Optical Switching Behavior of Liquid Crystals in Self-Assembled Colloid Structures

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OUTLINE

I. **Introduction**

II. **Categories of liquid-crystal / matrix samples**

- Liquid-crystal in colloid-templated cavities
- Liquid-crystal within self-assembled colloid
- PDLC cells (comparison)

III. **Experimental measurements**

- Intensity transmission vs. electric field
- Diffraction behavior
- Switching times

IV. **Results / Comparisons**

V. **Summary / Future Directions**

Introduction

Colloidal self-assembly

Þ **A route to useful structures**:

- photonic crystals with bandgaps, waveguide behavior **. . .**

Liquid crystals

Orientationally ordered molecules, with **dielectric anisotropy . . .**

- already exploited in well-known electro-optic devices (e.g., liquid-crystal displays, shutters, etc.)

Liquid Crystals + **Self-assembled Colloids** =

- **optical switching applications:**
  switchable diffraction, beam splitting, beam steering. . .

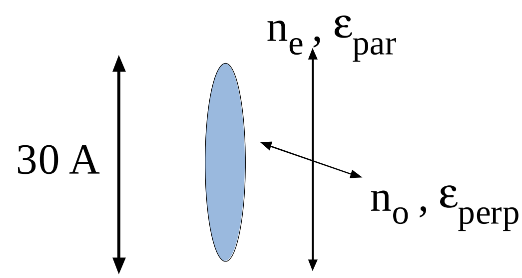
- **physics of liquid crystals in ordered cavity network**

Polymer **D**ispersed **L**iquid-**C**rystal cells

Ingredients: photo-curable polymer

and

liquid crystal



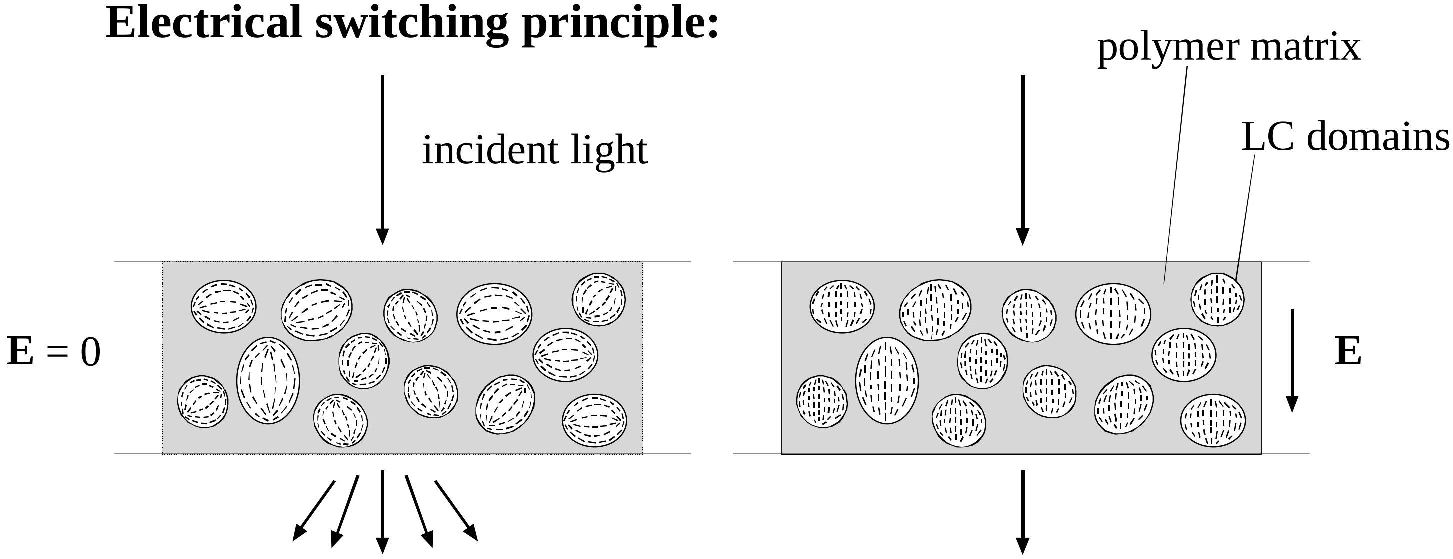
e.g. Norland Optical Adhesive

+ Merck "TL205"
(multi-component nematic mixture)

T_{NI} = 85 C; $\varepsilon_{par} > \varepsilon_{perp}$; $n_o = 1.53$; $n_e = 1.74$

Fabrication: Mix liquid crystal & prepolymer,
phase separate by UV irradiation . . .

Electrical switching principle:



$n_{polymer} \neq$ effective $n_{LC} \Rightarrow$

highly scattering

$n_{polymer} \cong n_o \Rightarrow$

transparent

In general, PDLC droplets not distributed in ordered fashion

⇒ **diffuse scattering, not Bragg diffraction**

Some methods to get *patterned* LC/polymer distribution:

1) holographic PDLCs:

C. Bowley, A. Fontecchio, G. P. Crawford, J. Lin, L. Li, S. Faris, Appl. Phys. Lett. ***76,*** *523 (2000).*

T. Bunning, L. Natarjan, V. Tondiglia, R. Sutherland, Annu. Rev. Mater. Sci. ***30****, 83 (2000).*

2) polymer-stabilized cholesteric diffraction gratings (PSCDGs):

S. Lee, S. Sprunt, L. C. Chien, Liq. Cryst. ***28****, 637 (2001).*

3) phase-separated composite films (PSCOF):

V. Vorflusev, S. Kumar, Science ***283****, 1903 (1999).*

- these give LC (or LC droplets) in plane or line distributions

⇒ **1-D or 2-D diffraction**

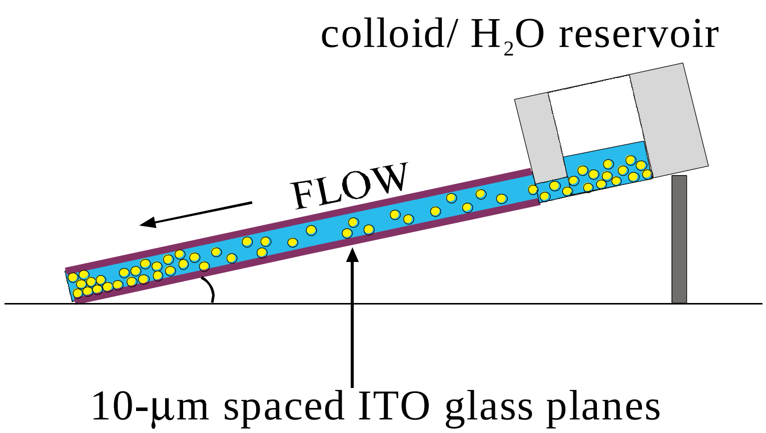
Colloid templates provide route to 3-D diffraction

