LIQUID CRYSTAL DISPLAY

A liquid crystal display (LCD) is basically a modulator of light. The liquid crystal (LC) is generally translucent in bulk, but a thin film (10 μm) can be transparent. By sandwiching a thin film of LC with a preferred orientation between two transparent glass plates and applying a potential difference across the film, the optical characteristics (transmission/scattering/birefringence/polarization) of the film can be changed. Various electro-optical effects arise from the nature of the organic molecules in the film, with their long-range order and alignment in the film as dictated by bounding surfaces. The types of LCDs in use today are classified based on the specific electrooptic effects involved. A large area of the LC film, sandwiched between two transparent glass plates (sometimes laminated with other passive optical components), exhibits changes in the optical property in certain selected areas of the film under the action of an electric field that is selectively applied in those areas. These changes are visible to the eye with a high contrast, against the background of nonactivated regions. By suitable patterning of the transparent electrodes, through which the voltages appear across the LC film, and selectively addressing the desired areas through the external voltages, a visual display of numerals, alphabets, and pictures are possible. Typical voltages necessary for the operation of an LCD is in the range of 5 V_{rms} to 6 V_{rms}. As the LCD is a light modulating device and not a light generating device, it requires either ambient light or an external light source. LCDs using the available ambient light have power consumption in the range of 1 $\mu W/cm^2$ as against their backlighted counterparts consuming in the mW range. Due to the low power consumption and low voltage operation, LCDs find extensive use in all portable display applications like handsets of telecommunication units, laptop computers, complex calculators, hand-held data displays and so on. By virtue of the slimness (<2 mm), high resolution and high reliability, LCDs are finding increasing applications in avionic cockpit displays. LCDs are also replacing the well-known cathode ray tubes (CRTs), the main competitor, in computer monitor applications. Compared with the other competing flat panel display devices like plasma display, electro-luminescent display, and field emission display, LCDs are superior in low voltage compatibility with the driving integrated circuits and power efficiency. All the attributes of the LCDs stem from the specific optical anisotropy of the basic liquid crystal molecules. What follows is a brief description of the types of LCDs, their alignment, the principle of their operation and driving, and their tremendous technological growth.

Atoms in a crystal are generally arranged in rows and columns in a well ordered pattern. But the molecules in an isotropic liquid, like water, are in random orientation and have no ordering. There are many organic materials which exhibit, in passing from solid to isotropic liquid, intermediate phases known as *mesophases.* These phases do not possess molecular ordering like that of a crystal or molecular disordering as in an isotropic liquid, like water. The molecular ordering in these phases is in between that of a crystal and an isotropic liquid. Hence the term *liquid crystal,* which is not a crystal. Reinitzer (1) discovered the liquid crystal in 1888 (a premonition for a $3\frac{1}{2}$ digit display).

There are two types of liquid crystals: (1) thermotropic liquid crystals and (2) lyotropic liquid crystals. If a temperature change causes a phase transition in a liquid crystal, that liquid crystal belongs to the thermotropic type. Lyotropic liquid crystals are those formed by the solution of rodlike entities in an isotropic solvent. The thermotropic liquid crystals are extensively employed for the fabrication of LCDs and hence the present article will be confined to the description and application of thermotropic liquid crystals. Although the liquid crystal was discovered in 1888, it was not until 1968 that its use in displays was well demonstrated by Heilmeier et al. (2). The LCD invented by Heilmeier et al. is based on the dynamic scattering mode, which is seldom used in the modern LCDs, and hence the reader may find the details of this mode in Ref. 2.

THERMOTROPIC LIQUID CRYSTAL

Generally, the molecules of the LC are elongated and rigid. They resemble long rods but exceptions (3) to this geometry do exist. A typical LC molecule has a structure with benzene rings linked by central and terminal groups. Figure 1(a) shows this general structure and Fig. 1(b) illustrates the structural formula for the liquid crystalline compound, 3,4,5-trifluorophenyl employed in the latest LCDs (4). For a list of central and terminal groups commonly observed in various LC compounds, interested readers may refer to Ref. 5. The polarizability, including the direction, of the central and the end groups, and the size of the LC molecule are related to the stability of the LC phase and its physical properties

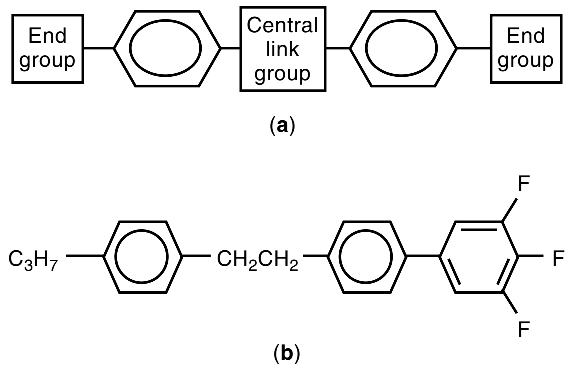


Figure 1. (a) General structure of liquid crystal molecule. (b) Structure of 3,4,5-trifluorophenyl liquid crystal.

like the dielectric constant, refractive index, viscosity, elasticity, and phase transition temperature. For detailed physical properties of LC, the reader may refer to Refs. 6–9. For a vivid description of the operation of LCDs, the best way is to adopt the 'long-rod' model of LC molecule. In an ordered fluid like LC, the regular arrangement of the molecule is characterized by a parameter known as *order parameter* which plays a major role in the theoretical description of liquid crystal. There are mainly three classes of LCs which are employed in LCDs. These are discussed below.

