DISSIPATIVE OPTICAL SOLITONS (DOSs): TOWARDS NANOSIZES AND ATTODURATIONS

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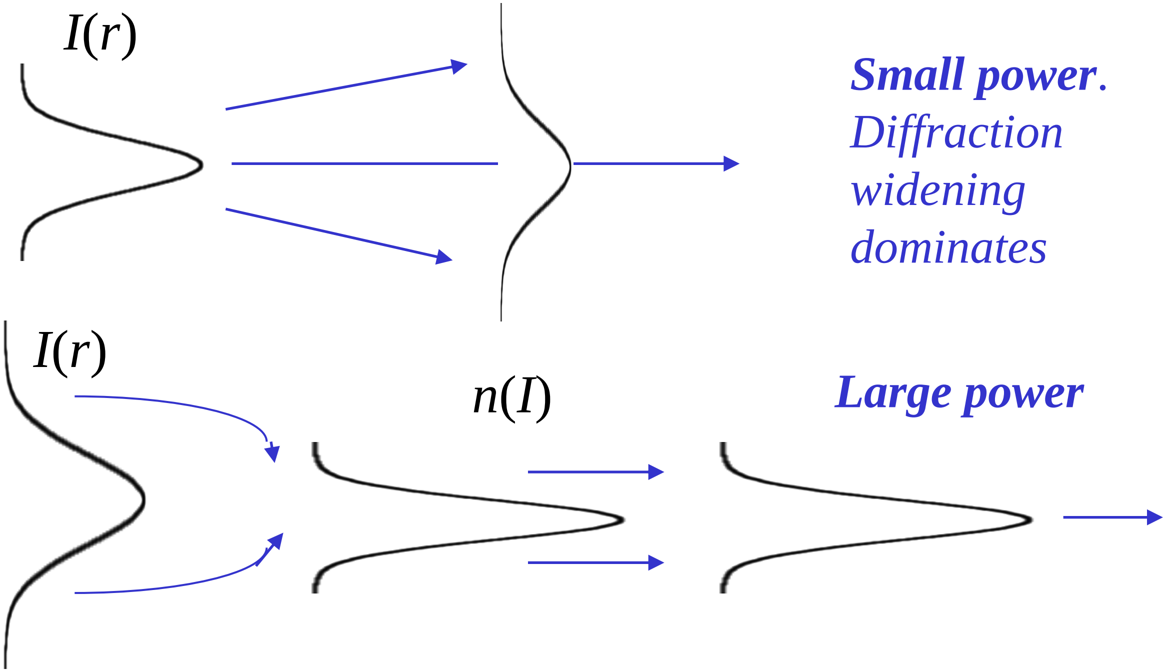
OUTLINE

DOS = Dissipative Optical Soliton, or Autosoliton

1. Introduction. Optical Soliton History, Terminology, Motivation
2. “Standard” envelope DOSs in wide-aperture driven nonlinear interferometers and lasers with saturable absoption
   - Pseudo-quantum features (discrete spectrum of main parameters)
   - Internal structure (topology of energy flows)
   - Weak and strong interaction of DOSs
   - Symmetry and Eulerian mechanics
3. Discrete dissipative solitons, including knot solitons.
4. Extreme DOSs
   - “Nanosolitons” – nanosized DOSs in driven molecular chains
   - “Attosolitons” – subfemtosecond DOSs on the basis of self-induced transparency
5. Conclusion

Conservative Spatial Optical Solitons (1962)

Self-focusing (including self-trapping) of optical beams in transparent media with intensity-dependent refractive index $n(I)$

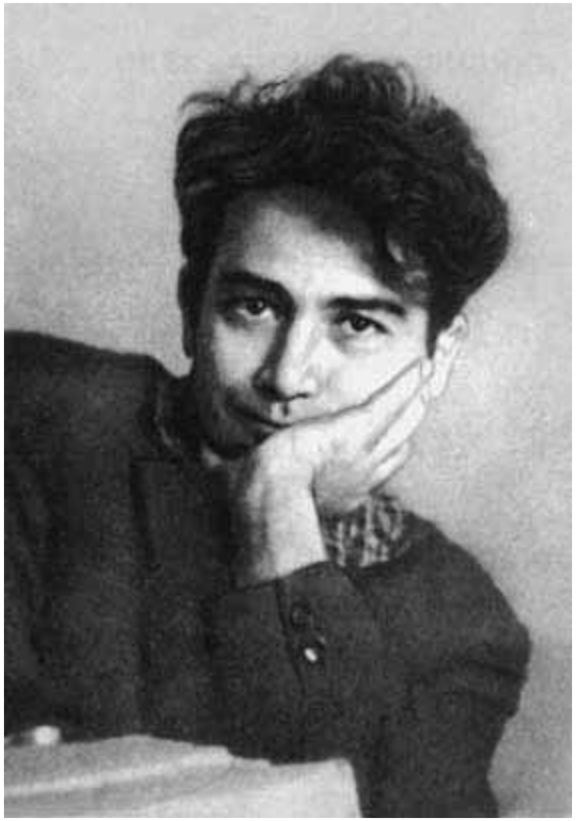


***Small power**. Diffraction widening dominates*

Large power

Nonlinear focusing and their stabilization due to the balance with diffraction widening (below optical damage threshold)

Theory: Talanov, Litvak; Chiao, Garmire, Townes; Akhmanov, Sukhorukov, Khokhlov; Zakharov; …

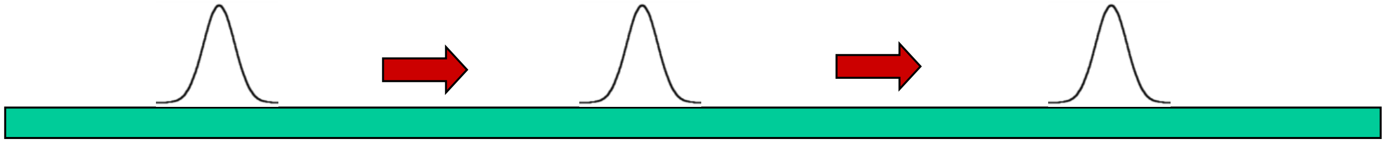


G.A. Askaryan
1928-1997

Are similar solitons possible with nonlinearity of gain and absorption?

Spatio-Temporal Analogy

Temporal solitons in a single-mode fiber [A. Hasegawa, F. Tappert, 1973]



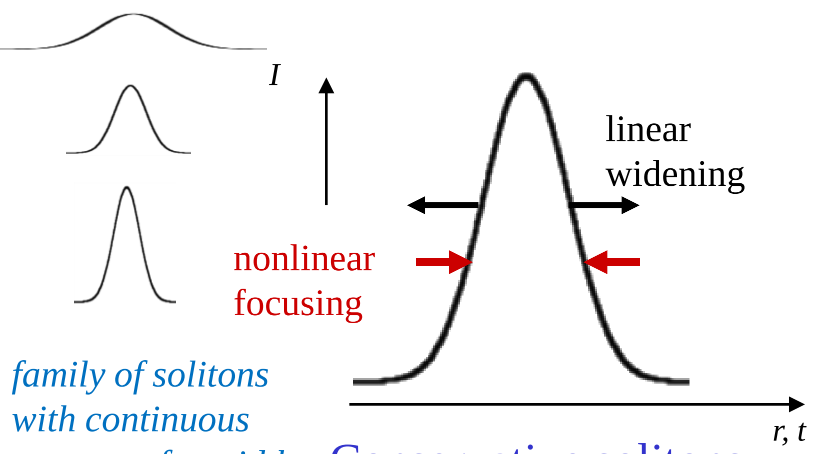
Optical pulse widening due to frequency dispersion is compensated by nonlinear focusing

Experiment: Mollenauer et al.

In Russia: Nonlinear fibre optics, A.M. Prokhrov, E.M. Dianov et al., …

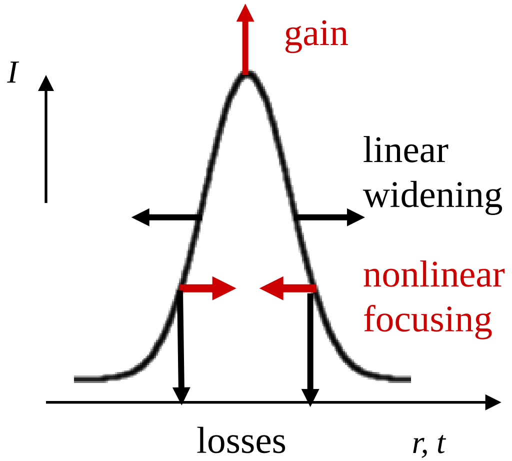
2002: Commercial solitonic communication line, DWDM, Australia, 3, 875 km, 1.6 Tbit/s

Yu.S. Kivshar, G.P. Agrawal. Optical Solitons. From Fibers to Photonic Crystals, Acad.Pr, 2003



family of solitons with continuous spectrum for width

Conservative solitons



Dissipative solitons

Discrete spectrum of main parameters -> suppression of effect of noise, robustness

AUTOSOLITON *(dissipative soliton)* is a stable field structure localized due to nonlinear balance of energy input and output in homogeneous or periodically modulated non-conservative medium or system.

Motivation for research of DOSs

- For science: Wave-particle dualism.

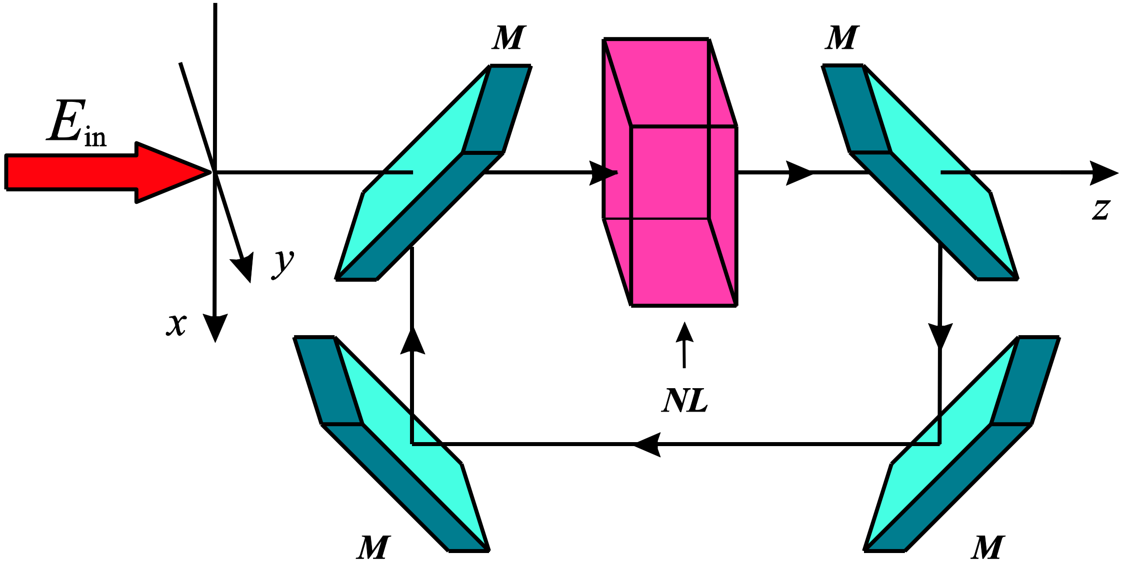
If dissipative solitons corresponds to “particles”, what are features of these particles?

The diversity of the dissipative optical solitons and unusual type of their features.

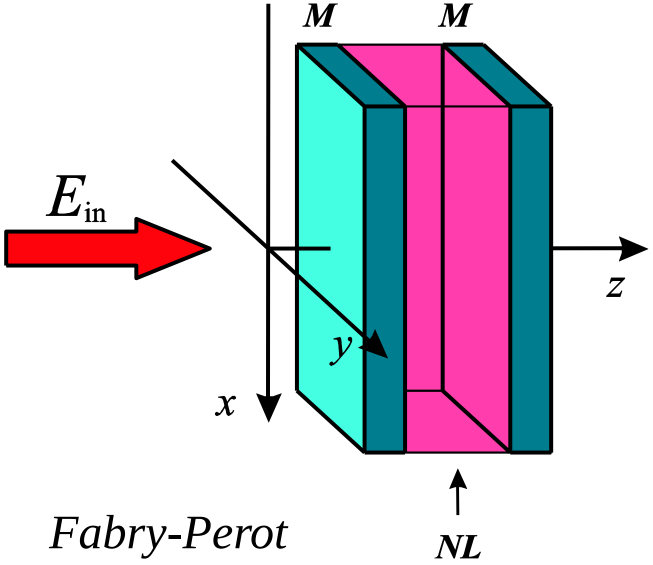
- For applications: Coding information by solitons, and then to record, store, and process information. What are the features of dissipative solitons promising for these applications?

- Tendencies in research of dissipative optical solitons.

Driven Wide-Aperture Nonlinear Interferometer



Ring cavity



Fabry-Perot interferometer

M – mirrors

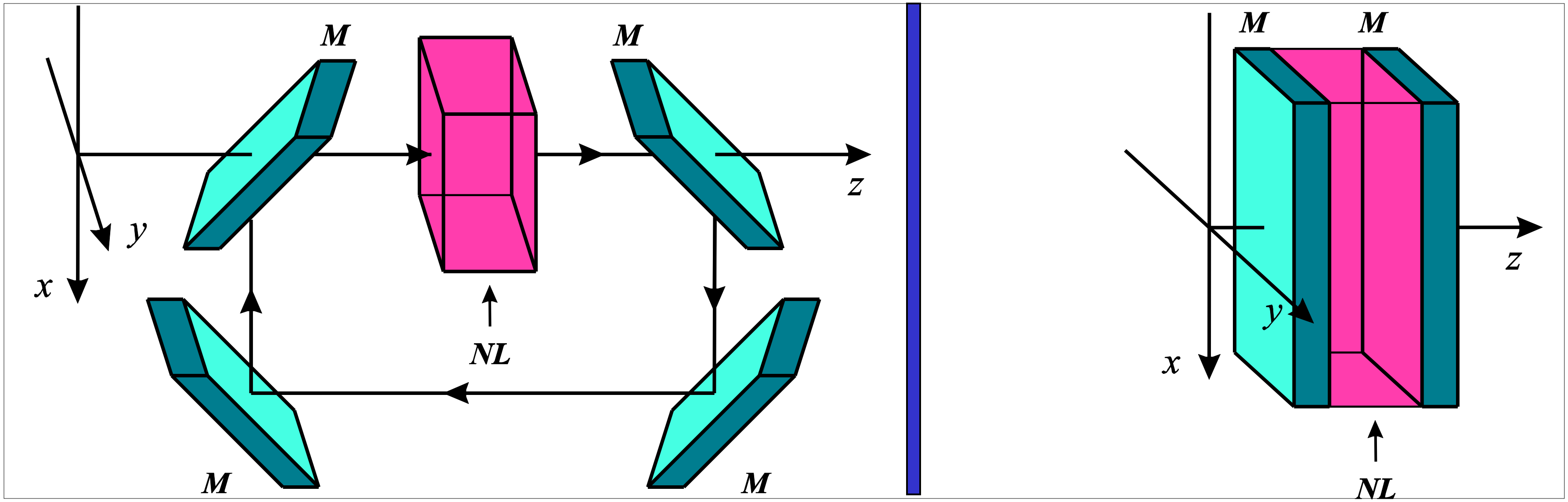
NL – medium with optical nonlinearity

E_{in} – amplitude of coherent holding radiation

Field phase and frequency are determined by holding radiation

[Rosanov, Semenov, 1980] – modulational instability (filamentation); [Rosanov, Semenov, Khodova, 1983, 1988, …] – spatial DOSs

Wide-Aperture Laser with Saturable Absorption



M – mirrors

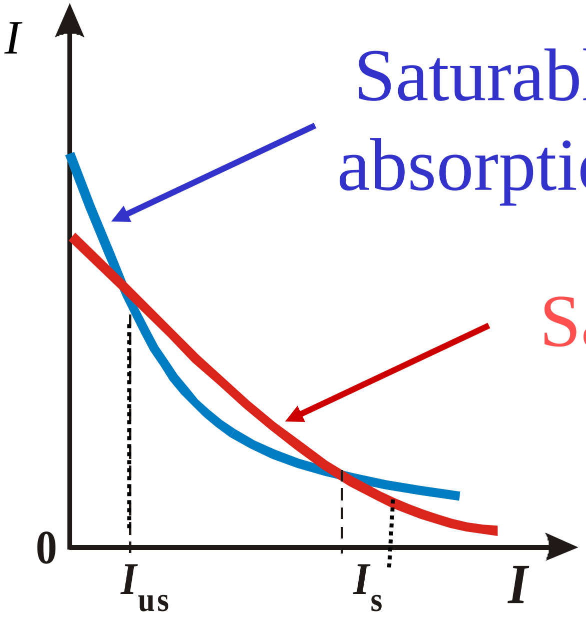
NL – medium with nonlinear gain and absorption

Envelope “laser solitons”:
[Rosanov, S. Fedorov, 1992]

No coherent holding radiation, incoherent pump (laser schemes)

Zero background. Free phase, frequency as eigenvalue.

Bistability and Laser Solitons



Saturable absorption

Saturable gain

The case of instantaneous nonlinearity (class A lasers)

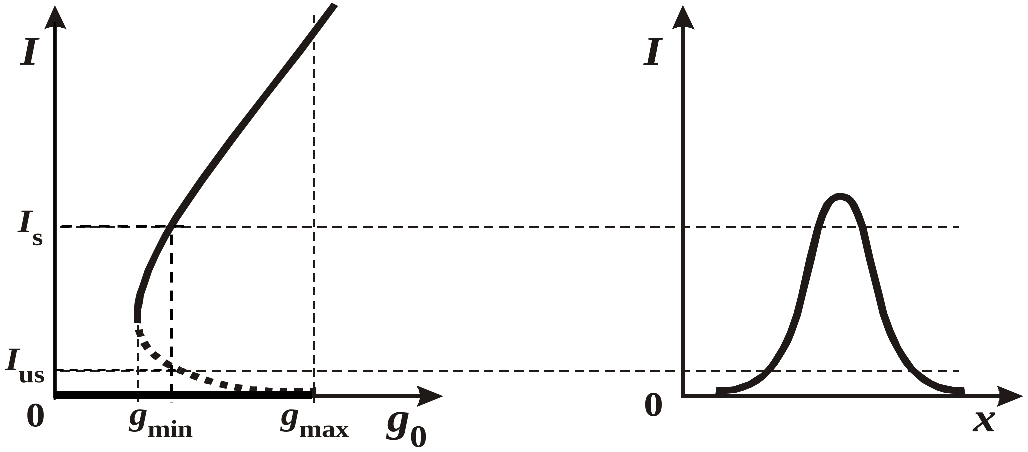
← $g_0 = \text{const}$

g_0 - small-signal gain

$I = |E|^2$ - intensity

Bistability for

$g_{\min} < g_0 < g_{\max}$



Soliton intensity profile

Hard excitation of lasing by external beam-pulse

Governing Equation for Laser Schemes

$$\boxed{\frac{\partial E}{\partial \zeta} = (i+d)\Delta_D E + Ef(|E|^2)}$$

$\tilde{E} \equiv \mathrm{Re}[E \exp(ikz - i\omega t)]$

$I = |E|^2$ - intensity

D = 1, 2, 3.

