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Optics of cholesterics with oblique helicoidal director

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KENT STATE

ADVANCED MATERIALS AND LIQUID CRYSTAL INSTITUTE at Kent State University

NSF

Outline

- **Oblique helicoidal cholesteric (Ch$_{OH}$) state as continuously tunable 1D photonic crystal**

- **Effect of the surface alignment on Bragg reflection**

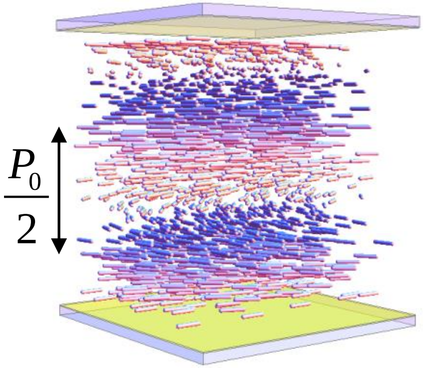
- **In-situ measurement of bend elastic constant in Ch phase**

- **Bragg diffraction at oblique incidence; polarization dependency**

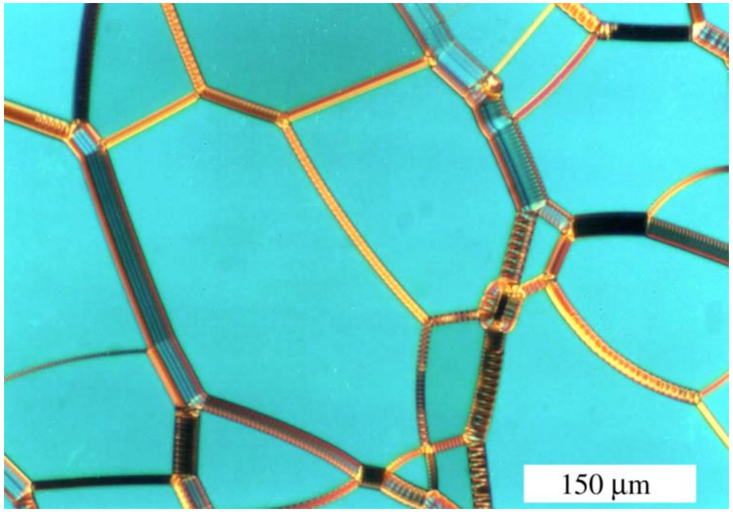
Cholesterics as 1D photonic crystals

Naturally occurring colors – result of ***Bragg reflection*** at the periodic structure with the period close to the wavelength of visible light.

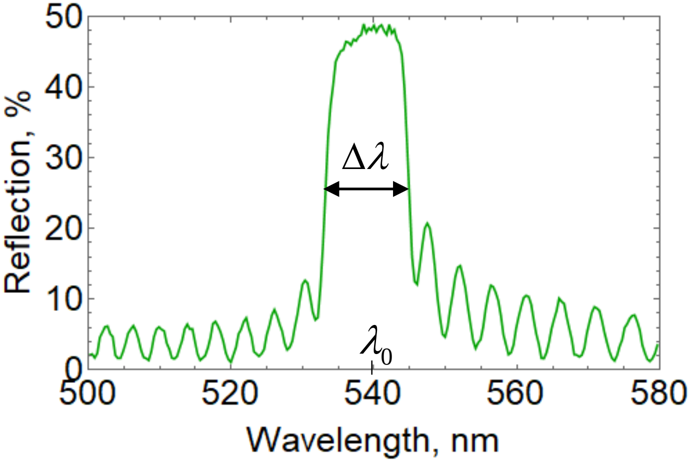
λ_0 − Bragg wavelength
$\Delta\lambda$ − Bandwidth, or width at the half−amplitude



Period ~ 0.1-1 mm



Polarizing microscope texture of the cholesteric liquid crystal



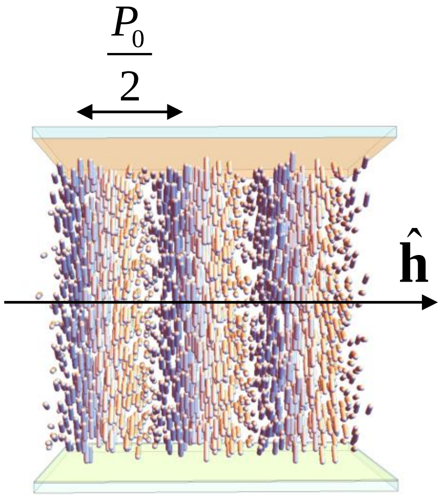
$$\Delta\lambda = \Delta n \frac{P_0}{2}$$

$$\lambda_0 = \bar{n} \frac{P_0}{2}$$

O.D. Lavrentovich, Handbook of liquid crystals, Ch. 6, 2014

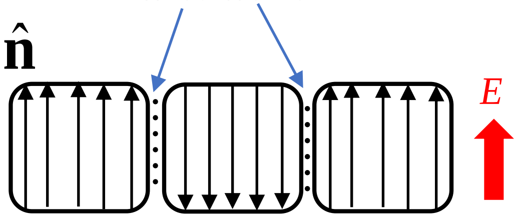
Cholesterics with positive dielectric anisotropy, $\Delta\varepsilon > 0$

Attempt to control the pitch by the applied field **E** leads to distortion of the helical structure and transformation to a nematic state (N) with the director $\hat{\mathbf{n}}$ along the field (here, $\hat{\mathbf{h}}$ is the helix axis).

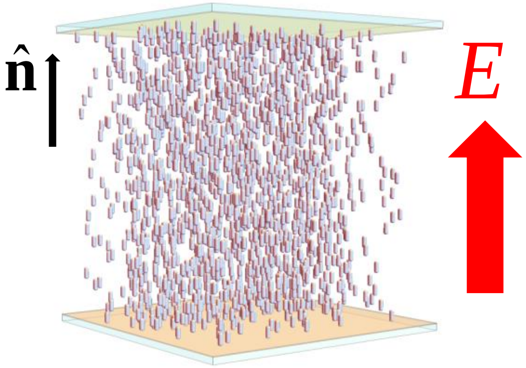


Ch cell

Twist walls

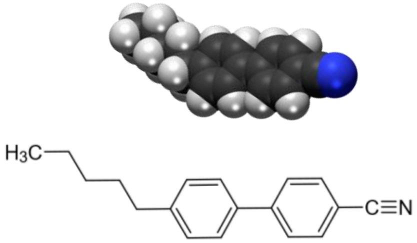


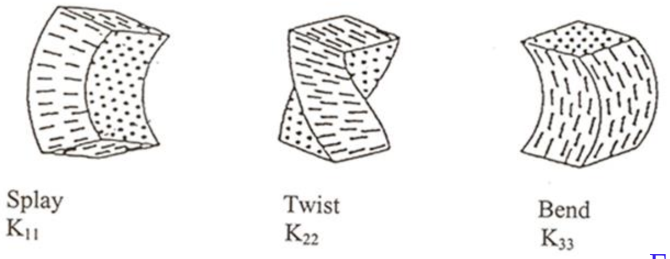
Single-harmonic modulation of the director is destroyed under the action of applied field

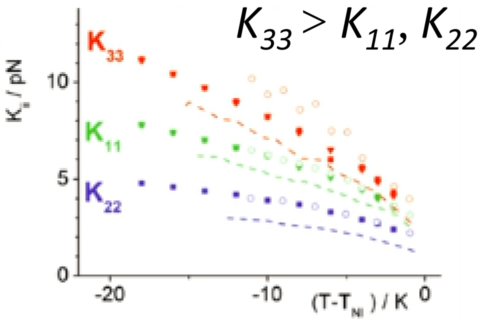


Transition to a nematic state

Material: rod like molecules which are hard to bend, i.e. bend elastic constant K_{33} is large as compared to twist K_{22} and splay K_{11} moduli. Ch period is continuously tuned by the temperature, but *not* by applied field. *Common example:* 5CB molecule







Ferrarini et al, J. Chem. Phys. **131**, 054104 (2009)

Oblique helicoidal cholesteric (Ch_{OH}) state, $\Delta\varepsilon > 0$

Theoretical prediction:

R. B. Meyer, Applied Physics Letters **12**, 281 (1968). ;
P. G. De Gennes, Solid State Communications **6**, 163 (1968).

