Control of the flow of light with soft topological solitons

Guilhem Poy

Faculty of Physics and Mathematics, Ljubljana

February 17, 2021

Univerza v Ljubljani
Fakulteta za matematiko in fiziko

arrs
JAVNA AGENCIJA ZA RAZISKOVALNO DEJAVNOST
REPUBLIKE SLOVENIJE

MARIE CURIE ACTIONS

Outline

The cholesteric phase

- Nematic liquid crystal: no positional order, mean molecular orientation $\boldsymbol{n}$

The cholesteric phase

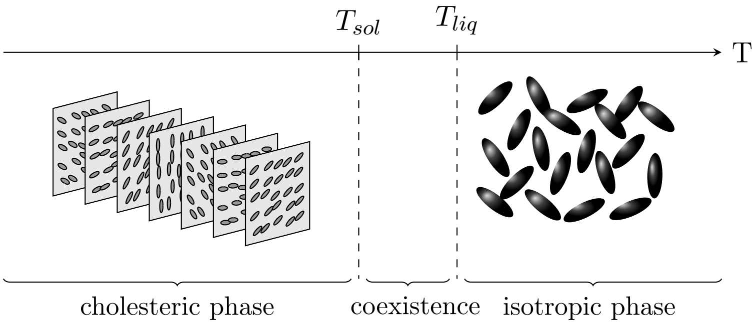
- Nematic liquid crystal: no positional order, mean molecular orientation $\boldsymbol{n}$
- Nematic phase + chiral molecules: cholesteric phase.

The cholesteric phase

- Nematic liquid crystal: no positional order, mean molecular orientation $\boldsymbol{n}$
- Nematic phase + chiral molecules: cholesteric phase.
- Effect of chirality: helix structure for the director vector field $\boldsymbol{n}$.

The cholesteric phase

- Nematic liquid crystal: no positional order, mean molecular orientation $\boldsymbol{n}$
- Nematic phase + chiral molecules: cholesteric phase.
- Effect of chirality: helix structure for the director vector field $\boldsymbol{n}$.

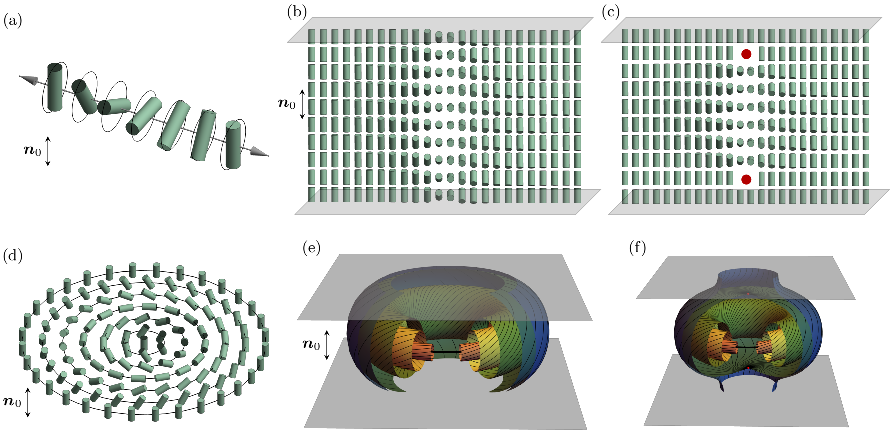


Two classes of soft topological solitons in confined homeotropic samples

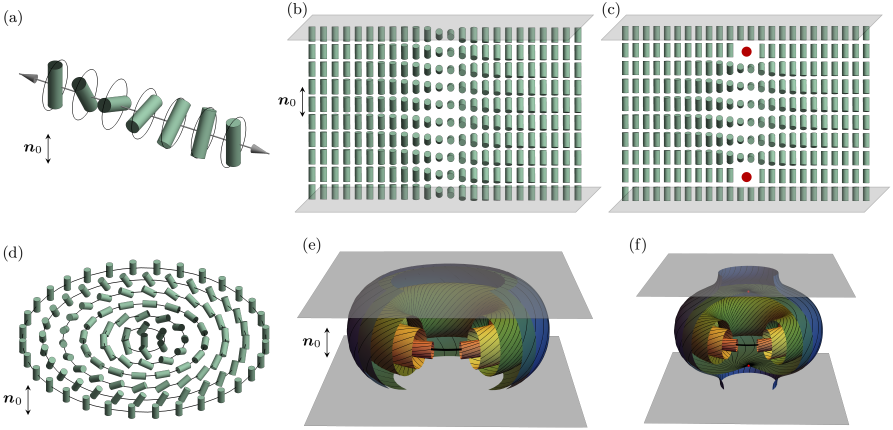
- Thin cholesteric layer: unwound background state $\boldsymbol{n} = \boldsymbol{n}_0$