Nematic, Smectic, and Cholesteric Liquid Crystal

The ordering of molecules as represented in Fig. 2 characterizes what is known as *nematic* phase (in Greek, *nema* means thread as the LC appeared like threads under the microscope in those days) of LC. The director $\boldsymbol{n}$ refers to the general tendency of the overall molecular orientation and is a unit vector pointing along the average direction of the LC molecule. The value of $\boldsymbol{n}$ is nonzero for liquid crystalline phase and zero for an isotropic phase. Figure 2 refers to an idealized nematic phase in which the "head" (*) and "tail" of the molecule are equally likely to point up and the long axis of molecules are perfectly parallel to each other. In this case the value of the

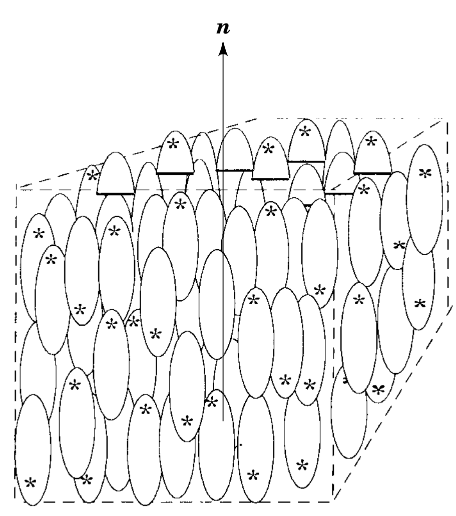


Figure 2. Structure of nematic phase of liquid crystal.

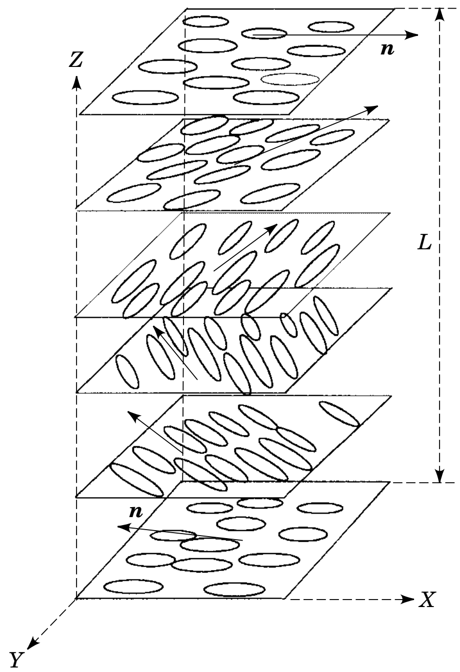


Figure 3. Structure of cholesteric liquid crystal.

order parameter is unity. Figure 3 depicts the molecular ordering characteristic of "cholesteric" phase (similar to the structure in cholesterol). It is easy to observe the helical twist of the director axis. The director goes through a twist of Π radians in the Z-direction with a periodicity whose spatial period L is equal to half the pitch. If the pitch is made infinite, the cholesteric phase is nothing but a nematic as in Fig. 2. In other words, the nematic phase is a limiting case of the cholesteric phase. Figure 4 represents the molecular ordering characteristic of "smectic" phases A, B, and C. One can see the layered nature of the molecules and their tilt. The smectic B phase exhibits the long axes of the molecules in a hexagonal layer structure. Ordering of the constituent molecules within the layers is characteristic of smectic B phase. Smetic B phase finds little use in LCDs.

Polymorphism in Thermotropic Liquid Crystal

Increase of temperature in many thermotropic materials causes interesting transitions. When the temperature is raised, many materials pass from the solid to liquid crystalline phase. As the temperature is further increased, the materials exhibit many phases of liquid crystalline structure before they become isotropic liquid. For example, a material on gaining heat can pass through the sequence: solid-to-smectic B-to-smectic C-to-smectic A-to-nematic-to-isotropic or solid-to-cholesteric-to-isotropic or solid-to-smectic A-to-cholesteric-to-isotropic. This is *polymorphism.* Various studies on the ordering-disordering of the molecules during these phase transitions reveal the changes in the order parameter. There are many theories formulated to explain the physical properties of LC. Generally, the physical properties of liquid crystals are anisotropic (not the same in all directions). This interesting feature is exploited in LCDs and hence a description of the anisotropy is in order.

