School of Modern Optics

9 May 2013, Puebla, Mexico

Lecture 4

Optical vortex generation using liquid crystals II

Etienne Brasselet

Singular Optics & Liquid Crystals group

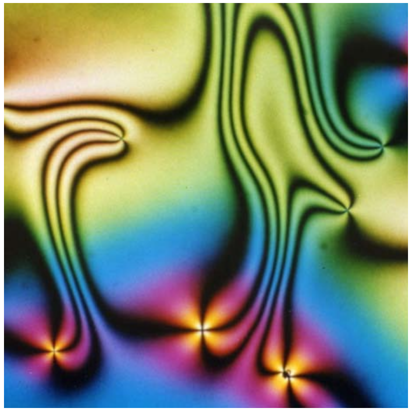
www.loma.cnrs.fr/spip.php?rubrique331

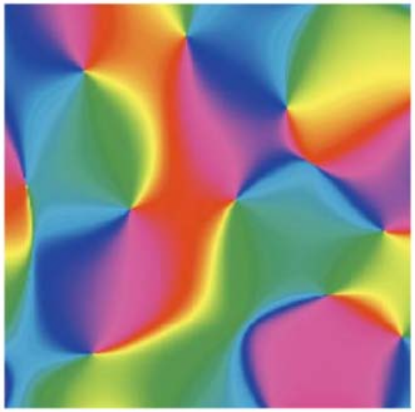
Laboratoire Ondes et Matières d'Aquitaine
CNRS, Université Bordeaux 1, France

Introduction : topological interplay between matter and light

Imprinting material topological information on light

Liquid crystal defects





Optical phase singularities

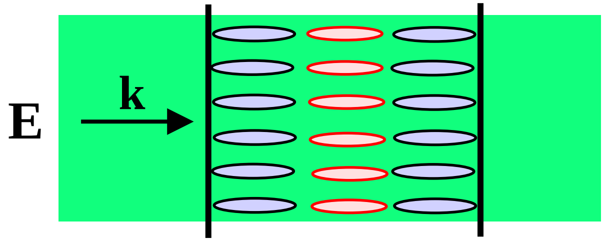
Imprinting optical topological information on matter

Outline

1. Light-induced liquid crystals topological defects
2. On-demand optical vortex generation
3. Nonlinear spin-orbit optical phenomena
4. Reconfigurable metastable light-induced vortex arrays

1980 **Optical Fréedericksz transition : a "regular" manifestation of the optical torque**

$$I > I_F \sim \mathrm{kW/cm^2}$$



Regular reorientation

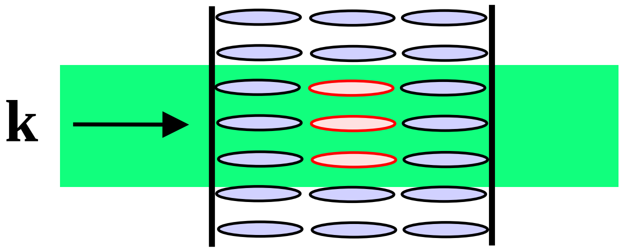
A. S. Zolot'ko et al., JETP Lett. **32**, 158 (1980)

Optical reorientation of liquid crystals

1980 **Optical Fréedericksz transition : a "regular" manifestation of the optical torque**

30 years of studies (effects of : geometry, polarization, dopants, beam size, …)

2009 **Original geometry revisited**

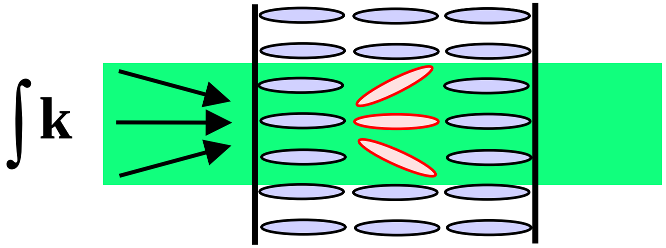


Optical reorientation of liquid crystals

1980 Optical Fréedericksz transition : a "regular" manifestation of the optical torque

30 years of studies (effects of : geometry, polarization, dopants, beam size, …)

2009 Original geometry revisited : a "singular" manifestation of the optical torque

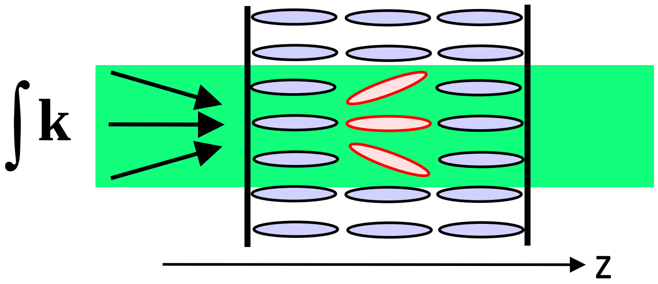


$$\Delta\mathbf{r} \cdot \Delta\mathbf{k} \neq 0$$

Topological optical reorientation

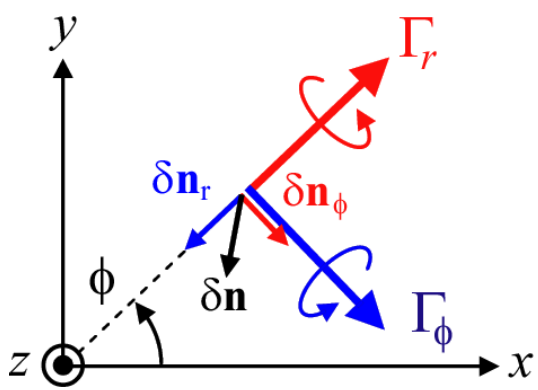
E. Brasselet, Opt. Lett. **34**, 3229 (2009) ; E. Brasselet, J. Opt. **12**, 124005 (2010)

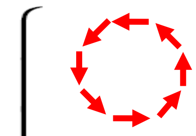
Topological optical reorientation : qualitative features



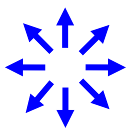
Optical torque density

$$\mathbf{\Gamma} = \frac{1}{2}\varepsilon_0\varepsilon_a \mathrm{Re}[(\mathbf{n}\cdot\mathbf{E}^*)(\mathbf{n}\times\mathbf{E})]$$
$$= \frac{1}{2}\varepsilon_0\varepsilon_a \mathrm{Re}(-E_z^* E_\phi\,\mathbf{e}_\mathrm{r} + E_z^* E_\mathrm{r}\,\mathbf{e}_\phi)$$
$$= \boxed{\Gamma_\mathrm{r}\,\mathbf{e}_\mathrm{r}} + \boxed{\Gamma_\phi\,\mathbf{e}_\phi}$$





Azimuthal reorientation mode



Radial reorientation mode

Topological optical reorientation : optical singularity at work ?

Let us consider a Gaussian beam under paraxial approximation

$$\mathbf{E}_\perp = E_0 u(r,z)\exp[-i(\omega t - kz)]\,\mathbf{e}_\perp$$

with

$$u(r,z) = \frac{w_0}{w(z)}\exp\left[-\frac{r^2}{w^2(z)} + i\frac{kr^2}{2z(1+z_0^2/z^2)} - i\arctan(z/z_0)\right]$$

The longitudinal field is usually neglected … but can be calculated anyway !

$$\nabla\cdot\mathbf{E} = 0 \quad\Rightarrow\quad \partial_z E_z = -\nabla_\perp\cdot\mathbf{E}_\perp$$

$$\Rightarrow\quad E_z = \frac{i}{k}\nabla_\perp\cdot\mathbf{E}_\perp + o(1/kw)$$

Circular polarization case

$$\mathbf{e}_\perp = \mathbf{e}_\sigma = \frac{\mathbf{e}_x + i\sigma\mathbf{e}_y}{\sqrt{2}}\ ,\ \sigma = \pm 1$$

$$\boxed{\mathbf{E}_z = -\frac{i}{z_0 + iz}\frac{r}{\sqrt{2}}e^{i\sigma\phi}(\mathbf{E}_\perp\cdot\mathbf{e}_\sigma^*)\,\mathbf{e}_z}$$

Topological optical reorientation : optical singularity at work ?

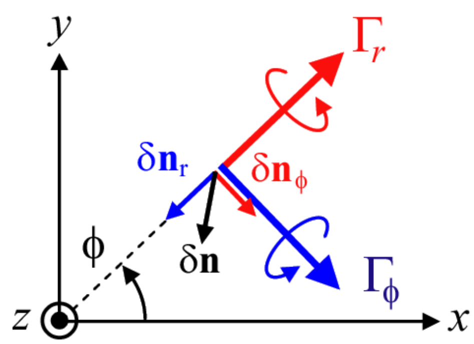
Total field for circular polarization state

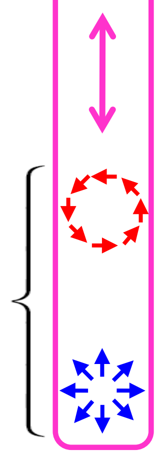
$$\mathbf{E} = E_0 u(r,z)\exp[-i(\omega t - kz)]\left(\boxed{\mathbf{e}_\sigma} - \frac{i}{z_0 + iz}\frac{r}{\sqrt{2}}\boxed{e^{i\sigma\phi}}\mathbf{e}_z\right)$$

Spin angular momentum

Orbital angular momentum

Longitudinal optical vortex with unit topological charge





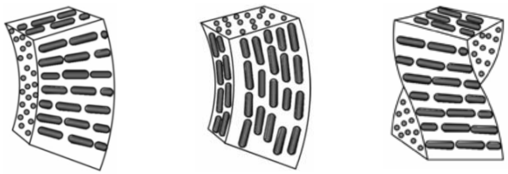
Azimuthal reorientation mode

Radial reorientation mode

Total free energy minimization

$$\mathcal{F} = \int_0^L \int_0^\infty \int_0^{2\pi} r(\underline{F_{\rm el}} + \underline{F_{\rm opt}})\, d\phi\, dr\, dz$$

