3. Liquid Crystals (LCs)

3.1 Physical properties of liquid crystals

3.2 Molecular structure and phase of liquid crystals

3.3 Main application: liquid crystal displays

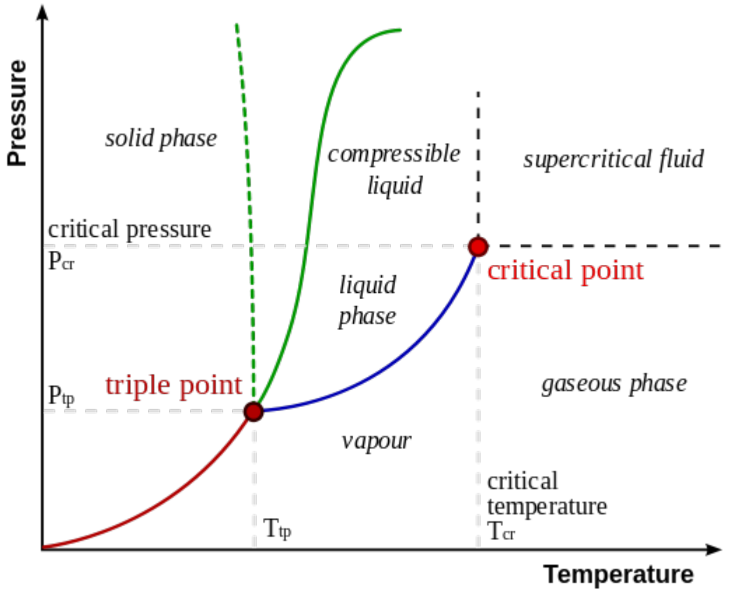
3.1 Physical properties of liquid crystals

4 Fundamental states

- Solid
  - Molecules occupy a specific position
  - Cohesion: metallic, covalent, ionic bonds
  - Crystalline solids: molecules are also oriented in a specific way
- Liquid
  - Can flow
  - Molecular forces bind molecules firmly but not rigidly
- Gas
  - Collection of isolated molecules
  - Interaction mainly by collision
- Plasma

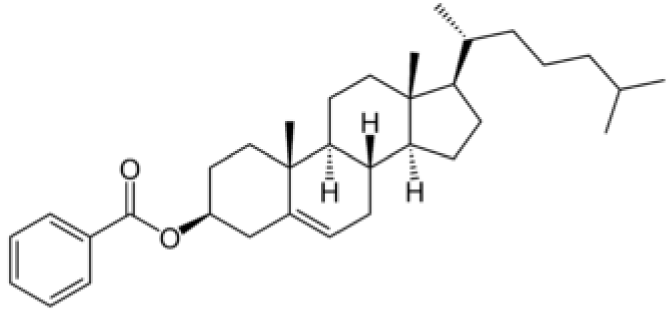
Phase diagram

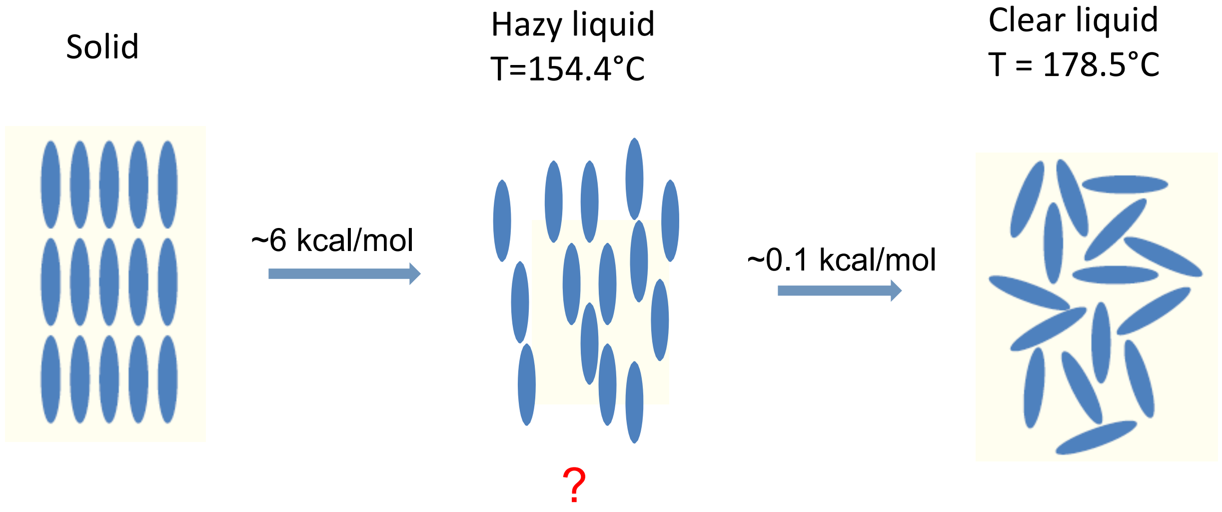
- Characteristics: changes with p, T



The discovery of liquid crystals

- Discovered in 1888
- Botanist Reinitzer observed 2 melting points in cholesteryl benzoate





New phase of matter: liquid crystal phase

From the latent heat point of view LCs are rather liquid like, from the optical point of view they behave like an anisotropic solid.

Microscope with heating stage and polarizing filters

(Otto Lehmann 1900)

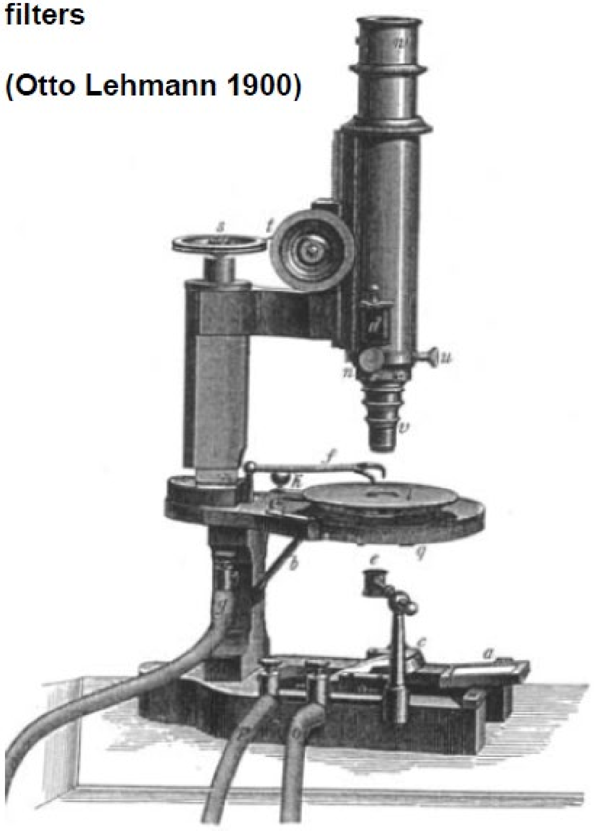


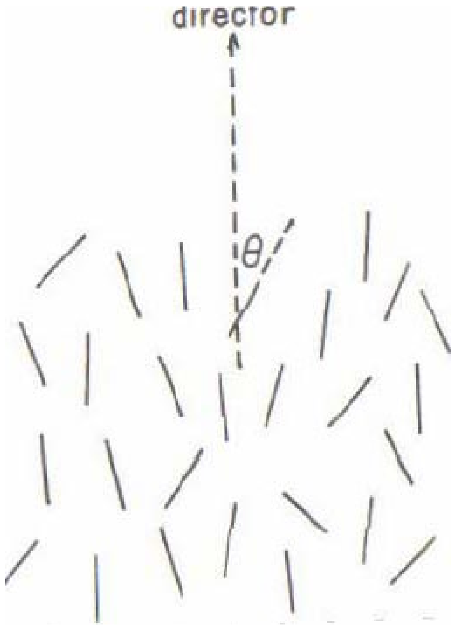
Fig. 20.

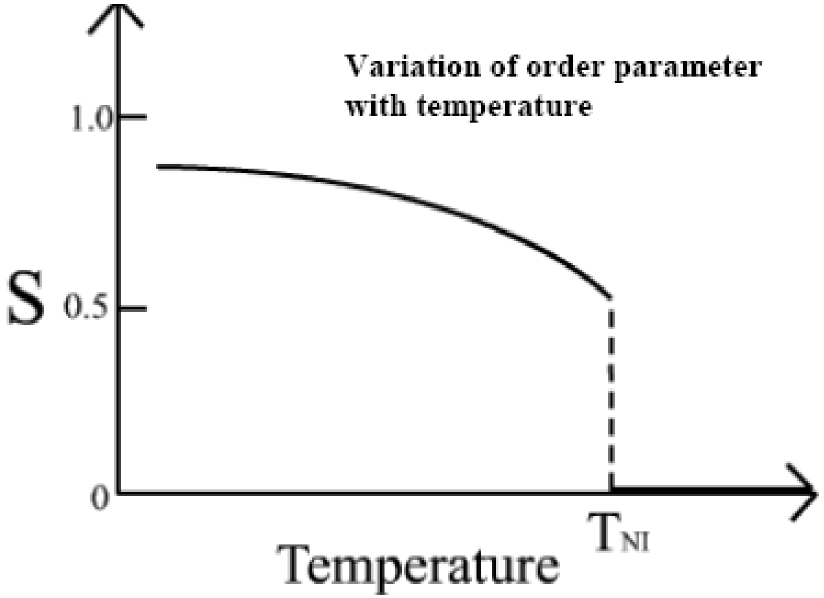
It was Otto Lehmann, who gave this phase the name "liquid crystals".

