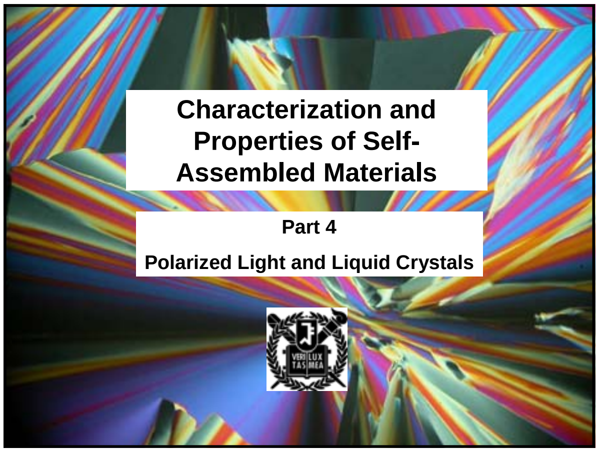
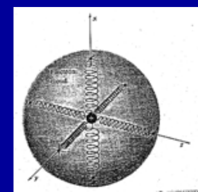
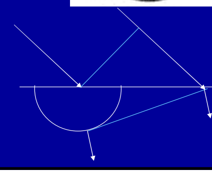


BIREFRINGENCE IN OPTICALLY ANISOTROPIC MEDIA

- Light propagates through absorptions and re-emissions on bound electrons
- Each electron re-emits a spherical wave (isotropic materials)
- envelope of all spherical waves reconstitute the plane wave
- explains:
  - refraction
  - diffraction

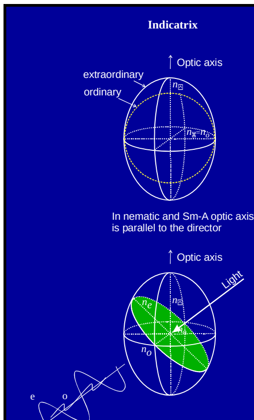




BIREFRINGENCE IN OPTICALLY ANISOTROPIC MEDIA

- Isotropic: Refractive index $n = c/v$
- Anisotropic: Light is split in two components, "ordinary" and "extraordinary" ray
- Electric vectors $\mathbf{E}_o$ and $\mathbf{E}_e$ of the two rays are polarized perpendicular to each other.
- They have different refractive indices, n_o and n_e:

  $v_o = c/n_o$
  $v_e = c/n_e$



Indicatrix = ellipsoid describing angular dependence of n_e.

(n_o does not depend on beam direction).

Cross-section ⊥ to light ray is an ellipse.

Electric vectors $\mathbf{E}_e$ and $\mathbf{E}_o$ are ∥ to its principal axes.

n_e and n_o are given by the lengths of its principal axes.

Optic axis = the axis ⊥ to which the section through indicatrix is circular.

In uniaxial systems unique axis = "optic axis".

Light propagating along optic axis is not split.

(To the light propagating along optic axis, material appears isotropic).

Birefringence of a material

parallel to optic axis $n_{\parallel} = c/v_{\parallel}$

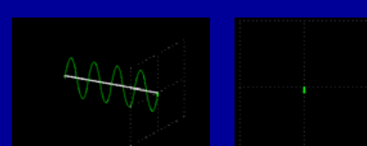
perpendicular to optic axis $n_{\perp} = c/v_{\perp} = n_o$

Birefringence of material

$\Delta n = n_{\parallel} - n_{\perp}$

- If $n_{\parallel} > n_{\perp}$ - positive birefringence (prolate ellipsoid)
- If $n_{\parallel} < n_{\perp}$ - negative birefringence (oblate ellipsoid)

Linearly (plane) polarized light (vertical)



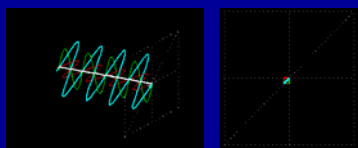
oscilation of electric field vector

animation by András Szilágyi (szia@enzim.hu)
http://www.enzim.hu/~szia/cddemo/edemo0.htm

Linearly (plane) polarized light (tilted)

Polarizer rotated by 45 deg to projection of optic axis.

