FACULTY OF ENGINEERING
AND ARCHITECTURE

ELECTRONICS AND INFORMATION SYSTEMS DEPARTMENT
LIQUID CRYSTALS AND PHOTONICS RESEARCH GROUP

LIQUID CRYSTALS AND LIGHT EMITTING MATERIALS FOR PHOTONIC APPLICATIONS

Kristiaan Neyts April 2018 Lecture series at WAT in Warsaw

GHENT UNIVERSITY

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nb-photonics
Center for Nano- and Biophotonics
Ghent University

Liquid Crystals and Photonics

OVERVIEW

Liquid crystal properties (10h)

Properties of nematic liquid crystals
Nematic order parameter
Polarization and dielectric constant
Elastic energy
Surface alignment
Electrical energy
Freederickz treshold
VAN mode
Variable phase retarder
IPS mode
TN mode
Polarization microscopy

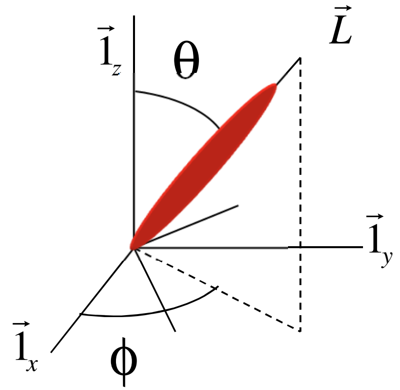
ELASTIC ENERGY

In a **1D geometry** (*L* depending only on *z*)

$$f_{elastic} = \tfrac{1}{2}\left(K_{11}\left(\nabla\cdot\vec{L}\right)^2 + K_{22}\left(\vec{L}\cdot\left(\nabla\times\vec{L}\right)\right)^2 + K_{33}\left(\vec{L}\times\left(\nabla\times\vec{L}\right)\right)^2 \right)$$

only $\dfrac{\partial}{\partial z}$

$$\vec{L} = \begin{pmatrix} \cos\phi(z)\sin\theta(z) \\ \sin\phi(z)\sin\theta(z) \\ \cos\theta(z) \end{pmatrix}$$



$$f_{elastic} = \tfrac{1}{2}\left(K_{11}\left(\sin\theta\frac{\partial\theta}{\partial z}\right)^2 + K_{22}\left(\sin^2\theta\frac{\partial\phi}{\partial z}\right)^2 + K_{33}\left(\left(\cos\theta\frac{\partial\theta}{\partial z}\right)^2 + \left(\cos\theta\sin\theta\frac{\partial\phi}{\partial z}\right)^2\right)\right)$$

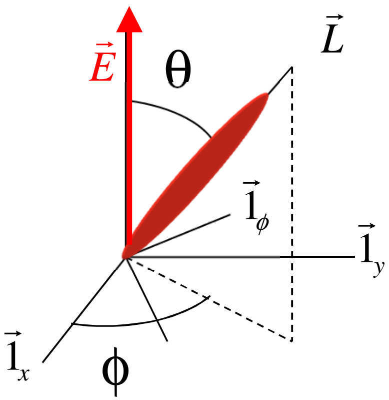
ELECTRIC ENERGY

Electric energy density (with source)

$$f_{electric} = -\tfrac{1}{2}\vec{D}\cdot\vec{E} = -\tfrac{1}{2}\left(\overline{\overline{\varepsilon}}\vec{E}\right)\vec{E} = -\tfrac{1}{2}\varepsilon_{\perp}E^{2} - \tfrac{1}{2}\Delta\varepsilon\left(\vec{L}\cdot\vec{E}\right)^{2}$$

$$\overline{\overline{\varepsilon}}\vec{E} = \varepsilon_{\perp}\vec{E} + \Delta\varepsilon\left(\vec{L}\vec{L}\right)\vec{E} = \varepsilon_{\perp}\vec{E} + \Delta\varepsilon\vec{L}\left(\vec{L}\cdot\vec{E}\right)$$

$$\begin{cases} \vec{L}\cdot\vec{E} = E\cos\theta \\ \vec{L}\times\vec{E} = -E\sin\theta\,\vec{1}_{\phi} \end{cases}$$



given field E (for example V/d)

$\Delta\varepsilon>0$: lowest energy when L and E are parallel

$\Delta\varepsilon<0$: lowest energy when L and E are perpendicular

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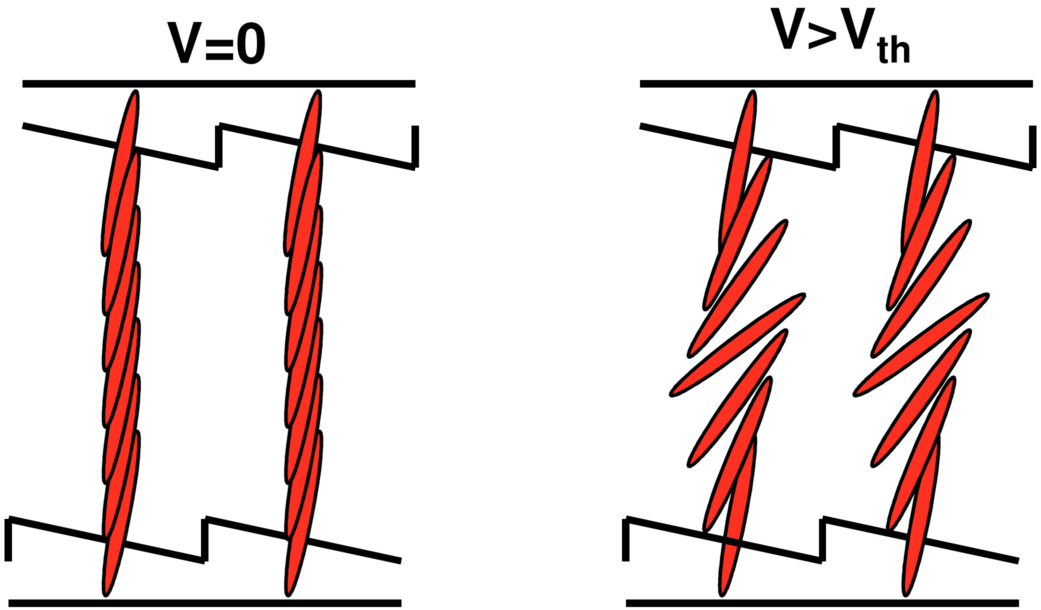
VERTICALLY ALIGNED NEMATIC (VAN)

1D structure, material with $\Delta\varepsilon < 0$, $\Delta n > 0$

homeotropic alignment

- for $V = 0$: $\theta \approx 0$ $\Gamma \approx 0$
- for $V > V_{th}$: molecules rotate: θ , Γ, Δn increase