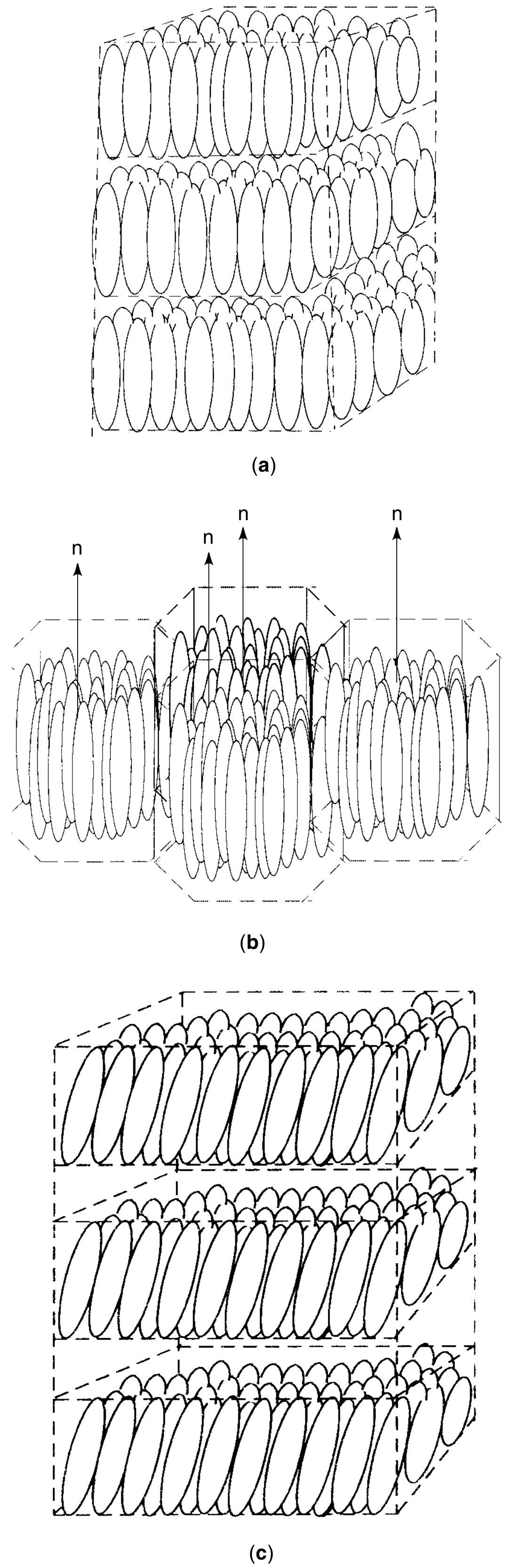


Figure 4. (a) Structure of smectic A order of liquid crystal. (b) Structure of smectic B order of liquid crystal. (c) Structure of smectic C order of liquid crystal.

ANISOTROPY IN LIQUID CRYSTAL

The chemical structure and the accompanying difference in electron density along the short and long axis of the LC molecule determine certain physical properties like the dielectric constant, magnetic susceptibility, refractive index, and electric conductivity. Of the many anisotropic physical properties, the two major properties of importance to LCDs are the dielectric and optical anisotropy. The majority of LC materials employed in LCDs have the optic axis in one direction (uniaxial). Figure 5 represents the anisotropy in physical properties of LC. There are two indices of refraction (birefringence or double refraction) and two dielectric constants in two principal directions of optic axis. Dielectric anisotropy of LC is defined as $\Delta\epsilon = \epsilon_{\parallel} - \epsilon_{\perp}$ and the optical anisotropy is defined as $\Delta\eta = \eta_{\parallel} - \eta_{\perp}$ (birefringence). Anisotropy in physical properties arises due to the chemical structure of the LC molecule. For example, an LC molecule with a strong on-axis polar group exhibits substantial positive $\Delta\epsilon$ whereas that with an off-axis polar group exhibits large negative $\Delta\epsilon$. Preferred orientation of the long axes of the molecules play an important role in the optical anisotropy.

PRINCIPLE OF TWISTED NEMATIC LIQUID CRYSTAL DISPLAY

Figure 6(a) illustrates the basic principle of a twisted nematic liquid crystal display (TN-LCD). Voltage dependent optical activity invented in 1971 (10) is the basis for this widely popular display. The glass substrate-1 has a layer of nematic LC whose long axes lie horizontally on the substrate. For the sake of simplicity, only one molecule represents a surface layer. A special technique of polyimide coating and rubbing (11) on the substrate imposes desired orientation of the director of the surface layer on the substrate and the surface layer on the substrate is strongly anchored. The alignment of the long axes of the LC layer on glass substrate-2 is perpendicular to that on substrate-1. There is usually a gap of 6 to 8 μm between the substrates (thin LC film occupying this gap is transparent whereas thick films are translucent). The LC director undergoes a gradual twist of 90° as we go from substrate-1 to substrate-2. Both the substrates have a transparent conductive coating of indium-tin-oxide (ITO) underneath the aligning polyimide layer (50 nm). ITO serves as the electrodes for the TN-LCD. In the "off" state (no voltage on the electrodes), a plane polarized light entering substrate-1 rotates its plane of polarization in accordance with the *gradual twist* of the LC layers and emerges at the top analyzer which allows the vibrations of the E-vector of the polarized light in the direction indicated in Fig. 6(a). Thus, a viewer sees a bright background looking down the analyzer if a plane polarized light illuminates the cell from below the substrate-1. This is the "normally white" cell. On the other hand, if the cell faces a gradually increasing potential difference, the LC

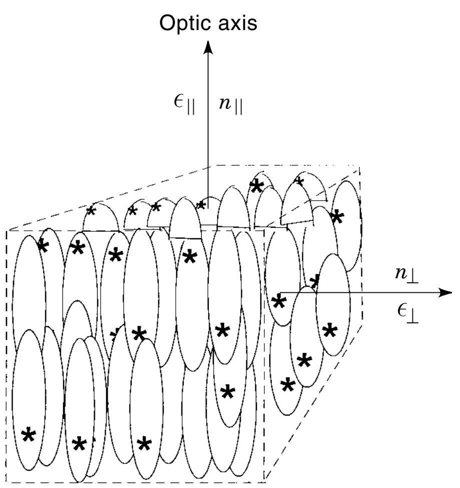


Figure 5. Optical anisotropy in liquid crystal.

