Optical properties of heliconical liquid crystals

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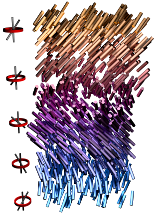
Motivation

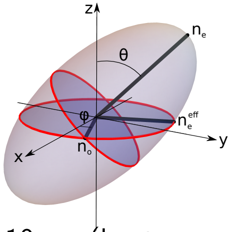
- Heliconical liquid crystals provide interesting novel possibilities for optics and photonics

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

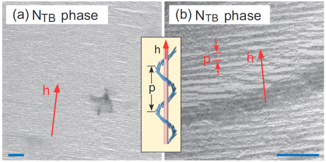
where $\varphi(z) = 2\pi z/p$

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

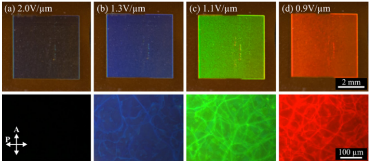




- Two main types of systems: 1.: pitch $p \sim 10\,\mathrm{nm}$ (bent-core LC), 2.: p in optical range (rod-like & linked by flexible chain)



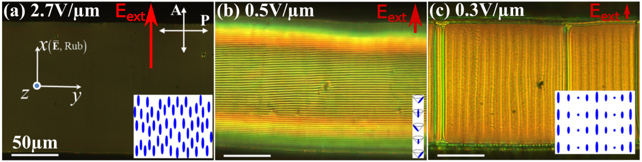
FFTEM images, $p \approx 14\,\mathrm{nm}$.
Chen et al., PRE 89, 022506 (2014).



Xiang et al., Proc. Natl. Acad. Sci. 113, 12925 (2016).

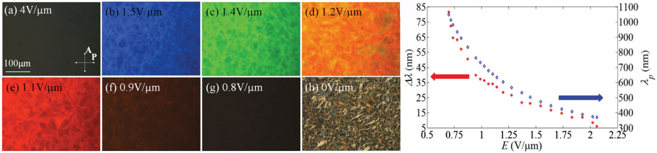
Properties of heliconics with pitch in optical range

- Large elastic anisotropy: $K_3 \ll K_2$



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

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



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

Contents

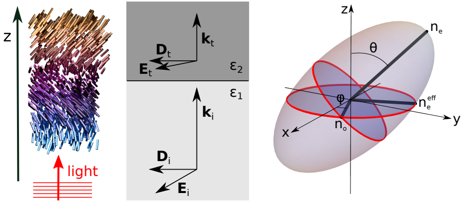
- Heliconical band gap as dependent on changing material properties (θ, p)
- Electric **E** and magnetic **H** eigenmodes inside heliconics
- Poynting vector **P** profiles

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**: $\nabla \times \left\{ \underline{\underline{\epsilon}}^{-1} \left(\nabla \times \mathbf{H} \right) \right\} = \left(\frac{\omega}{c} \right)^2 \mathbf{H}$
  - 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 **E** and **D** fields

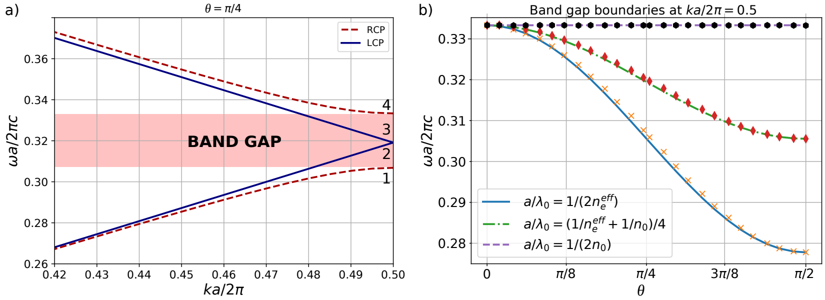


- On-axis propagation
- **D**-field:
  - $\mathbf{D} \perp \mathbf{k} \rightarrow \mathbf{D}$ stays in plane of boundary
  - Since $D_z = 0$ for heliconics, we can follow the derivation of the band-gap for cholesterics
  - Light of same handedness as structure: has band gap, opposite handednesses: no band gap
  - Effective periodicity: $p/2$ with n_o and n_e^{eff}
- **E**-field:
  - $\mathbf{E} \nparallel \mathbf{D}$ since $\mathbf{D} = \varepsilon_0 \underline{\underline{\varepsilon}} \mathbf{E}$