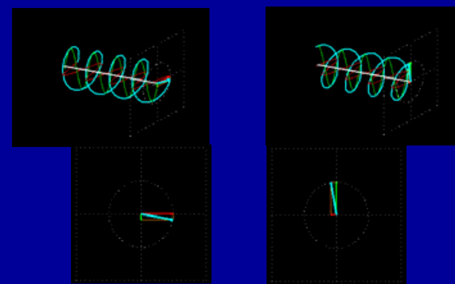
Horizontal and vertical components oscilate in phase ($\Gamma = 0$)



oscilation of electric field vector

Circularly polarized light

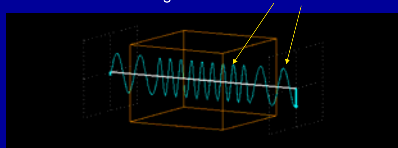
angle between polarizer and optic axis = 45 º, $\Gamma = \pm 90^o$



left CP light | right CP light
$\Gamma = 90^o$ | $\Gamma = -90^o$

Linearly (plane) polarized light <u>retarded</u> while passing through isotropic medium (refraction)

Note that wavelength shrinks! *v = c/n*

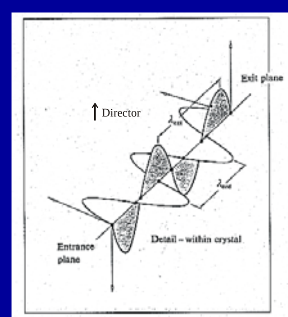


frequency and energy of photons remain constant:

ν = const

E = h ν = const

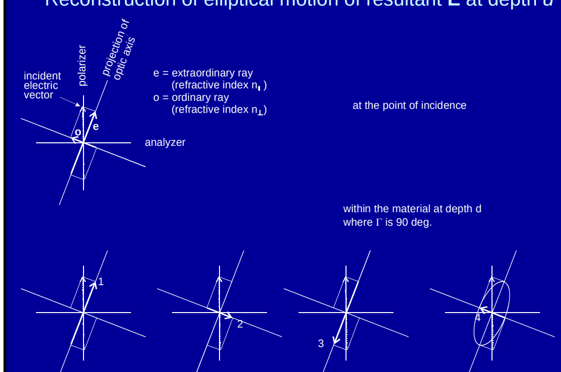
Propagation of *e* and *o* waves theough anisotropic material



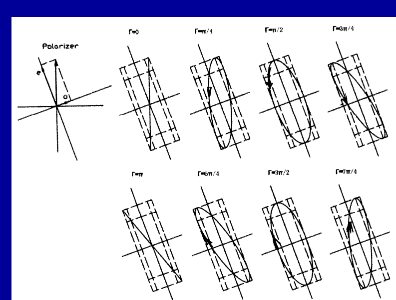
- The two beams propagate through material at different speeds, corresponding to v_o and v_e.
- At any given point along beampath resultant E-vector generally describes elliptical motion (elliptically polarized light). In special cases linearly or circularly polarized.
- phase difference between the two components at depth *d*:

$$\Gamma = \frac{2\pi}{\lambda}(n_e - n_o)d$$

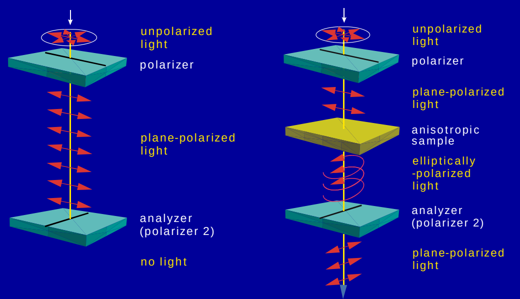
Reconstruction of elliptical motion of resultant **E** at depth *d*