Elastic distortion modes



Splay Bend Twist

Maxwell's equations

Paraxial solution in c-cut anisotropic media

A. Ciattoni *et al.*, JOSA B **18**, 156 (2001)

A. Ciattoni *et al.*, JOSA A **20**, 163 (2003)

E. Brasselet *et al.*, Opt. Lett. **34**, 1021 (2009)

Ansatz for singular reorientation modes

$$\delta \mathbf{n} = \delta n_{\rm r}\, \mathbf{e}_{\rm r} + \delta n_\phi\, \mathbf{e}_\phi + \delta n_z\, \mathbf{e}_z \quad \text{with} \quad \delta n_z = (1 - \delta n_{\rm r}^2 - \delta n_\phi^2)^{1/2} - 1$$

Axial symmetry : $\partial \Gamma_{{\rm r},\phi} / \partial \phi = 0 \quad \Rightarrow \quad \delta n_{{\rm r},\phi} = \mathcal{R}(r)\mathcal{Z}(z)$

Topological optical reorientation : a model

Total free energy minimization

$$\mathcal{F} = \int_0^L \int_0^\infty \int_0^{2\pi} r(F_{\rm el} + F_{\rm opt})\, d\phi\, dr\, dz$$

Elastic distortion modes

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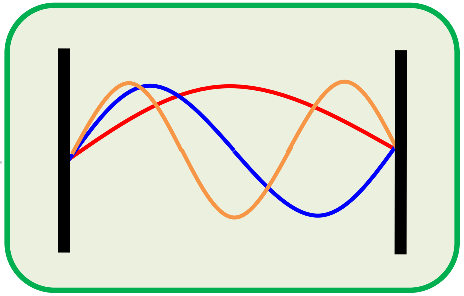

Axial symmetry : $\partial \Gamma_{{\rm r},\phi}/\partial\phi = 0 \;\Rightarrow\; \delta n_{{\rm r},\phi} = \mathcal{R}(r)\mathcal{Z}(z)$

Longtudinal boundary conditions : $\mathcal{Z}(0,L) = 0 \;\Rightarrow\; \mathcal{Z}(z) = \sum_m A^{(m)} \sin(mqz),\; q = \pi/L$

Topological optical reorientation : a model

Total free energy minimization

$$\mathcal{F} = \int_0^L \int_0^\infty \int_0^{2\pi} r (F_{\mathrm{el}} + F_{\mathrm{opt}}) d\phi dr dz$$

Elastic distortion modes

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Ansatz for singular reorientation modes

$$\delta\mathbf{n} = \delta n_{\mathrm{r}}\, \mathbf{e}_{\mathrm{r}} + \delta n_\phi\, \mathbf{e}_\phi + \delta n_z\, \mathbf{e}$$

$$\boldsymbol{\Gamma} = \tfrac{1}{2}\, \varepsilon_0 \varepsilon_a \mathrm{Re}(-E_z^* E_\phi\, \mathbf{e}_{\mathrm{r}} + E_z^* E_{\mathrm{r}}\, \mathbf{e}_\phi)$$

$$\mathbf{E} = E_0 u(r,z) \exp[-i(\omega t - kz)] \left(\mathbf{e}_\sigma - \frac{i}{z_0 + iz} \frac{r}{\sqrt{2}} e^{i\sigma\phi}\, \mathbf{e}_z \right)$$

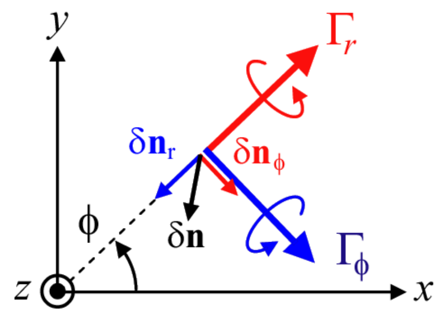
Axial symmetry : $\partial \Gamma_{\mathrm{r},\phi} / \partial \phi = 0 \;\Rightarrow\; \delta n_{\mathrm{r},\phi}$

Longtudinal boundary conditions : $\mathcal{Z}(0,L) = 0 \;\Rightarrow\; \mathcal{Z}(z) = \sum_m A^{(m)} \sin(mqz),\; q = \pi/L$

Transverse boundary conditions : $\mathcal{R}(0,\infty) = 0 \;\Rightarrow\; \mathcal{R}(r) = (r/w) \exp(-2r^2/w^2)$

Topological optical reorientation : a model

Ansatz for singular reorientation modes



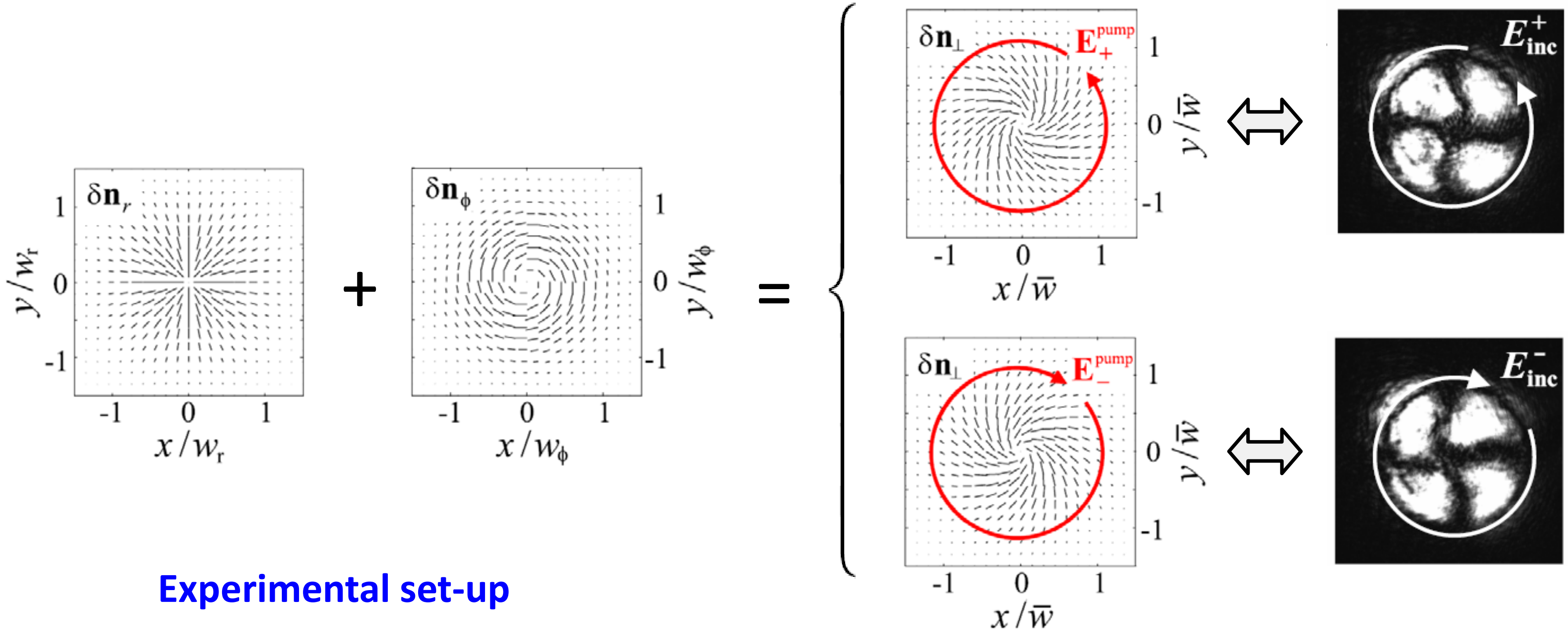
$$\boxed{\delta n_{\mathrm{r},\phi}(r, z) = \frac{r}{w_{\mathrm{r},\phi}} \exp(-2r^2/w_{\mathrm{r},\phi}^2) \sum_m A_{\mathrm{r},\phi}^{(m)} \sin(mqz)}$$

Retaining only the first longitudinal mode (m=1)

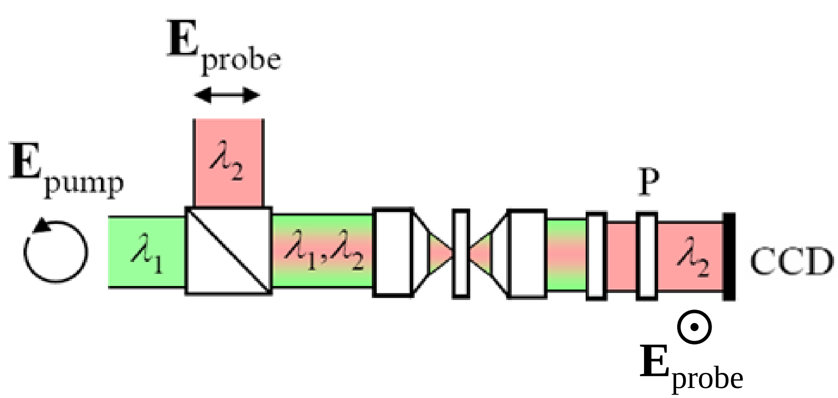
$$\boxed{\frac{\partial \mathcal{F}}{\partial u_k} = 0 \ , \ \mathbf{u} = (A_\mathrm{r}, A_\phi, w_\mathrm{r}, w_\phi)}$$

E. Brasselet, J. Opt. **12**, 124005 (2010)

Model **Experiment**



Experimental set-up



Spin controlled
Light-induced chiral elastic modes

Topological optical reorientation : why hidden for 30 years ?

Theoretical reason

Plane wave is easier !