E – electric field envelope (mean-field approximation);

ζ – evolution variable (time or longitudinal co-ordinate);

d – effective diffusion coefficient (angular selectivity);

$\Delta_D = \nabla_D^2$ – D-dimensional Laplacian, $\Delta_2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$

$f\left(|E|^2\right)$ – medium nonlinearity + linear losses

$$\boxed{f(|E|^2) = -1 + \frac{g_0}{1+|E|^2} - \frac{a_0}{1+b|E|^2}}$$

gain *absorption*

Class A laser with fixed polarization

[Suchkov 1966]

Governing Equation for Interferometers

$$\boxed{\frac{\partial E}{\partial t} = i\Delta_D E + Ef(|E|^2) + E_{in}}$$

E – electric field envelope (mean-field approximation);

E_{in} – holding radiation amplitude;

$\Delta_D = \nabla_D^2$ – D-dimensional Laplacian, D = 1 or 2.

$f\left(|E|^2\right)$ – medium nonlinearity + linear losses + detuning

For interferometers with Kerr nonlinearity (2D)

[Lugiato, Lefever 1987]

$$\frac{\partial E}{\partial t} = \underset{\substack{\uparrow \\ \text{diffraction}}}{i\Delta_{\perp} E} + \underset{\substack{\uparrow \\ \text{refractive} \\ \text{index} \\ \text{nonlinearity}}}{i|E|^2 E} - (\underset{\substack{\uparrow \\ \text{linear} \\ \text{losses}}}{1} + \underset{\substack{\uparrow \\ \text{detuning}}}{i\Theta})E + \underset{\substack{\uparrow \\ \text{holding} \\ \text{radiation}}}{E_{\text{in}}}$$

DOSs Quasi-Quantum Features

NONLINEAR INTERFEROMETER

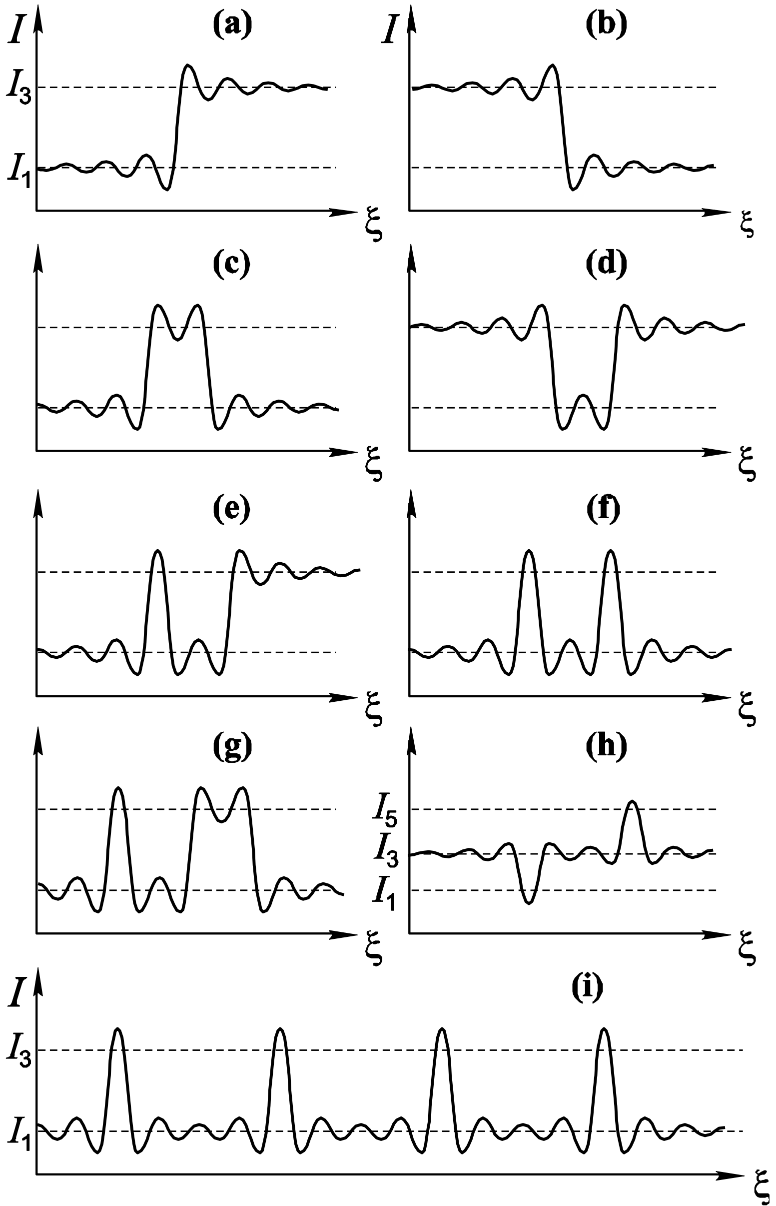
(1D)

Exactly solvable model: step-wise nonlinearity [Rosanov, 1992]

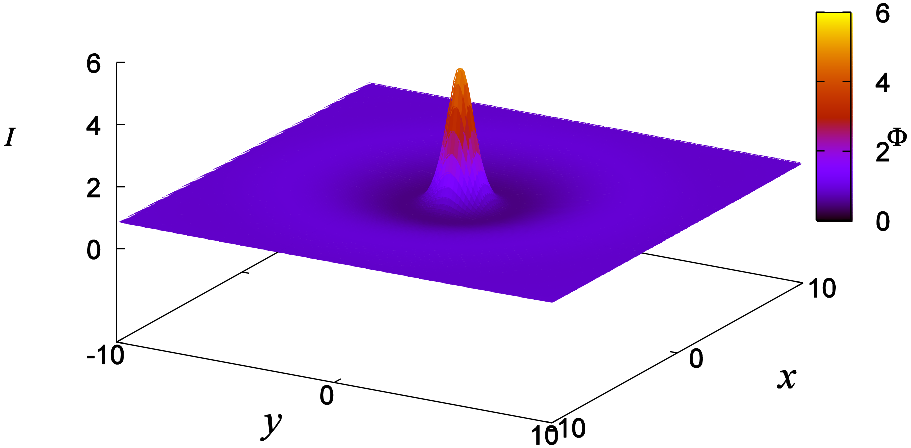
Discrete spectrum of single DOS width – quasi-atom

Discrete spectrum of inter-soliton distance for soliton pairs – quasi-molecule

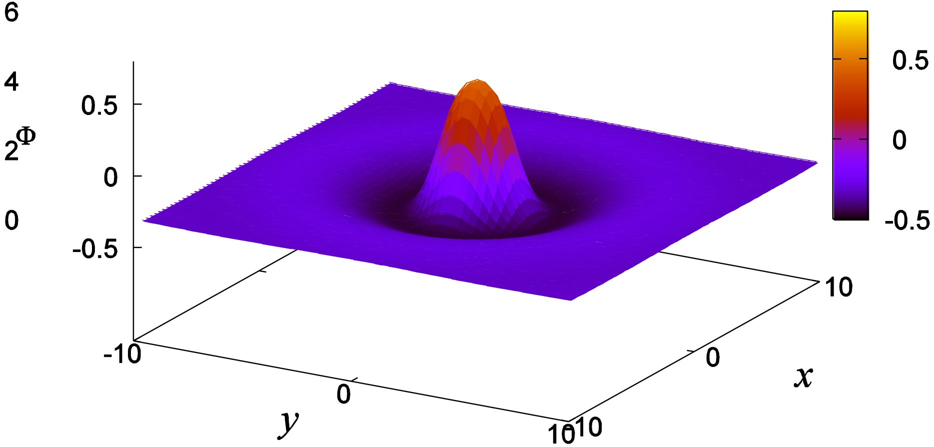
Band structure for periodic chains of solitons – quasi-solid



Single 2D-Soliton in Interferometer



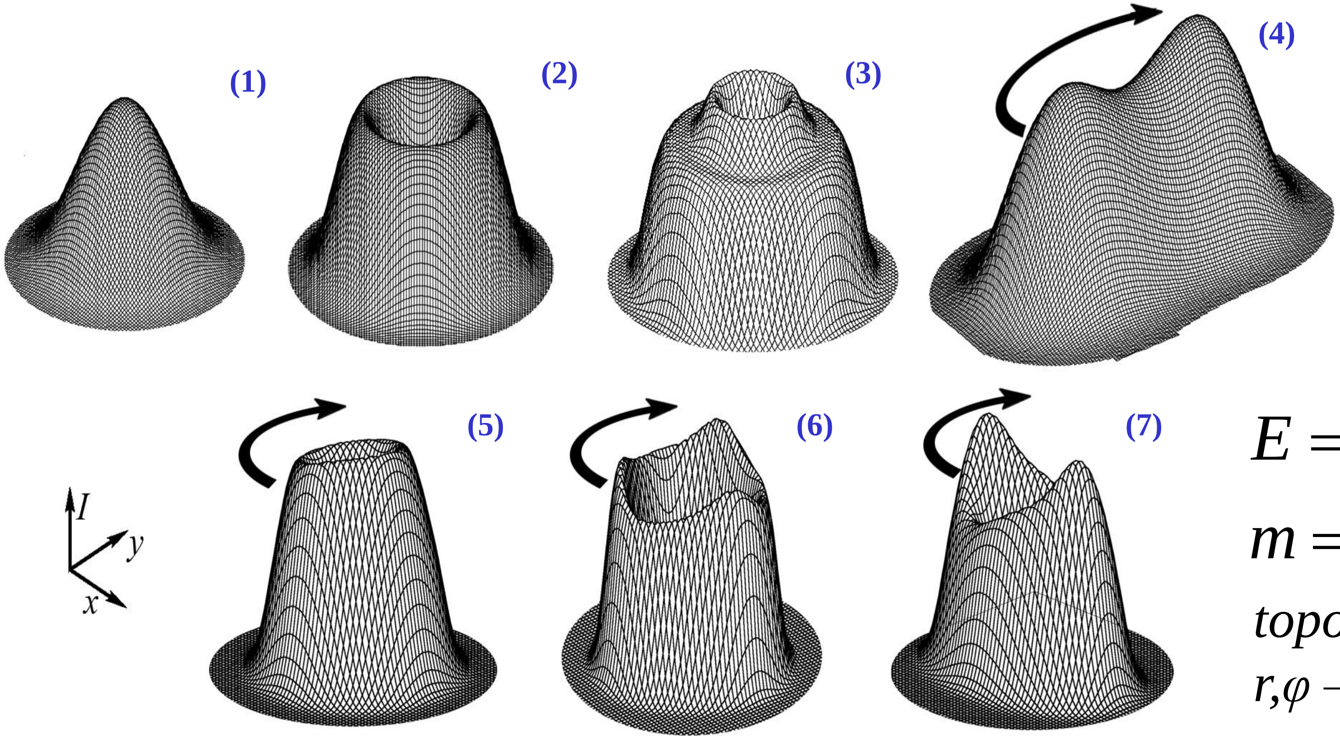
Intensity



Phase

2D-DOSs in lasers with saturable absorption

Transverse intensity distributions:



1 – 3:

$$E = A(r)\exp(im\varphi - i\alpha t)$$

$$m = 0, \pm 1, \pm 2 -$$

topological charge,
r,φ – polar coordinates,
α – frequency shift

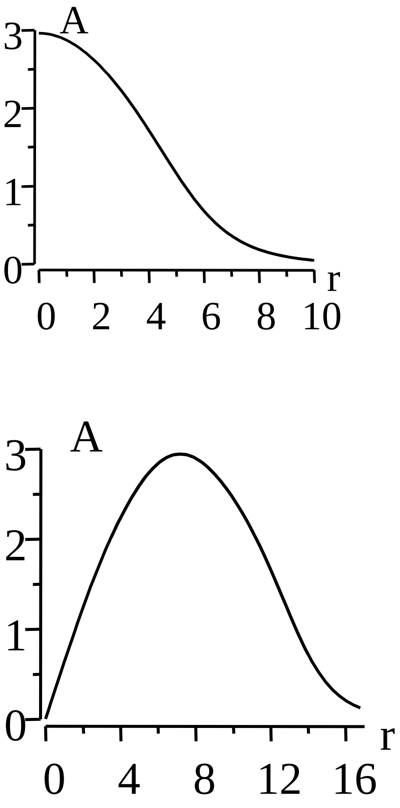
1 – fundamental DOS (regular wavefront); 2, 3, 5-7 – vortex DOSs;
4, 6, 7 – rotating DOSs; 5 – Moon-like motion

Soliton Internal Structure

Single symmetric laser solitons: radial profiles and energy flows

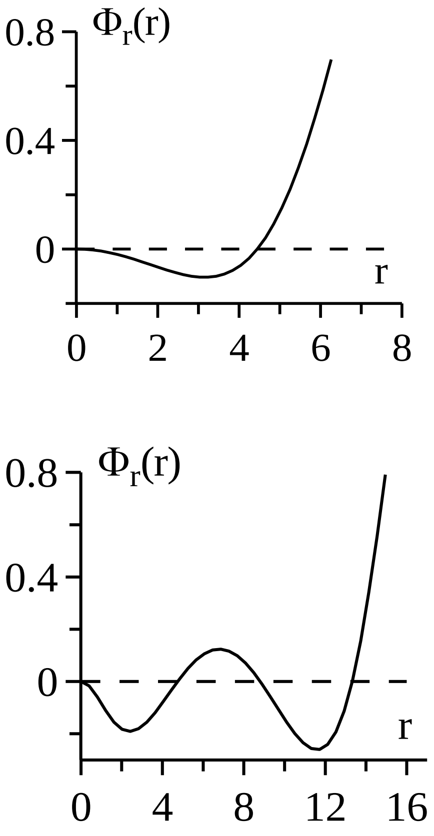
Symmetry to rotation at any angle

$$A = |A(r)|$$

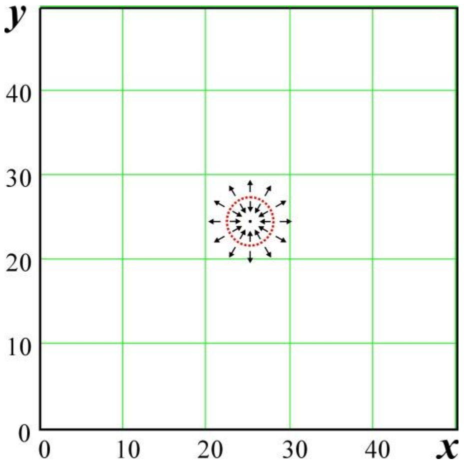


Real amplitude

$$\Phi = \Phi_r(r) + m\varphi$$



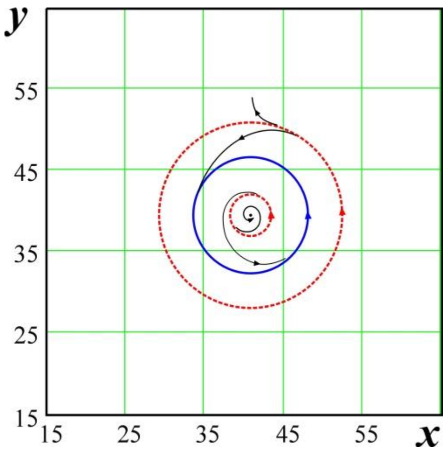
Radial phase



Energy flows portrait

$m = 0$

$$\mathbf{S}_{\perp} \sim I \nabla_{\perp} \Phi$$



$m = 1$

Focus,
one “stable” and
two “unstable”
limit cycles

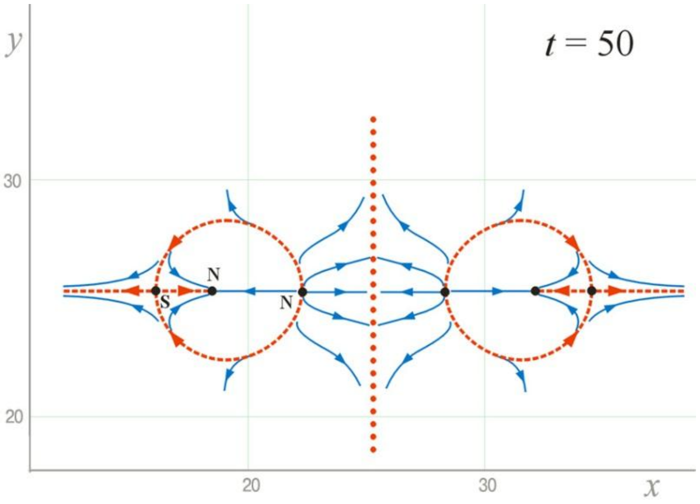
Closed lines: soliton identification

Weak *vs* Strong Interactions of DOSs

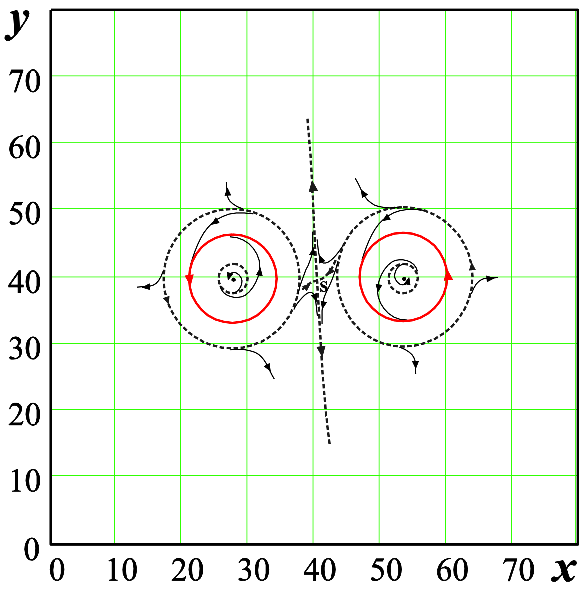
Weak interaction of DOSs: closed lines in the energy flow portraits are the same as for individual DOSs.
Strong interaction of DOSs: disappearance of some closed lines of individual DOSs and/or birth of new lines common for a number of DOSs.

