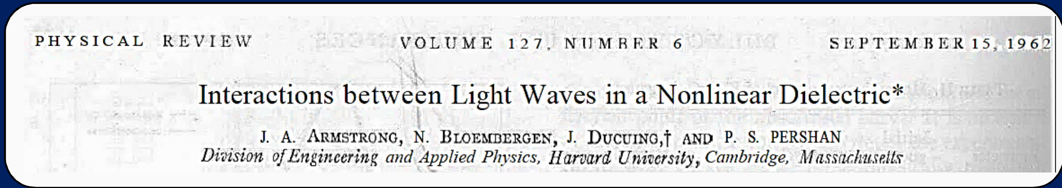
FI255 - Tópicos de Óptica e Fotônica II

Óptica Não-Linear

14ª. aula

Prof. Cid B. de Araújo
UNICAMP - 22 de junho de 2018

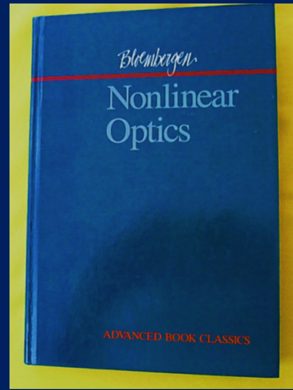
General theoretical approach


PHYSICAL REVIEW VOLUME 127, NUMBER 6 SEPTEMBER 15, 1962

Interactions between Light Waves in a Nonlinear Dielectric*

J. A. Armstrong, N. Bloembergen, J. Ducuing,† and P. S. Pershan

Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts



When there is inversion symmetry:

$\chi^{(j)} \equiv 0$

j = even

$$P_L + P_{NL} = \epsilon_0 \sum_{N=0}^{\infty} \chi^{(2N+1)} E^{(2N+1)}$$

$$n_N \propto Re\ \chi^{(2N+1)}$$

Nonlinear refractive index

$$\alpha_N \propto Im\ \chi^{(2N+1)}$$

Nonlinear absorption coefficient

linear + nonlinear

$$n = n_0 + n_2 I + n_4 I^2 + n_6 I^3 + \cdots$$

$$\alpha = \alpha_0 + \alpha_2 I + \alpha_4 I^2 + \alpha_6 I^3 + \cdots$$

High-order nonlinearities

- Generation of higher harmonics
- Multiphoton excitation processes
- Multi-wave mixing

Studies of multiphoton ionization: 60´s; Many studies in the 70´s, 80´s.

Multiphoton dissociation and ionization processes applied to isotope separation (70´s and 80´s).

More recently:
Solitons, filamentation, extreme events, generation of VUV and soft X-rays – 400th harmonic, proposals for attosecond X-ray pulse generation ....

Eq. de Maxwell   regime espacial

$$\nabla^2\vec{E} - \frac{1}{c^2}\frac{\partial^2\vec{E}}{\partial t^2} = \mu_0\frac{\partial^2\overrightarrow{P_L}}{\partial t^2} + \mu_0\frac{\partial^2\overrightarrow{P_{NL}}}{\partial t^2}$$

$$\vec{P}_L = \epsilon_0\epsilon_L\vec{E}(\vec{r},t) \qquad \vec{P}_{NL} = \epsilon_0\epsilon_{NL}\vec{E}(\vec{r},t) \qquad \Delta n = n_{2E}|\vec{E}|^2$$

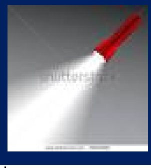
$$\nabla^2\vec{E} - \frac{1}{c^2}\frac{\partial^2[(n_0+\Delta n)^2\,\vec{E}]}{\partial t^2} = 0$$

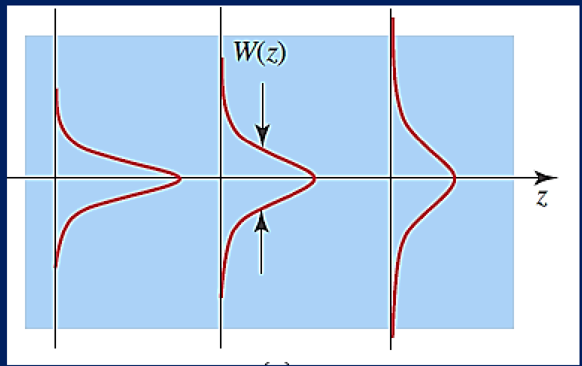
$$\vec{E}(\vec{r},t) = \vec{A}(\vec{r})\exp[\,i(kz-\omega t)]$$

SVEA - slowing varying envelope approximation

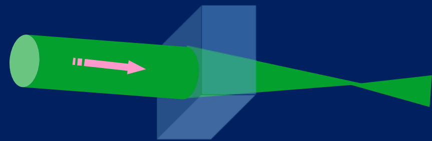
$$i\frac{\partial\vec{A}}{\partial z} = -\frac{1}{2k}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\vec{A} - \frac{n_{2E}}{n_0}k|\vec{A}|^2\vec{A}$$

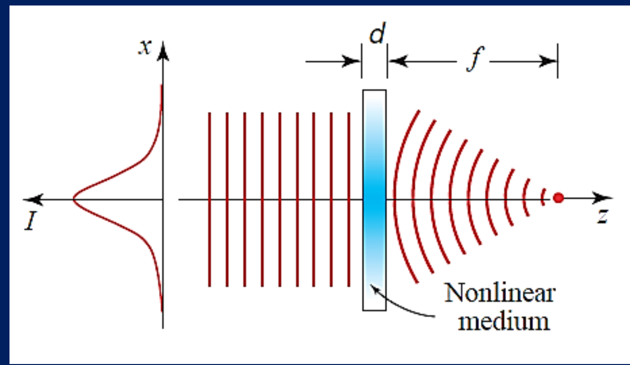
Diffraction



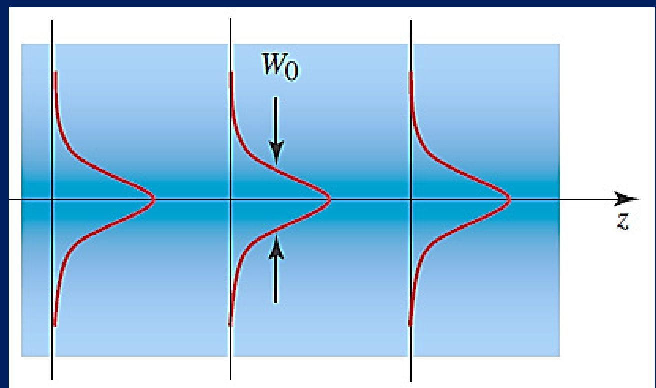


Self-focusing





Bright Spatial Soliton



What is "soliton" ?

A soliton is a wave with a unique shape that travels undisturbed without changing. Solitons require a balance between nonlinearity and dispersion.

Optical solitons are often thought of in the time domain, especially in fibers, where pulse compression due to the optical nonlinearity can overcome the tendency of dispersion to spread pulses out as they travel down a fiber.

This happens only for discrete values of the pulse energy and, for positive nonlinearities, the dispersion must be anomalous (negative).

Solitons are also called solitary waves and were first discovered in water waves traveling down a canal.

Solitons are unique in that they can interact with other solitons and emerge from the collision unchanged, except for a phase shift.

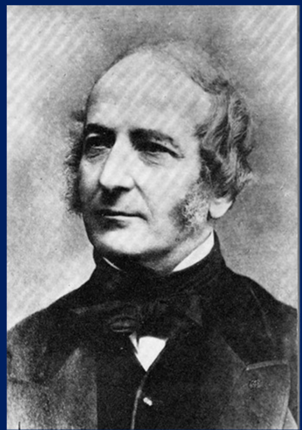
Solitons

Wave with a unique shape that travels undisturbed without changing

John Scott Russell (1808-1882)

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

Russell, Report on Waves.
Report of the fourteenth meeting of the British Association for the Advancement of Science, York, September 1844.



How did Russell observe a soliton?

Bright engineer: invented an improved steam-driven road carriage in 1833. The ``Union Canal Society'' of Edinburgh asked him to set up a navigation system with steam boats

Solitons

Coast (BBC2 24/04/13)

Many Faces of Solitons

Quantum Field Theory

- Quantum solitons
- Monopoles
- Instantons

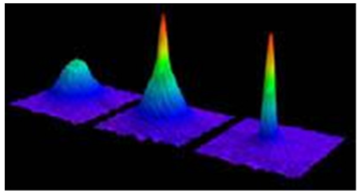
General Relativity

- Bartnik-McKinnon solitons (black holes)

Biochemistry

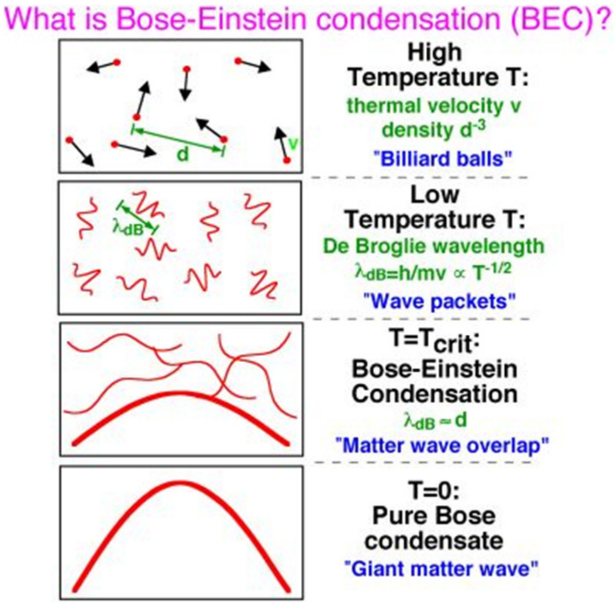
- Davydov solitons (protein energy transport)

BEC



Cold atoms

- Coherent matter waves
- Dilute alkali gases



Optical solitons

solutions of Maxwell's equation with NL polarization terms

Wave with special shape such that propagates without change their shape.

When one soliton interacts with another soliton they do not change their shape but, the phases of the electric fields change.

Temporal and spatial solitons

Nonlinear Schrödinger Equation: (1+1)D

Scalar theory

$$E(x,z,t) = A_m a(x,z) e^{i(k_0 n z - \omega t)}$$

$$\frac{1}{2k_0 n_0}\frac{\partial^2 a}{\partial x^2} + i\frac{\partial a}{\partial z} + \frac{k_0 n_0 n_2}{2\eta_0}|a|^2 a = 0$$

Difraction x self-focusing

$$\left|\frac{\partial^2 a(x,z)}{\partial z^2}\right| << \left|k_0 \cdot \frac{\partial a(x,z)}{\partial z}\right|$$

$$\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$$

$$a(x,z) = \text{sech}(x/X_0)\exp(i\,z/2L_d)$$

Soliton solution

$$L_d = X_0^2 k_0 n_0$$

$$X_0 = \frac{1}{k_0 n_0}\sqrt{\frac{2\eta_0}{|n_2||A_m|}}$$

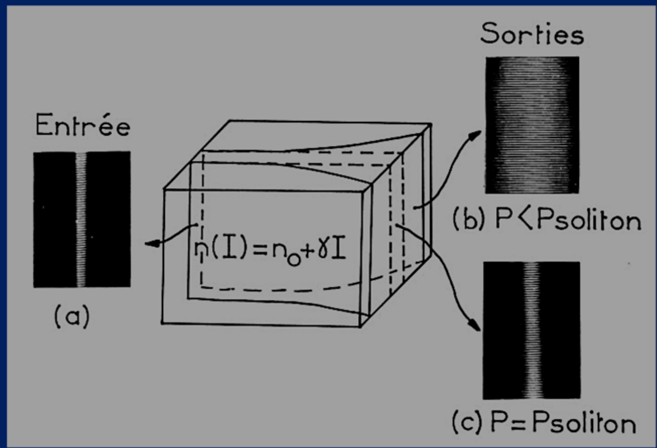
Zakharov, Shabat, Sov. Phys. JETP 34 (1972) 62

(1+1)D spatial solitons in CS_2

$n_2 > 0$

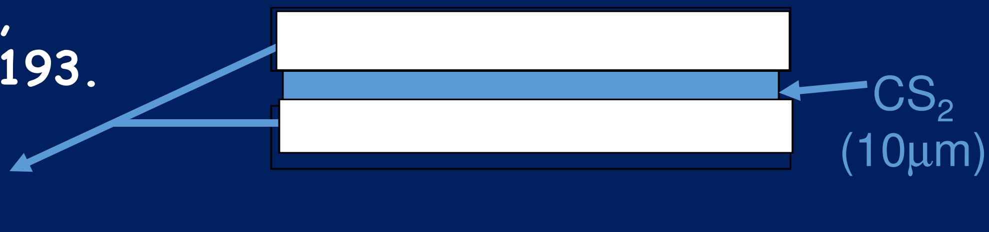
Beam focused by cylindrical lenses

Barthélémy, Maneuf, Froehly, Opt. Commun. 55 (1985) 201.



