SECTION 3
LIQUID CRYSTAL DISPLAYS
AN INTRODUCTION

MATERIALS, CONCEPTS & ELECTRO-OPTICS

Liquid Crystal Displays (2^{nd} Edition)
Ernst Leuder. Pub Wiley / SID, Ch2, pp3-20.
Handbook of Visual Display Technology (2^{nd} Edition)
Pub Springer 2016

Twisted Nematic and Supertwisted Nematic LCDs
Peter Raynes
Pages 2077-2090

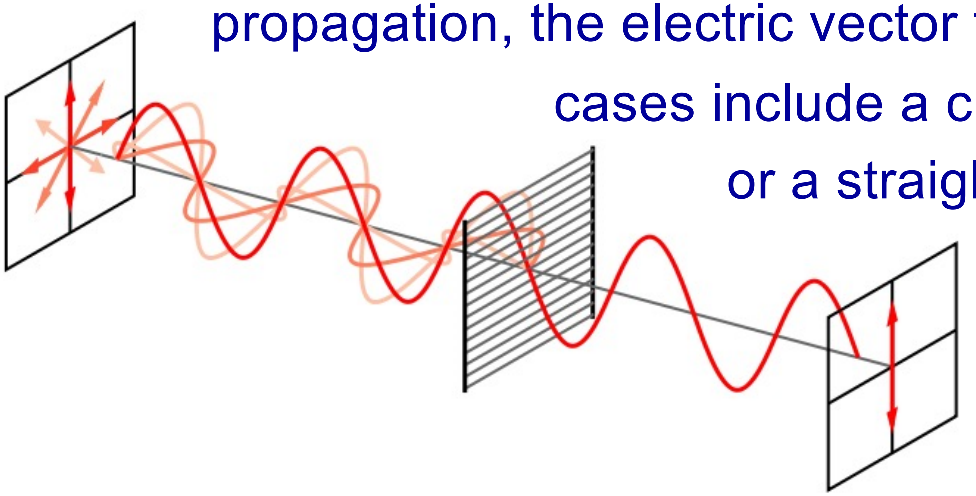
Optics of Liquid Crystals and Liquid Crystal Displays
Philip W. Benzie, Steve J. Elston
Pages 1979-2002

Polarized Light

Visible light is a form of Electro-Magnetic Radiation (EMR) with wavelength in the region 390 - 750 nm (790 – 400 THz).

EMR has both electric and magnetic field components, which stand in a fixed ratio of intensity to each other, and which oscillate in phase perpendicular to each other and perpendicular to the direction of energy and wave propagation.

When projected on to the plane normal to the direction of propagation, the electric vector traces an ellipse. Special cases include a circle (circularly polarized) or a straight line (linearly polarized)



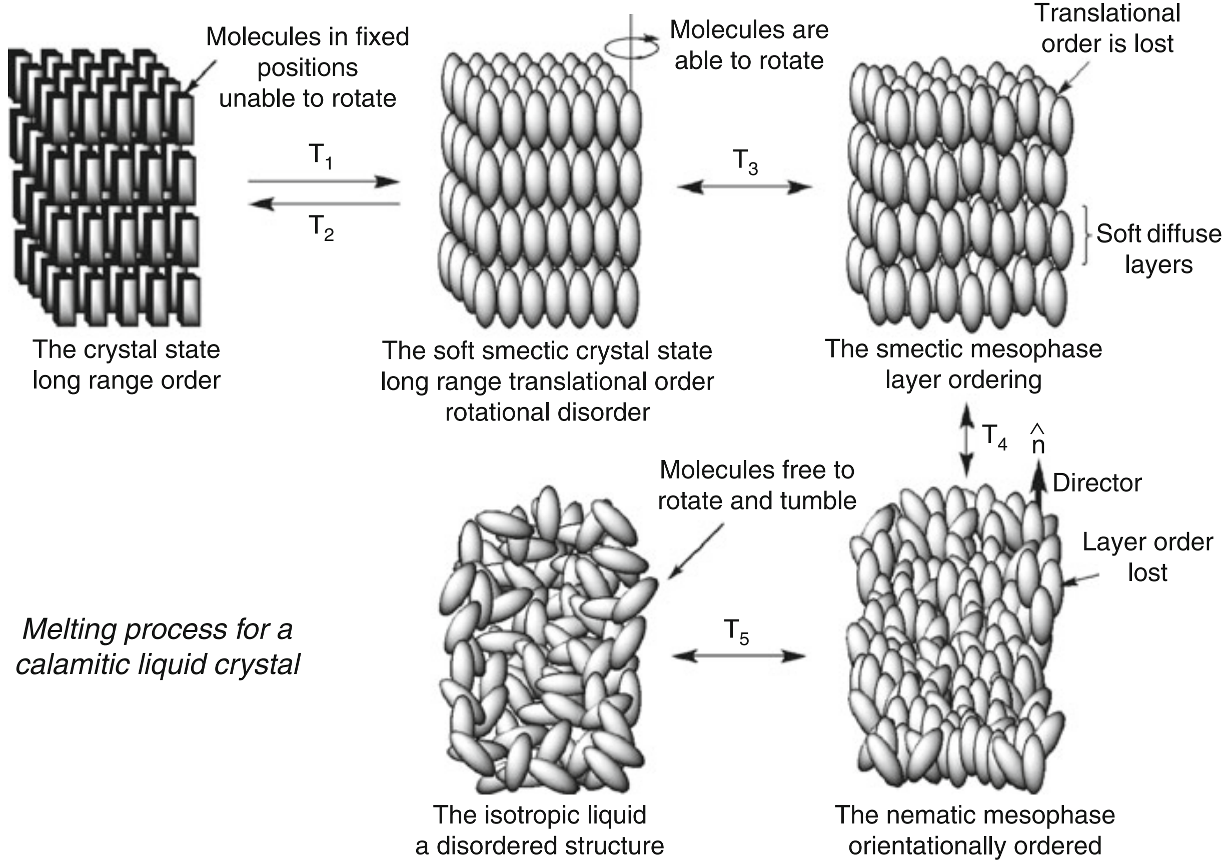
Animation – plane polarized wave

Animation - circular polarized light

Definition – Liquid Crystal

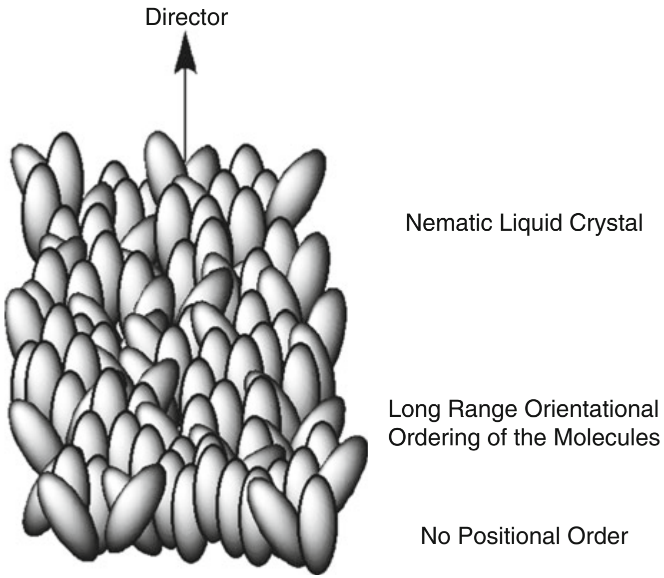
The term **“liquid crystal”** describes a group of meso-phases between solid crystal and isotropic liquid that exist for a number of organic molecular materials.