Energy flow portraits for laser DOSs

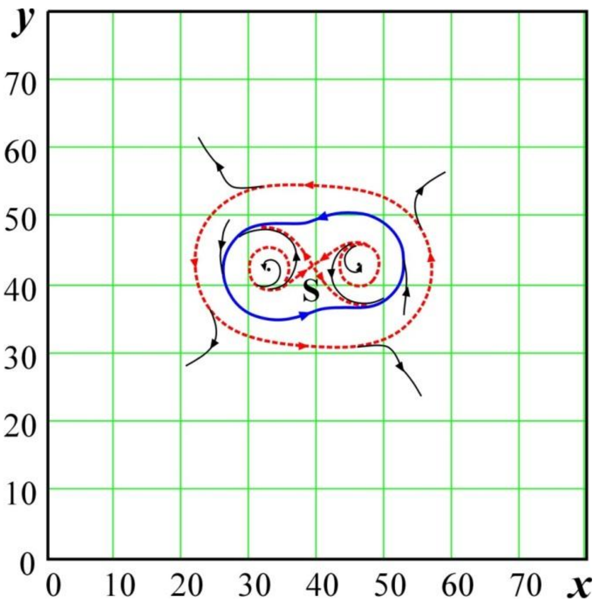
N – node, S - saddle



Weak interaction of two fundamental DOSs



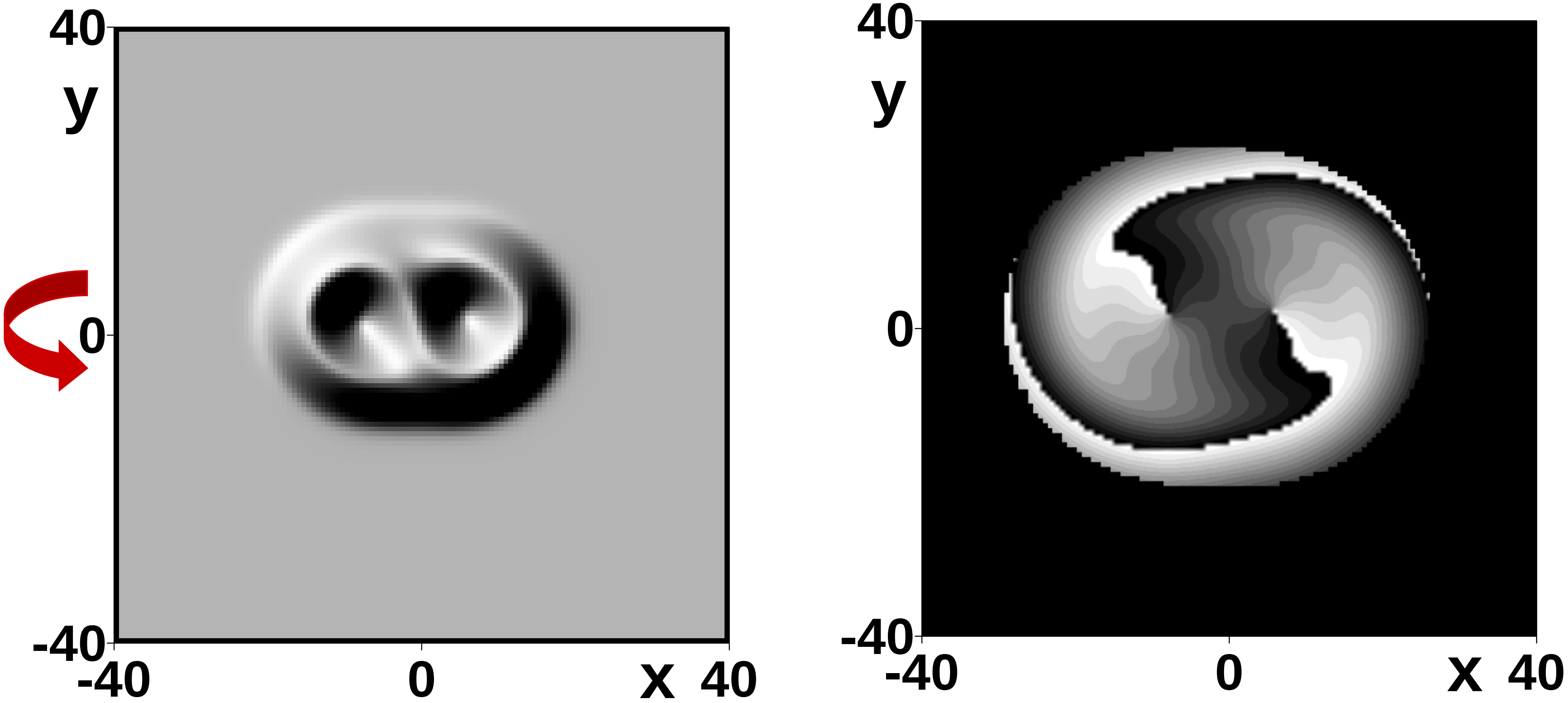
Weak interaction of two vortex DOSs



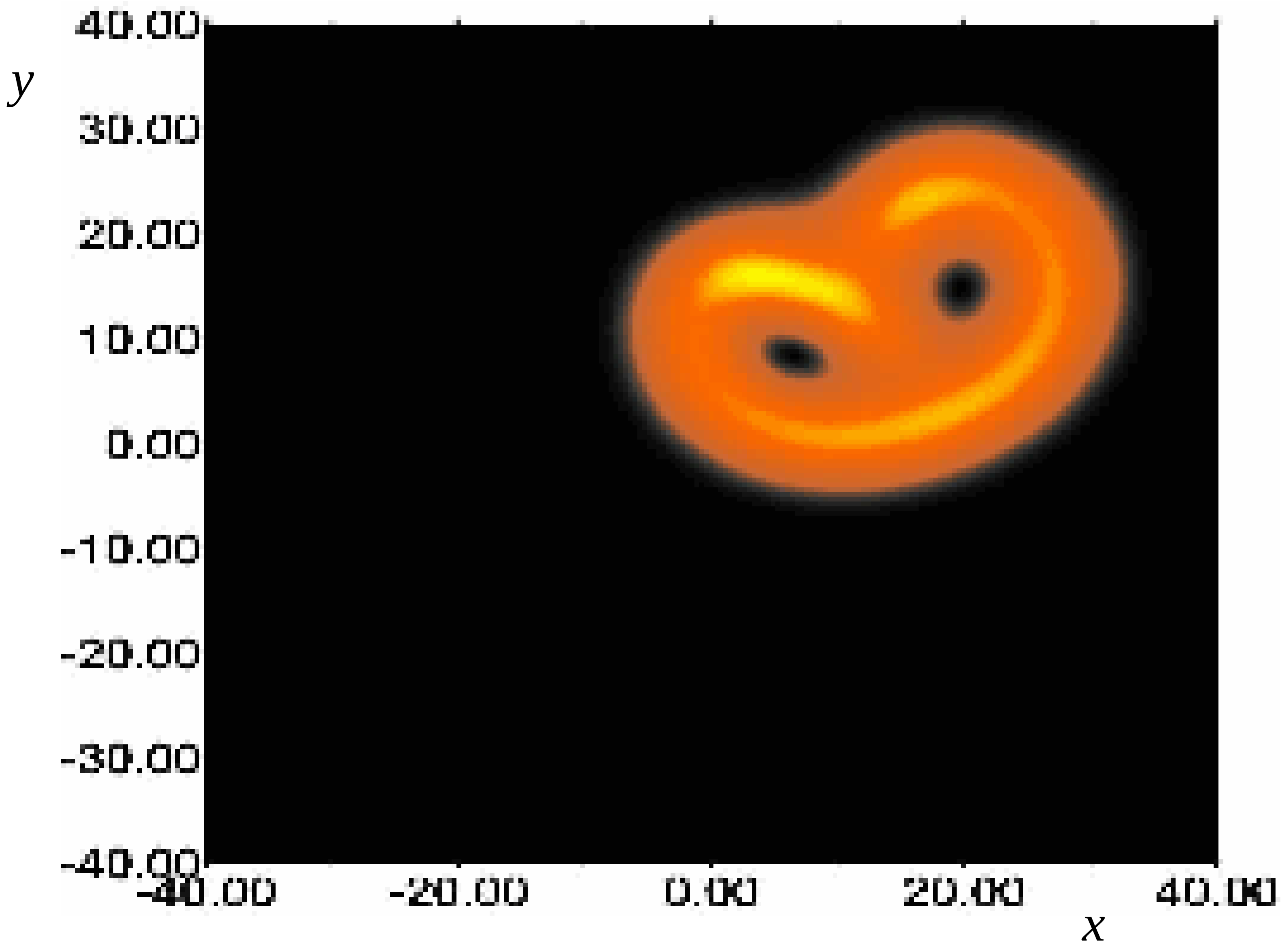
Strong interaction of two vortex DOSs

Rotating Pair of ***STRONGLY*** Coupled Vortex Solitons, $m = 1$

Central symmetry. Rotation, no revolution

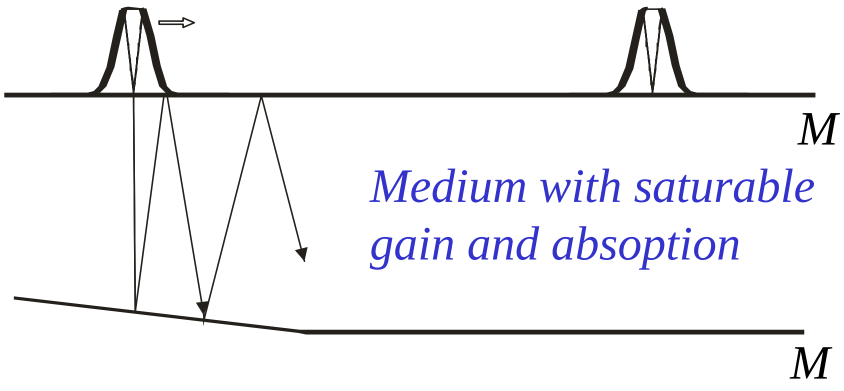


Two-Vortex Laser Soliton*



Formation of Strong Coupling

“Soliton collider”

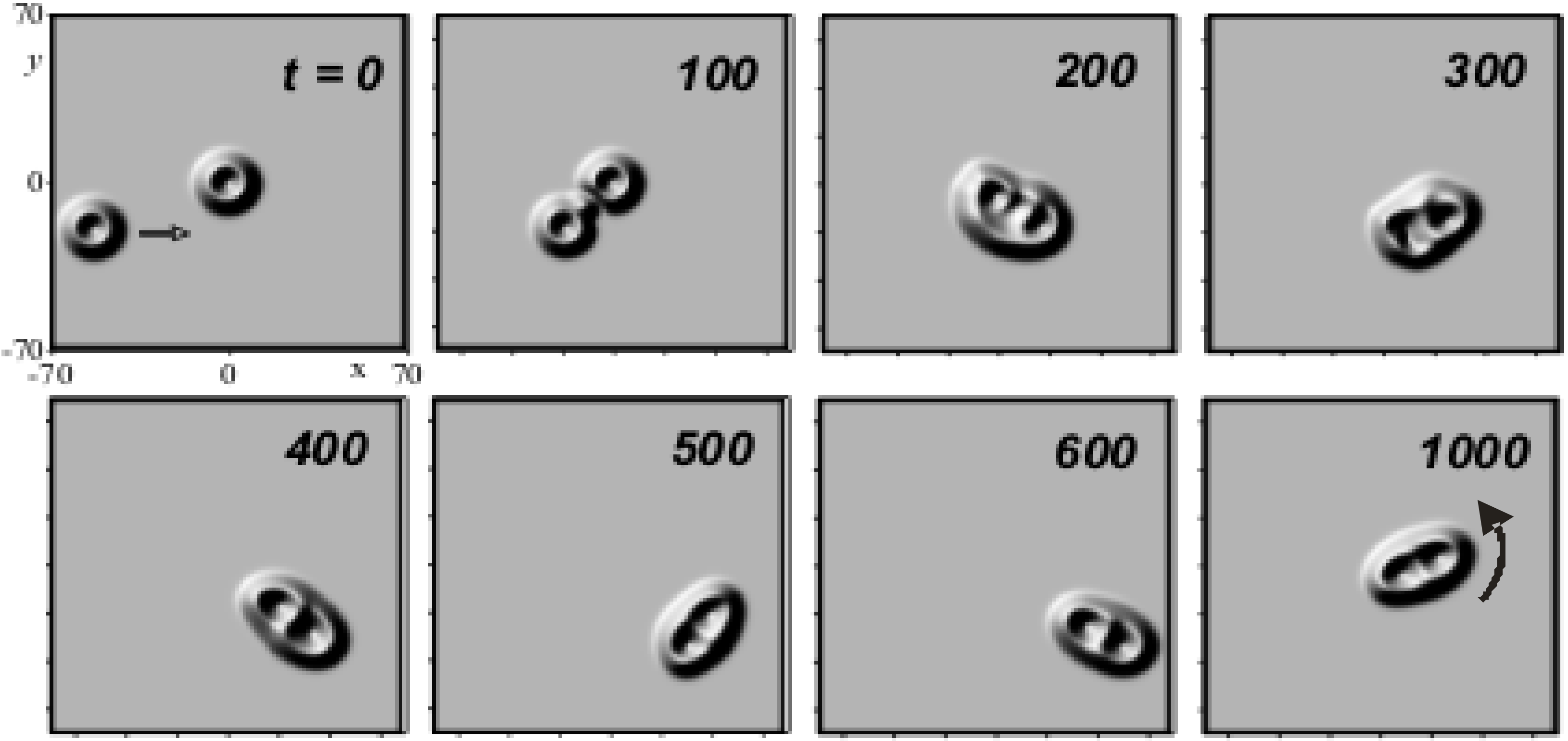


Medium with saturable gain and absoption

acceleration *collision*

M - mirror

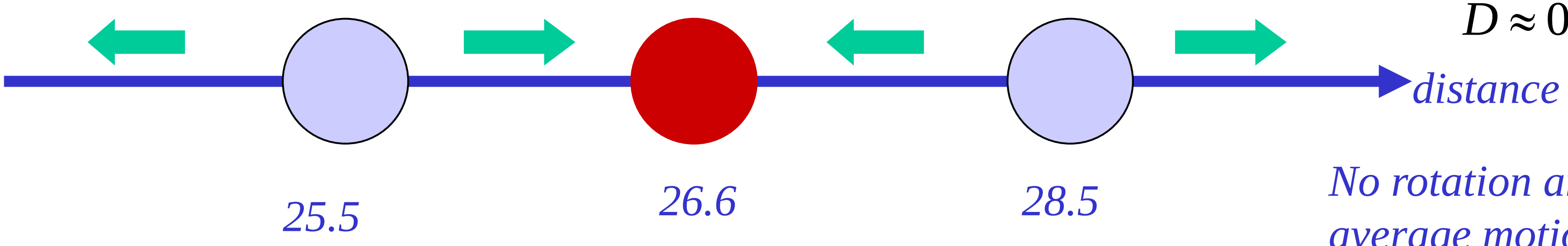
Intensity profiles



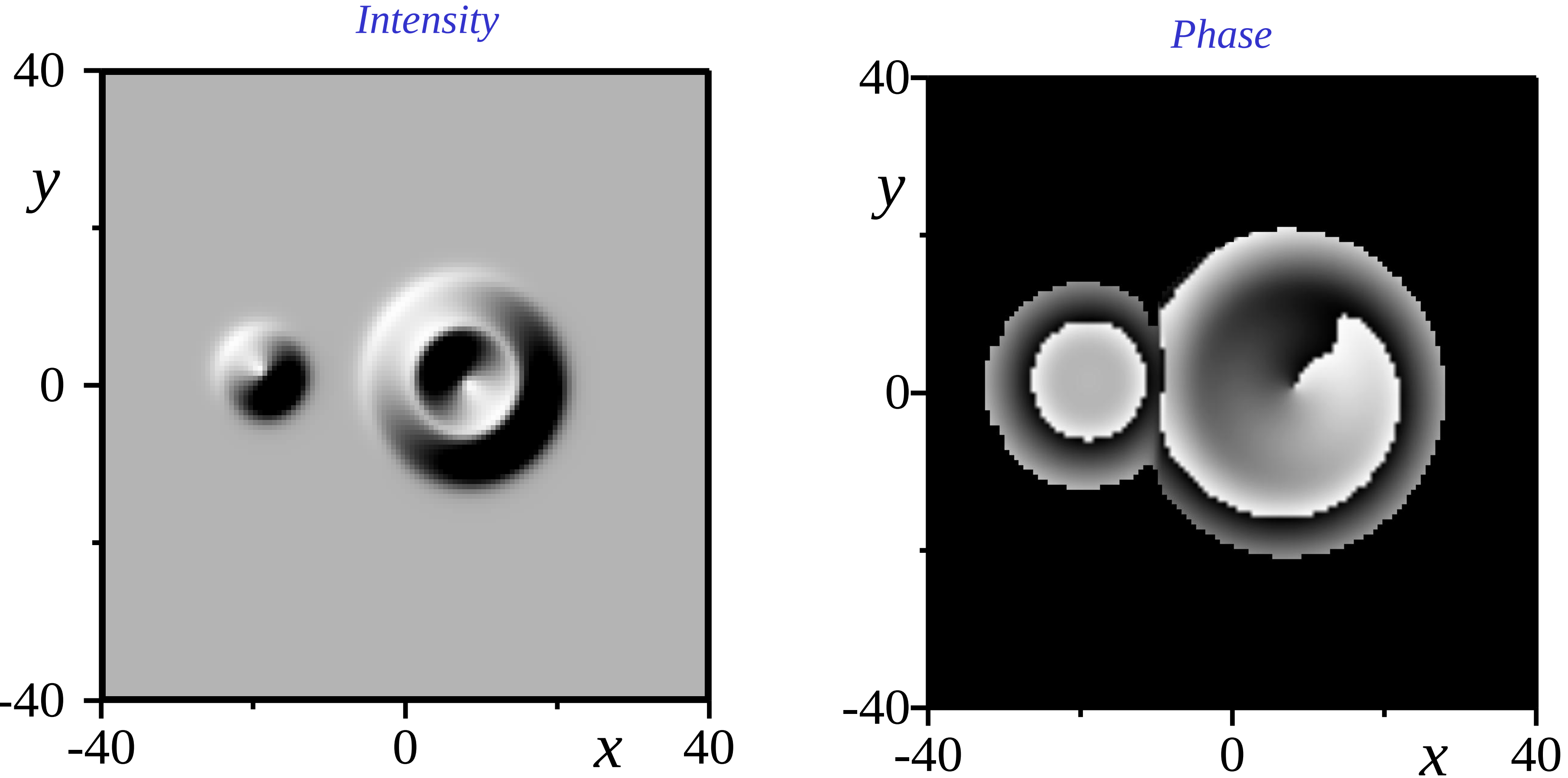
Incoherent coupling: Two laser DOSs with different topological charges and frequencies

$m_1 = 0, m_2 = 1$

$\tilde{D} \approx 0.07$

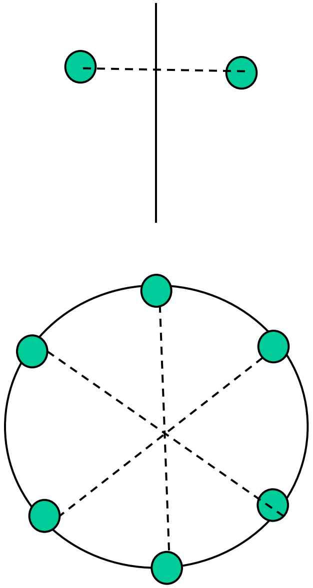


No rotation and average motion



Symmetry Elements

Simultaneous symmetry of instantaneous transverse distributions of intensity and energy flows



1. Axes of symmetry
2. Symmetry to rotation to angle $2\pi/n$, $n = 2, 3, \dots$

We will consider the cases when the symmetry is stable

Below: Four variants of symmetry and motion of stationary "solid-like" soliton complexes [Rosanov 2007]

(Transverse)
Coordinates
of DOS's centre

$$\mathbf{R}_c(t) = \frac{\int \mathbf{r}_\perp |E(\mathbf{r}_\perp) - E_b|^2 \, d\mathbf{r}_\perp}{\int |E(\mathbf{r}_\perp, t) - E_b|^2 \, d\mathbf{r}_\perp}$$

E_b – background field, $E_b = 0$ for laser (not-driven) schemes

Centre velocity: $\mathbf{V}_c(t) = \frac{d}{dt}\mathbf{R}_c$

Eulerian Mechanics (solid-like structures).