Two classes of soft topological solitons in confined homeotropic samples

- Thin cholesteric layer: unwound background state $\boldsymbol{n} = \boldsymbol{n}_0$
- At intermediate sample thickness:



Two classes of soft topological solitons in confined homeotropic samples



Localized robust birefringent structures ⇒ interesting interaction with light?

Light propagation tools in birefringent media

Experimental work in the group of Prof. Smalyukh, modeling work in Ljubljana.

G. Poy and S. Žumer. *Optics Express*, 28:24327, 2020

Light propagation tools in birefringent media

Experimental work in the group of Prof. Smalyukh, modeling work in Ljubljana.

- FDTD: out-of-the-question because of huge 3D meshes.

G. Poy and S. Žumer. *Optics Express*, 28:24327, 2020

Light propagation tools in birefringent media

Experimental work in the group of Prof. Smalyukh, modeling work in Ljubljana.

- FDTD: out-of-the-question because of huge 3D meshes.
- Custom-built beam propagation code:
  - ⋆ Wave-equation in anisotropic media: $\left[\partial_k\partial_k\delta_{ij} - \partial_i\partial_j + k_0^2\epsilon_{ij}\right] E_j = 0$

G. Poy and S. Žumer. *Optics Express*, 28:24327, 2020

Light propagation tools in birefringent media

Experimental work in the group of Prof. Smalyukh, modeling work in Ljubljana.

- FDTD: out-of-the-question because of huge 3D meshes.
- Custom-built beam propagation code:
  - ⋆ Wave-equation in anisotropic media: $\left[\partial_k\partial_k\delta_{ij} - \partial_i\partial_j + k_0^2\epsilon_{ij}\right] E_j = 0$
  - ⋆ After eliminating E_z and keeping only forward modes:

$$i\partial_z \boldsymbol{E}_\perp = -\boldsymbol{\mathcal{P}}\boldsymbol{E}_\perp$$

G. Poy and S. Žumer. *Optics Express*, 28:24327, 2020

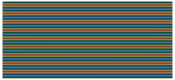
Light propagation tools in birefringent media

Experimental work in the group of Prof. Smalyukh, modeling work in Ljubljana.

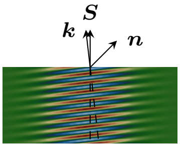
- FDTD: out-of-the-question because of huge 3D meshes.
- Custom-built beam propagation code:
  - ⋆ Wave-equation in anisotropic media: $\left[\partial_k \partial_k \delta_{ij} - \partial_i \partial_j + k_0^2 \epsilon_{ij}\right] E_j = 0$
  - ⋆ After eliminating E_z and keeping only forward modes:

$$i\partial_z \boldsymbol{E}_\perp = -\boldsymbol{\mathcal{P}} \boldsymbol{E}_\perp$$

  - ⋆ What's inside $\boldsymbol{\mathcal{P}}$?



Phase op. $\boldsymbol{K} \sim k_0^2 \boldsymbol{\epsilon}$



Walkoff op. $\boldsymbol{W} \sim (\boldsymbol{\epsilon}\, \boldsymbol{u}_z) \otimes \boldsymbol{\nabla}_\perp$

Diffraction op. $\boldsymbol{D} \sim \boldsymbol{\Delta}_\perp$

Light propagation tools in birefringent media

Experimental work in the group of Prof. Smalyukh, modeling work in Ljubljana.

