

Optical properties of heliconical liquid crystals

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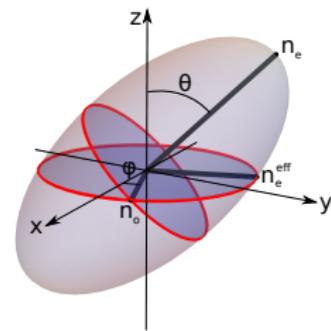
Motivation

- Heliconical liquid crystals provide interesting novel possibilities for optics and photonics

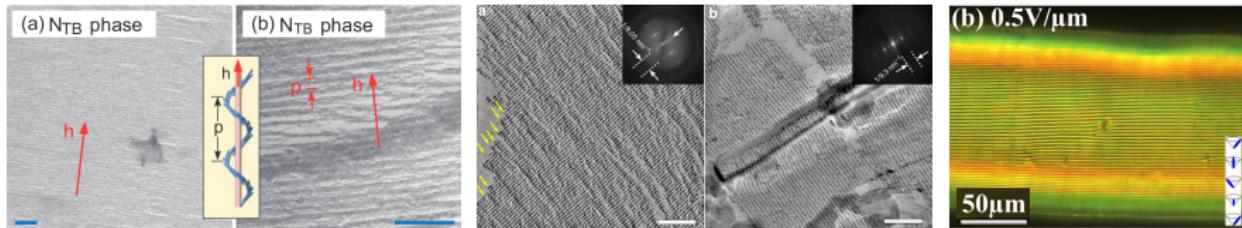
$$\mathbf{n} = \begin{pmatrix} \cos \varphi(z) \sin \theta \\ \sin \varphi(z) \sin \theta \\ \cos \theta \end{pmatrix}$$

where $\varphi(z) = 2\pi z/p$

and $\theta = \text{const.}$



- Two main size ranges:
1.: pitch $p \sim 10 \text{ nm}$ 2.: p in optical range

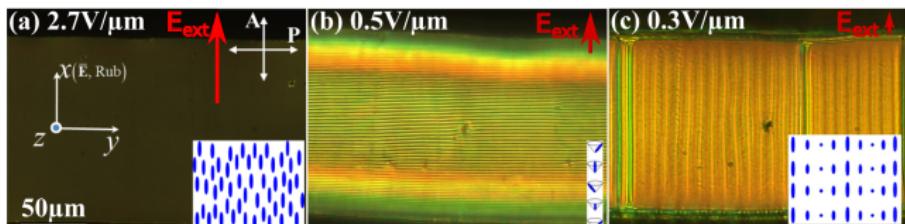


FFTTEM images, $p \approx 14 \text{ nm}$.
Chen et al., PRE 89, 022506 (2014).

FFTTEM images, a) $p = 8.05 \text{ nm}$, b) $p = 9.3 \text{ nm}$. Xiang et al., PRL 112, V. Borshch et al., Nat. Commun. 4, 2635 (2013). 217801 (2014).

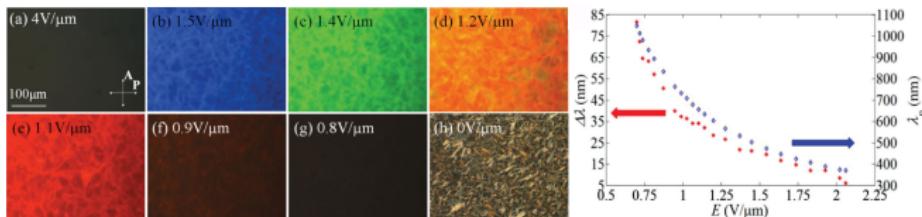
Properties of heliconics with pitch in optical range

- Large elastic anisotropy: $K_3 \ll K_2$



Xiang et al., PRL 112, 217801 (2014).

- Band gap tunability with external electric field \mathbf{E}_{ext}



Xiang et al., Adv. Mater. 27, 3014 (2015).