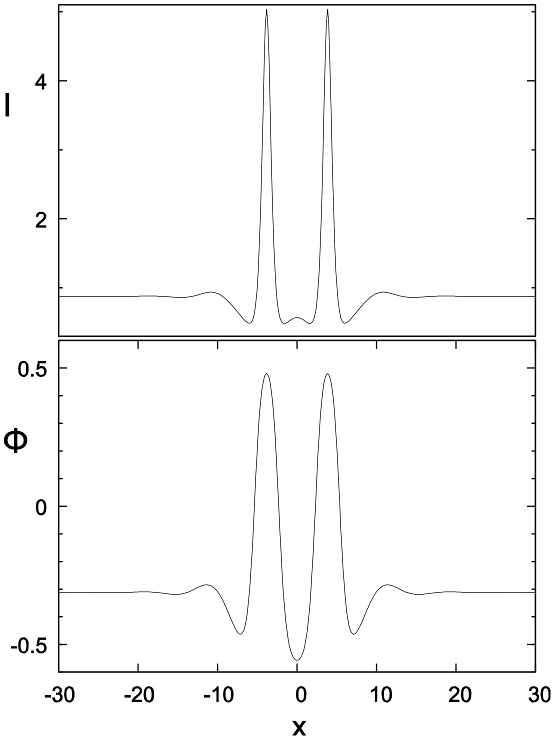
Driven 2D-interferometer (the same for lasers)

1. Two or more axes of symmetry ⟹ No (transverse) motion and rotation

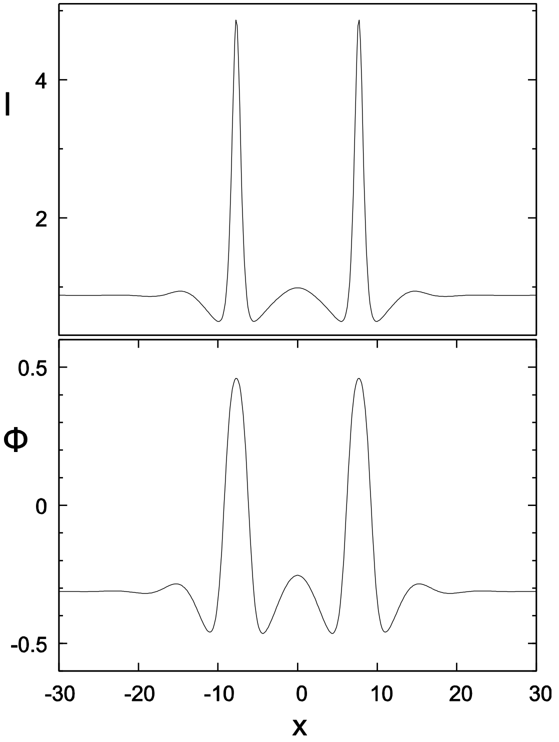
Examples: single DOSs, pairs of DOSs with inter-soliton distances $d_{1,2}$; section $y = 0$

Intensity

Phase



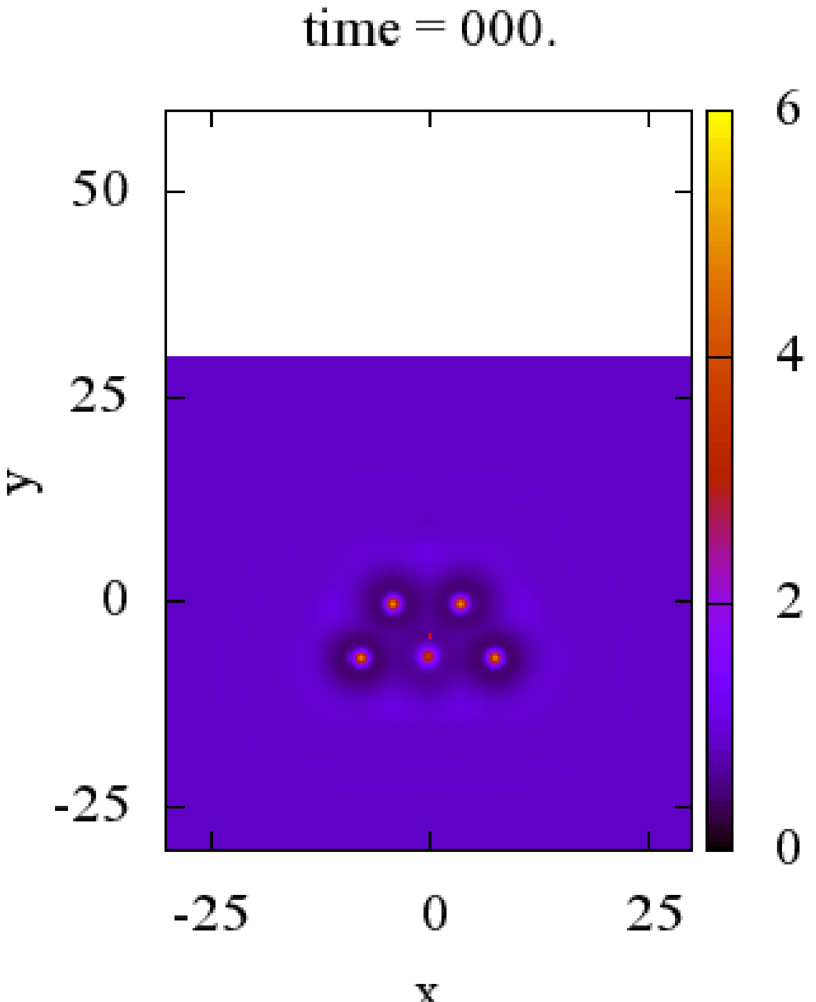
$d_1 = 7.66$



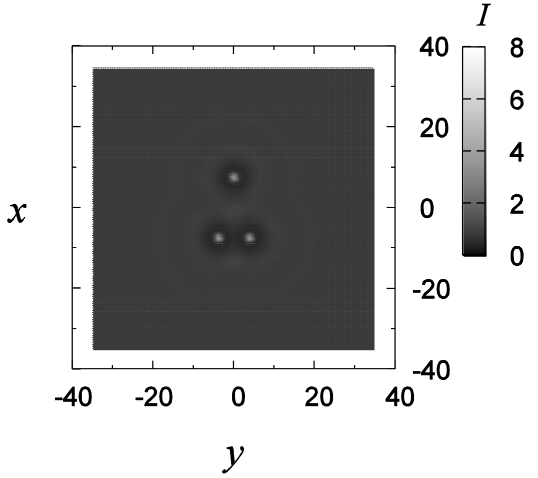
$d_2 = 15.43$

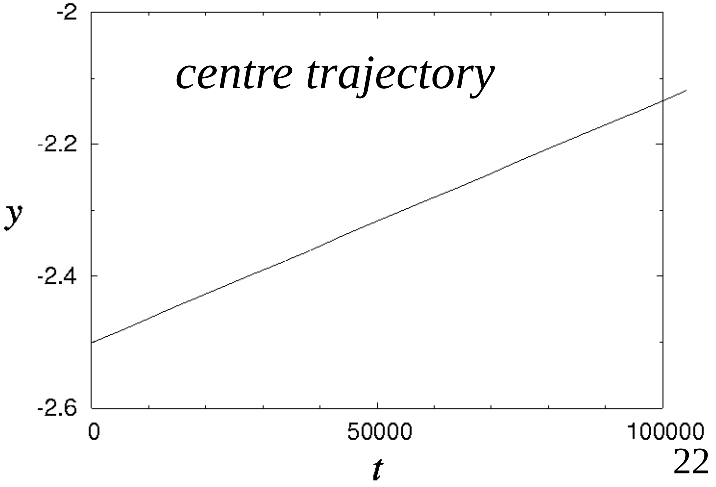
2. Only one axis of symmetry --- In-line motion with constant velocity without rotation

Driven nonlinear interferometer, weakly coupled DOSs



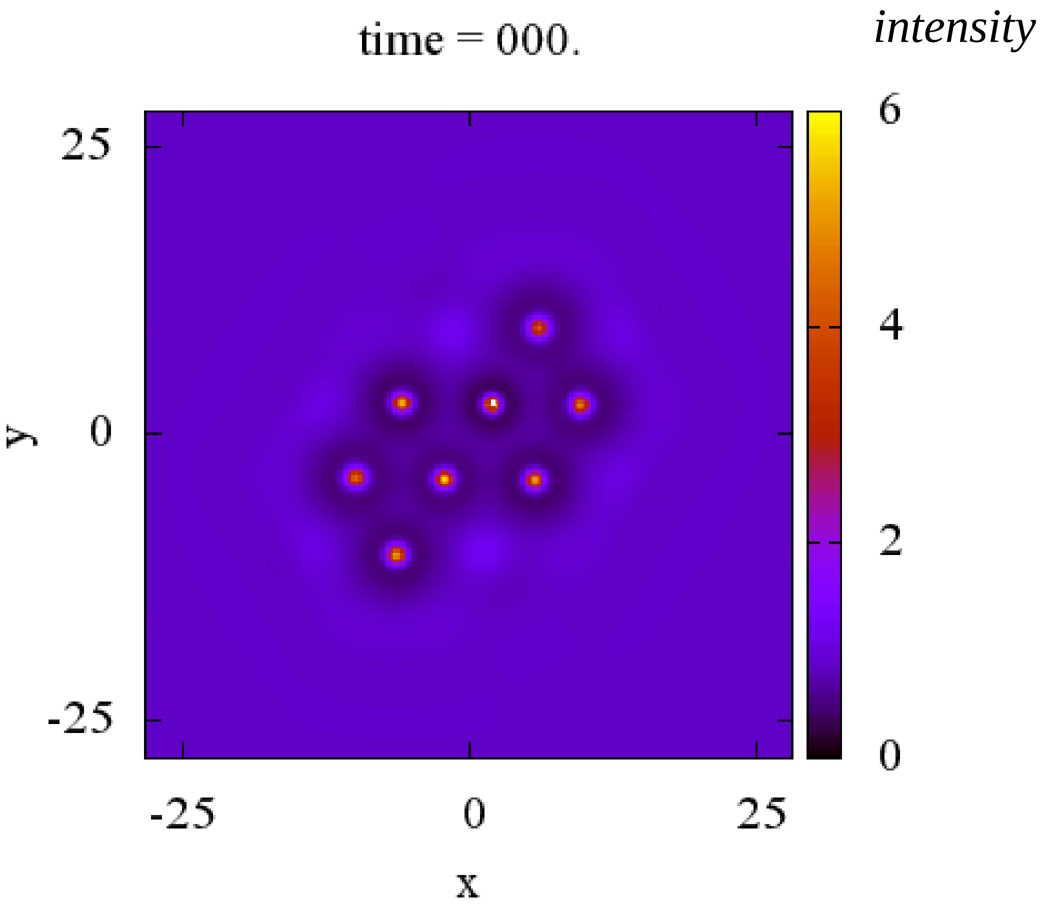
Intensity

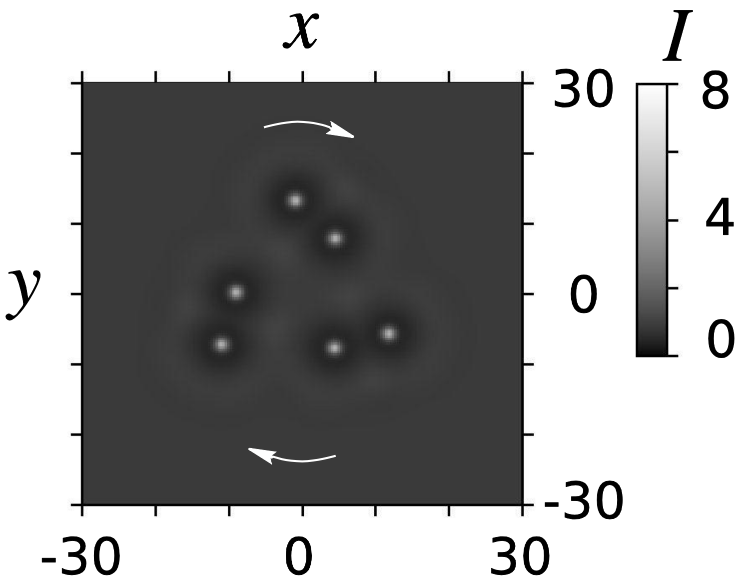




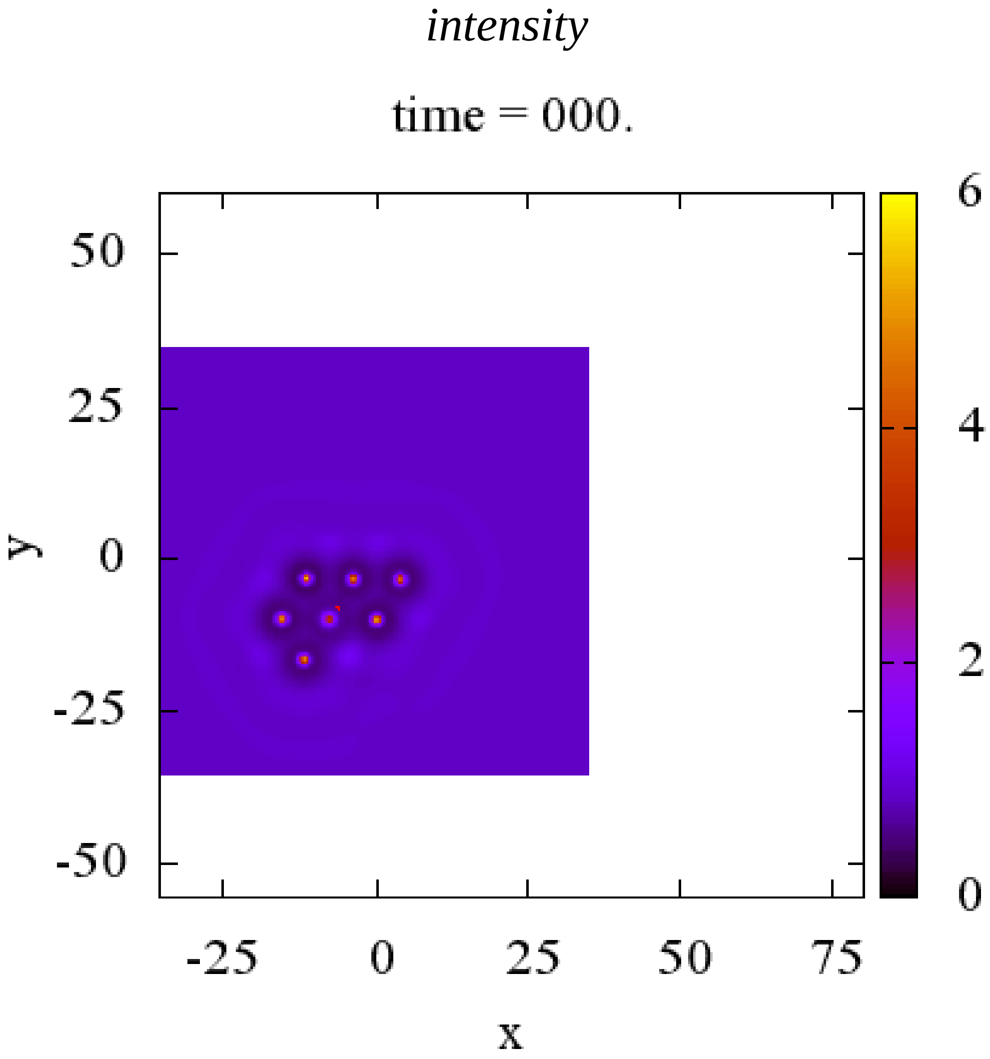
3. Symmetry to rotation --- Rotation with constant angular velocity, no centre motion