"Liquid-crystal imbibed in self-assembled colloid"

(flow cell assembly of close-packed colloids)

Materials: Colloid — 1.6 and 1.0 µm SiO_2 spheres,
Duke Scientific
(polydispersity < 3%)

10 µm gap sandwich cell, interior cell faces ITO-coated



(SCHEMATIC CROSS-SECTION, NOT TO SCALE)

1) allow ITO cell to fill from dilute colloid/water reservoir

2) colloid settles into close-packed poly-crystalline domains from cell outflow end upwards

3) once filled, allow cell to dry

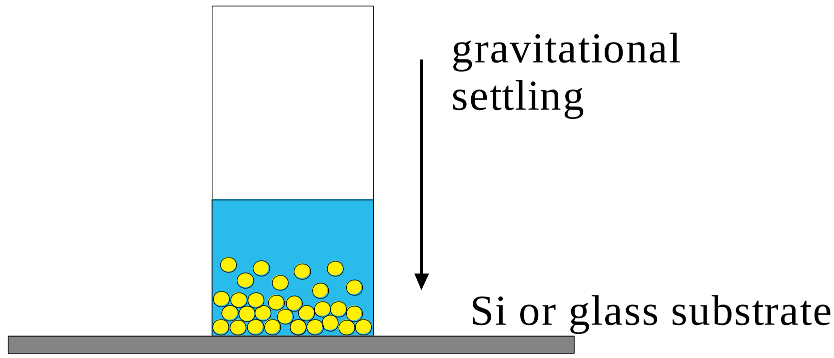
4) detach reservoir unit and imbibe with liquid-crystal

"Reverse" PDLC-like geometry

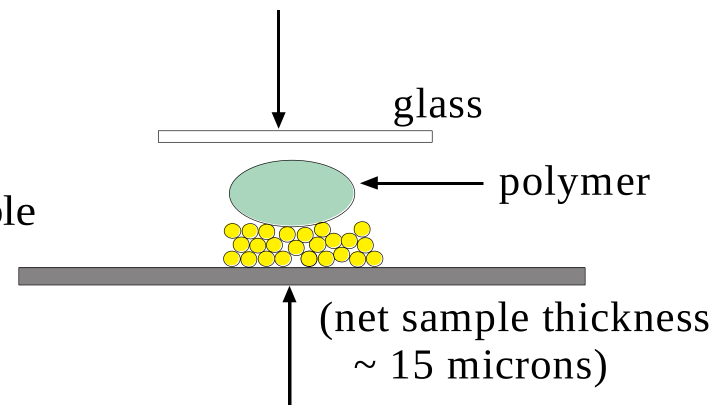
"Liquid Crystal in Colloid-Templated Cavities"

Multi-step process:

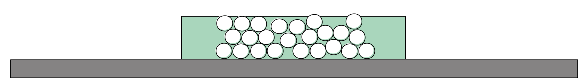
1) sedimentation of colloid
from dilute suspension
(e.g. 1.6 μm SiO_2)



2) after drying, cast with UV-curable
polymer



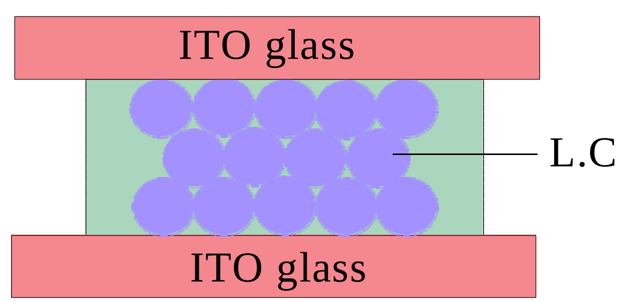
3) after polymer cures, remove colloid
via appropriate etch (HF or toluene)