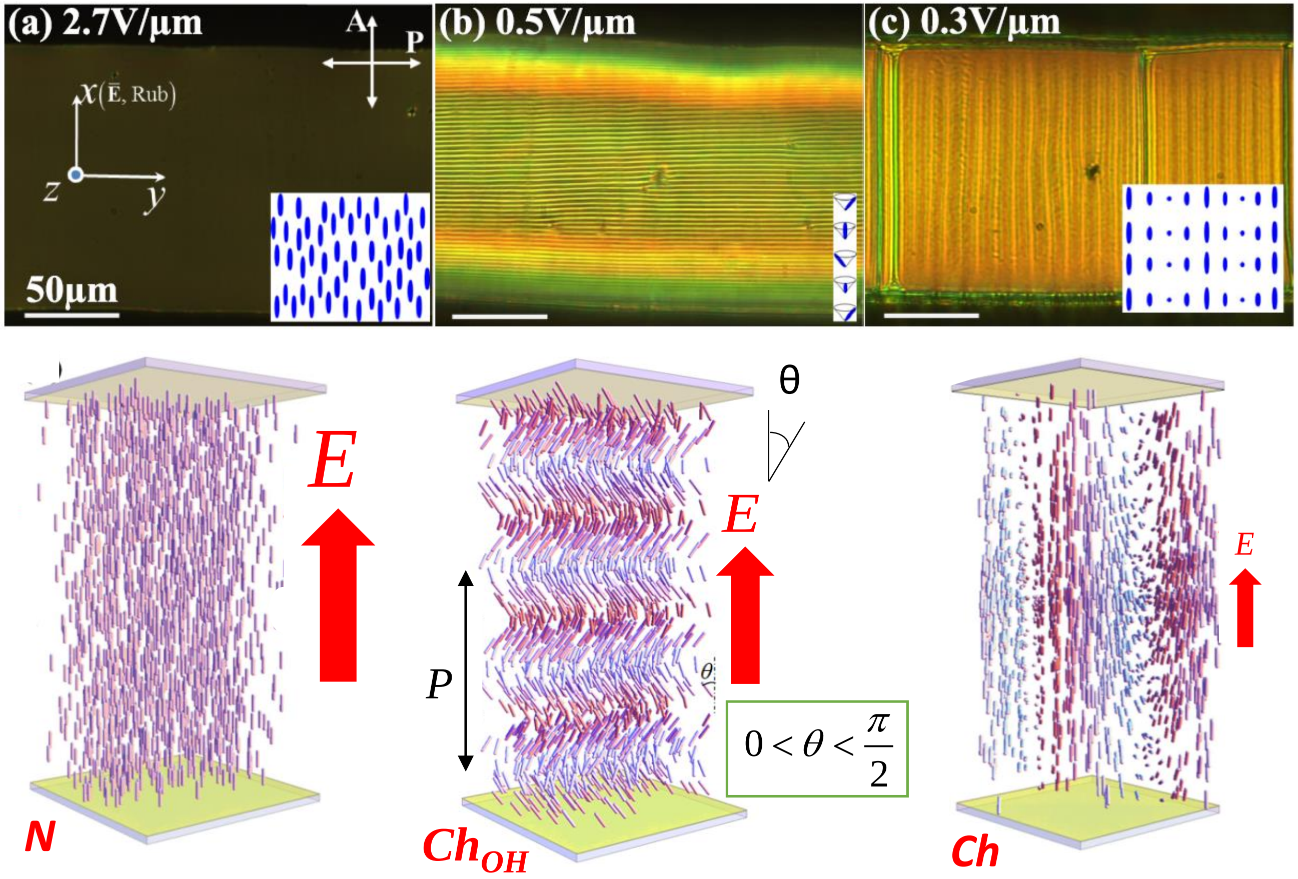
$E_{Ch} < E_{ChOH} < E_N$ when $K_{33}/K_{22} \leq 0.5$

Ch_{OH} pitch P and cone angle θ are both continuously tunable by the applied field E_{ChOH}

K_{22} and K_{33} are elastic constants of twist and bend

Experimental observation:

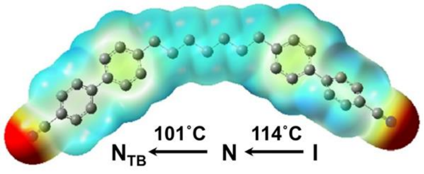
PRL **112**, 217801 (2014) PHYSICAL REVIEW LETTERS week ending 30 MAY 2014



$0 < \theta < \frac{\pi}{2}$

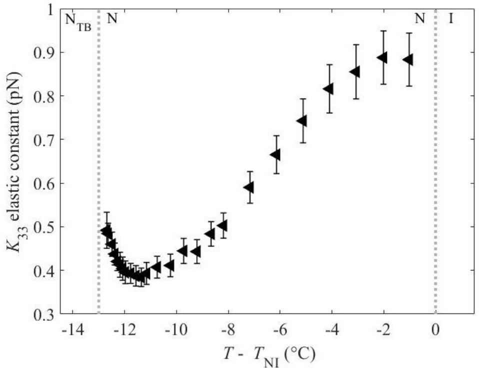
J. Xiang et al, Phys Rev Lett **112**(21), 217801 (2014).

Material:



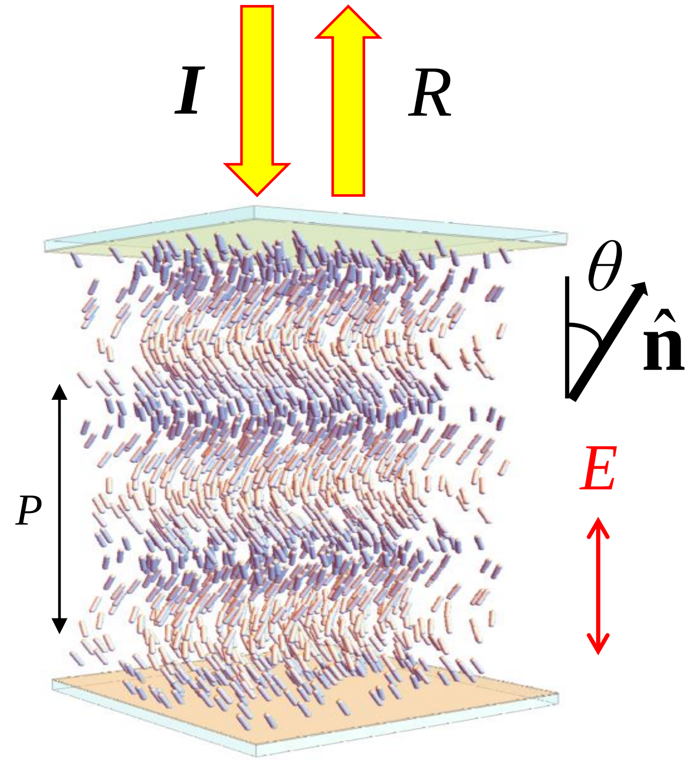
Flexible dimer
1″,7″ - bis(4-cyanobiphenyl-4′-yl) heptane (CB7CB)

is easy to bend (small K_{33})