- FDTD: out-of-the-question because of huge 3D meshes.
- Custom-built beam propagation code:
  - Wave-equation in anisotropic media: $\left[\partial_k\partial_k\delta_{ij} - \partial_i\partial_j + k_0^2\epsilon_{ij}\right] E_j = 0$
  - After eliminating E_z and keeping only forward modes:

$$i\partial_z \boldsymbol{E}_\perp = -\boldsymbol{\mathcal{P}}\boldsymbol{E}_\perp$$

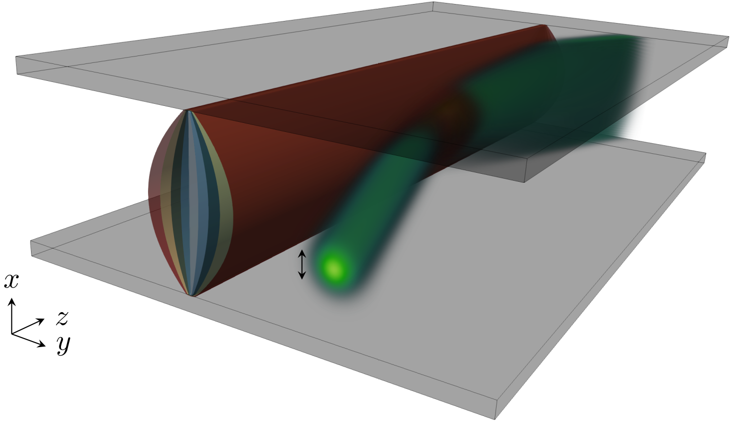
- Applications:
  - Open-source code for polarized optical micrograph simulation (google search: Nemaktis)
  - Closed-source code for wide-angle simulations (or non-linear optics)

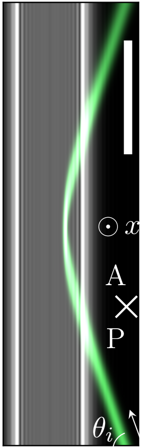
G. Poy and S. Žumer. *Optics Express*, 28:24327, 2020

Outline

Transmission and/or reflection

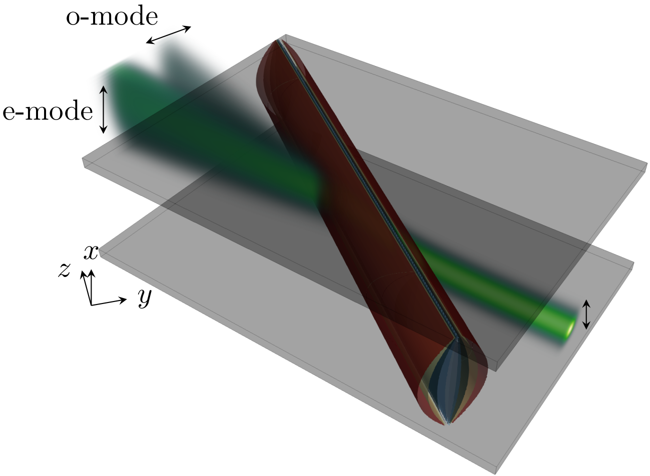
Reflection of incident extraordinary beam ($\theta_i = 70°$):

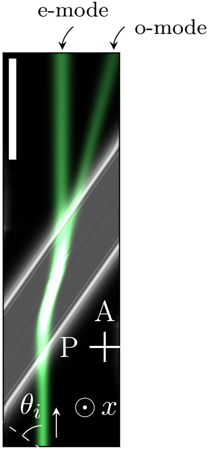




Transmission and/or reflection

Transmission of incident extraordinary beam ($\theta_i = 55°$):