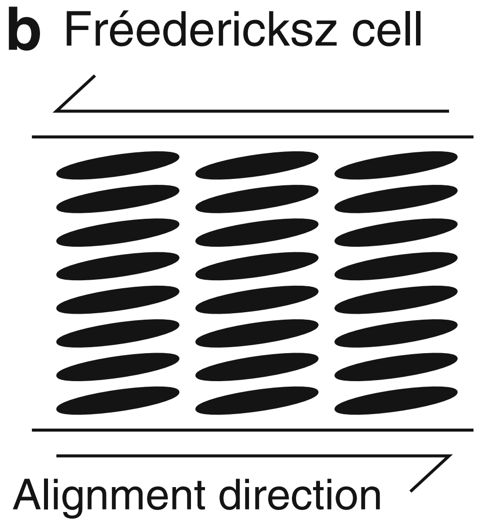
A <u>liquid crystal material</u> is a material that exhibits one or more of these meso-phases.



Melting process for a calamitic liquid crystal

Definition – Liquid Crystal





LC molecules are usually of a particular shape – rod-like (used in LCDs) or disk-like (used for other purposes)

When captured in a thin layer between two flat plates the LC materials can often be "aligned" by surface forces.

An applied electric field can then alter the LC alignment to provide a visible effect (brightness change, colour change).

LC Molecules and Polarizability

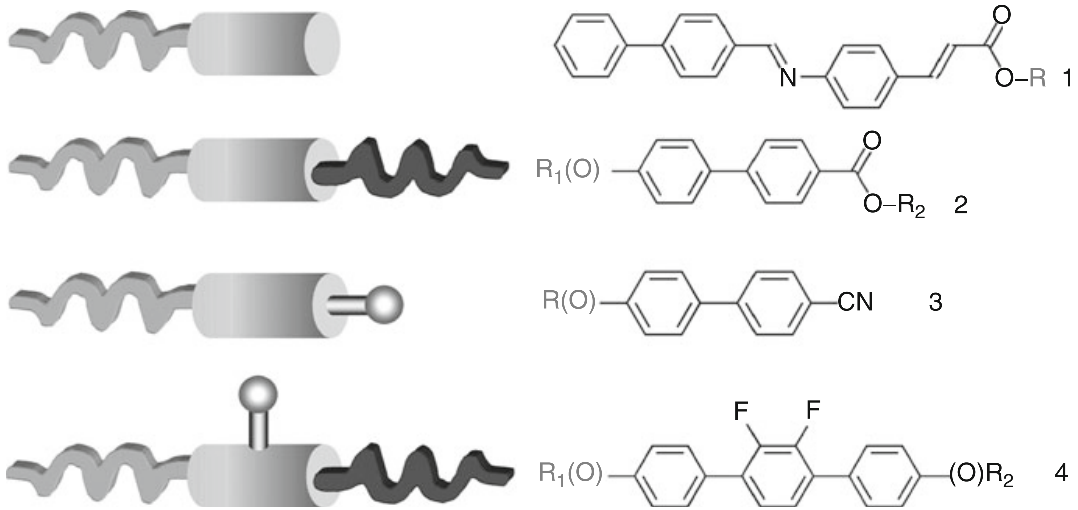
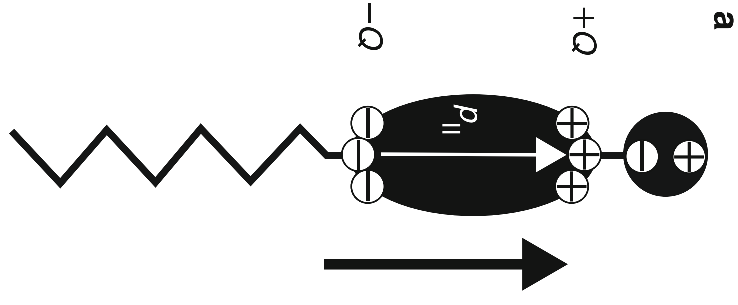
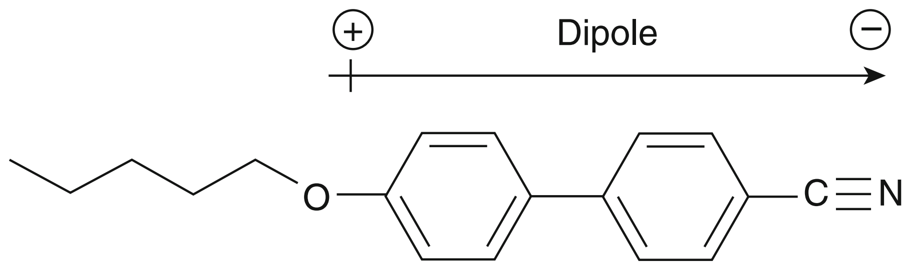


Fig. 12 Typical material design for rodlike liquid crystals (Gray et al. 1973, 1989; Gray and Harrison 1971; Goodby and Gray 1976a). Materials **3** and **4** show the design of liquid crystals found in display devices