G. Babakhanova, Z. Parsouzi et al, Phys Rev E **96**, 062704 (2017)

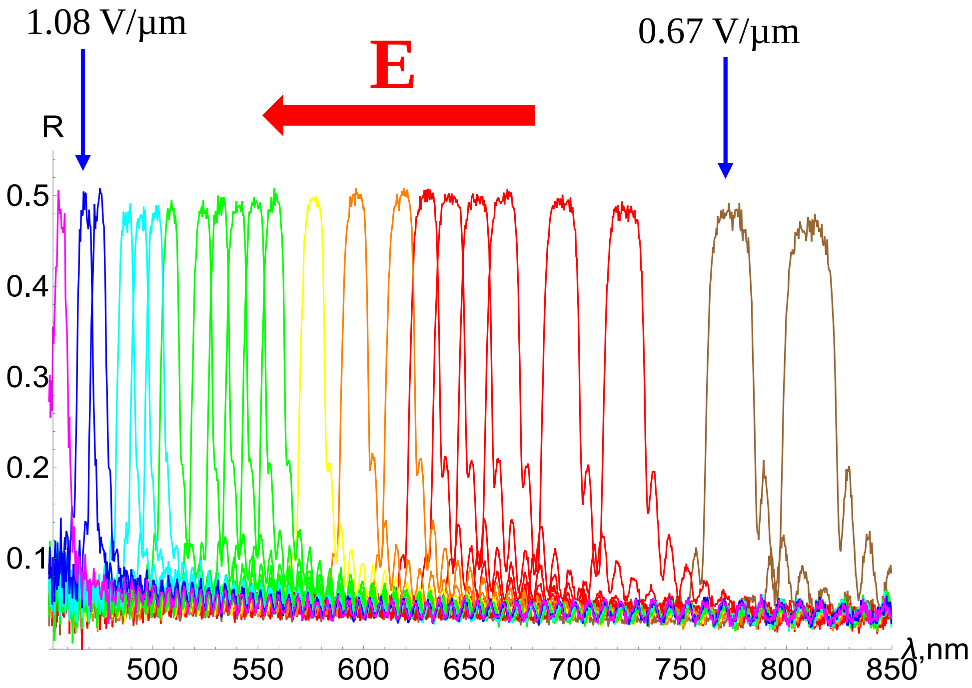
E-tuned Bragg reflection at normal incidence of light



$$\lambda_{Bragg} = \bar{n}P, \qquad \bar{n} = \frac{\left(n_e^{eff} + n_o\right)}{2}$$

$$n_e^{eff} = \frac{n_e n_o}{\sqrt{n_e^2 \cos^2\theta + n_o^2 \sin^2\theta}}$$

$$\Delta\lambda = \frac{K_{33}^2 E_N P_0 n_o}{2EK_{22}\left(K_{22} - K_{33}\right)}\left(1 - \frac{n_o^2}{n_e^2}\right)\left(\frac{E_N}{E} - 1\right)$$

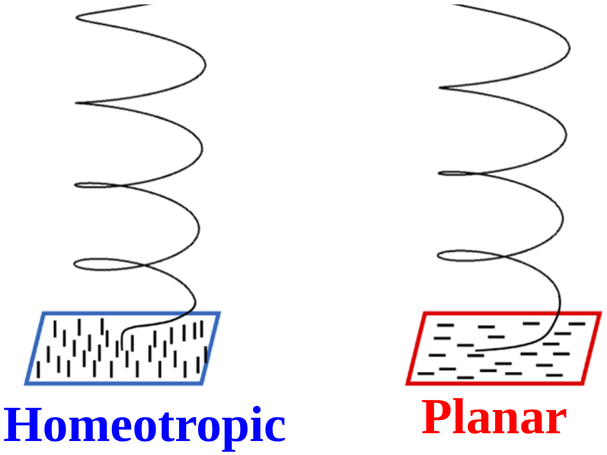


$$P = \frac{2\pi}{E}\sqrt{\frac{K_{33}}{\varepsilon_0 \Delta\varepsilon}}$$

$$\sin^2\theta = \frac{\kappa}{1-\kappa}\left(\frac{E_N}{E} - 1\right); \quad \kappa = \frac{K_{33}}{K_{22}}$$

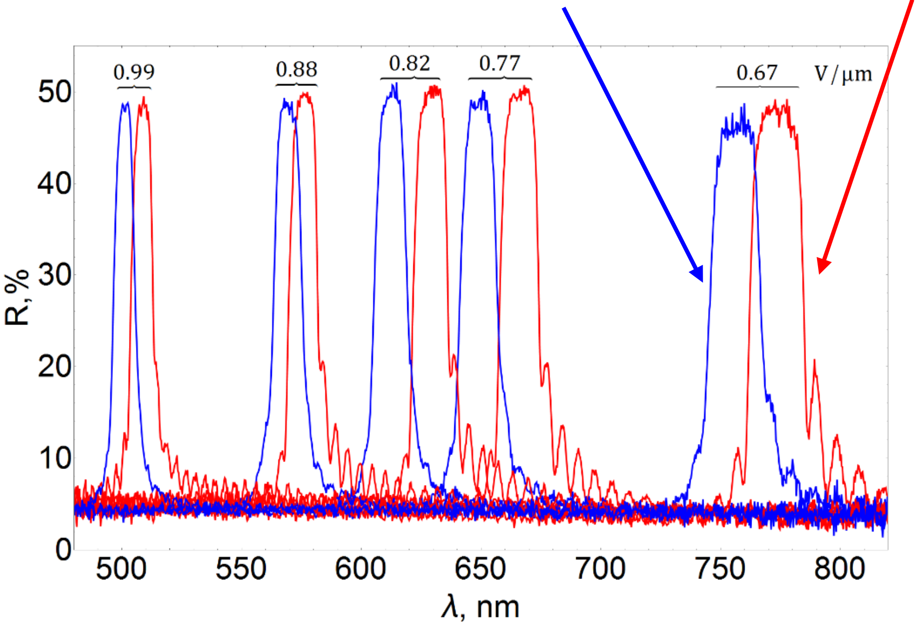
J. Xiang et al, Phys Rev Lett **112**(21), 217801 (2014); J. Xiang et al, Advanced Materials **27**, 3014 (2015).