Planar waveguides

Maneuf, Desailly, Froehly, Opt. Commun. 65 (1988) 193.



Picosecond lasers – 532 nm

Carbon disulfide: CS_2

VOLUME 74, NUMBER 15 PHYSICAL REVIEW LETTERS 10 APRIL 1995

Fifth Order Optical Response of Liquid CS_2 Observed by Ultrafast Nonresonant Six-Wave Mixing

Keisuke Tominaga and Keitaro Yoshihara

n_2: Couris *et al.*, Chem. Phys. Lett. **369**, 318 (2003).

n_4: Kong *et al.*, J. Phys. B: At. Mol. Phys. **42**, 065401 (2009).

$n_2 = +3.1 \times 10^{-19}$ m^2/W $\quad n_4 = -2.0 \times 10^{-35}$ m^4/W^2

Focusing nonlinearity **Defocusing nonlinearity**

(2+1)D Soliton

$E(x,y,z,t) = A\,a(x,y,z)\exp[\mathrm{i}(k_0 nz - \omega t)]$

NLSE
$$\frac{1}{2k_0 n_0}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)a + i\frac{\partial a}{\partial z} + \frac{k_0 n_0 n_2}{2\eta_0}|a|^2 a = 0$$

(2+1)D soliton is unstable in a pure Kerr medium

Catastrophic self-focusing

Chiao, Garmire, Townes PRL (1964)

High-order nonlinearity

Modified NLS equation

$\chi^{(5)}$

$$\frac{1}{2k_0 n_0}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)a + i\frac{\partial a}{\partial z} + \frac{k_0 n_0 n_2}{2\eta_0}|a|^2 a + \frac{k_0 n_0^2 n_4}{4\eta_0^2}|a|^4 a - \frac{\alpha_3}{2}\left(\frac{n_0}{2\eta_0}\right)^2 |a|^4 a = 0$$

These terms may stabilize the (2+1)D spatial soliton

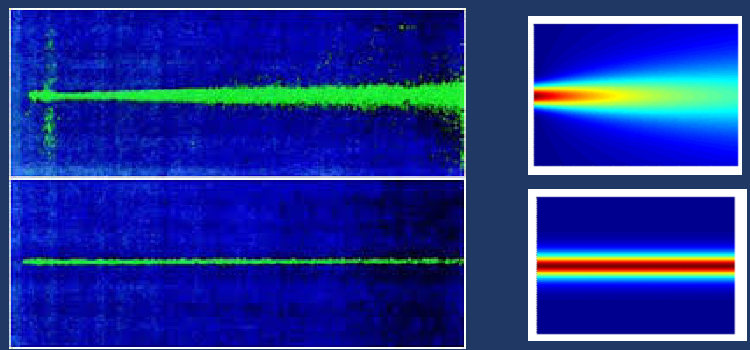
Este problema era conhecido desde a década de 60 mas a propagação estável de Sólitons espaciais em um meio homogêneo, isotrópico com não linearidade eletrônica não havia sido demonstrada

Experiência

NLSE

Propagação linear

Sóliton espacial



PRL 110, 013901 (2013) PHYSICAL REVIEW LETTERS week ending 4 JANUARY 2013

Robust Two-Dimensional Spatial Solitons in Liquid Carbon Disulfide

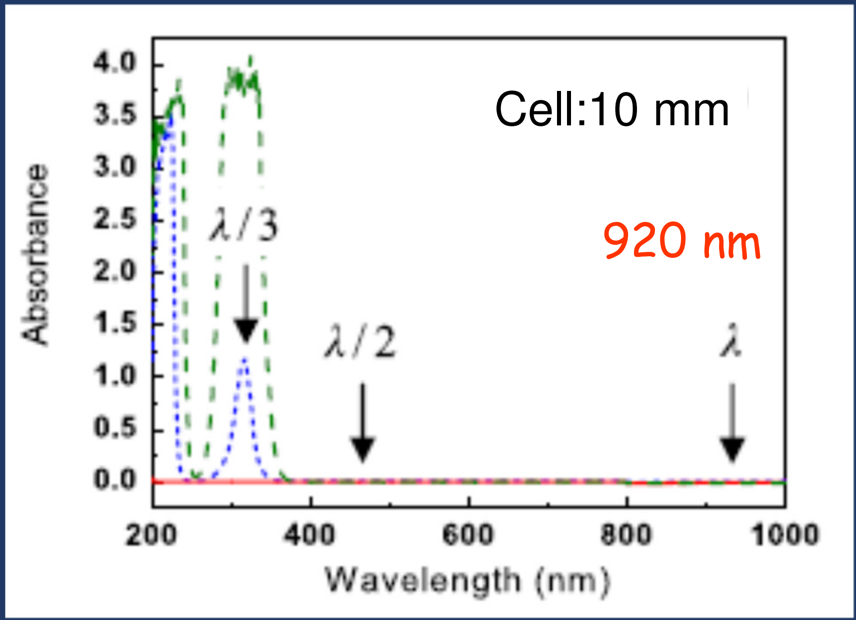
Edilson L. Falcão-Filho* and Cid B. de Araújo
Departamento de Física, Universidade Federal de Pernambuco, 50670-901 Recife, Pernambuco, Brazil

Georges Boudebs, Hervé Leblond, and Vladimir Skarka
LUNAM Université, Université d'Angers, Laboratoire de Photonique d'Angers, EA 4464, 49045 Angers, France

First demonstration of (2+1)D soliton propagating in a liquid

The laser wavelength was selected to be in the transparency region
but three-photon absorption is possible

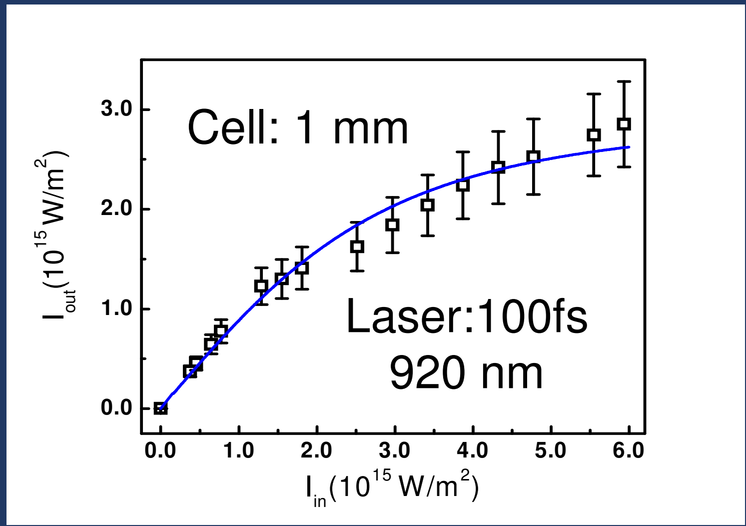
Very important: contributions of third and fifth order of opposite signals



Absorption spectra of CS_2 diluted in ethanol

$n_2 > 0$ $n_4 < 0$

Three-photon absorption of pure CS_2

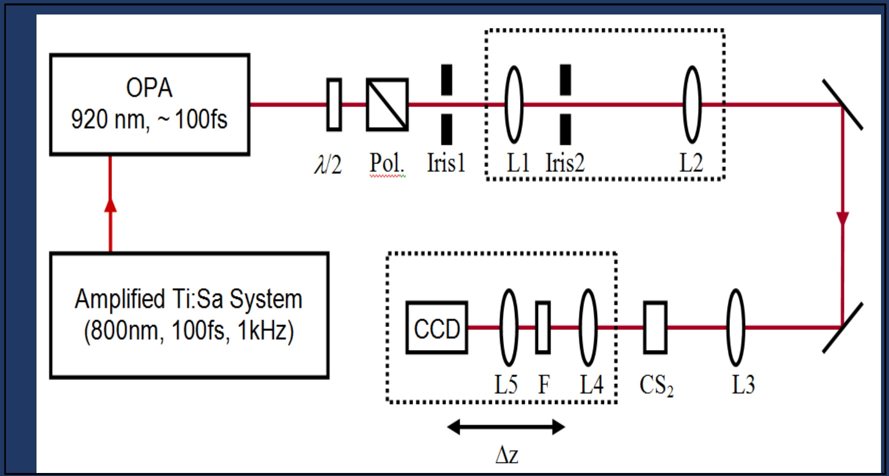


Optical limiting experiment

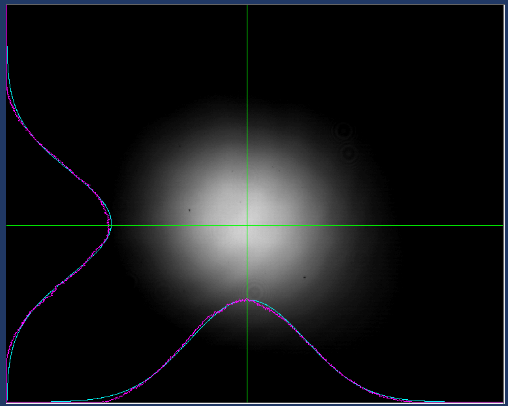
$$I_L = (1-R)^2 \frac{I_0}{\sqrt{1+2I_0^2(1-R)^2\alpha_3 L}}$$