Description with a generalization of Snell's law

From an exact eigenmode decomposition of Maxwell equations:

$$n^{(\alpha,m)} \sin \theta^{(\alpha,m)} = n_i \sin \theta_i$$

Description with a generalization of Snell's law

From an exact eigenmode decomposition of Maxwell equations:

$$n^{(\alpha,m)}\sin\theta^{(\alpha,m)} = n_i \sin\theta_i$$

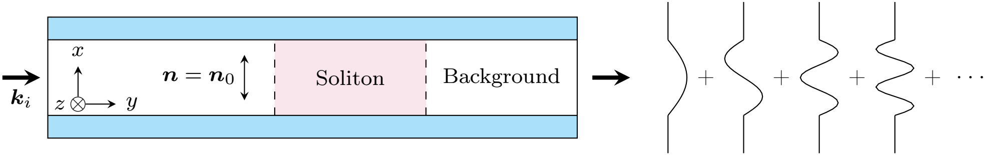
- Usual Snell law: n is the refractive index of an isotropic medium

Description with a generalization of Snell's law

From an exact eigenmode decomposition of Maxwell equations:

$$n^{(\alpha,m)} \sin\theta^{(\alpha,m)} = n_i \sin\theta_i$$

- Usual Snell law: n is the refractive index of an isotropic medium
- In our system, $n^{(\alpha,m)}$ = effective index of eigenmode $\{\alpha, m\}$ far from the soliton
  - ⋆ $\alpha = e, o$: polarisation state
  - ⋆ $m = 1, 2, \ldots$: mode index

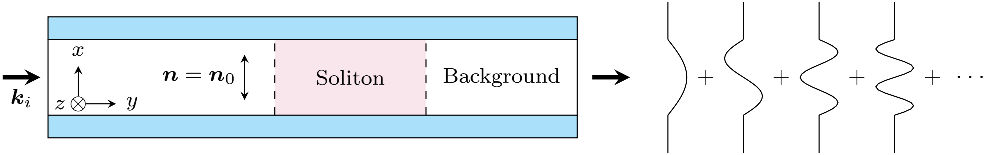


Description with a generalization of Snell's law

From an exact eigenmode decomposition of Maxwell equations:

$$n^{(\alpha,m)}\sin\theta^{(\alpha,m)} = n_i \sin\theta_i$$

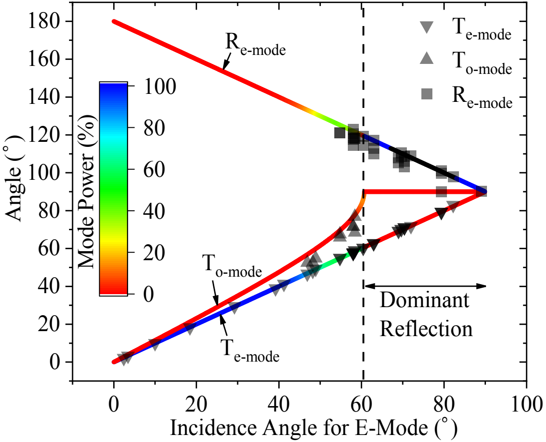
- Usual Snell law: n is the refractive index of an isotropic medium
- In our system, $n^{(\alpha,m)}$ = effective index of eigenmode $\{\alpha, m\}$ far from the soliton
  - $\alpha = e, o$: polarisation state
  - $m = 1, 2, \ldots$: mode index

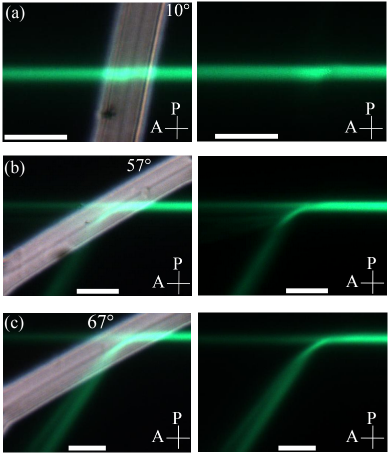


$\theta^{(\alpha,m)}$ does not depends on the choice of topological soliton!
(but Fresnel coefficients do)

