2D Topological Defects in Liquid Crystals

Seminar I

Jan Rugelj

Mentor: prof. dr. Miha Škarabot, dr. Uroš Jagodič
Nanosciences and Nanotechnologies, Doctoral degree

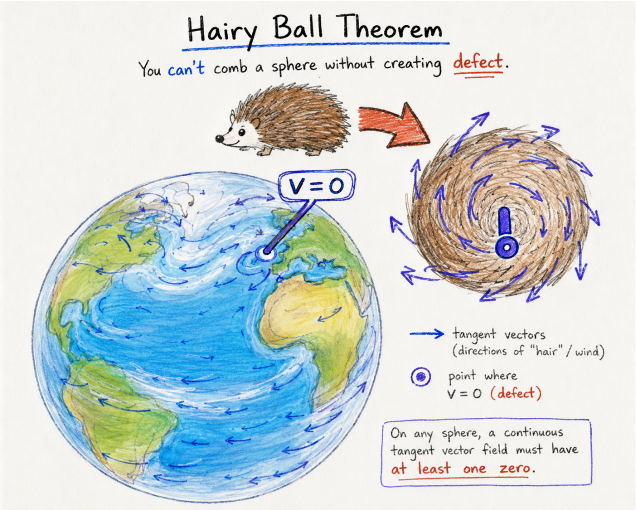
Ljubljana, 2026

Institut
"Jožef Stefan"
Ljubljana, Slovenija

Outline & Motivation

- Introduction
- Topological defects in liquid crystals
- Direct laser writing
- Results
- Conclusions

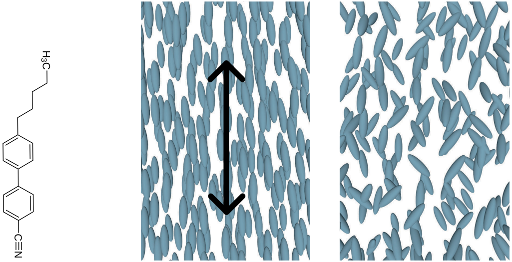
- Topological defects on 3D structures



What is a Liquid crystal?

- Orientational ordering
- Director field
- Order parameter: $S = \frac{1}{2}\langle 3\cos^2\theta - 1\rangle$
- Minimisation of free energy

$\hat{\boldsymbol{n}} \equiv -\hat{\boldsymbol{n}}$



(a) Molecular structure of 5CB

(b) Nematic phase

(c) Isotropic phase

Optical Birefringence & Retardance

- Different Refractive index
- Birefringece: $\Delta n = n_e - n_o$

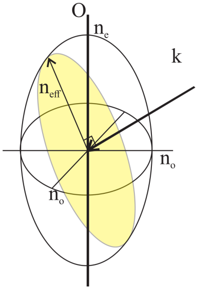


Figure: Birefringence

$$I_{out} = \frac{I_0}{2} \sin^2(2\varphi) \sin^2\left(\frac{\pi(n_e - n_o)d}{\lambda}\right)$$

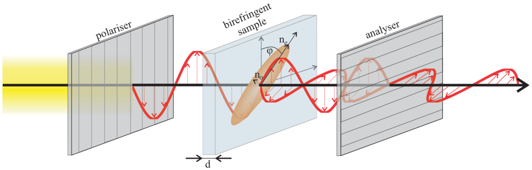


Figure: Retardance

Phase Transition

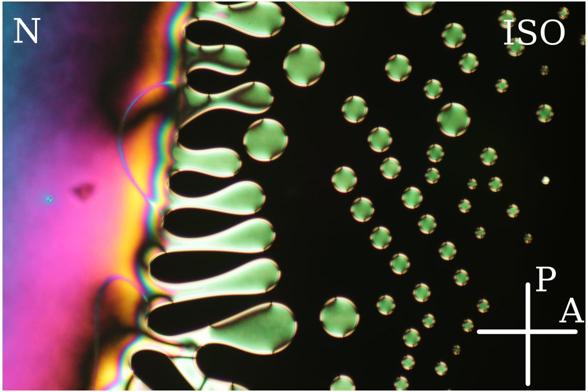


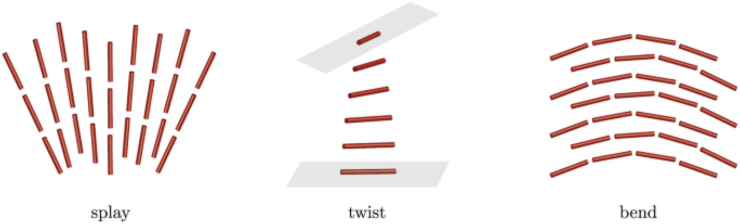
Figure: 5CB during phase transition: nematic (left), isotropic (right)