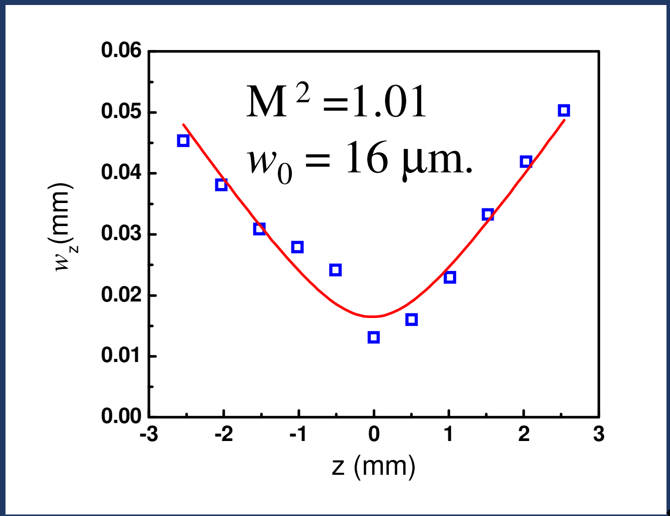
$a_3 = 5.8 \times 10^{-29}\ m^3/W^2$

setup and beam characteristics

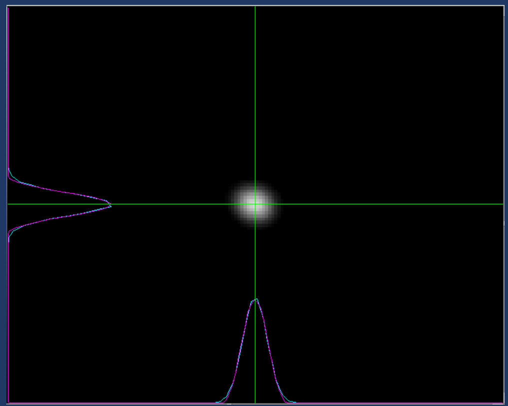


Entrance of L3: w = 2.0 mm



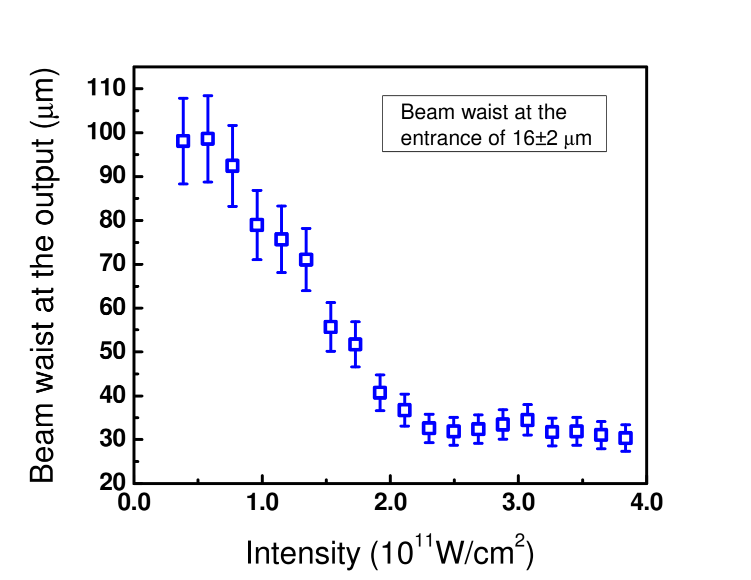


Focus: w_0 = 16 μm.

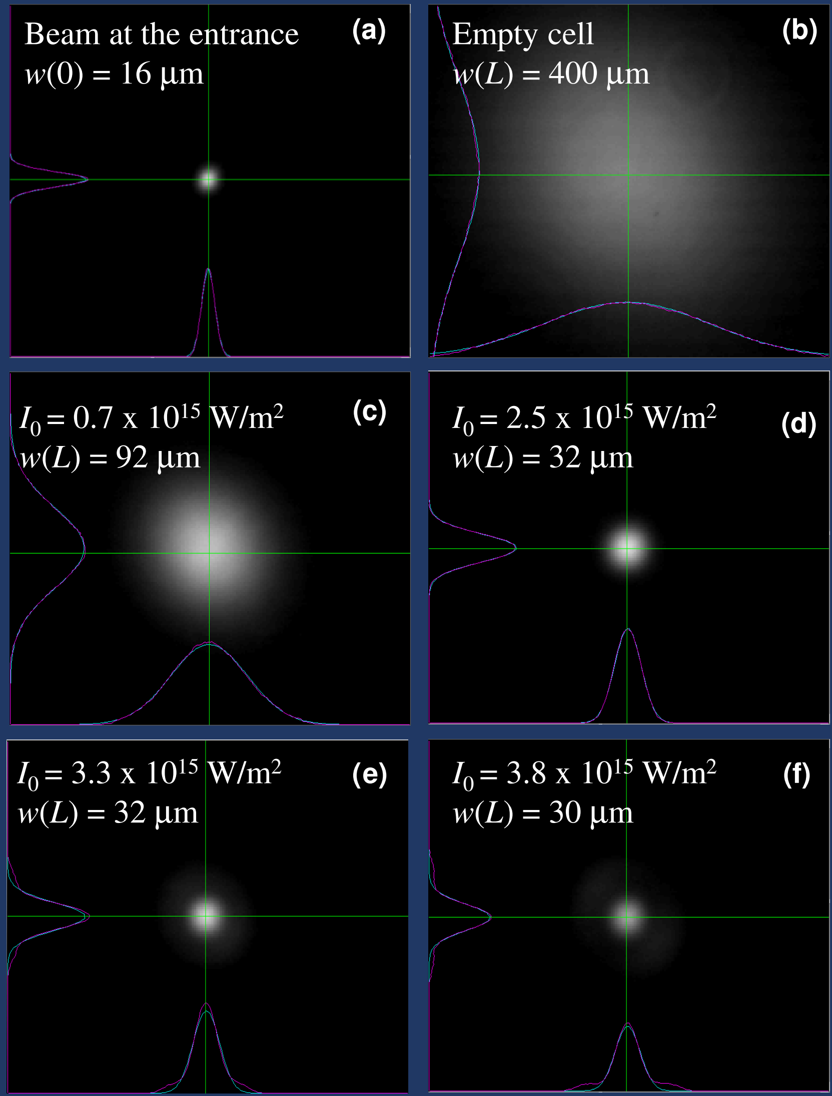


18

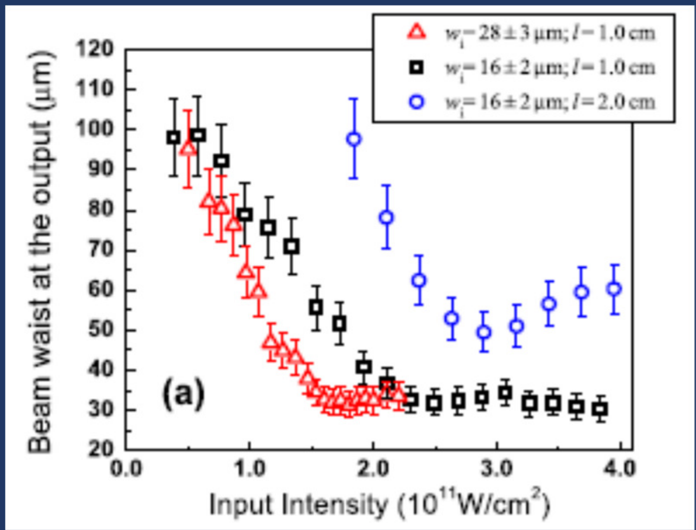
1.0 cm cell
Front face at the focus

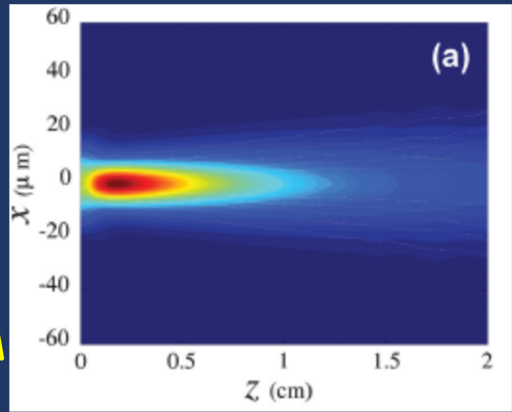


1 cm → $10z_0$

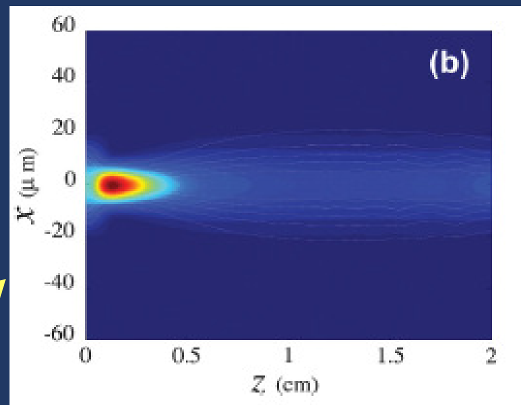


Various beams' waist and length of cells





0.8 x 10^{11} W/cm^2



NLS equation

1.6 x 10^{11} W/cm^2

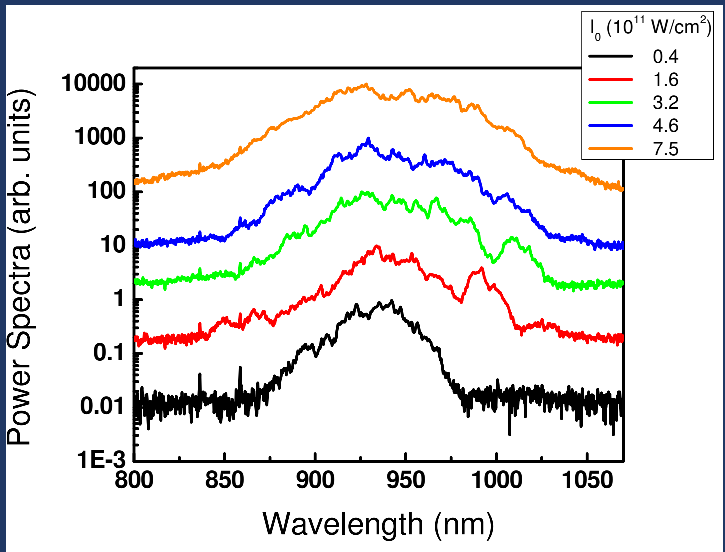
Spectral broadening

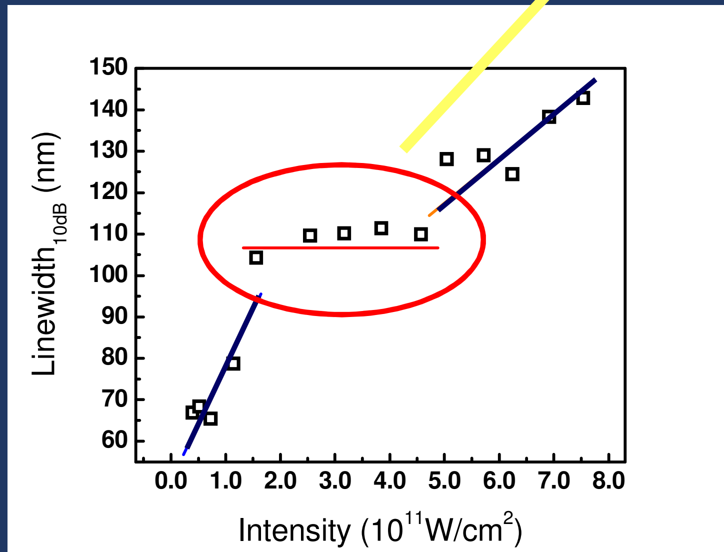
$$\phi(t) = \omega_0 t - \frac{2\pi}{\lambda_0} \cdot n(I)L$$

$$I(t) = I_0 \exp\left(-\frac{t^2}{\tau^2}\right)$$

$$\omega(t) = \frac{d\phi(t)}{dt}$$

Intensity clamping





Summary - bright spatial solitons

- (2+1)D spatial soliton propagation over more than $10z_0$ in CS_2 due to simultaneous contribution of the third- and the fifth-order susceptibilities.

- Intensity clamping effect which corroborates the soliton stability

- Computer simulations with the NLSE. Results in agreement with the experimental data.

(2+1)D soliton is stable in a homogeneous medium if:

$Re\,\chi^{(3)} > 0$ $\quad$ $Re\,\chi^{(5)} < 0$

Phys. Rev. Lett. 110 (2013) 013901

The contribution of $\chi^{(5)}$ prevents the catastrophic self-focusing

Is it possible to observe a stable (2+1)D soliton in a system with:

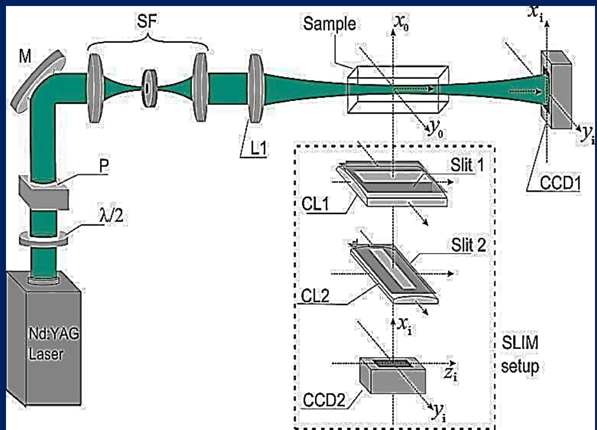
$Re\,\chi^{(3)} = 0$, $\quad Re\,\chi^{(5)} > 0$, $\quad Re\,\chi^{(7)} < 0$?