The order parameter

- Phase of matter between solid and liquid
  - No positional order (as in liquids)
  - Orientational order remains (as in solids)
  - Liquid like fluidity
  - Anisotropic materials properties, as in crystals

- Order Parameter:
  - Perfect crystal: S=1, isotropic liquid S=0 (θ=54.74°),
    All molecules are oriented in a horizontal plane (S= - 0.5)

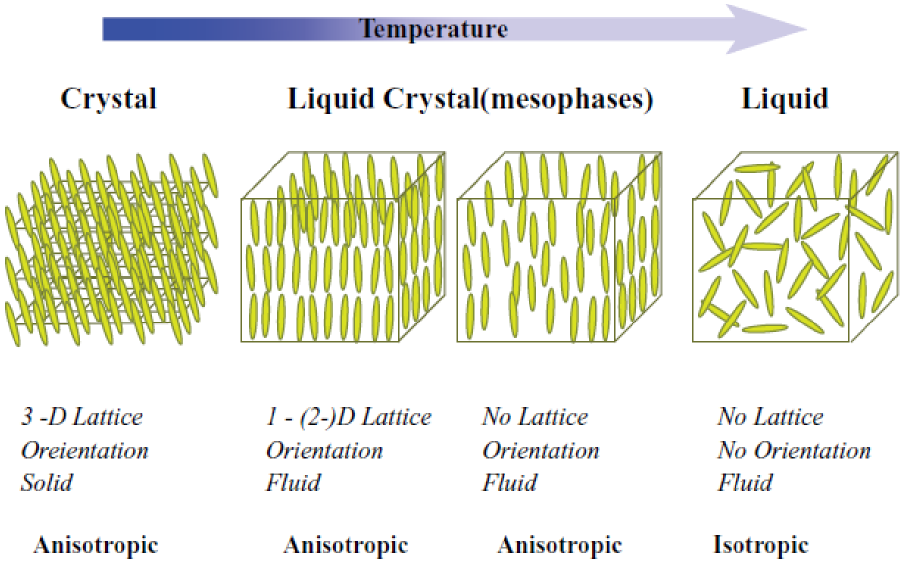




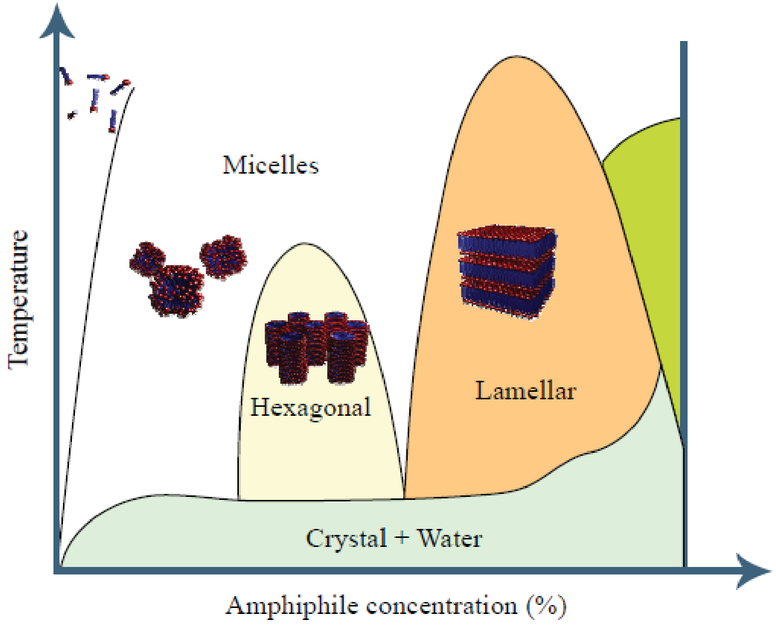
$$S = \frac{1}{2}\left\langle\left(3\cos^2\theta - 1\right)\right\rangle$$

Two types of Liquid Crystals

- Thermotropic (T dependent)
    - Only “mesogenic” constituents
    - Liquid crystalline phase in a T-window
    - Typical low molecular weight LCs



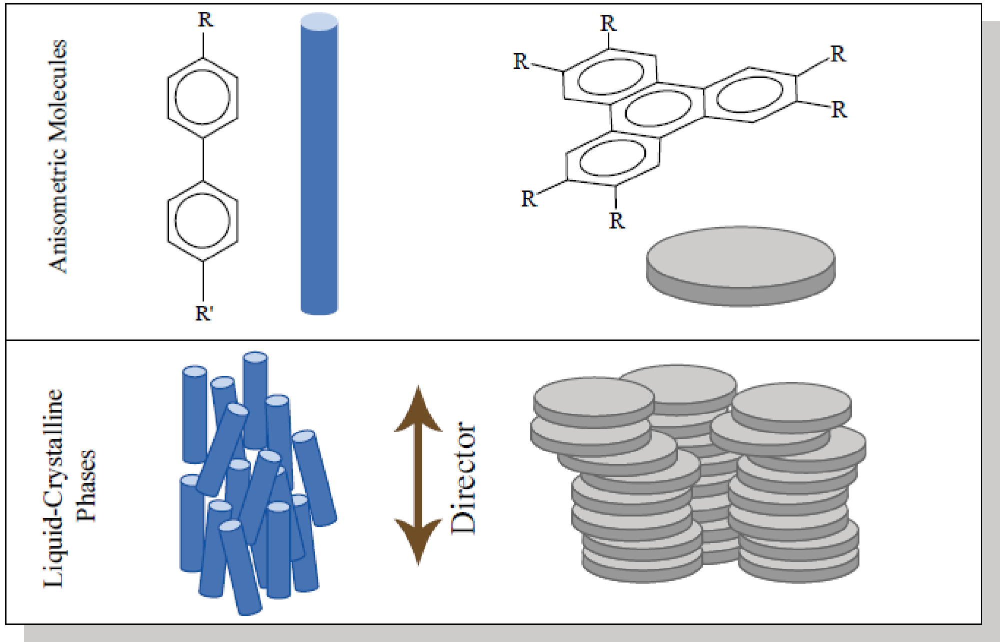
- Lyotropic (solvent conc. dependent)
    - “mesogenic” constituents in a solvent
    - Amphiphilics (soaps, …)



- LCs are classified by either their molecular or phase structure

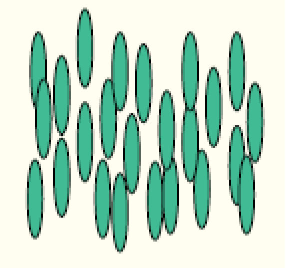
3.2 Molecular structure and phase of LCs

- Molecules that induce liquid crystallinity are called mesogens
- Key structural requirement for LCs is molecular shape anisotropy
  - More likely if the molecules have flat segments (e.g. benzene rings)
  - Strong dipoles and easily polarizable molecules seem important
  - Typical mesogens are needle like (calamitic) or disk-like (discotic)
  - Sanidic liquid crystals occur in lath like (board like) molecules

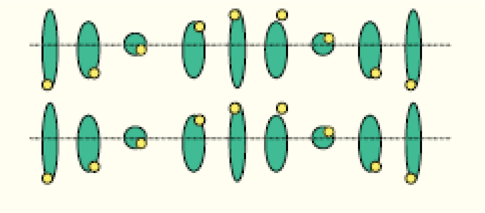


Liquid crystal phases

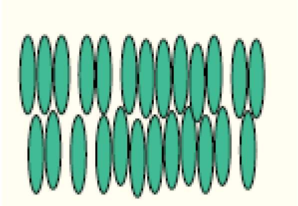
- Nematic (most common)
  - Long-range orientational order
  - No long-range order in position
  - Short-range translational order



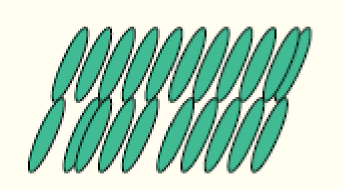
- Twisted nematic (cholesteric)
  - Long-range orientational order
  - No long-range order in position



- Smectic
  - Long-range orientational order
  - Long-range one-dimensional translational order

