Feedback

- in GLE: Chirped-sech soliton solutions known but unstable
- Stabilized by *coupling to resonant filter* suppressing background
- simplest model for laser with FSF


\[
g_0 = \kappa (1 + i \alpha)(\mu - 1) - i \omega_m,
g_2 = -\kappa (1 + i \alpha) \mu,
\tilde{\sigma} = \sigma \lambda,
\]
Laser with saturable absorber

Saturable absorber:
Linear absorption coefficient at low power
Bleaching of absorption at high power

Pioneer: Rosanov (St. Petersburg)
Here: Material from Cargese summer school 2006

Bistability for
$g_{\text{min}} < g_0 < g_{\text{max}}$
Gain compensates nonsaturable losses

Soliton intensity Profile
“Homoclinic Connection”
Saturable absorption stabilizes background:
Absorptive bistability
Laser solitons due to saturable absorption

INLN group: Genevet et al., PRL 101, 123905 (2008)

Face-to-face coupled VCSELs

- absorptive optical bistability
- solitons
- independently controllable

Power low, absorption, Finesse low

Power high, absorber bleached, Finesse high

A) B) C) D)
For the orbital angular momentum lover

- A doughnut beam or **optical vortex** has a spiral phase structure, a singularity at the centre and carries orbital angular momentum

- Stable soliton solution for **self-defocusing** wave equation

- But unstable in **self-focusing** medium, decays into bright solitons

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**Stable**
Swartzlander, OPN 10, 10 (1993)
(defect in bright homogeneous state)

**Unstable**
Tikhonenko, JOSAB 12, 2046 (1995)

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Cavity vortex solitons

- **absorptive:**
  - theory: Rosanov group, e.g. Federov et al., IEEE QE 39, 197 (2003)
  - first experiment: INLN, Genevet et al., PRL 104, 223902 (2010)

Nested hysteresis curves
Clusters of solitons and “rings”
Cavity vortex solitons II

- **self-focusing:**
  - experiment: none to our knowledge
  - specific prediction in a cubic complex Ginzburg-Landau equation with filter
    → simplest model for a laser with frequency-selective feedback
    Paulau et al., Opt. Exp. 18, 8859 (2010); PRE 84, 036213 (2011)

*Note:*

- vortex solitons with integer m form **discrete family of 2D high order solitons**
- this possibility exists only in systems in which the **phase is free**
  i.e. in lasers and other oscillators without coherent injection
FSF: LI-curve and bistability

Monitor region of interest around one soliton (not whole aperture!)

Ring with three maxima

"singular optics" special issue

Fundamental bright soliton

Background State (off-state)

(on-state)
Interference Patterns (self-interference)

Self-interference (overlapping)  intensity

On top of each other

Experimental  Simulation

Shifted sideways, slightly vertically

Stronger shifts

Evidence for one phase singularity with m=1 → vortex

Synchronization

- We saw that solitons are in generally mutually incoherent due to disorder, i.e. have different frequencies and phases.
- What happens if two are together and interact?

What about the solitons?

Huygens 1665

Coupled clocks synchronize: Frequency- and phase-locking
Adler scenario

- **Adler equation:**
  Archetypical equation for frequency- and phase-locking of nonlinear oscillators in presence of detuning
  \[
  \frac{d\Phi}{dt} = \Delta \omega - \varepsilon \sin(\Phi)
  \]

- Stable locking at 0 or \(\pi\) for \(\Delta \omega = 0\)
- with detuning still locking for \(\Delta \omega < \varepsilon\)

Adler, Proc. IRE (1946)

Paulau et al., PRL 108, 213904 (2012)
Experiment: How to control detuning?

- Tilt $\beta$ of VBG → controls detuning in external cavity (feedback phase)
- different arm length $\Delta L$ → mutual detuning or offset of combs
  → align to be “zero” or multiples of free spectral range
- Shift $\Delta L$ by a few $\mu m$ by PZT
  → change detunings by a few tens of MHz
- Near and far field profiles of solitons unaffected but positions are

Similar to control of detuning between coupled microchip lasers (R. Roy et al.)
Experiment: Phase locking

Can jump together
Can jump to a “common” mode,
Single freq.