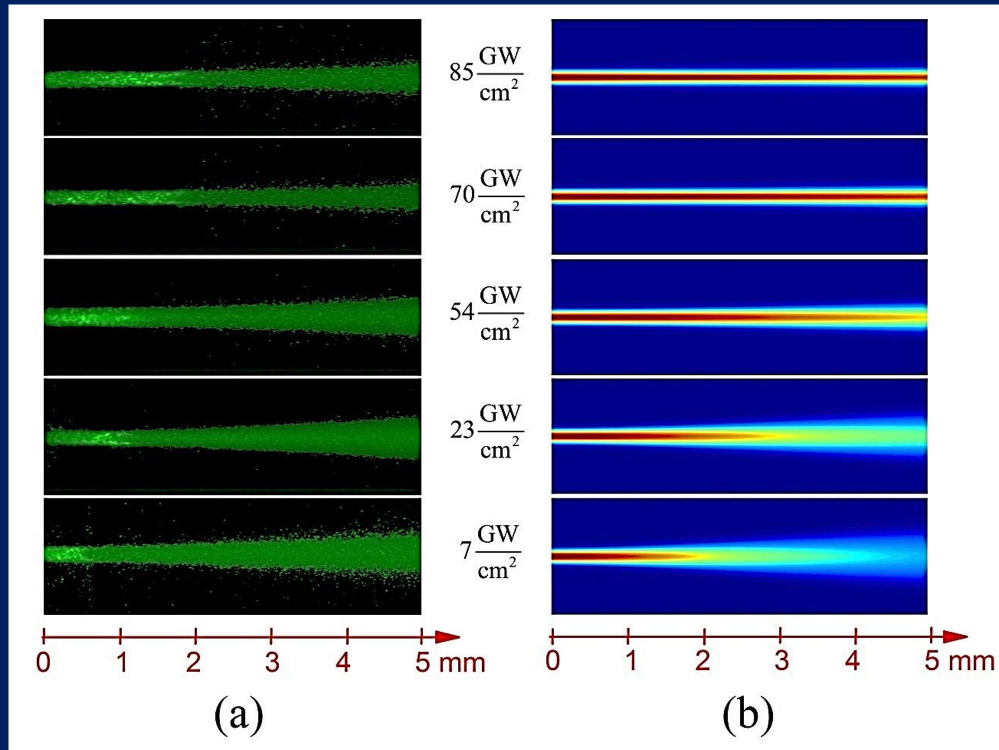
$$2ik\frac{\partial E}{\partial z} + \Delta E = -\frac{\omega^2}{c^2}\left[3\chi_{eff}^{(3)}|E|^2 E + 10\chi_{eff}^{(5)}|E|^4 E + 35\chi_{eff}^{(7)}|E|^6 E\right]$$

First observation of 2D Spatial-Solitons in a quintic-septimal medium

Silver NPs in acetone

$$n_2 = 0; \;\; n_4 > 0; \;\; n_6 < 0$$

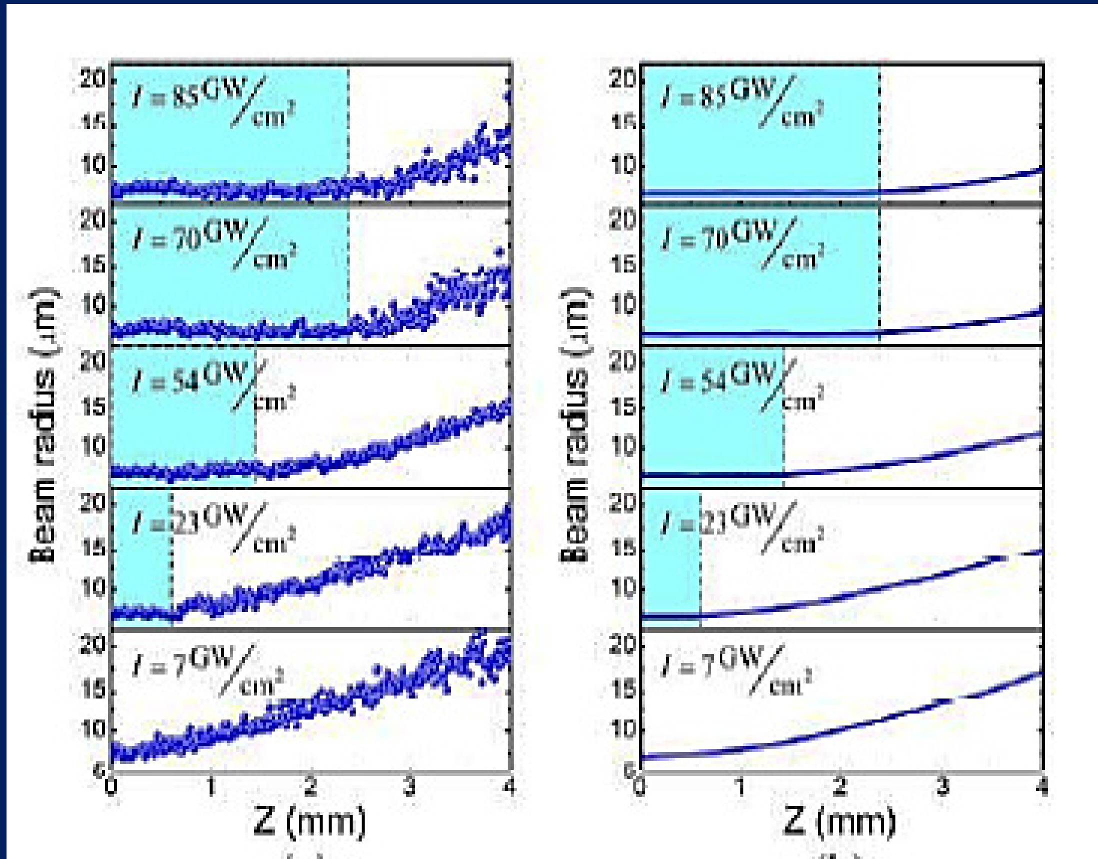




experiment   theory

Reyna, Jorge, de Araújo, de Araújo et al. , Phys. Rev. A 90 (2014) 063835
J. Lumin. 169 (2016) 492-496

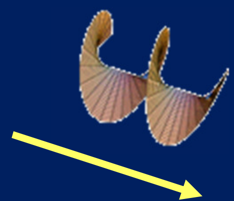
$$2ik\frac{\partial E}{\partial z} + \Delta E = -\frac{\omega^2}{c^2}\left[\cancel{3\chi_{eff}^{(3)}|E|^2}\, E + 10\chi_{eff}^{(5)}|E|^4 E + 35\chi_{eff}^{(7)}|E|^6 E\right]$$



experiment theory

Optical vortices

- Beams with phase singularity
- Zero field in the center of the vortex
- Helical wavefront
- Phase

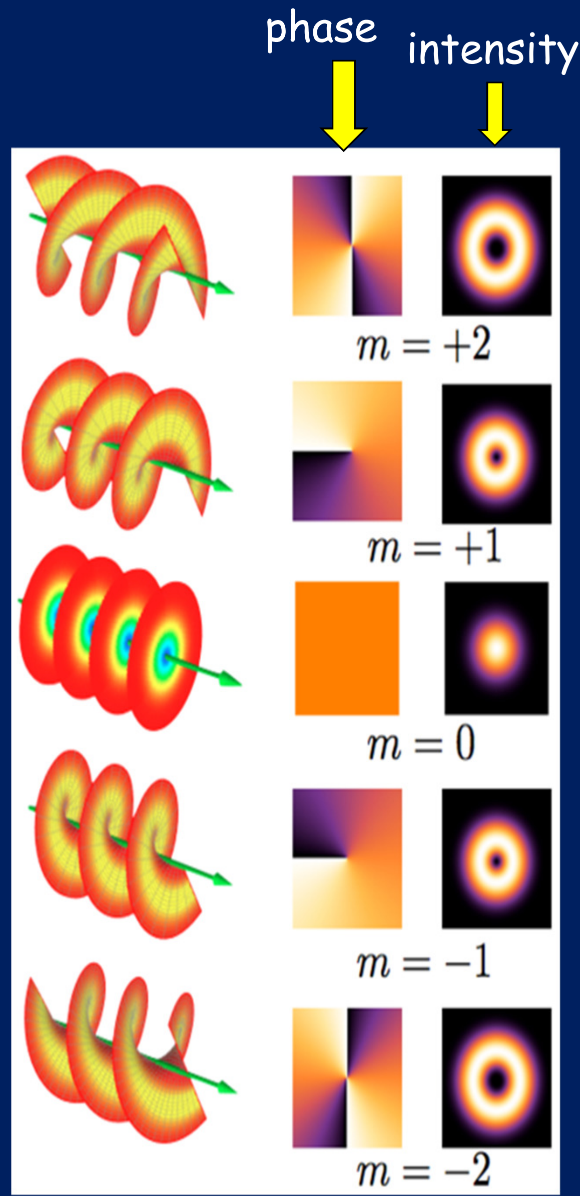


$$\phi(t,z,\theta) = kz + \omega t + m\theta$$

$m = 0$ Plane wave

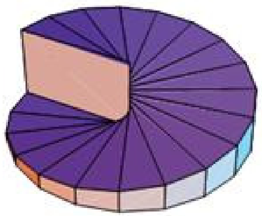
$m \neq 0$ Wave with topological phase

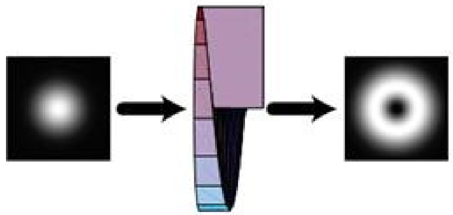
m is the "topological charge"