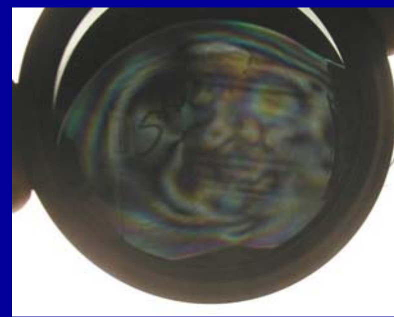
Elliptically polarized light at different depths in sample



Crossed polarizers



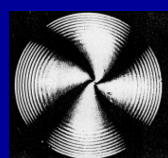
Unannealed glass between crossed polarizers



Three Causes of Extinction of Light Passing through Anisotropic Medium between Crossed Polarizers

1.) *Thickness* is such that at the exit the phase difference $\Gamma = 2k\pi$ (path difference = $k\lambda$).

- Exiting light is linearly polarized parallel to **P**, i.e. is in the same state as at the point of incidence ("***coincidental extinction***").
- For this type of extinction light must be *monochromatic*.
- If white light is used, this type of extinction produces ***colour.***

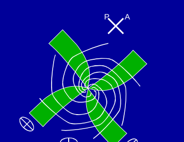


Nematic droplet between crossed polarizers.
Black concentric rings are where $\Gamma = k^*2\pi$

Three Causes of Extinction of Light Passing through Anisotropic Medium between Crossed Polarizers

2.) One of the principal axes of the elliptical section through the indicatrix is *parallel* to polarizer.
(projection of unique axis is ∥ or ⊥ to **P**).

- Incident light is not split (intensity of one component = 0).
  - → light remains plane-polarized throughout the sample and is absorbed by analyser.
- Responsible for
  - black "propeller blades" in nematic droplet
  - Maltese cross in polymer spherulites.



Disclination in nematic drop

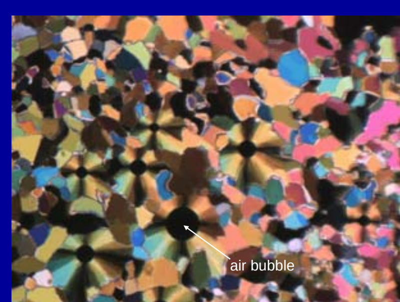
Ringed polymer spherulites

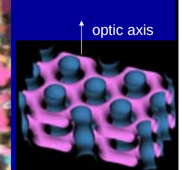
Three Causes of Extinction of Light Passing through Anisotropic Medium between Crossed Polarizers

3.) Sample is viewed along the optic axis.

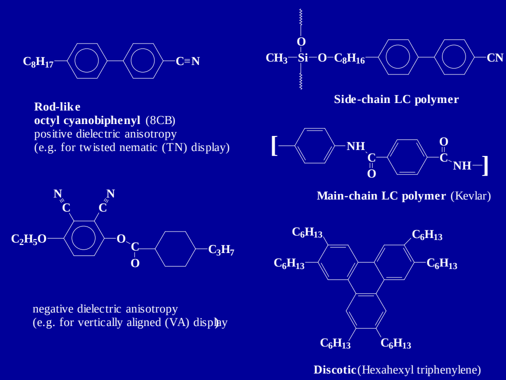
- Cross-section through the indicatrix is circular → Any two components of light propagate with same velocity.
- Light leaves the sample with same polarization as on entry (i.e. ∥ to P).
- Responsible for
  - concentric dark rings in banded spherulites (light parallel to polymer chains).
  - dark regions of ***homeotropic*** alignment In liquid crystals (i.e. where the director is normal to the glass slide).