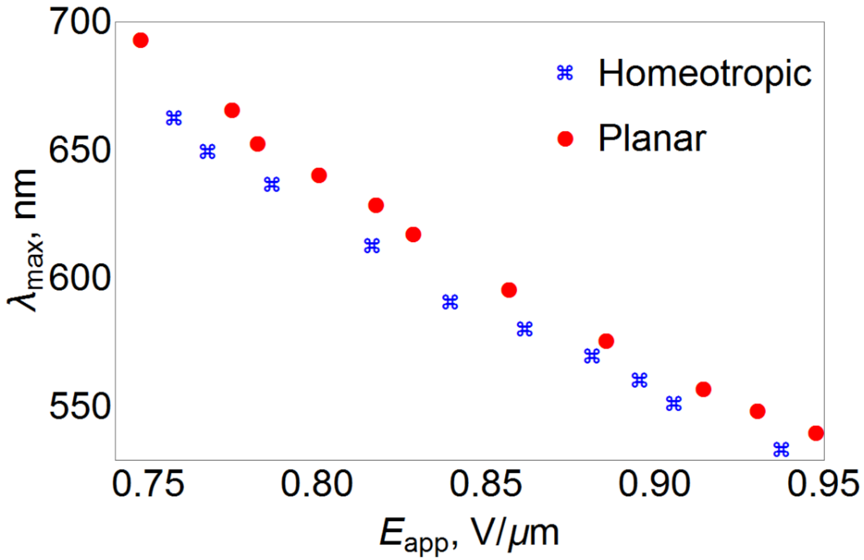
At constant applied field, reflection wavelength is *different* in planar and homeotropic cells



At the same value of the field, spectra in homeotropic Ch$_{OH}$ cells are blue-shifted, and in the planar Ch$_{OH}$ cells are red shifted.

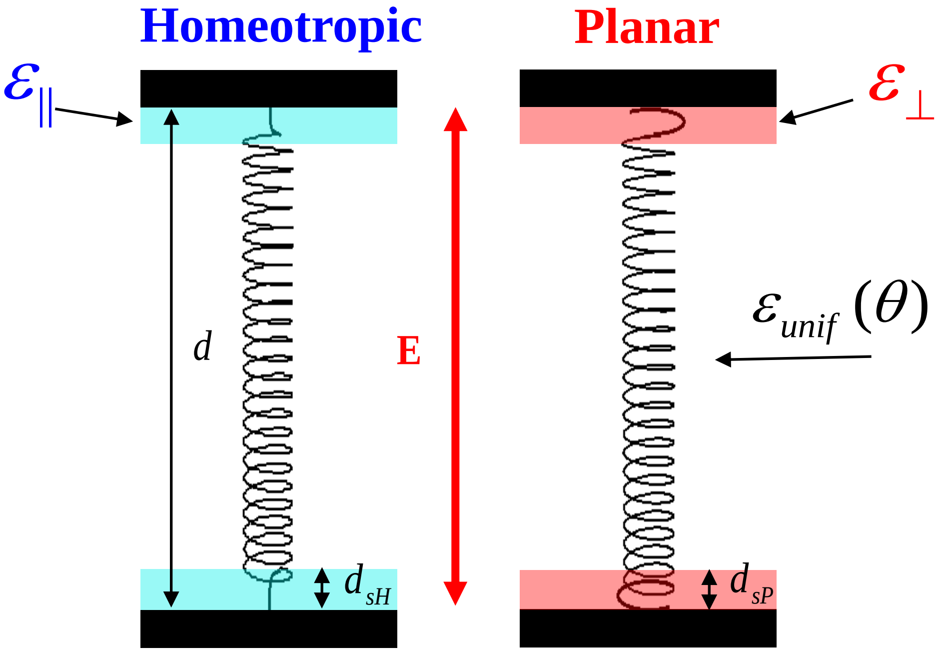
Can be used in sensing applications





Iadlovska, O.S., et al., Optics Letters, 43(8), 1850 (2018).

Dielectric properties are not uniform near substrates



$$\boxed{E_{unif} = \frac{E_{applied}}{1 \pm \text{"correction for } \varepsilon_{surface}\text{"}}}$$

&

$$\boxed{\lambda^{unif}_{Bragg} \propto \frac{1}{E_{unif}}}$$

$$E_{unif,H} > E_{unif} > E_{unif,P}$$

$$\lambda_{Bragg,H} < \lambda^{unif}_{Bragg} < \lambda_{Bragg,P}$$

$$\langle \varepsilon_{surface} \rangle = \frac{\varepsilon_{unif} + \varepsilon_{\parallel,\perp}}{2}$$

with $\varepsilon_{\parallel} > \varepsilon_{unif} > \varepsilon_{\perp}$

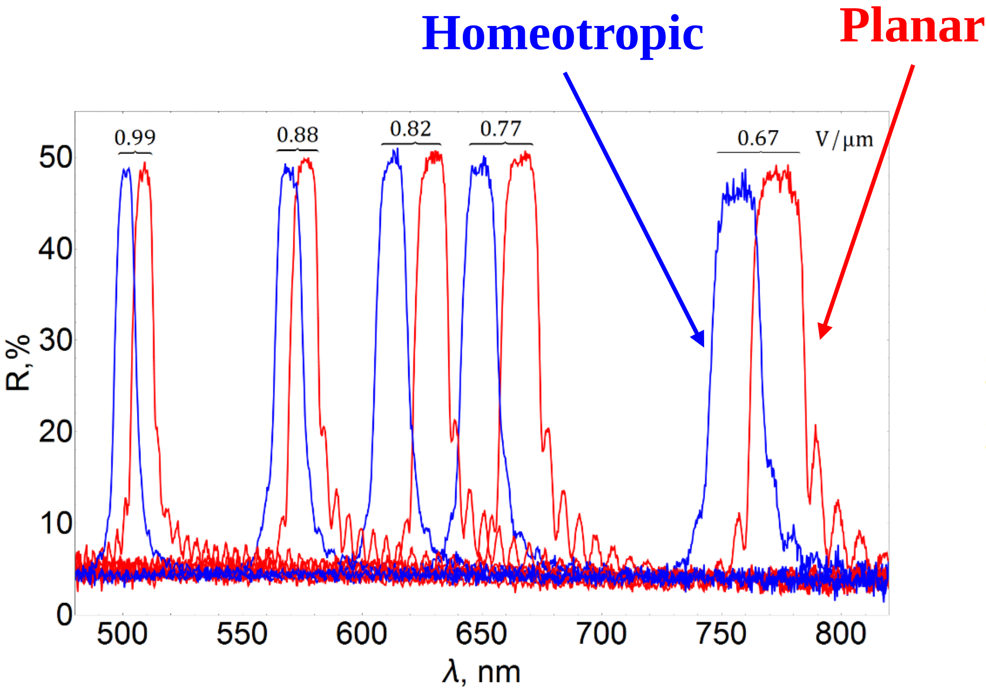
and $\varepsilon_{unif} = \varepsilon_{\perp} \sin^2\theta + \varepsilon_{\parallel} \cos^2\theta$

Iadlovska, O.S., et al., Optics Letters, 43(8), 1850 (2018).