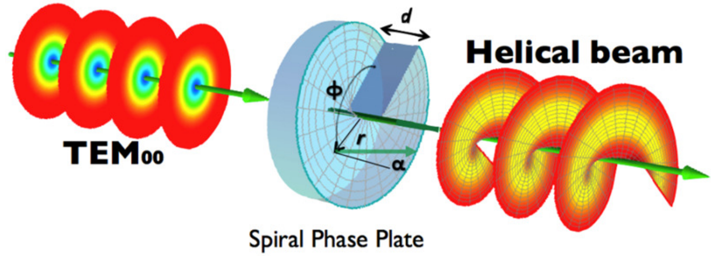


Optical Vortex beam carries an orbital angular momentum of $m\hbar$ per photon

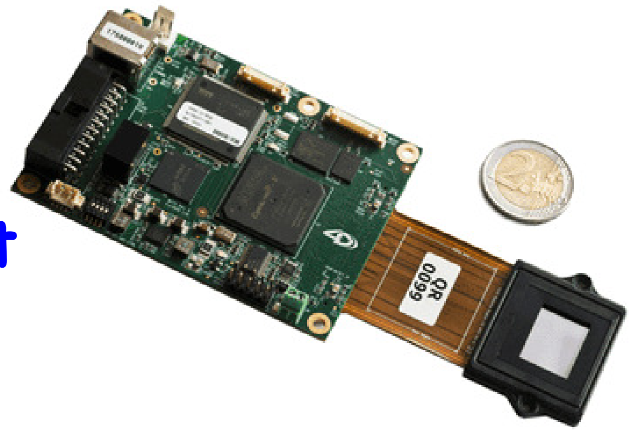
Vortex phase plate





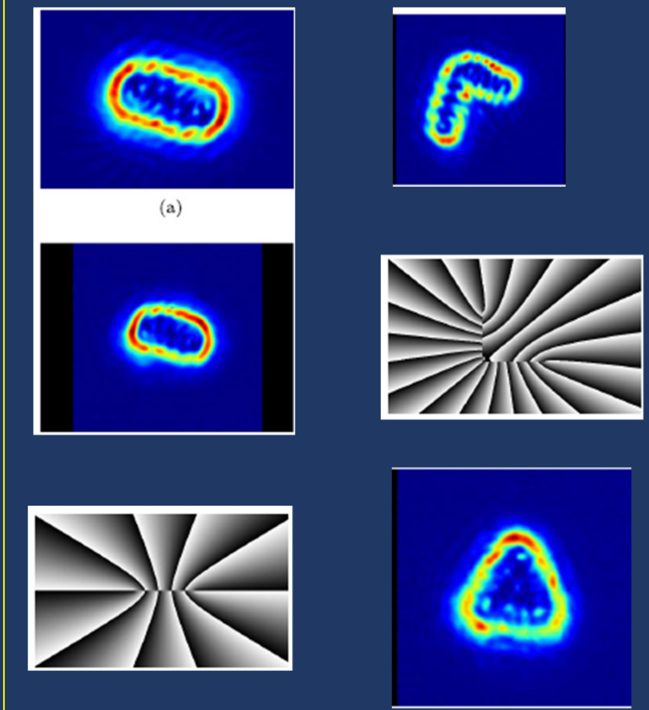


Images from the internet



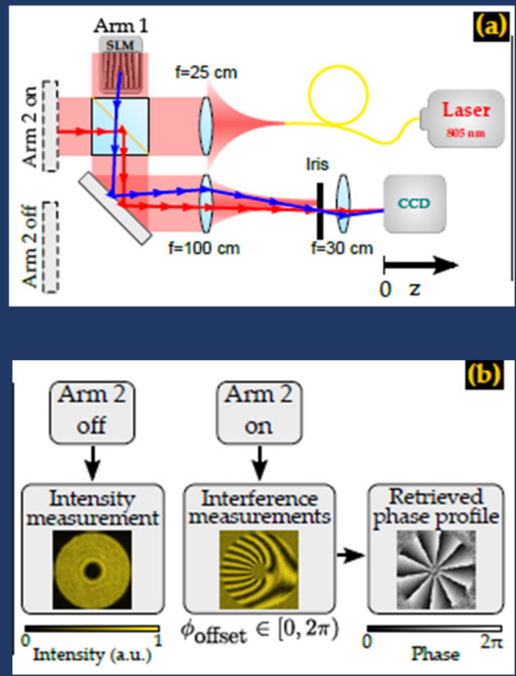
Spatial light modulator

Shaping optical beams with topological charges



Amaral, Falcão-Filho, de Araújo
Opt. Lett. 38 (2013) 1579

Characterization of topological charge and orbital angular momentum of shaped optical vortices



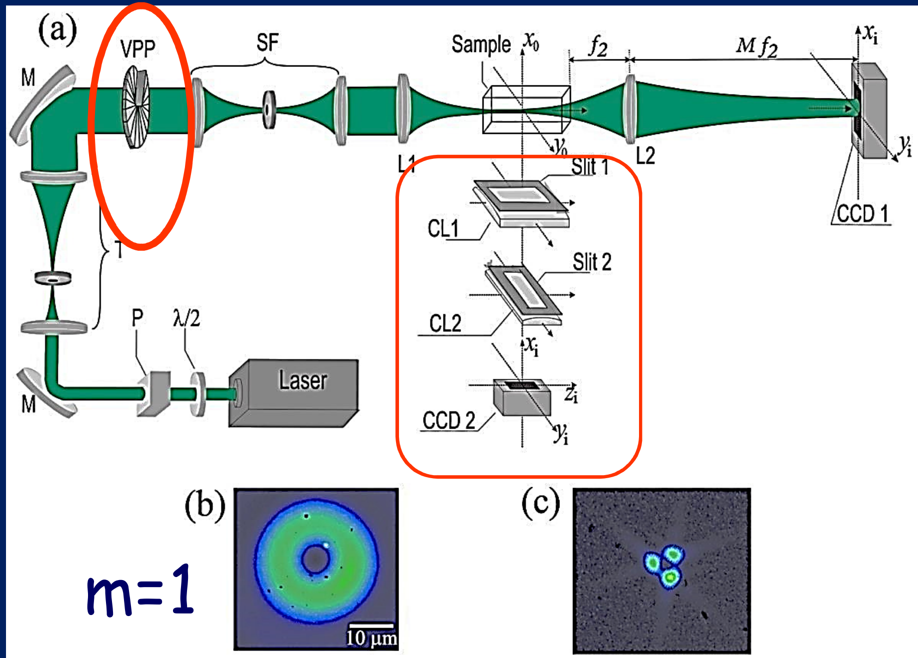
Amaral, Falcão-Filho, de Araújo
Opt. Express 22 (2013) 30315

PHYSICAL REVIEW A 93, 013840 (2016)

Robust self-trapping of vortex beams in a saturable optical medium

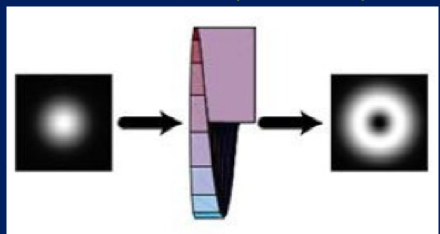
Albert S. Reyna,[1,*] Georges Boudebs,[2] Boris A. Malomed,[1,†] and Cid B. de Araújo[1]

532 nm
80 ps
10 Hz



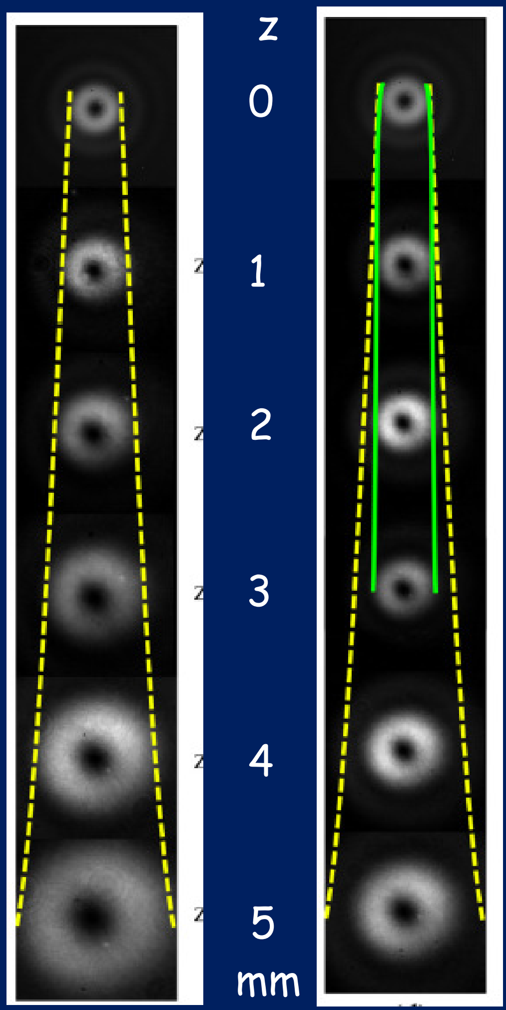
CS_2

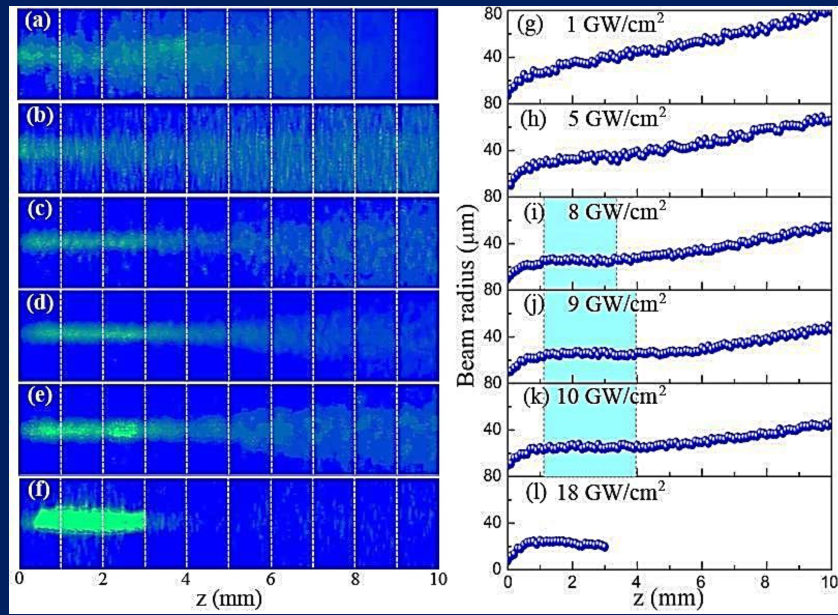
VPP- vortex phase plate



Optical Vortex beam carries an orbital angular momentum of $m\hbar$ per photon

Optical Vortex Solitons in CS_2





$$i\frac{\partial E}{\partial z} = -\frac{1}{2n_0 k}\nabla_\perp E - \left[\frac{kaI^2}{1+b^2I^2} + i\frac{\gamma I^2}{2}\right]E$$

First observation of an OVS in a self-focusing medium with local nonlinearity

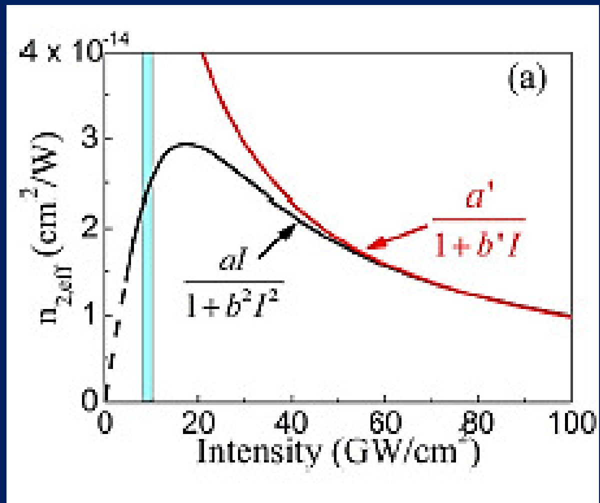
Optical Vortex Soliton - OVS

Stable propagation in a self-defocusing medium
Unstable propagation in self-focusing

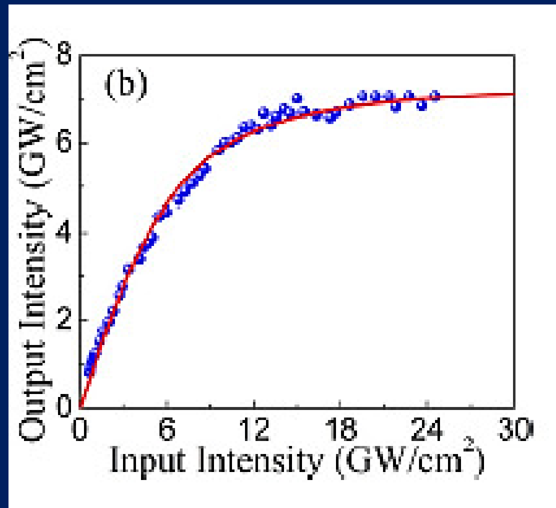
Conditions on the NLSE to observe stable OVS in a self-focusing medium?