Driven nonlinear interferometer





4. No elements of symmetry - Moon-like motion



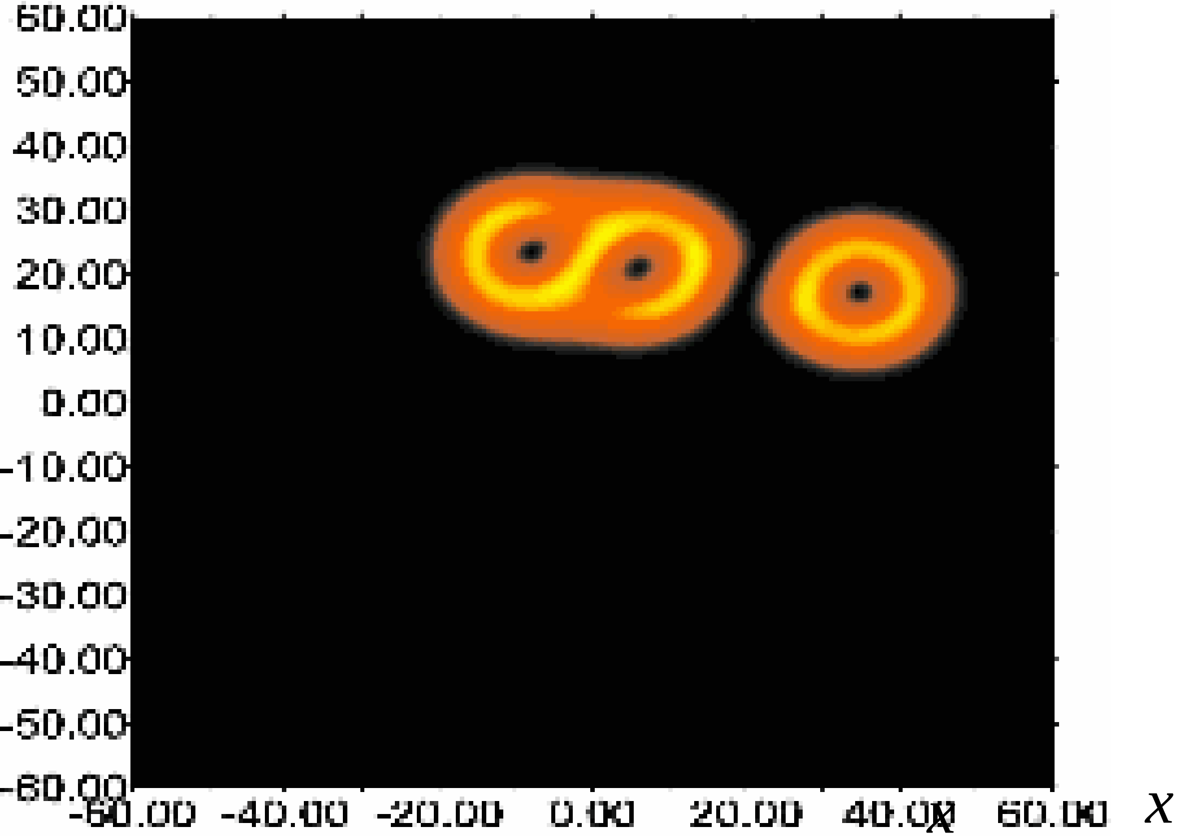
Rotation of asymmetric complex with its simultaneous rotation with the same period

More Complicated Motion of Laser Solitons:“Core” + “satellite”*

Topological charge *m* = 1

“Planetary system”

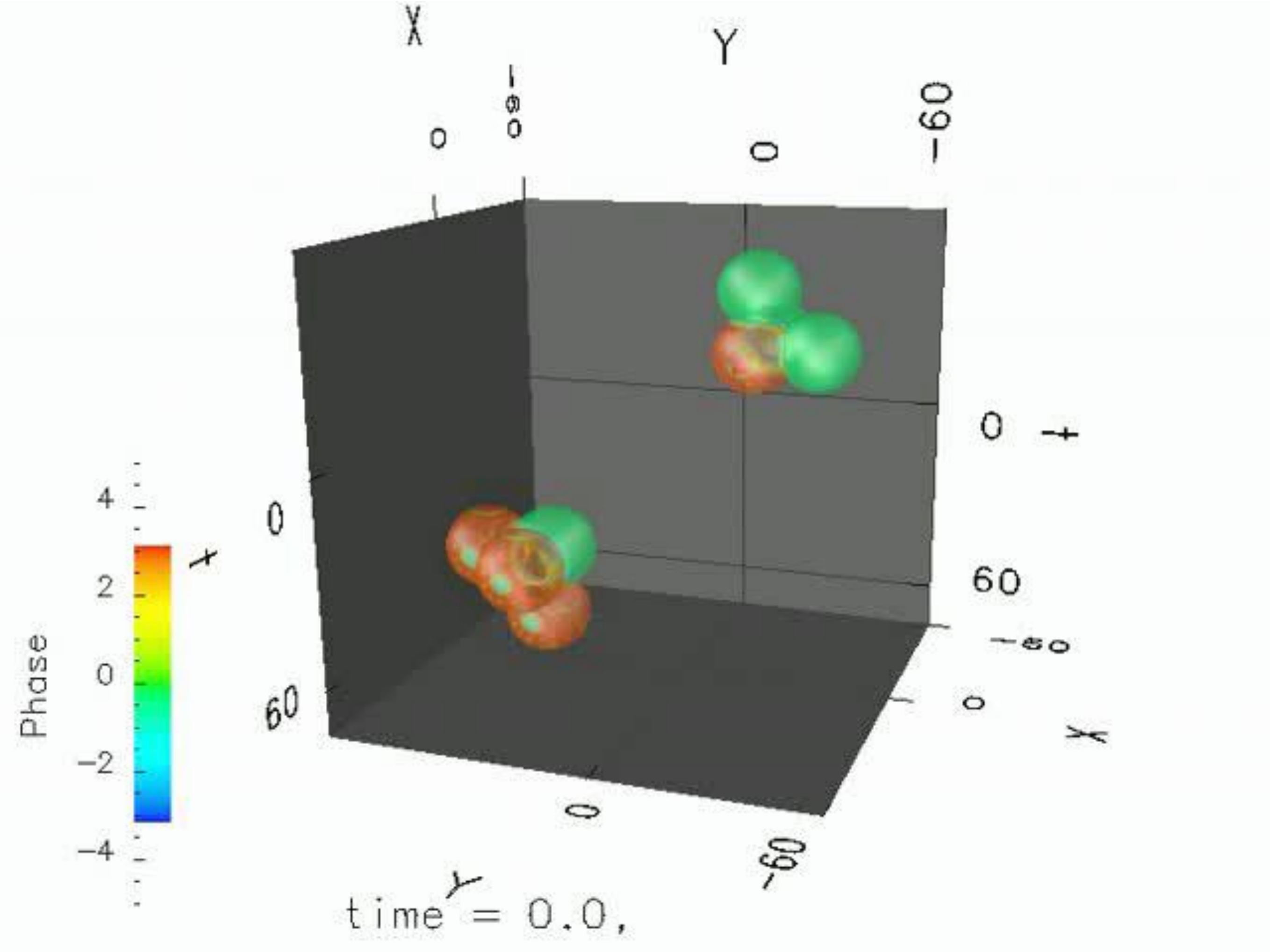
Intensity



“Core” – a rotating pair of strongly coupled vortex solitons.

“Satellite” is weakly coupled with the core, their frequencies differ.

3D-Laser Soliton Complexes and Their Collision*

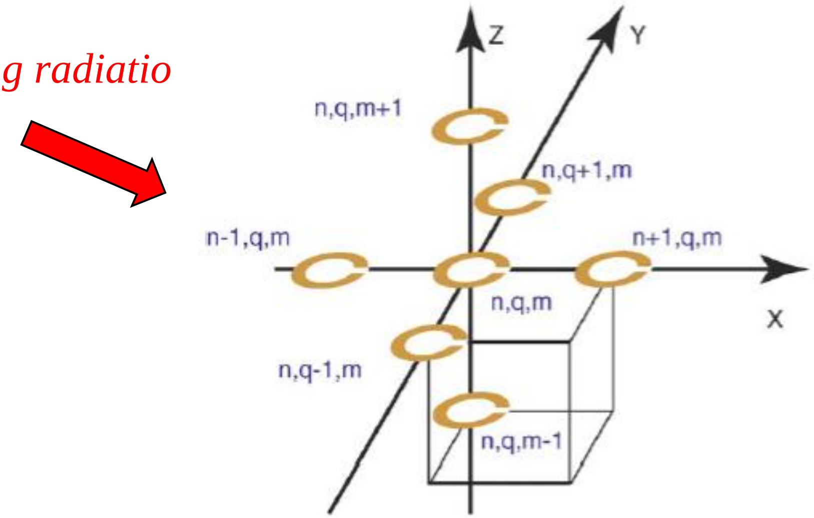


Relative motion in co-propagated system of coordinates

Discrete Dissipative Solitons *(microwaves)*

A cubic lattice of weakly coupled nonlinear split-ring resonators driven by coherent holding radiation

Holding radiatio



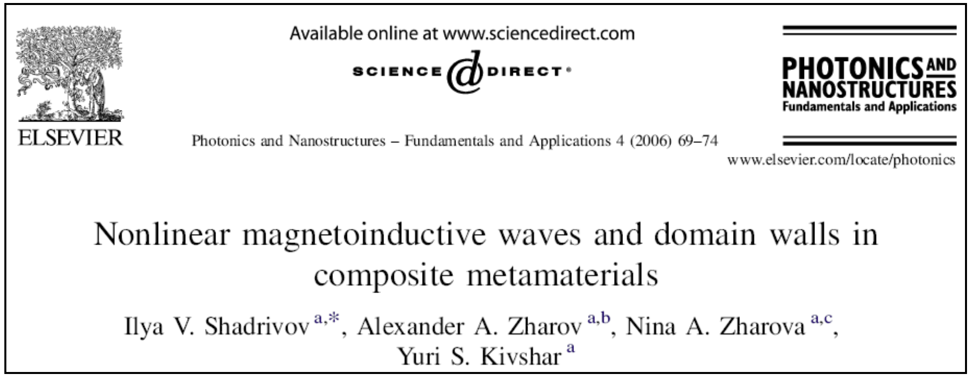
$$i\frac{d}{d\tau}\Psi_{n.q.m}-(2\Omega-i\gamma+\alpha|\Psi_{n.q.m}|^2)\Psi_{n.q.m}-\Sigma=$$

$$2\kappa(\Psi_{n.q.m+1}+\Psi_{n.q.m-1}-2\Psi_{n.q.m})-$$

$$\kappa(\Psi_{n+1.q.m}+\Psi_{n-1.q.m}+\Psi_{n.q+1.m}+\Psi_{n.q-1.m}-4\Psi_{n.q.m})$$

Ψ – magnetization, Ω – frequency detuning, γ – losses,
Σ – holding radiation amplitude, κ – coupling coefficient
Analytical perturbation approach for weak coupling

Discrete Dissipative Solitons, 1D and 2D



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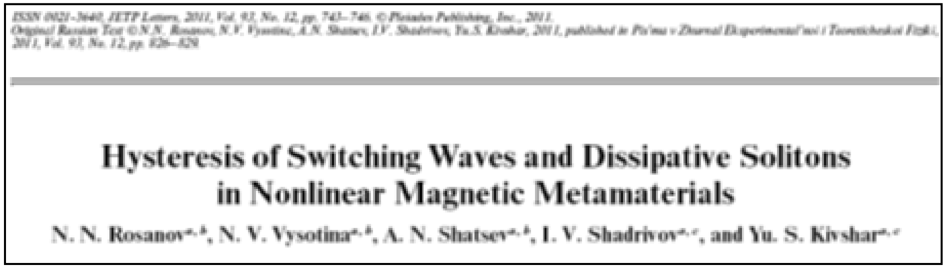
Nonlinear magnetoinductive waves and domain walls in composite metamaterials

Ilya V. Shadrivov [a,*], Alexander A. Zharov [a,b], Nina A. Zharova [a,c], Yuri S. Kivshar [a]



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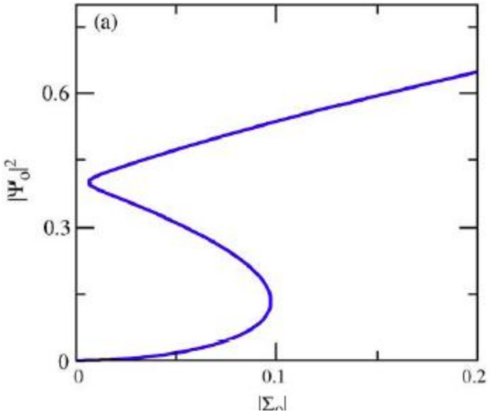
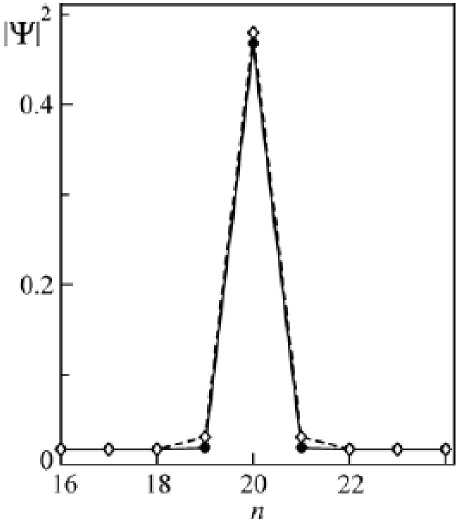
Hysteresis of Switching Waves and Dissipative Solitons in Nonlinear Magnetic Metamaterials

N. N. Rosanov [a, b], N. V. Vysotina [a, b], A. N. Shatsev [a, b], I. V. Shadrivov [a, c], and Yu. S. Kivshar [a, c]

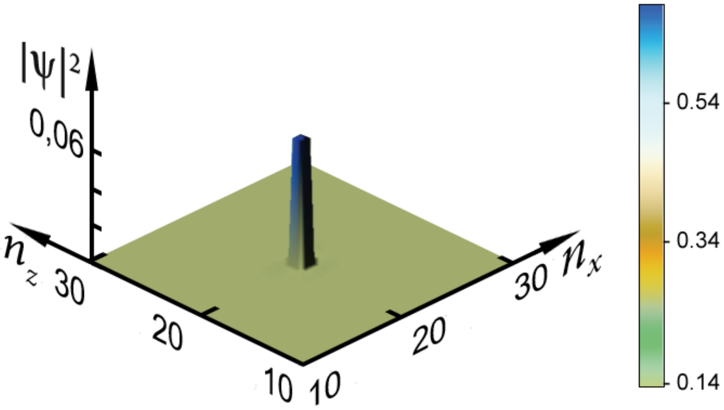


Bistability

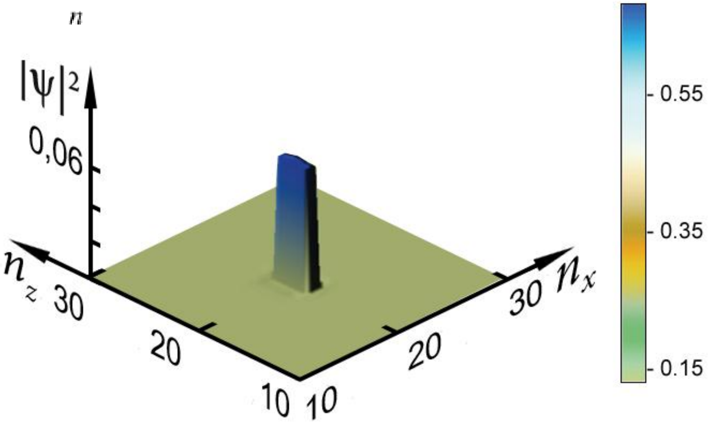


Perturbation theory with weak coupling

1D-discrete DOS

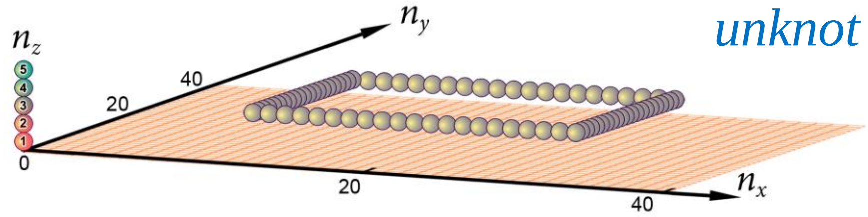


2D-discrete DOSs



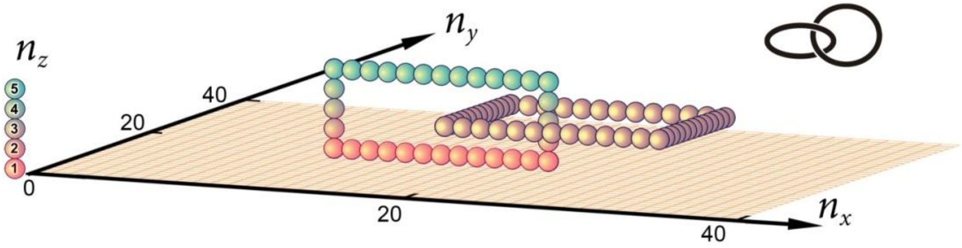
3D-Topological Discrete Solitons

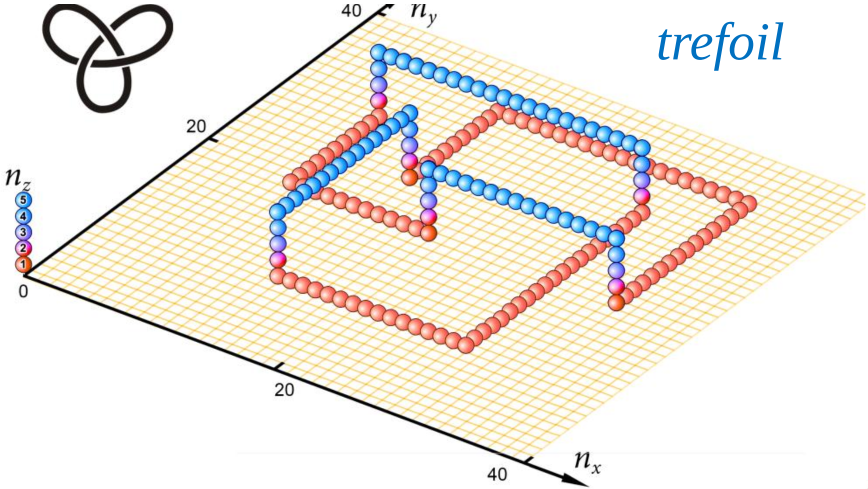
Knots - closed lines without intersections – location of elements excited to the upper state