Peaks separation is growing towards the red part of spectrum

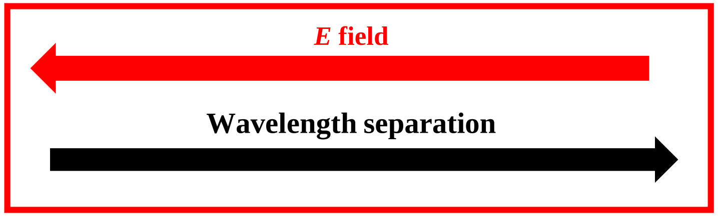
Experiment

$$\lambda_{Bragg,H} < \lambda_{Bragg,P}$$



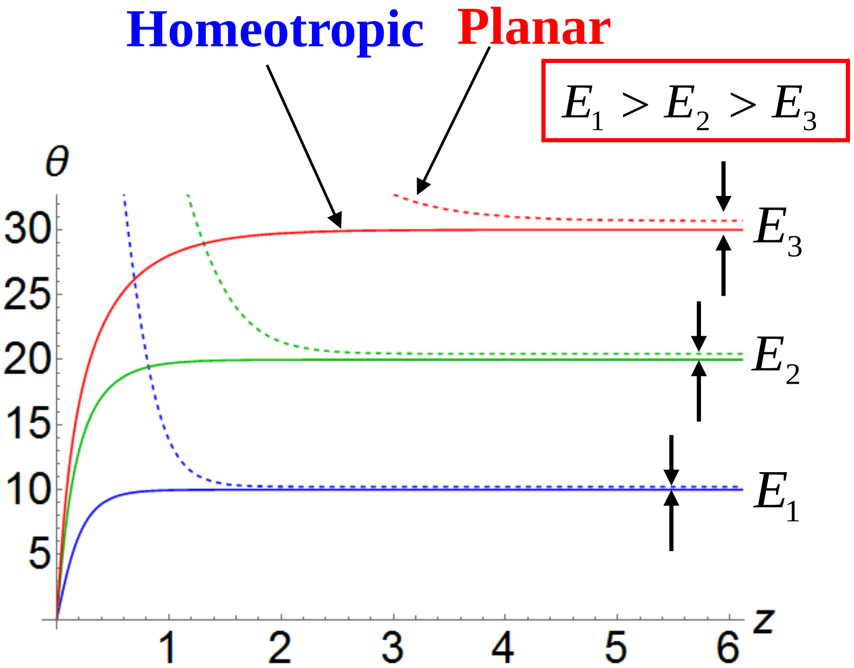
Iadlovska, O.S., et al., Optics Letters, 43(8), 1850 (2018).

Simulations

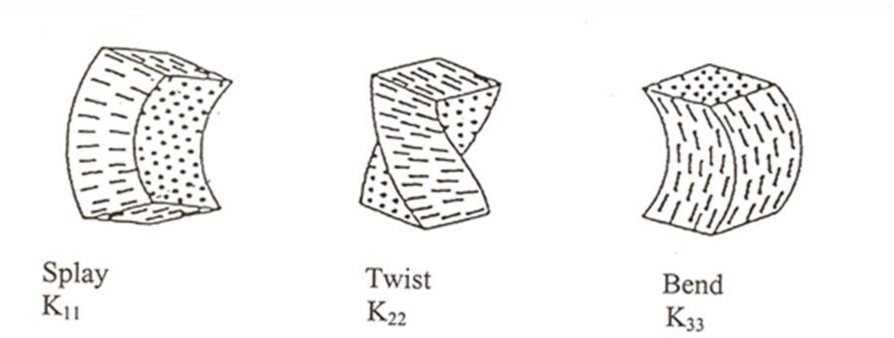

***E* field**

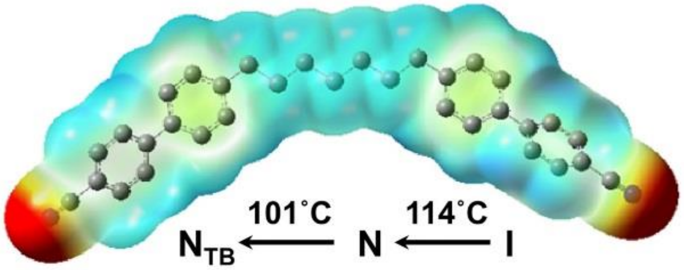
Wavelength separation

Ch_{OH} director model quantifies the director field difference in the two cells



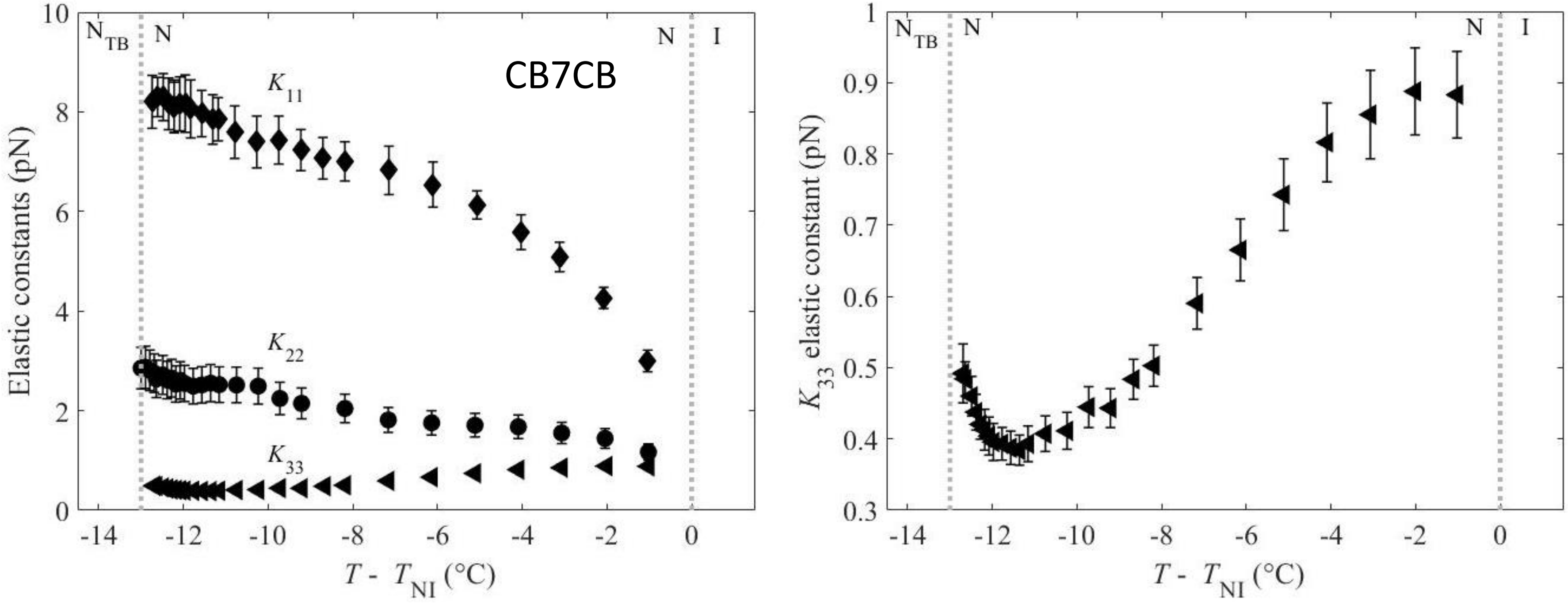
Elasticity of the flexible dimer CB7CB, the first N_{tb} material





Flexible dimer CB7CB is easy to bend (small K_{33})

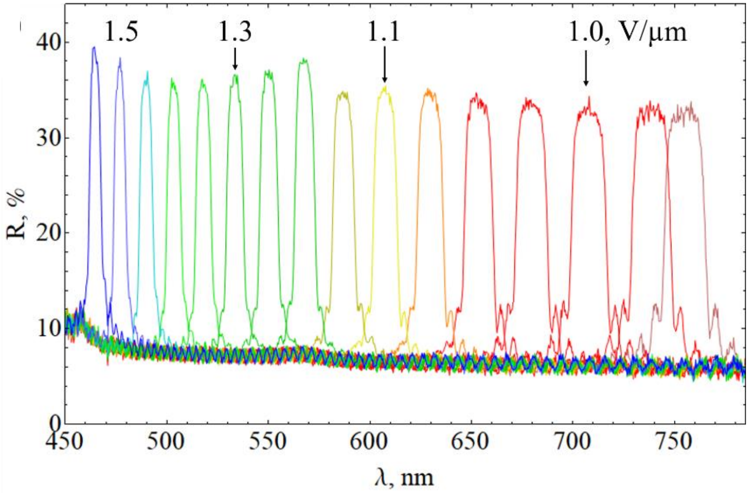
Elastic constants of Splay K_{11}, Twist K_{22}, and Bend K_{33} measured in nematic phase:

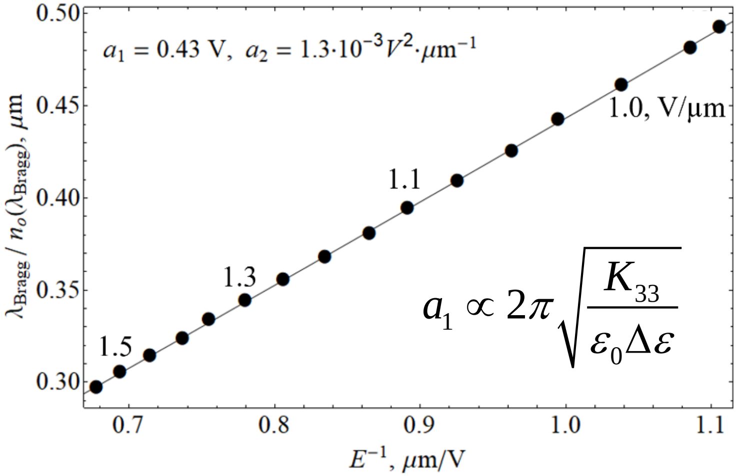


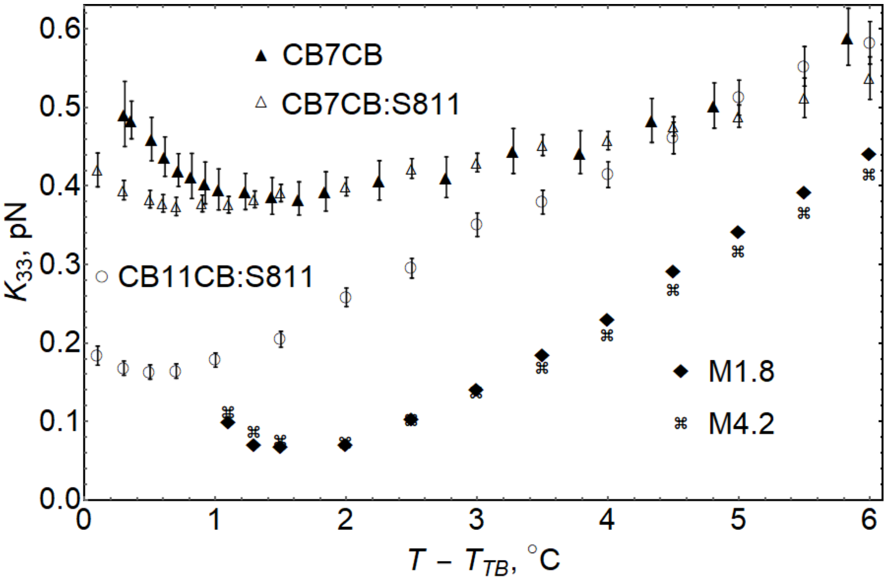
G. Babakhanova, Z. Parsouzi et al, Phys Rev E 96, 062704 (2017)

In-situ measurement of bend elastic constant in Ch

Values of K_{33} are deduced from the optical spectra.

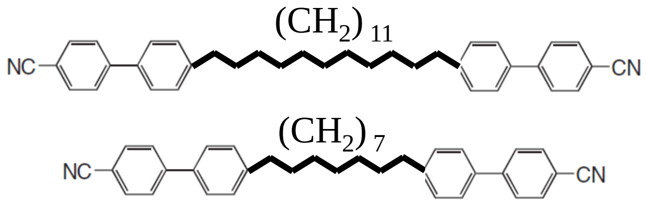






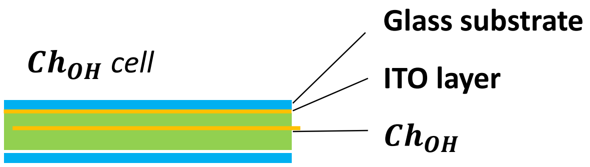
$$\frac{\lambda_{Bragg}}{n_o} = \frac{2\pi}{E}\sqrt{\frac{K_{33}}{\varepsilon_0\Delta\varepsilon}}$$

Longer flexible dimer CB11CB has smaller bend modulus as compared to shorter CB7CB molecule.

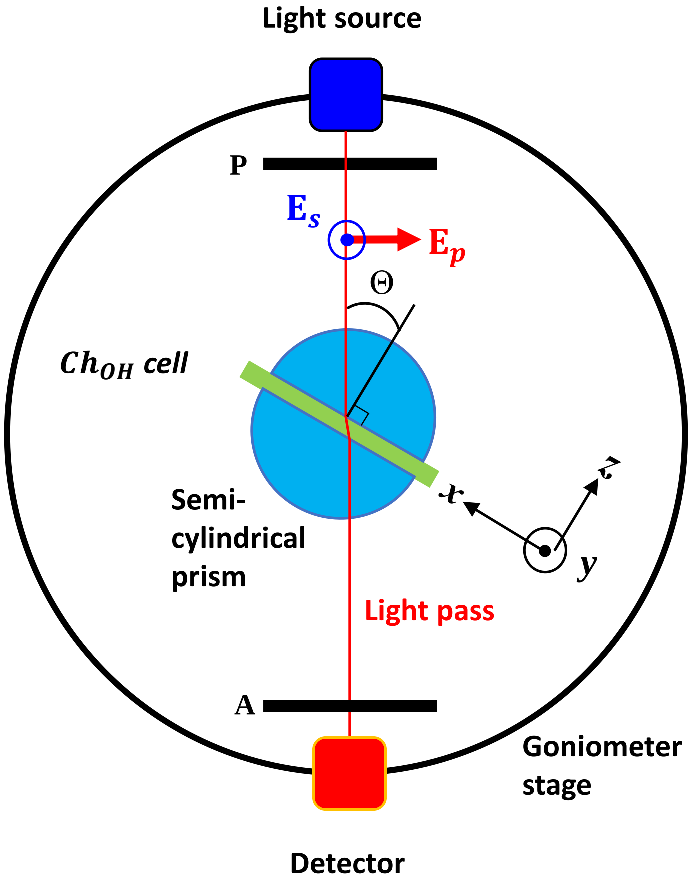


Iadlovska, O.S., et al., Phys Rev Research 2, 013248 (2020)