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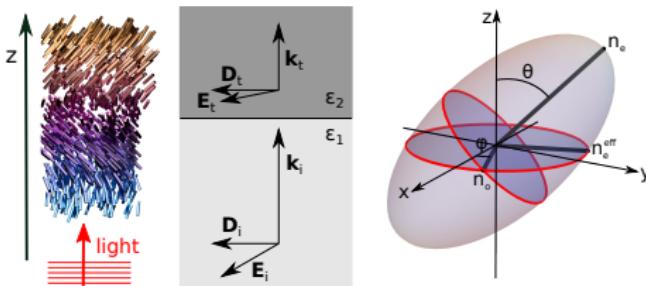
- Heliconical band gap as dependent on changing material properties (θ , p)
- Electric **E** and magnetic **H** eigenmodes inside heliconics
- Poynting vector **P** profiles

A. Bregar, M. Štimulak and M. Ravnik, *Photonic properties of heliconical liquid crystals*, submitted to Optics Express.

Numerical methods

- Frequency domain method
 - Eigenvalue method for determining the band diagrams and eigenmodes
 - Solving in Fourier space for a specific wave vector **k**:
$$\nabla \times \{\underline{\epsilon}^{-1} (\nabla \times \mathbf{H})\} = \left(\frac{\omega}{c}\right)^2 \mathbf{H}$$
 - Eigenvectors ... **H**-eigenmodes,
eigenvalues ... eigenfrequencies $\omega_n(\mathbf{k})$
- FDTD (Finite-difference time-domain method):
 - Solving time-dependent Maxwell's equation, gives info about light propagation
 - Leapfrog stepping in time for light **E** and **H** fields on a staggered cubic Yee mesh

Analysis of \mathbf{E} and \mathbf{D} fields



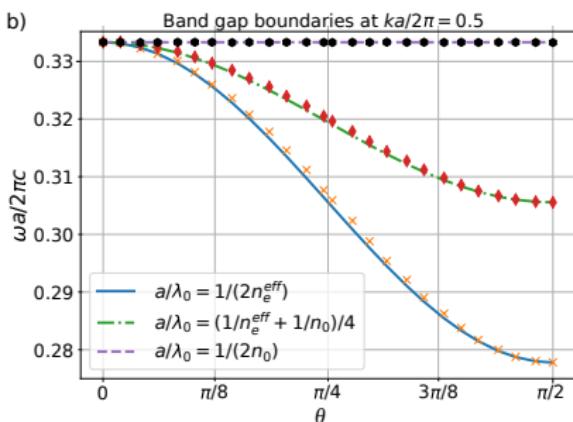
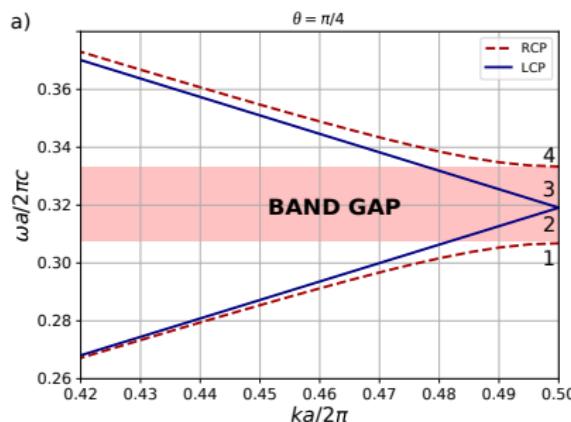
- On-axis propagation
- \mathbf{D} -field:
 - $\mathbf{D} \perp \mathbf{k} \rightarrow \mathbf{D}$ stays in plane of boundary
 - Since $D_z = 0$ for heliconics, we can follow the derivation of the band-gap for cholesterics
 - Light of same handedness as structure: has band gap, opposite handednesses: no band gap
 - Effective periodicity: $p/2$ with n_o and n_e^{eff}
- \mathbf{E} -field:
 - $\mathbf{E} \nparallel \mathbf{D}$ since $\mathbf{D} = \epsilon_0 \underline{\epsilon} \mathbf{E}$

Opening of the BG with θ

- We have quantified the band-gap position and width
- BG boundaries depend on n_o and effective extraordinary refractive index $n_e^{eff} = \frac{n_o * n_e}{\sqrt{n_o^2 \sin^2 \theta + n_e^2 \cos^2 \theta}}$
- BG for vacuum wavelengths between