Mosaic texture – rotating the sample between crossed polarizers

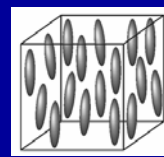




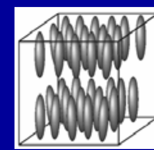
Examples of Liquid Crystal Compounds (Mesogens)



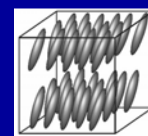
Common Liquid Crystal Phases



Nematic



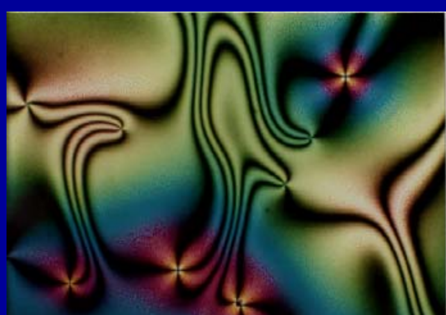
Smectic A



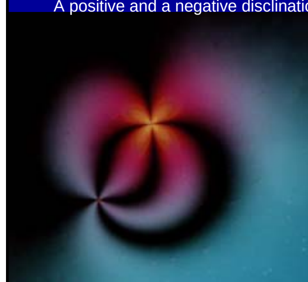
Smectic C

Recommended book:
Collings, Peter J., "Liquid crystals: nature's delicate phase of matter"
(2nd ed.: Collings and Hird)

Schlieren texture – Nematic LC



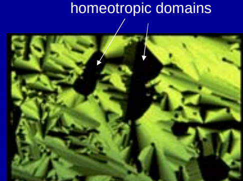
A positive and a negative disclination



Director lines made visible by bubble decoration

"Focal conic" texture of a smectic-A LC

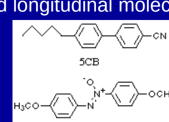
homeotropic domains



How to design a LCD?

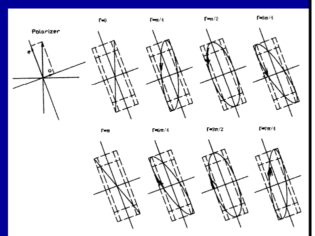
- Use crossed polarizers and switch between planar and homeotropic?

- Use electric field to enforce homeotropic?
  - need longitudinal molecular dipole: -CN, -F, $-NO_2$
  - e.g.

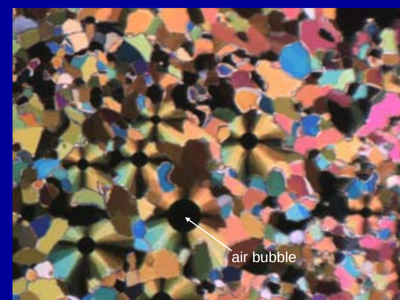


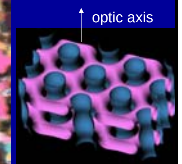
- Need transparent electrodes?
  - ITO (Indium Tin Oxide) evaporated on glass.
- Avoid Schlieren texture?
  - rub glass surface.
- Maximise brightness?
  - make thickness *d* such that
    $$\Gamma = \frac{2\pi}{\lambda}(n_e - n_o)d = \pi$$
  - Make rubbing direction 45º to polarizer.

➔ 100% light intensity should exit through 2nd polarizer in the <u>off</u> state.



Mosaic texture – rotating the sample between crossed polarizers





- If rubbing direction (director) at 45º to polarizer, and
- thickness *d* such that

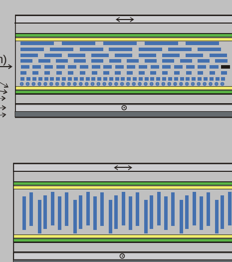
$$\Gamma = \frac{2\pi}{\lambda}(n_e - n_o)d = \pi$$

➔ 100% light intensity should exit through 2nd polarizer in the <u>off</u> state.