Polar and Polarizable molecular system

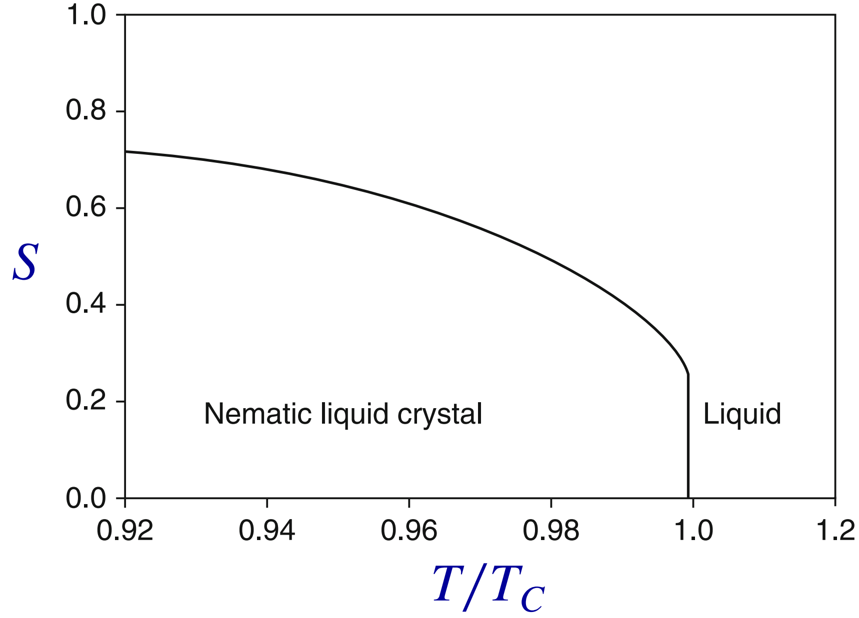
Order Parameter

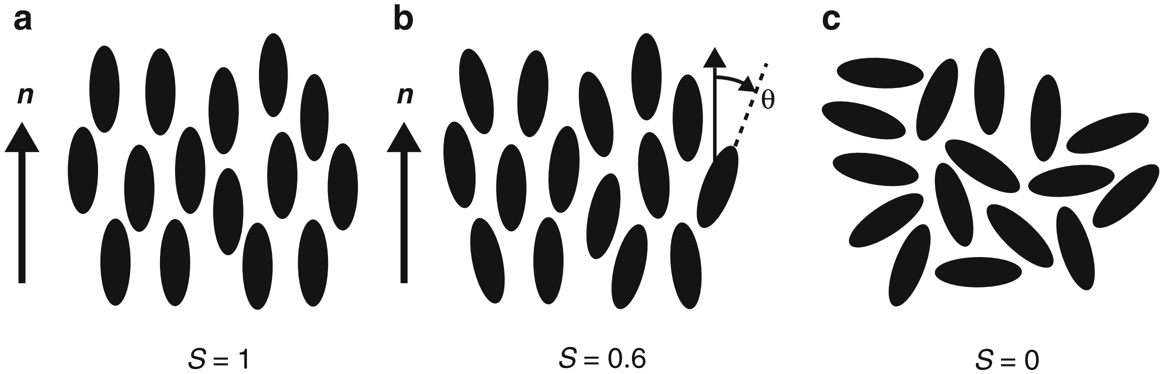
The Order parameter S is a measure of how mutually well-aligned the molecules are.

$$S = \tfrac{1}{2}\,(3\cos^2\theta - 1)$$

where

$$S = (1 - T/T_C)^b$$

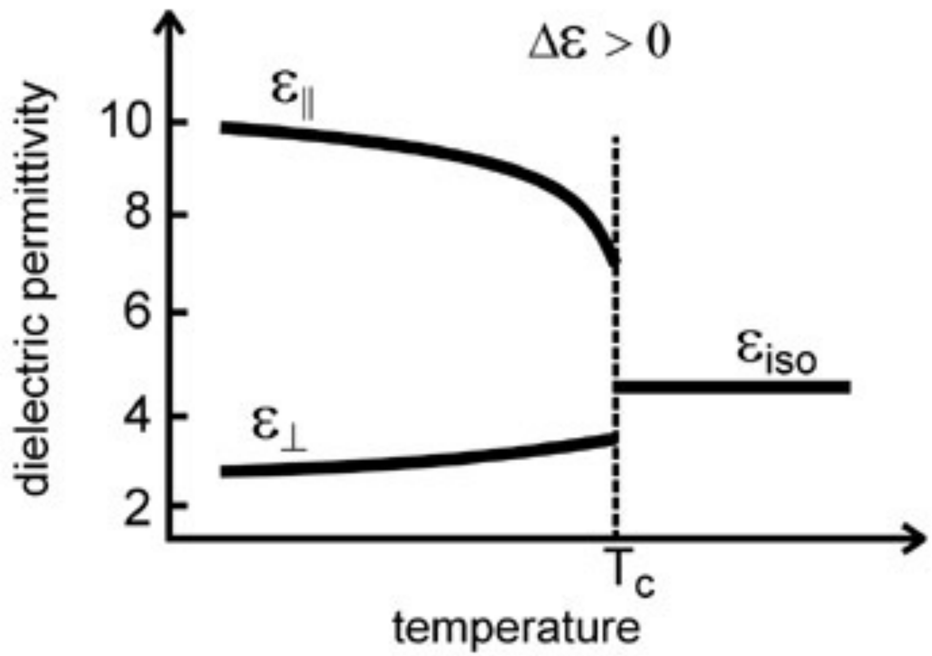




Dielectric Permittivity

Dielectric properties of LCs are related to the response of LC molecules to the application of an electric field.

Permittivity ε is a physical quantity that describes how an electric field affects and is affected by a dielectric medium and is determined by the ability of a material to polarize in response to an applied electric field.



Dielectric Anisotropy and LC switching

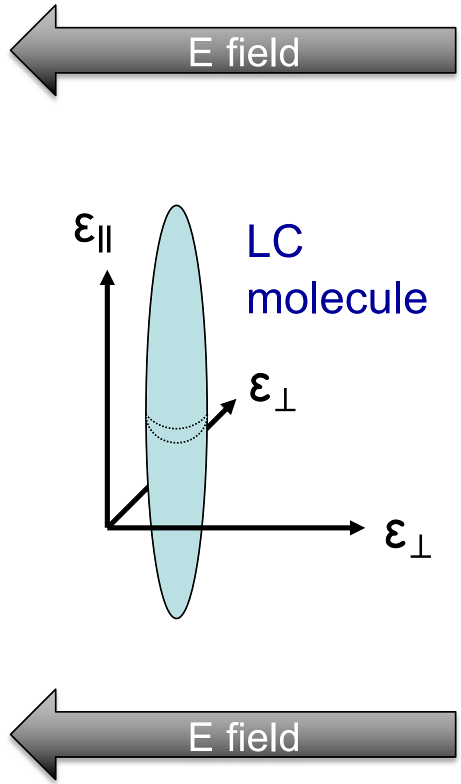
The dielectric anisotropy

$$\Delta\varepsilon = \varepsilon_{||} - \varepsilon_{\perp}$$

can take positive and negative values.

If an electric field is applied orthogonal to its director the liquid crystal will tend to rotate to align the director with the electric field assuming that the director and the dipole moment (more precisely the larger component of the dielectric anisotropy) are essentially co-linear.

In LCs with a positive (*negative*) dielectric anisotropy will align the director parallel (*perpendicular*) to the applied electric field



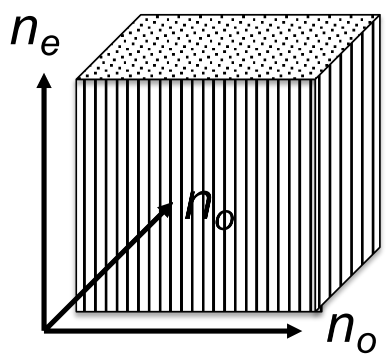
Animated example of positive ➔

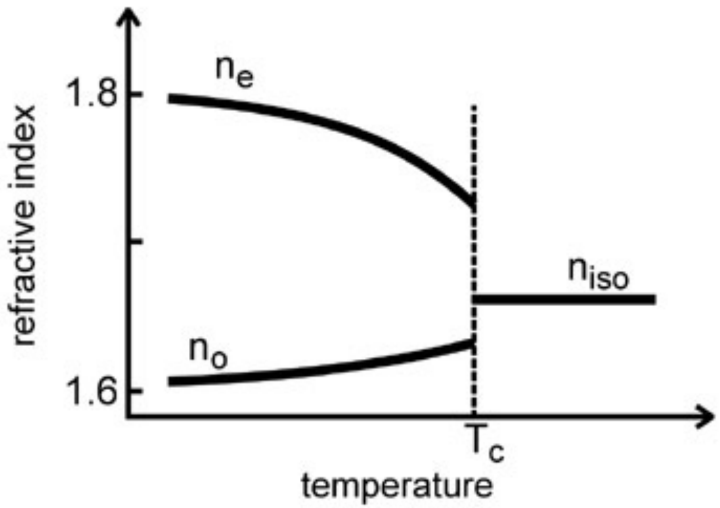
Birefringence (Optical Anisotropy)

Birefringence is the optical property of a material having a refractive index that depends on the polarization and propagation direction of light. Optically anisotropic materials are said to be **birefringent**. The birefringence is often quantified by the maximum difference in refractive index within the material.

A **birefringent** material is one in which the refractive index along one axis (extra-ordinary) is different to that along the other two (ordinary) perpendicular axes.

Many LC configurations exhibit switchable birefringence.





LC Materials

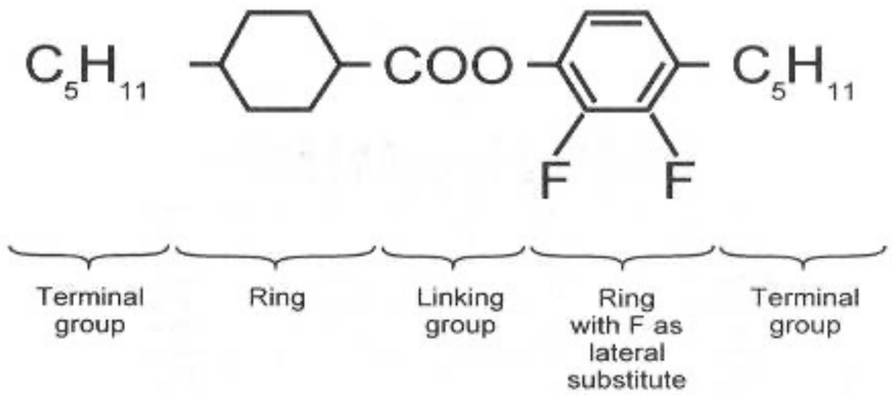
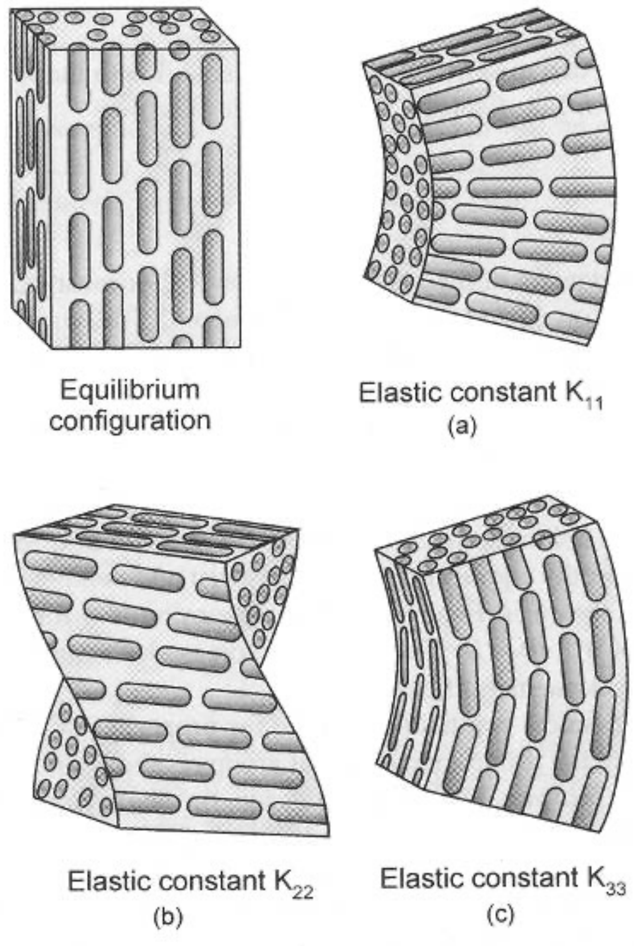


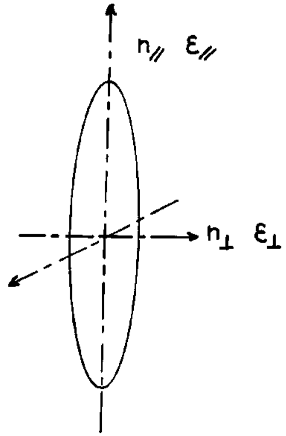
Table 2.2 Properties of nematic LC materials with a wide temperature range

	MLC-1380000	MLC-13800100	MLC-1390000	MLC-13900100
Transition temp. smectic-nematic	$< -40°C$	$< -40°C$	$< -40°C$	$< -40°C$
Clearing pt T_c	110°C	111°C	110.5°C	110.5°C
Rotational viscosity, 20°C	228 mPas	151 mPas	235 mPas	167 mPas
$\Delta\varepsilon$ 1 kHz, 20°C	+8.9	+5.0	+8.3	+5.2
$n_0 = n_\perp$	1.4720	1.4832	1.4816	1.4906
$n_e = n_\parallel$	1.5622	1.5735	1.5888	1.5987
Δn	+0.0902	+0.0903	+0.1073	+0.1081

Properties of LCs

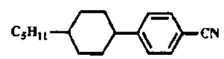


(a) Splay
(b) Twist
(c) Bend

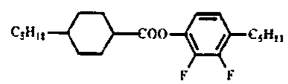


Dielectric anisotropy

$\Delta\varepsilon = \varepsilon_{//} - \varepsilon_{\perp}$



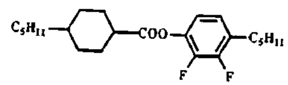
$\varepsilon_{//} = 17.7$ $\varepsilon_{\perp} = 4.8$ $\Delta\varepsilon = +12.9$



$\varepsilon_{//} = 3.5$ $\varepsilon_{\perp} = 5.6$ $\Delta\varepsilon = -2.1$

Birefringence

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



$n_e = 1.529$ $n_o = 1.472$ $\Delta n = 0.057$

Nematic LC – typical properties

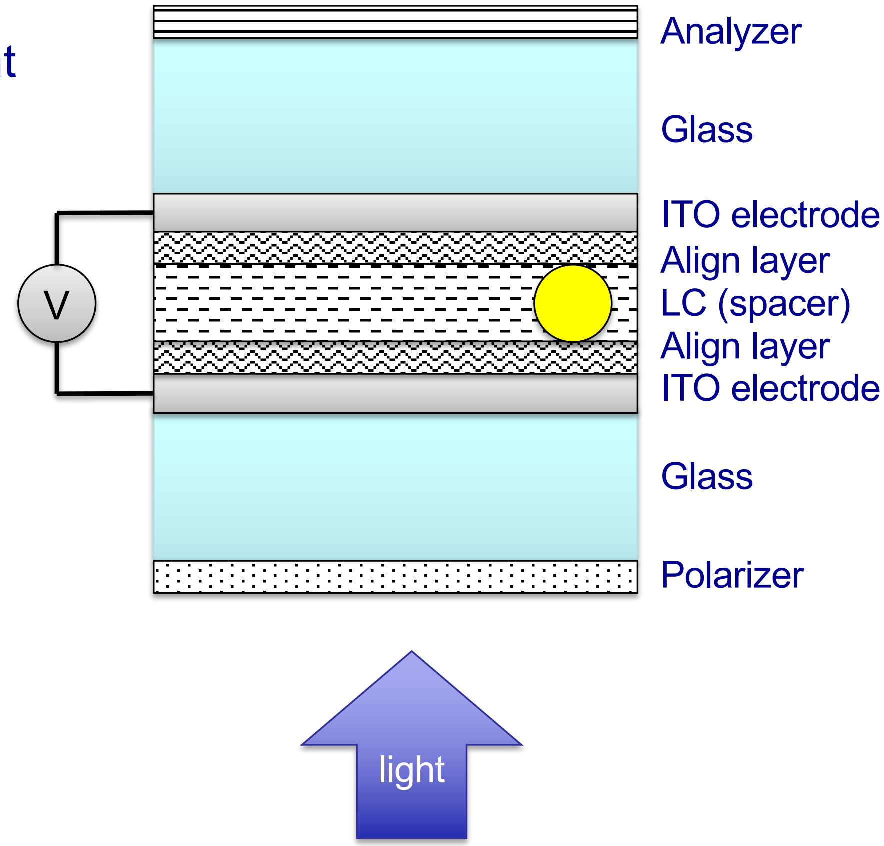
Parameter	Symbol	Typical value	Comments
Clearing point	T_{Cl}	80 °C	Max operating temperature
Sm-N transition	$T_{S\text{-}N}$	-40 °C	Min operating temperature
Optical Anisotropy	$\Delta n = n_e - n_o$	1.562 - 1.477 = 0.085	Determines optical performance
Dielectric Anisotropy	$\Delta\varepsilon = \varepsilon_{//} - \varepsilon_{\perp}$	10.5 - 3.5 = 7	Determines response to E field
Threshold Voltage TN cell	$V_{th,10}$	1.6 V	Voltage at 10% trans (NB mode)
Elastic Constants	K_{11}, K_{22}, K_{33}	10^{-11} N	Important for response time
Rotl Viscosity at 20°C	η_r	100 mPa.s	Important for response time

Basic LC cell

Details

- LC layer <1 to several μm thick
- Thickness uniformity is important
- Alignment layer is mechanical / chemical
- Indium Tin Oxide (ITO) is a **transparent conductive material**

- In a modern LCD there are very many additional features
- Anti-Reflection layers
- Circular polarizer
- Compensation layer(s) to aid viewing angle
- RGB Colour filters layer, etc

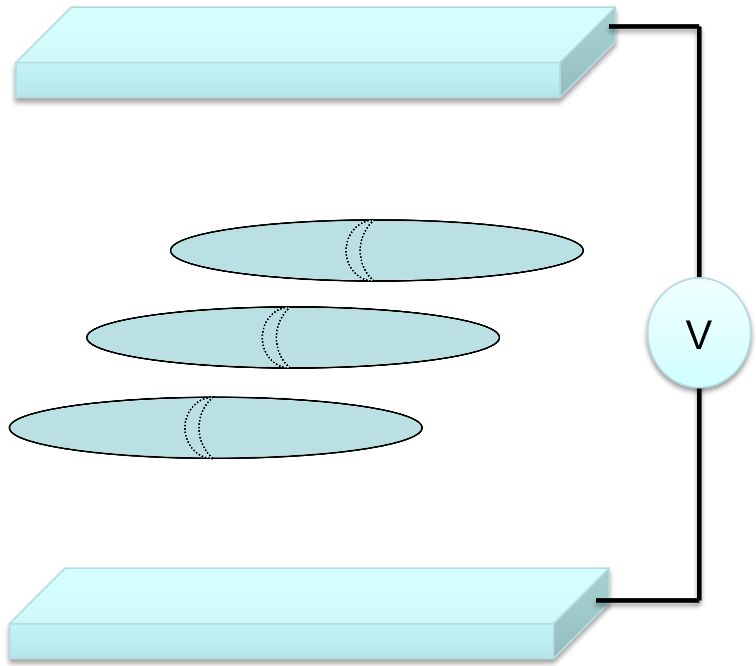


Freedericksz Transition

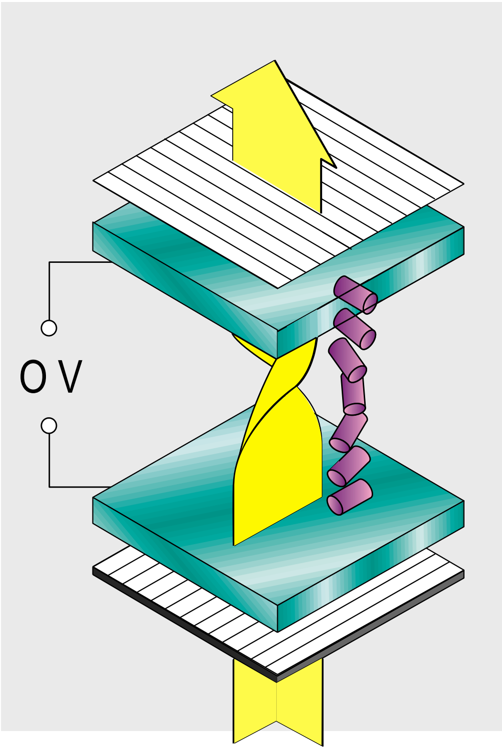
Recall the dielectric anisotropy in LCs

$$\Delta\varepsilon = \varepsilon_{||} - \varepsilon_{\perp}$$

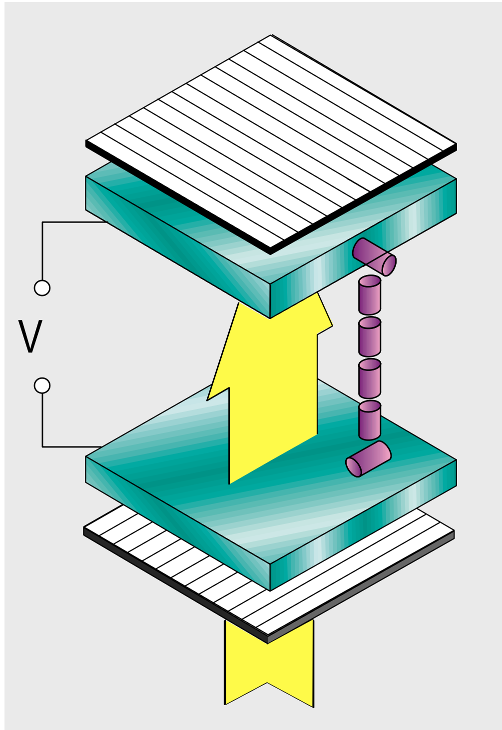
If then an electric field is applied orthogonal to the director the liquid crystal will tend to rotate to align the director with the electric field assuming that the director and the dipole moment (more precisely the larger component of the dielectric anisotropy) are essentially co-linear. The reorientation starts in the middle where there is little surface interaction.



Twisted Nematic (TN) Effect



Nematic LC responds slowly (>>ms) to the RMS value of a medium frequency (>kHz) ac drive waveform



Crossed polarizers Drive voltage = zero Twisted Nematic LC Light passes through	*Intermediate voltage* *Some light passes*	Crossed polarizers Drive voltage = Vmax LC untwisted Light blocked

Aside on real LCDs

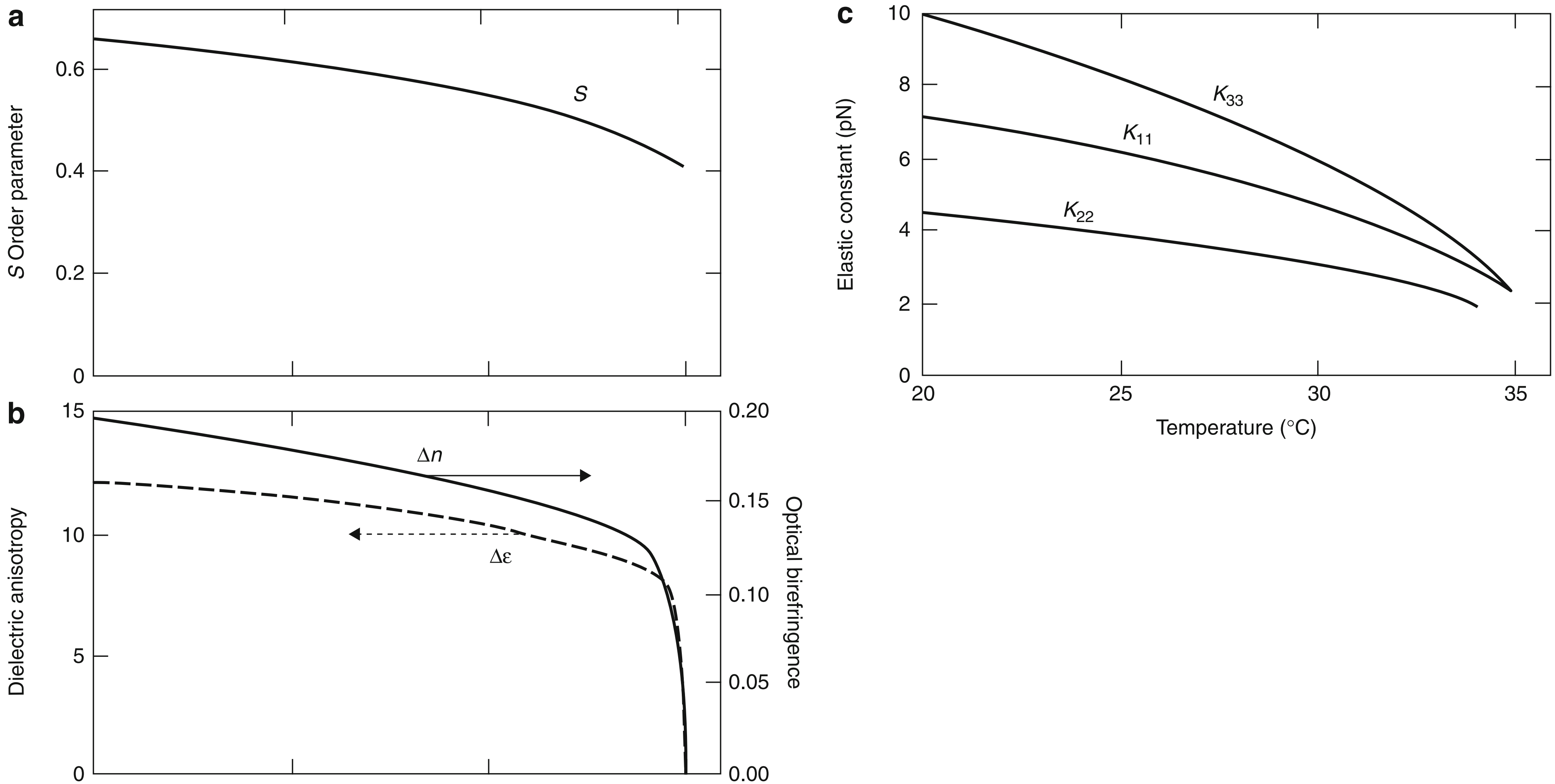
It is relatively straightforward to explain the principle of how an LC cell operates (i.e., how to make a single cell of LC go dark or bright).

Making a high definition high performance LCD that works well is much more challenging

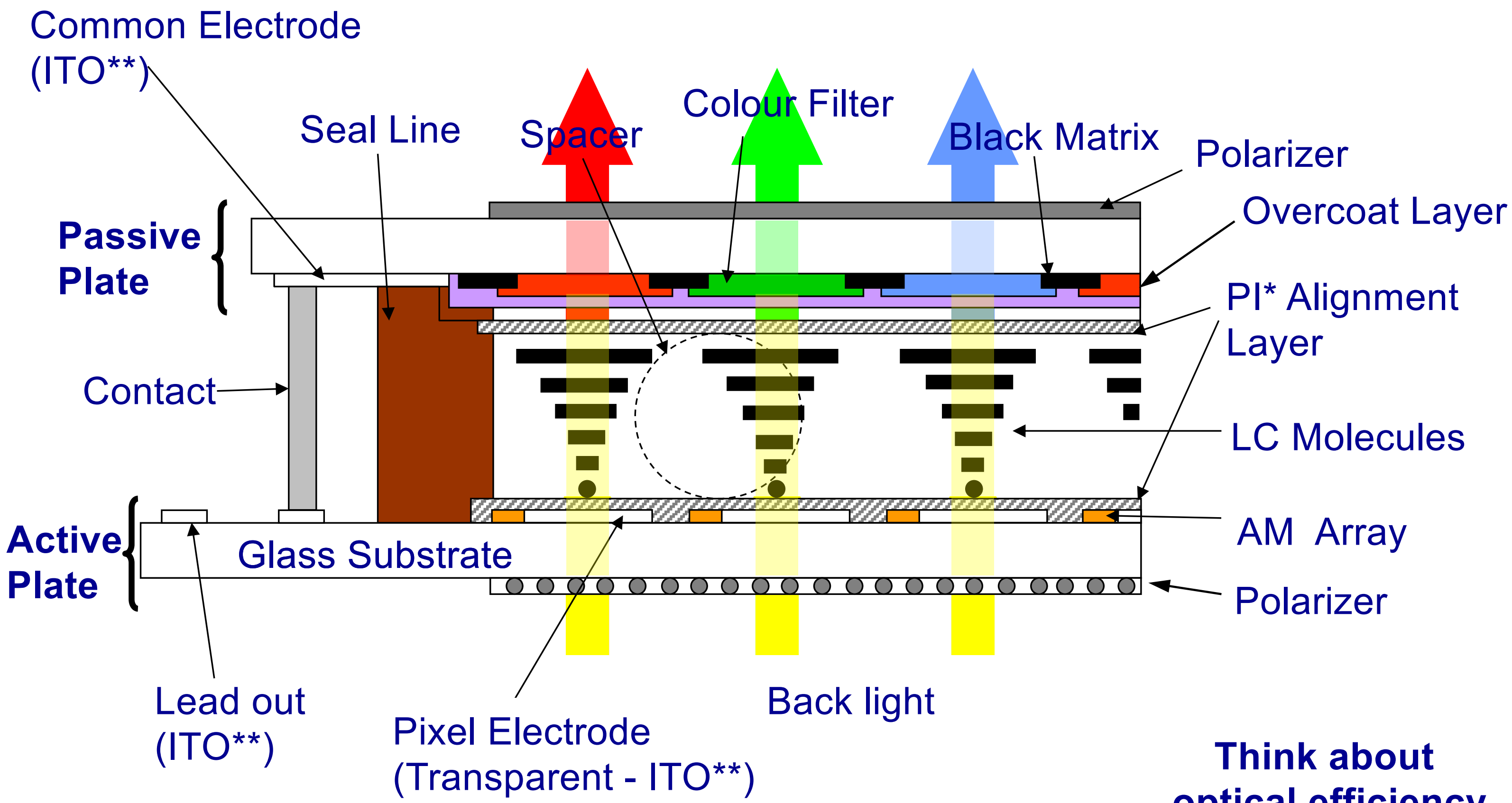
- Many small close pixels
- Colour (ie wide range of wavelengths)
- Wide viewing angle
- Large temperature range
- High brightness
- High contrast ratio, etc.

Much of that detail is beyond the scope of this course.

Effect of Temperature



Transmissive AMLCD Overview



ITO** = Indium Tin Oxide

*PI = Polyimide

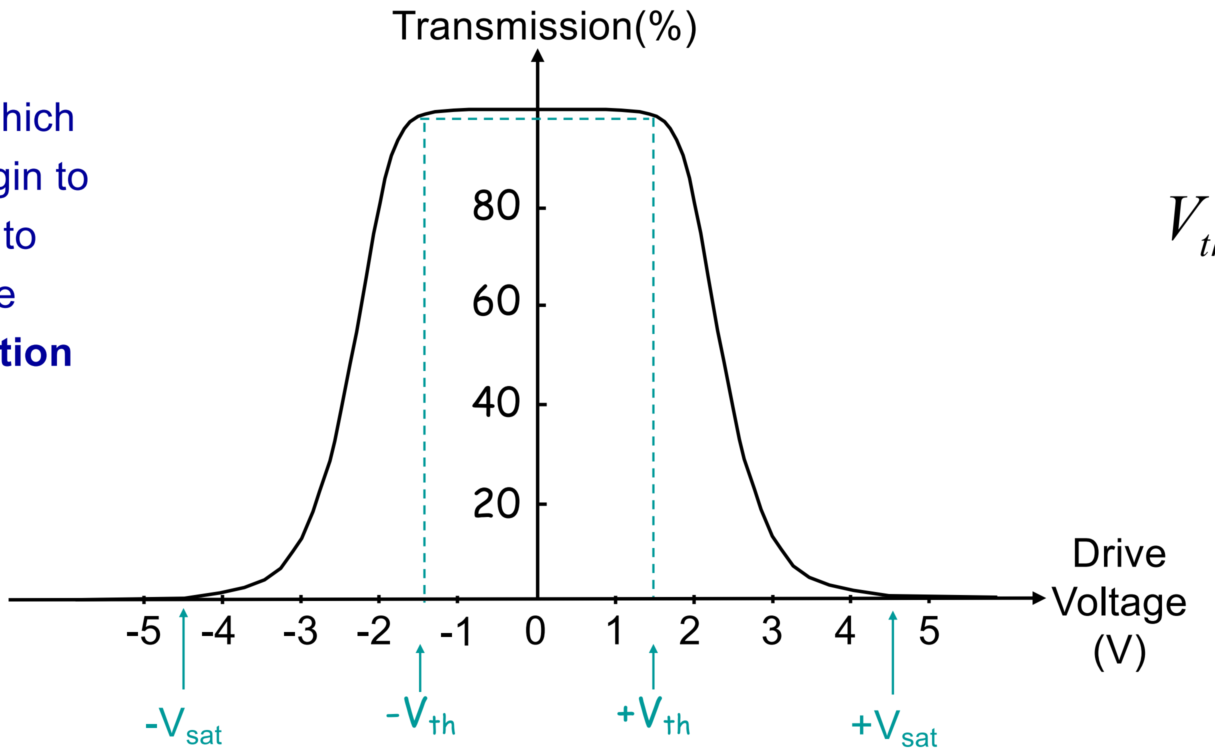
Think about optical efficiency = light out / light in. See later

TN LC Transmission-Voltage Curve

Typical TN LC material with crossed polarizers...

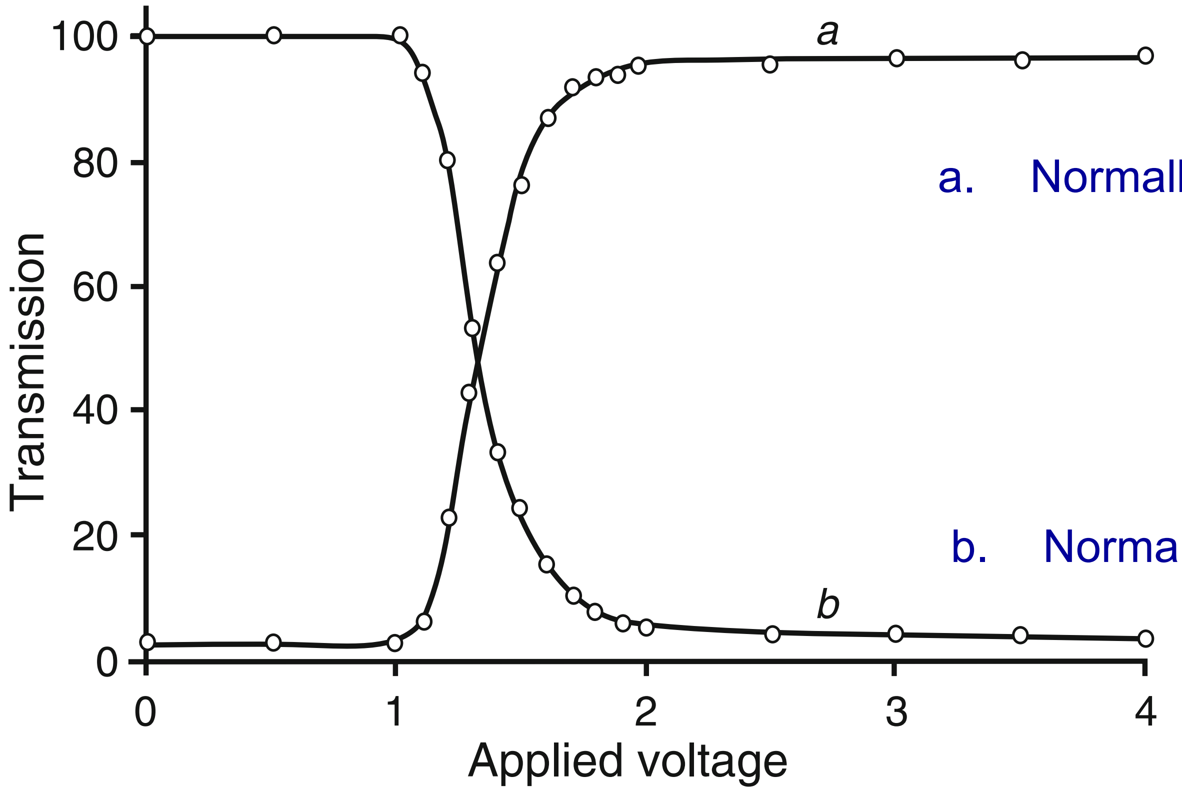
Same effect for +ve & -ve voltages ! Important for inversion drive schemes.