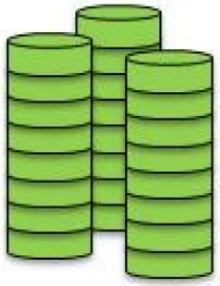


Smectic A



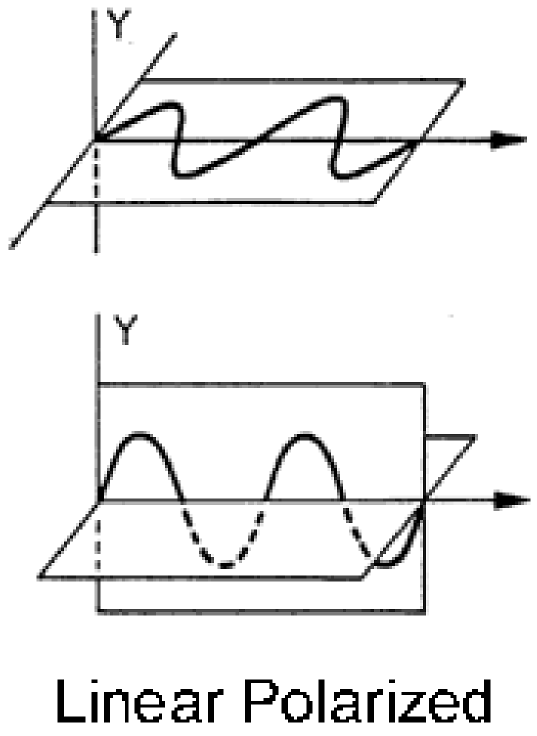
Smectic C

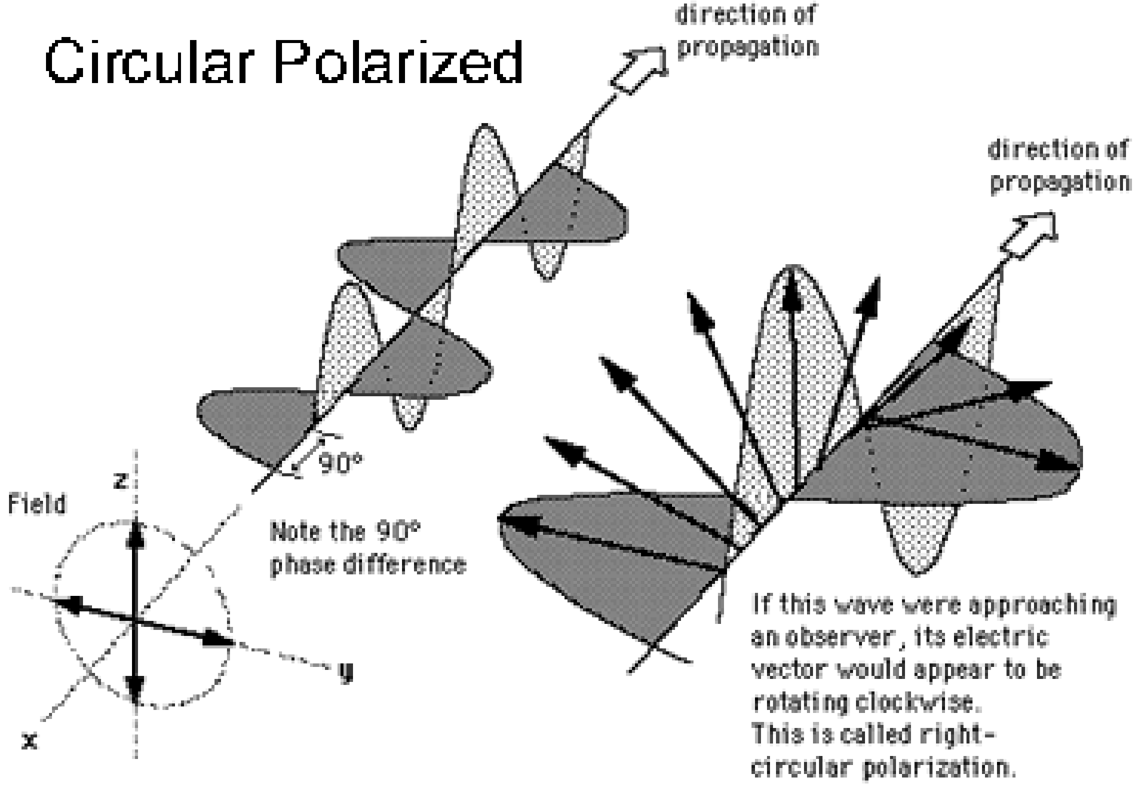
- Columnar
  - Long range orientatonal order
  - Various phases possible, e.g. 2D hexagonal packing of colunms



The polarization states of light

- Polarized light beam
- The light wave can be considered as a superposition of two light waves having parallel und perpendicular polarization
- Dephasing will cause a rotation of the electrical field vector. For a phase shift of $\pi/2$, circularly polarized light is obtained. In general elliptically polarized light is obtained.

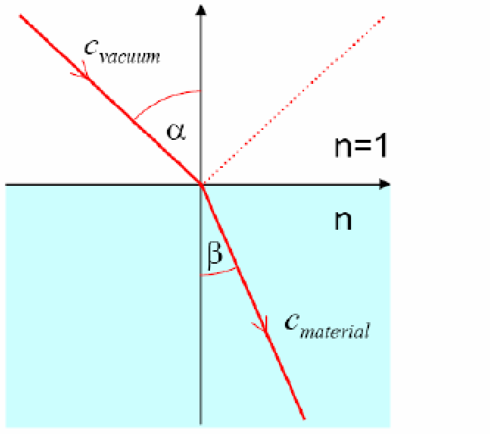


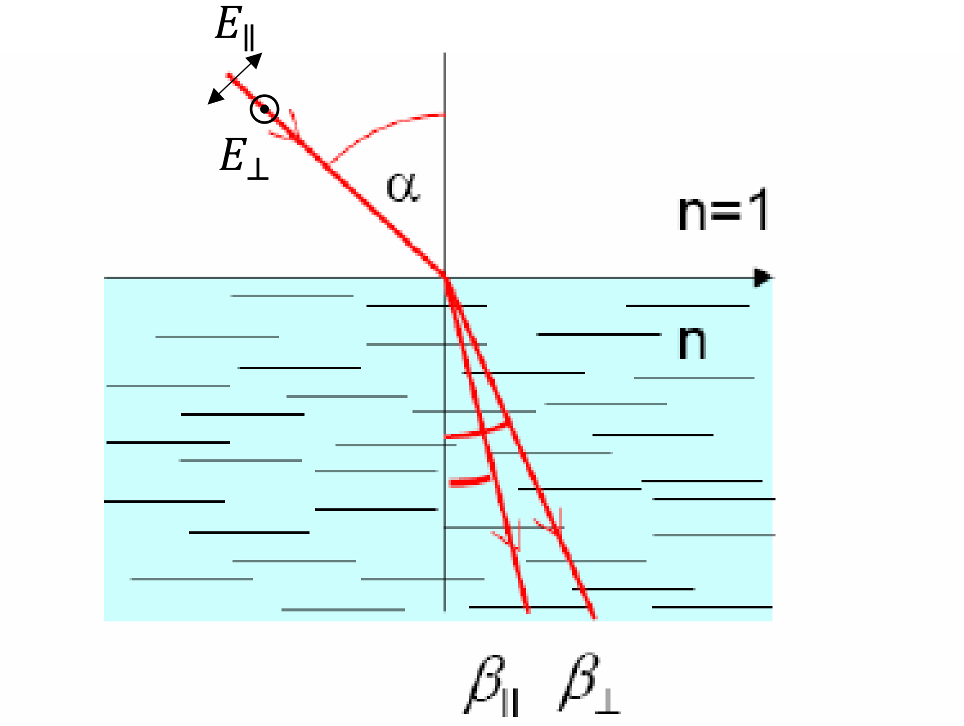


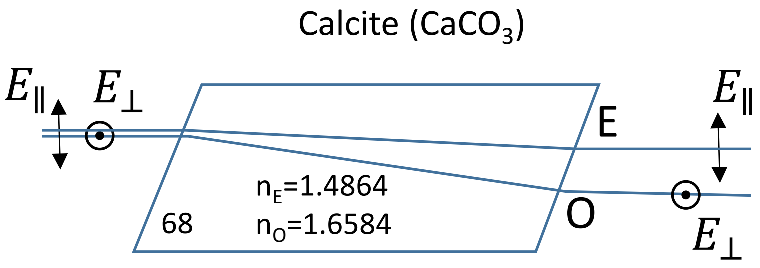
Birefringence (it is all about the polarization of light)

Snells law

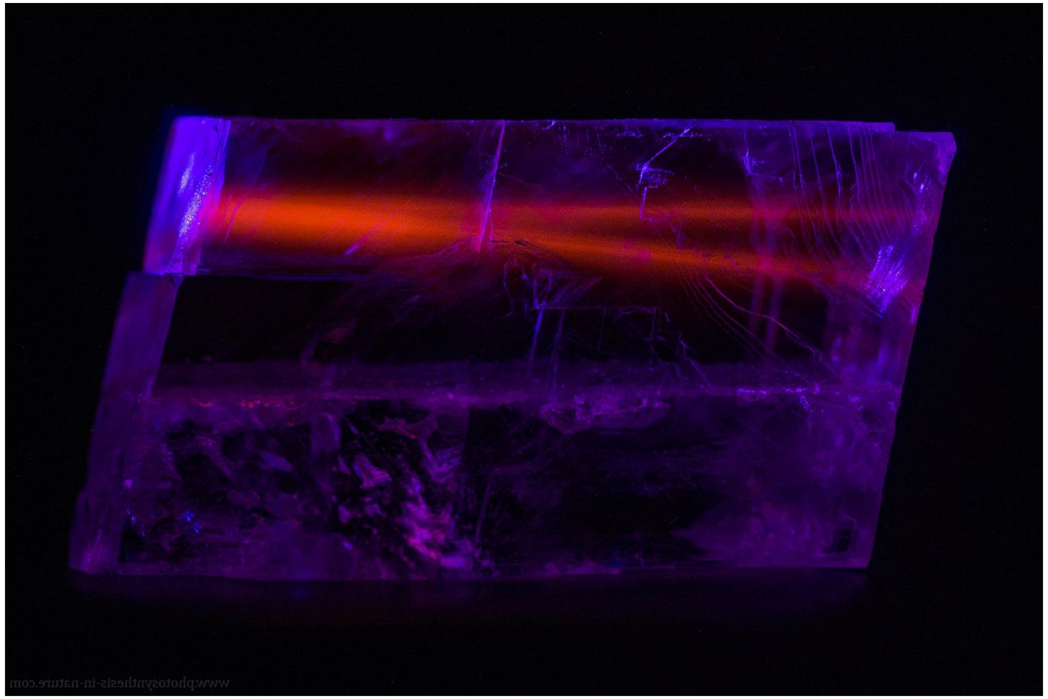
$$n = \frac{\sin\alpha}{\sin\beta} = \frac{c_{vacuum}}{c_{material}}$$







Birefringence through a calcite crystal. The optic axis lies in the plane.