Topological reorientation

$\theta_0 \sim 100$ mrad

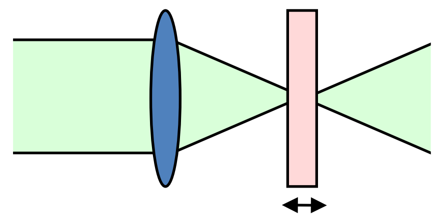
$\Downarrow$

$z_0 < L$

$\Downarrow$

Plane wave inappropriate

Experimental reason



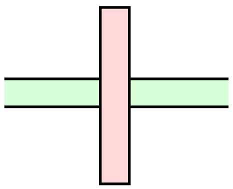
$w_0 \sim$ 10–100 μm

$\theta_0 \sim$ 1–10 mrad

L ~ 10–100 µm

$\Downarrow$

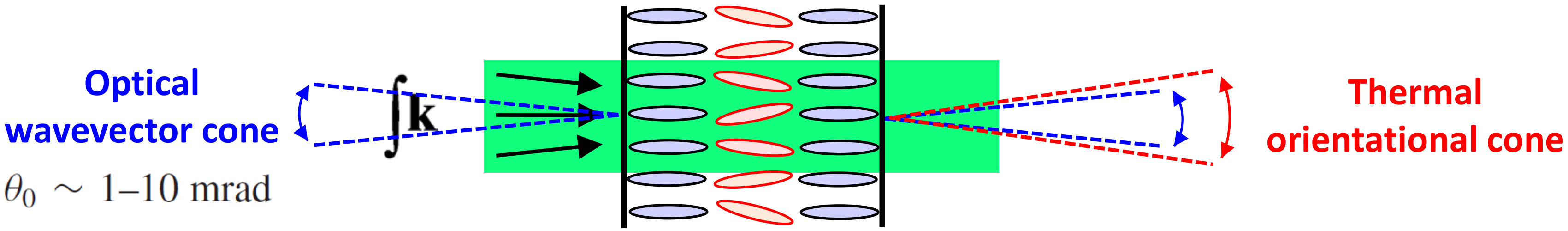
z_0 ~ mm–cm



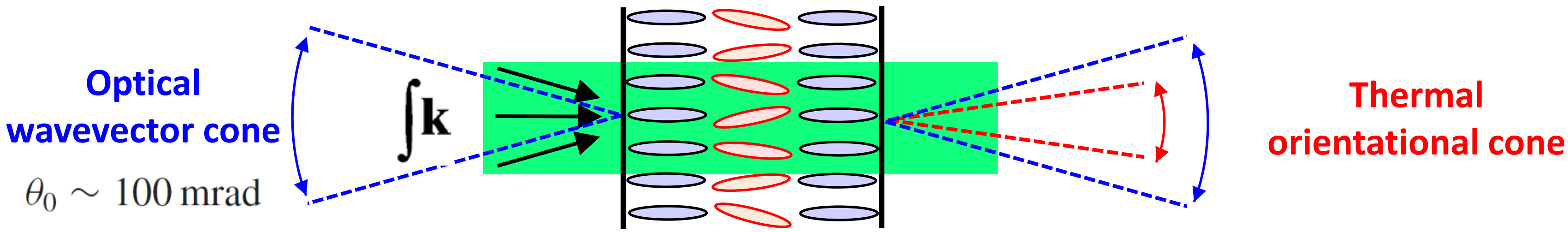
Cylindrical beam approximation

Topological optical reorientation : why hidden for 30 years ?

Regular collective reorientation



Singular collective reorientation



Outline

1. Light-induced liquid crystals topological defects

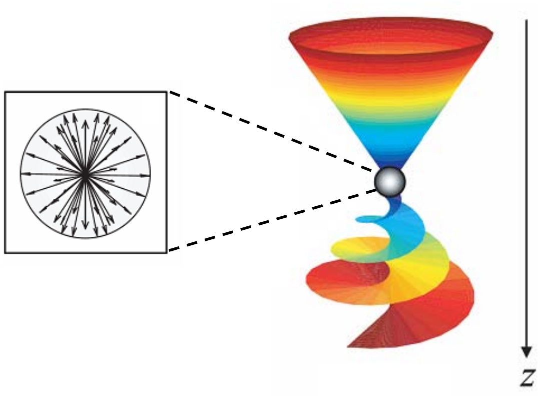
2. **On-demand optical vortex generation**

3. Nonlinear spin-orbit optical phenomena

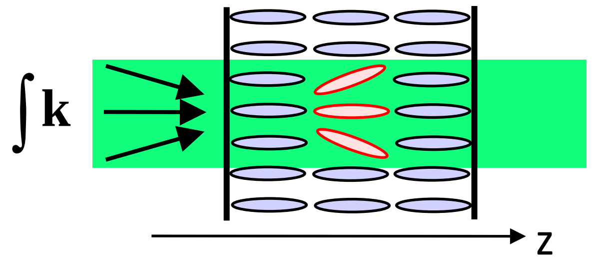
4. Reconfigurable metastable light-induced vortex arrays

On-demand optical vortex generation

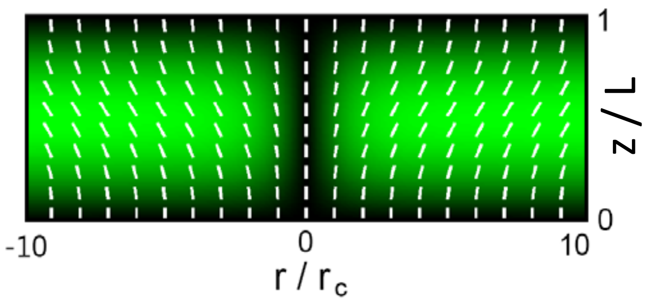
3D radial birefringence natural option

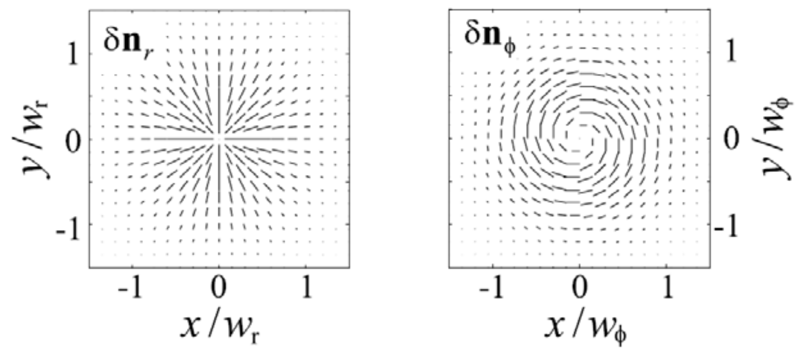


Light-induced option : topological reorientation



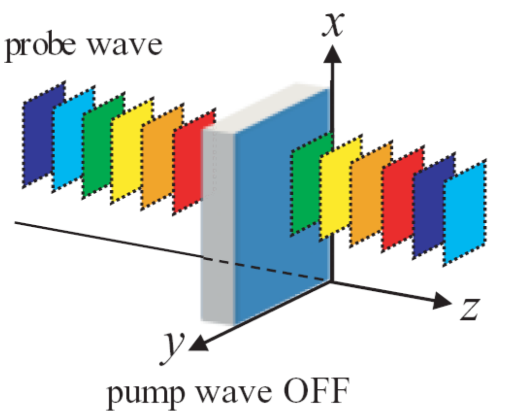
Light-induced on-demand umbilical defects