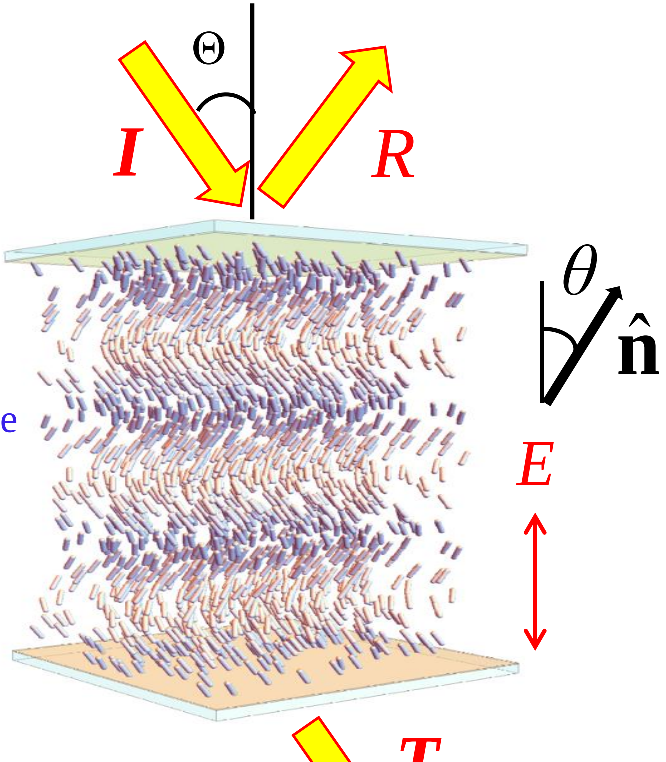
Oblique incidence at Ch_{OH} structure



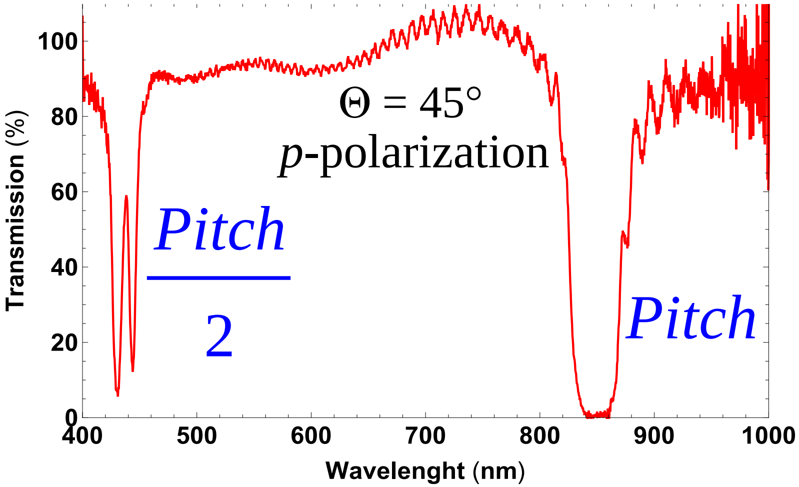
Oblique incidence setup
in transmission mode



Diffraction from Ch_{OH} structure at oblique incidence of light reveals forbidden bands associated with the full pitch P and the half-pitch $P/2$