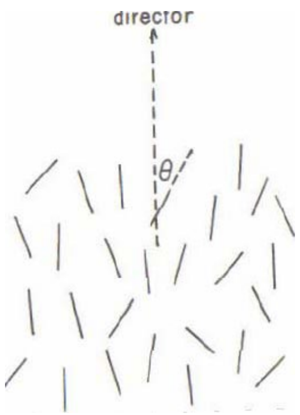
Nematic liquid crystals

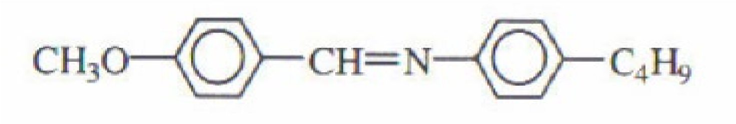
- Short-range positional order, but long range orientational order
- Rotational freedom around the long axis
- Free to move in the direction of the long axis
- Ten thousands of components are forming nematic structures

Order Parameter S:

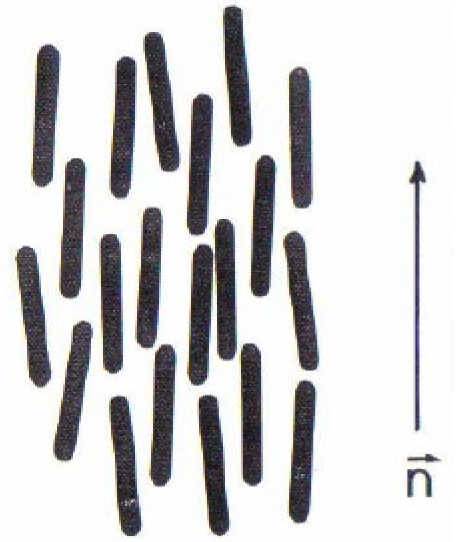
Perfect crystal: S=1 (or S= - 0.5),
isotropic liquid S=0 (θ=54.74°)

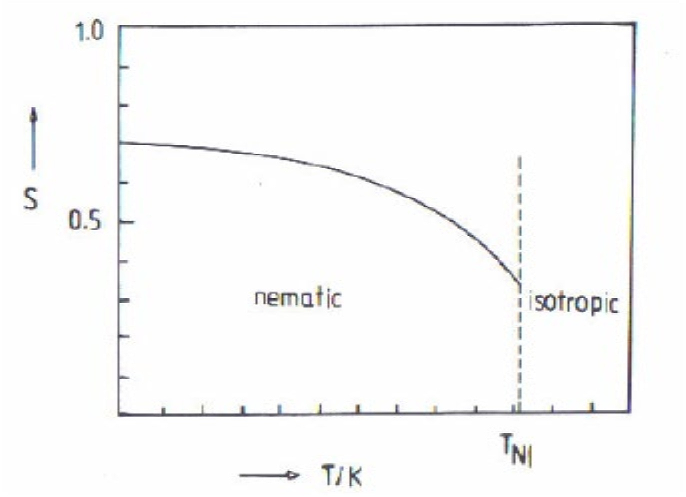
$$S = \tfrac{1}{2}\left\langle \left(3\cos^2\theta - 1\right)\right\rangle$$



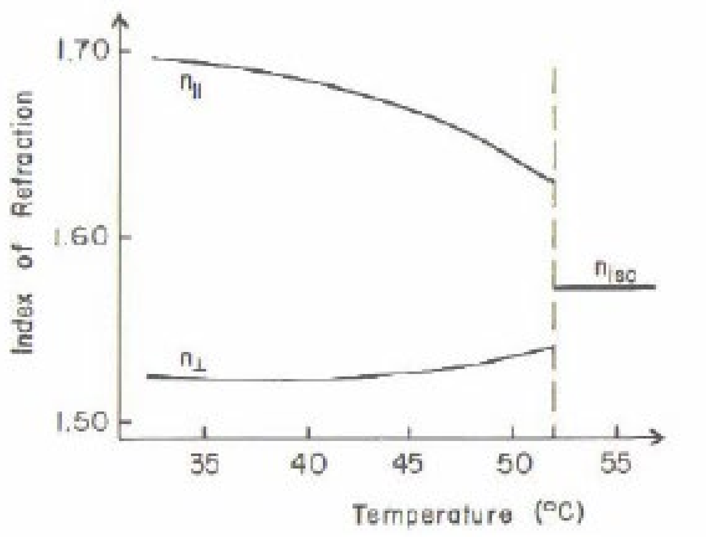


4-methoxybenzylidene-4'-n-butylaniline (MBBA)



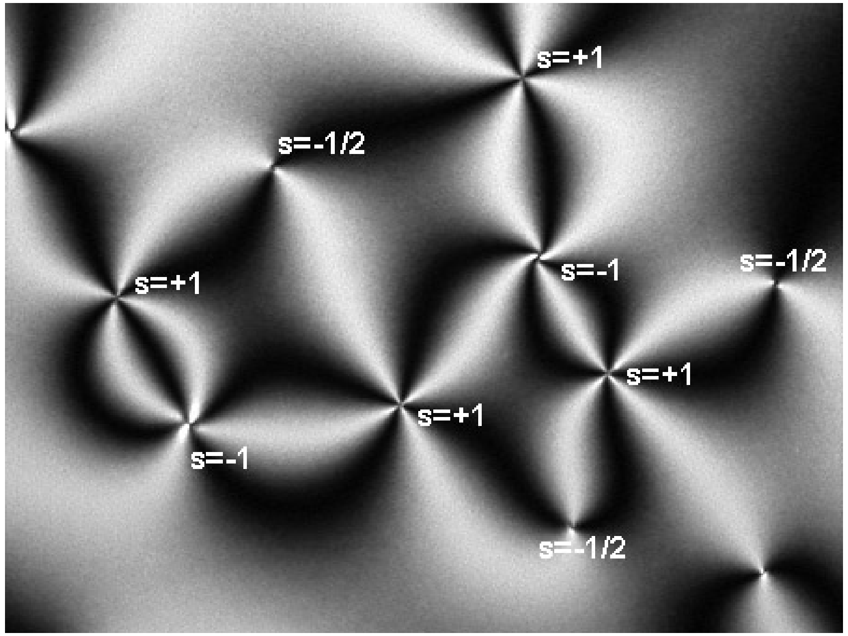


Light polarized parallel to director travels slower

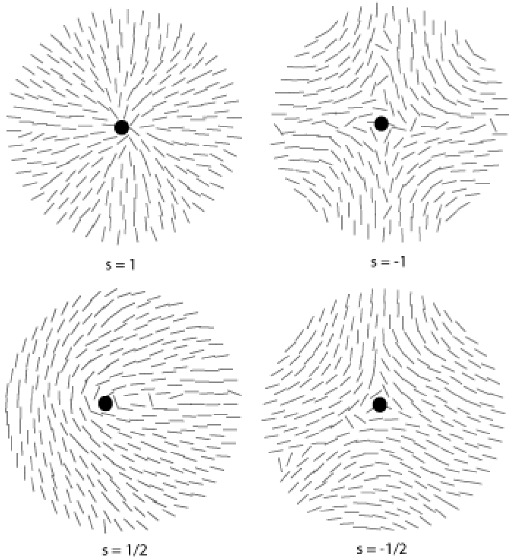


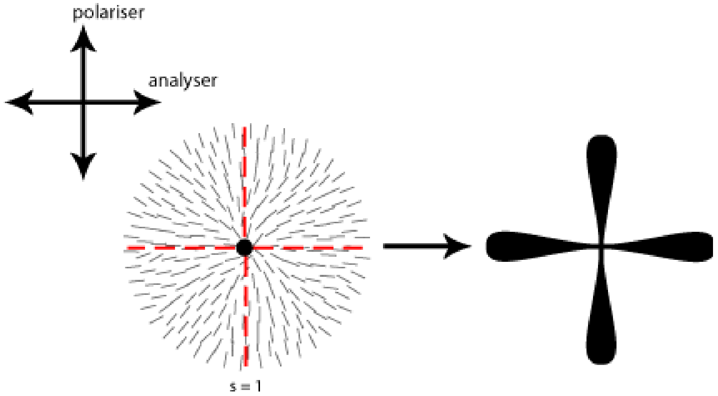
Optical properties of Nematic liquid crystals

- Schlieren texture under crossed polarizers
- Liquid crystals contain defects, they are called disclinations



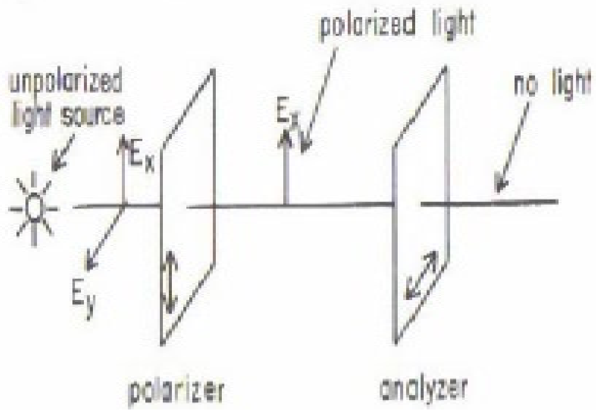
- Crystal appears bright due to the anisotropy of the refractive index (rotation if the polarization)
- Exceptions are where light is oriented parallel or perpendicular to the director





Microscopy under crossed polarizers (Otto Lehmann) was crucial to observe liquid crystals and its defects such as the Schlieren structure of nematic LCs.

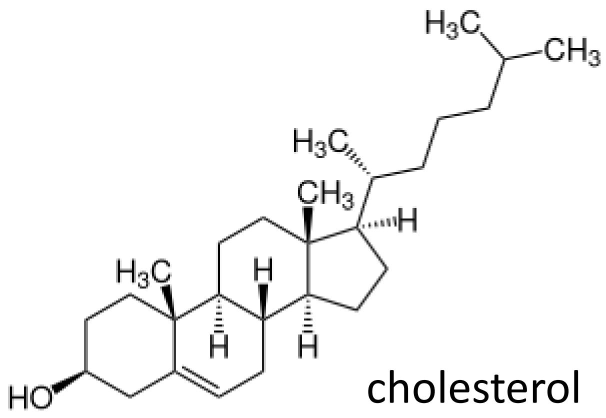
For understanding the rotation of polarization, we decompose the light beam's polarization in a component parallel and perpendicular to the LC director, respectively.