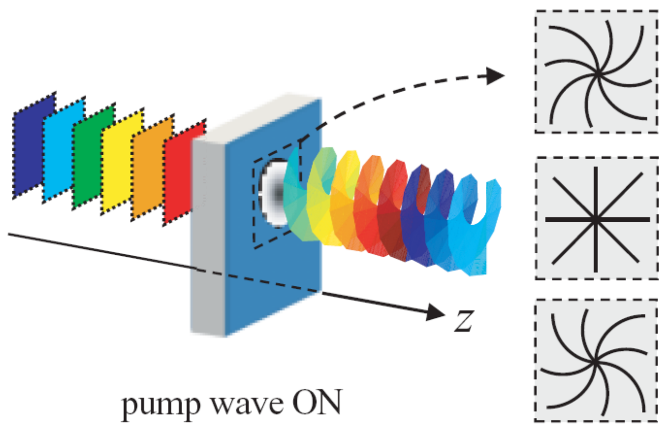




Flexible spin-orbit converters

On-demand optical vortex generation : principle



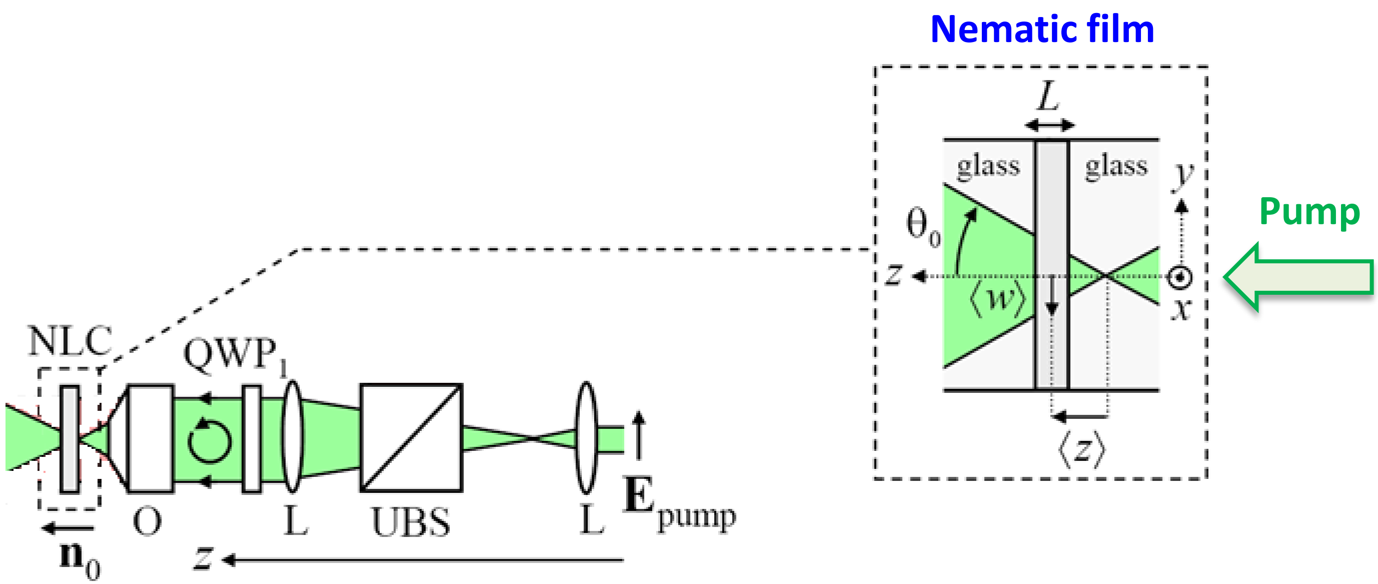


On-demand local encoding of optical phase singularities

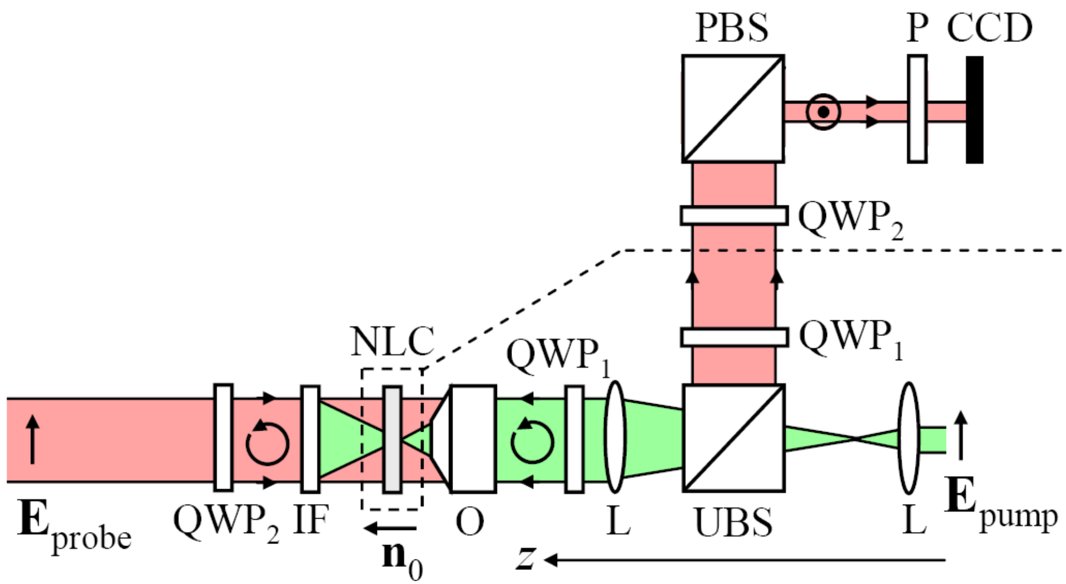
Induced by light and mediated by matter

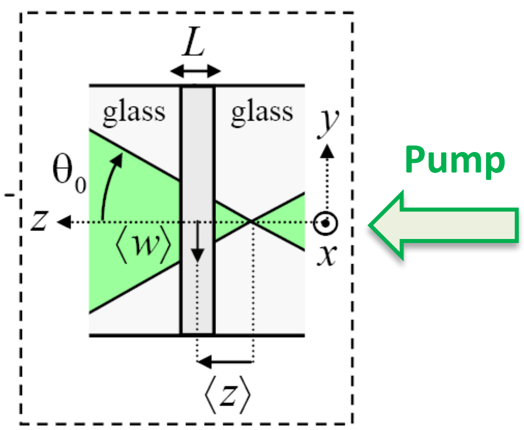
E. Brasselet, PRA **82**, 063836 (2010)

On-demand optical vortex generation : the experiment

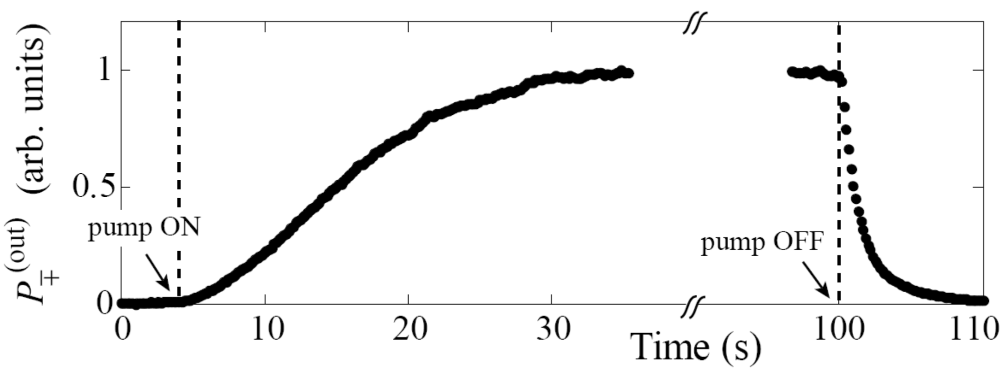


On-demand optical vortex generation : the experiment

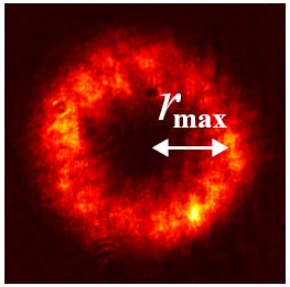




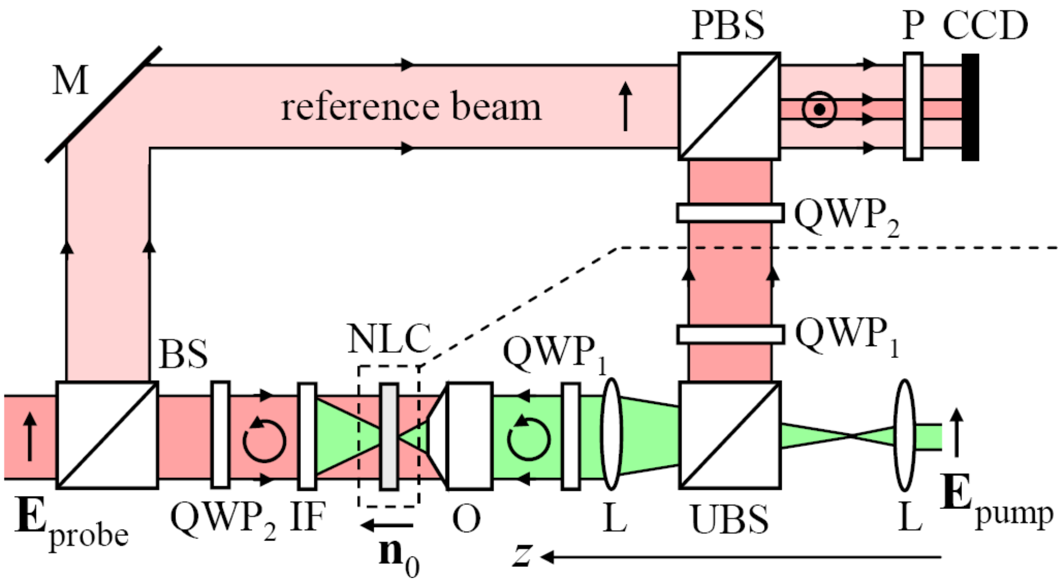
Rewritable process : writing-erasing cycle



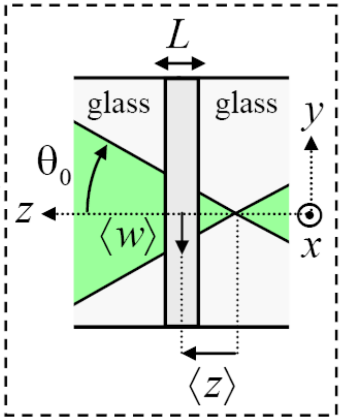
Steady vortex



On-demand optical vortex generation : the experiment

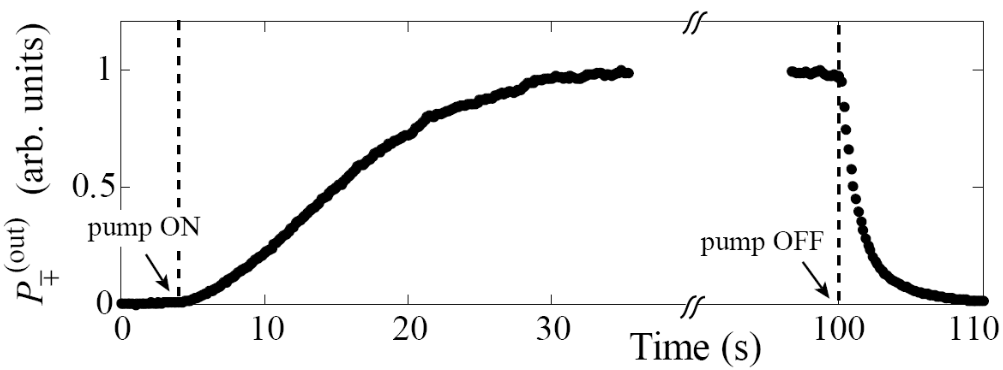


Nematic film

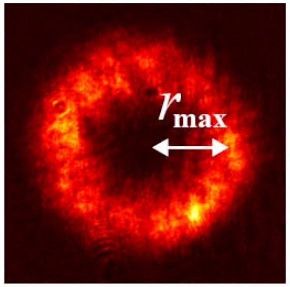


Pump

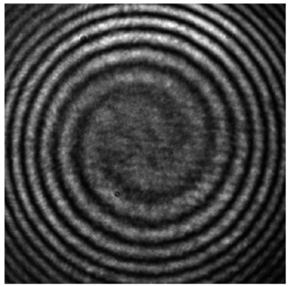
Rewritable process : writing-erasing cycle