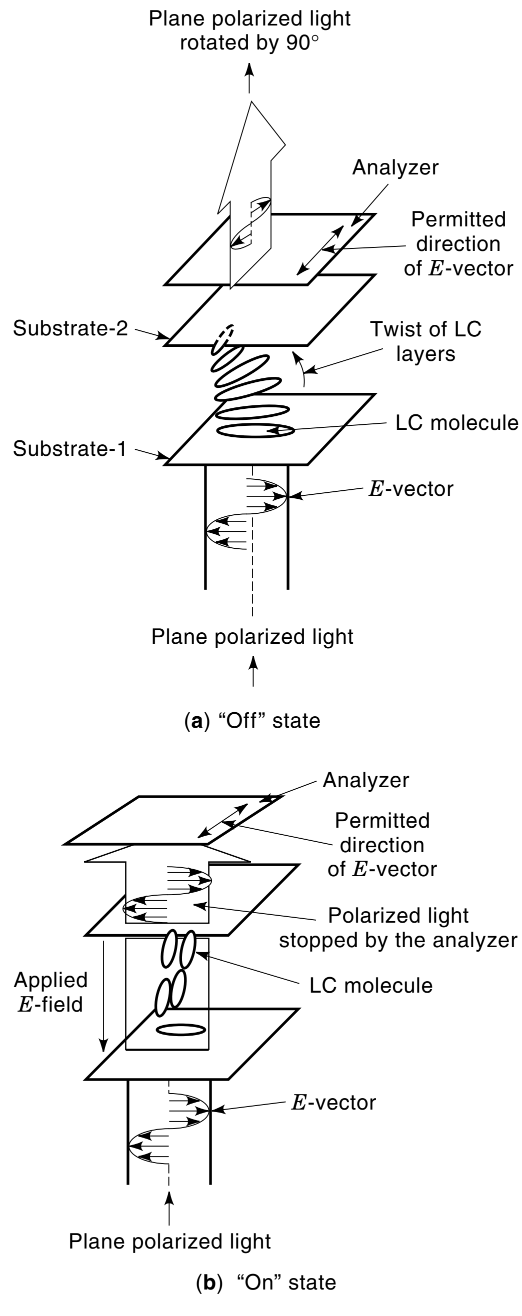


Figure 6. (a) Principle of twisted nematic liquid crystal display (in the "off" state). (b) Principle of twisted nematic liquid crystal display (in the "on" state).

molecules, by virtue of their positive $\Delta\epsilon$, start untwisting and aligning with their long axes parallel to the field. This transition does not start till a threshold voltage is reached. In modern TN-LCDs (cell of 6 m) a potential difference of 3 to 5 V between the substrates, the LC molecules will orient themselves with their long axes parallel to the field as shown in Fig. 6(b). However, a thin layer close to the substrate is strongly anchored to the surface and is little affected by the externally applied field. Figure 6(b) shows the nonemergence of the plane polarized light when it passes through the cell in the "on" state. The plane of polarization is unaffected as it passes through the vertical LC layer dictated by the applied electric field. The analyzer does not permit this plane of polarization to pass through it. A viewer looking down the analyzer now sees a dark background. In commercial TN-LCDs, there are two crossed polarizers laminated on the external surfaces of the glass substrates to serve as a polarizer to polarize the light going through the LC cell and analyzer to absorb or transmit the polarized light in the desired plane. In this example, under the no-field condition, if the two polarizers have the same orientation (parallel polarizers), then the "normally white" status will change to "normally black" status. On-field status will accordingly reverse. Figure 6(b) shows the long axes of the molecules are nearly perpendicular to the cell walls and this results in a near *homeotropic* alignment. If the molecular axes are parallel to the cell walls, it is termed as *homogenous* alignment. The transition from the twisted homogenous alignment to the near homeotropic alignment involves complex elasticity of LC and hence the threshold voltage at which the untwisting and vertical alignment of LC molecules occur is dependent on the elastic constants, dielectric anisotropy, and the degree of twist. The relation is given by (5)

$$V_{\text{th}} = \sqrt{[K_{11}\pi^2 + (K_{33} - 2K_{22})\varphi_o^2] \cdot 1/\epsilon_0\Delta\epsilon} \tag{1}$$

where K_{11}, K_{22}, and K_{33} are the splay, twist, and bend elastic constants, ϵ_0 is the permittivity of free space, and φ_0 is the twist angle ($= \pi/2$). This expression is for a cell with a tilt angle of zero (angle between the long axes of the LC molecules and the surface of the substrate). However, modern LCDs do have a small tilt angle to remove the ambiguity about which way to tilt when the field is applied. Modern LC mixtures used in TN-LCDs have V_{th} between 0.7 V to 2.0 V. The transition from the "off" state to the "on" state and vice versa involves a time factor which relates (5) to the following:

$$T_{\text{on}} = \frac{\eta d^2}{[\epsilon_0\Delta\epsilon V^2 - \text{K}\pi^2]} \tag{2}$$

$$T_{\text{off}} = nd^2/\pi^2 K \tag{3}$$

where n is the proper viscosity of LC, K the appropriate elastic constant, V the voltage applied, and d is the cell gap. The cell gap requires utmost control (due to its square term) and should be as small as possible to have fast response. Typical response time of TN-LCDs is between 20 ms to 50 ms.