Comparison with experiments

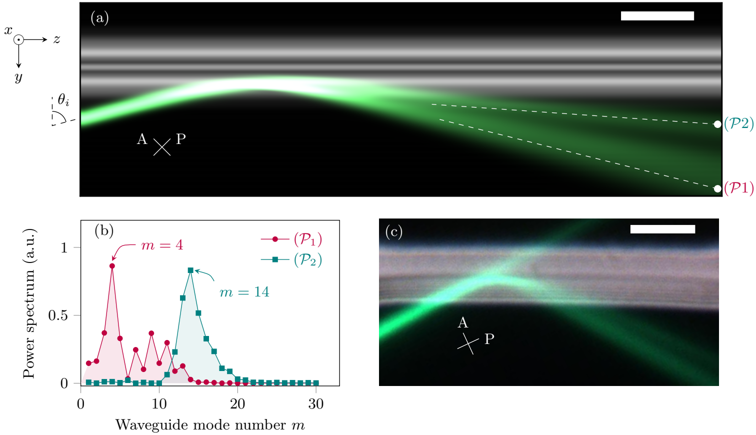
Small mode index approximation in thick samples: $n^{(\alpha,m)} \approx n_\alpha \sqrt{1-(m/m_0)^2} \approx n_\alpha$





Comparison with experiments

Splitting of eigenmode packets (strongly depends on x-profile): $n^{(\alpha,m_1)} \neq n^{(\alpha,m_2)}$



Outline

Ray-tracing description

Hamiltonian reformulation of century-old Fermat-Grandjean theory:

$$\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}\bar{s}} = \frac{\partial \mathcal{H}^{(\alpha)}}{\partial \boldsymbol{p}}$$

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}\bar{s}} = -\frac{\partial \mathcal{H}^{(\alpha)}}{\partial \boldsymbol{r}}$$

G. Poy and S. Žumer. *Soft Matter*, 15:3659–3670, 2019

Ray-tracing description

Hamiltonian reformulation of century-old Fermat-Grandjean theory:

$$\begin{aligned} \frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}\bar{s}} &= \frac{\partial \mathcal{H}^{(\alpha)}}{\partial \boldsymbol{p}} \\ \frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}\bar{s}} &= -\frac{\partial \mathcal{H}^{(\alpha)}}{\partial \boldsymbol{r}} \end{aligned}$$

- Canonical variables $\{\boldsymbol{r}, \boldsymbol{p}\}$: position and momentum of "light bullets".

G. Poy and S. Žumer. *Soft Matter*, 15:3659–3670, 2019

Ray-tracing description

Hamiltonian reformulation of century-old Fermat-Grandjean theory:

$$\begin{aligned} \frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}\bar{s}} &= \frac{\partial \mathcal{H}^{(\alpha)}}{\partial \boldsymbol{p}} \\ \frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}\bar{s}} &= -\frac{\partial \mathcal{H}^{(\alpha)}}{\partial \boldsymbol{r}} \end{aligned}$$

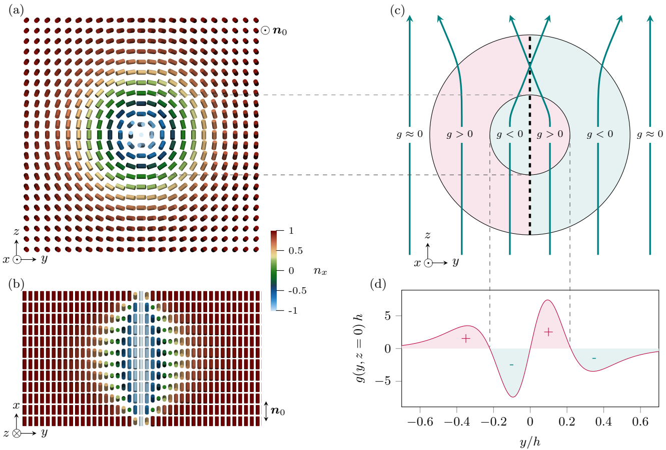
- Canonical variables $\{\boldsymbol{r}, \boldsymbol{p}\}$: position and momentum of "light bullets".
- Hamiltonian for ordinary and extraordinary rays:

$$\begin{aligned} \mathcal{H}^{(o)} &= \frac{|\boldsymbol{p}|^2}{2\epsilon_\perp} \\ \mathcal{H}^{(e)} &= \frac{\epsilon_\perp |\boldsymbol{p}|^2 + \epsilon_a \left|\boldsymbol{n}(\boldsymbol{r}) \cdot \boldsymbol{p}\right|^2}{2\epsilon_\perp \epsilon_\parallel} \end{aligned}$$