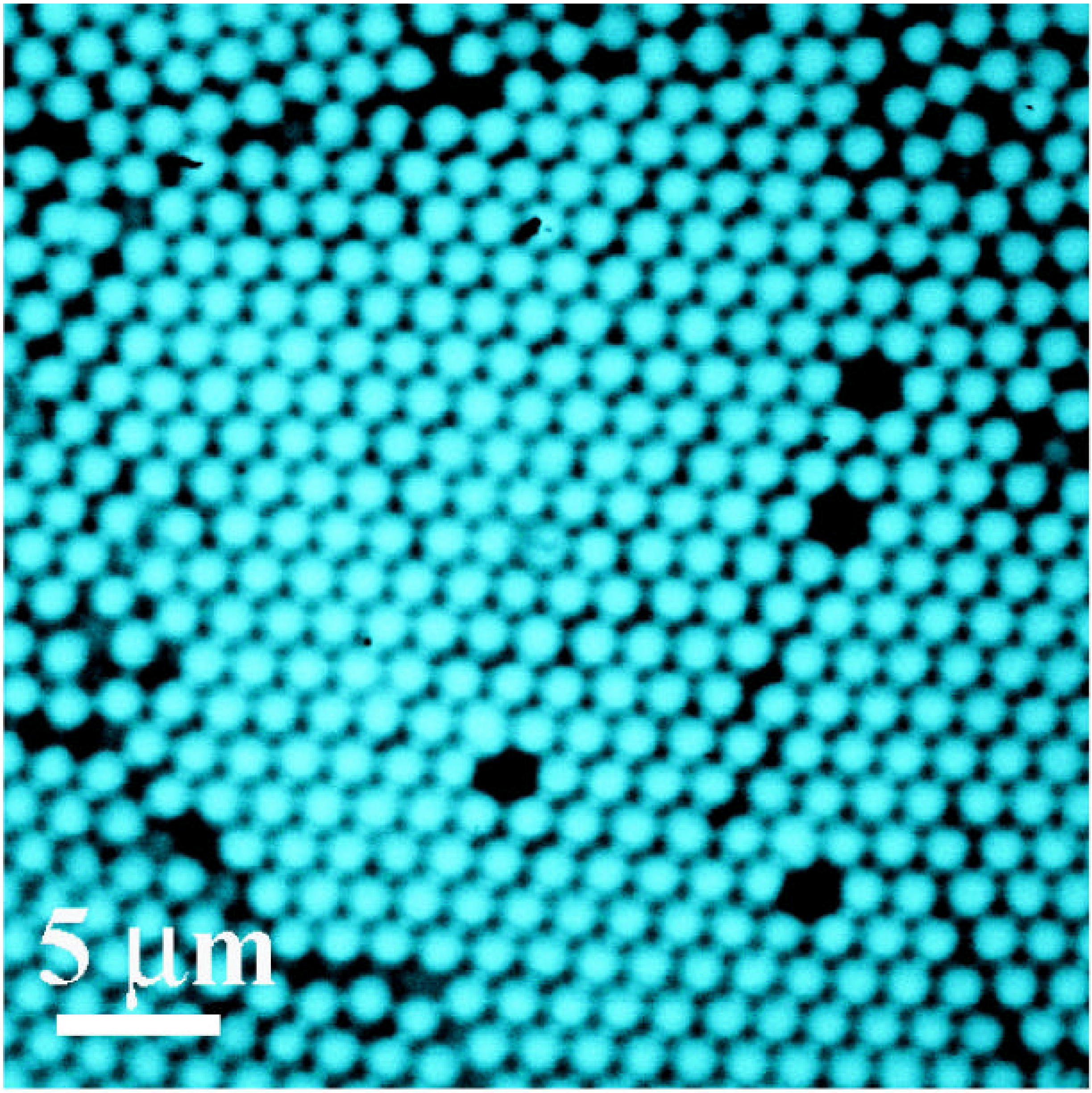


4) transfer of templated membrane
onto ITO-glass

5) imbibe porous network region with
liquid-crystal

6) cap cell with ITO glass and seal





Confocal microscope image, 1.6μm-templated "direct" structure (rhodamine/ethanol)

Summarizing sample categories

1) "**Reverse" structures:** LC in sedimented colloid matrix

1.6, 1.0, or 1.6 & 1.0 μm mixture diameter SiO_2 colloid in ITO cell of 10 μm spacing, imbibed with TL205 liquid crystal

2) "**Direct" structures:** LC in colloid-templated polymer matrix

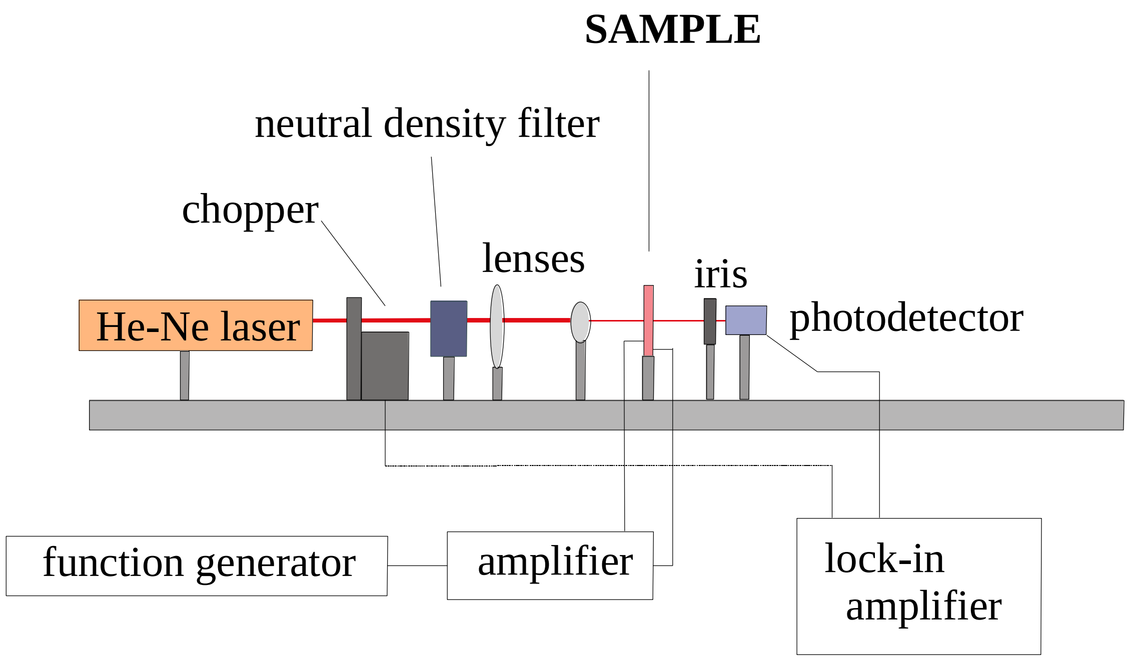
~25 μm spacing ITO cells containing TL205 liquid crystal in connected pore network left by sedimented 1.6 μm SiO_2 colloid

3) **PDLCs:**

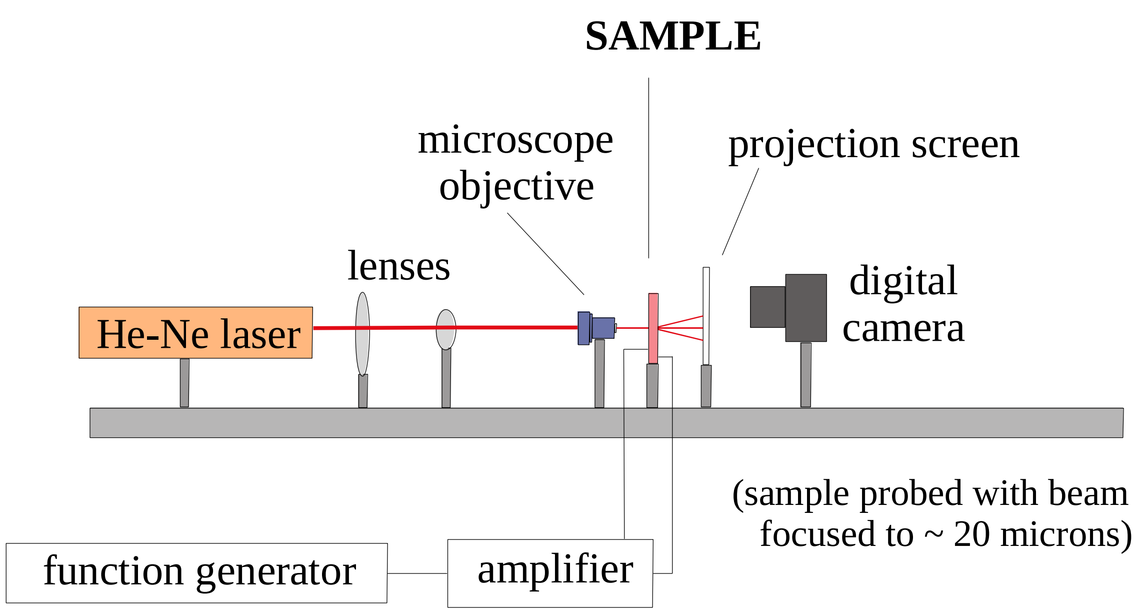
High LC volume fraction mixtures, in ITO cells:

e.g. ~ 65% TL205 / 35% Norland optical adhesive #73
80% TL205 / 20% Merck polymer PN393