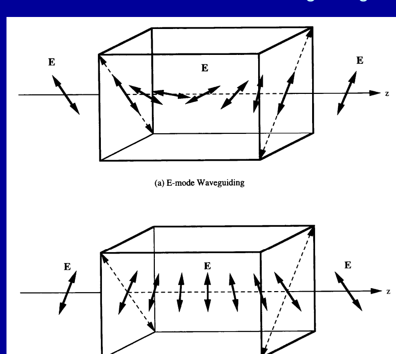
However, 2 problems:

1. light would have to be <u>*monochromatic*</u> and <u>*d* very precise</u> – impractical
2. low contrast - darkness would <u>depend on voltage</u>, or else <u>high voltage</u> needed to make molecules stand up fully (true homeotropic)

TN cell ("normally white") – cross-section



E-mode and O-mode waveguiding in a TN cell

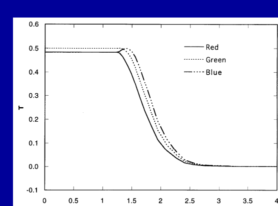


E-mode (polarizer parallel to director)

O-mode (polarizer normal to director)

Q: How would you construct a "normally black" cell?

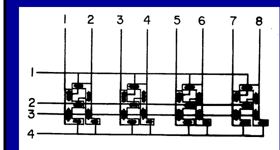
% Transmission *vs* Voltage in a 90 deg TN Cell

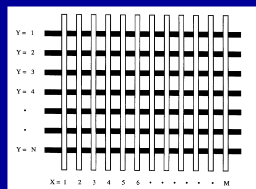


Light transmission through a "normally white" TN LCD as a function of applied voltage

Abrupt drop in light transmission - ***Fredericksz transition*** (molecular orientation turns from planar to homeotropic).

Addressing Pixels - Multiplexing





Watches, calculators, mobile phones

Electrodes specially shaped.
8 electrodes sufficient for all digits + decimal point.

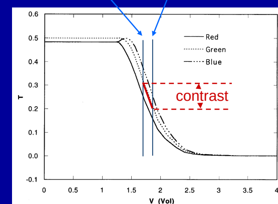
Passive matrix display

Fine mesh of ITO strip electrodes
- rows – bottom electrodes
- columns – top electrodes

Entire display is scanned 25 times per second.
Between pulses switched state relies on persistence

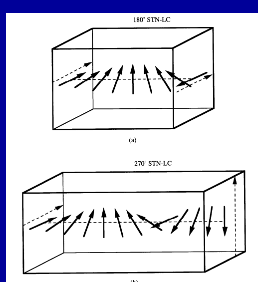
Operating window for a scanned passive matrix TN LCD

average OFF voltage   average ON voltage



How to improve contrast?
How to make a fast response LCD?

Supertwisted Nematic (STN) Display



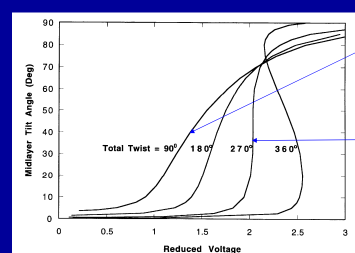
STN gives:

- sharper Fredericksz transition
- wider viewing angle

How does the director know it should twist by 180^o or 270^o?

Use chiral compound.

Midlayer tilt angle *vs* voltage for TN and STN cells with different twist angles



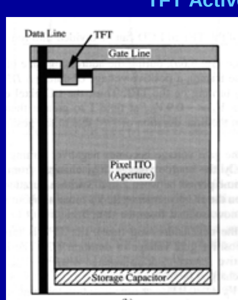
In the ON state of TN molecules are not perfectly oriented normal to glass surface.

This degrades contrast.

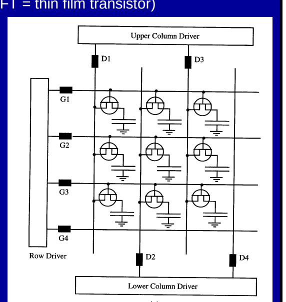
The steepest change in tilt with voltage – 270 deg cell.

Ideal: maximum change in contrast for minimum change in V. Important in multiplexing of large displays.