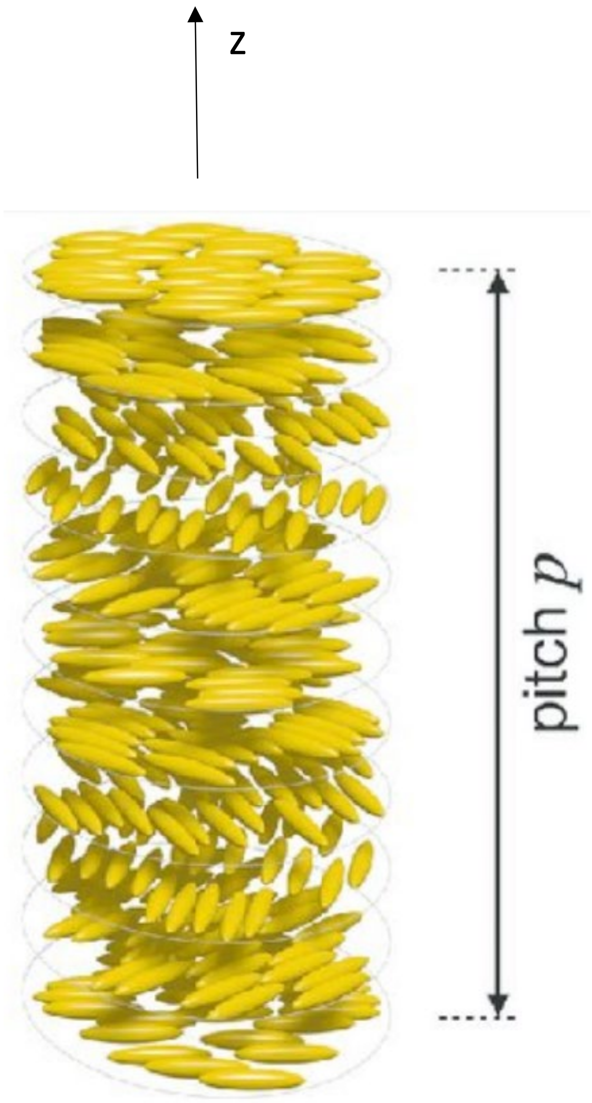
http://dept.kent.edu/spie/liquidcrystals/textures1.html
http://www.doitpoms.ac.uk

Cholesteric (chiral nematic) LCs

- Nematic alignment with a twist
- Also called chiral nematic
- First observed in derivatives of cholesterol
- The director rotates along an axis z



cholesterol



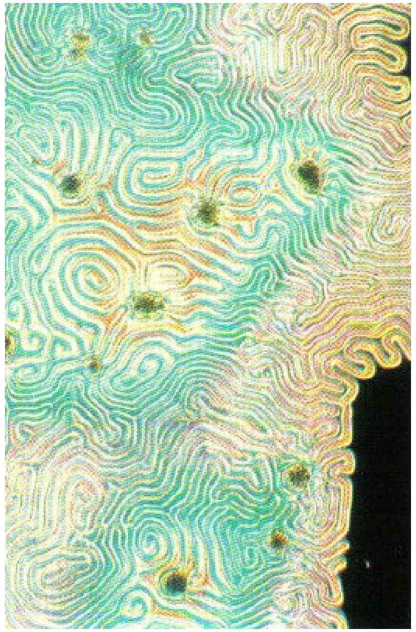
Optical properties

- Also turns the linear polarization of light propagating along the z-direction
- Because of their chirality, different from nematic LCs, Linearly polarized light this time is decomposed into right handed and left handed circularly polarized light to understand birefringence
- Now n_R and n_L differ, where n_R and n_L denote right and left circularly polarized light, respectively. Left and right circularly polarized light beams travel with different speeds and therefore the phase between these two beams is shifted when passing through the crystal.
- This is called optical activity
- Typically: 300° / mm
- If the wavelength is equal to the pitch P, a strong Bragg reflection occurs, accompanied with a divergence of the optical activity

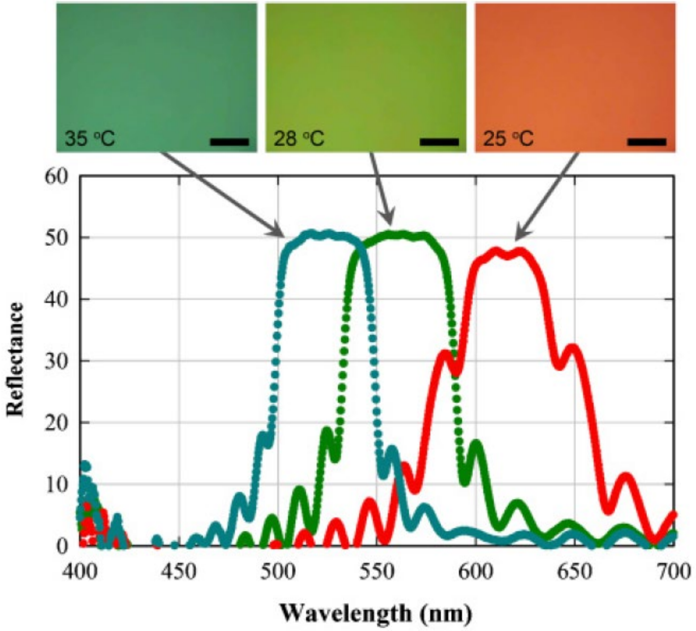
Applications of chiral nematic liquid crystals

Chiral nematic liquid crystals show a fingerprint structure in the natural form. The linewidth of this pattern are individual turns of the helix. The distance between two striations represent the pitch.

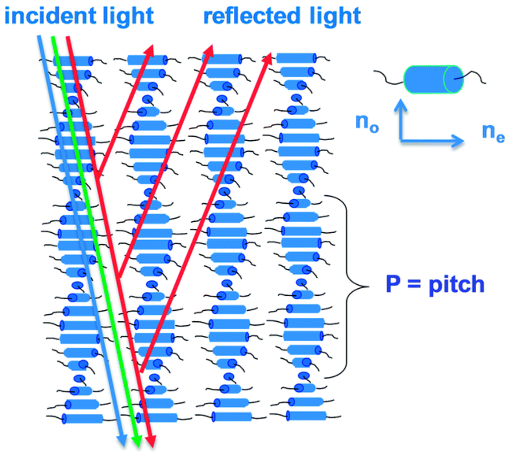
In a device, the helical axis is usually oriented perpendicular to the substrate and is sandwiched between to two electrodes or cover layers. When the pitch corresponds to the wavelength of the light (in the LC medium), strong reflection is observable.