Elastic Constants

Frank–Oseen elastic free energy density:

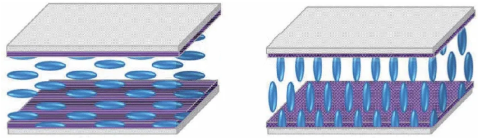
$$f_{\mathrm{FO}} = \frac{K_1}{2}(\nabla \cdot \hat{\boldsymbol{n}})^2 + \frac{K_2}{2}(\hat{\boldsymbol{n}} \cdot \nabla \times \hat{\boldsymbol{n}})^2 + \frac{K_3}{2}(\hat{\boldsymbol{n}} \times \nabla \times \hat{\boldsymbol{n}})^2$$

- K_1 – **splay** (divergence of $\hat{\boldsymbol{n}}$)
- K_2 – **twist** (helical rotation about $\hat{\boldsymbol{n}}$)
- K_3 – **bend** (curvature in the plane containing $\hat{\boldsymbol{n}}$)
- For 5CB at 25 °C: $K_1 \approx 6.4\,\mathrm{pN}$, $K_2 \approx 3.0\,\mathrm{pN}$, $K_3 \approx 10.0\,\mathrm{pN}$

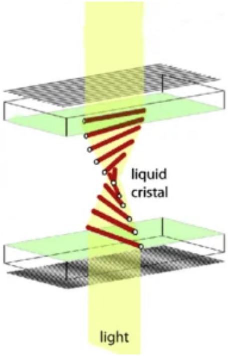


Surface Alignment

- Liquid crystal cell
- Planar (parallel) – rubbed polyimide
- Homeotropic (perpendicular) – silane



(a) Homeotropic and planar alignment



(b) Twisted nematic cell

Surface Alignment - Berreman Groove Model

- Elastic distortion cost:
  $$W_{az} = \frac{\pi^3 K}{2} \frac{A^2}{\lambda^3}$$
- Groove amplitude and pitch effect the alignment strength

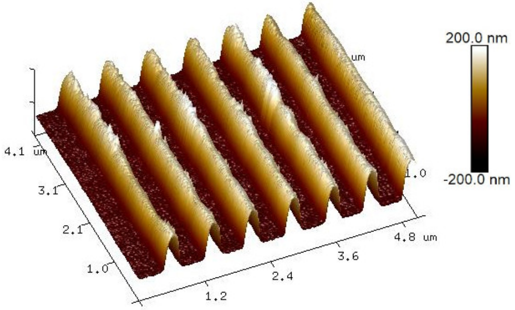


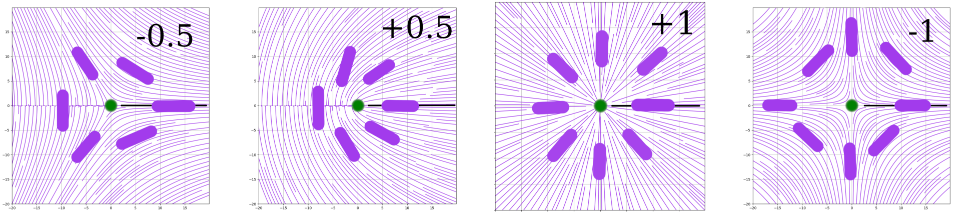
Figure: AFM image of grooves

Berreman, Phys. Rev. Lett. **28**, 1683 (1972)

Topological Defects

Winding number (topological charge):

$$s = \frac{1}{2\pi} \oint_{\mathcal{C}} d\theta$$

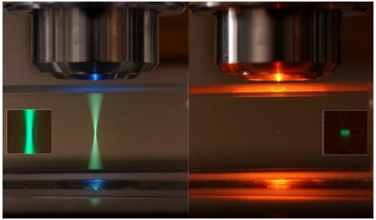


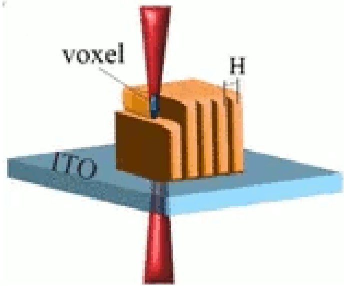
(a) $k = -0.5$ (b) $k = +0.5$ (c) $k = +1.0$ (d) $k = -1.0$