Optics of 90° Twisted State

The previous description highly simplifies the rotation of the plane of polarization of the plane polarized light as it passes through the LC cell with a twist of 90°. The rotation occurs in both cases when the incident light is plane polarized parallel or perpendicular to the director. However, the propagation of light through a TN-LCD is complex. The 90° rotation is both due to the birefringence of LC as well as the optical activity of LC. Basic principles of optics in anisotropic media apply to LC. In a uniaxial medium, if the direction of propagation of light is along the optic axis (director axis), there is no birefringence of the incident light (polarized or unpolarized), and the ray of light travels as an ordinary ray due to uniaxial symmetry. A ray of light polarized parallel to the optic axis, but propagating perpendicular to the optic axis, travels as an extraordinary ray with a speed different from the ordinary ray. However, a ray of light polarized perpendicular to the optic axis, and also propagating perpendicular to it, travels as an ordinary ray. Light (polarized or unpolarized) propagating in all other directions, splits (birefringence) into two components—namely, ordinary and extraordinary rays, and they travel with different speeds. An unpolarized light propagating perpendicular to the optic axis also exhibits birefringence. The extraordinary and ordinary components will travel at different velocities with their linear polarization mutually perpendicular to each other. During this process, the phase shift occurs continuously as the rays travel through the structure. Two linearly polarized components with a phase difference of 90° results in elliptically polarized light and when the light exits a plane polarizer (analyzer in this case) there emerges a plane polarized light with its plane of polarization rotated through 90° compared to its incident plane. For a vivid pictorial description of this, the reader may refer to Ref. 12. Mauguin's condition (13) that satisfies the 90° rotation is as follows:

$$|\Delta nd/\lambda| \gg 0.5 \tag{4}$$

where λ is the wavelength of light in vacuum. Typical values of Δn lie between 0.1 and 0.2. A thin LC film gives fast response for the cell operation and hence one can barely manage to meet this condition for a particular value of λ. Any deviation from this condition means that a plane polarized light propagating through the 90° twist cell will not rotate its plane of polarization by exactly 90° and this may result in some transmission through the "normally black" (parallel polarizers) cell. This residual transmission needs to be minimum for good display characteristics. For a normally black cell with 90° twist TN layer, Gooch and Tarry (14) arrived at minimum transmission for white light at various Δnd values. Transmission minima in modern TN-LCDs occur for Δnd values of 0.48 μm, 1.09 μm, and 1.68 μm. Typically fast TN-LCDs operate close to 0.48 μm, whereas clock LCDs and the like operate in the second and third minimum. Thus in the "off" state the TN-LC cell, satisfying the above condition appears white (normally white mode) between crossed polarizers in the absence of any defect in alignment and twist. However, when a voltage applied across the cell increases, the optics of the cell changes.

Optics of "On" State

Figure 7(a) represents the state of the cell viewed at normal incidence, with crossed polarizers, as the voltage across the cell gradually increases. Figure 7(b) depicts the deformation of the molecular configuration with the applied voltage. The applied voltage is with reference to a threshold voltage. The

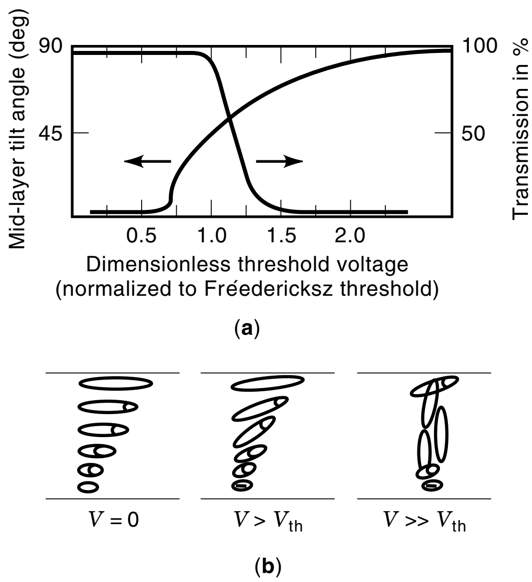


Figure 7. (a) Applied voltage versus transmission and mid-layer tilt angle in a twisted nematic liquid crystal cell. (b) Behavior of twisted nematic liquid crystal under applied electric field.