Steady vortex

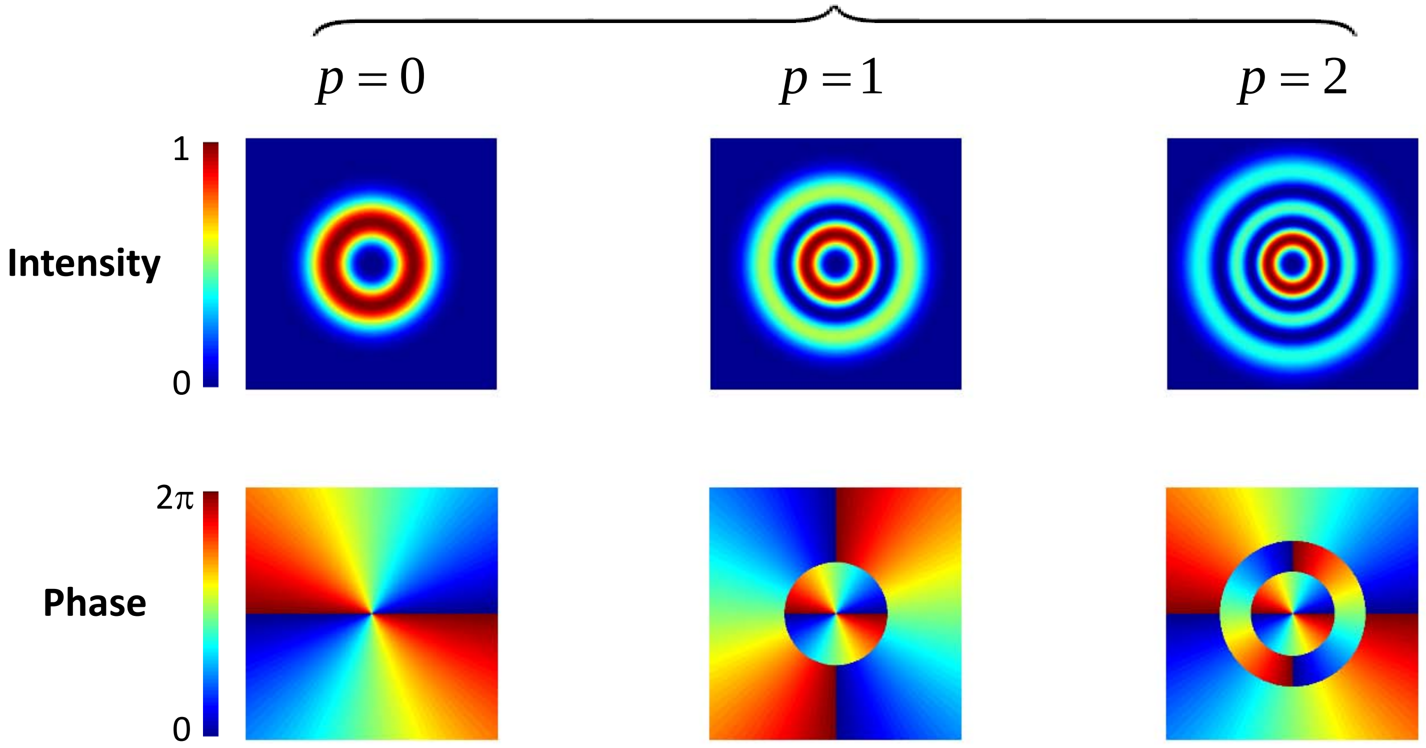


Topological charge two



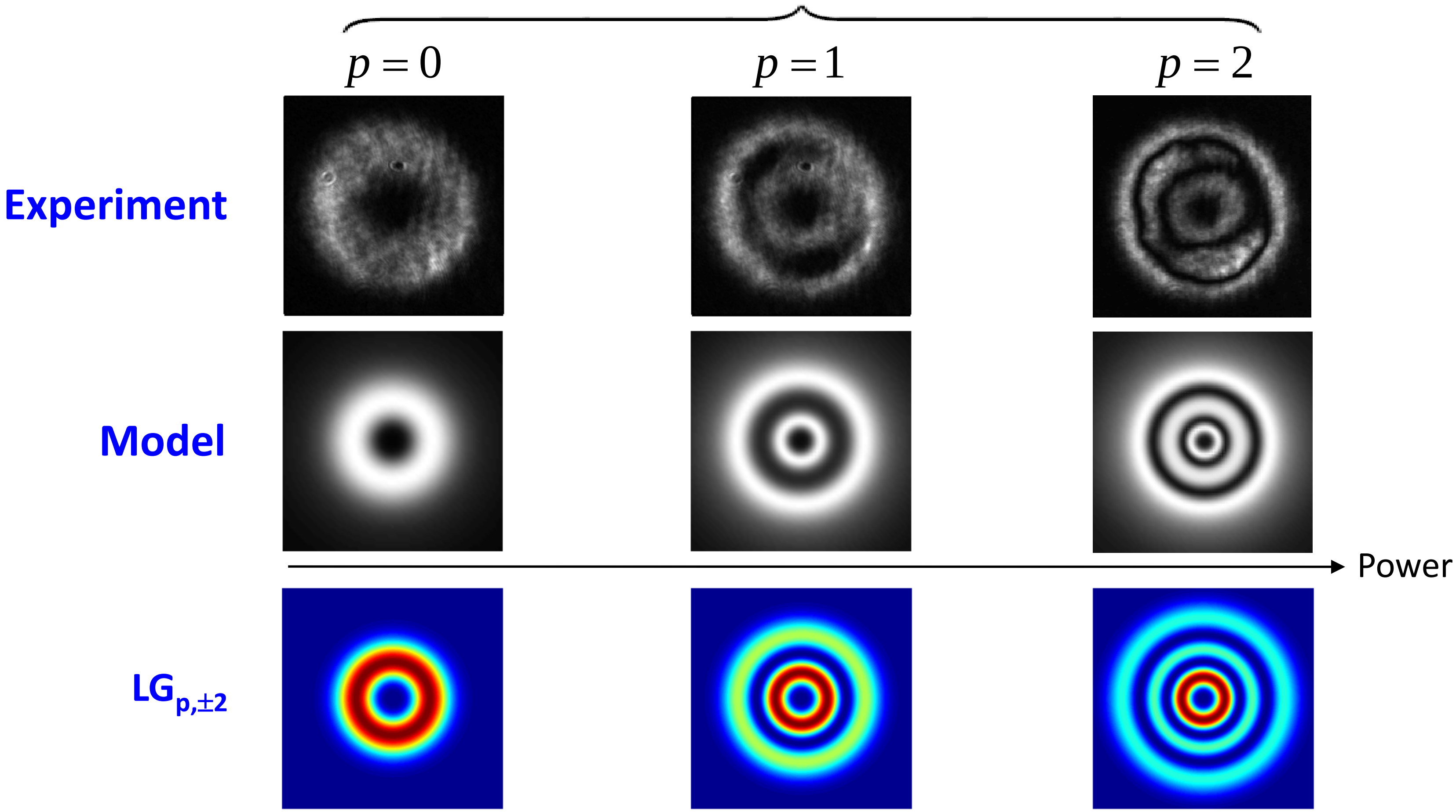
Higher-order light-induced optical vortices ?

Higher-order radial LG modes : $LG_{p,\pm2}$



Higher-order light-induced optical vortices ?

Different radial index : analogy with $LG_{p,\pm 2}$ beams



What about self-induced effects ?

Outline

1. Light-induced liquid crystals topological defects

2. On-demand optical vortex generation

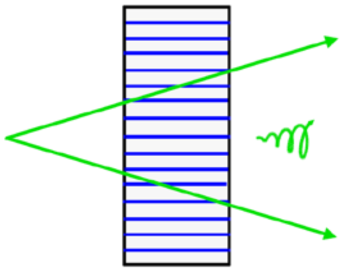
3. **Nonlinear spin-orbit optical phenomena**

4. Reconfigurable metastable light-induced vortex arrays

From linear to nonlinear optical spin-orbit interaction

No defect $\leftrightarrow$ Linear regime

Circularly polarized Gaussian beam

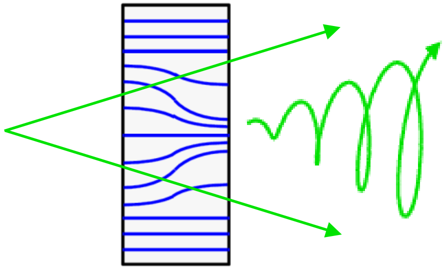


Contra-circularly polarized vortex beam

What is the effect of a light-induced topological defect ?