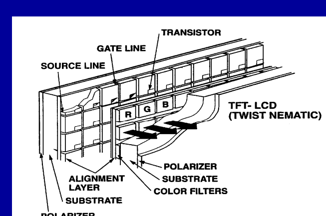
TFT Active Matrix Display



(TFT = thin film transistor)



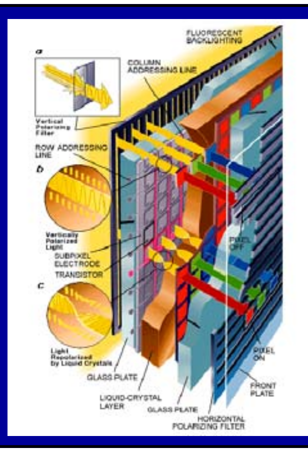
1 pixel = a complete TN LCD
electric pulse triggers TFT to switch
TFT remains switched on until next pulse



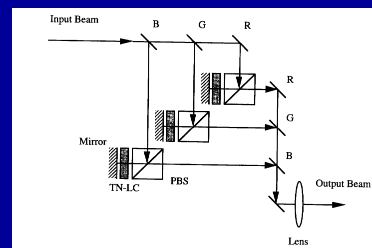
TFT active matrix display - layout

Disadvantages: High cost of production
Higher energy consumption than TN or STN

TFT active matrix display



LCD Projector

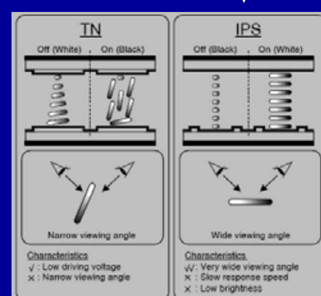


LCD based on in-plane rotation of molecules by 45^0 ??

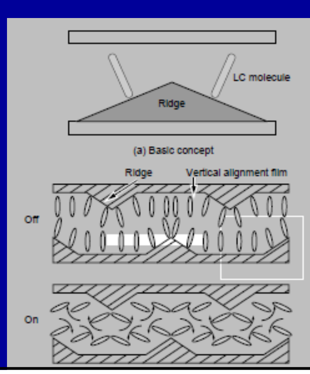
polarizers

bright
dark

Latest nematic displays: In-Plane Switching



Vertically aligned nematic (VAN) LCD

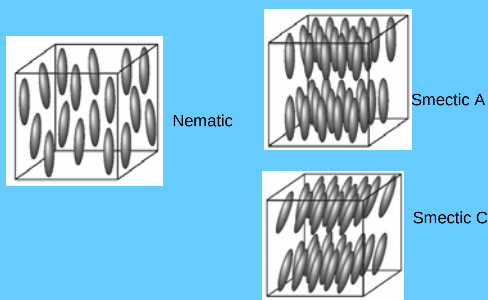


How to effect in-plane rotation with electric field
⊥ to plane of display??

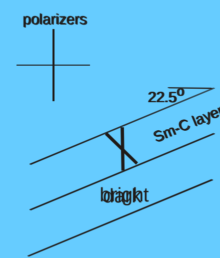
polarizers

bright
dark

Common Liquid Crystal Phases

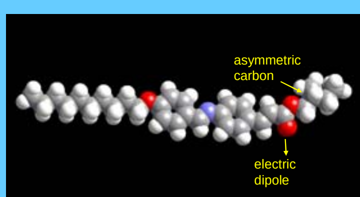


Use Smectic-C phase and change tilt direction



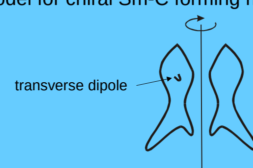
- How to rotate molecules ***in plane*** by applying electric field ***normal*** to glass.