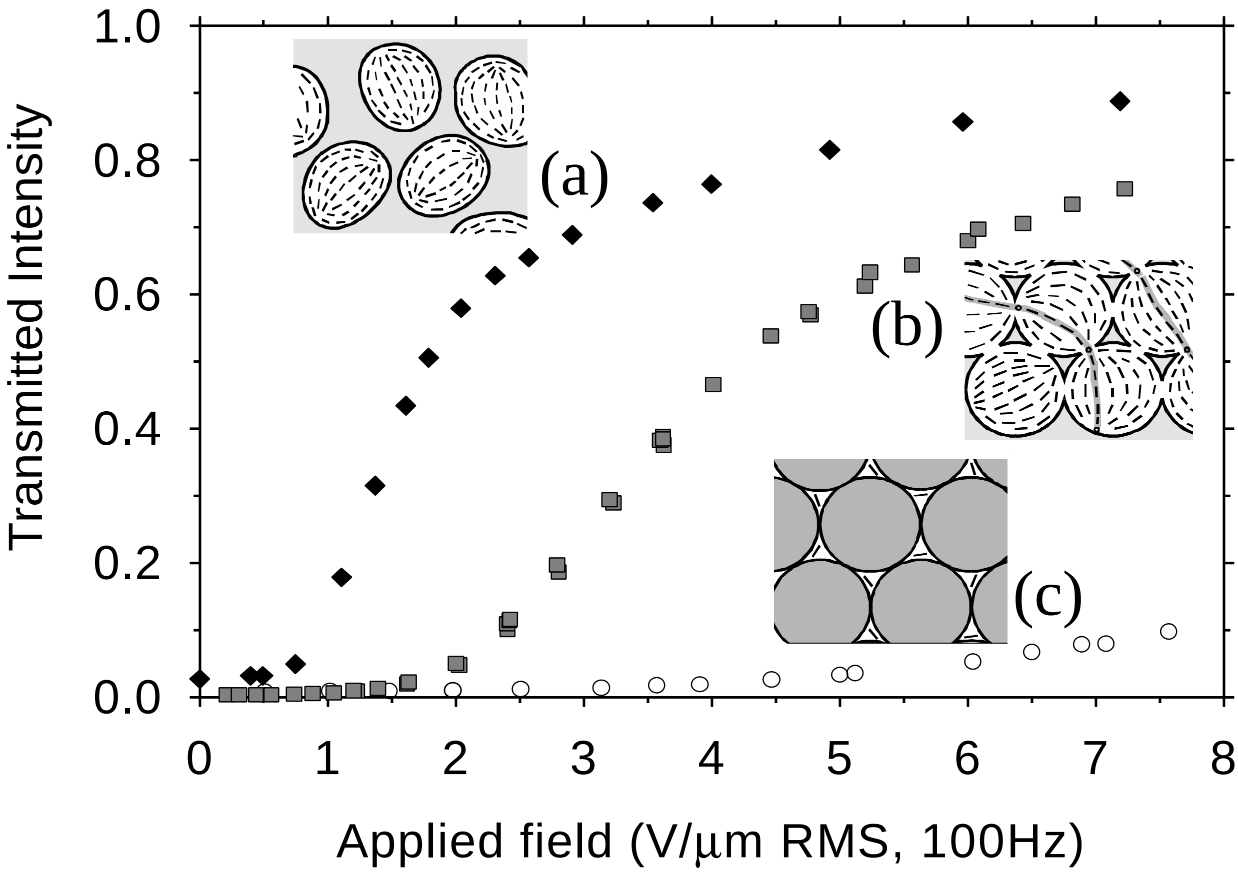
① TRANSMISSION INTENSITY



② DIFFRACTION BEHAVIOR



Transmission Responses Compared

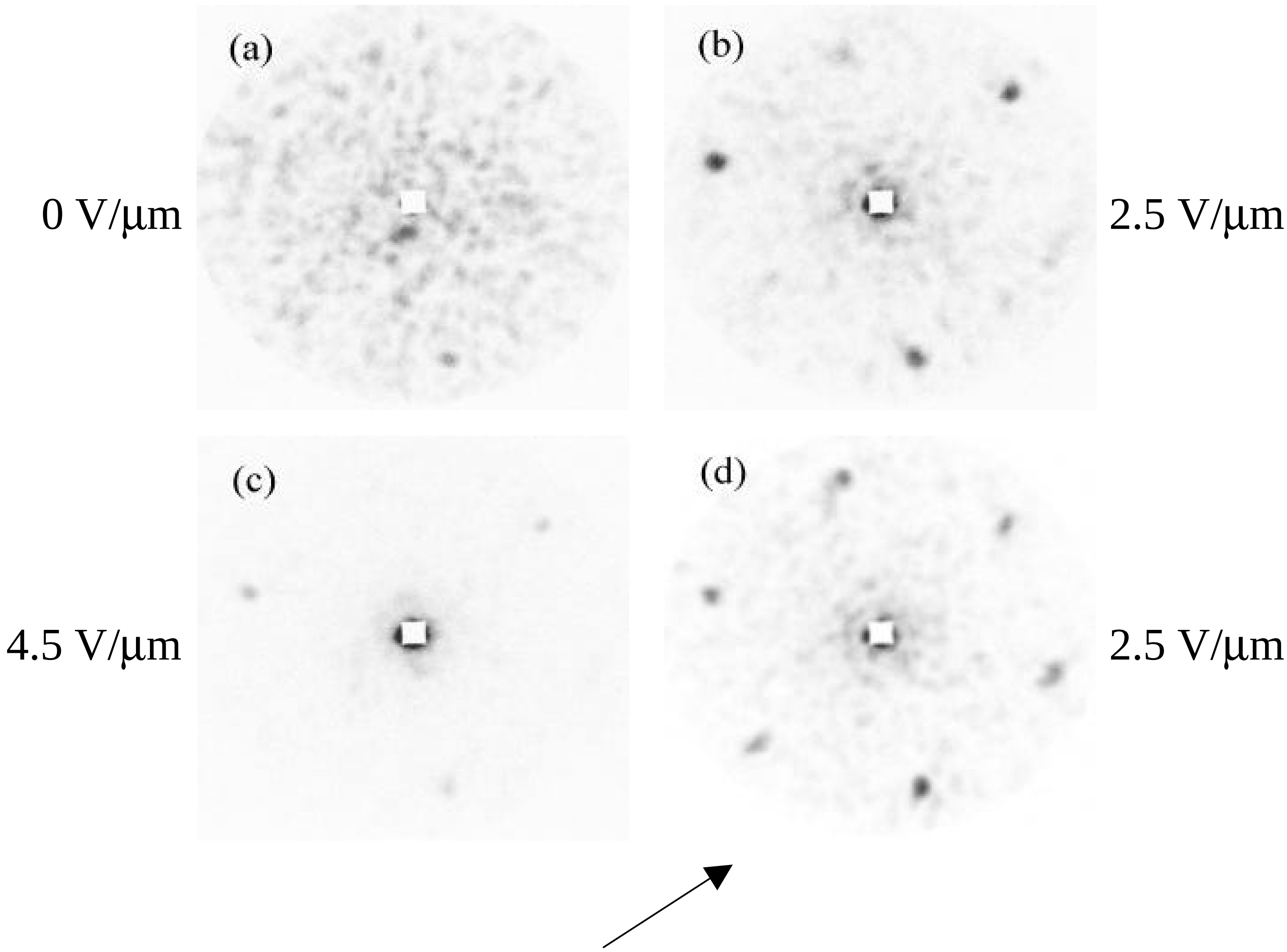


(a) PDLC: 65% TL205 / 35% Norland 73
(b) "direct": 1.6 μm-templated,
TL205 in Norland 73
(c) "reverse": TL205 in 1.6μm silica

LC in opal structures:
D. Kang, J. E. Maclennan, N. A. Clark, A. Zakhidov, and R. H. Baughman, Phys. Rev. Lett. **86**, 4052 (2001).

Diffraction patterns from 1.6mm-templated "direct" sample