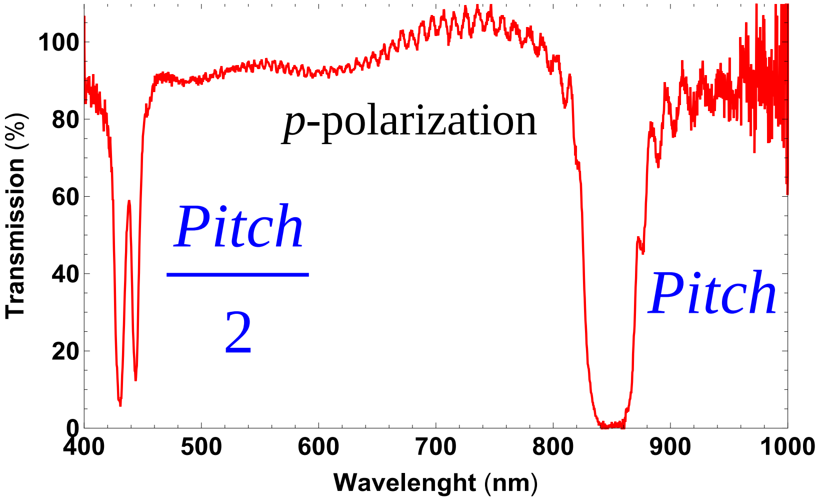


$E = 1.47$ V/μm

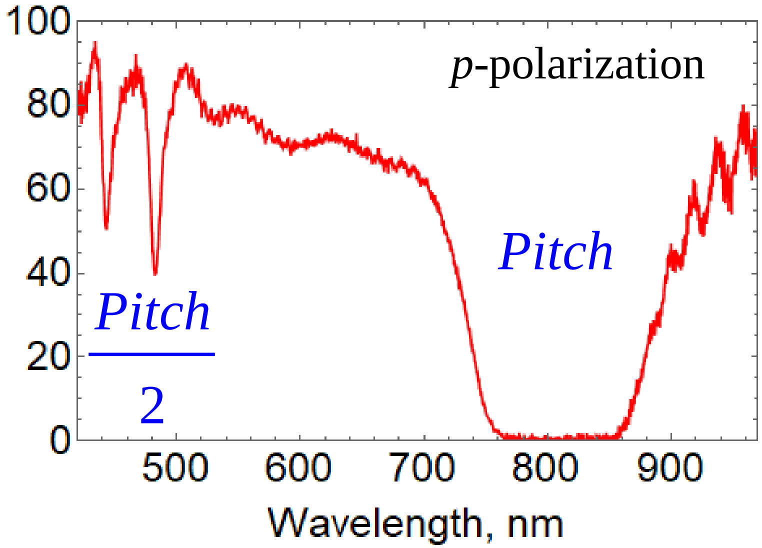


E- and *Θ*-tuned Bragg diffraction at oblique incidence

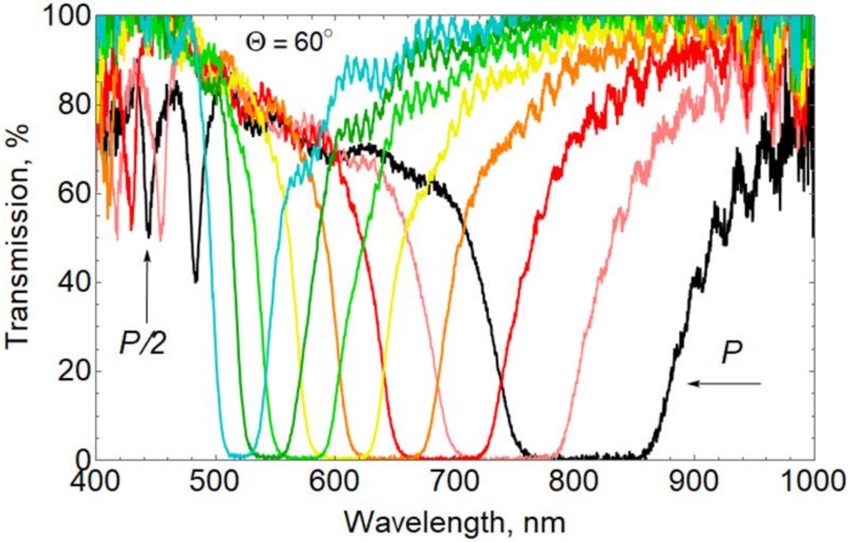
Θ = 45° E = 1.47 V/μm



Θ = 60° E = 1.11 V/μm

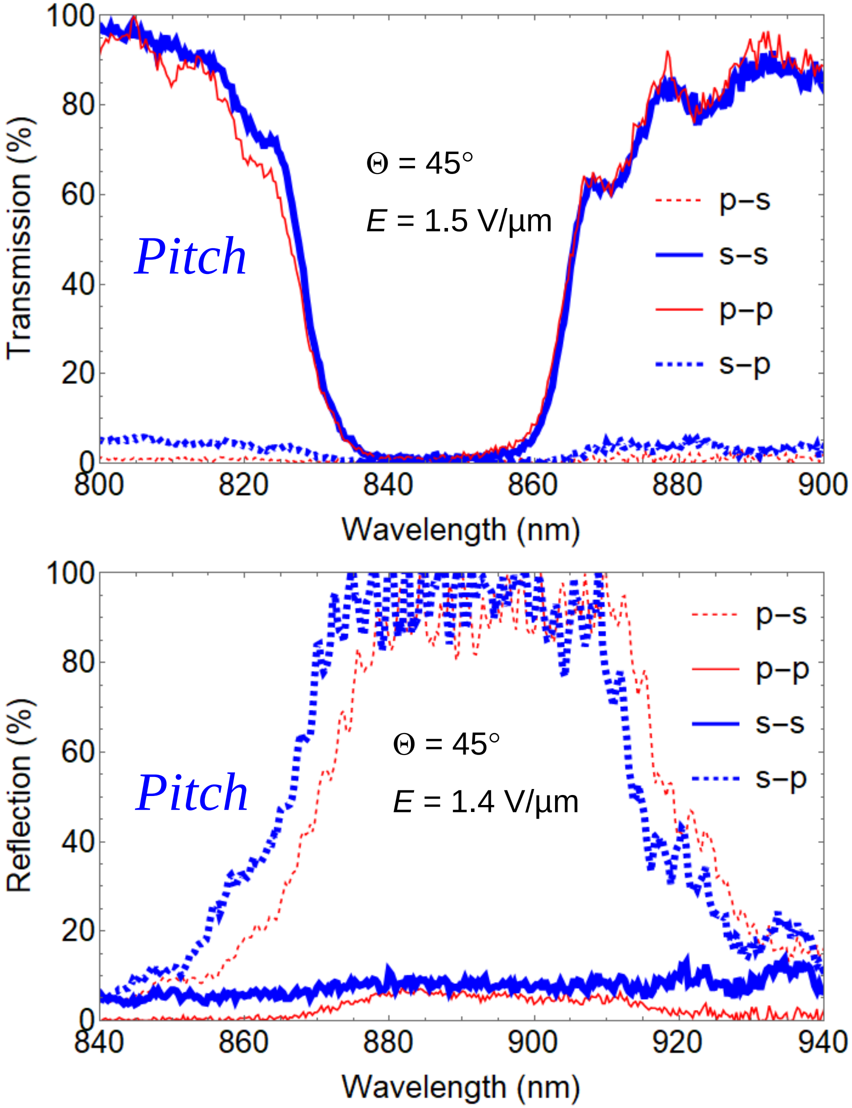


Incidence Θ = 60°
p-polarization

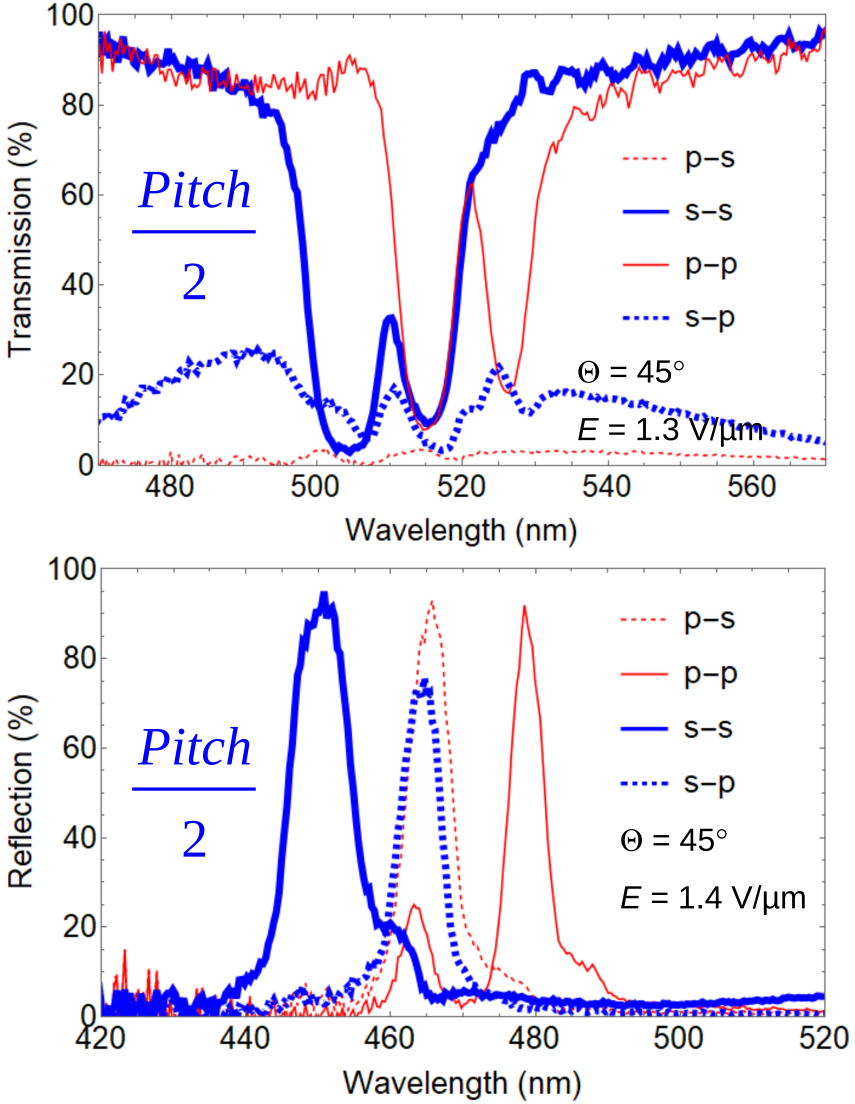


Diffraction at the full pitch *P* is characterized by a wide bandwidth and total reflection at a large angles of incidence Θ

Oblique incidence: polarization characteristics



The full pitch bandgap is a singlet, polarization independent



The half-pitch is a triplet whose lateral peaks are polarization dependent, while the central peak is not.

Summary

- Oblique helicoidal cholesteric (Ch_{OH}) state is continuously tunable by applied field; the single-harmonic periodicity is preserved
- Bragg reflection from Ch_{OH} is sensitive to the surface alignment: a blue shift of spectra is observed in homeotropic cells and red shift is observed in planar cells
- Bragg spectra at the Ch_{OH} can be used to measure bend elastic constant of the *Ch phase*
- At oblique incidence, diffraction at the half- and full pitch is observed at a varying angle of incidence. Diffraction at the half-pitch is a triplet whose lateral peaks are polarization dependent, while the central peak is not. The full pitch bandgap is a singlet characterized by a wide bandwidth and total reflection at a large angle of oblique incidence

I want to thank my advisors Dr Oleg Lavrentovich and Dr Sergij Shiyanovskii for all their help and guidance, and my colleagues and friends for fruitful discussions and collaboration, as well as our collaborators for supply of the twist-bend materials.

Graham R Maxwell
(REU program)

Kamal Thapa

Synthesis of twist-bend materials:
Quan Li and students Hao Wang, Hari K. Bisoyi, Kent State University, USA
Corrie T. Imrie, and students Daniel Paterson, Grant Strachan and Ewan Cruickshank, University of Aberdeen, Scotland, UK
Georg H. Mehl, Christopher Welch, University of Hull, UK

National Science Foundation: CHE-1659571 (REU program); ECCS-1906104

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