tilt angle refers to the angle of the director with respect to the substrate plane. A polyimide surface aligning technique imparts a small tilt angle (2° to 3°) to the LC molecules at the substrate surface. In the graph, the values of the tilt angles are for the LC molecules in the mid-layer of the cell. A "normally white or bright" cell represented in Fig. 7(a) does not exhibit any change in transmission till around a normalized voltage of 1 despite the fact there is a change in tilt angle well below this voltage. Between normalized voltage of 1 and 2 there is a substantial change in the tilt angle accompanied by a steep decrease in transmission. At higher voltages the tilt angle asymptotically approaches 90° due to $\Delta\epsilon$ being positive resulting in the destruction of the twist [$V \gg V_T$ in Fig. 7(b)] and hence no rotation of the plane of polarization. The steep characteristic of the cell is the most significant factor in electronic addressing of LCDs. On removal of the applied voltage, the LC molecules restore their twist and the restoration period (decay time or "off" time) relates (Eq. 3) to the elasticity and viscosity of the LC in addition to the cell gap. A similar material property, applies to the "on" time (Eq. 2). If the cell faces a periodic voltage, the characteristic response time of the LC by virtue of its visco-elasticity can be significantly larger than the period of the wave. Further, the induced polarization of LC is proportional to the field that induces polarization. Both these aspects make the TN-LCDs optically respond to rms voltages rather than the peak value of the applied voltage. The transmission curve [Fig. 7(a)] will be exactly opposite for the normally black cell. The foregoing description is for a transmissive cell. The same behavior holds true for a reflective cell in which the back of the cell has a polarizer laminated with a reflector. The light enters the front polarizer (crossed with the back polarizer) and rotates its plane of polarization as it passes through the cell, goes through the back polarizer, reflects back at the reflector surface, comes through the back polarizer, comes through the cell (LC twist), enters the front polarizer and back to the observer. Thus the cell appears bright, but in this case the light has traversed the cell twice. Application of a sufficient voltage across the cell turns the cell dark. If there is sufficient ambient light, the cell requires no extra lighting. This type of reflective cell finds extensive use in watch LCDs, calculator LCDs, and the like used in gas stations and other applications. However, most high information content LCDs like those used in laptop computers and avionic displays employ LCDs based on transmissive cell. Under low ambient light conditions, as the LCDs do not generate light but only modulate the light, all LCDs based on transmissive cell require backlighting and those based on reflective cell require front-lighting.

TWISTED NEMATIC LIQUID CRYSTAL DISPLAY FABRICATION

Generally the fabrication of any LCD is complex. However, a brief procedure for TN-LCD is worthy of mention here. Figure 8 is a cross-section of a color TN-LCD with matrix electrodes. The substrates are of hard glass plates with a flatness of around 0.05 μm. The bottom substrate has lines of ITO (15 ohms/square) electrodes patterned after sputtering ITO to a thickness of 0.04 μm. A thin film transistor (TFT) processed with every ITO pixel electrode is integral with the bottom substrate. The function of TFT is to drive every pixel independently (the description of thin film transistor-liquid crystal display or TFT-LCD follows under a separate title). A polyimide layer of 0.05 μm thickness is printed on ITO layer and rubbed (or buffed) for aligning LC molecules with a pretilt of 2° to 3°. The LC film in TN-LCDs may contain a chiral dopant for preventing reverse twist which can create optical defects in the display. The top plate contains a sputtered coating of black-matrix (two layer coating of CrO/Cr of approx. total thickness of 200 nm) to increase the contrast and reduce the unwanted front reflection. Adjacent to the black-matrix are color filter layers of red, blue, and green (each 2 μm thick) spin-coated and patterned to a designed format to yield a color display when the modulated light passes through them. A protective film of SiO_2 is coated over the color filter and a continuous film of ITO (100 Ω/square) is sputtered on the SiO_2 layer to serve as a common electrode for the display. A polyimide layer is printed on ITO layer and rubbed in a direction perpendicular to the direction on the bottom substrate. This process is to impart a twist of 90° to the LC molecules when they are filled between the substrates. Spacer particles of 5 μm to 7 μm in diameter are sprayed on the bottom substrate uniformly and the top substrate is printed with an epoxy for peripheral seal. The substrates are cured and aligned accurately (permissible error of 3 μm) and held under pres-

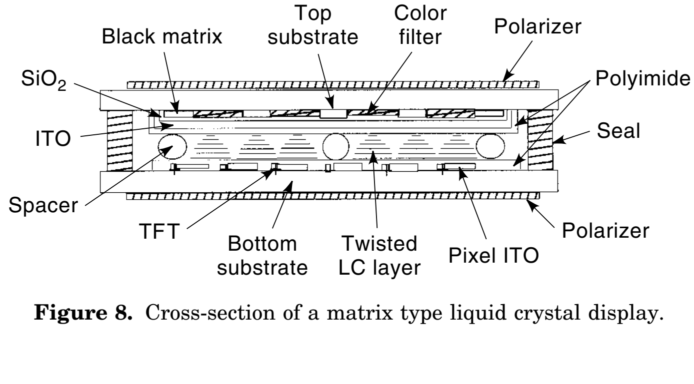


Figure 8. Cross-section of a matrix type liquid crystal display.

sure with heat for three hours to complete the seal. An alternative method for sealing employs ultra-violet (UV) epoxy and UV curing under pressure and heat. The sealing is done leaving a hole for LC filling. The space between the substrates is evacuated through the hole and LC is filled by vacuum-suction through this hole. Subsequently, the hole is sealed. Lamination of polarizers in the proper orientation completes the basic LCD fabrication. For detailed information on fabrication, see Refs. 15 and 16.