➔ use ***chiral*** molecules with ***transverse*** dipole



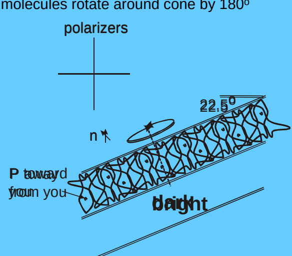
"Chiral Fish"

- 1 fin only - no mirror plane
- model for chiral Sm-C forming molecule

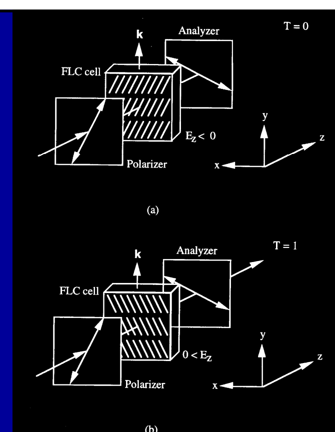


Ferroelectric Sm-C* switching

•ferroelectric LC – has net electric dipole ("spontaneous polarization")
•changing polarity of ITO electrodes
→ molecules rotate around cone by 180°



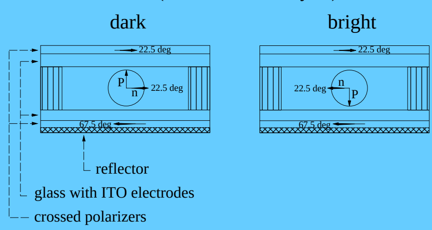
FLC display



dark

bright

SURFACE STABILIZED FERROELECTRIC LCD (SSFLCD)
(View normal to layers)

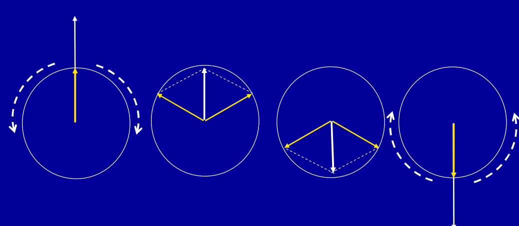


smectic layers in plane of paper

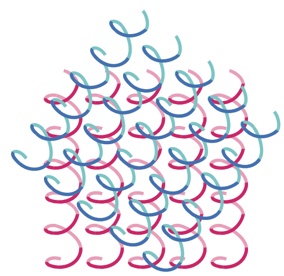
- **Advantages of FLC display:**
  - 100 times ***faster switching*** compared to TN
  - ***bistable*** – needs no power to maintain either of the states
  - ➔ suitable for ***large displays*** without active matrix
- **Disadvantages:**
  - problems with alignment defects
  - sensitive to pressure

Splitting linearly polarized light into circularly polarized components

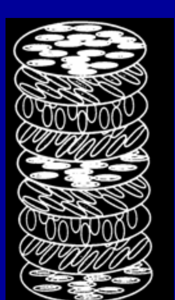
- Linearly polarized light can be split into a right and a left **circularly polarized component**

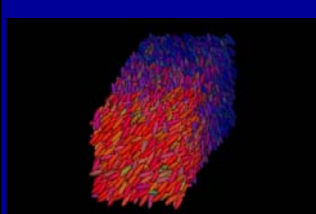


Chiral Nematic (Cholesteric) LC



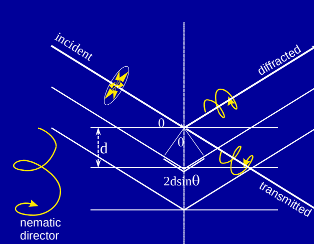
Chiral Nematic (Cholesteric) LC





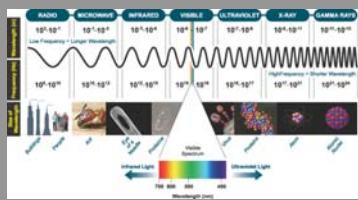
simulation

Light Diffraction on a Chiral Nematic ("Selective Reflection")



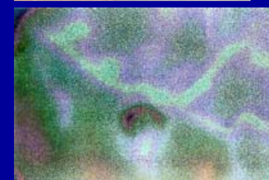
- Only selected wavelength diffracted
  - Other wavelengths unaffected
- Only one circularly polarized component diffracted
- **helical pitch changes with *T***
  - ➔ λ changes with *T*
  - "***thermochromic***" dye (LC thermometer)
- λ affected by viewing angle ("iridescent" colour)
  - but at near-normal incidence little change with angle

Electromagnetic spectrum



Application of Cholesterics

- LC thermometers
  - medical
  - thermal imaging of surface (engineering, medicine)
  - textiles
- Optical filters
- Potentially: photonic applications
  - e.g. lasers

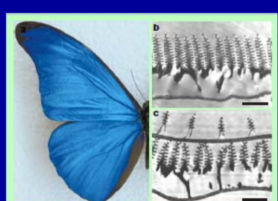


Thermochromic paint reveals tumour beneath the skin

Iridescent colours in nature

- chitin shell of beetles
- fish scales
- inside of shellfish shells
- butterfly wings
- also on some banknotes, cards etc.