Saturable NL refractive index and NL absorption

CS_2
532 nm
psec



Effective NL refractive index



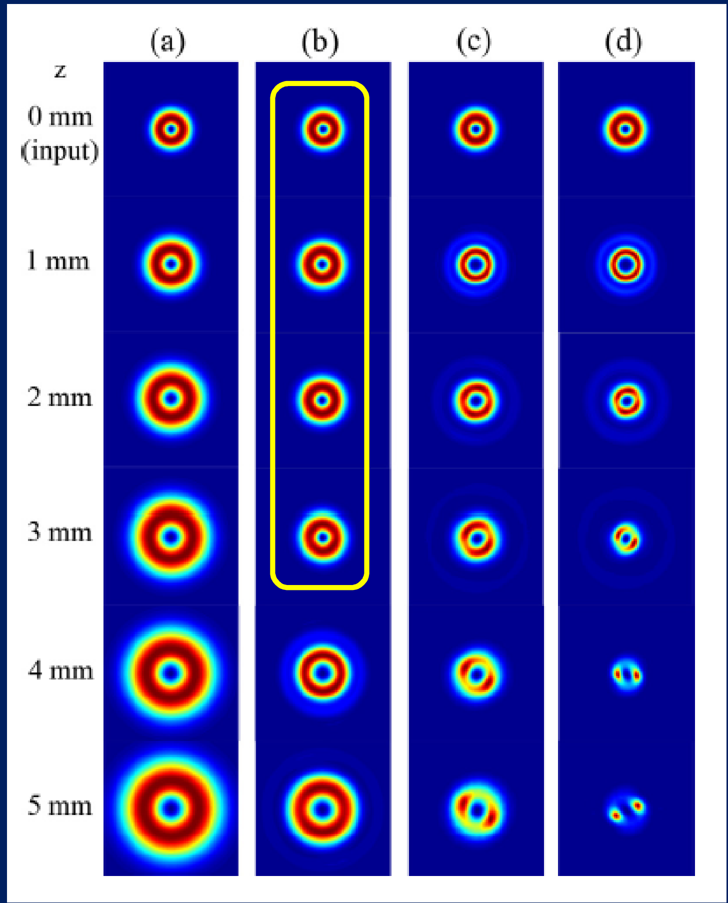
NL transmittance

This experiment

Besse, Leblond, Boudebs
Phys. Rev. A 89 (2014) 043840

Numerically simulated images
showing the evolution of the transverse vortex-beam profiles

$$i\frac{\partial E}{\partial z} = -\frac{1}{2n_0 k}\nabla_\perp E - \left[\frac{k\alpha I^2}{1+b^2 I^2} + i\frac{\gamma I^2}{2}\right]E$$



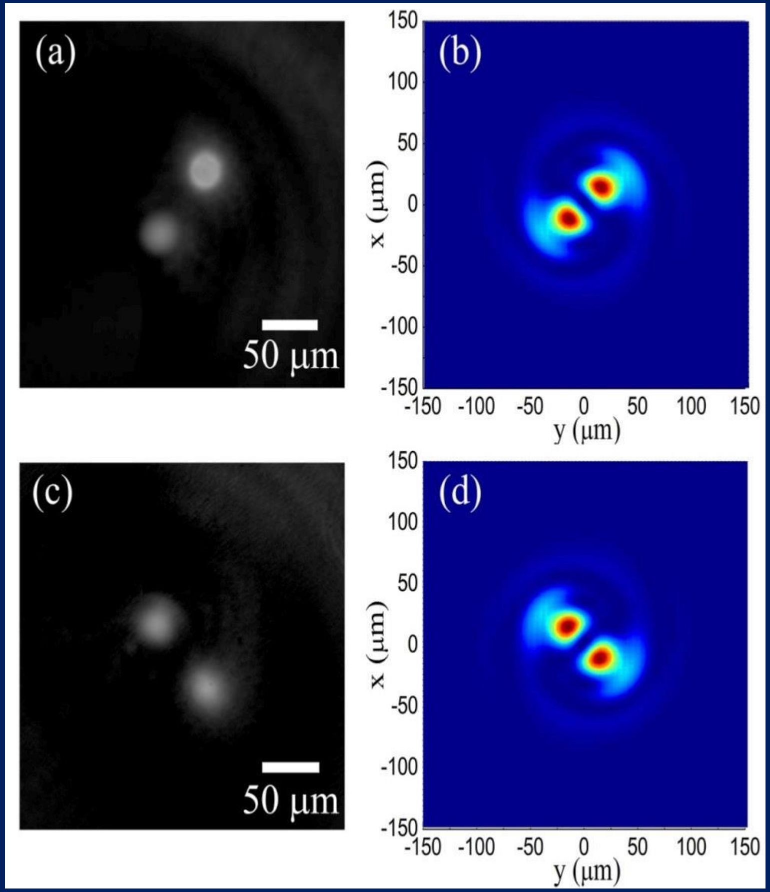
1 9 12 15 GW/cm²

Azimuthal symmetry breaking

$I = 18\, GW/cm^2$ $I = 15\, GW/cm^2$

$m = +1$

$m = -1$



Considering 3PA

Stable OVS

$8\, GW/cm^2 \leq I < 10\, GW/cm^2$

splitting

$13\, GW/cm^2 \leq I$

No 3PA

$7.4\, GW/cm^2 \leq I \leq 7.6\, GW/cm^2$

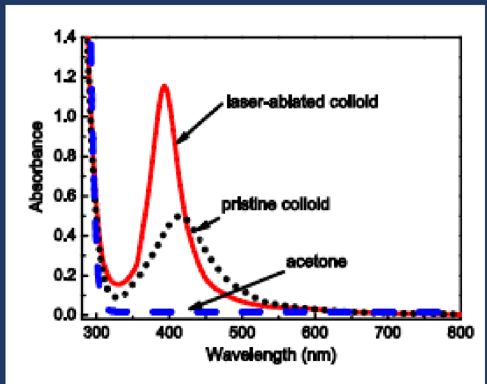
$8\, GW/cm^2 \leq I$

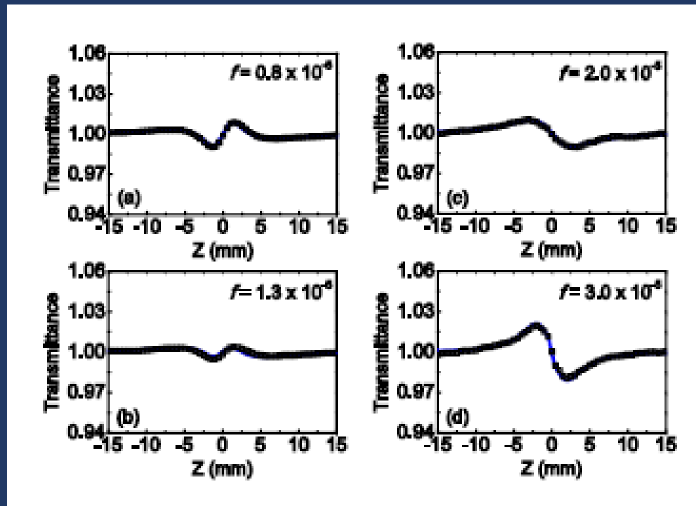
FILM

topological charge m = +1 final.mp4

Observation of fifth-order refraction in a colloid with supressed third-order refraction

Silver NPs in acetone

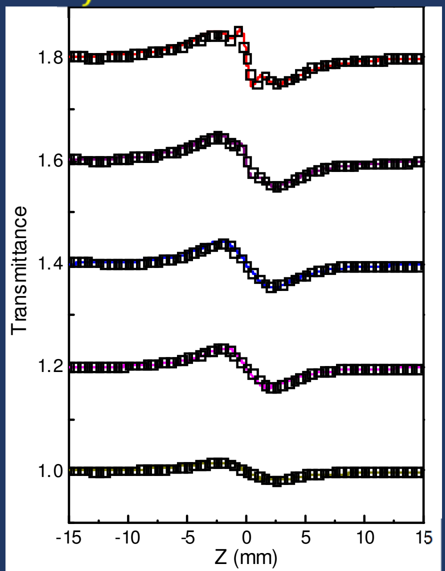




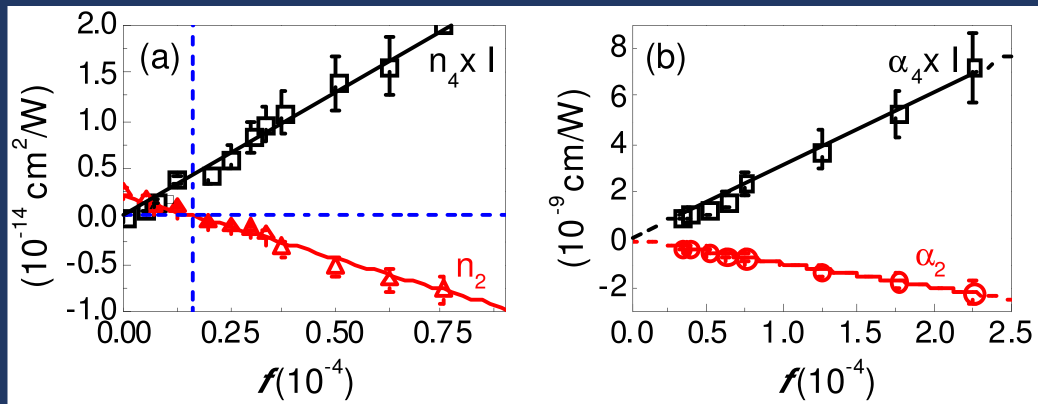
Z-scan

532 nm
Single pulses
5 GW/cm^2

$f = 5.0\ x\ 10^{-5}$



9
8
6
4
2
GW/cm^2



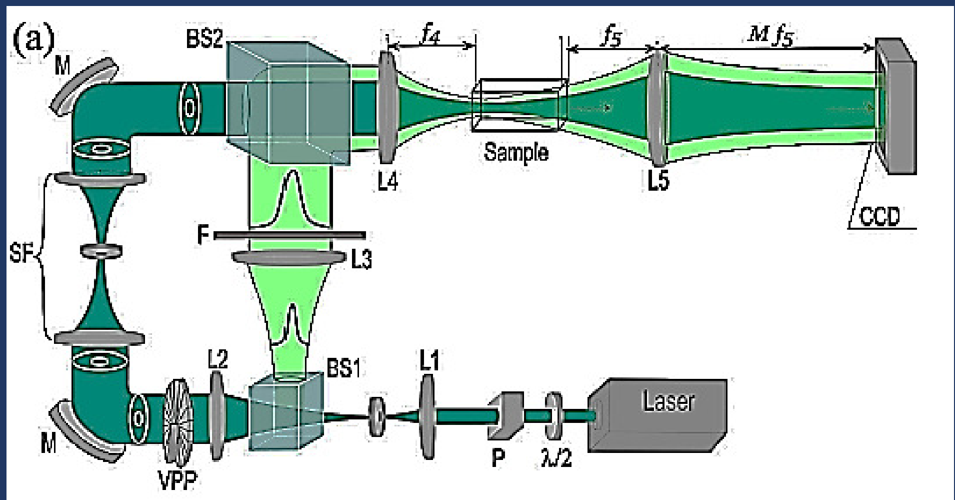
9 GW/cm^2

PHYSICAL REVIEW A **93**, 013843 (2016)

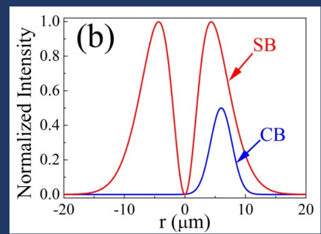
Taming the emerging beams after the split of optical vortex solitons in a saturable medium