TL205 liquid crystal in Norland 73



Estimate for diffraction angle, considering:

- random HCP stacking,
  Bragg rods in reciprocal space
- particle spacing d = 1.58µm
- refraction out of sample cell
- $n_{LC} = (0.667n_o^2 + 0.333n_e^2)^{1/2} = 1.60$
- $n_{eff} = (0.75n_{LC}^2 + 0.25n_{polymer}^2)^{1/2} = 1.59$
- $\theta = \sin^{-1}[(4/3)^{1/2}\,\lambda/(n_{eff}\,d)]$

PREDICTED diffraction angle:

27.6°

MEASURED diffraction angle:

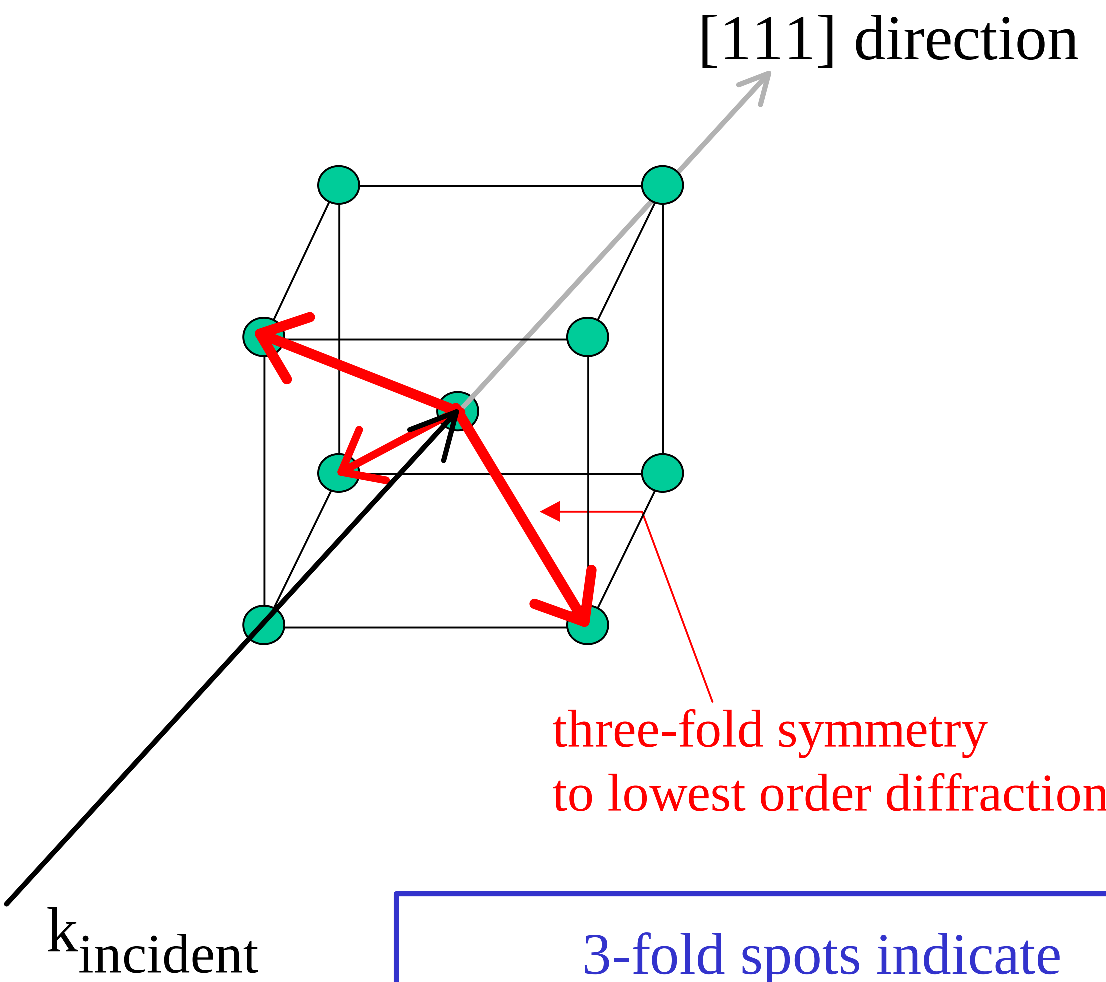
27 ± 1°

Why the three-fold symmetry ?