$$V_{th} = \sqrt{\frac{K_{33}}{|\Delta\varepsilon|}} \cdot \pi$$

bend and splay

pretilt determines switching

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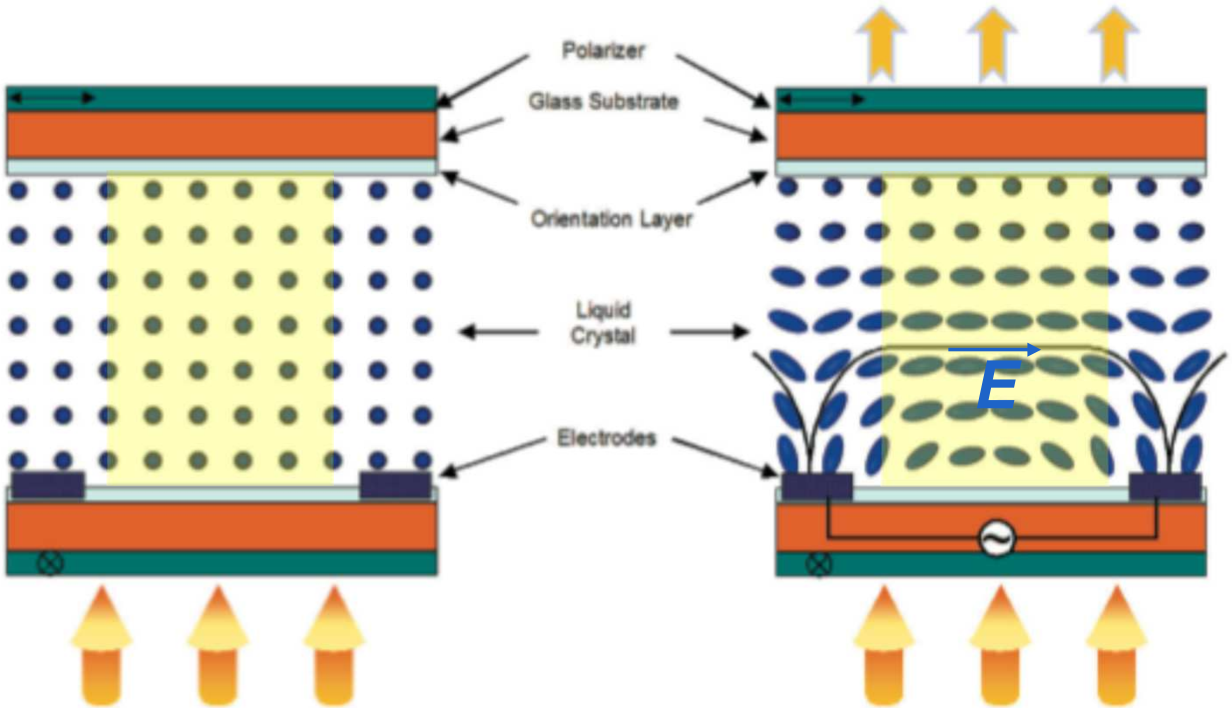
IN PLANE SWITCHING (IPS) MODE

initially: director homogeneous

with voltage: director reorients in plane



IN PLANE SWITCHING (IPS) MODE

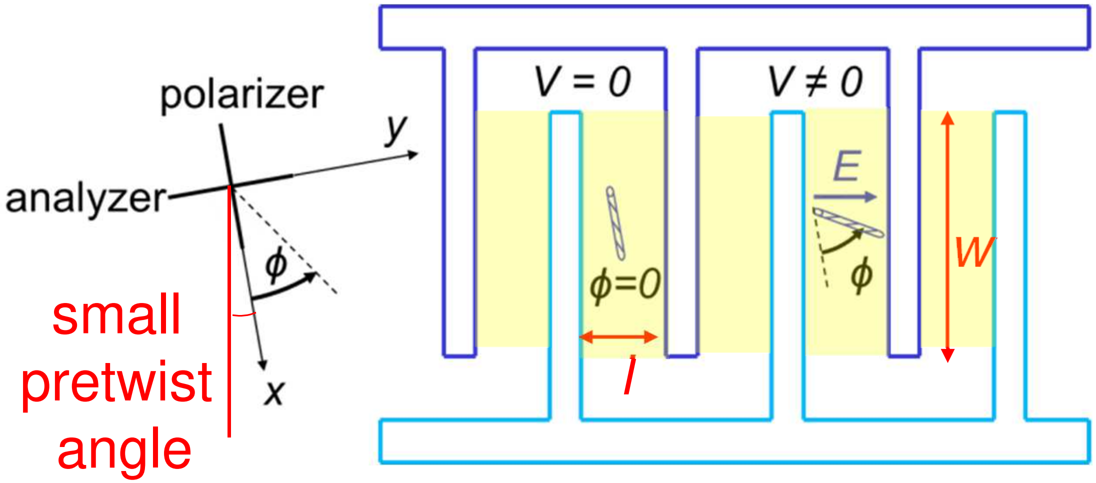
initially: director homogeneous

$\phi=0$ when $V=0$

with voltage: director reorients in plane ($\Delta\varepsilon>0$)

$\phi>0$, increases with V

E-field: $\phi_E=80^o$



interdigitated electrodes

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IN PLANE SWITCHING (IPS) MODE

Variation of the azimuth angle ϕ

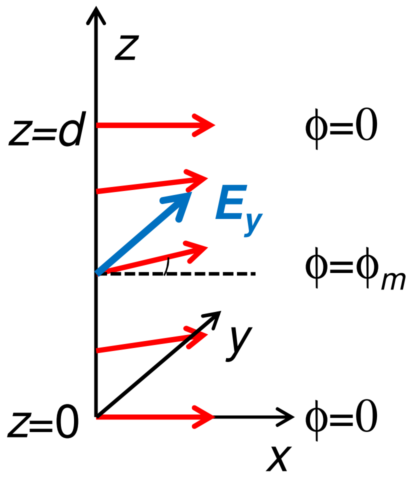
only twist, neglect pretwist, field E_y

$$\phi = \phi_m \sin\left(\frac{\pi z}{d}\right)$$

$$\theta = \pi/2$$

$$\phi_m << 1$$

$$\sin\phi \approx \phi_m \sin\left(\frac{\pi z}{d}\right)$$



$$f_{elastic} = \tfrac{1}{2}\left(K_{11}\left(\sin\theta\frac{\partial\theta}{\partial z}\right)^2 + K_{22}\left(\sin^2\theta\frac{\partial\phi}{\partial z} - q_0\right)^2 + K_{33}\left(\left(\cos\theta\frac{\partial\theta}{\partial z}\right)^2 + \left(\cos\theta\sin\theta\frac{\partial\phi}{\partial z}\right)^2\right)\right)$$

$$F_{elastic} = \tfrac{1}{2}K_{22}wl\int_0^d\left(\frac{\partial\phi}{\partial z}\right)^2 dz = \tfrac{1}{2}K_{22}wl\int_0^d\left(\phi_m\frac{\pi}{d}\cos\left(\frac{\pi z}{d}\right)\right)^2 dz = \tfrac{1}{4}K_{22}wl\left(\phi_m\frac{\pi}{d}\right)^2 d$$

IN PLANE SWITCHING (IPS) MODE

Variation of the azimuth angle ϕ

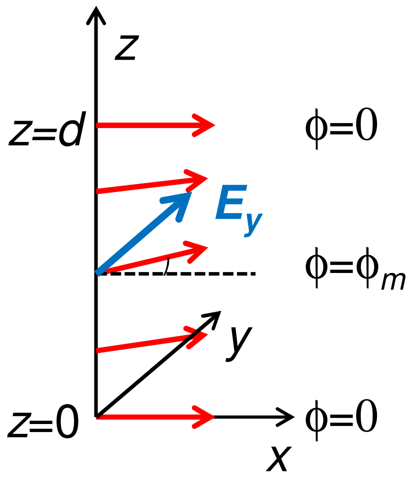
only twist, neglect pretwist, field E_y

$$\phi = \phi_m \sin\left(\frac{\pi z}{d}\right)$$

$$\theta = \pi/2$$

$$\phi_m << 1$$

$$\sin\phi \approx \phi_m \sin\left(\frac{\pi z}{d}\right)$$



$$f_{electric} = -\tfrac{1}{2}\varepsilon_\perp E^2 - \tfrac{1}{2}\Delta\varepsilon\left(\bar{E}\cdot\bar{L}\right)^2$$

$$F_{electric} = -\tfrac{1}{2}wl\int_0^d\left(\varepsilon_\perp + \Delta\varepsilon\sin^2\phi\right)E^2dz = -\tfrac{1}{2}wl\int_0^d\left(\varepsilon_\perp + \Delta\varepsilon\left(\phi_m\sin\left(\frac{\pi z}{d}\right)\right)^2\right)\frac{V^2}{l^2}dz$$

$$= -\tfrac{1}{2}wl\varepsilon_\perp\frac{V^2}{l^2}d - \tfrac{1}{4}wl\cdot\Delta\varepsilon\cdot\phi_m^2\frac{V^2}{l^2}d$$

IN PLANE SWITCHING (IPS) MODE

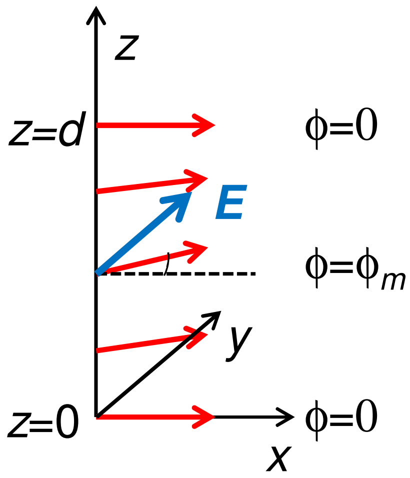
Variation of the azimuth angle ϕ

only twist, field E_y

$$\phi = \phi_m \sin\left(\frac{\pi z}{d}\right) \qquad \theta = \pi/2$$

$$\phi_m << 1$$

$$\sin\phi \approx \phi_m \sin\left(\frac{\pi z}{d}\right)$$



$$F_{total} = F_{elastic} + F_{electric} = \tfrac{1}{4} K_{22} wl \left(\phi_m \frac{\pi}{d}\right)^2 d - \tfrac{1}{2} wl\varepsilon_\perp \frac{V^2}{l^2} d - \tfrac{1}{4} wl \cdot \Delta\varepsilon \cdot \phi_m^2 \frac{V^2}{l^2} d$$

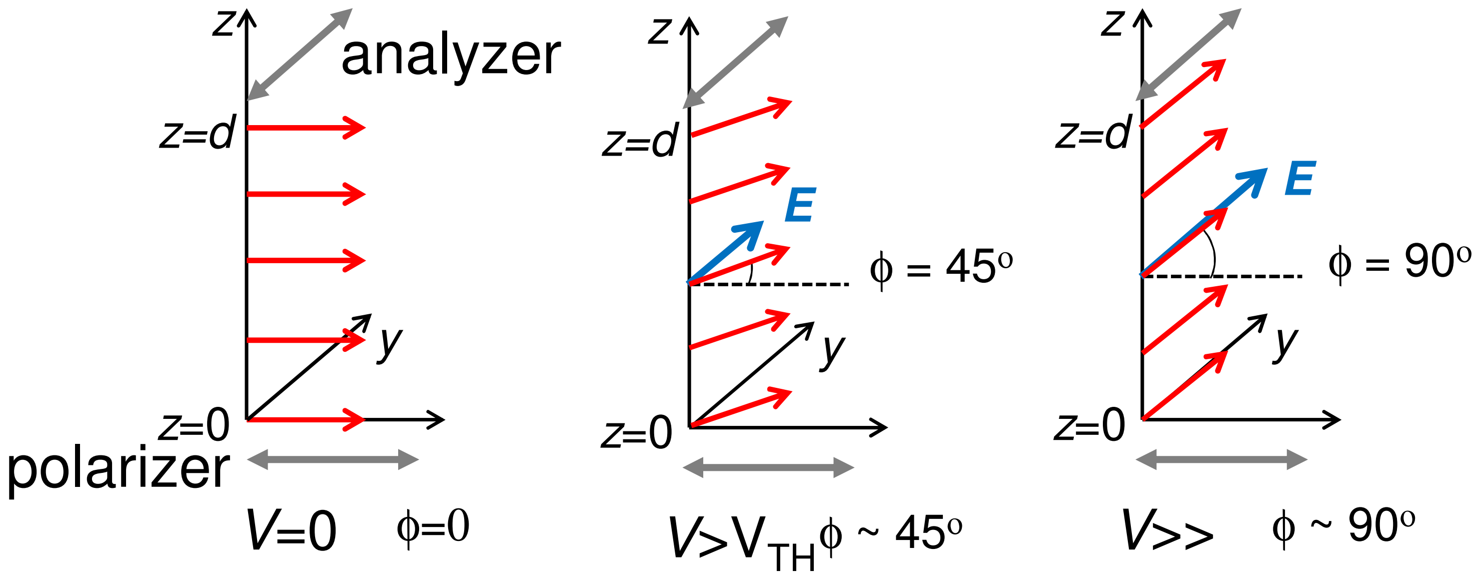
$$\frac{\partial F_{total}}{\partial \phi_m} = \tfrac{1}{4} K_{22} wl\, 2\phi_m \frac{\pi^2}{d} - \tfrac{1}{4} wl \cdot \Delta\varepsilon \cdot 2\phi_m \frac{V^2}{l^2} d = \tfrac{1}{2} wl\phi_m \left(\underline{K_{22} \frac{\pi^2}{d} - \Delta\varepsilon \frac{V^2}{l^2} d} \right)$$

threshold voltage makes this zero

$$\boxed{V_{TH} = \pi \frac{l}{d} \sqrt{\frac{K_{22}}{\Delta\varepsilon}}} \qquad V < V_{TH} \rightarrow \quad \phi = 0$$

IN PLANE SWITCHING (IPS) MODE

Transmission? ~ layer with homogeneous ϕ (*V*)



dark state | bright state | dark state

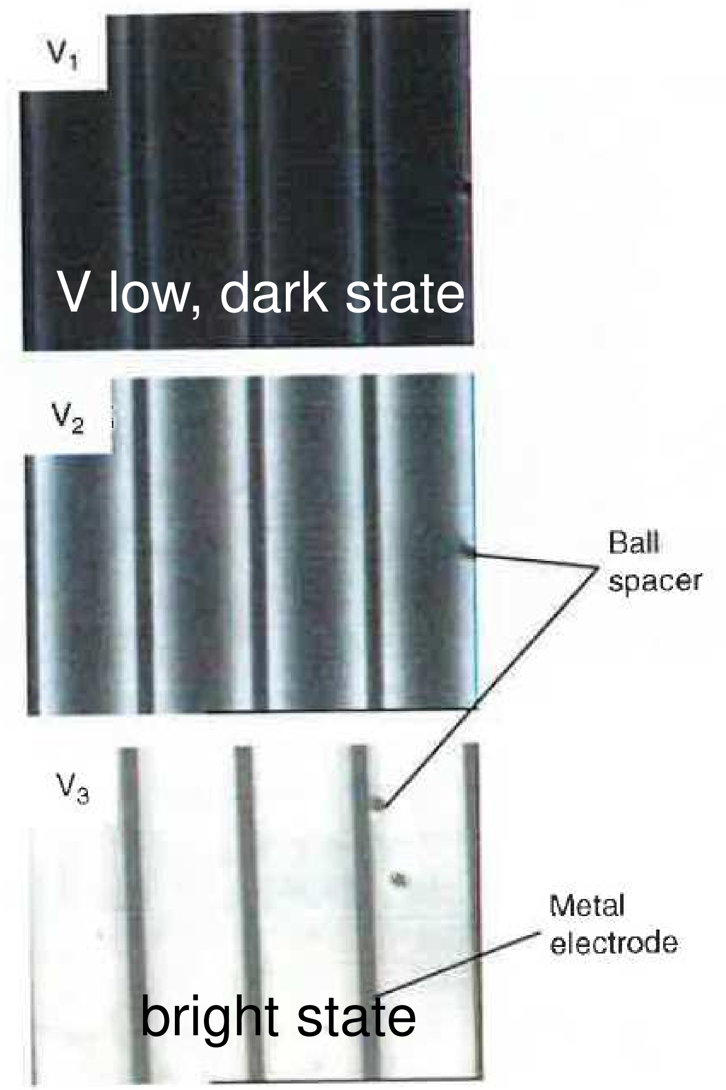
$$T = \frac{1}{2}\sin^2 2\phi \sin^2\left(\underbrace{\frac{\pi(n_e - n_o)d}{\lambda}}_{\Gamma/2}\right)$$

IN PLANE SWITCHING (IPS) MODE

Images of IPS transmission

switching occurs first
near the electrodes
(highest field)

areas above the electrodes
do not switch and remain dark
Al can be used instead of ITO
(lower brightness)

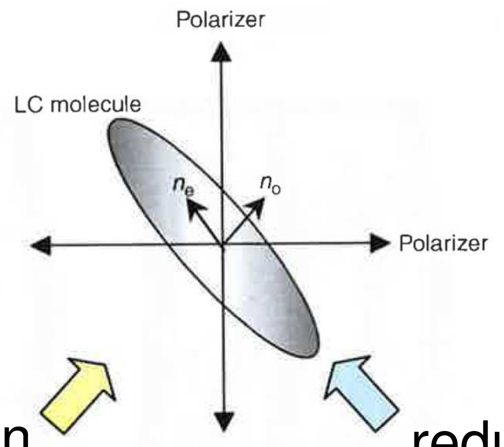


IN PLANE SWITCHING (IPS) MODE

viewing angle dependency (off-normal) of the bright state?
(bright state, φ=45^{o} is optimized for green)

small dependency (<VA), because the director is planar, retardation depends on the azimuth of observation

vertical:
retardation $\Gamma = \pi$
for green light



increased retardation
(see next slide)
$\Gamma=\pi$ for yellow

reduced retardation Γ
because $n_{eff} < n_e$
$\Gamma=\pi$ for blue

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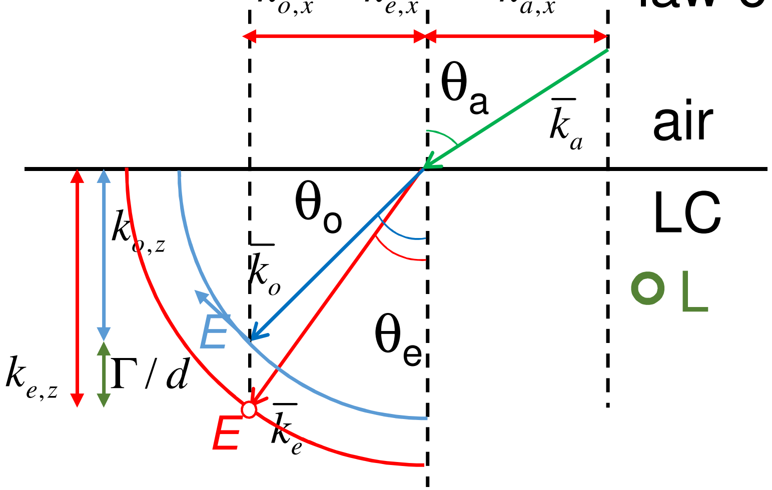
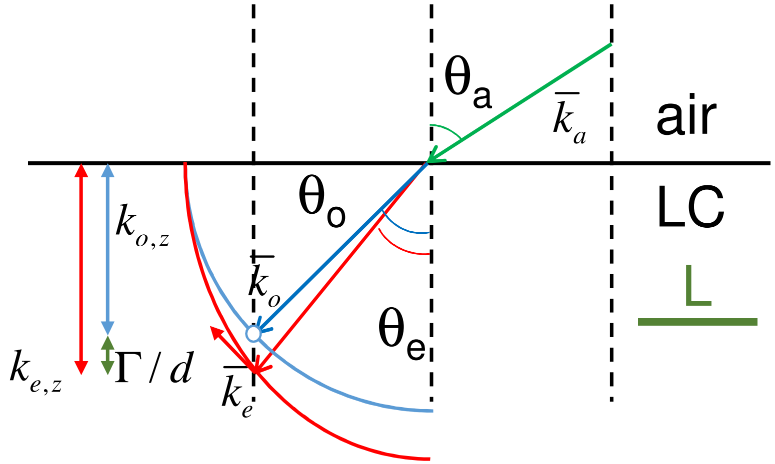
EXTENDED JONES CALCULUS (OFF-ANGLE)

law of Snellius





$$\Gamma = k_{e,z} d - k_{o,z} d$$
$$= \frac{2\pi d}{\lambda}\left(n_e \cos\theta_e - n_o \cos\theta_o\right)$$
$$= \frac{2\pi d}{\lambda}\left(\sqrt{n_e^2 - \sin^2\theta_a} - \sqrt{n_o^2 - \sin^2\theta_a}\right)$$

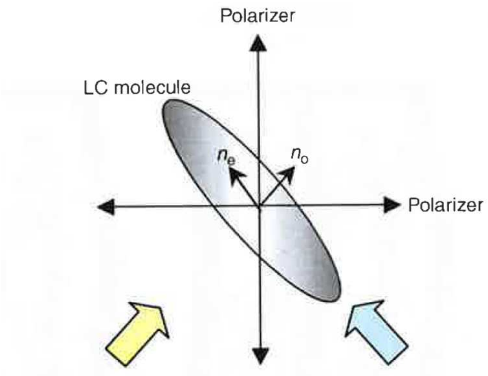
Γ increases with θ_a

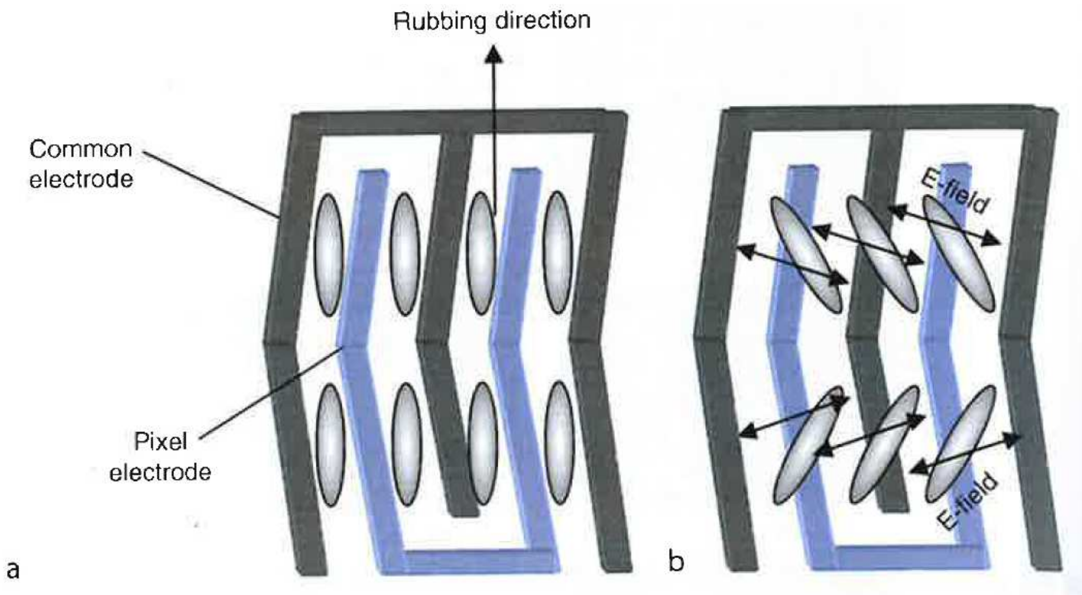
$$\Gamma = k_{e,z} d - k_{o,z} d$$
$$= \frac{2\pi d}{\lambda}\left(n_{eff} \cos\theta_e - n_o \cos\theta_o\right)$$
$$= \frac{2\pi d}{\lambda}\left(\sqrt{n_{eff}^2 - \sin^2\theta_a} - \sqrt{n_o^2 - \sin^2\theta_a}\right)$$

Γ decreases with θ_a

IN PLANE SWITCHING (IPS) MODE

Multi-domain to solve viewing angle problems





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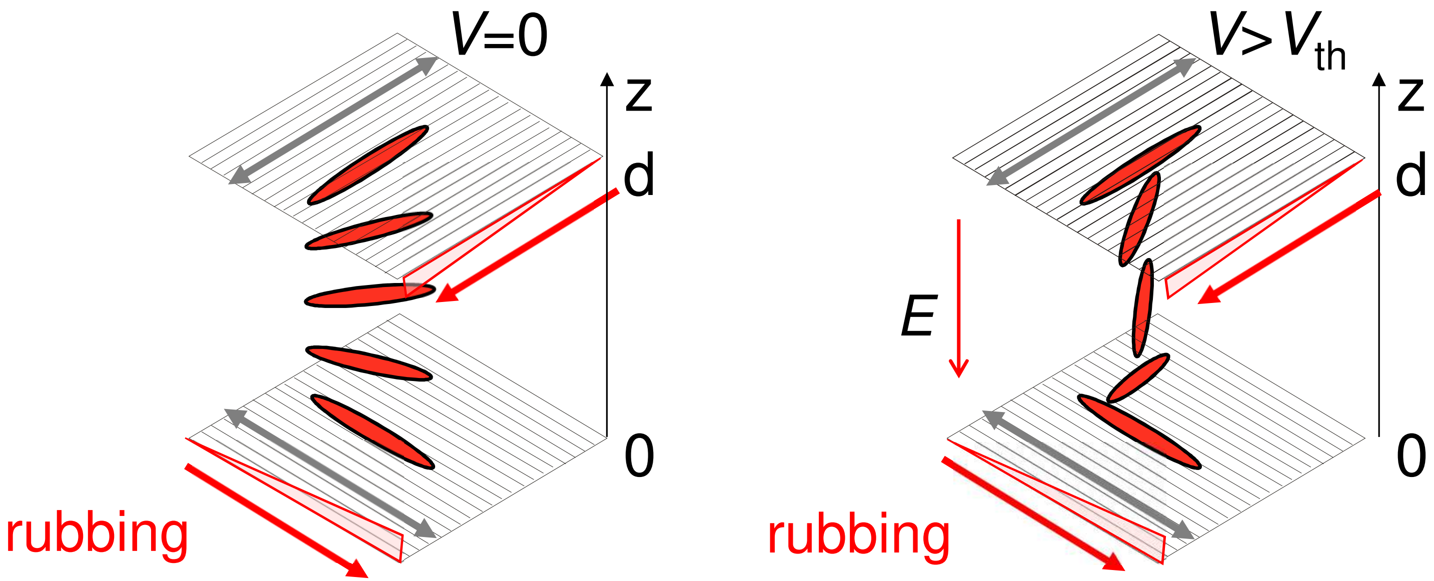
TWISTED NEMATIC MODE

Cell with initial twist of 90°



pure twist
bright state

LC aligns with the field
some splay and bend
dark state

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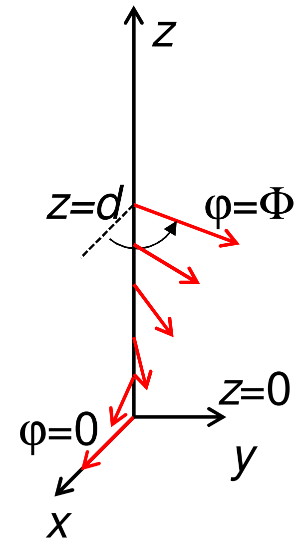
LAYER WITH TWIST

A layer with total thickness *d* and total twist Φ
can be treated as *N* layers each with

- thickness *d*/*N*
- retardation Γ/N
- azimuth of *L*: $\varphi(z)=\Phi . z/d$

$$\Gamma = \frac{2\pi}{\lambda}\left(n_{eff} - n_o\right)d$$



$$\overline{\overline{J}}_{tot} = \overline{\overline{J}}\left(\Phi, \frac{\Gamma}{N}\right) \cdot \overline{\overline{J}}\left(\frac{N-1}{N}\Phi, \frac{\Gamma}{N}\right) \cdot \ldots \cdot \overline{\overline{J}}\left(\frac{1}{N}\Phi, \frac{\Gamma}{N}\right)$$

$$= \prod_{n=1}^{N} \overline{\overline{J}}\left(\frac{n}{N}\Phi, \frac{\Gamma}{N}\right)$$

$$= \prod_{n=1}^{N} \underbrace{\begin{bmatrix} \cos\frac{n\Phi}{N} & -\sin\frac{n\Phi}{N} \\ \sin\frac{n\Phi}{N} & \cos\frac{n\Phi}{N} \end{bmatrix}}_{R} \begin{bmatrix} e^{-i\Gamma/2N} & 0 \\ 0 & e^{i\Gamma/2N} \end{bmatrix} \underbrace{\begin{bmatrix} \cos\frac{n\Phi}{N} & \sin\frac{n\Phi}{N} \\ -\sin\frac{n\Phi}{N} & \cos\frac{n\Phi}{N} \end{bmatrix}}_{R^{-1}}$$

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LAYER WITH TWIST

Total Jones matrix for N layers?

$$\bar{\bar{J}}_{tot} = \prod_{n=1}^{N} \begin{bmatrix} \cos\frac{n\Phi}{N} & -\sin\frac{n\Phi}{N} \\ \sin\frac{n\Phi}{N} & \cos\frac{n\Phi}{N} \end{bmatrix} \begin{bmatrix} e^{-i\Gamma/2N} & 0 \\ 0 & e^{i\Gamma/2N} \end{bmatrix} \begin{bmatrix} \cos\frac{n\Phi}{N} & \sin\frac{n\Phi}{N} \\ -\sin\frac{n\Phi}{N} & \cos\frac{n\Phi}{N} \end{bmatrix}$$

$$= \ldots$$

$$= \begin{bmatrix} \cos\Phi & -\sin\Phi \\ \sin\Phi & \cos\Phi \end{bmatrix} \left\{ \begin{bmatrix} e^{-i\Gamma/2N} & 0 \\ 0 & e^{i\Gamma/2N} \end{bmatrix} \begin{bmatrix} \cos\frac{\Phi}{N} & \sin\frac{\Phi}{N} \\ -\sin\frac{\Phi}{N} & \cos\frac{\Phi}{N} \end{bmatrix} \right\}^N$$

$$= \begin{bmatrix} \cos\Phi & -\sin\Phi \\ \sin\Phi & \cos\Phi \end{bmatrix} \begin{Bmatrix} \cos\frac{\Phi}{N} e^{-i\Gamma/2N} & \sin\frac{\Phi}{N} e^{-i\Gamma/2N} \\ -\sin\frac{\Phi}{N} e^{i\Gamma/2N} & \cos\frac{\Phi}{N} e^{i\Gamma/2N} \end{Bmatrix}^N$$

Power N of a matrix?

LAYER WITH TWIST

Power of a matrix? diagonalize the matrix by finding the eigenvalues λ and the eigenvectors

$$\begin{Bmatrix} \cos\frac{\Phi}{N}e^{-i\Gamma/2N} & \sin\frac{\Phi}{N}e^{-i\Gamma/2N} \\ -\sin\frac{\Phi}{N}e^{i\Gamma/2N} & \cos\frac{\Phi}{N}e^{i\Gamma/2N} \end{Bmatrix}^N ? \qquad \begin{vmatrix} \cos\frac{\Phi}{N}e^{-i\Gamma/2N}-\lambda & \sin\frac{\Phi}{N}e^{-i\Gamma/2N} \\ -\sin\frac{\Phi}{N}e^{i\Gamma/2N} & \cos\frac{\Phi}{N}e^{i\Gamma/2N}-\lambda \end{vmatrix}=0$$

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LAYER WITH TWIST

eigenvectors of the matrix?

$$\begin{pmatrix} J_x \\ J_y \end{pmatrix} \approx \begin{pmatrix} \Phi \\ i\frac{\Gamma}{2} \pm i\Omega \end{pmatrix}$$

$$\Omega = \sqrt{\Phi^2 + \frac{\Gamma^2}{4}}$$

eigenmodes

short pitch CLC

for $\Phi >> \Gamma$ $\begin{pmatrix} J_x \\ J_y \end{pmatrix} \sim \begin{pmatrix} 1 \\ \pm i \end{pmatrix}$ circular P

circularly polarized light

RH and LH with different speed

long pitch: Mauguin

for $\Gamma >> \Phi$ $\begin{pmatrix} J_x \\ J_y \end{pmatrix} \sim \begin{pmatrix} 0 \\ 1 \end{pmatrix}; \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ linear P

polarized parallel and perp

to the director

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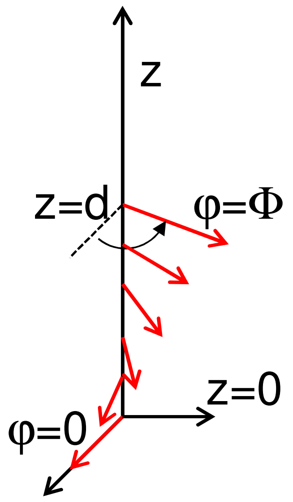
LAYER WITH TWIST

A layer with total thickness *d* and twist Φ

$$\Gamma = \frac{2\pi}{\lambda}\left(n_{eff} - n_o\right)d \qquad \Omega = \sqrt{\Phi^2 + \frac{\Gamma^2}{4}}$$



$$\overline{\overline{J}}_{tot} = \prod_{n=1}^{N} \overline{\overline{J}}\left(\frac{n}{N}\Phi, \frac{\Gamma}{N}\right)$$

$$= \overline{\overline{J}}_{tot} = \begin{bmatrix} \cos\Phi & -\sin\Phi \\ \sin\Phi & \cos\Phi \end{bmatrix} \begin{pmatrix} \cos\Omega - i\frac{\Gamma}{2}\frac{\sin\Omega}{\Omega} & \Phi\frac{\sin\Omega}{\Omega} \\ -\Phi\frac{\sin\Omega}{\Omega} & \cos\Omega + i\frac{\Gamma}{2}\frac{\sin\Omega}{\Omega} \end{pmatrix}$$

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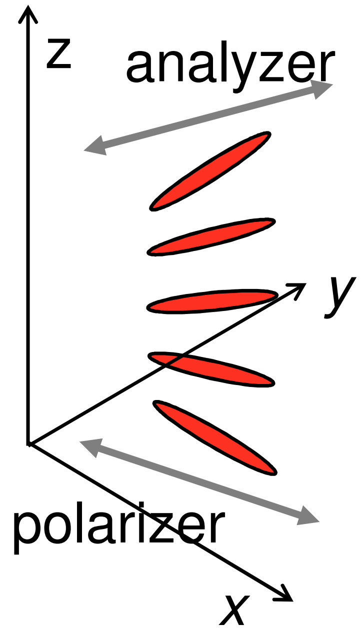
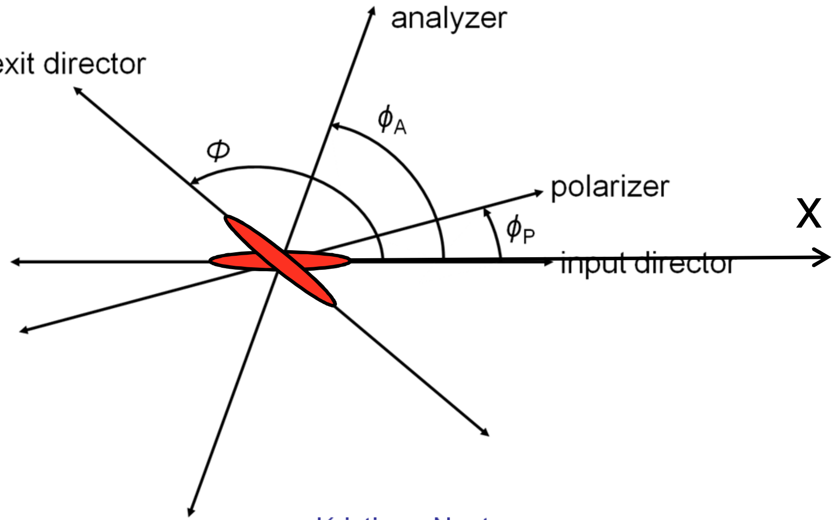
TWISTED NEMATIC MODE

Transmission in the off state?

$$\overline{\overline{J}}_{TN} = \begin{bmatrix} \cos\Phi & -\sin\Phi \\ \sin\Phi & \cos\Phi \end{bmatrix} \begin{pmatrix} \cos\Omega - i\dfrac{\Gamma}{2}\dfrac{\sin\Omega}{\Omega} & \Phi\dfrac{\sin\Omega}{\Omega} \\ -\Phi\dfrac{\sin\Omega}{\Omega} & \cos\Omega + i\dfrac{\Gamma}{2}\dfrac{\sin\Omega}{\Omega} \end{pmatrix}$$



Jones matrix in the system *xy*



$$\Gamma = \frac{2\pi\Delta n d}{\lambda}$$

$$\Omega = \frac{\sqrt{\Gamma^2 + 4\Phi^2}}{2}$$

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TWISTED NEMATIC MODE

$R(\phi_A)$ $R(-\phi_P)$

$$\begin{pmatrix} E_{out} \\ 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \cos\phi_A & \sin\phi_A \\ -\sin\phi_A & \cos\phi_A \end{pmatrix} \bar{\bar{J}}_{TN} \begin{pmatrix} \cos\phi_P & -\sin\phi_P \\ \sin\phi_P & \cos\phi_P \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} E_{in} \\ 0 \end{pmatrix}$$

$$= \begin{pmatrix} \cos\phi_A & \sin\phi_A \\ 0 & 0 \end{pmatrix} \begin{bmatrix} \cos\Phi & -\sin\Phi \\ \sin\Phi & \cos\Phi \end{bmatrix} \begin{pmatrix} \cos\Omega - i\frac{\Gamma}{2}\frac{\sin\Omega}{\Omega} & \Phi\frac{\sin\Omega}{\Omega} \\ -\Phi\frac{\sin\Omega}{\Omega} & \cos\Omega + i\frac{\Gamma}{2}\frac{\sin\Omega}{\Omega} \end{pmatrix} \begin{pmatrix} \cos\phi_P E_{in} \\ \sin\phi_P E_{in} \end{pmatrix}$$

$$= \begin{pmatrix} \cos(\Phi-\phi_A) & -\sin(\Phi-\phi_A) \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \cos\Omega - i\frac{\Gamma}{2}\frac{\sin\Omega}{\Omega} & \Phi\frac{\sin\Omega}{\Omega} \\ -\Phi\frac{\sin\Omega}{\Omega} & \cos\Omega + i\frac{\Gamma}{2}\frac{\sin\Omega}{\Omega} \end{pmatrix} \begin{pmatrix} \cos\phi_P E_{in} \\ \sin\phi_P E_{in} \end{pmatrix}$$

$$\frac{E_{out}}{E_{in}} = \left(\cos(\Phi-\phi_A)\left(\underline{\cos\Omega} - i\underline{\frac{\Gamma}{2}\frac{\sin\Omega}{\Omega}}\right) + \sin(\Phi-\phi_A)\Phi\underline{\frac{\sin\Omega}{\Omega}}\right)\cos\phi_P E_{in}$$

$$+\left(\cos(\Phi-\phi_A)\Phi\underline{\frac{\sin\Omega}{\Omega}} - \sin(\Phi-\phi_A)\left(\underline{\cos\Omega} + i\underline{\frac{\Gamma}{2}\frac{\sin\Omega}{\Omega}}\right)\right)\sin\phi_P E_{in}$$

simpson…

$$= \cos(\Phi-\phi_A+\phi_P)\underline{\cos\Omega} + \sin(\Phi-\phi_A+\phi_P)\Phi\underline{\frac{\sin\Omega}{\Omega}} - i\cos(\Phi-\phi_A-\phi_P)\underline{\frac{\Gamma}{2}\frac{\sin\Omega}{\Omega}}$$

TWISTED NEMATIC MODE

$$\frac{E_{out}}{E_{in}} = \cos(\Phi - \phi_A + \phi_P)\cos\Omega + \sin(\Phi - \phi_A + \phi_P)\Phi\frac{\sin\Omega}{\Omega} - i\cos(\Phi - \phi_A - \phi_P)\frac{\Gamma}{2}\frac{\sin\Omega}{\Omega}$$

$$T = \frac{1}{2}\left[\cos(\Phi - \phi_A + \phi_P)\cos\Omega + \sin(\Phi - \phi_A + \phi_P)\Phi\frac{\sin\Omega}{\Omega}\right]^2 + \frac{1}{2}\left[\cos(\Phi - \phi_A - \phi_P)\frac{\Gamma}{2}\frac{\sin\Omega}{\Omega}\right]^2$$

$$\begin{cases} \Gamma = \dfrac{2\pi\Delta n d}{\lambda} \\ \Omega = \dfrac{\sqrt{\Gamma^2 + 4\Phi^2}}{2} \end{cases}$$

example: 90º twist device, Φ= 90º , ϕ_P = 0º , ϕ_A = 90º

$$\Phi - \phi_A - \phi_P = 0$$

$$\Phi - \phi_A + \phi_P = 0$$

$$T = \frac{1}{2}[\cos\Omega]^2 + \frac{1}{2}\left[\frac{\Gamma}{2}\frac{\sin\Omega}{\Omega}\right]^2$$

$$= \frac{1}{2}\left[\cos^2\Omega + \frac{\Gamma^2}{\Gamma^2 + 4\Phi^2}\sin^2\Omega\right] = \frac{1}{2}\left[1 - \frac{4\Phi^2\sin^2\Omega}{\Gamma^2 + 4\Phi^2}\right]$$

TWISTED NEMATIC MODE

example: 90° twist device, Φ= 90°, ϕ_P = 0°, ϕ_A = 90°

$$T = \frac{1}{2}\left[1 - \frac{4\Phi^2 \sin^2\Omega}{\Gamma^2 + 4\Phi^2}\right]$$

Maximum transmission *T*=1/2 when: $\sin\Omega = 0$

$$\Omega = \frac{\sqrt{\Gamma^2 + 4\Phi^2}}{2} = m\pi$$

$$\Rightarrow \quad \Gamma^2 = 4\pi^2\left(m^2 - \tfrac{1}{4}\right)$$

$$\Rightarrow \quad \frac{\Delta n d}{\lambda} = \sqrt{m^2 - \tfrac{1}{4}}$$

Condition of Gooch and Tarry
chosen for λ=550 nm, *m*=1

example: $$d = \sqrt{m^2 - \tfrac{1}{4}}\,\frac{\lambda}{\Delta n} = \sqrt{\frac{3}{4}}\,\frac{550\text{ nm}}{0.2} = 2.38\ \mu\text{m}$$

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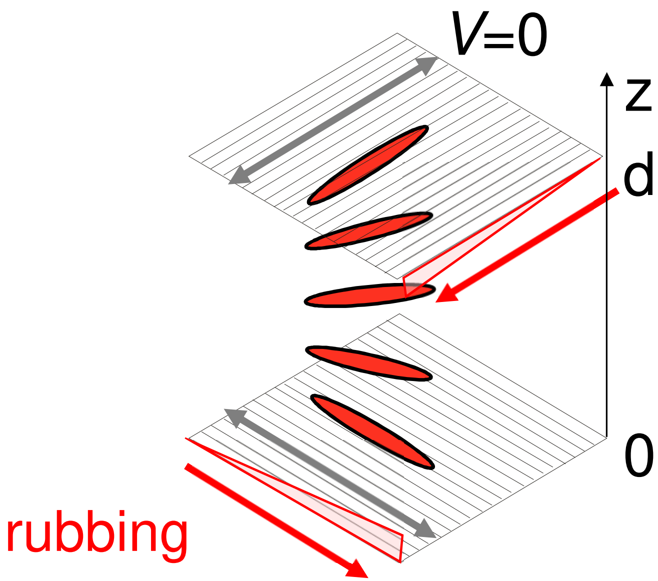
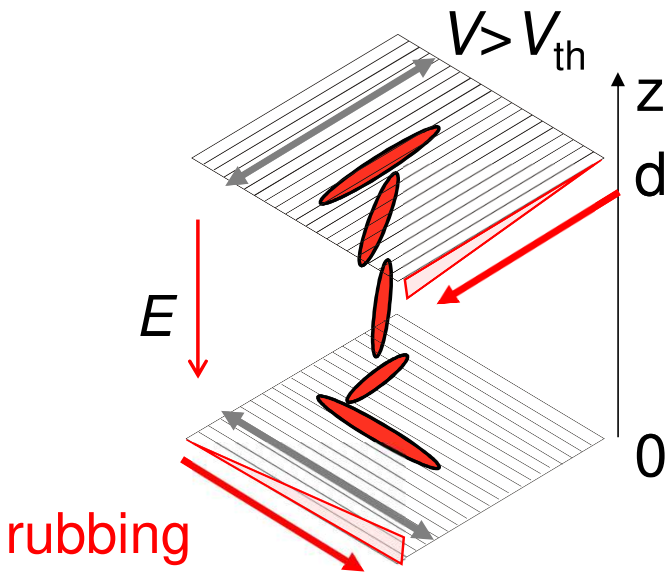
TWISTED NEMATIC MODE

switching: threshold voltage?





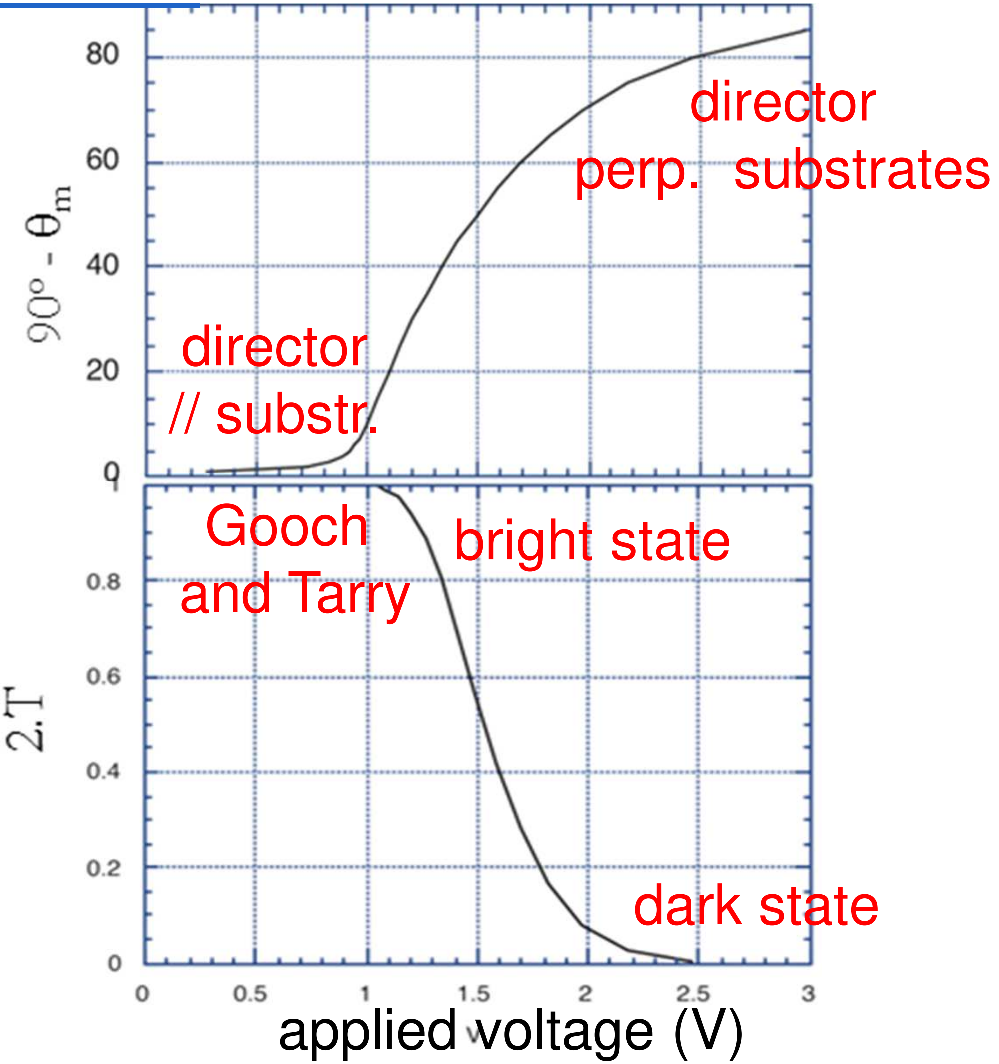
$$V < V_{th} = \pi\sqrt{\frac{K_{11} - \frac{1}{2}K_{23} + \frac{1}{4}K_{33}}{\Delta\varepsilon}}$$