Two solitons operating on neighbouring external cavity modes shift together

Cut through far field patterns
No (weak) features: Far field essentially incoherent sum of single solitons

Fringes with strong visibility: evidence for frequency- and phase locking

Shift of fringe pattern → change of locking phase

Ackemann et al., Book chapter (2013)
Experiment: Adler

(Nearly) complete locking:

Adler range

(analytical curve (red) scaled in x and shifted in y)

partial locking
via some sharing of external cavity modes

Nice qualitative agreement

Paulau et al., PRL 108, 213904 (2012)
Disorder and locking

- Temporal and spatial systems react very different to disorder
  - **Temporal (longitudinal):** Bound states with $\pi/2$ phase between constituents predicted for complex cubic-quintic Ginzburg Landau equation are actually observed in mode-locked fiber lasers (Grelut) averaging along cavity axis $\rightarrow$ each LCS sees *all* disorder

- **Spatial:** Each LCS sees only *local* disorder
  - Translational modes strongly damped
  - *synchronization dynamics, Adler scenario* frequency *and* phase locking

- Nevertheless new features
  - self-localized
  - bistable
  - potential of reasonably *large disordered networks*

- **Ideas to control disorder locally**

http://www.montefiore.ulg.ac.be/~mauroy/interest.htm
Mode-locking and temporal solitons

Pulses in ultrafast, mode-locked lasers can be understood in many (not all!) configurations as temporal dissipative solitons

- Balance dispersion and self-phase modulation
- Cavity losses and driving
- Bistable (self-starting problem)

Simplified treatment by cubic-quintic Ginzburg-Landau equation

\[ i\psi_z + D\psi_{tt}/2 + |\psi|^2\psi + v|\psi|^4\psi = i\delta\psi + i\varepsilon|\psi|^2\psi + i\beta\psi_{tt} + i\mu|\psi|^4\psi \]

Major contributors

- Fundamental theory: Akhmediev
- Experiment on molecules, dynamics, ...: Grelu, Cundiff
- For high-power lasers: Keller, Wise

Recent review: Grelu, Akhmediev, Nat. Phot. 6, 84 (2012)
Summary: Laser solitons

- **Cavity soliton laser**
  - Optically controllable *microlasers* based on *spatial dissipative solitons*!
  - Disorder important in realization (FSF as tool to probe)
  - Synchronization: Frequency and phase-locking (Adler scenario)
  - Vortex solitons as high order states

- Different mechanisms, but common features
  - Dispersive vs. absorptive optical bistability
  - Decisive is that there is a mechanism *suppressing lasing in the background* (absorptive of off-resonant to filter)

- **Outlook**: 3D localization, mode-locking of spatial solitons (*Friday*!); networks of phase-locked LCS, local control of inhomogeneities; miniaturization, monolithic integration; cluster of solitons and understanding of connection to high-order solitons and inhomogeneities

Setup for compensation

- **spatially modulated** injection
  - spatially modulated carrier distribution
  - spatially modulated refractive index
  - compensation of variations in cavity resonance
Demonstration of control

1. Find 2 solitons with similar thresholds
2. Apply SLM beam locally to soliton with higher threshold
3. Soliton thresholds overlap

- SLM for VIS, efficiency in NIR low
  → low power
  → needs to be resonant to microcavity

- first step towards homogenization
Large-scale homogeneity

- improve beam shape
  - optimize temperature difference between bottom and top heating filament of the effusions cells
- improve homogeneity of substrate temperature
  - reduce temperature level of growth
  - enhance uniformity of substrate holder rings

result:
- $< 0.012 \text{ GHz} / \mu\text{m}$
- $< 2.5 \text{ GHz} / 200 \mu\text{m}$

R. Jäger et al., Ulm Photonics, unpublished
Time-resolved optical spectrum

Blue detuned excitation (20 ns pulse)  
Excitation at grating frequency

Shift of carrier frequency $\rightarrow$  
evolution via unstable LCS $\rightarrow$  
spectral simplification

Still evolution via unstable LCS
Even simpler: Ginzburg-Landau model


Linear loss (gain) and frequency detuning

\[
\frac{\partial E}{\partial t} = g_0 E + g_2 |E|^2 E + i\Delta E + F + in(x)E,
\]

\[
\frac{dF}{dt} = -\lambda F + \tilde{\sigma} E,
\]

Nonlinear gain (loss) and self focusing (defocusing)

- Diffraction
- Filtered Feedback

Width of filter

Feedback strength

Pinning potential

\[
n(x) = \frac{-n_j}{2} \left[ \cos \left( \frac{\pi(x-x_j)}{W} \right) + 1 \right]
\]


Homogeneous system

Work by P. Paulau, note $\alpha = 0.5 << \alpha \approx 5$

Soliton amplitude  Soliton phase (chirp)

- **Foci** at phase $\pi/2$ **stable**
- **Saddles** at phases 0 and $\pi$ **always unstable**
- qualitatively very similar to perturbatively obtained diagram for cubic-quintic GLE; temporal solitons in fiber lasers; Akhmediev et al, PRL 79, 4047 (1997); Tuarev et al, PRE 75, 045601(R)(2007)