Laser-induced defect $\leftrightarrow$ Nonlinear regime

Circularly polarized Gaussian beam

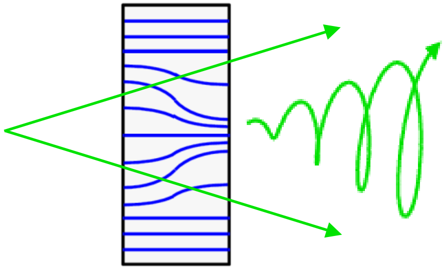


M. El Ketara and E. Brasselet, Opt. Lett. **37**, 602 (2012)

Nonlinear regime

Topological optical reorientation at work

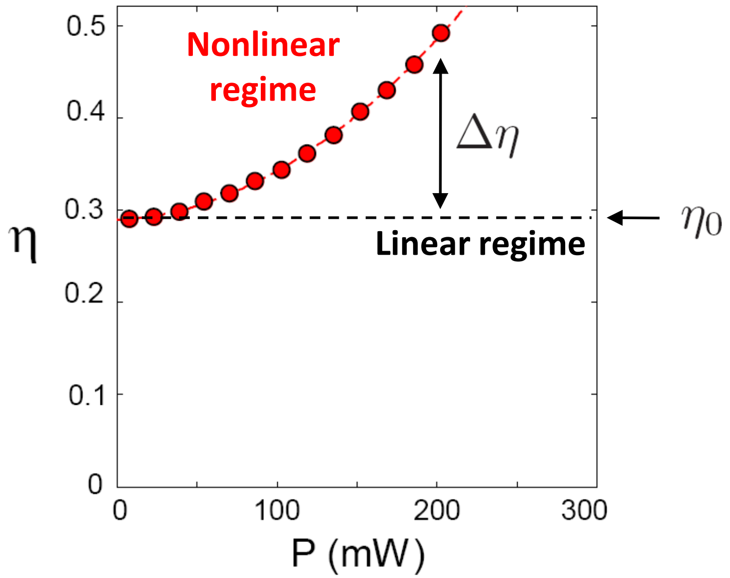
Circularly polarized Gaussian beam



$$\eta = \eta_0 + \Delta\eta$$

Efficiency of the vortex generation

Experiment

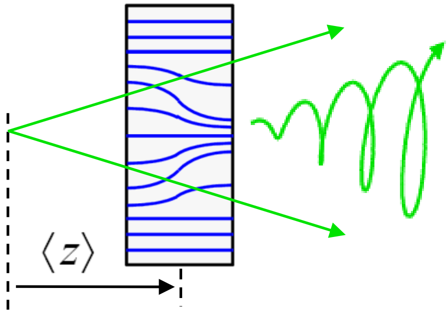


Self-induced spin-to-orbital angular momentum conversion

Nonlinear regime

Topological optical reorientation at work

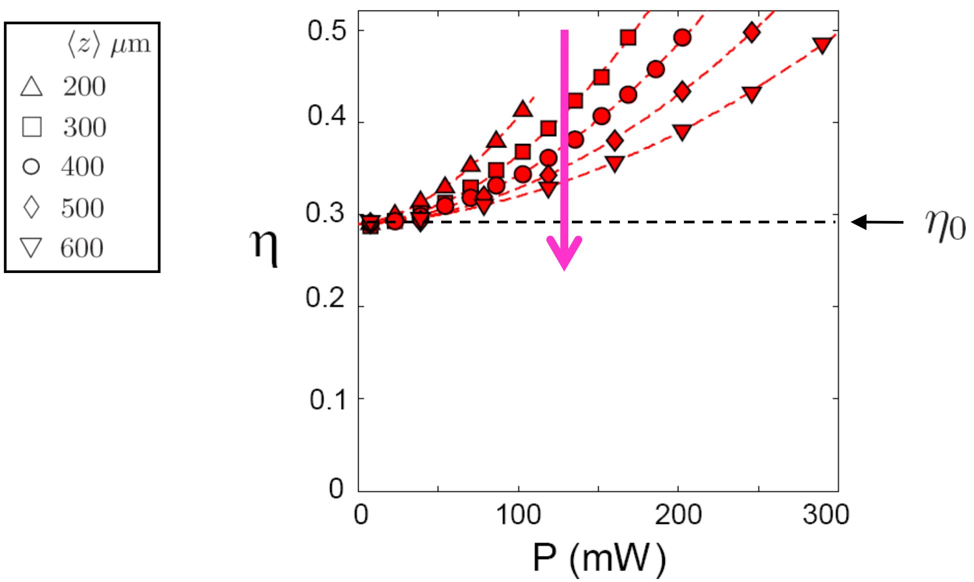
Circularly polarized Gaussian beam



$$\eta = \eta_0 + \Delta\eta$$

Efficiency of the vortex generation

Experiment



Beam spot increases

$\Downarrow$

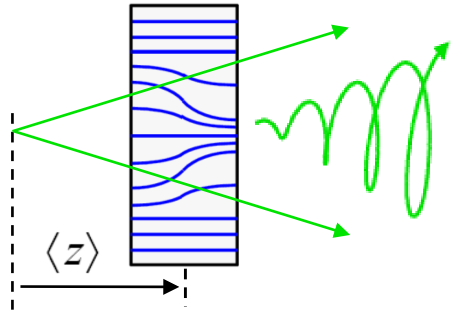
Intensity decreases at fixed power

Self-induced spin-to-orbital angular momentum conversion

Nonlinear regime

Topological optical reorientation at work

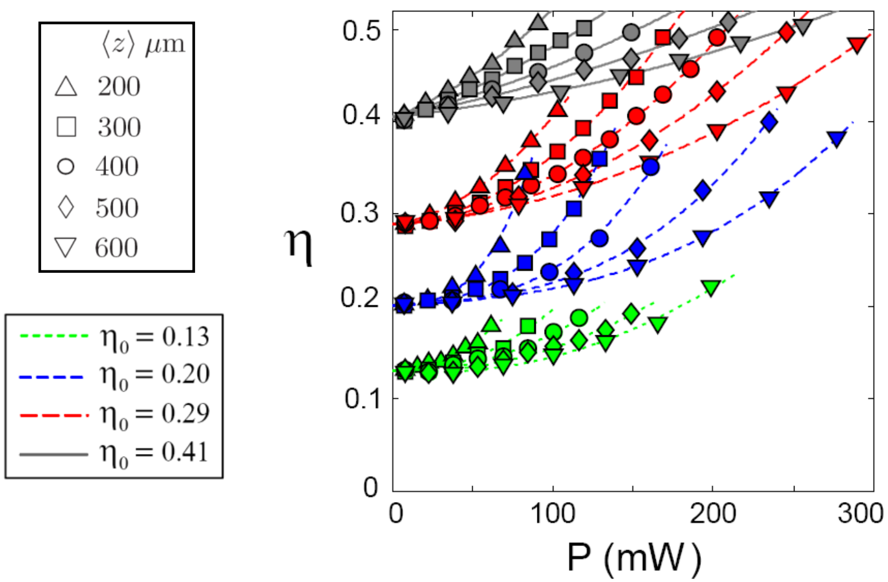
Circularly polarized Gaussian beam



$$\eta = \eta_0 + \Delta\eta$$

Efficiency of the vortex generation

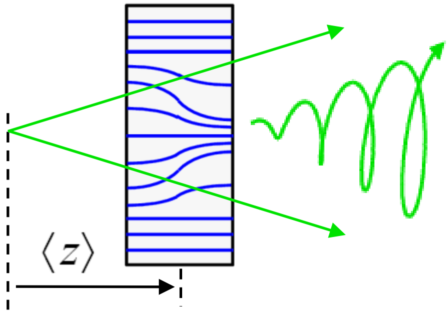
Experiment



Nonlinear regime

Topological optical reorientation at work

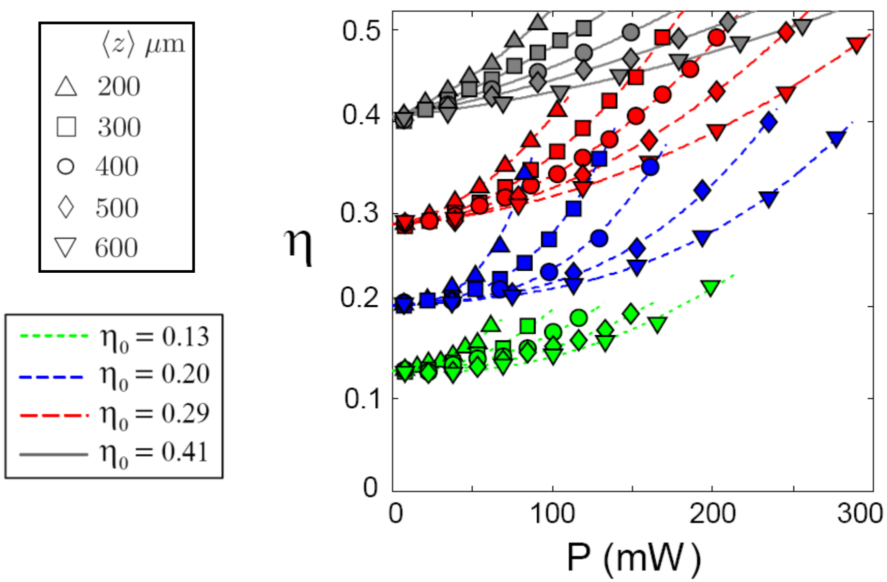
Circularly polarized Gaussian beam



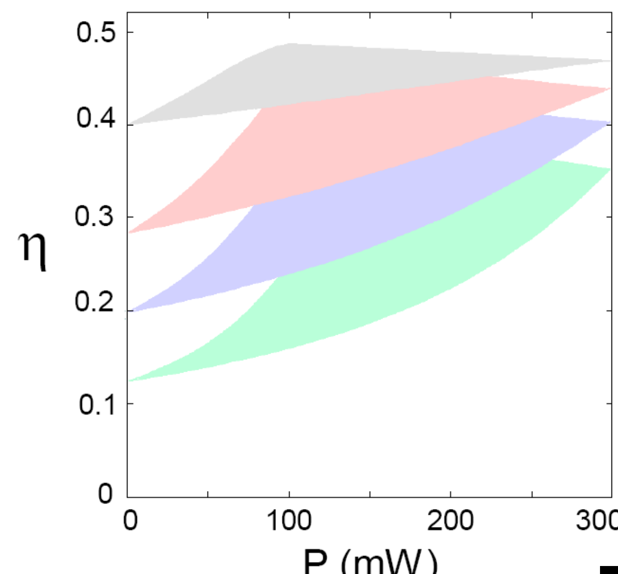
$$\eta = \eta_0 + \Delta\eta$$

Efficiency of the vortex generation

Experiment



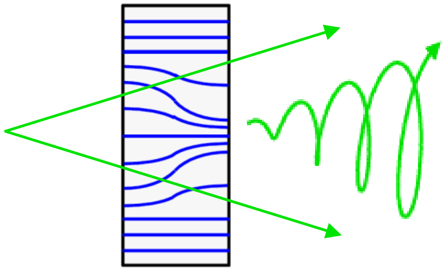
Model



Nonlinear regime

Topological optical reorientation at work

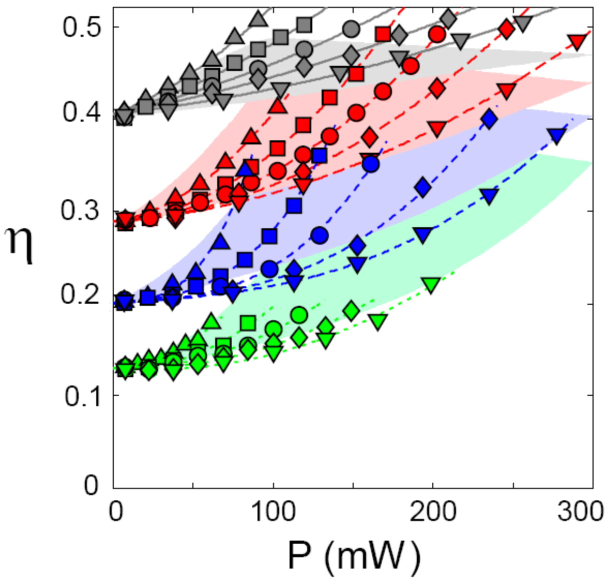
Circularly polarized Gaussian beam



$$\eta = \eta_0 + \Delta\eta$$

Efficiency of the vortex generation

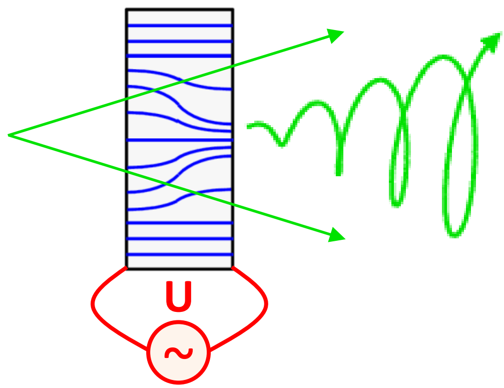
Experiment vs. Model



Electrically enhanced nonlinear optical spin-orbit coupling

Enhanced nonlinearity using « negative nematics » (ε_a<0)