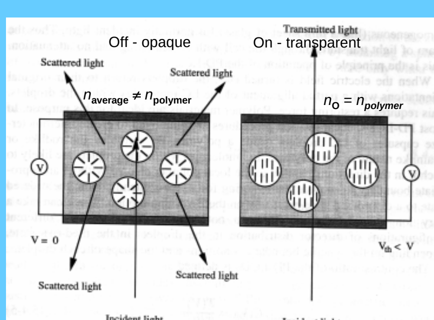
- **colour changes with viewing angle**



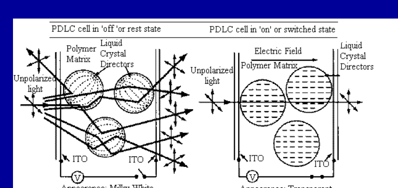
1.5 μm

Optical filters

Polymer Dispersed Liquid Crystals



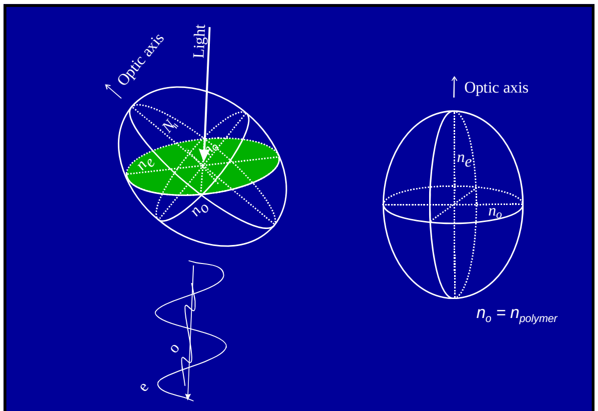
Polymer Dispersed Liquid Crystals



OFF
opaque, translucent

ON
transparent

(from D. Lundstroem and J. Ylbar, KTH, Stockholm)



- **Production of PDLC**
  - dissolve LC in monomer, add UV initiator, spread between ITO-coated glass plates
  - illuminate with UV → polymerize monomer
  - LC phase separates into droplets

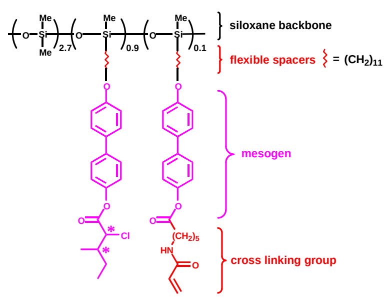
•Application

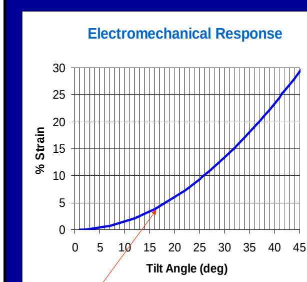
–privacy panels (offices, car windows)

–PDLC displays (shaped and multiplexed ITO electrodes)

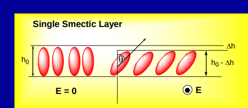
- •low resolution, usually large displays
- •no need for polarizers

Liquid Crystal Elastomers





Simple cosine model for electromechanical response as a function of induced smectic tilt angle, in electroclinic liquid crystal elastomers (ELCEs) coupled to an a.c. electric field (θ ∝ E).



Current state of the art
(R. Zentel, *Nature*, 2001, **410**, 447)

Electro-mechanical studies of monodomain LCE

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