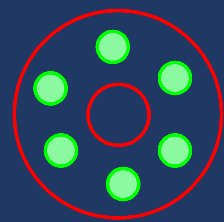
Albert S. Reyna* and Cid B. de Araújo

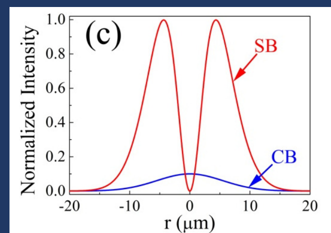
Possible applications of OVS in all-optical devices

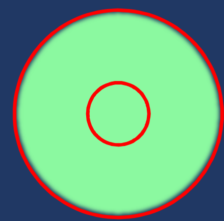


532 nm, 80 ps, 10Hz



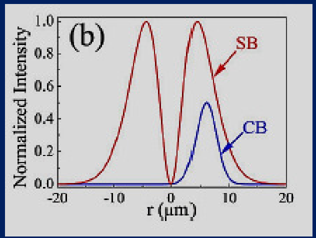




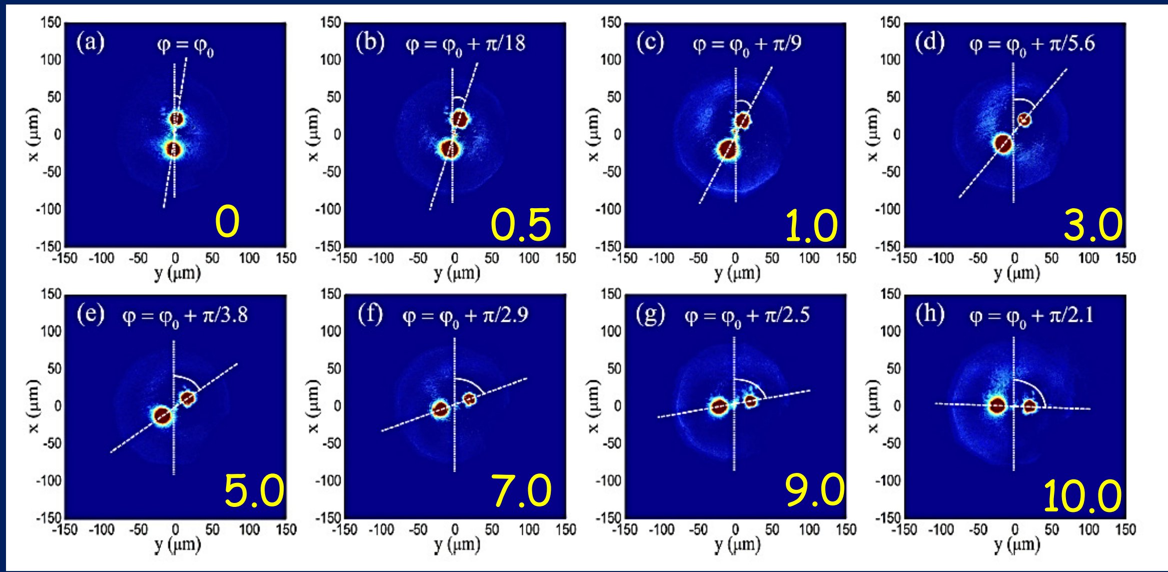


cell length: 10 mm

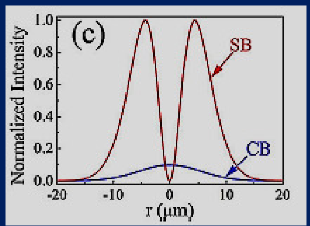
VB intensity
18 GW/cm^2

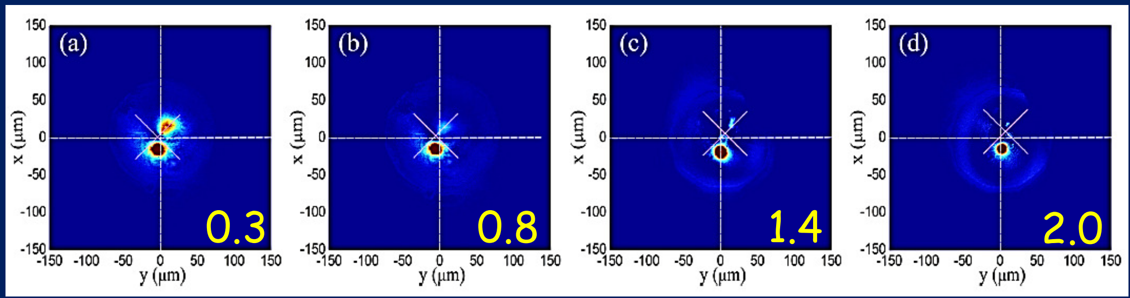


Control beam
GW/cm^2



Control beam less intense than the signal beam



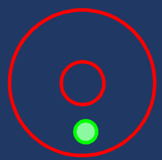


Control of energy transfer

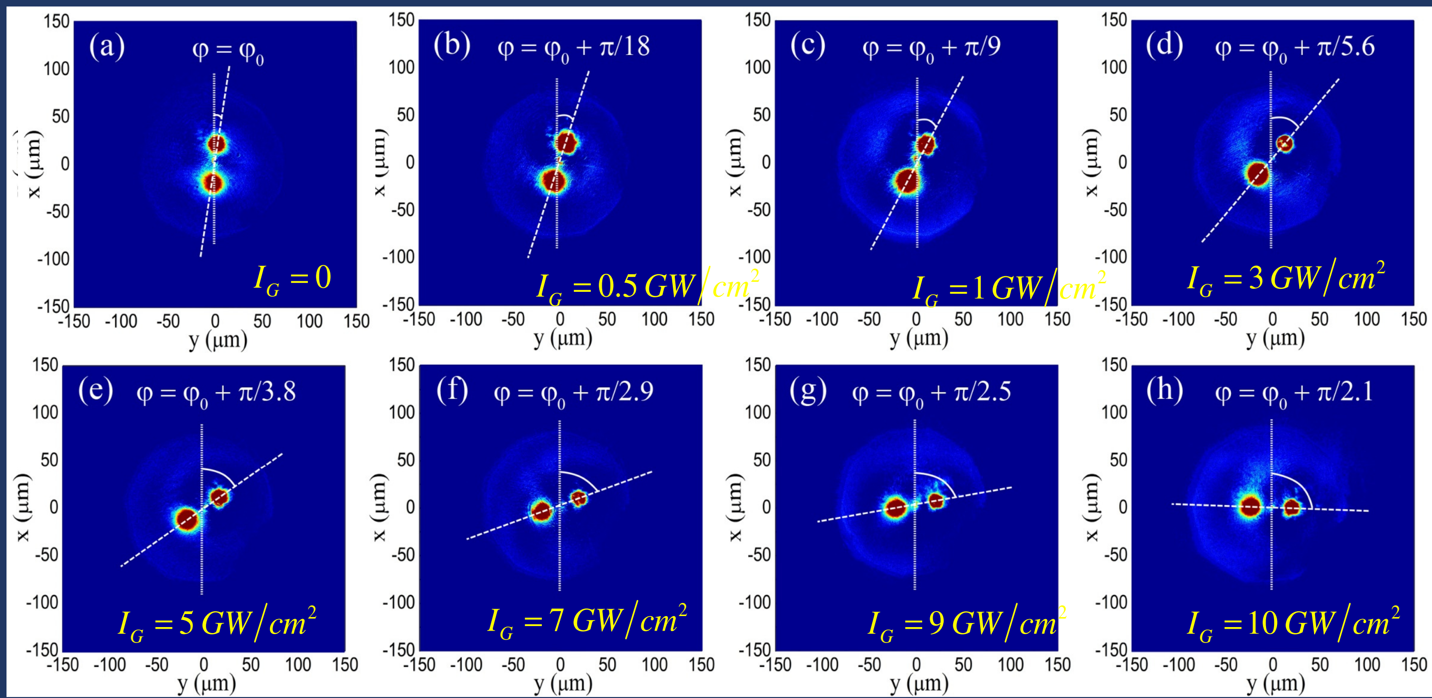
Two coupled NL equation considering saturable nonlinearity and 3PA

Vortex beam → $$i\frac{\partial E_S}{\partial z} = -\frac{1}{2n_0k}\nabla_\perp E_S - \left[\frac{ka\left(I_S^2 + I_S I_C\right)}{1+b^2\left(I_S + I_C\right)^2} + i\frac{\gamma}{2}\left(I_S^2 + 3I_S I_C\right)\right]E_S$$

Gaussian beam → $$i\frac{\partial E_C}{\partial z} = -\frac{1}{2n_0k}\nabla_\perp E_C - \left[\frac{ka\left(I_C^2 + I_S I_C\right)}{1+b^2\left(I_S + I_C\right)^2} + i\frac{\gamma}{2}\left(I_C^2 + 3I_S I_C\right)\right]E_C$$



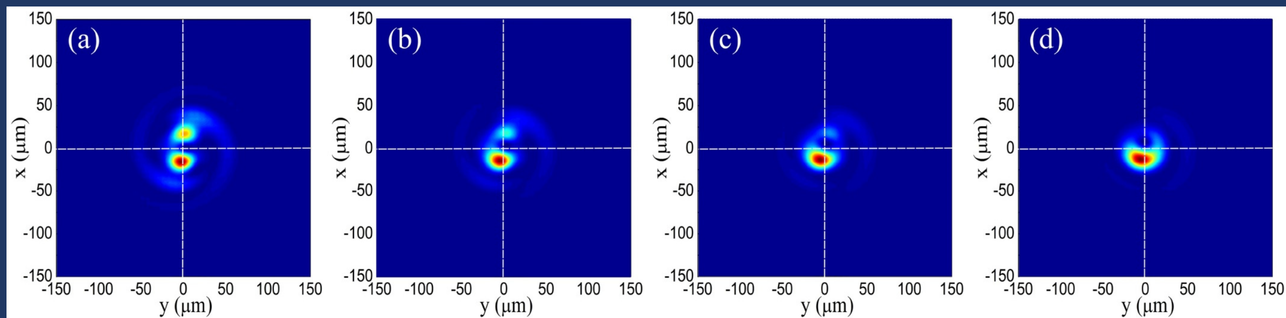
$I_v = 18\, GW/cm^2$



Two coupled NL equation considering saturable nonlinearity and 3PA

Vortex beam → $$i\frac{\partial E_S}{\partial z} = -\frac{1}{2n_0k}\nabla_\perp E_S - \left[\frac{ka\left(I_S^2+I_SI_C\right)}{1+b^2\left(I_S+I_C\right)^2} + i\frac{\gamma}{2}\left(I_S^2+3I_SI_C\right)\right]E_S$$

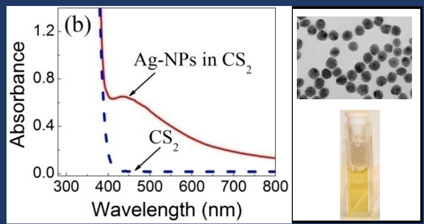
Gaussian beam → $$i\frac{\partial E_C}{\partial z} = -\frac{1}{2n_0k}\nabla_\perp E_C - \left[\frac{ka\left(I_C^2+I_SI_C\right)}{1+b^2\left(I_S+I_C\right)^2} + i\frac{\gamma}{2}\left(I_C^2+3I_SI_C\right)\right]E_C$$



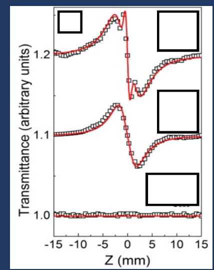
Phys. Rev. A 93, 013843 (2016)