Circularly polarized
Gaussian beam

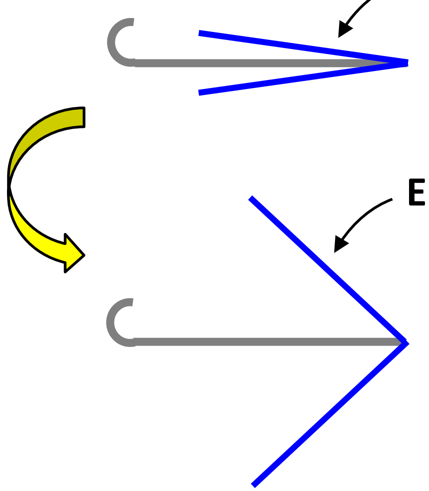


$$\eta = \eta_0 + \Delta\eta$$

Efficiency of the vortex generation

Opening of the « liquid crystal umbrella »

Here is the director



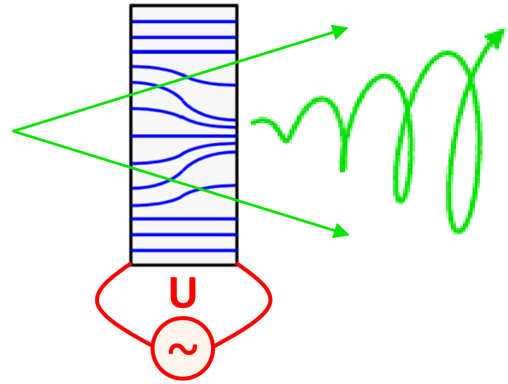
Electro-assisted reorientation

Here is the electrical
power supply

Electrically enhanced nonlinear optical spin-orbit coupling

Enhanced nonlinearity using « negative nematics » (ε_a<0)

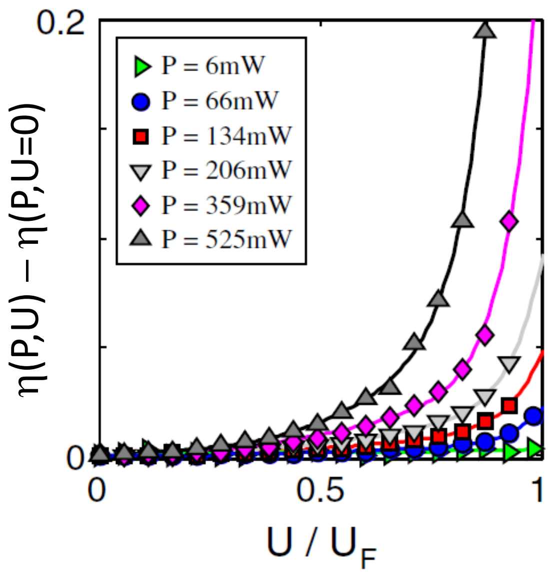
Circularly polarized Gaussian beam



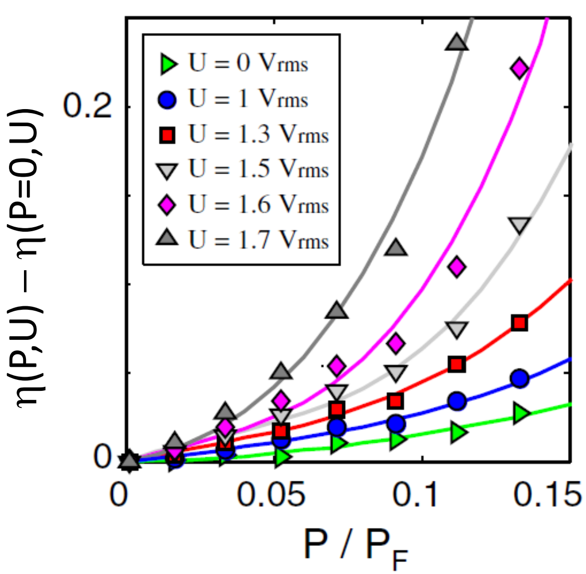
$$\eta = \eta_0 + \Delta\eta$$

Efficiency of the vortex generation

Fixed input power P



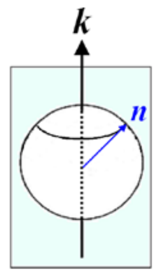
Fixed applied voltage U



What about the director precession ?

Regular optical reorientation

Nothing to declare



Regular collective precession

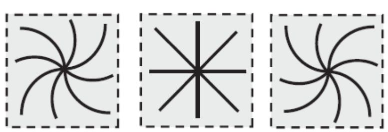
0

Threshold

Power

Singular optical reorientation

Light-induced defect



Singular collective precession ?

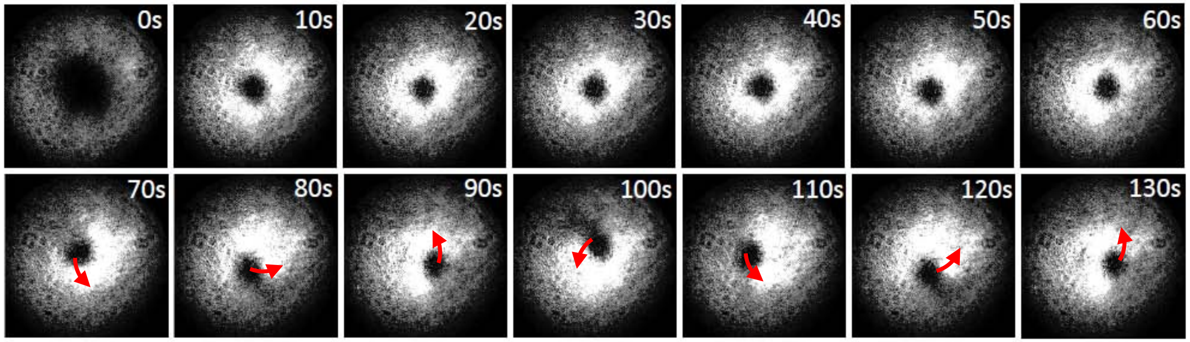
0

Power

Self-induced optical vortex beam precession

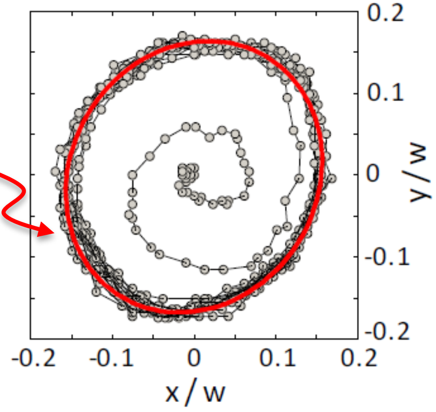
Axial symmetry spontaneously breaks above a threshold