Interaction plane: distance - phase
Results with traps of equal depths

Trap depth about 0.48 GHz

- Traps destroy translational symmetry and stabilize motion-unstable states

- below a certain distance (here ≈ 1.65 CS width): **anti-phase locking**

- above: **in-phase locking**
Results with unequal traps

Trap depth different by 3%

- below a certain distance (here 2.06 CS width)
  - synchronization
  - “non-standard” phase
  - here 2.415

- above a certain distance
  - unlocked
Outlook: Complex networks of LCS

- **Coherently driven systems:** complex interactions via intensity (oscillating tails) but **no** phase dependence

- **Propagational solitons:** phase sensitive interactions, depending on launching conditions

- **Laser cavity solitons** combine features of these two cases and adds new
  - (optical) phase, spatial phase and polarization (phase between x, y comp.) are Goldstone modes
  - **Phase, location, and polarization are free to change during dynamics**
  - Complex network with many degrees of freedom
  - pioneering work: Akhmediev, Vladimirov, Rosanov, + coworkers
Asymmetry from the grating

- CS ≈ on-axis

- CS exactly at Littrow freq. → exact retro-reflection

- CS slightly blue detuned → \textit{angle} → wavefront tilted to the right

- CS slightly red detuned → \textit{angle} → wavefront tilted to the left

\textbf{Tilted wavefront induces drift!}
Drifting excitations

Ignite CS in a situation, in which it is only transient, monitor by APD array

- velocity: 1.4 µm / ns
- drift distance: > 50 µm
- Delay: ~ 40 ns

Caution:
Measurement in far field indicate that angle increase by 2.5°
soliton character likely but needs to be confirmed

Tanguy et al., PRA 78, 023810 (2008)
CS Application – All-optical delay line

In CSL
- velocity: 1.4 µm / ns
- drift distance: > 50 µm
- Delay: ~ 40 ns

In amplifier exp. (Nice)
- velocity: 4.7 µm / ns
- drift distance: 36 µm
- Delay: 7.5 ns

Motivation:
All-optical *delay line* as buffers in photonic networks
History: Cavity solitons

**cavity soliton** = (spatially) self-localized, bistable solitary wave in a cavity

- stabilized by counteraction of
  - nonlinearity vs. diffraction
  - driving vs. dissipation

**driven cavity (optical bistability)**

Probably first simulations:
McLaughlin, et al. PRL 51, 758 (1983)

Bifurcations of hexagons

tilted wave argument selects length scale not type of pattern

- $q_x$
- $q_y$

|$q_c$| stripes

generic in 2D

hexagons

bifurcation to hexagons **subcritical**

region of **coexistence** of homogeneous solution and hexagons
In bistable range: Cavity solitons and patterns

Tlidi et al., PRL 73, 640 (1994)

Firth+Scroggie, PRL 76, 1623(1996)

CS very similar to constituent of a hexagon

„localized pattern“

CS (or LS) = part of a pattern
Fronts and cavity solitons

a) **front** between half-plane with hexagons and half-plane with homogeneous solution stationary at *one* value of stress parameter

b) **Pomeau-front** stationary for *finite* range of stress parameter due to locking at modulated interface

general prediction (1D):

LS / CS occur in vicinity of Pomeau front

Coullet et al., PRL 84, 3069 (2000)
Vertical-cavity (regenerative) amplifier

- Homogeneous holding beam
- Focused addressing beam

VCSEL/VCA-cavity

Electrically pumped above transparency, but below threshold

\[ VCA = \text{vertical-cavity (regenerative) amplifier} \]

+ Homogeneous holding beam

Independent manipulation of two CS

“Cavity solitons as pixels in semiconductor microcavities”

60 × 60 µm²

Out of a device with diameter 150 µm

reflected intensity

2.5 µs

switching of a single CS

Taranenko et al., Appl. Phys. B 75, 75 (2002), semiconductor, dominantly absorptive nonlinearity

FIGURE 2 Bright soliton (dark in reflection). 3D represen-
tivity: a view from above; and b view from below
Experiments: CS in cavities

- Kreuzer, Neubecker (Darmstadt): liquid crystals
  - Bistable single spots; no external control
  - Identification as “self-induced modes”
  - An experiment before its time (later Louvergneaux (Lille))

- Taranenko, Weiss (PTB): absorbing and self-defocusing driven VCSELs
  PRA 61, 063818 (2000); APB 75, 75 (2002) ... 
  - Probably first observation of CS in semiconductor microcavity
  - But complete independent manipulation of two not demonstrated