2-D close-packed layer, or random HCP stacking thereof, gives **six-fold** symmetric pattern...

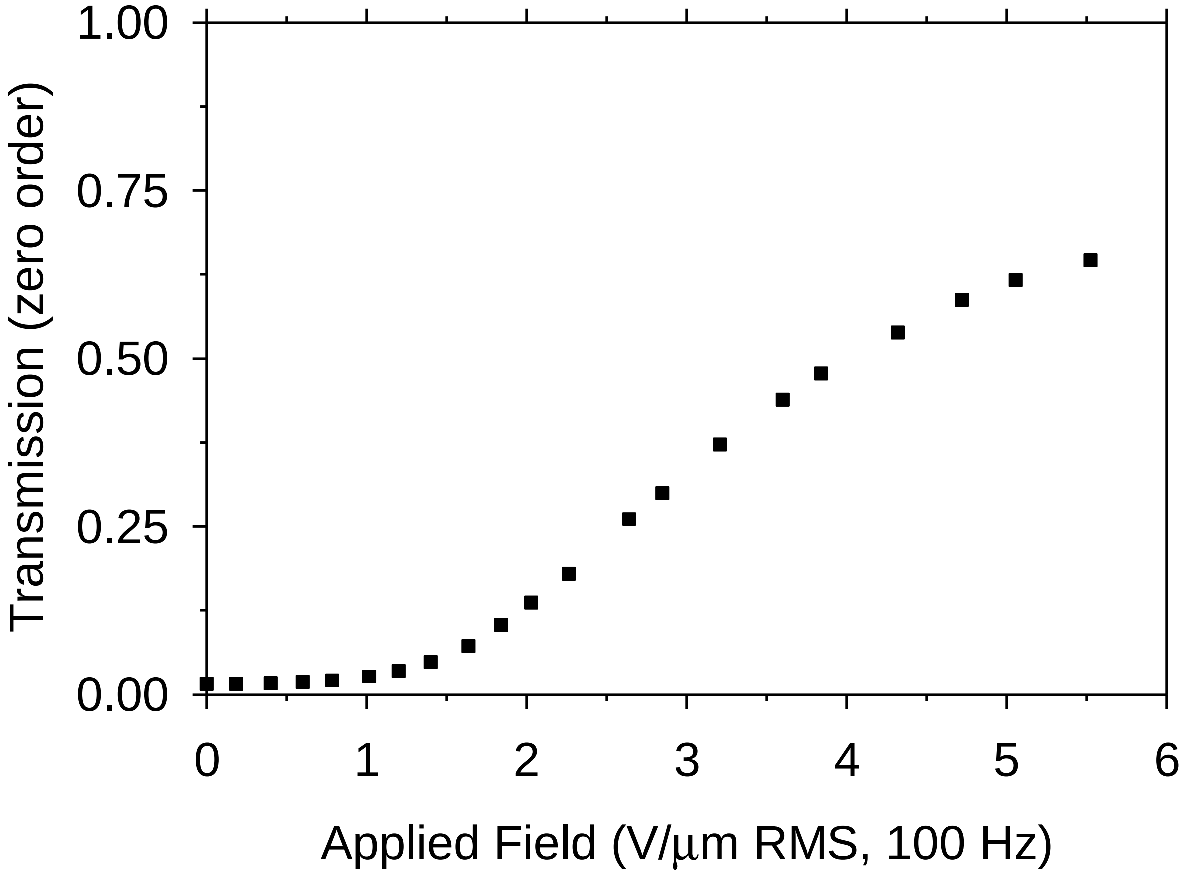
BUT

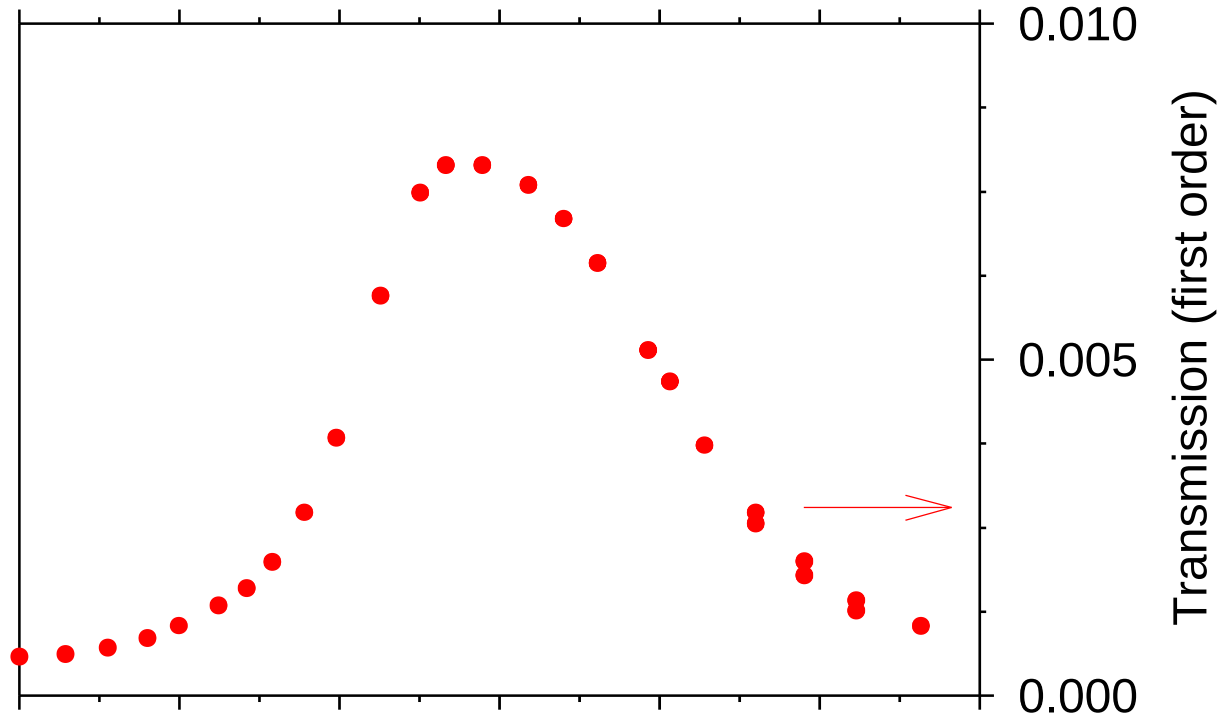
Reciprocal lattice to FCC is BCC:



3-fold spots indicate
the 3-D order (FCC) aspect
of the switchable diffraction

"Direct" structure: 1.6mm-templated sample
TL205 (liquid crystal) in Norland 73 (polymer)





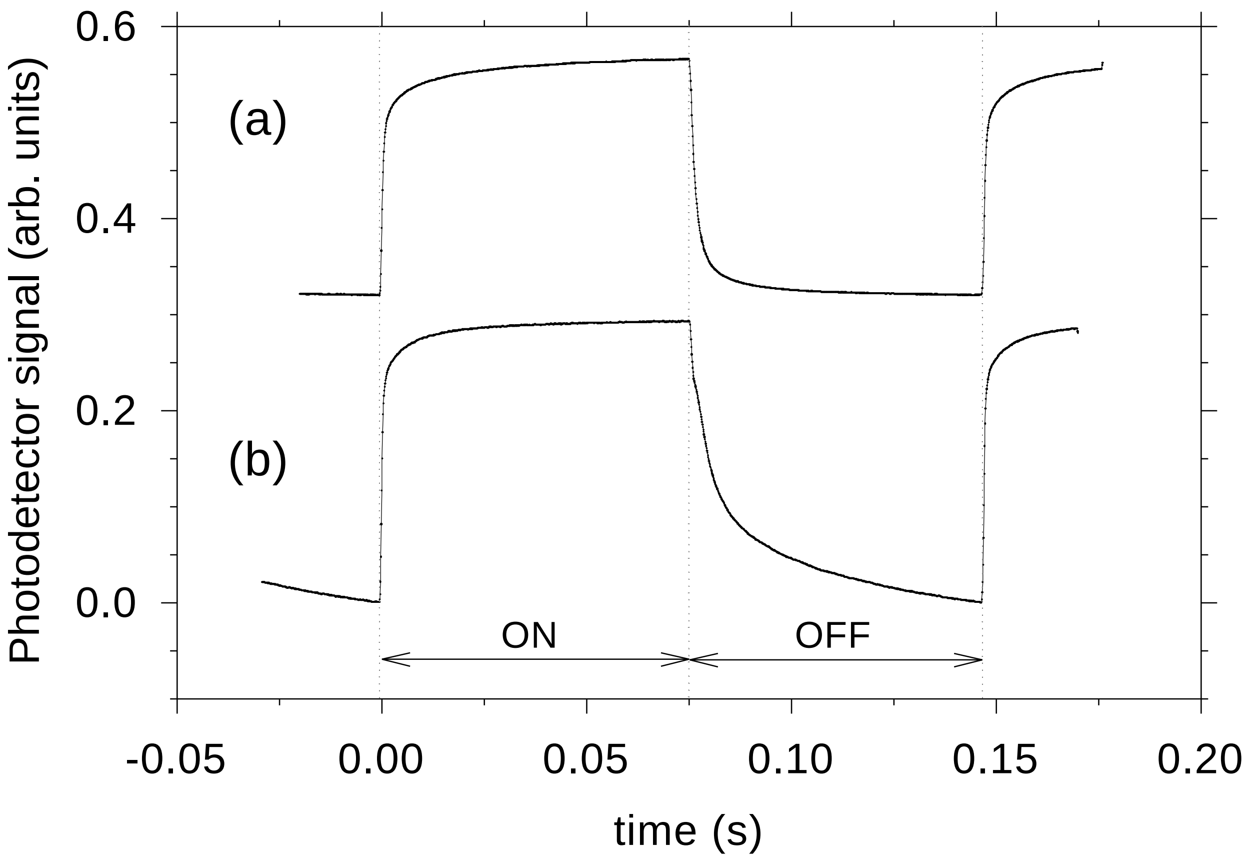
"3 state switch":

Closed --> Diffracting --> Open

Transmission responses, gated 1 kHz signal, 4.5 V/μm RMS:

a) "direct" (1.6μm-templated, TL205 / Norland 73)

b) PDLC (TL205 / Norland 73)



Surprising:

conventional PDLC prediction (bipolar droplet configuration):

$$t_{fall} \sim R^2 / (L^2 - 1)$$

R a characteristic size

L anisotropy measure

e.g. P. Drzaic, *Liquid Crystal Dispersions* (1995)