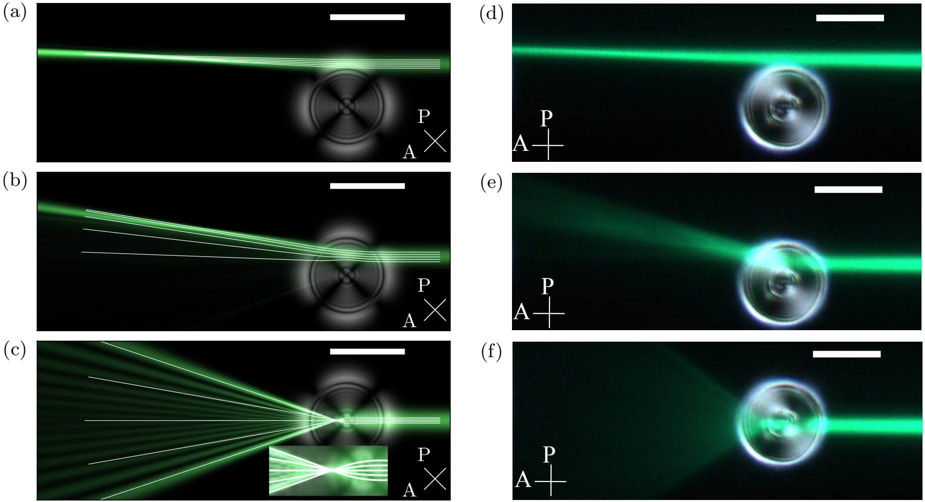
G. Poy and S. Žumer. *Soft Matter*, 15:3659–3670, 2019

Ray-tracing description

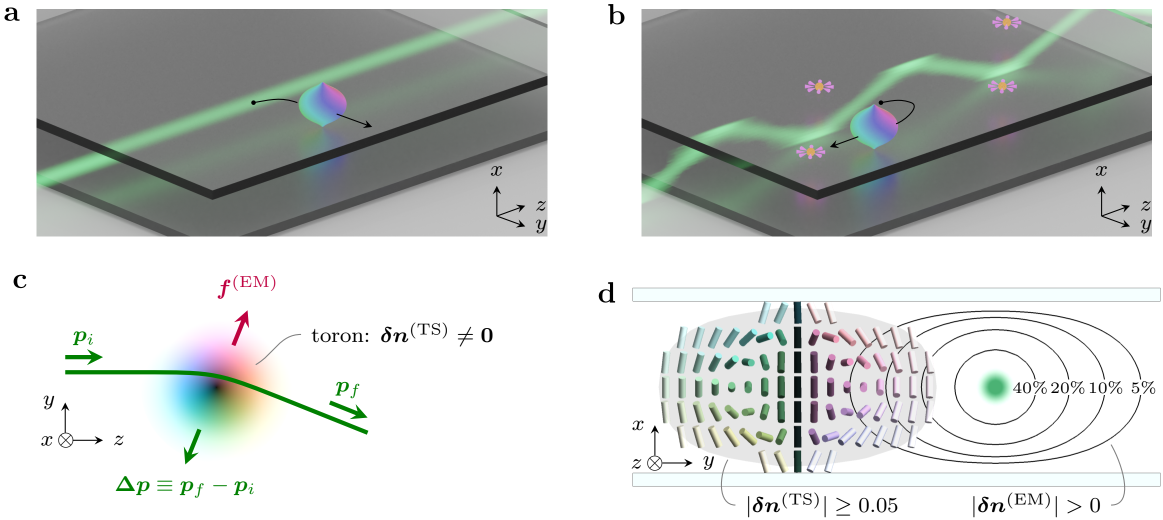
Simplification with 2D rays: $\mathrm{d}p_y/\mathrm{d}z \approx -(\epsilon_a/2n_0)\,g$, where $g \equiv \partial n_z^2/\partial y$