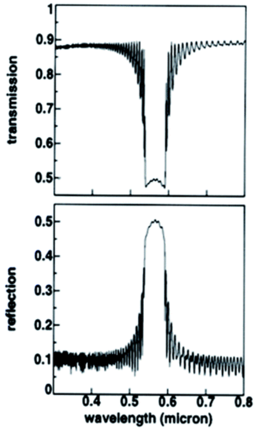


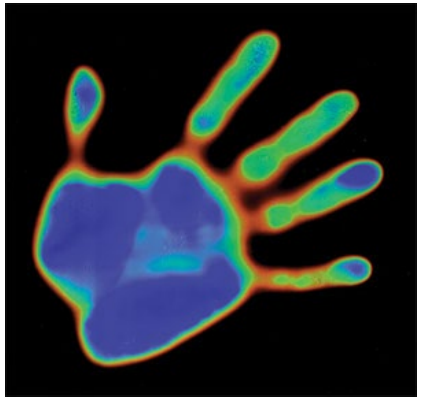
The pitch can depend on temperature

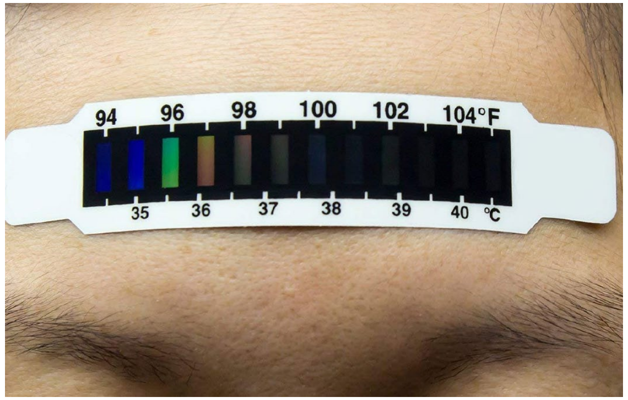


K.-S. Bae et al., Jpn. J. Appl. Phys. 49 (2010) 084103



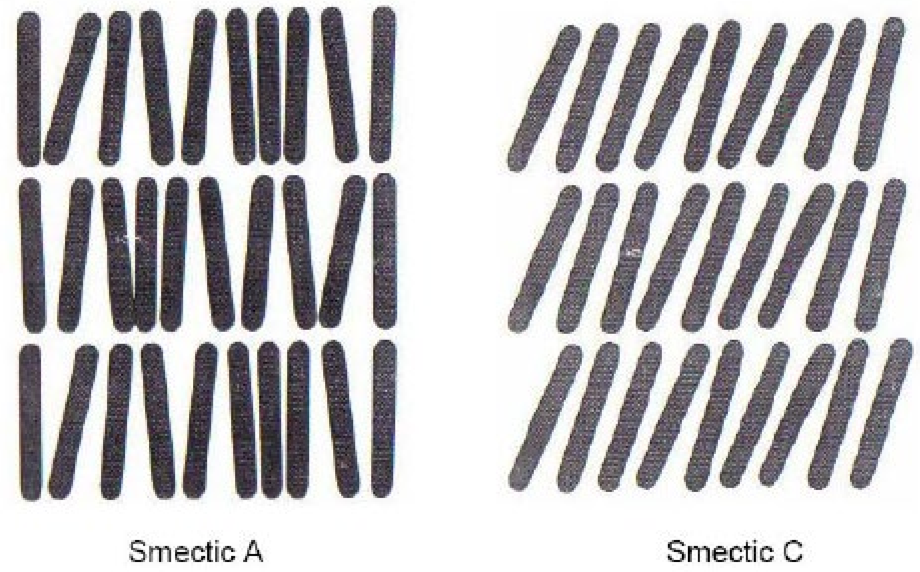


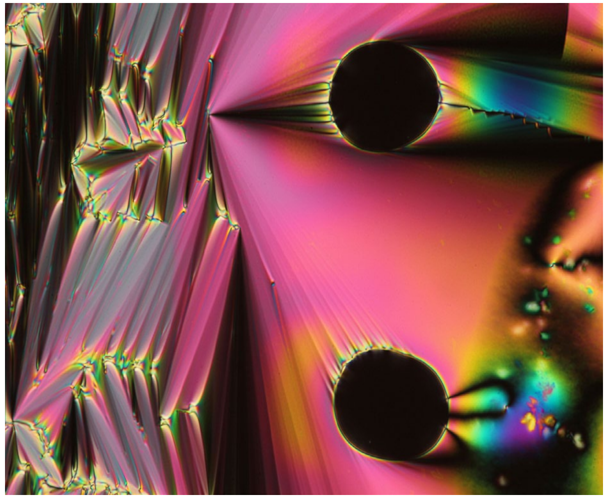


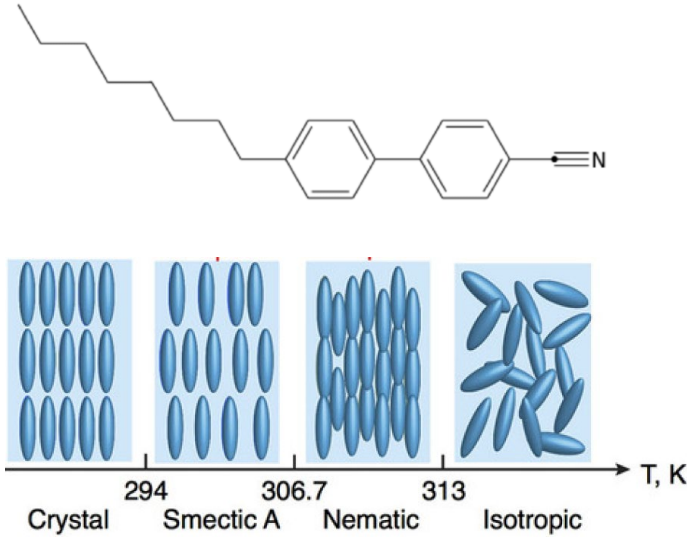


Smectic liquid crystals

- Smectic is greek for soap, first observed on ammonium and alkali salts
- Stratification: some correlation in position next to orientational ordering
- Many different types (A, B, C, ……, M), chronological sequence of their discovery
- Smectic A and Smectic C are phases without order in the layers
- Smectic C has a biaxial symmetry
- A number of substances exhibit nematic and smectic phases
- The lower the temperature, the greater the degree of order
- Basic structural information can be obtained from X-ray analysis







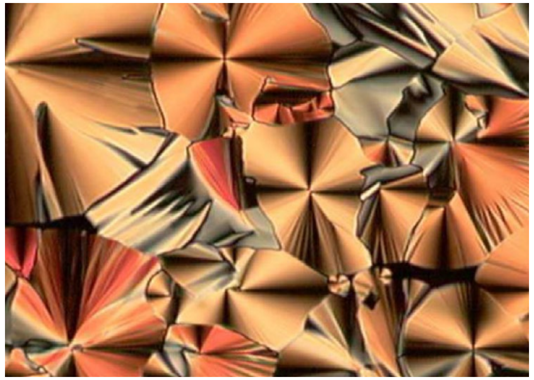
Bragg condition:

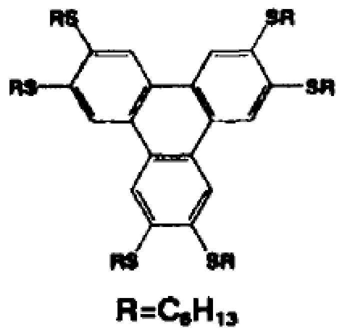
$$2d\ sin\theta = n \cdot \lambda$$

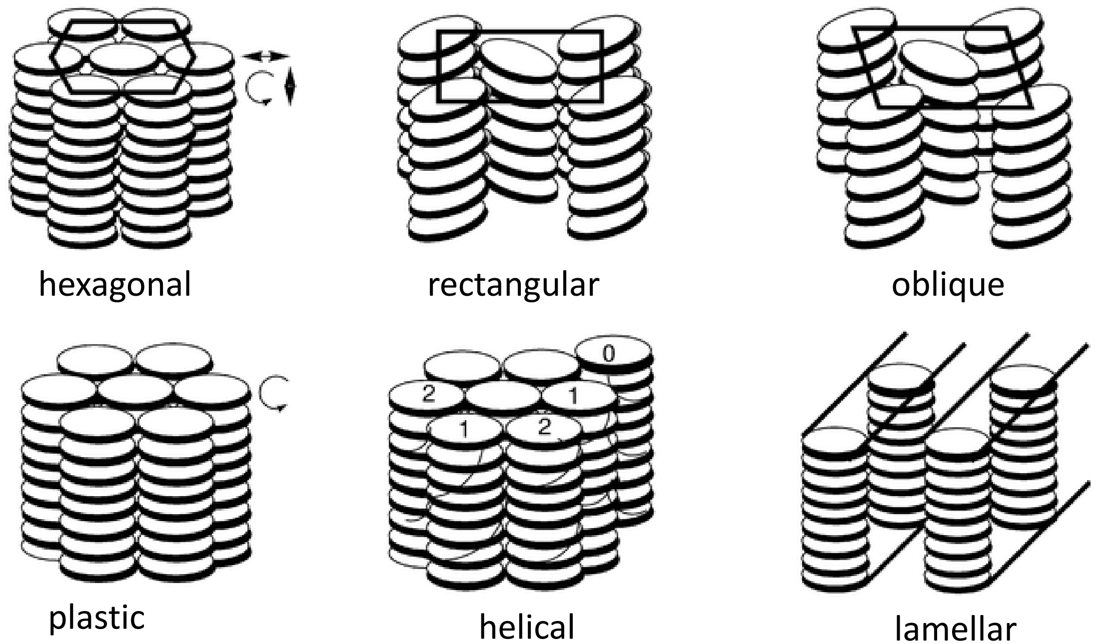
n = 1, 2, 3, ……..diffraction order
θ is the glancing angle
d is the distance between Bragg planes

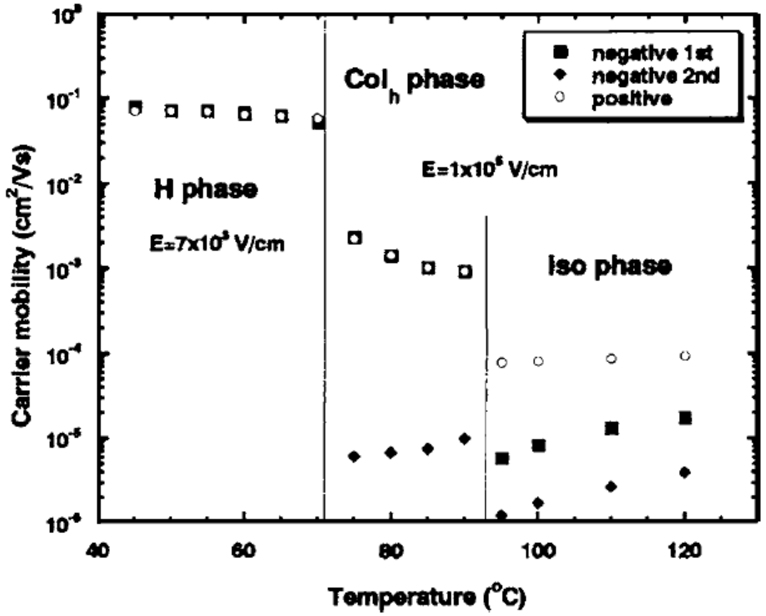
Discotic liquid crystals

- Disc-like, axis perpendicular to the plane orient in a particular direction
- There is a discotic nematic phase (orientational order, but no positional order)
- Columnar phase is also called smectic discotic









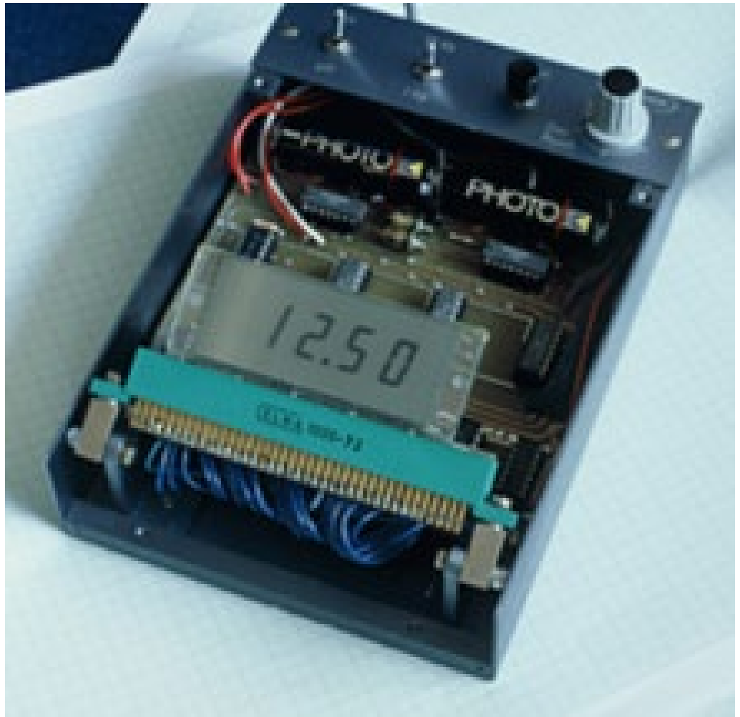
H. Iino et al., Appl. Phys. Lett. 87, 192105 (2005)

3.3 Main application: liquid crystal displays

- LCD displays are passive displays (control of brightness of a pixel is done indirectly)

  Controlled is the transmission or reflection of light
- Correspondingly, the light source is either the ambient light or a back light
- Different electro-optical effects are used:
  - **Optical activity in twisted nematic LCs**
  - Birefringence in twisted nematic LCs
  - Scattering in smectic LCs
  - Scattering in polymer encapsulated LCs
  - Field effects in chiral smectic LCs
- Requirements
  - Electro-optical field effect
  - Materials properties (e.g. optical activity over a wide temperature range, strong electrical dipole moment)
  - Manufacturing technologies

Martin Schadt receives the European Inventors Award 2013



First digit prototype TNLCD made in 1971 at Hoffmann-La Roche

Twisted nematic LCDs (TN-LCDs)

Developed in the early 70th, workhorse of LCD technology

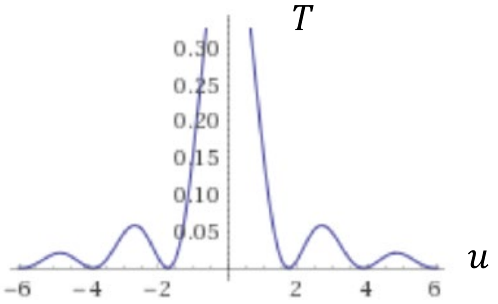
- When there is no voltage applied, the optical activity of the LC produces a rotation of the polarization director (see figure to the right)

L…light beam, P_2…linear polarizer at the entrance of the light beam. G….glass, E_2…orientation layer, LC…liquid crystal, E_1…orientation layer, P_1…linear polarizer at the exit, I…image.

