
Appendix A

A.1 What are liquid crystals?

Solid, liquid and gaseous states are three well known states of matter. Solid may be either crystalline or amorphous. In a crystalline state of matter, the solid forms a three-dimensional lattice having both positional and orientational order. When it is heated above the melting point, it turns into an isotropic liquid having neither positional nor orientational order. Similarly on cooling, the isotropic liquid converts into crystalline solid. Some materials exhibit an intermediate state of matter called the liquid crystalline state between a solid crystal and an isotropic liquid. In liquid crystalline state the fluid appears turbid and is found to be strongly birefringent when observed between cross polarizers.

The discovery of liquid crystals is thought to have occurred nearly 150 years. In 1877, Otto, Lehmann used a polarizing microscope with a heated stage to investigate the phase transitions of various substances. He found that one substance would change from a clear liquid to a cloudy liquid before crystallising but thought that this was simply an imperfect phase transition from liquid to crystalline state. Austrian botanist Friedrich Reinitzer observed that, when cholesteryl benzoate became a cloudy liquid and then to isotropic phase on heating. Upon cooling, the liquid **turned** blue before finally crystallizing. He was the first to suggest that this cloudy fluid is a new phase of matter in the year 1888. Consequently, he has been given the credit for the discovery of the liquid crystalline phase.

A.2 Types of liquid crystals

There are two main classes of liquid crystals – thermotropic and lyotropic. The phase transitions of thermotropic liquid crystals depend on temperature, while those of lyotropic liquid crystals depend on both temperature and concentration. Thermotropic liquid crystals are used in display applications. Most nematic liquid crystals consist of molecules shaped like the rod have no periodic structure, but remain approximately parallel to one another as shown in Figure A-1a. The direction of the long axis is called the director \hat{n} , is apolar in nature, i.e., $+\hat{n}$ and $-\hat{n}$ are physically equivalent. Rod shaped molecules are also termed calamitic. Other shapes of molecules are disk-shape (discotic) [41] and bent-shape (banana) [42] as shown in Figure A-1b and Figure A-1c respectively. Apart from the thermotropic and lyotropic definitions, liquid crystal are classified into four types

depending on molecular arrangements i.e., nematic, cholesteric, smectic and columnar liquid crystals. In the following section a very brief description of these liquid crystals is given.

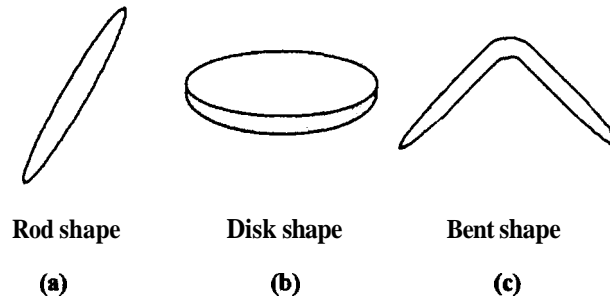


Figure A-1 Schematic of (a) Rod shape, (b) Disk shape and (c) Bent shape liquid crystals

A.2.1 Nematic liquid crystal

The name nematic is derived from the Greek word *nematos* meaning thread-like. Nematic liquid crystals, when viewed between crossed polarizers through a microscope, have threads distributed all over the **area**. In the nematic state the only restriction is that molecules should be more or less parallel to each other. This type of ordering is called orientational ordering as shown in Figure A-2. Molecules can move in all the three dimensions and can rotate freely along the long molecular axes. The average direction of the long axis of the molecules is called the director. Nematic liquid crystals are the most widely used liquid crystals in the display applications.

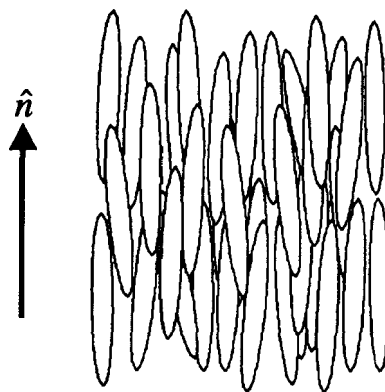


Figure A-2 Schematic of the Nematic liquid crystalain phase

A.2.2 *Smectic liquid crystal*

The smectic liquid crystals are closer to solids as they exhibit one-dimensional positional order as well as orientational order. Based on miscibility and X-ray studies smectic phases are further classified into **SmA**, **SmB**, **SmC**, ..., **SmK** depending on the molecular arrangement within the layers. Figure A-3 shows the schematic representation of **SmA** and **SmC** phases.

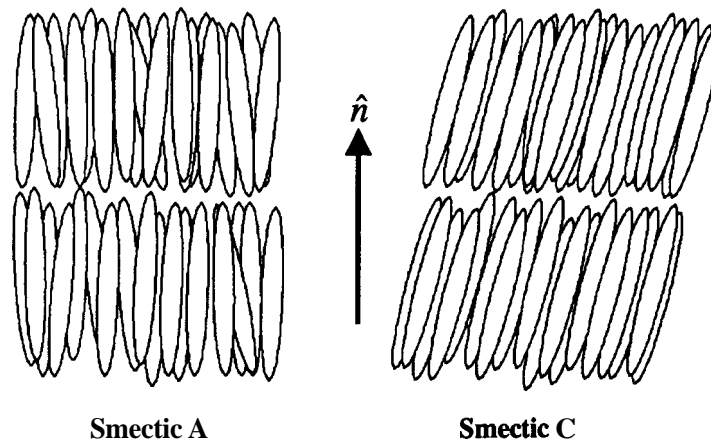


Figure A-3 Schematic of Smectic A and Smectic C liquid crystals

A.2.3 *Cholesteric liquid crystal*

Cholesteric liquid crystal is thermodynamically equivalent to a nematic except for the chiral induced twist in the directors, as shown in Figure A-4. This twist is due to the presence of one or more chiral centers within the molecules. Cholesteric liquid crystals are not regarded as a separate phase but just as a nematic phase having a finite pitch.

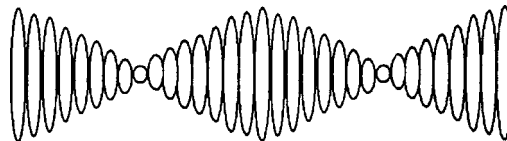


Figure A-4 Schematic of the Cholesteric liquid crystals

A.2.4 *Columnar liquid crystal*

Discotic liquid crystal molecules contain disk-like cores. They stack to form columnar phases with long-range two-dimensional order of the columns and liquid-like intracolumnar order as shown in Figure A-5.