$P > P_c$

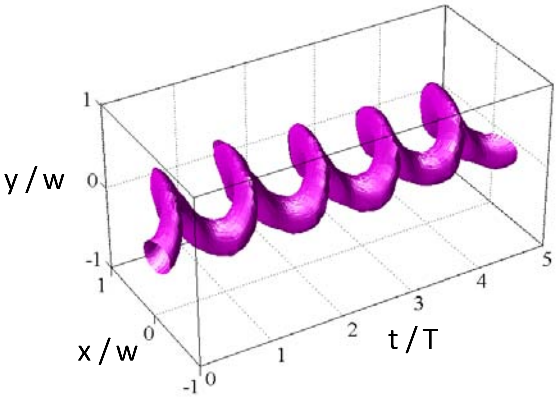


Optical vortex dynamics

Stationary trajectory

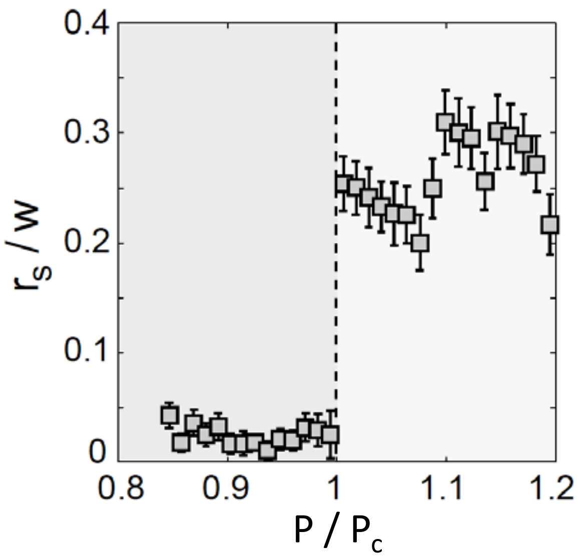


Vortex core dynamics

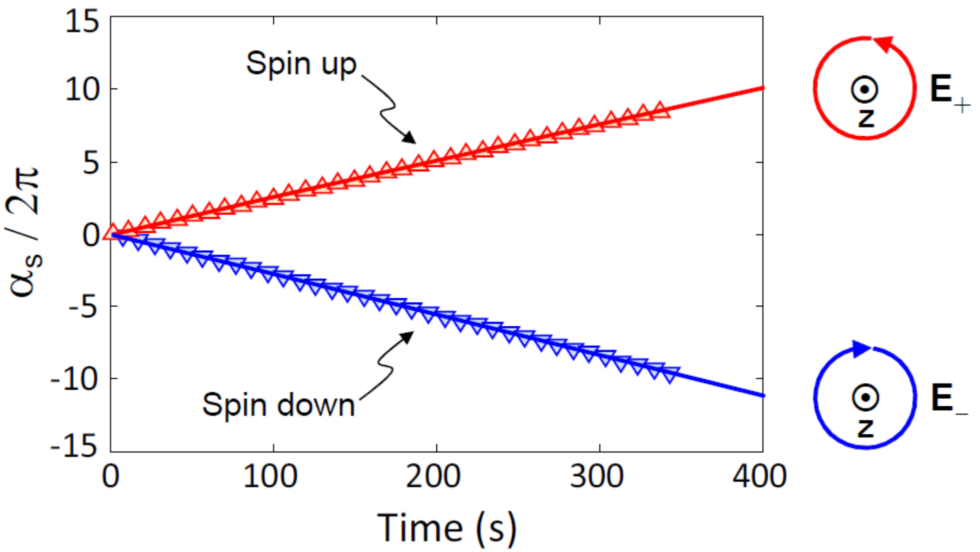


M. El Ketara and E. Brasselet, submitted.

Threshold behavior



Spin-dependent orbiting motion



However, all reported effects relax when the beam is turned off …

Outline

1. Light-induced liquid crystals topological defects

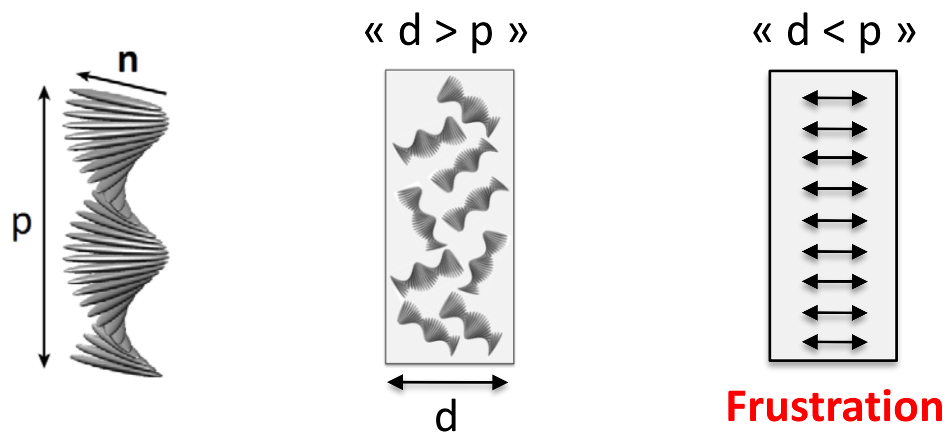
2. On-demand optical vortex generation

3. Nonlinear spin-orbit optical phenomena

4. **Reconfigurable metastable light-induced vortex arrays**

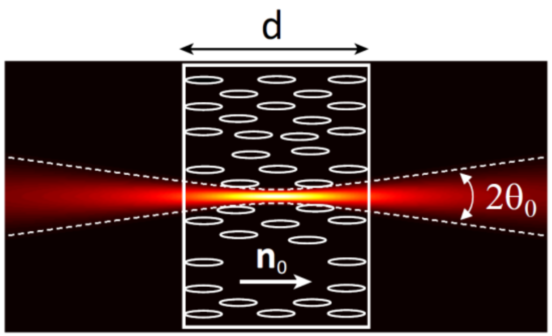
Laser-induced permanent defects in frustrated cholesterics

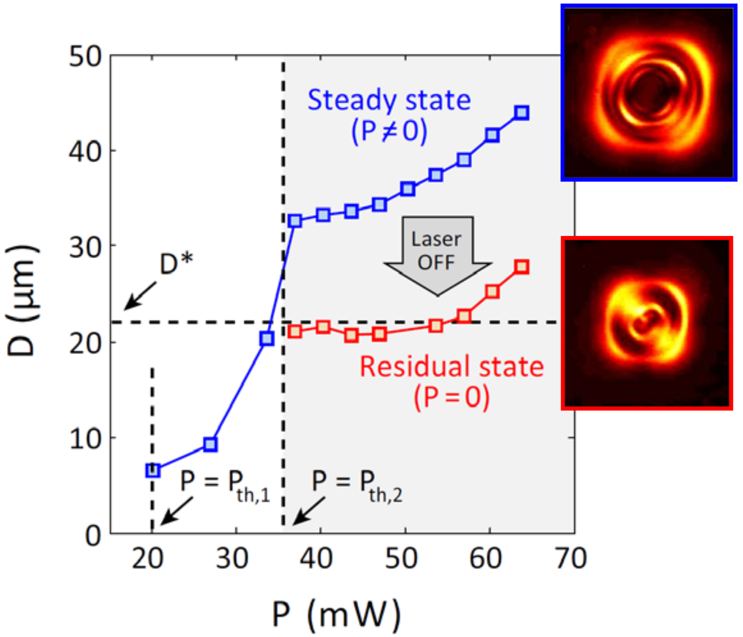
Cholesteric film with perpendicular boundary conditions



Frustration

The experiment

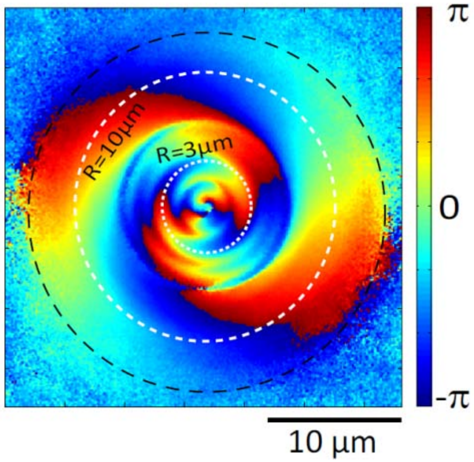


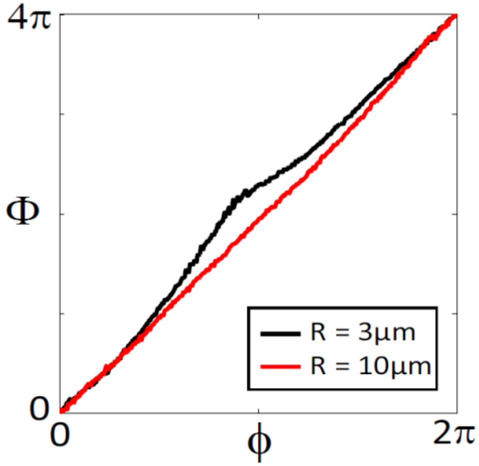


B. Yang and E. Brasselet, J. Opt. **15**, 044021 (2013)

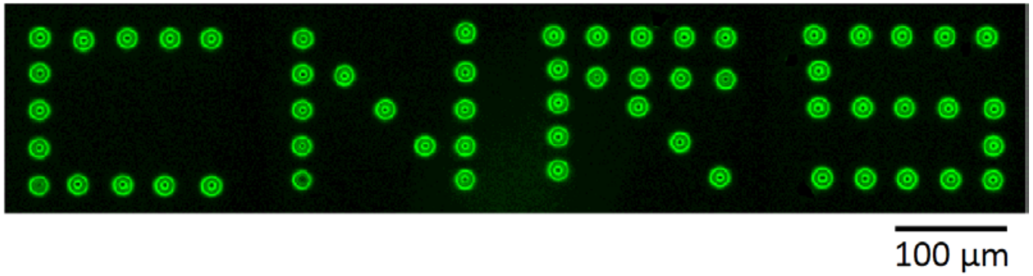
Arbitrary vortex arrays from optical winding of frustrated cholesterics

Spin-orbit optical vortex generation





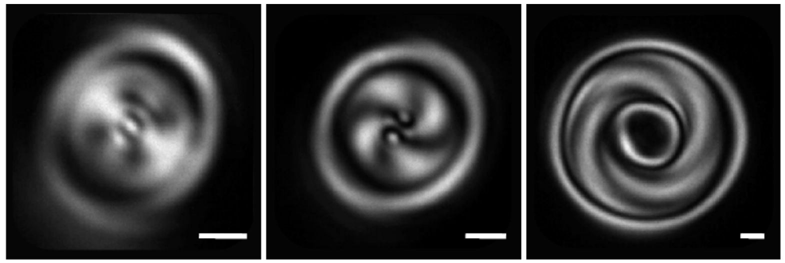
Switchable arbitrary vortex arrays



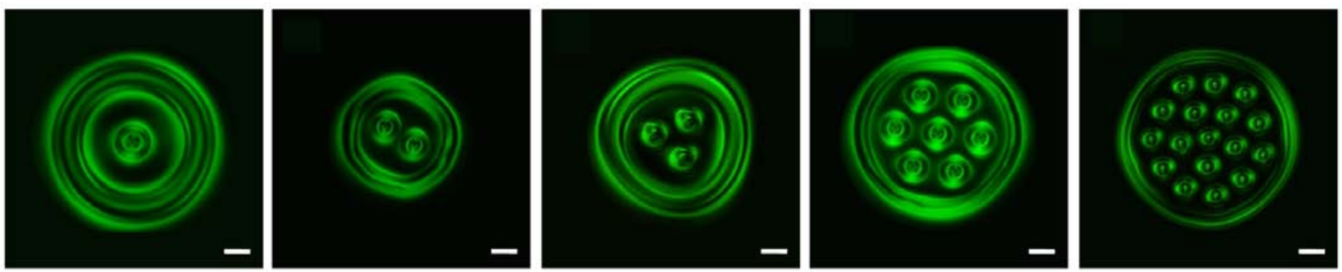
B. Yang and E. Brasselet, J. Opt. **15**, 044021 (2013)

Frustrated cholesterics under Gaussian beams : topological gallery

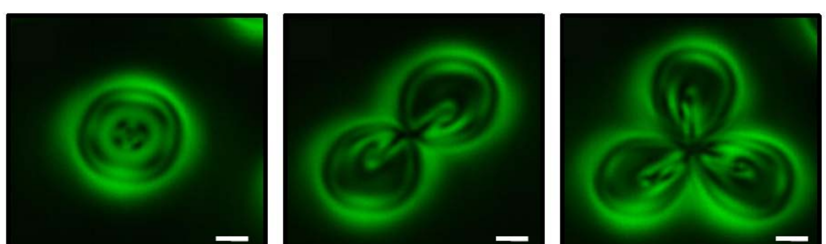
Topological diversity



Topological families



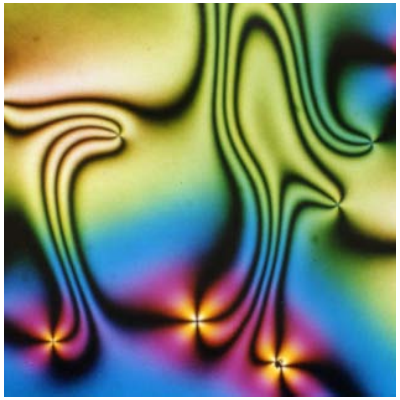
Topological multimers

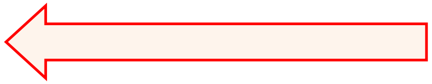


C. Loussert and E. Brasselet, in preparation.

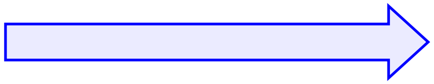
Matter/Waves interaction in presence of singularities

Light-induced singular patterning of matter





Spin-orbit interaction



Matter-induced singular patterning of light