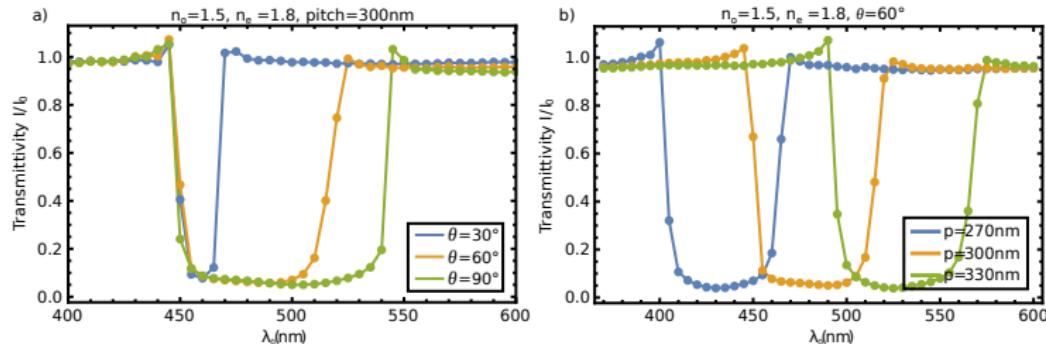
$$p n_o < \lambda_0 < p n_e^{eff}, \quad n_o < n_e$$

$$p n_o > \lambda_0 > p n_e^{eff}, \quad n_e < n_o$$



Transmittivity

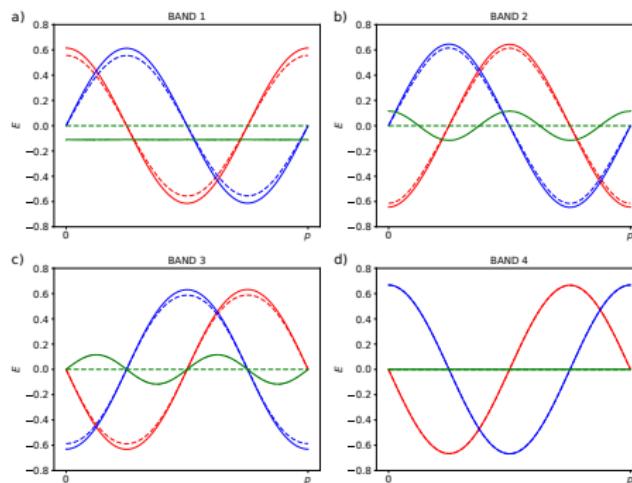
- Band gap width depends on θ
- Central position of band gap depends on p



- From transmittivity spectra $\rightarrow p$ and θ determined uniquely

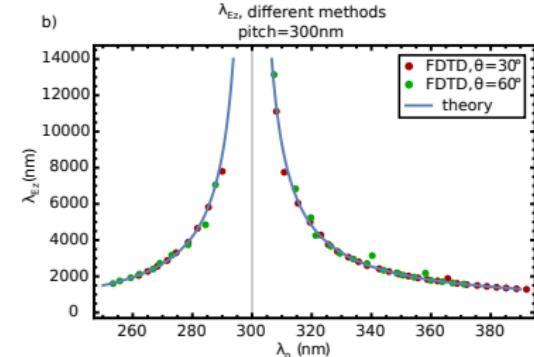
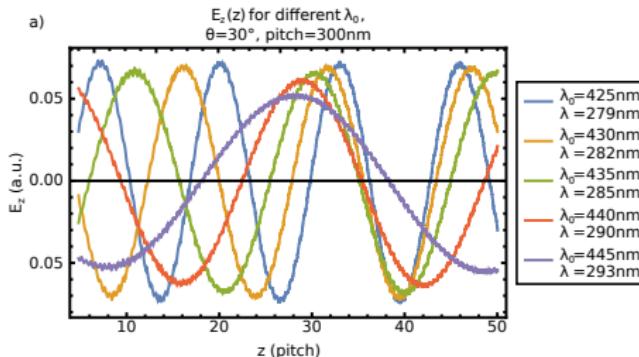
Band gap edge modes