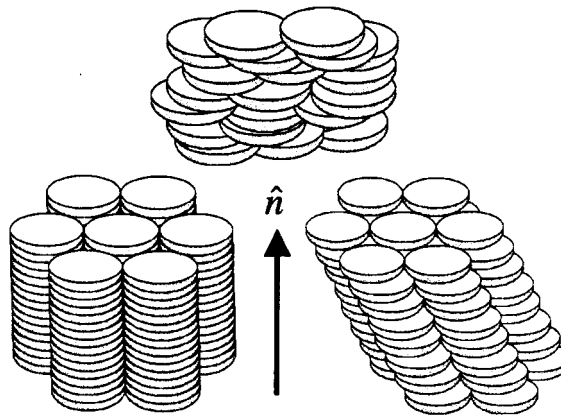


Figure A-5 Schematic of the disk shaped liquid crystals arranged in the columnar phase

A.3 Properties of liquid crystals

The performance of display is dependent on elastic constants, dielectric anisotropy, birefringence and viscosity [43]. None of the single liquid crystal material has all the physical properties required for a display. The mixtures presently being used in liquid crystal displays (LCDs) are eutectic mixtures of chemically and photochemically stable mesogens. The material properties of these mixtures are also being tweaked by taking proper components from the structural point of view and by varying the compositions.

A.4 Liquid Crystal Materials

There are many criteria's in making liquid crystal materials for many practical applications. Main criteria for display applications are, broad range liquid crystalline phase around room temperature, good chemical and photochemical stability, low viscosity, large dielectric anisotropy and the degree of ordering of molecule orientation. A typical rod-like liquid crystal molecule has a molecular structure as shown in Figure A-6. Core (A,B and C) can be defined as a rigid part containing the linking groups (A) and X ,Y are terminal groups.



Figure A-6 Schematic of the typical molecular structure of rod-like liquid crystal molecule.

By various combinations of the core, central linkage and terminal groups, practical liquid crystal compounds can be designed and synthesized. As already said, it is difficult to find a

single liquid crystal compound that has all the characteristics required for a display applications. The liquid crystal materials for various display types are also varies from low information content displays for wristwatches, calculators to high information content applications like Personal Digital Assistants and **laptops** etc.

A.5 Liquid crystal cell

A liquid crystal cell consists of a thin layer of a liquid crystal material sandwiched between two glass plates. The glass substrate is uniformly coated with a transparent conducting material for electrical connectivity. The transparent conducting layer is usually Indium oxide or indium tin oxide (**ITO**). The optical transmission coefficient of the transparent conducting layer is at least 90% and the surface resistivity is some tens or hundreds of ohms. The electrode patterns are obtained by etching the unwanted portions in the transparent conducting layer. Thermosetting epoxy adhesive is widely used as a sealant to seal the liquid crystal cell. In order to maintain uniform cell gap glass fibers or glass beads with a uniform diameter are used as spacers. The gap between the two glass plates is typically 4–10 μm . A uniform and stable liquid crystal molecular alignment is essential for a liquid crystal cell. This is because most of the **electro-optic** effects depend on the liquid crystal having an initial molecular orientation, which is changed to a new orientation under the effect of an external electric field. The main liquid crystal molecular alignments are shown in Figure A-7 at the inner surface of the cell. The three main liquid crystal molecules alignments are briefly explained below.

A.5.1 Liquid Crystal alignment

A.5.1.1 Homeotropic

The liquid crystal molecules are arranged perpendicular to the substrates. The homeotropic alignment is obtained by coating the substrates with a surfactant like octadecyloxysilane (ODSE), which sticks to the surface with the long octadecyl chains projecting away in a direction more or less normal to the surface.

A.5.1.2 Homogeneous

The liquid crystal molecules are uniformly parallel to the surface of the substrates. Polyimides have been used for the homogeneous alignment layers because of high

stability. By buffing the polyimide with a cloth liquid crystal molecules are aligned parallel to substrate with long molecular axis of the molecules in the rubbing direction of rubbing.

A.5.1.3 Tilted

The liquid crystal molecules are tilted at a certain angle to the substrates. It can be achieved by oblique evaporation technique using SiO or MgF_2 .

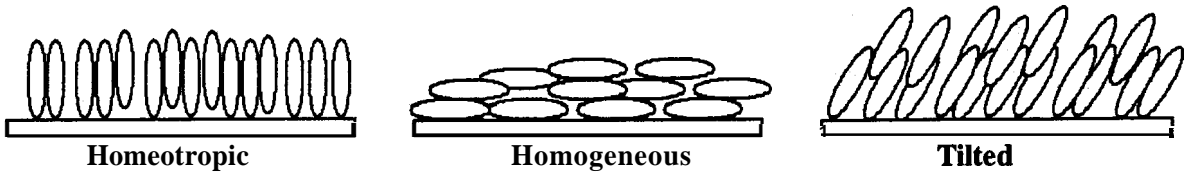


Figure A-7 Types of molecular surface alignment

A.5.1.4 Pretilt angle

The homogeneous alignment process for liquid crystal molecules is necessary for both upper and lower glass substrates with a small pretilt for display applications. The pretilt angle is very important in electro-optic applications when an electric field is applied to the cell to reorient the liquid crystal molecules. The rod-like molecules can turn in two ways following the application of an electric field as shown in the Figure A-8(a) called reverse tilt. This will result in the multi domains since the molecules are oriented in different directions. Which is not preferred in the display applications.