$$V > V_{th}$$

TWISTED NEMATIC MODE

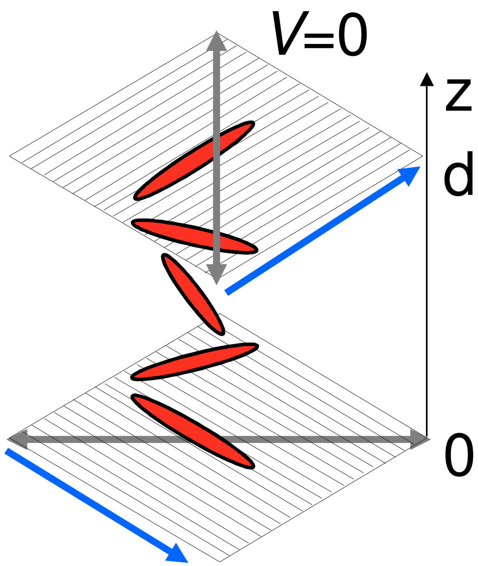
mid-plane tilt

transmission

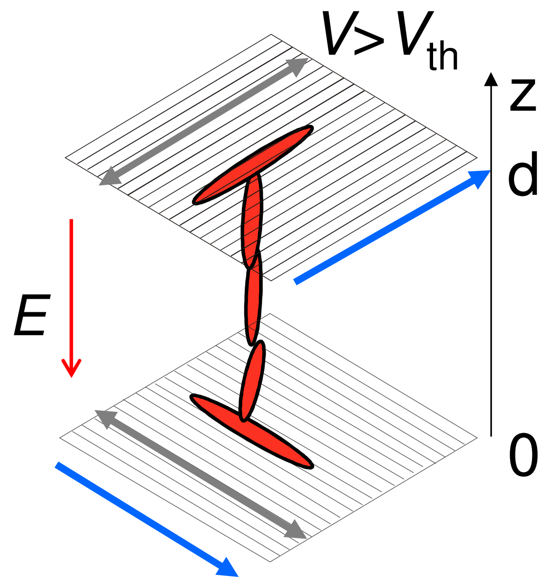


SUPER TWISTED NEMATIC MODE

Cell with larger initial twist (ex: 270°)



pure twist
bright state
(chiral dopant needed)



LC aligns with the field
some splay and bend
dark state

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SUPER TWISTED NEMATIC MODE

example: 270° twist device, Φ= 270° , ϕ_P = 45° , ϕ_A = 315°

$$T = \frac{1}{2}\left[\cos\left(\Phi-\phi_A+\phi_P\right)\cos\Omega+\sin\left(\Phi-\phi_A+\phi_P\right)\Phi\frac{\sin\Omega}{\Omega}\right]^2$$

$$+\frac{1}{2}\left[\cos\left(\Phi-\phi_A-\phi_P\right)\frac{\Gamma}{2}\frac{\sin\Omega}{\Omega}\right]^2$$

$$\begin{cases}\phi_P=45^o\\ \Phi-\phi_A=-45^o\end{cases}\Rightarrow\begin{cases}\Phi-\phi_A+\phi_P=0\\ \Phi-\phi_A-\phi_P=-90^o\end{cases}$$

$$\Rightarrow T=\frac{1}{2}\cos^2\Omega=\frac{1}{2}\cos^2\sqrt{\left(\frac{\pi\Delta nd}{\lambda}\right)^2+\Phi^2}$$

Maximum transmission (bright) T=1/2 when

$$\Omega=\frac{\sqrt{\Gamma^2+4\Phi^2}}{2}=\sqrt{\left(\frac{\pi\Delta nd}{\lambda}\right)^2+\Phi^2}=m\pi$$

$$\Rightarrow \frac{\Delta nd}{\lambda}=\sqrt{m^2-\left(\frac{\Phi}{\pi}\right)^2}$$

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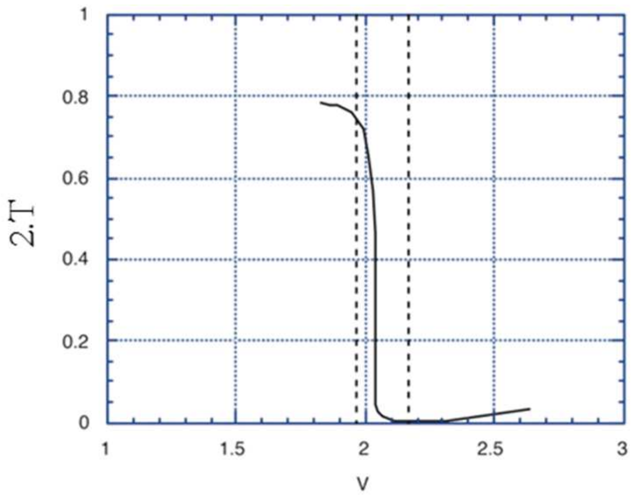
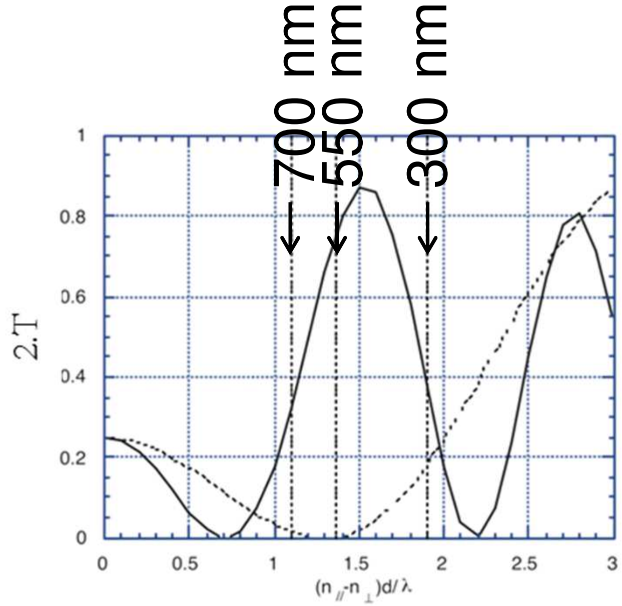
SUPER TWISTED NEMATIC MODE

example: 270° twist device, Φ= 270° , ϕ_P = -30° , ϕ_A = 210°

different values to obtain good dark state (and $2T_{bright}$<1)



steep *T-V* characteristic



green bright state
purple dark state

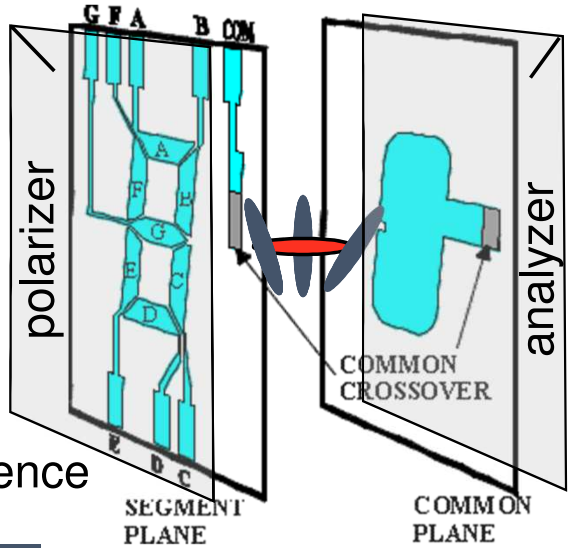
DIRECT DRIVING

LCD reacts to $|V^2|$

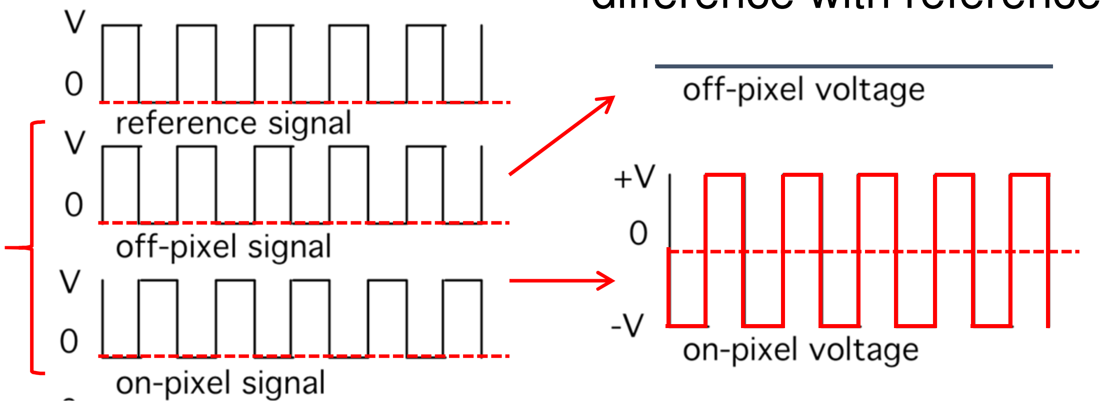
AC driving to avoid chemical reactions in the LC

one electrode per segment

reflective display



difference with reference



TN – LCD

off: bright state

on: dark state

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