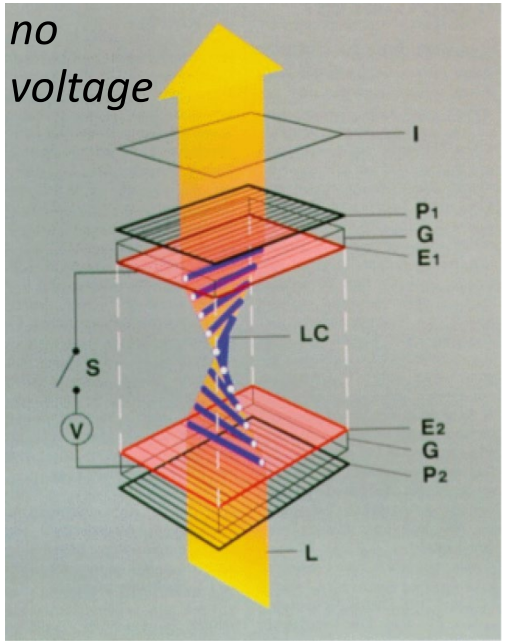
The transmitted light T through a TN liquid crystal film but with the top polarizer parallel (not perpendicular as in the figure to the right) to the bottom polarizer is strongly dependent on the thickness d of the device:

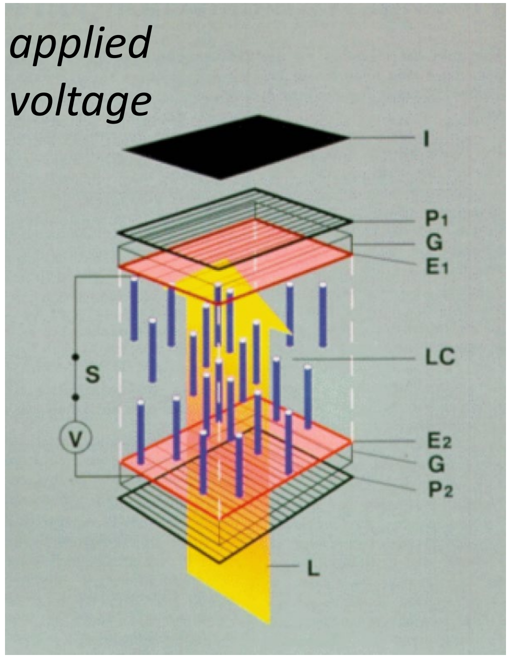
$$T = \frac{1}{2}\frac{\sin^2\left(\pi/_2\sqrt{1+u^2}\right)}{1+u^2} \qquad u = 2d\frac{\Delta n}{\lambda}$$

d is the thickness of the device, $\Delta n = n_{\parallel} - n_{\perp}$ and λ is the wavelength:



- With applied voltage, molecules align parallel to the electrical field due to the interaction of the applied electric field with the dipole moment of the mesogens.
- Polarized light experiences the layer as isotropic and all light is blocked at P_1



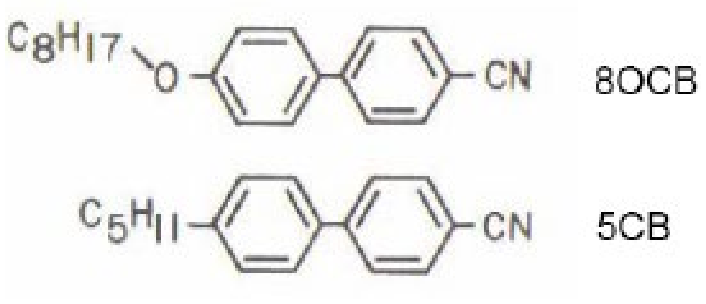


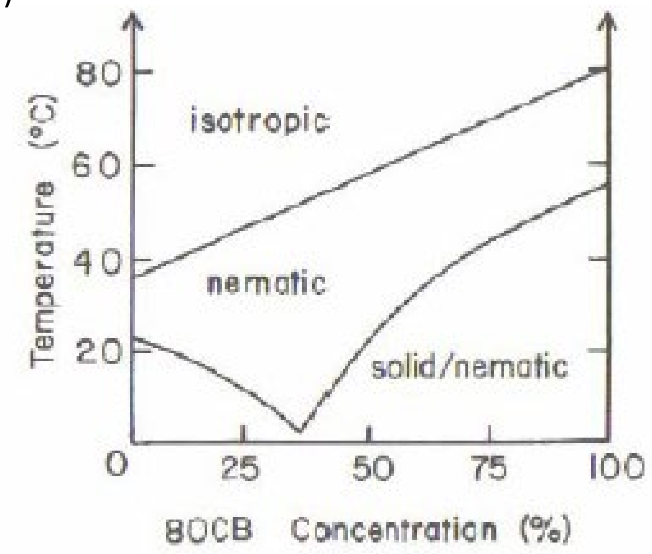
Twisted nematic LCs

- LCs have to be transparent (colorless), operate in a large temperature range, be chemically stable, have low viscosity
- TN-LCDs have a very good contrast ratio
- Can also be used with ambient light, then a reflector is placed below the polarizer P2, light will pass twice through the active material
- In 1985, the super twisted nematic LC (STN-LC) was introduced by using a chiral dopant. Here the rotation is 270°. Advantages include sharper brightness versus voltage characteristics and better viewing angle.

Blends

- LCDs do not work at high and low temperatures (phase transitions)
- Mixing different LCs, allows to engineer optimized phase diagrams
- Mixture of p-n-pentyl-p'cyanobiphenyl (5CB) and p-n-ocrtyloxyl-p'cyanobipheny (8OCB)
- 35% 5CB and 65% 8OCB has a nemantic range of 5°- 50°C.

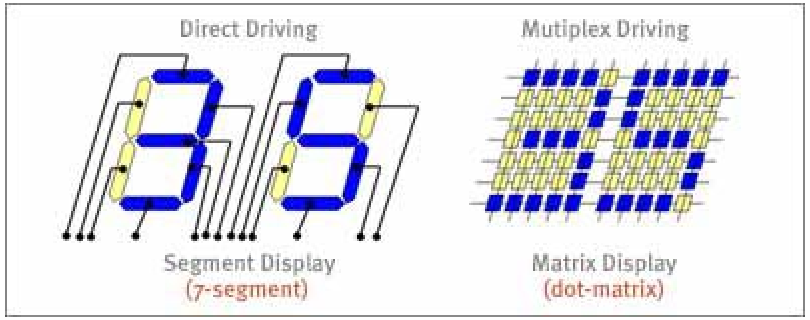




Information display technology

- There are two ways to produce a liquid-crystal image with such cells: the segment driving method and the matrix driving method.
- Direct addressing (segment driving method)
  - Each area of the crystal is connected circuitry that applies a voltage, characters are defined by patterned electrodes
  - Limited to small number of segments, simple displays
- Multiplexing (passive matrix display)
  - Characters and pictures are displayed in a matrix format
  - High resolution displays

Direct versus multiplex driving

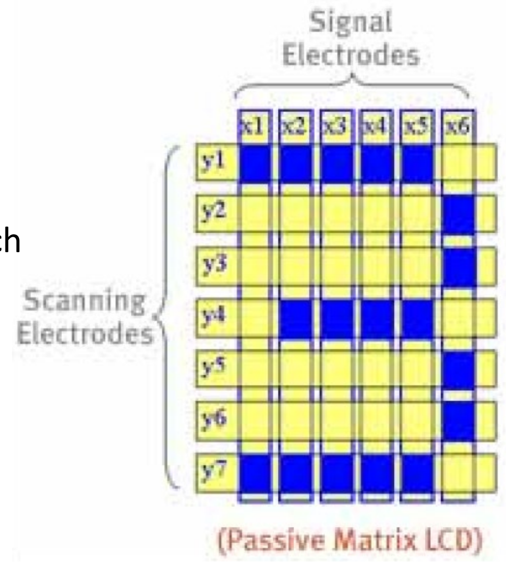


For an n x m pixel matrix:

Direct driving: n x m connections
Multiplex driving: n + m connections

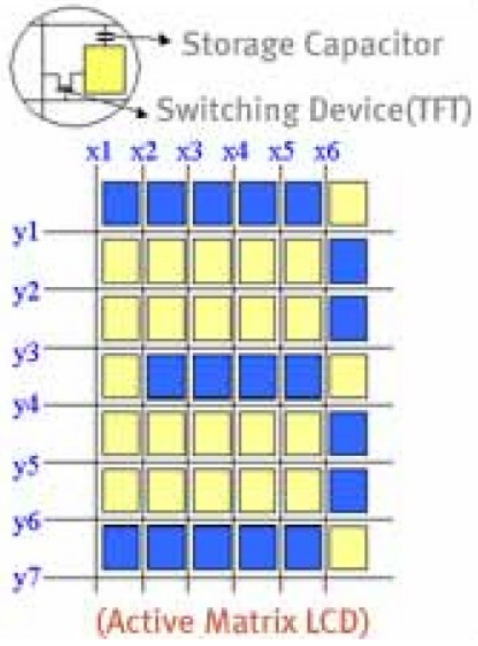
Passive-Matrix LCD (PMLCDs)