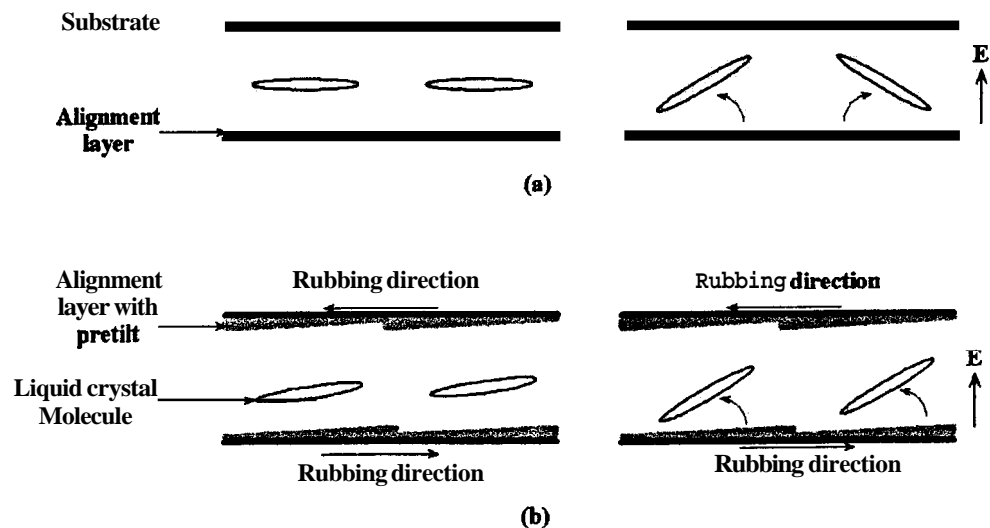


Figure A-8 Schematic representation of (a) reverse tilt in an unrubbed cell and (b) by introducing pretilt to the LC molecules by rubbing to avoid reverse tilt.

A small tilt angle of the molecular axis will help turning all the molecules in the same direction. This will give the single domain, which is very much essential in display applications. The most popular method to form the alignment layer consists of coating the top and bottom glass substrates with a polyimide and by rubbing the polyimide with a cloth. Nanometer (1×10^{-9} meters) size grooves are formed and the liquid crystal molecules align in the direction of the grooves. In the process of rubbing some polyimide strands slightly lift up from the surface along the rubbing direction and the liquid crystal molecules usually tilt up in the direction of rubbing. This produces a pretilt of -2° to 3° which is necessary for a uniform appearance of the display. Thus by introducing pretilt angle, reverse tilt can be eliminated as shown in the Figure A-8(b).

Apart from the reverse tilt the display uniformity will be affected by the reverse twist. That is molecular twist may be left handed and right handed between the two substrates in different places, which forms the multiple domains. The reverse twist is common in the absence of the electrical field. Reverse twist is eliminated by adding cholesteric material so that all the molecules undergo uniform twist depending on the handedness of the cholesteric material.

Hence, the pretilt angle determines what direction the LC molecules have to tilt, when an electrical field is applied and the cholesteric additive decides the liquid crystal molecular twist between the two glass substrates. After the alignment layer, cell assembling is very crucial in order to obtain a uniform cell gap between the two glass substrates. Spacers are used to obtain a uniform cell thickness.

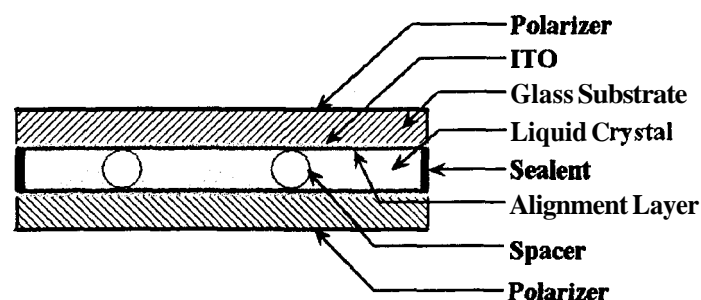


Figure A-9 Schematic representation of liquid crystal cell

After the spacers are scattered on the one of the glass substrate, it is attached to the other glass substrate leaving a small gap to fill the liquid crystal material. Thermosetting epoxy adhesive is used to seal the two glass substrate. The empty cell is filled with liquid crystal material and the fill hole is immediately sealed by adhesive epoxy resins that have no chemical interaction with the liquid crystal material to avoid contamination. **Polarizers** are attached to the liquid crystal cell in the end. Figure A-9 shows the cross-section of a liquid crystal display cell.

A.6 Electro-optic effects in liquid crystals

Optical state of a liquid crystal cell can be controlled by the application of an electric or magnetic field or by changing temperature. The optical characteristics of the liquid crystal cell changes due to the reorientation of the molecules resulting in absorption, reflection or scattering of light. This phenomenon of induced optical modulation due to electric or magnetic fields or by temperature is termed as electro-optic or magneto-optic or **thermo-optic** effects of the liquid crystals respectively. Almost all commercial displays are based on electro-optic effect. In general LCDs are classified as reflective, transmissive and tranreflective types. In the reflective type, ambient light is used to illuminate the display. This is achieved by combining a reflector with the rear polarizer. It works best in an outdoor or well-lighted environment in positive contrast mode. Transmissive LCDs have a transparent rear polarizer and do not reflect ambient light. Hence, transmissive LCDs require a backlight to be visible. They work best in negative contrast mode and low light conditions with the backlight on continuously. Transreflective LCDs is a mixture of the reflective and transmissive types, with the rear polarizer having partial reflectivity. Here, backlight is provided for use in all types of lighting conditions. The **backlight** can be left off where there is sufficient outside lighting. This will help in conserving power. In darker environments, the backlight is turned on to provide a bright display. Transreflective LCDs works well even when operated in direct sunlight.

A.6.1 dielectric and Optical anisotropy

The anisotropy in the dielectric constant of the liquid crystals allows them to be aligned by an applied electric field due to their induced and permanent dipole moments. Thus, if $\Delta\epsilon = \epsilon_{\parallel} - \epsilon_{\perp}$ is the anisotropy in the dielectric constant, where ϵ_{\parallel} and ϵ_{\perp} are

respectively the values of the dielectric constant measured with the applied electric field parallel and perpendicular to the director. Liquid crystal materials, having positive dielectric anisotropy i.e., $\Delta\epsilon > 0$ will align with the director (2) parallel to an applied electric field (E). Materials with $\Delta\epsilon < 0$ (negative dielectric anisotropy) will align with the director (2) orthogonal to the electric field as illustrated in Figure A-10.

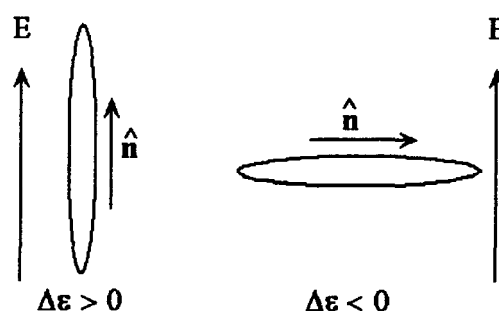


Figure A-10 Schematic representation of liquid crystal director orientation with positive and negative dielectric anisotropy on application of electric field (E).

The dielectric anisotropy of the liquid crystal mixture has strong dependency on the frequency range. The frequency at which the dielectric anisotropy changes its sign is called crossover frequency. Usually this crossover frequency is quite high ($> 50\text{kHz}$), in lower frequency range the dielectric anisotropy is almost constant and when it approaches near the cross over frequency the value of dielectric constant ϵ_{\parallel} decreases monotonically as the frequency is increased. However, the dielectric constant ϵ_{\perp} does not change when the frequency is increased even up to several MHz, where the dipole moment of molecules cannot follow the change in electric field. As a result, the dielectric anisotropy changes from a positive to a negative value at higher frequencies. The threshold voltage is inversely proportional to the square root of the dielectric anisotropy ($\Delta\epsilon = \epsilon_{\parallel} - \epsilon_{\perp}$) of the liquid crystal mixture (see equation A.4). It is always preferable to operate the display so that the frequency spectrum falls in the flat region, where dielectric anisotropy remains constant.

Light traveling perpendicular to the director, is subjected to two refractive indices, that is n_{\parallel} for the light with polarisation vector parallel to the director, and n_{\perp} for the light whose polarisation vector is perpendicular to the director. This phenomenon is known as double refraction or birefringence. The optical anisotropy $\Delta n = n_{\parallel} - n_{\perp}$.

Important electro-optic effects for display applications are compared in Table 1-1. Of these electro-optic effects, twisted nematic effect is the most popular in display applications. During the past few **years** bistable liquid crystal displays have attracted attention because of wide viewing angle characteristics, reduced power consumption, passive driving and low cost. In this thesis TN LCDs have been used for the studies on addressing techniques and development of controllers. Principle of operation of TN and STN LCDs are discussed in the next section.

Display	Matrix Type	Response Time	Viewing Angle	Gray Shades	Driving Voltage(V)	Remarks
TN[44]	Passive and Active	~(50– 150)ms	Poor	Good	~ 5	Very common in small display modules and with TFT backed active matrix in a highly multiplexed display modules
STN[45]	Passive	~(100-200)ms	Fair	Fair	~ (5–15)	Medium and portable applications
GH [46][47][48]	Passive	Same as TN	Fair	Fair	~ 5	Not very popular now a days.
VAN[49][50]	Active	< 25ms	Good	Poor	~ 5	Not a promising technology for commercial application
IPS [51,52,53]	Active	~ 40ms	Very Good	Moderate	~ 8	Large display with IPS mode is commercially available.
BTN[54,55]	Passive	~ 5ms	Good	Bad	~ 25	R and D but not very promising
Ch-LCD [56]	Passive	~(50 – 100)ms	Moderate	Poor	~ 40	R and D
ZBD [57,58,59]	Passive		Good	Fair	~ 20	R and D but very promising technology
FLC [60,61]	Passive	~ (20 – 100) μ s	Good	Fair	~ 40	Not very popular for commercial point of view.

Table A-1

A.7 Twisted Nematic (TN) effect

The twisted nematic (TN) structure consists of a thin layer of nematic liquid crystal contained between parallel glass plates. The electrode patterns are obtained by etching the unwanted portions of the transparent conducting layer. The inner surface have a thin polyimide coating on the transparent electrode pattern several hundred angstroms thick. The polyimide layer is unidirectionally rubbed to align the liquid crystal molecules (director) at the surfaces parallel to the rubbing direction with a small pretilt. The upper substrate is rubbed at right angles to the rubbing direction of the lower substrate. The upper and lower substrate plates are separated by a gap of 4-10 μm using a spacer. Thus in the unactivated state (i.e., without any external electric field) the liquid crystal molecules undergoes a uniform 90° twist in the region between the substrates as shown in the Figure A-11(a).

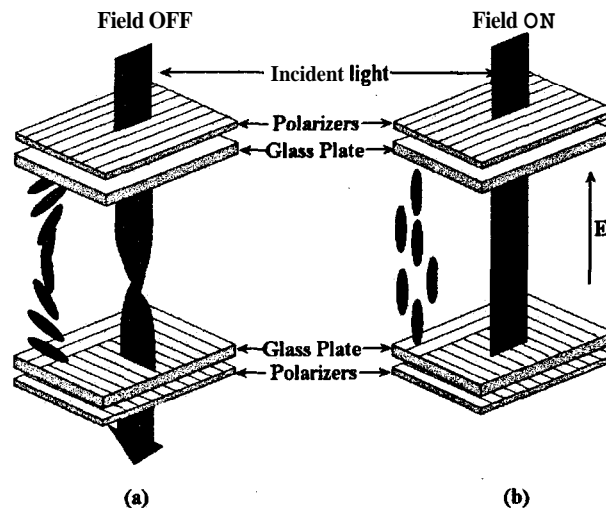


Figure A-11 Principle of operation of a twisted nematic liquid crystal display in the normally white mode (Figure adopted from reference [62]).

The nematic liquid crystal material with positive dielectric anisotropy ($\Delta\epsilon > 0$) is used for twisted nematic displays. If sufficiently strong electric field (E) is applied across the upper and lower transparent electrodes of the glass plates, the twisted structure distort and liquid crystal molecules tend to align parallel to the field as shown in the Figure A-11(b). This property has been utilized to construct a practical device where the twisted structure is placed between parallel or crossed polarizers. The device can be switched to a homeotropic state by means of an external electric field. If the polarizers are placed parallel to the rubbing direction in the field OFF state, linear polarized light from the upper polarizer propagates through the layer with a gradual rotation in its plane of polarization following

the twisted structure and emerges out at the bottom polarizer with 90° twist (Figure A-11(a)) and the display appears transparent (i.e., bright). In the field ON state, the polarization direction of the light is no longer rotated and the linearly polarized light from the top polarizer intersect the second polarizer in the crossed position where it is absorbed (Figure A-11(b)) and the display appears dark. The difference in transmission of light between the field OFF and field ON states is exploited in TN LCDs to obtain the bright and dark states. In display applications ac electric field is preferred because dc electric field shorten the display life.

A.7.1 *Electro-optic performance of TN displays*

A monochromatic light wave propagation along the helical axis of a **uniformly** twisted nematic layer can be described by a superposition of two characteristic waves called normal modes. In a local **cartesian** coordinate system, considering one axis parallel to the direction of propagation. The normal modes are in general, elliptically polarised in the plane perpendicular to the direction of propagation. The major axis of the vibrational ellipse is parallel and perpendicular to the nematic director respectively. Only in the **limit**

$$\Delta n d \gg \frac{\phi \lambda}{\pi} \quad (\text{A.1})$$

the normal modes can be considered to be linearly polarised. In equation (2.1) Δn is the birefringence. ϕ is the total twist angle, d is the layer thickness and λ is the wavelength of incident light. This inequality is known as the Mauguin condition [63]. For a 90° twisted nematic cell this condition reduces to

$$\Delta n d \gg \frac{\lambda}{2} \quad (\text{A.2})$$

An important optical property of this structure is that, the plane of the polarization of light transmitted through the cell will follow the director twist. If a **linearly** polarized light is incident on the cell in such a way that the plane of polarization is parallel (or perpendicular) to the director at the entrance surface, then the plane of linear polarization too is rotated by 90° as light traverses the cell. In the liquid crystal cells actually used in TN displays, this inequality is only approximately fulfilled, resulting in a reduction of the display brightness and there is an undesirable coloration caused by optical interference of the normal modes. The optical transmission (T) of un-activated [64] TN cell in a normally black mode (between parallel **polarizers**), for 90° twisted structure is given by the equation

$$T = \frac{\sin^2 \left(\left(\frac{\pi}{2} \right) \sqrt{1+u^2} \right)}{(1+u^2)} \quad (\text{A.3})$$

Where $u = 2 d \frac{\Delta n}{\lambda}$

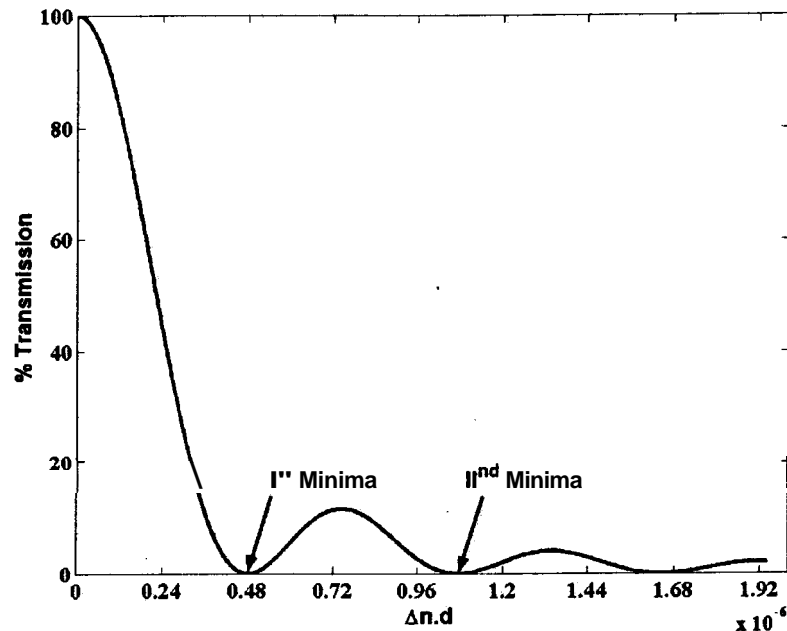


Figure A-12 Transmission of a TN cell as a function of $\Delta n d$ at $\lambda=555\text{nm}$ indicating first and second minimum values at $0.48\mu\text{m}$ and $1.08\mu\text{m}$ respectively.

Figure A-12 shows the transmission as a function of $\Delta n d$ at $\lambda=555\text{nm}$. It is zero only for the discrete values of $\sqrt{1+u^2} = 2, 4, \dots$ or $u = \sqrt{3}, \sqrt{15}, \dots$. These values are known as the first ($\Delta n d = 0.48\mu\text{m}$) and second minimum ($\Delta n d = 1.08\mu\text{m}$) conditions respectively. The transmission minima (and maxima) are caused by the interference of the slightly elliptical normal modes. TN LCDs can be operated in two different modes, that is positive contrast mode and negative contrast mode. These modes can be achieved by changing the orientation of the polarizers in the front and rear of the LCD panel. If the polarizer directions are in parallel, it is called negative contrast mode (i.e., normally black mode). In this type, polarizers are placed so that they are parallel to the rubbing direction of one of the glass substrate. If the polarizers are crossed then this type is called positive contrast

mode (i.e., normally white mode). The light transmission across the normally black mode TN LCDs with application of voltage is shown in Figure A-13.

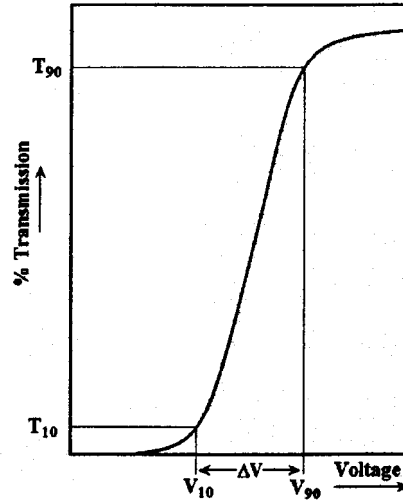


Figure A-13 The electro-optic curve of the normally black mode TN LCD.

The voltage at which the light transmission is **10%** of the maximum change in the transmission is called threshold voltage (V_{th}) and the voltage at which the light transmission is **90%** of the maximum change is called saturation voltage (V_{sat}). The electro-optic response of the TN LCD does not have the sharp threshold. The threshold voltage of the TN LCDs is given by

$$V_{th} = 2\pi \left[\pi \frac{K_{11} + \frac{K_{33} - 2K_{22}}{4}}{\Delta\epsilon} \right]^{1/2} \quad (\text{A.4})$$

Where, K_{11} , K_{22} and K_{33} are the splay, twist and bend elastic constants respectively and $\Delta\epsilon$ is the anisotropy of the dielectric constant. To achieve the maximum contrast in the display, the ON pixels should get a voltage greater than or equal to V_{sat} . For a given LC mixture, by studying the electro-optic characteristics it is possible to find maximum number of rows (N_{max}) can be addressed using the passive matrix LCDs with out loosing the contrast [5].

That is,

$$N_{\max} = \left(\frac{\left(1 + \frac{\Delta V}{V_{th}}\right)^2 + 1}{\left(1 + \frac{\Delta V}{V_{th}}\right)^2 - 1} \right)^2 \quad (\text{A.5})$$

Where, ΔV is the difference between V_{sat} and V_{th} i.e., $\Delta V = (V_{sat} - V_{th})$. From equation (A.5) it is clear that, to multiplex more number of rows in the matrix LCDs, the difference between saturation voltage (V_{sat}) and the threshold voltage (V_{th}) should be small. On the other hand, the broader electro-optic characteristics of TN LCDs are useful in generating gray shades and it has been exploited in active matrix LCDs.

(a) Response Time

The electro-optic response of the twisted nematic liquid crystal cell is as shown in the Figure A-14 when the applied voltage is very much larger than the threshold voltage (V_{th}). The response time is characterised to three constants, the delay time (τ_{dr} and τ_{df}), the rise time (τ_r) and the fall time (τ_f). The delay time τ_{dr} is the time from the start of the pulse trains to the transmission of the light reaches 10% of the final value. The τ_{df} is the delay time between final value of the transmission to the 90% transmission after the turning off the applied signal. The rise time τ_r is defined as the time between the transmission to rise from 10% to 90% of the final value. Similarly, the fall time τ_f is the time between the transmission to fall from 90% to 10% of the final value.

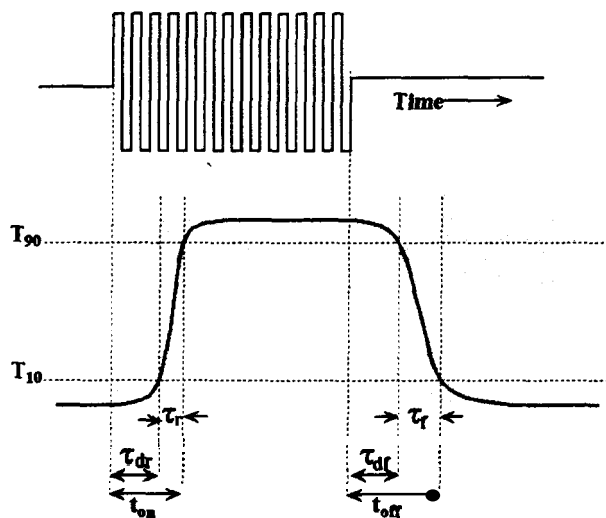


Figure A-14 Electro-optic response characteristics of the liquid crystal cell.

The rise and fall times are given by,

$$\tau_r = \frac{\eta}{\frac{\Delta\epsilon}{8\pi} E^2 - K \frac{\pi^2}{d^2}} \quad (\text{A.5})$$

and

$$\tau_f = \frac{\eta d^2}{K\pi^2} \quad (\text{A.6})$$

Where, η , $\Delta\epsilon$ and K are the viscosity, anisotropy of the dielectric constant and average curvature elastic constant of the liquid crystal material used respectively. The rise time and fall time are directly proportion to the square of the cell thickness d . That is as d increases the response time increases. The response time should be lower for many of the display applications. In this case one can reduce the cell thickness without affecting the **Mauguin** limit [63] to get the maximum contrast. That is by choosing the liquid crystal mixture with appropriate optical anisotropy (An) to tune the ($An d$) to the first minima. Compared to first minimum in the Figure A-12, second minimum is broader. In this case slight mismatch in the ($An d$) does not effect the display contrast. But the larger cell thickness increases the response time. Also, the rise and fall times are directly proportional to the viscosity (η) of the liquid crystal material. Hence, the rise and fall times fluctuates as the variations in the ambient temperatures. The variation in viscosity value is very marginal if one uses the very broad range room temperature liquid crystal mixtures.

(b) Viewing Angle

All twisted nematic liquid crystal displays suffer from poor performance at wide viewing angles due to the optical characteristics of TN liquid crystal materials. Poor viewing angle characteristics and contrast ratio of TN LCDs are still problems in their use in large displays. The viewing angle characteristics of the normally white mode are shown in Figure A-15, where curves of equal contrast ratio are in polar diagrams, known as iso-contrast diagram. Every point on these diagram corresponds to a certain viewing direction characterized by a polar and an azimuthal angle. The center of the diagram refers to ON-axis viewing. For a good display it is desirable to have good contrast over a wide viewing

angle. Among the solutions for the improvement of viewing angle characteristics, In-plane switching (IPS) mode and vertically aligned (VA) LCDs are considered to be good. However, disadvantages of these are in the complex driving method. The amplitude of applied signal voltage to drive active devices like Thin Film Transistors (TFT) become large and it will increase the cost as compared to the low cost passive matrix LCDs. Apart from these types a fabrication technique of TN LCDs without rubbing the substrate surfaces are more interesting. The TN LCDs fabricated by the non-rubbing technique is called Amorphous Twisted Nematic (ATN) LCDs [65]. Thus non-rubbing technique contributes not only in the electro-optic response improvements but also simplifies the production process and hence cost.

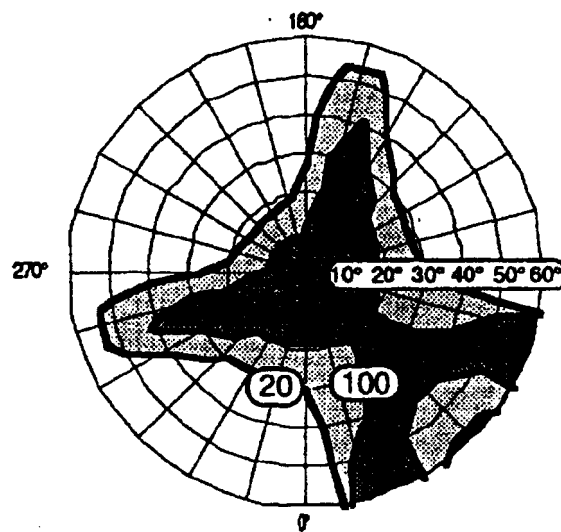


Figure A-15 ISO-contrast viewing diagram of the normally white mode TN LCD.

(c) Material parameters

The steepness of the **electrooptic** curve is depends on the elastic constant bend (K_{33}), twist (K_{22}), splay (K_{11}) coefficients and also the dielectric parameter $\gamma = \left(\frac{\epsilon_{\parallel} - \epsilon_{\perp}}{\epsilon_{\perp}} \right)$ of the liquid crystal mixture. Apart from these material parameters the pretilt angle at the inner surface of the display cell is also an important device parameter that affects the steepness of the electro-optic curve. The number of lines that can be multiplexed depends on the steepness of the electro-optic characteristic. The liquid crystal materials that are available do not develop a steep enough electro-optical curve for multiplexing more than 64 rows.

The steepness can be increased and even made infinite by increasing the twist angle from 90° to 180° – 270° . A remarkable improvement in the electrooptic curve steepness is observed and realized using Super Twisted Nematic (STN) effect.

A.8 *Super Twisted Nematic (STN) effect*

In the year 1980, Nehring and Scheffer demonstrated the Super Twisted Nematic LCDs which has a twist of over 180° , typically between 210° and 270° . The basic structure of the STN LCD is shown in Figure A-16.

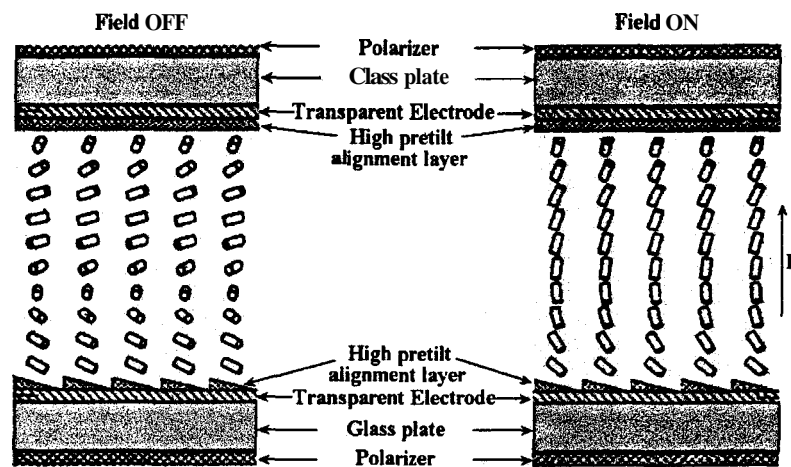


Figure A-16 Schematic of STN cell in field OFF and ON states (figure adapted from reference [45]).

This shows a much smaller voltage switching range with good contrast ratio and a better viewing angle. In this configuration the steepness of the electro-optic curve is increased and even made infinite by just increasing the layer twist angle from 90° to 180° – 270° . At still higher twist angles the electro-optic curve become double-valued, defining a region of bistability and hysteresis[54]. In order to obtain a twist angle greater than 90° a chiral material is doped into the nematic liquid crystals which has positive dielectric anisotropy. By adding the definite handedness of the chiral material a larger twist is ensured in the right direction. The amount of dopant is controlled by a pitch length p , which is the distance measured along the helical axis for the director to rotate by one full rotation (i.e., 360°). The pitch of the LC mixture is easily modified to the required value with different cell thickness d . The pitch is inversely proportional to the concentration of the dopant. The

cell thickness to the pitch ratio $\left(\frac{d}{p}\right)$ is adjusted to meet the condition $\left(\frac{d}{p}\right) = \left(\frac{\phi}{2\pi}\right)$ (Refer Table A-2).

A.8.1 Electro-optic Performance of STN displays

A schematic of a STN LCD is shown in Figure A-16. The STN display requires two polarizers like TN displays, one in front and one at the back. The polarizers of STN LCDs are orientated depending on the total twist of LC director and the $\Delta n \cdot d$ of the cell. The optical transmission (T) [66] of an unactivated STN cell using Generalized Geometric Optics Approximation (GGOP) for twisted structure of ϕ is given by the equation below. The coordinate system used in the GGOP is as shown in Figure A-17.

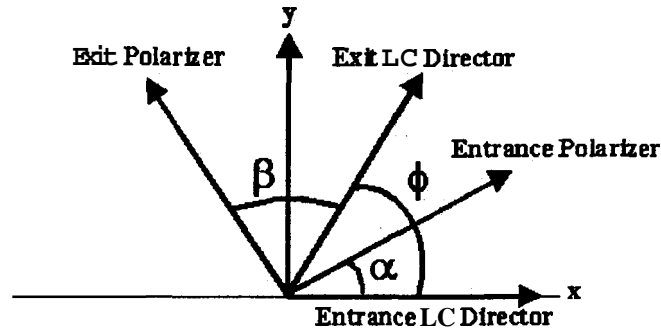


Figure A-17 The coordinate system used in the Generalized Geometric Optics Approximation (GGOP) analysis for optical transmission of a LC cell.

$$T = \cos^2(\alpha - \beta) + \sin^2(X) \sin(2\beta) \sin(2\alpha) + \frac{\phi}{2X} \sin(2X) \sin(2\alpha - 2\beta) + \phi^2 \frac{\sin^2 X}{X^2} \cos(2\beta) \cos(2\alpha) \quad (\text{A.7})$$

$$\text{Where, } X = \sqrt{\phi^2 + \left(\frac{\Gamma}{2}\right)^2} \quad \Gamma = \frac{2\pi}{\lambda} \Delta n \cdot d$$

α = azimuth angle of the polarizer measured from the local director $\hat{n}(z=0)$

β = azimuth angle of the polarizer measured from the local director $\hat{n}(z=d)$

d = Cell thickness and ϕ = total twist.

The threshold value for the liquid crystals can be improved significantly by setting the twist angle, ϕ to 180° – 270° .

The midlayer tilt angle of LC molecules versus reduced voltage are shown in Figure A-18 along with TN LC cell (i.e., Total twist = 90°). The Figure A-18 shows that when the twist angle ϕ of the cell is 270° , the midlayer tilt of the LC molecules rises sharply very close to the threshold value.