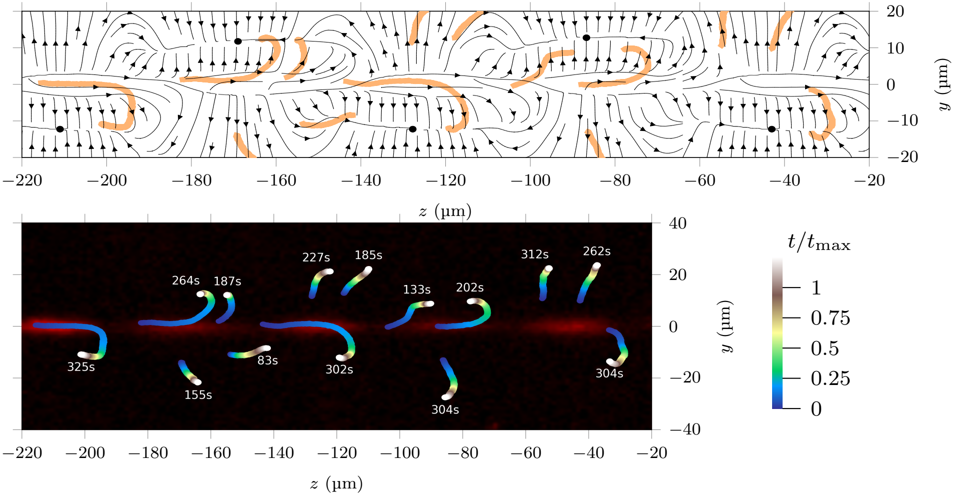
Light deflection and lensing with pinned torons



Extension to the nonlinear optical regime with mobile torons



Toron trajectories around 'bouncing' optical soliton



Outline

Take-home message

Soft topological solitons can reliably control the flow of light at the microscopic level

A. J. Hess, G. Poy, J.-S. B. Tai, S. Žumer, and I. I. Smalyukh. *Physical Review X*, 10:031042, 2020

Take-home message

Soft topological solitons can reliably control the flow of light at the microscopic level

- Topological protection $\Rightarrow$ robust to external perturbation

A. J. Hess, G. Poy, J.-S. B. Tai, S. Žumer, and I. I. Smalyukh. *Physical Review X*, 10:031042, 2020

Take-home message

Soft topological solitons can reliably control the flow of light at the microscopic level

- Topological protection $\Rightarrow$ robust to external perturbation
- Order parameter space fully covered $\Rightarrow$ maximum index contrast

A. J. Hess, G. Poy, J.-S. B. Tai, S. Žumer, and I. I. Smalyukh. *Physical Review X*, 10:031042, 2020

Take-home message

Soft topological solitons can reliably control the flow of light at the microscopic level

- Topological protection $\Rightarrow$ robust to external perturbation
- Order parameter space fully covered $\Rightarrow$ maximum index contrast
- Can be easily created or tuned with external fields

A. J. Hess, G. Poy, J.-S. B. Tai, S. Žumer, and I. I. Smalyukh. *Physical Review X*, 10:031042, 2020

Take-home message

Soft topological solitons can reliably control the flow of light at the microscopic level

- Topological protection $\Rightarrow$ robust to external perturbation
- Order parameter space fully covered $\Rightarrow$ maximum index contrast
- Can be easily created or tuned with external fields
- Modeling techniques: Snell law, ray-tracing, beam propagation.

A. J. Hess, G. Poy, J.-S. B. Tai, S. Žumer, and I. I. Smalyukh. *Physical Review X*, 10:031042, 2020

Take-home message

Soft topological solitons can reliably control the flow of light at the microscopic level

- Topological protection $\Rightarrow$ robust to external perturbation
- Order parameter space fully covered $\Rightarrow$ maximum index contrast
- Can be easily created or tuned with external fields
- Modeling techniques: Snell law, ray-tracing, beam propagation.
- Applications: logical gates, guided self-assembly

A. J. Hess, G. Poy, J.-S. B. Tai, S. Žumer, and I. I. Smalyukh. *Physical Review X*, 10:031042, 2020

Avertisement

Thank you for your attention!

Total internal reflection can be bypassed by "sliping" under the CF's defects: