Nonlinear Beam Dynamics in Photonic Lattices and Nanosuspensions

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Introduction: What do we do with light?

- Spatial solitons & dynamics
- Photonic structures
- Defect and surface states
- Beam engineering
- Trapping and manipulation
- NLO in soft matter
Make particle-like beams: optical solitons

A spatial soliton exists through a balance between diffraction and nonlinear process.

Spatial Soliton

Self-trapping through nonlinear effect

Diffraction

Broadening during propagation

Solitons behave like particles
Make crystal-like photonic structures
molding the flow of light

2D solitonic lattice

1D lattice with a defect

2D lattice with a defect

2D ring lattice akin to PCF

2D lattice with corners and edges

1D superlattice and interfaces

Ionic-type lattices

Opt. & Photonics News
“Optics of the Year, 2002-2009”
Make light guides without optical fiber

PBG guidance

1D

2D

Low-index core

TIR guidance
Make light to turn around corner

Blue (488 nm)  Green (532 nm)  Red (633 nm)
Make light to travel in ballistic trajectory

Self-accelerating Airy beams

Y. Hu et al, OL (2010).
Make rotating light beams

Control of micro-particles

Propelling patterns

Rotating tweezers

Multi-trap dynamical optical tweezers

P. Zhang et al, OL (2010).
Trapping & transporting aerosols

Make bottle light beams

Moving particles


Via photophoresis force

absorbing carbon or silicon particle
Optical periodic structures

1D
- Waveguide array
- Thin film

2D
- Photonic crystal
- PCF

3D
- Scaffold
- Woodpile

Fabricated photonic crystals
- Time-domain frequency modes
- Typically do not have high nonlinearity

Nonlinear waveguide arrays (Photonic Lattices)
Spatial beam dynamics in photonic lattices

\[ i \frac{\partial \psi}{\partial z} + \frac{1}{2} \nabla^2_{\perp} \psi + n_2 |\psi|^2 \psi + \Delta n_{Array}(r_{\perp}) \psi = 0 \]

**Diffraction**  **Kerr NL**  **Periodic index**

**Nonlinear Schrödinger equation**

\[ i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + U_0 |\psi|^2 \psi + V(\vec{r})\psi \]

**Gross-Pitaevskii equation in BEC**
Why photonic lattices?

Fundamental issues explored in a simple optical setting have tight link to solid state physics, photonic crystals, BEC, etc...

Solitons, modulation instability...
Optical Bloch waves,
Band-gap guidance, Defect states,
Photonic superlattices and quasicrystals,
Random lattices & disorder phenomena
Bloch & Rabi oscillations, Zener tunneling,
Dynamical localization, CDT,
X waves and shock waves,
Tamm and Shockley surface states,
Anderson localization,
Quantum correlation,
......

Kivshar /Agrawal’s book (2005)
Spatial solitons in photonic lattices

Linear discrete diffraction

Nonlinear lattice solitons

Discrete solitons

Gap solitons

H. Martin & Z. Chen
SFSU 2003
Examples of optical spatial solitons

- “Saddle” solitons
- Surface and interface solitons
- Self-imaging solitons
- Rotating and self-accelerating solitons
- Nonlinear self-induced transparency
“Saddle” Solitons

Square lattice

$k_x$, $k_y$

$\Gamma_1$

M1

X1

Anomalous diffraction

Normal diffraction

Hybrid Nonlinearity

Saddle soliton

Similar to the “Optical Bullet” by balancing dispersion in time and diffraction in space simultaneously!
Saddle solitons

Induced lattice

Existence curve

Soliton profile

Phase structure

Spectrum

Soliton solution

Soliton output

Interferograms

spectrum

Experimental results

X1 Bloch modes

Träger et al OE (2006)
Nonlinear Tamm states

Surface Solitons

X. Wang et al., PRL (2007); A. Szameit et al., PRL (2007)

1D surface solitons:
S. Suntsov et al., PRL (2006);
C. R. Rosberg et al., PRL (2006);
Shockley-like surface states

First observation of linear optical Shockley state
Malkova et al., OL 09
Wang et al., PRA 09
OPN: “Optics in 2009”

Probe beam propagates along the surface linearly.
No nonlinear self-action!
Self-imaging Solitons

Can nonlinear lattices transmit texts and images?
Stable gap solitons of arbitrary shapes

Photonic lattices induced under self-defocusing NL

\[ i \frac{\partial U}{\partial z} + \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} - V(x, y)U - |U|^2 U = 0, \]

Intensity

Intensity

Yang et al., OL (2011).
Soliton-based Image transmission

Stable gap soliton clusters of arbitrary shapes!