PRINCIPLE OF TWISTED NEMATIC LIQUID CRYSTAL DISPLAY DRIVING (ADDRESSING)

Generation of Display Pattern

With reference to Fig. 6b, the basic cell in the "on" state had a voltage across the twisted LC layer. It is possible to apply voltage to the LC layer through transparent electrodes like indium-tin-oxide (ITO). If the pattern of ITO is like a square then a transmissive cell will appear like a dark square in the "on" state. Figure 9 shows the ITO pattern sandwiching a TN-LC layer in a simplified matrix LCD. Substrate-1 and 2 carry the transparent ITO stripes orthogonal to each other. When the LC layer faces no voltage, the twist exists over the entire area of the panel. However, if a voltage appears across the layer in the cross-over regions of the electrodes, the twist in those voltage selected regions disappears. A "normally black" display will appear bright (cross-hatched in Fig. 9) at the cross-over regions. Thus, by suitably voltage-selecting the cross-over regions through proper addressing technique, it is possible to generate a desired pattern or picture. Every cross-over can be activated to serve as a picture element (pixel). The display pattern depends on the electrode cross-over (overlap) pattern, be it a numeric display or special symbol display or television picture display.

Matrix Addressing

The purpose of any driving scheme for displaying information on an LCD is to bring out (1) maximum contrast (2) high resolution (3) many gray shades (4) wide viewing angle (5) good color purity and picture quality (6) low cost. There are many types of LCDs and hence the techniques of driving them are different. Broadly speaking, there are two major addressing techniques. The passive matrix addressing technique employs the driving element (and address electronics) outside the LCD, whereas the active matrix addressing places the driving element (TFT) inside the LCD. Early development of driving schemes was based on the concept of LCDs responding to peak voltages rather than the rms voltages as is now well known. For a clear illustration of driving techniques for matrix LCDs based on rms response, see Ref. 15. Simple numeric LCDs employ "continuous driving" scheme, whereas high information content displays employ "multiplex driving" scheme. Figure 10(a) depicts the principle of continuous driving. Substrate-2 generally lays over substrate-1 in alignment in the regular package. The substrate-1 has only one common connection and the substrate-2 has 23 individual connections. Signal voltage to the common electrode pulsates from 0 to V. "Off" segments receive signal voltages in phase with the common electrode, with the result that there is no voltage difference between the common electrode and the "off" segments. The signal voltages of the "on" segments are 180° out of phase with the common electrode and hence the voltage difference between the "on" segments and the common electrode varies between $+V$ and $-V$. All driving techniques employed in LCD driving minimize a net dc voltage across the LCD to prevent electrochemical degradation of LC material. In continuous driving mode, each segment employs its own driver and the applied voltages can be increased to obtain a good contrast of the display. Figure 10(b) shows the matrix equivalent of the continuous drive scheme. The matrix scheme, which can generate the same display pattern, has only 10 connections as against the 24 connections in continuous drive scheme. The principle of driving involves *amplitude selection method,* which is discussed next.

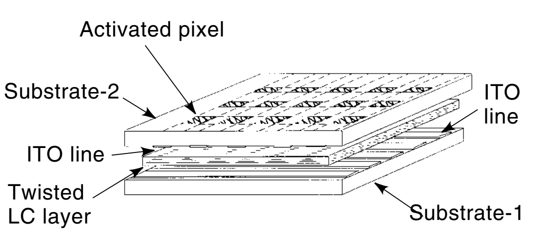


Figure 9. Schematic of a matrix electrodes sandwiching the twisted nematic liquid crystal layer.

Amplitude Selection Method. This method utilizes the property of LCD optically responding to the rms voltages rather than the peak voltages. Figure 11 illustrates the principle of driving for the matrix of N rows and 1 column, although the column may be any number M. The corresponding matrix of Fig. 10(b) is four rows and six columns. The row voltage is normally held at zero. In the illustration, the row voltage of the first row goes from 0 to V and returns to 0 within an interval of t, at which time the row voltage of the second row climbs from 0 to V. Subsequent row voltages are applied in succession as per this time interval up to the Nth row and the whole sequence is repeated with reverse polarity. The first sequence is termed as frame 1 and the corresponding period is T. The selection interval is $t = T/N$. The drive wave forms on the column electrodes carry the information to be displayed on the LCD. The illustration shows the column signals alternating between $+v$ and $-v$. According to the illustration, in the first interval the first row receives a row signal voltage of V. During the same interval, the first column receives a column voltage of $-v$. The voltage of the first row electrode with respect to the column 1 electrode ("on" pixel signal), during this interval, is $V + v$. For the second interval, the pixel signal for row 2 and column 1 is $V - v$ which is designed to be below the threshold voltage for any change in transmission of the LCD and hence the pixel at the cross-over of row 2 and column 1 will be "off." This principle applies to a matrix of N rows and M columns. In one frame period, during the selection time, the "on" pixels receive a voltage of $V + v$ and the "off" pixels receive a voltage of $V - v$. During the remaining $N - 1$ time intervals, an alternating voltage of $+v$ and $-v$ appear on these pixels. Row signals repeat every frame at a frequency of 60 Hz. This amplitude selection method can be applied to the four row-six column matrix of Fig. 10(b) to take advantage of the reduced number of connections and still display the same information shown in Fig.