B. Wu, J. H. Erdmann, and J. W. Doane, Liq. Cryst. **5**, 1453 (1989)

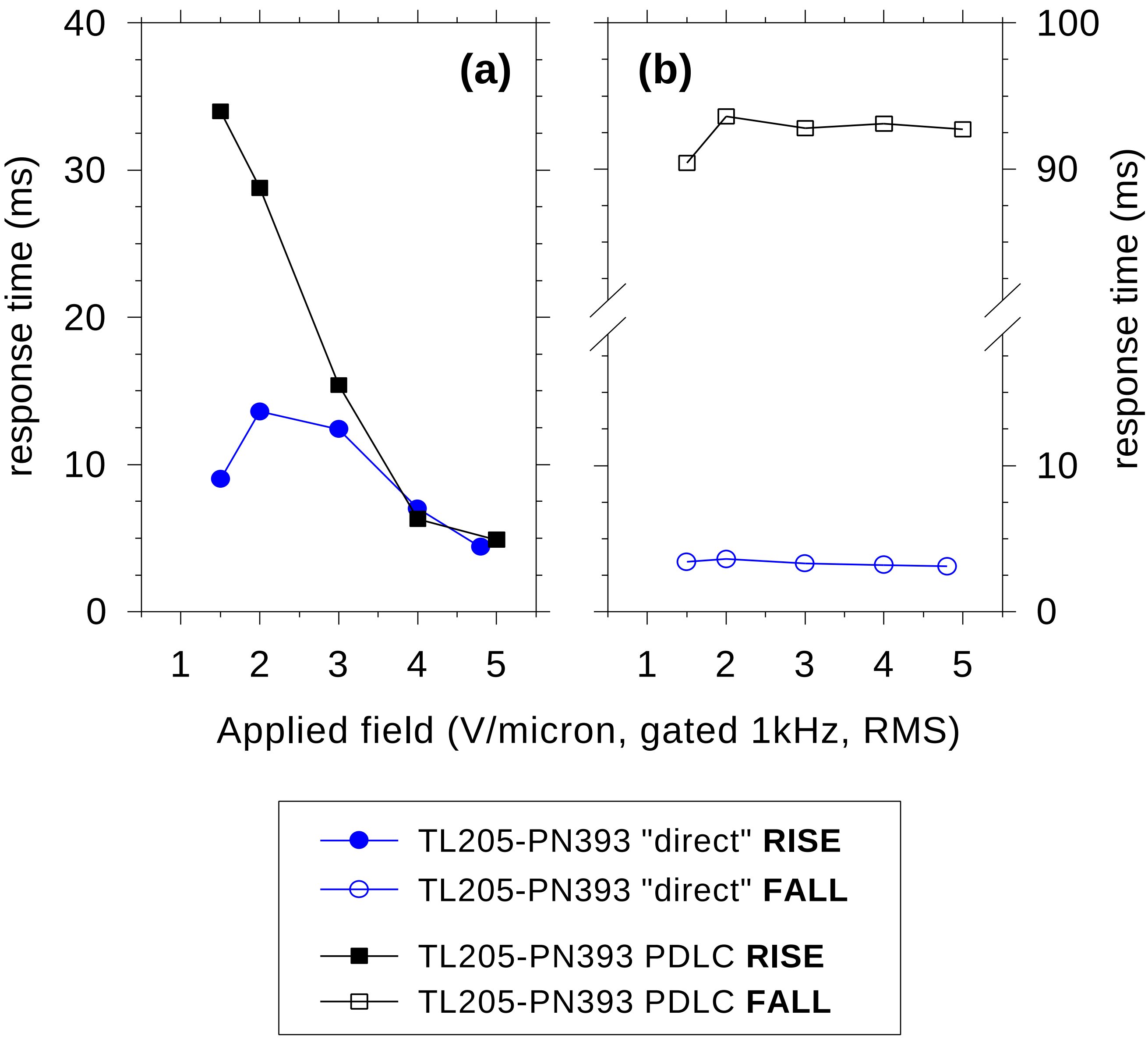
Comparison of (a) Rise and (b) Fall Times

1.6 micron templated "direct" PN393-TL205 sample

and

80.3% TL205 / 19.7% PN393 PDLC

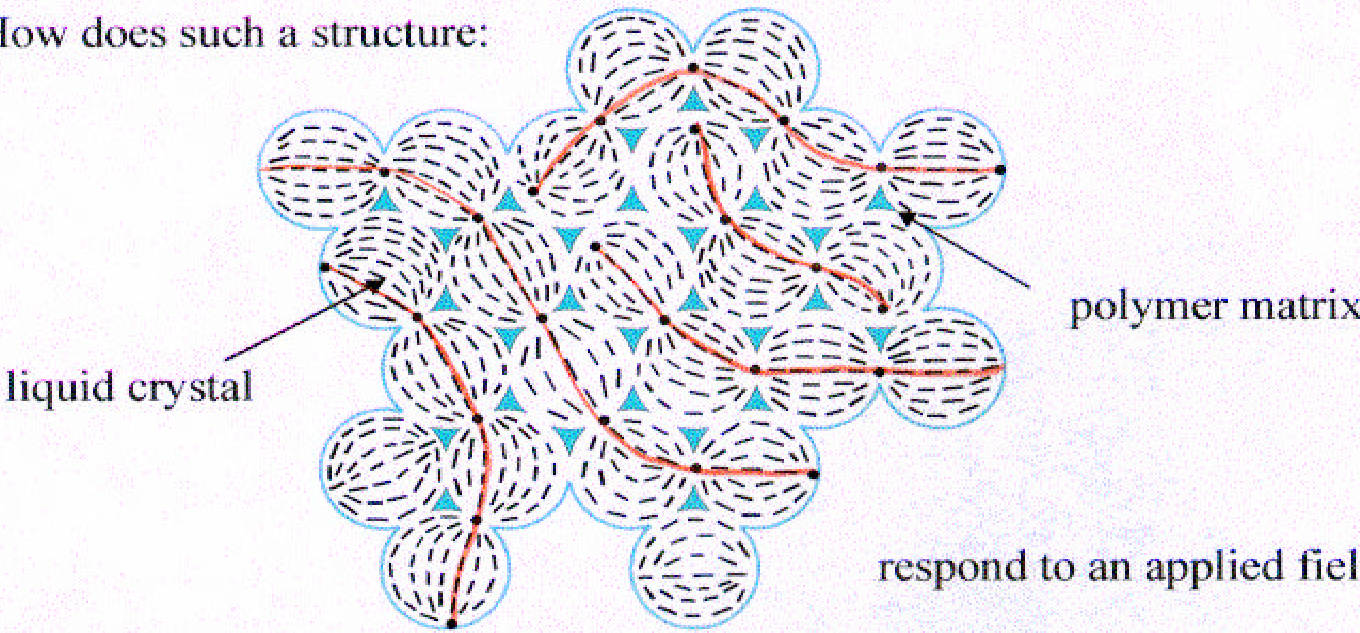
(droplet size ~2 microns)



Situation in connected network of spherical domains may create more complicated switching situation...

e.g.

How does such a structure:



respond to an applied field?

- each spherical liquid-crystal domain is connected to 12 nearest neighbors...
- a distribution of sizes of the interconnected droplet regions throughout the overall sample
- possibility for degenerate energies between different arrangements in the network of director defects
- role of distorted cavity shapes in pinning preferred boojum placements within typical PDLCs replaced here by defects in the connectivity of the liquid-crystal cavities ?

Summary

1) **Demonstrated electrically switchable, 3-D transmission Bragg diffraction from liquid-crystal in colloid-templated structures**

- **possible alternative basis for switching, beam steering, beam splitting applications**

2) Comparisons: transmission response and switching times

- "direct" templated samples
- PDLCs
- LC in colloid crystal interstitial spaces

- **"direct" sample results disagree with expectations based on conventional PDLC behavior**
- **role of connected liquid-crystal domains**

Some Future Research Ideas

1) utilize colloid crystals made with **templating methods**;
   explore wider range of **colloid sizes** (e.g., 0.5 μm size)

2) alter **liquid-crystal anchoring** conditions

3) role of LC domain connectivity: modeling;
   vary **degree of connectivity** experimentally

4) **other crystal symmetries** for polymer templates:
   e.g., simple cubic; is bistable switching possible?