unknot

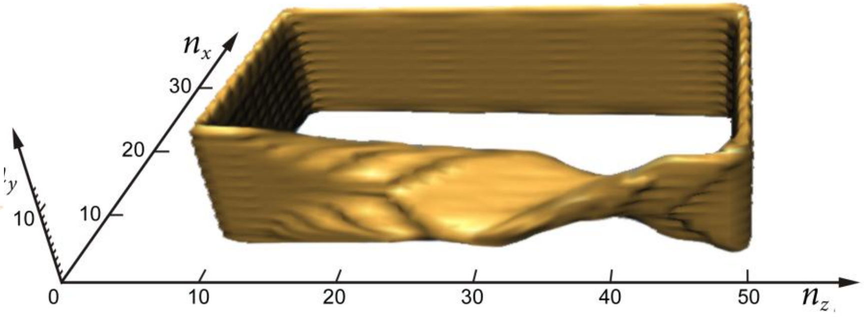
Hopf link



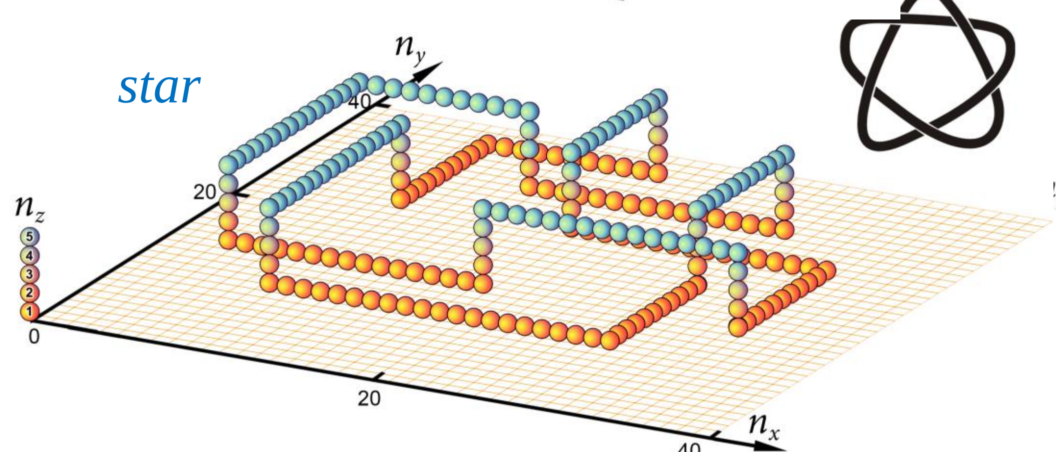


trefoil

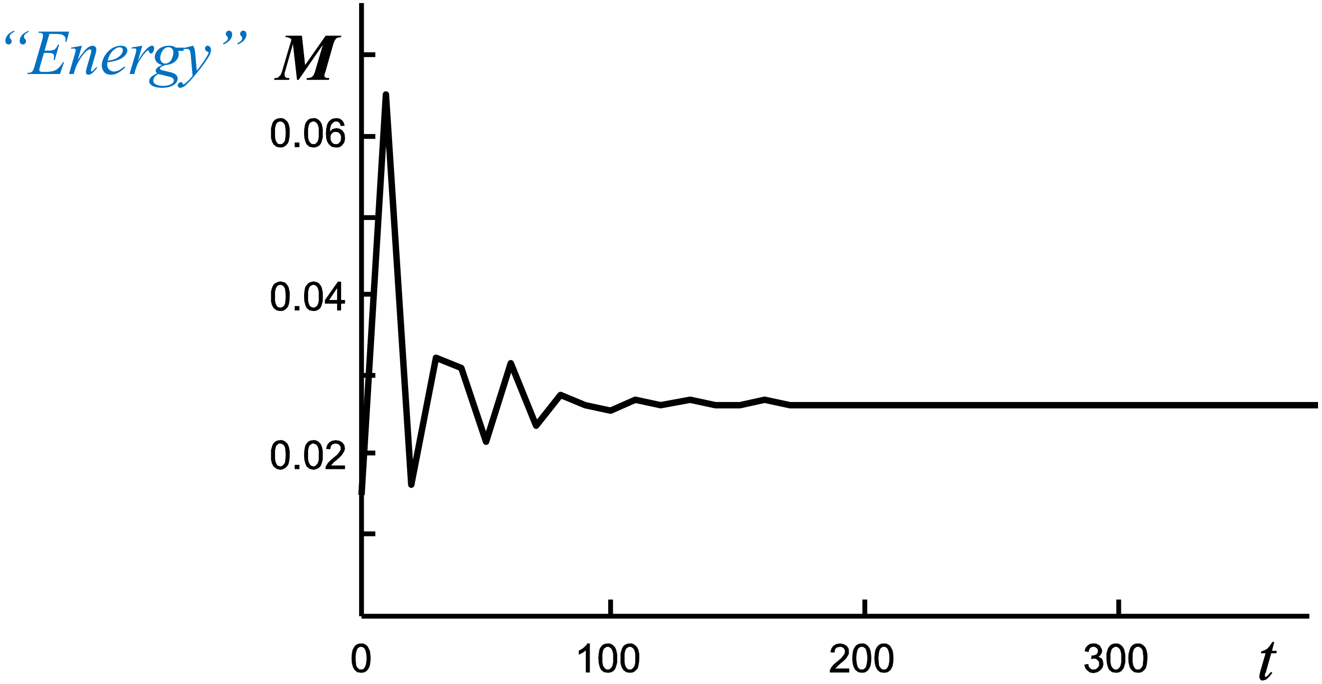
Möbius-like band



star

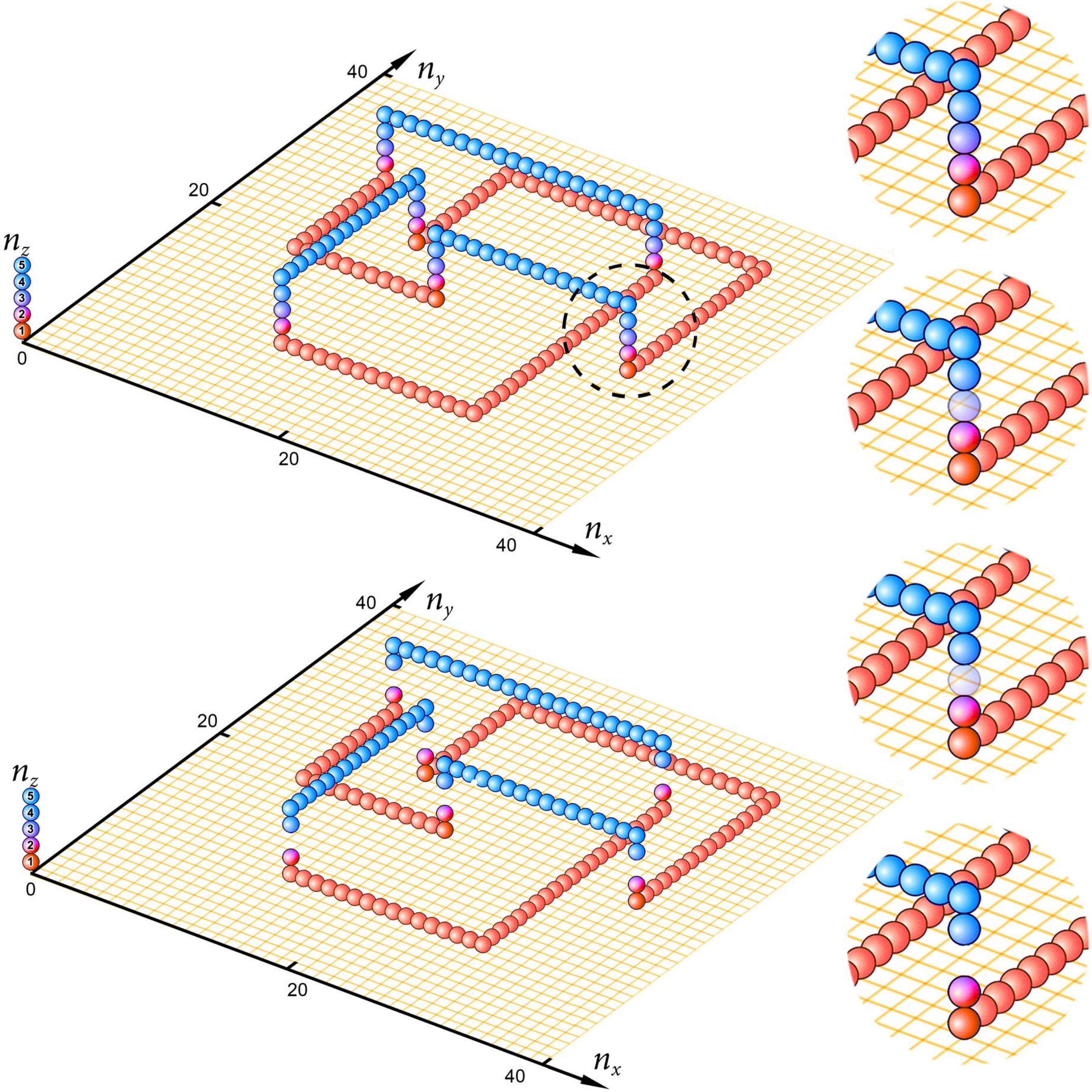


Stability



Transient period

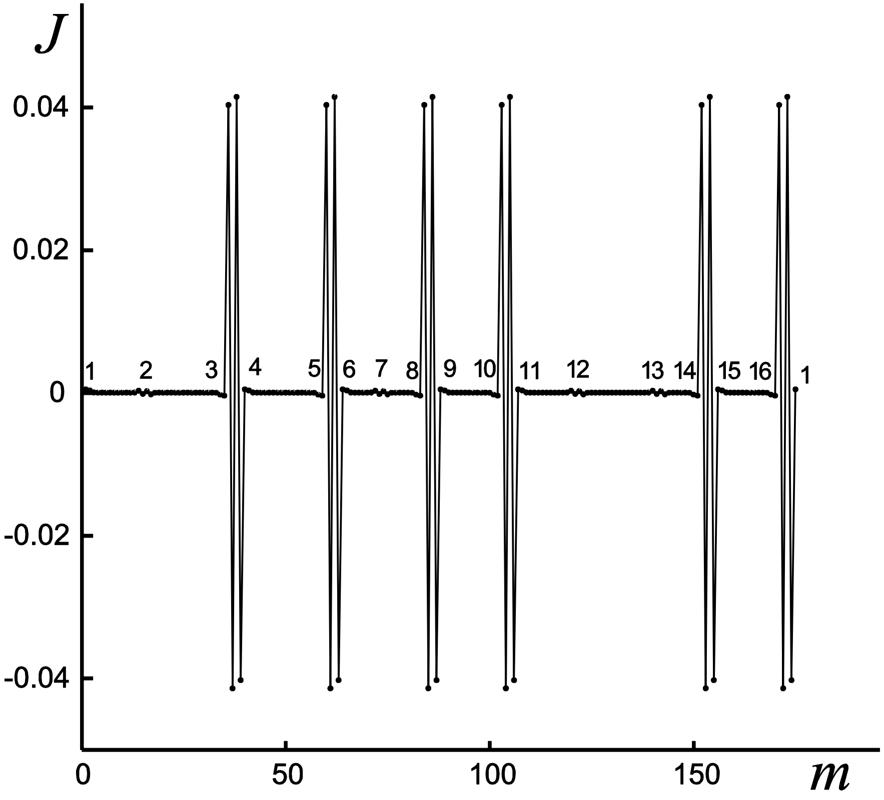
Decay of trefoil with increase of coupling coefficient

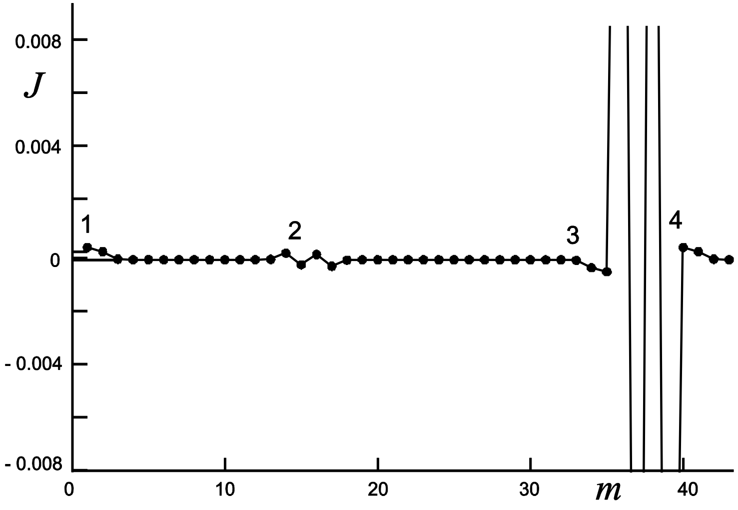


The scheme is highly anisotropic

Line disintegration

Discrete Currents





$$J_m = 2\,\mathrm{Im}(\Psi^*_m \Psi_{m+1})$$

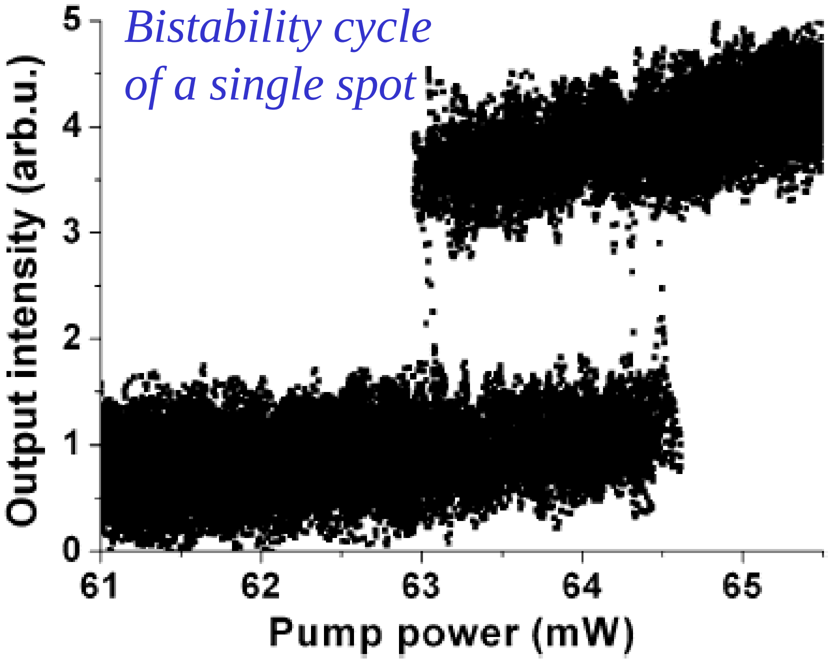
Experiments

T. Elsass, K. Gauthron, G. Beaudoin, I. Sagnes, R. Kuszelewicz, S. Barbay. Fast manipulation of laser localized structures in a monolithic vertical cavity with saturable absorber. Appl. Phys. B ***98****, 327 (2010).*

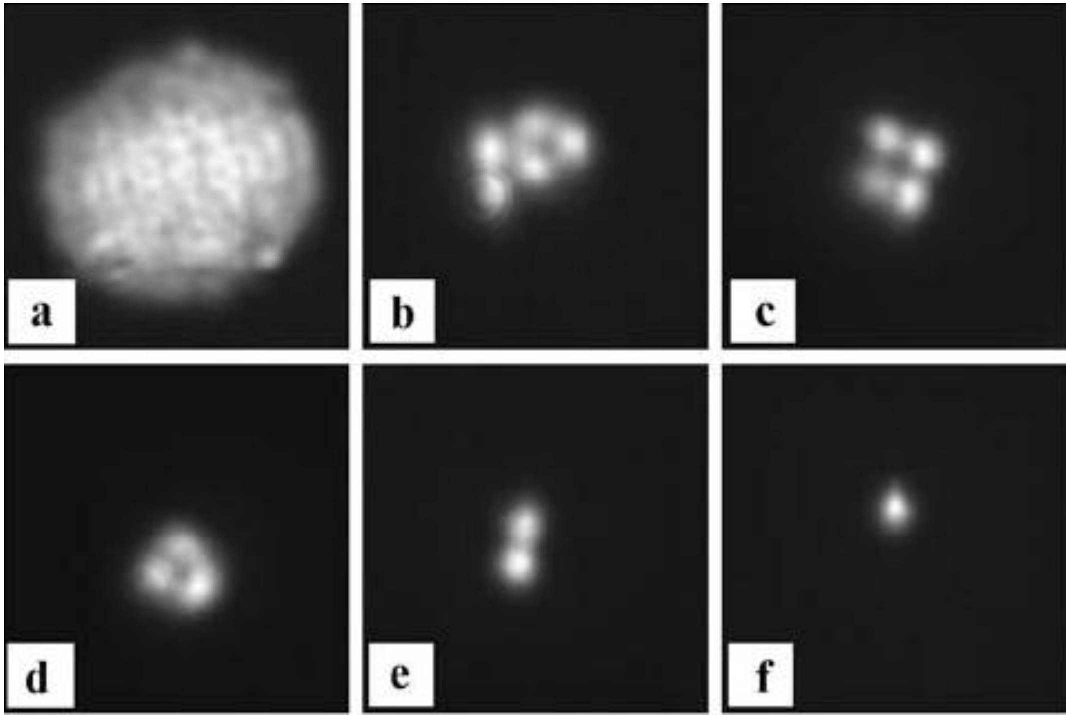
VCSEL, gain – two quantum wells
$In_{0.2}Ga_{0.8}As/Al_{0.05}Ga_{0.95}As$.
A saturable absorber: one quantum well
$In_{0.2}Ga_{0.8}As/Al_{0.22}Ga_{0.78}As$

Pump power = 20 – 130 mW

Writing process ~ 10 ns, erasure < 1 ns



Bistability cycle of a single spot

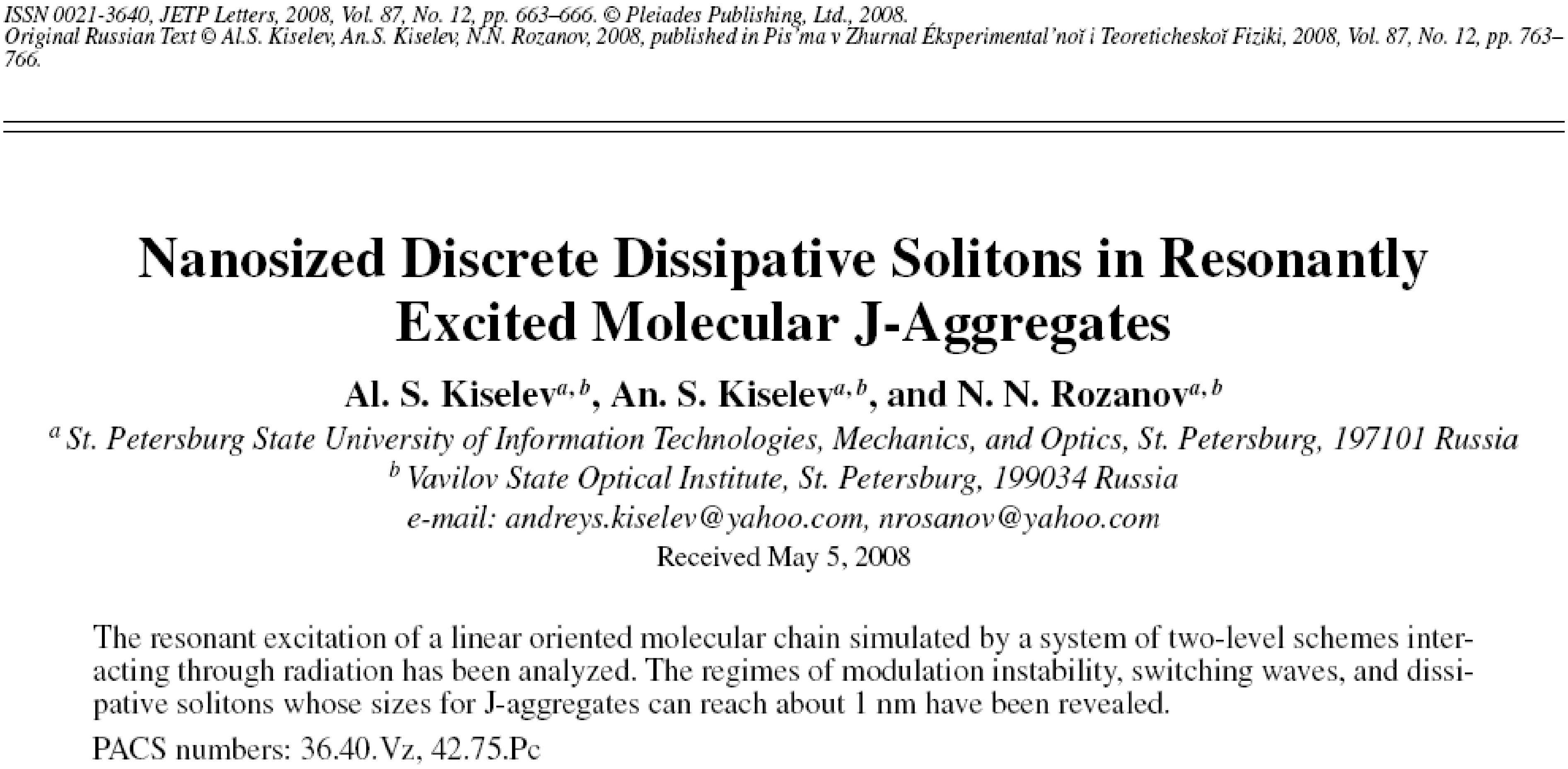


a – lasing over the whole aperture
b-e – complexes of DOSs
f – a single DOS

Promising scheme: quantum dot laser with saturable absorber.