Yang et al., OL (2011).

Experimental results

Simulation results
What about disordered lattices?

Sim.

Exp.

Speckle ring

Input

Output @1cm

BZ spectrum

“Average period 15μm”

“Index modulation ~10^{-4}”
Image transmission in disordered lattice

Experimental results
Self-trapping of engineered optical beams

Rotating beams

Bottle beams

Airy beams

Auto-focusing beams
Rotating beams: from Moiré technique

Interferogram of plane waves

plane wave and vortex
Vortex grating + moving stripe grating
Experimental Results: Control of micro-particles

Dielectric Sphere

$m = 2$
$m = 3$
$m = 4$

Particle size: 3µm

P. Zhang et al, OL (2010).
Noninstantenous nonlinearity


\[ f_1 + f_2 + f_3 + f_4 + f_5 + f_6 = \text{Time average} \]

Noninstantenous nonlinearity

Average intensity

SBN (Strontium Barium Niobate)

\(~1\text{s}\)
Self-trapping of propelling beam

Simulation results

<table>
<thead>
<tr>
<th>Input</th>
<th>Linear beam evolution</th>
<th>Nonlinear beam evolution</th>
<th>Diffraction</th>
<th>Self-trapping</th>
</tr>
</thead>
</table>

Input $I$

| Nonlinear output | Linear output | Diffraction | Self-trapping |

Input $f$
Self-trapping of propelling beam

Experimental results

Time average

Instantaneous
Airy Beams

Non-diffracting, Self-accelerating, Self-healing

1D

2D

Truncated

Infinite energy

Finite energy

Nondiffracting optical waves

Bessel beam
(Cylindrical coordinate)

Mathieu beam
(Elliptic coordinate)

Parabolic beam
(Parabolic coordinate)

Airy beam in 1D

\[ \psi(s, \xi) = Ai(s - \frac{\xi^2}{4}) \exp[i(\frac{s\xi}{2} - \frac{\xi^3}{12})] \]

The only possible nondiffracting wave in 1D
Self-healing property
Transverse momentum (self-bending)

Siviloglou et al., PRL (2007)
Proposed Applications

Particle manipulation

Curved plasma channel

Spatial-temporal light bullets

Routing SPP
Airy beams: Light in ballistic trajectory

Self-accelerating Airy beams

Y. Hu et al, OL (2010).
Nonlinear Control of Airy Beams

Self-defocusing nonlinearity

Output

Spectrum

Optical boomerang?

Nonlinear Dynamics in Colloidal Suspension

Brownian motion  Optical forces  Nonlinear scattering  Soliton effects

Colloidal Physics
Soft-matter

Statistical
Mechanics

Optics
Nonlinear Optics

Fluid mechanics

Life sciences

Chemistry/
electrochemistry

An interdisciplinary field
Nonlinearity in Colloidal Suspension

- Optical forces attract/repel high/low index suspensions

\[ n_{\text{particle}} > n_{\text{background}} \]

Positive Polarizability

\[ n_{\text{particle}} < n_{\text{background}} \]

Negative Polarizability

R. El-Ganainy, D. N. Christodoulides, et al., OPT. EXPRESS (2007)
Nonlinear beam dynamics in nano-suspensions

Polystyrene nano-suspensions

"Air bubble" nano-suspensions

Linear propagation

Nonlinear propagation

\[ \Delta n_{NL} \bigg|_{\text{max}} = 1.5 \times 10^{-4} \]

\[ \Delta n_{NL} \bigg|_{\text{max}} = 3.5 \times 10^{-4} \]
Self-trapping in nanosuspension

**Input**

- NP1 0.3% PTFE in Gly-H2O
- 200nm
- $n_p = 1.34$

**Output**

- 11 µm FWHM
- 32 µm FWHM
- 12 µm FWHM
- $n_b = 1.44$

**Parameters**

- 4 mW
- 3W
- 50 µm
Self-induced transparency in nanosuspension

200nm particles, concentration 0.3%
At same input power

Negative Polarizability

Positive Polarizability
Summary: What have we done with light?

- Spatial solitons & dynamics
- Photonic structures
- Defect and surface states
- Beam engineering
- Trapping and manipulation
- NLO in soft matter
Thank you for your attention!

Website: http://www.physics.sfsu.edu/~laser/

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