Demonstration of optically induced waveguide using OVS

Metal colloid



Z-scan of AgNP in CS_2

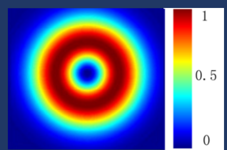


$n^{(NL)} < 0$

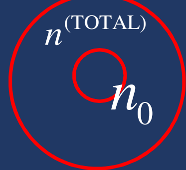
Self-defocusing medium

$$n^{(TOTAL)} = n_0 + n^{(NL)} < n_0$$

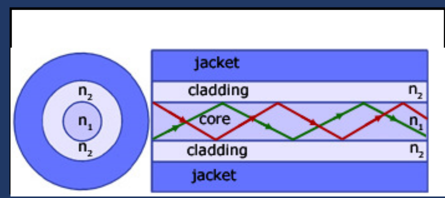
Vortex beam profile ($l = +1$)



Intensity



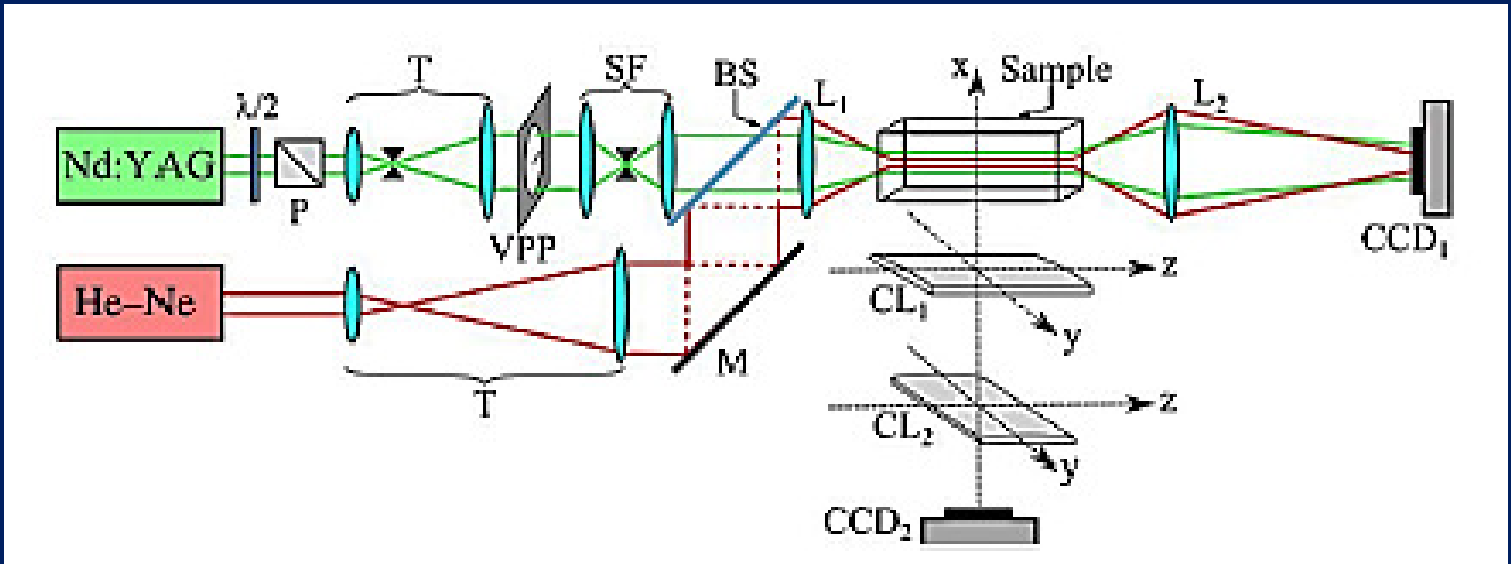
Optical fiber



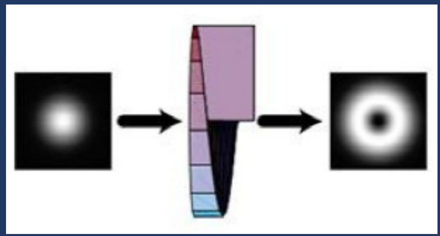
Optics Letters 41 (2016) 191

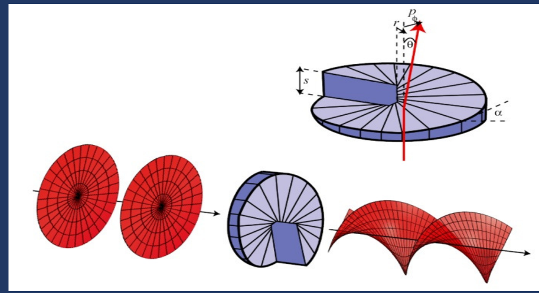
Guiding and confinement of light induced by optical vortex solitons in a cubic–quintic medium

ALBERT S. REYNA* AND CID B. DE ARAÚJO



VPP- vortex phase plate



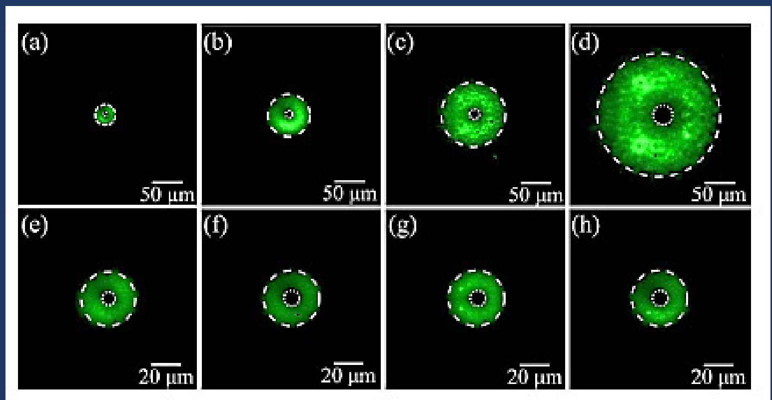


Optical Vortex beam carries an orbital angular momentum of $m\hbar$ per photon

Ag NPs (9.0 nm) suspended in acetone $f = 3 \times 10^{-5}$

$$\chi_{\mathrm{eff}}^{(3)} = -(8.3 + i2.7) \times 10^{-21}\ \mathrm{m}^2/\mathrm{V}^2$$

$$\chi_{\mathrm{eff}}^{(5)} = (2.8 + i0.2) \times 10^{-35}\ \mathrm{m}^4/\mathrm{V}^4$$

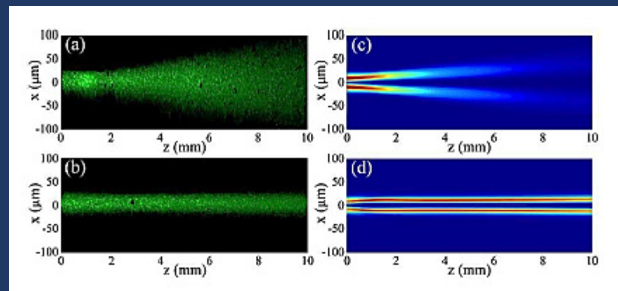


Z= 0 3 5 10 mm

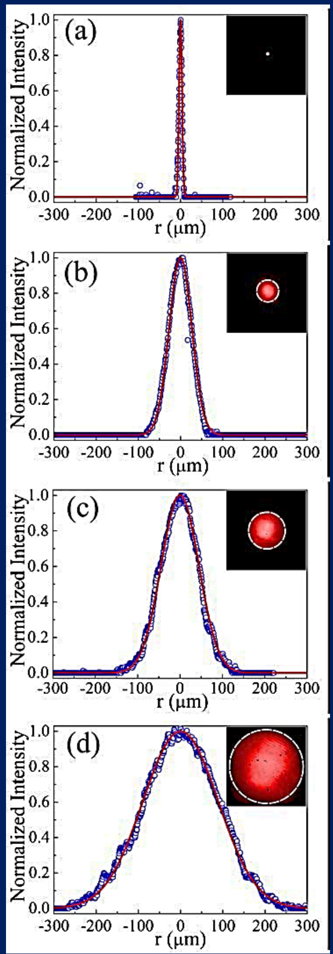
0.1

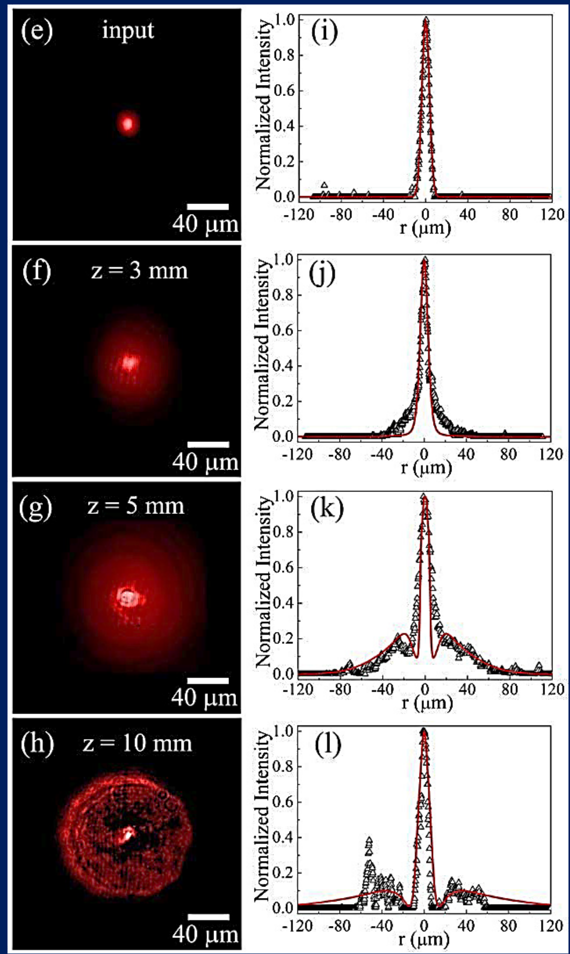
3.0

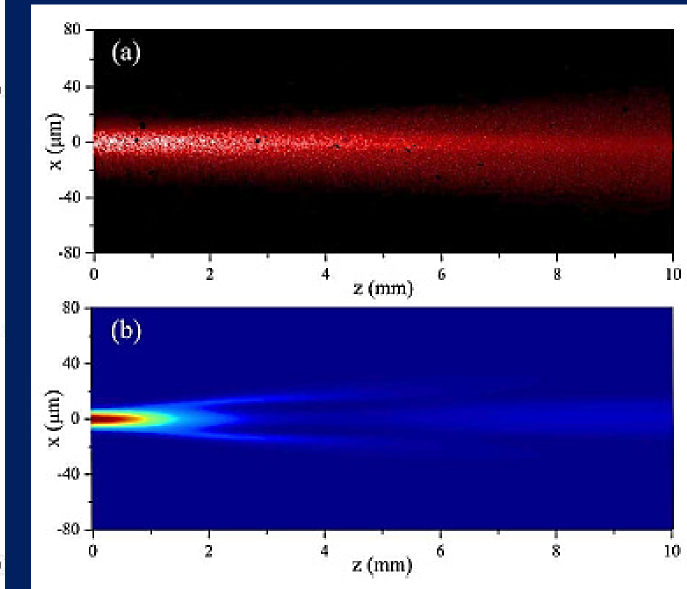
GW/cm^2



10 mm - 25 Z_R







HeNe

Guided HeNe

$I_{OVS} = 3.0\ GW/cm^2$

$I_{HeNe} = 0.1\ GW/cm^2$

Exploitation of high-order electronic nonlinearities allows::

- observation of (2+1)D bright spatial solitons in a homogeneous NL medium with electronic nonlinearity.
- observation of stable propagation of optical vortex solitons (OVS) in a medium with saturable refractive index and presenting NL absorption.
- controlling the instability of an OVS by using a control beam with smaller intensity than the OVS.
- guiding and confinement of an OVS in a self-defocusing cubic-quintic medium