Extreme DOSs. Nanosolitons

DISSIPATIVE MOLECULAR SOLITONS IN LINEAR ORIENTED MOLECULAR J-AGGREGATES DRIVEN WITH LASER RADIATION



ISSN 0021-3640, JETP Letters, 2008, Vol. 87, No. 12, pp. 663–666. © Pleiades Publishing, Ltd., 2008.
Original Russian Text © Al.S. Kiselev, An.S. Kiselev, N.N. Rozanov, 2008, published in Pis'ma v Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki, 2008, Vol. 87, No. 12, pp. 763–766.

Nanosized Discrete Dissipative Solitons in Resonantly Excited Molecular J-Aggregates

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Received May 5, 2008

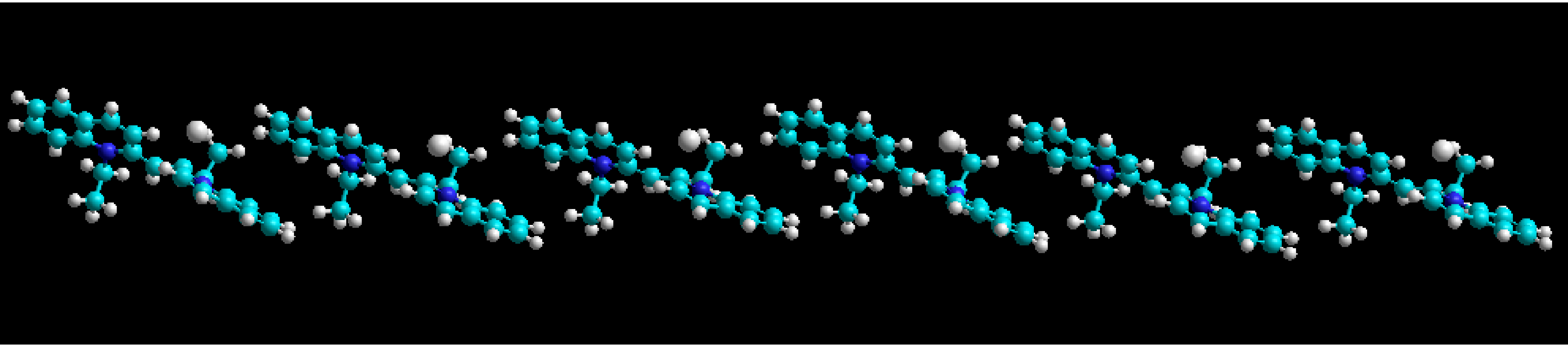
The resonant excitation of a linear oriented molecular chain simulated by a system of two-level schemes interacting through radiation has been analyzed. The regimes of modulation instability, switching waves, and dissipative solitons whose sizes for J-aggregates can reach about 1 nm have been revealed.

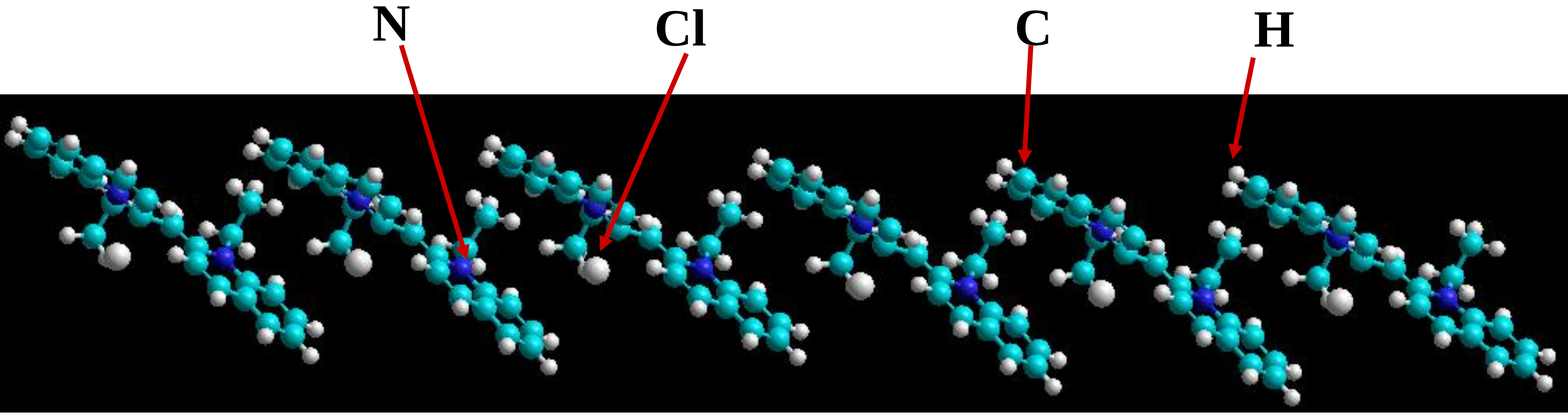
PACS numbers: 36.40.Vz, 42.75.Pc

Linear oligomers of molecules pseudoisocyanine-chloride $\mathbf{PIC_n:Cl_n}$

PIC = ***Pseudoisocyanine***

Stable configuration:



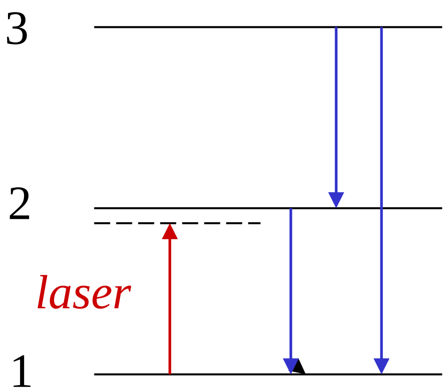


Quantum-chemistry code GAMES
[V.G. Maslov]

Metastable configuration

Simplified Model

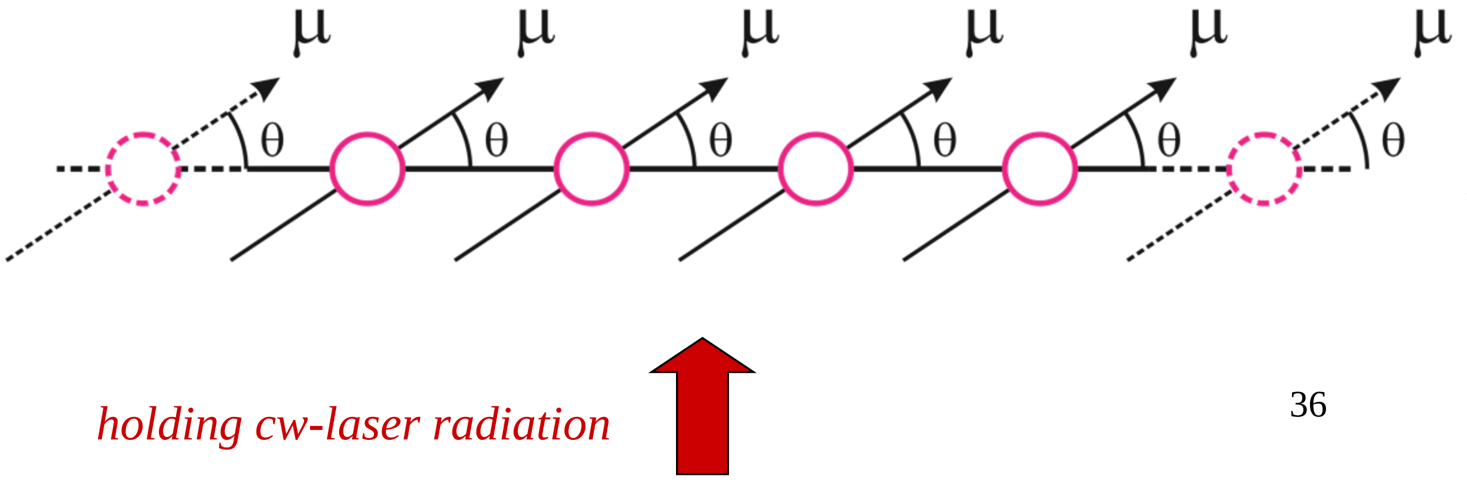
One-particle density matrix approach; three-level scheme of electronic transitions; bistability [Malyshev et al. 1998]



~ *quantum-mechanical Neuman (Bloch) equations for density matrix*

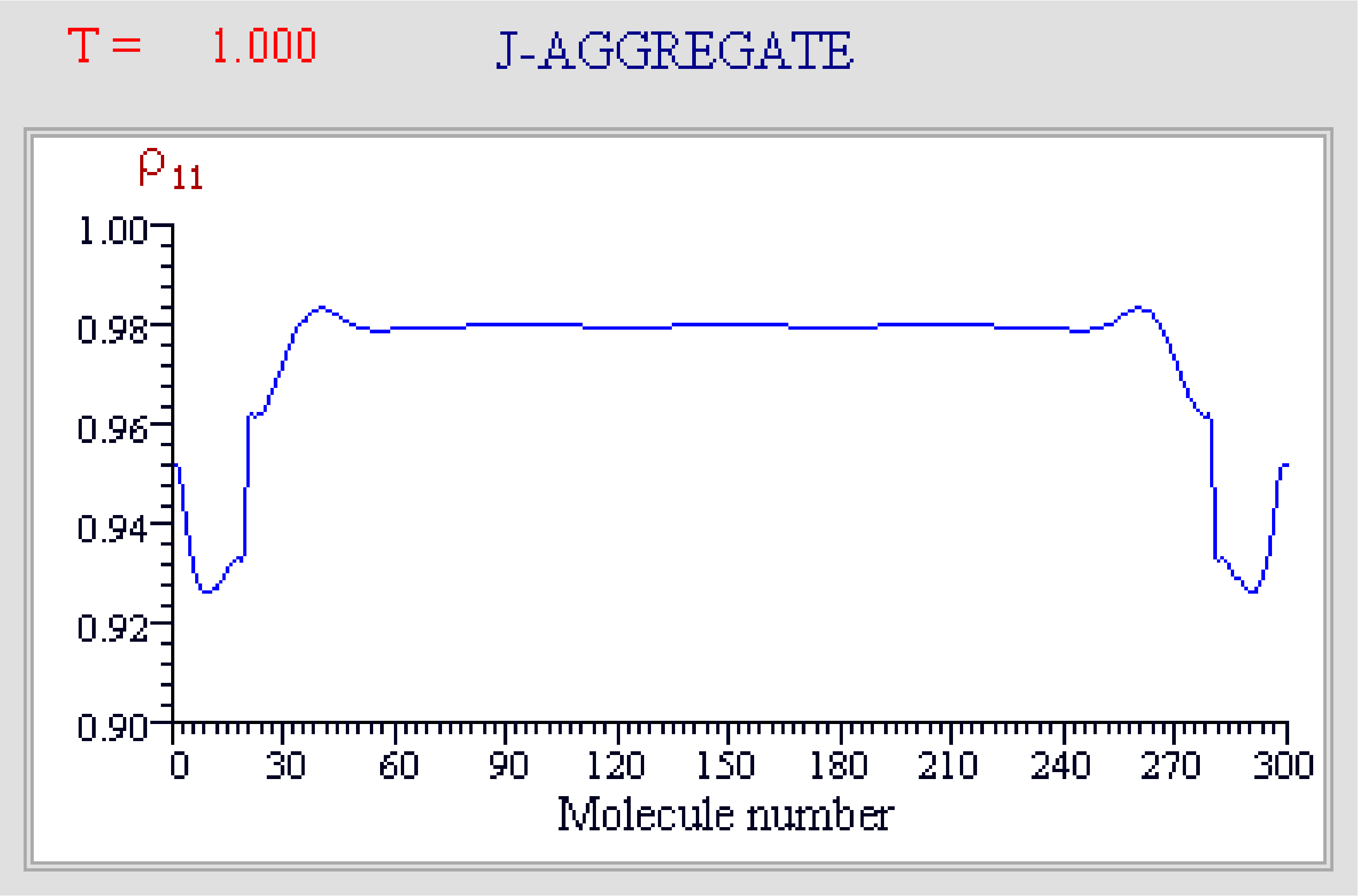
Interaction of molecules via radiation

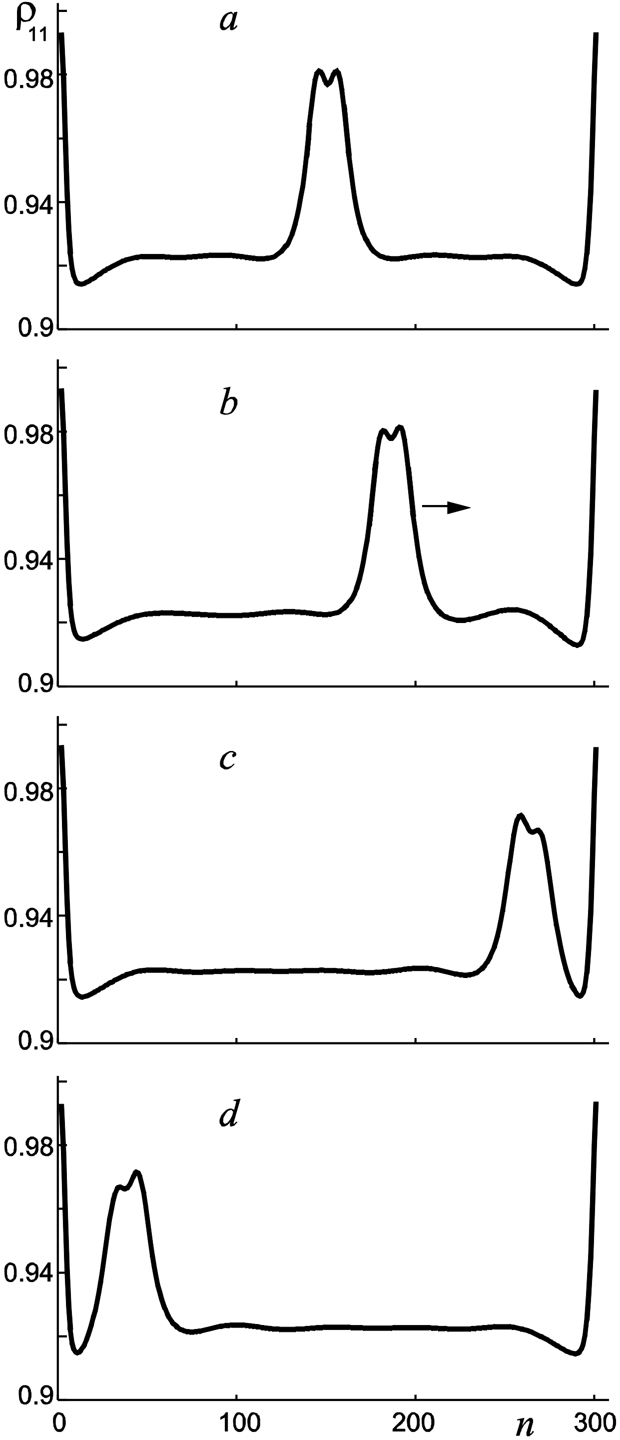
$$E_n = E_{laser} + \sum_{m \neq n} E_{mn}$$



holding cw-laser radiation

Nanosoliton Formation*





Controlling Soliton Position

Oblique incidence of laser radiation

(a) angle of incidence φ = 0,
motionless soliton;
(b) φ = 0.1, soliton moves to the right;
(c) φ = 0.1, soliton stops
near the chain right edge;
(d) φ = - 0.1, soliton moves to the left
and stops near the chain left edge.

Soliton can be moved through
the whole molecular chain
in both directions

Towards Attosolitons: Few-cycle dissipative optical solitons

Idea: Self-induced transparency, effect of dissipative factors

Scheme: single-mode fiber doped with active (with pump) and passive (without pump) centres (atoms, ions, quantum dots).

Without active centres and dissipative factors, conservative solitons of self-induced transparency form a family with continuously varying parameter (maximum intensity and corresponding width).

After introduction of weak linear small-signal gain, there is transition in the family to solitons with higher intensity and smaller width (collapse).

When any mechanism arrests the collapse, extremely short localized pulses with extremely high peak intensity should occur.