- Each pixel is addressed for more than one frame time
- The effective voltage applied to the LC must average the signal voltage pulses over several frame times, which results in a slow response time of greater than 150 msec and a reduction of the maximum contrast ratio
- The addressing of a PMLCD also produces a kind of crosstalk that produces blurred images

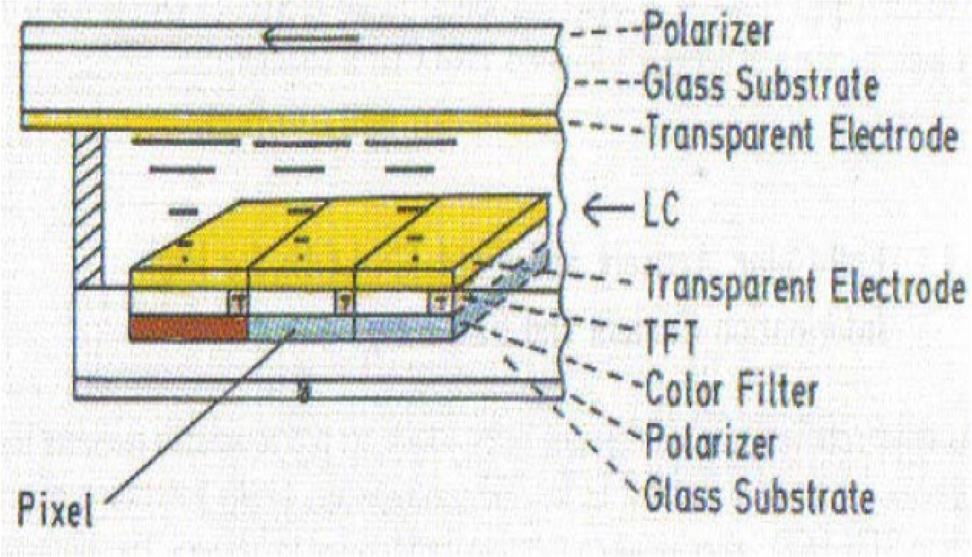


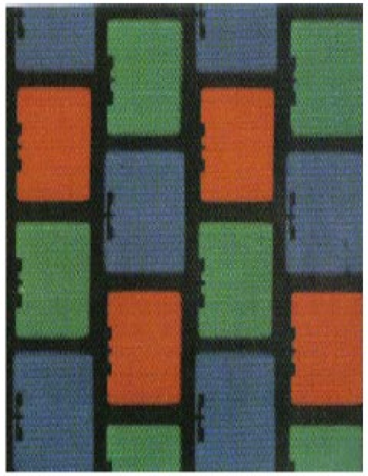
Active-Matrix LCDs (AMLCDs)

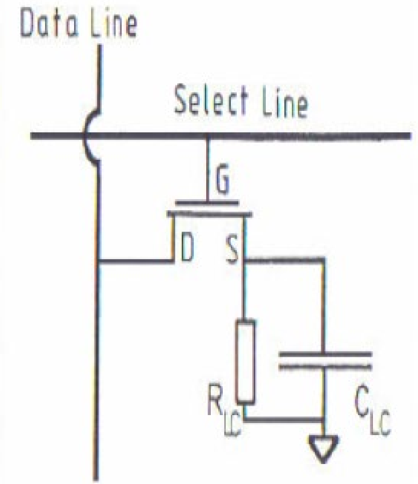
- A switching device and a storage capacitor are integrated at each cross point of the electrodes
- Removes the multiplexing limitations by incorporating an active switching element
- There are many kinds of AMLCD. For their integrated switching devices most use transistors made of deposited thin films, which are therefore called thin-film transistors (TFTs)
- Non-linear device with sharp on/off threshold
- Very fast
- Precise brightness control



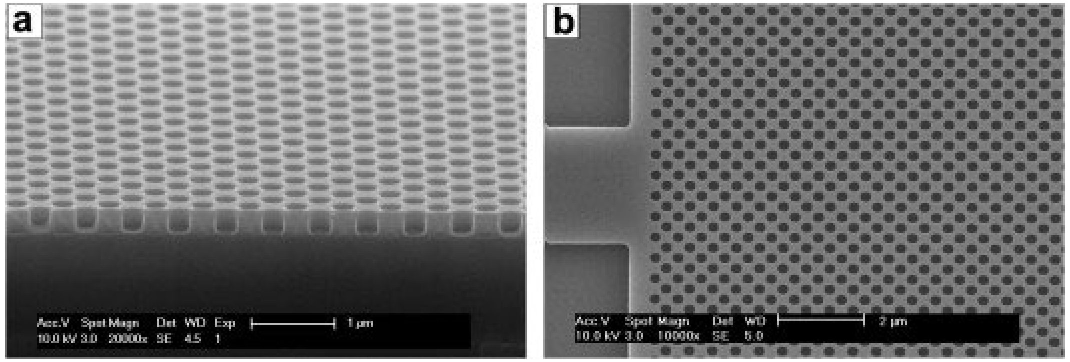
Color LC Display

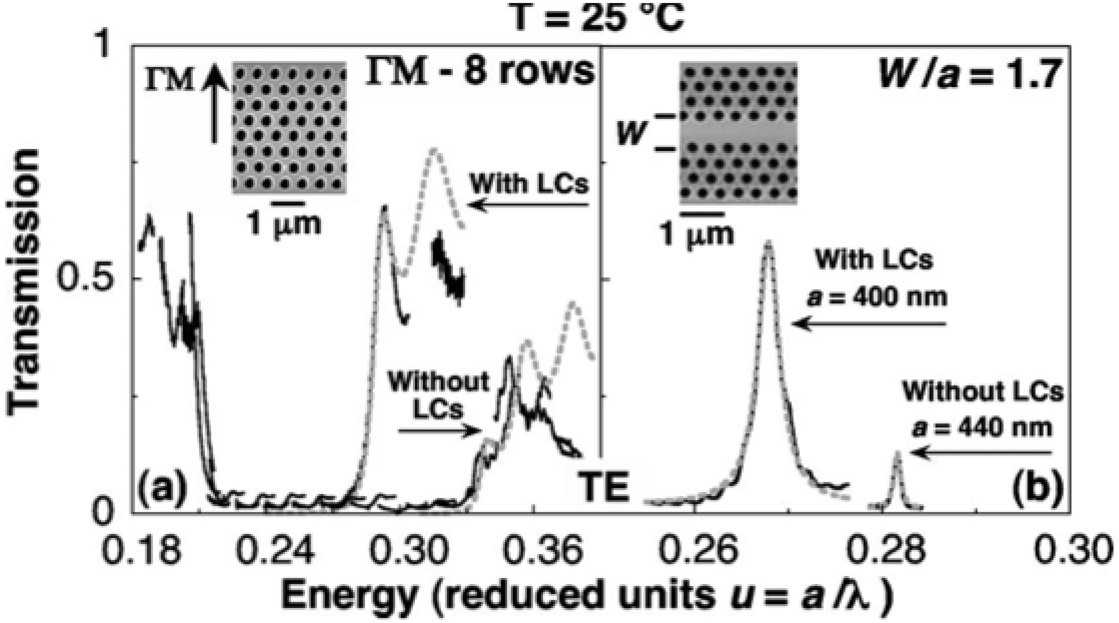


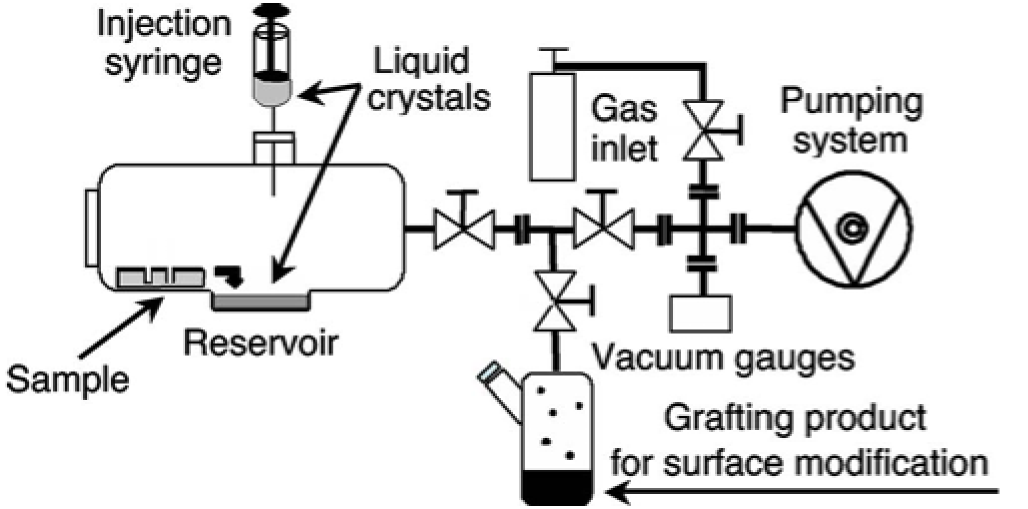




Tuning and Trimming of 2D photonic crystals by LC infiltration







Planar PhCs consisting of a triangular lattice of air holes were etched by chemically assisted ion beam etching CAIBE through a nominally undoped InP/Ga,In As,P /InP vertical waveguide grown by metalorganic vapor phase epitaxy. The waveguide is single mode for λ=1.5 μm.

J. Martz et al., JOURNAL OF APPLIED PHYSICS 99, 103105 2006