- We determine band gap edge modes
- $\mathbf{E} \nparallel \mathbf{D}$ since $\mathbf{D} = \varepsilon_0 \underline{\mathbf{E}}$
- In cholesterics: $E_z = 0$, in heliconics: $E_z \neq 0$
- On band gap edge: Eigenmodes right- or left-circularly polarized waves with additional E_z -component



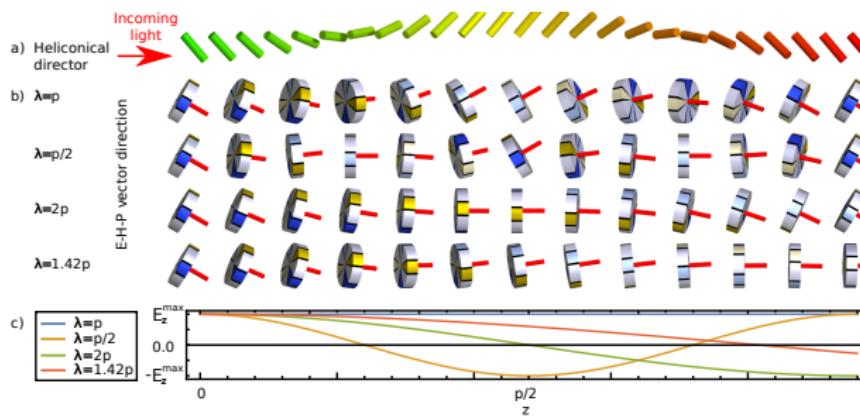
Dependence of E_z on λ

- E_z oscillates sinusoidally: E_z will be the same in size when xy -angle between \mathbf{D} and \mathbf{n} increases by $2m\pi$, $m \in \mathbb{Z}$.
- $\lambda_z^{LCP} = \frac{\lambda p}{p + \lambda}$, $\lambda_z^{RCP} = \pm \frac{\lambda p}{p - \lambda}$, always $\lambda_z^{RCP} > \lambda_z^{LCP}$
- RCP: E_z constant, $\lambda_z \rightarrow \infty$ when on edge of BG, otherwise it is smaller and depends on λ/p
- LCP: $\lambda_z = \lambda/2$ on edge of BG



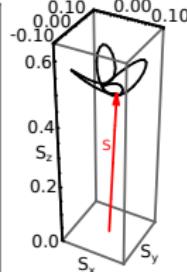
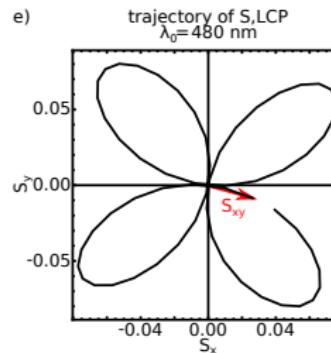
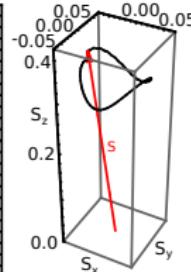
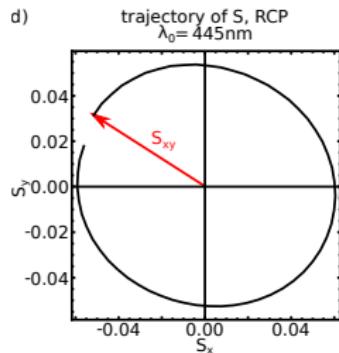
Poynting vector

- if $E_z \neq 0 \rightarrow P_{xy} \neq 0$
- Poynting vector rotates about the propagation axis
- RCP: wavelength of E_z rotation increases when nearing the band gap \rightarrow tilt of \mathbf{P} constant



Poynting vector

- if $E_z \neq 0 \rightarrow P_{xy} \neq 0$
- Poynting vector rotates about the propagation axis
- On BG edge in one pitch length: \mathbf{P} of RCP rotating circularly, \mathbf{P} of LCP describing a four-leaf clover



Conclusion

We have explored the photonic properties of heliconical liquid crystals:

- Quantifying of the photonic band gap opening with p , θ : the band gap widens with larger θ and moves to larger wavelengths with increasing the pitch p
- Analysis of **E** eigenmodes:
at the band edge the modes are circular, otherwise elliptic;
emergence of non-zero E_z component
- Interesting variability of the Poynting vector:
cone-like and four-leaf like patterns

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