N. V. Vyssotina, N. N. Rosanov, V. E. Semenov, S. V. Fedorov, S. Wabnitz, 2006

Model

Radiation propagation: 1D (plane waves), fixed polarization

Full wave equation:

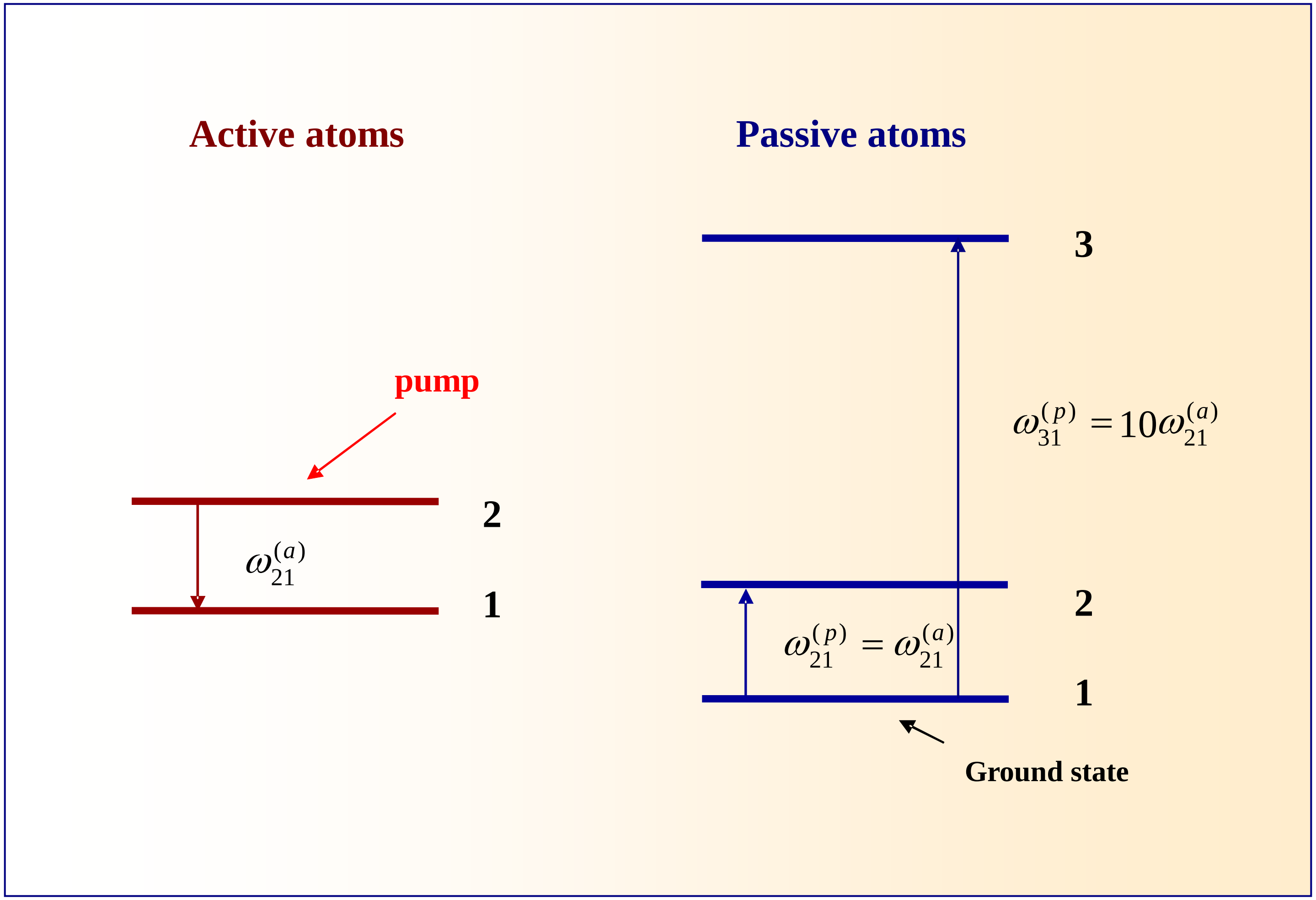
$$\frac{\partial^2 E}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}(E + 4\pi P) = 0$$

E – electric field
t – time,
z – propagation coordinate
c – light velocity in vacuum
P – medium polarization

No approximations of slowly varying amplitude and unidirectional propagation

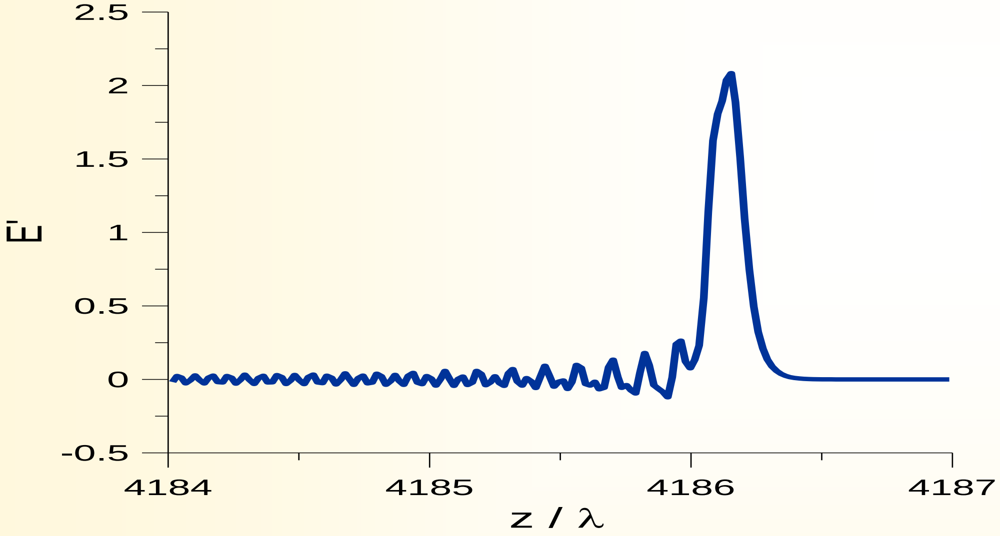
Constitutive equations – quantum mechanical Neuman (Bloch) equations for density matrix

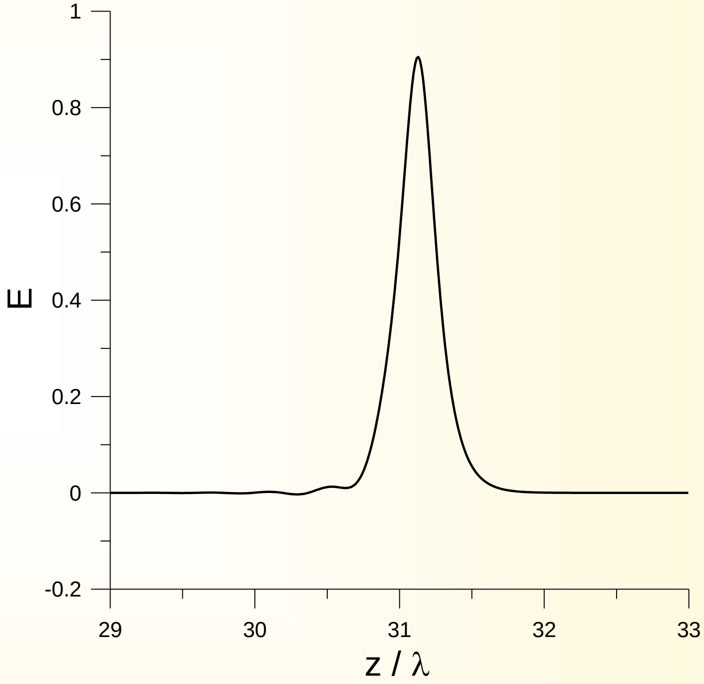
Variant: Three-level passive atoms + two-level active atoms



Examples of stable video-solitons

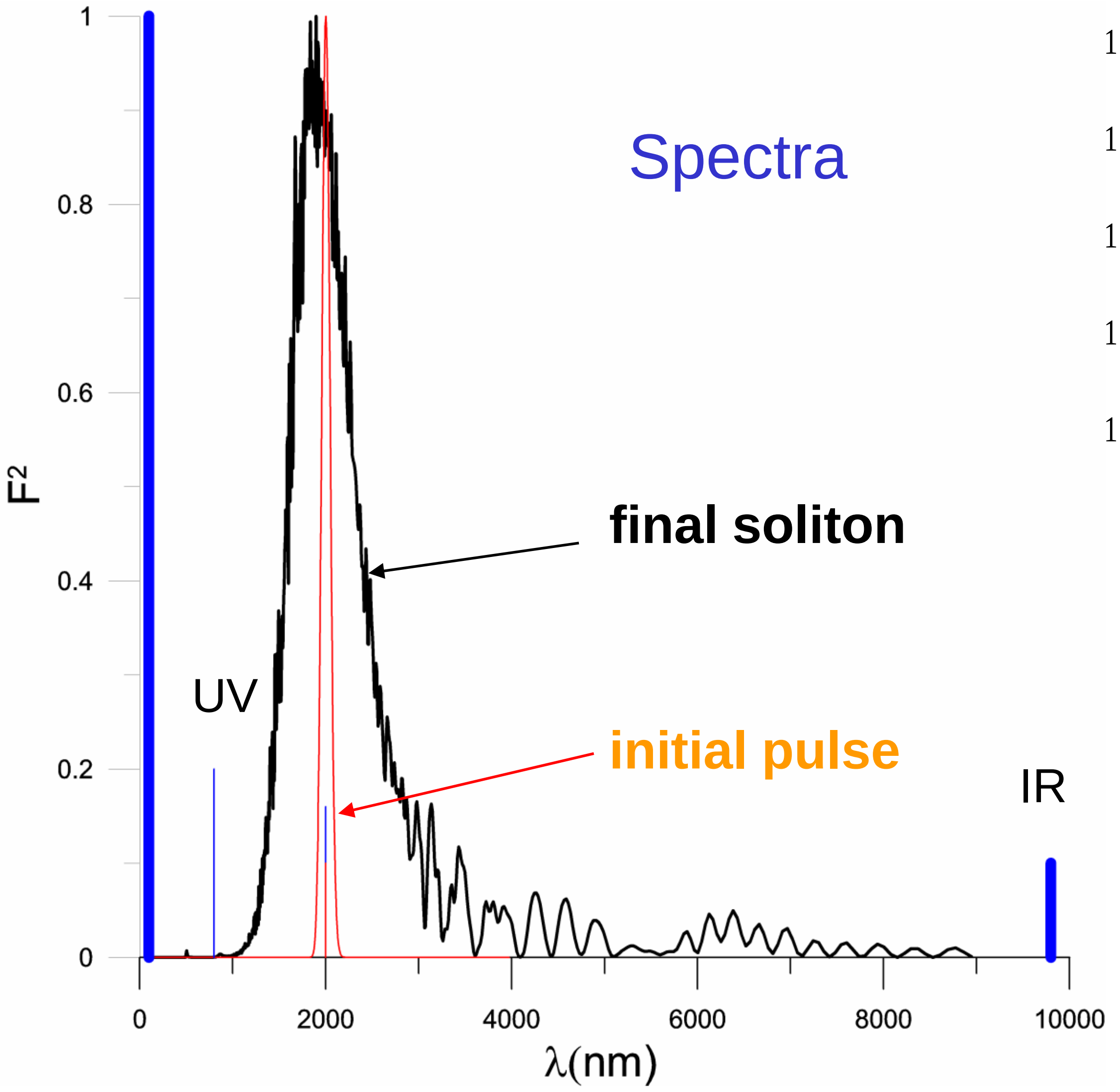
(full field, not envelope)

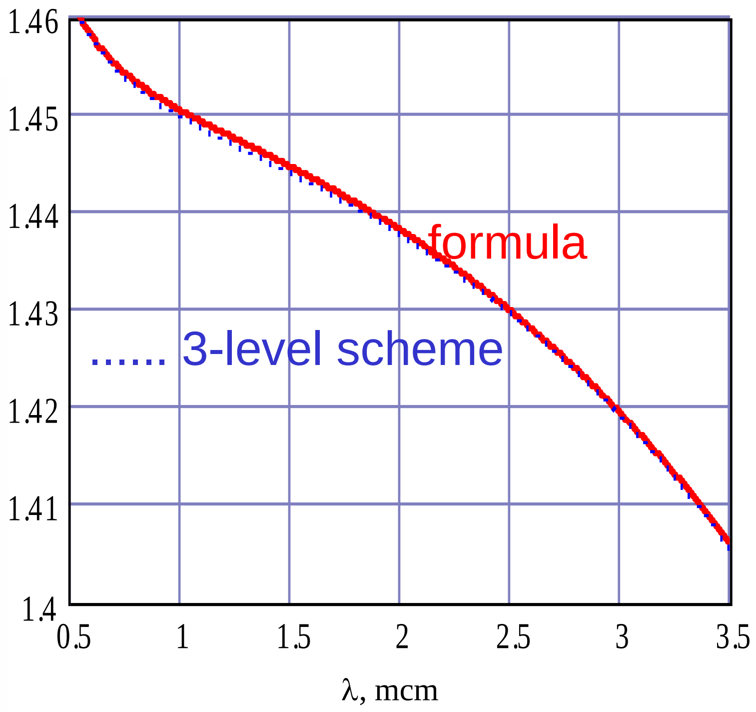




(for different parameters of the 3rd level)

Taking into account matrix absorption bands

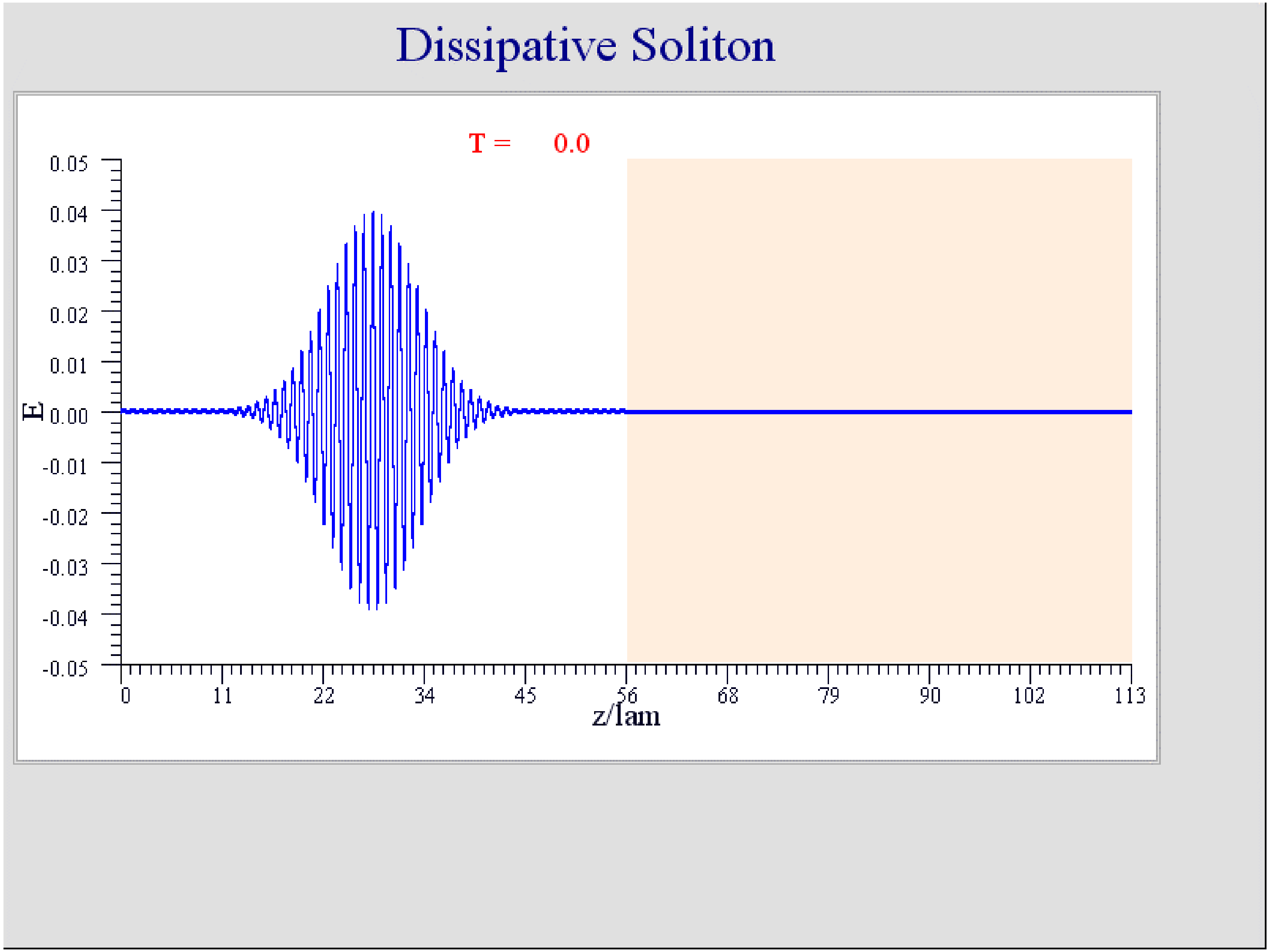




Refractive index in the transparency band

Coherent supercontinuum. Promising are schemes with quantum dots

Formation of Few-cycle DOS from an Initial Femtosecond Pulse*



Conclusions

Standard, or envelope Dissipative Optical Solitons (DOSs):

- Quasi-quantum features – ***discrete type of the spectrum of main parameters*** – provide ***higher stability*** of DOSs in the presence of noise. Therefore they are promising for information applications with heightened requirements to the precision and operation reliability.
- ***Large diversity*** of DOSs' types. They are not "elementary", but have ***internal structure*** determined by the ***topology of energy flows***. This topology allows one to distinguish between ***weak and strong interactions*** of DOSs.
- DOS mobility and mechanics. ***Symmetry and Eulerian mechanics*** of solid-like soliton complexes. Their ***curvilinear motion***.
- Not presented here topics: DOSs' quantum features (Brownian motion and squeezed states); Effect of relaxation; …

Tendency to extreme (not envelope) solitons.

Nanosized dissipative molecular solitons.

Few cycle solitons using dissipative (gain/absorption) factors. Nonlinear widening of gain spectrum.

Not achieved yet: Combination of nanosizes and attoduration –-> light dots

Great scope for fundamental research and applications.

Conclusion in Short:

Brevius, Angustius, Fortius!

(Shorter – in time and space, Stronger!)

E-mail: nrosanov@yahoo.com

N.N. Rosanov.
Dissipative
Optical Solitons.
From Micro- to
Nano- and Atto-.
Moscow,
Fizmatlit, 2011
(in Russian)

15th International Conference

«Laser Optics 2012»

St.Petersburg, Russia, June 25-29, 2012

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