The critical point at which the LC molecules begin to re-orient in response to an E-field is called the **Freedericksz Transition**



$$V_{th} = \pi \sqrt{\frac{K_{11}}{|\Delta\varepsilon|}}$$

TN LC Transmission-Voltage Curve



a. Normally Black / Dark

b. Normally White / Bright

Some Characteristics of LC devices

Steady-state response

- Detail follows – a few to a few 10's of Volts

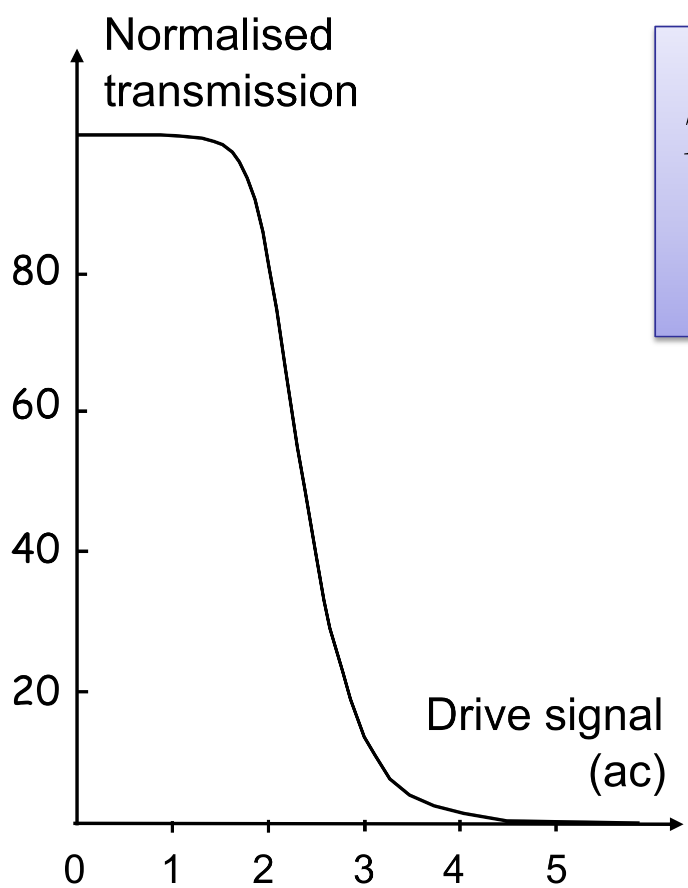
Response speed

- **Nematic** – analog response ~ ms
- **(Ferroelectric** – binary (bistable) response ~ μs)

Other

- dc balance requirement
  - Long-term V d.c. causes electro-chemical degradation
  - Require a.c. drive for long lifetime
- Temperature limitations
  - At very low T, LC freezes solid
  - At very high T, LC melts to anisotropic liquid
  - In between, properties (e.g. switch speed) vary significantly

LC Switching Time



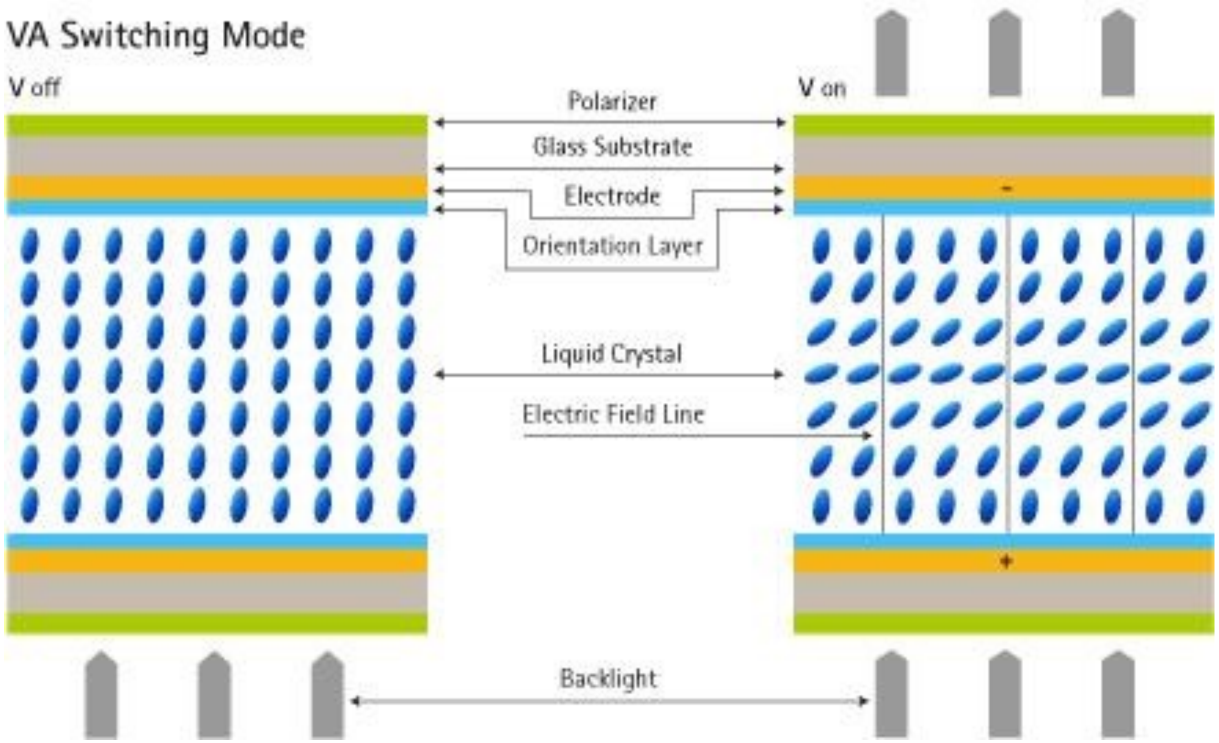
$$T_{rise} = \frac{\eta_r d^2}{\pi^2 K_{11}} \frac{1}{\left(\frac{\Delta\varepsilon}{\pi^2 K_{11}} (V_1 - V_{th})^2 - 1 \right)}$$

$$T_{fall} = \frac{\eta_r d^2}{\pi^2 K_{11}}$$

Vertically Aligned LC

In vertical alignment (VA) LCDs, homeotropic liquid crystals – i.e. those aligned normal to the substrate surface – are switched parallel to the glass substrate by the application of an electric field which is normal to the substrate.

This requires liquid crystal mixtures with <u>negative</u> dielectric anisotropy which are aligned perpendicular to the electric field.



In-Plane Switching (IPS) LC

The IPS (in-plane switching) configuration puts the electrodes whose electrical fields are used to switch the LC molecules are only found on one of the two substrates in the form of strip electrodes.

The resulting electrical field is inhomogeneous and mostly aligned parallel to the substrate surface in the first approximation.

Molecules are switched between two states that are both parallel to the substrate, hence – in-plane switching