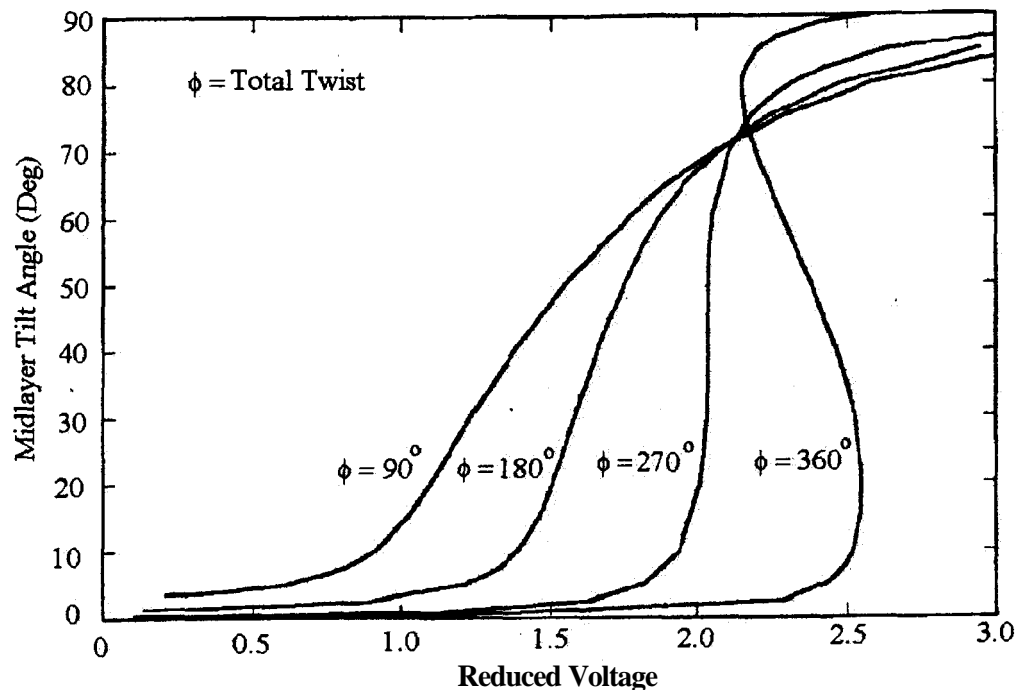


Figure A-18 Electro-distortion curve for TN ($\phi=90^\circ$) and STN ($\phi \geq 180^\circ$) cells.

When an ordinary light enters the first polarizer, the light becomes linearly polarized light. The polarizer film is placed so that the direction of the linearly polarized light forms an angle α with respect to the entrance LC director of the cell. The birefringence of the liquid crystal molecule turns this light into elliptically polarized light when it comes out of the LC cell on the other end. The second polarizer film kept at an angle β allows the light that is oriented in the direction of the transmission axis of the exit polarizer film.

As in the case of TN LCD, application of a voltage across the upper and lower electrodes, orients the LC molecules in the central portion of the LC layer more or less parallel to the electric field and the twisted structure disappears. Therefore, the light comes out of the exit polarizer with different intensity. This is due to the difference in the birefringence with the twisted and untwisted structure of LC molecules. Hence, two different mode can be obtained as in the case of TN LCD. The light transmission across the STN LCDs by application of voltage is shown in Figure A-19. The STN LCDs with twist angle greater

than 180° has more steeper electro-optic characteristics as compared to TN LCDs (Figure A-13). For a 270° twist the electro-optic curve is almost infinite. Hence, the difference between V_{10} and V_{90} for the 10% and 90% transmission, respectively is very small, hence more number of lines can be multiplexed. The main disadvantage of early STN LCDs were slow response time ($> 100\text{ms}$) and they produce blue and yellow images rather than black and white.

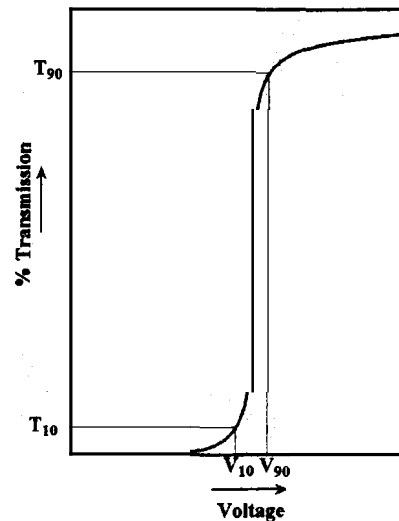


Figure A-19 Typical electro-optic curve for an STN cell showing the steep electro-optic characteristics.

The Optical Mode Interface (OMI) [67] mode refers to the technique of suppressing the coloration in the yellow mode by reducing the optical path difference (i.e., $\Delta n \cdot d$) of the 180° liquid crystal cell from $0.85\mu\text{m}$ to approximately $0.6\mu\text{m}$. In this case the total optical transmission drops to 70%, this results in poor contrast. To avoid coloration, the Double Super Twisted Nematic (D-STN) [68] mode has been developed, in which an LC panel containing a twist of the opposite handedness is placed in front of the exit polarizer film. But slight mismatch in total twist or thickness variation of one of the LC panel again gives coloration. This technique is not popular because of bulkiness and manufacturing difficulties. Later instead of using second LC panel as a phase compensation a phase-difference film is used, which has the same effect as the liquid crystal layer and this mode is referred to as Film Super Twisted Nematic (F-STN) LCDs [69].

The steepness of the electro-optic curve depends on physical parameters of the liquid crystal mixture and also the geometry of the super twisted nematic display cell as tabulated in the Table A-2.

Parameter	Effect
Cell thickness to pitch ratio $\left(\frac{d}{p}\right)$	<p>A Super Twisted Nematic (STN) effect exists for</p> $\left(\frac{\phi}{2\pi} - 0.25\right) < \left(\frac{d}{p}\right) < \left(\frac{\phi}{2\pi} + 0.25\right)$ <p>Lower values of (d/p) ratio lead to a decrease in driving voltage and an increase in electro-optic curve steeper.</p> <p>Where, ϕ is the total twist angle</p>
Pretilt angle (θ_0)	<p>Higher pretilt angles shift the electro-optic curve to lower voltages with slightly increase its steepness.</p> <p>Contrast ratio decreases for larger pretilt angle.</p>
Bend to splay elastic constant ratio $\left(\frac{K_{33}}{K_{11}}\right)$	<p>For larger ratios the electro-optic curve steepness increases and also driving voltage become higher.</p>
Twist to splay elastic constant ratio $\left(\frac{K_{22}}{K_{11}}\right)$	<p>Decreasing the twist to splay elastic constant ratio shifts the upper portions of the electro-optic curve to lower voltages, thereby making it steeper.</p>
Dielectric ratio $\gamma = \left(\frac{\epsilon_{\parallel} - \epsilon_{\perp}}{\epsilon_{\perp}}\right)$	<p>The lower the ratio the steeper the electro-optic curve</p>

Table A-2: Effect of various device and material parameters on electro-optic curve characteristics of super twisted nematic cell.