Opening of the BG with θ

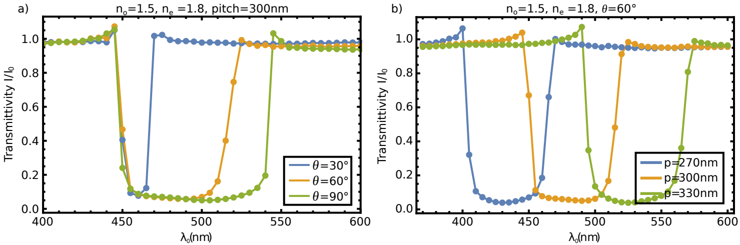
- We have quantified the band-gap position and width
- BG boundaries depend on n_o and effective extraordinary refractive index $n_e^{eff} = \dfrac{n_o * n_e}{\sqrt{n_o^2 \sin^2\theta + n_e^2\cos^2\theta}}$
- BG for vacuum wavelengths between

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



Transmittivity

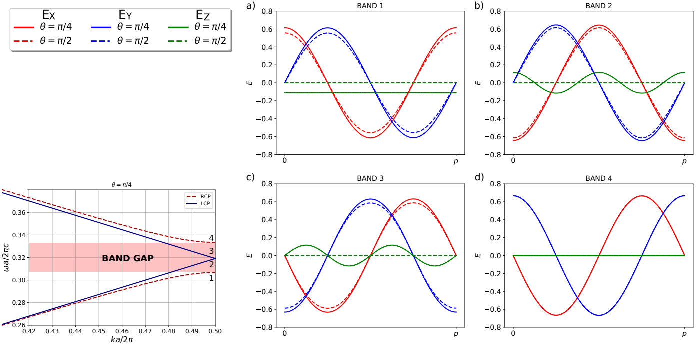
- Band gap width depends on θ
- Central position of band gap depends on p



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

Band gap edge modes

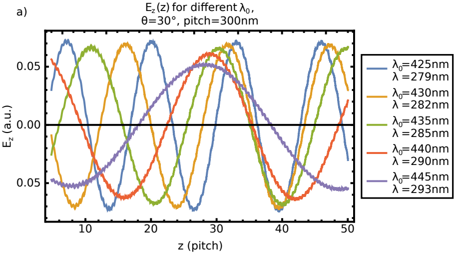
- We determine band gap edge modes
- $\mathbf{E} \nparallel \mathbf{D}$ since $\mathbf{D} = \varepsilon_0 \underline{\underline{\varepsilon}} \mathbf{E}$
- In cholesterics: $E_z = 0$, in heliconics: $E_z \neq 0$
- On band gap edge: Eigenmodes right- or left-circularly polarized waves with additional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



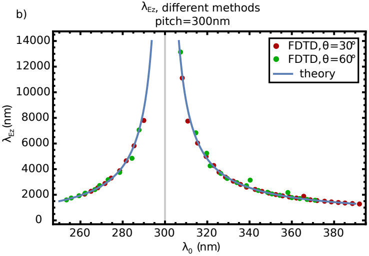
Dependence of E_z on λ

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

a)

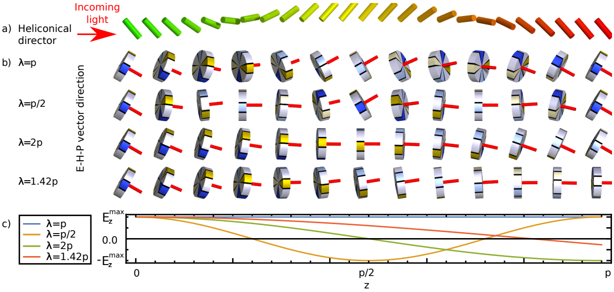


b)



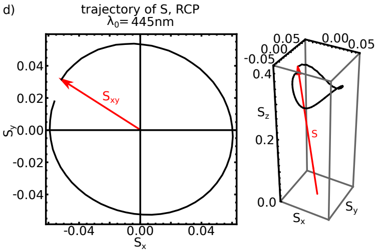
Poynting vector

- 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: **P** of RCP rotating circularly, **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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