Figure: Director field around defects (core marked in green)

Nanoscribe

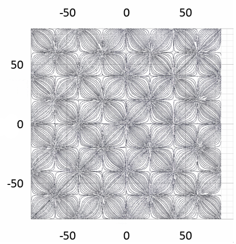
- Two–Photon polymerisation + Galvo → Direct laser writing
- Voxel size 100 nm x 300 nm, pulsed laser, $\lambda = 780$ nm
- 3D additive manufacturing beyond diffraction limit

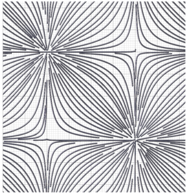


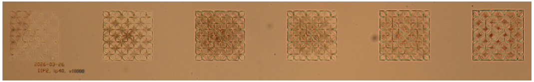


Results

- Alternating $+1$ and -1 defects
- Characterised by POM and AFM

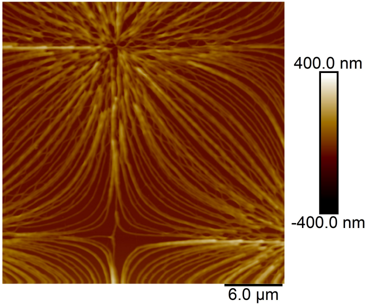




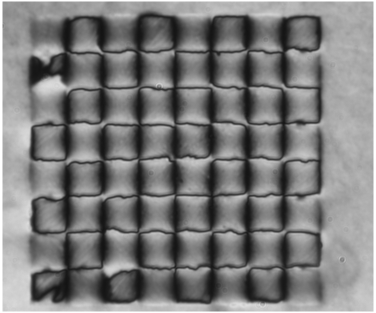


(a) Transmission mode optical microscope

Results



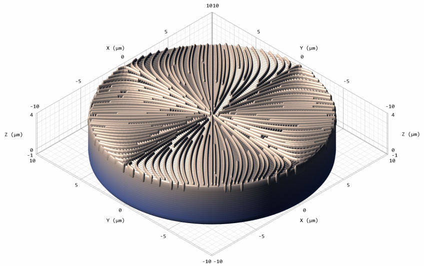
(a) AFM image



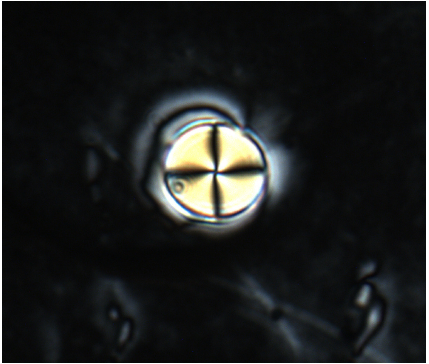
(b) POM image, crossed polarizers

Figure: Pitch 520 µm, Laser power = 35 %

Results

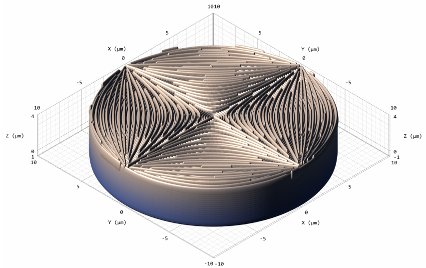


(a) Colloid with +1 defect

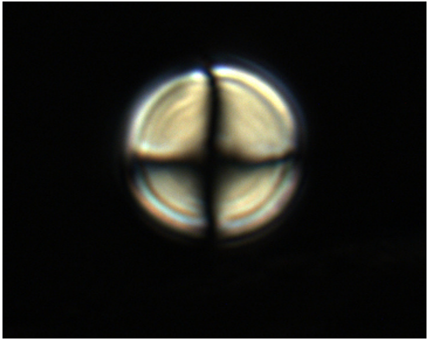


(b) POM image

Results



(a) Colloid with -1 defect



(b) POM image

Conclusion and Outlook

- Established theoretical foundations: Frank–Oseen elasticity, Berreman anchoring, topological classification
- DLW (Nanoscribe) enables arbitrary 2D director fields with designed defects
- Full characterisation loop: DLW $\rightarrow$ AFM $\rightarrow$ POM

Outlook:

- 2D alignment on both surfaces
- Alignment on 3D structures
- Defects on curved surfaces
- Defects on free floating objects (colloids)

Thank you!
Questions?