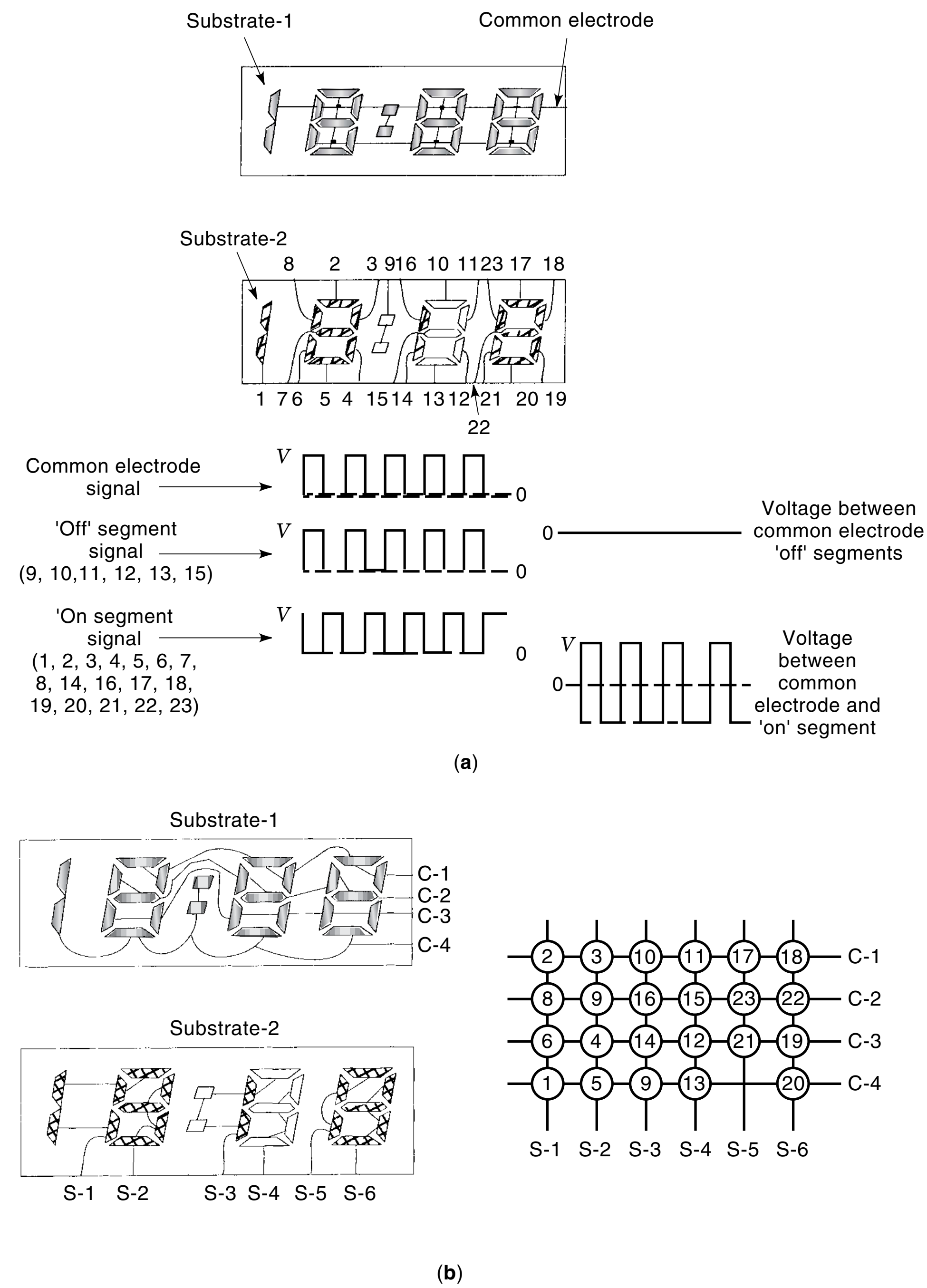


Figure 10. (a) Principle of continuous driving of a twisted nematic liquid crystal display. (b) Matrix equivalent of continuous drive scheme.

10(a). In this method, as shown in the previous example, the drive wave forms applied to the column electrodes carry the information to be displayed in the form of polarity modulation. During the early stages of LCD development, it was believed that the TN-LCD electrically responded to the peak voltage rather than the rms voltage. It was also believed that the "off" pixel needs to be below threshold voltage at all times to remain "off." Therefore $v = V_{th}$ and $V/v \leq 2$ apparently worked well for this concept. An "on" pixel, during selection period, according to this concept, will receive a voltage of $V + v = 3v$ and during the remainder of the frame period it will receive a voltage of $\pm v$ whereas an "off" pixel will receive a voltage of zero in the selection interval. Addressing scheme based on this peak voltage response scheme is termed as 3 : 1 scheme. According to this scheme, the "on" pixel responds to a voltage of $3V_{th}$ during selection period and does not respond to V_{th} during the remainder of the frame period. In reality, the LCD optically responds to the rms voltage present on the "on" pixel averaged over the frame period. According to this new concept, the "on" pixel responds to the rms voltage

$$\langle S_{on} \rangle = \sqrt{\frac{(V+v)^2 + (N-1)v^2}{N}} \tag{5}$$

A similar argument holds true for the "off" pixel. As this concept is based on the optical response of the LCD as determined by the rms (root-mean-square) voltage across the pixel, it is preferable to make the ratio $\langle S_{on} \rangle / \langle S_{off} \rangle$ (selection ratio) as

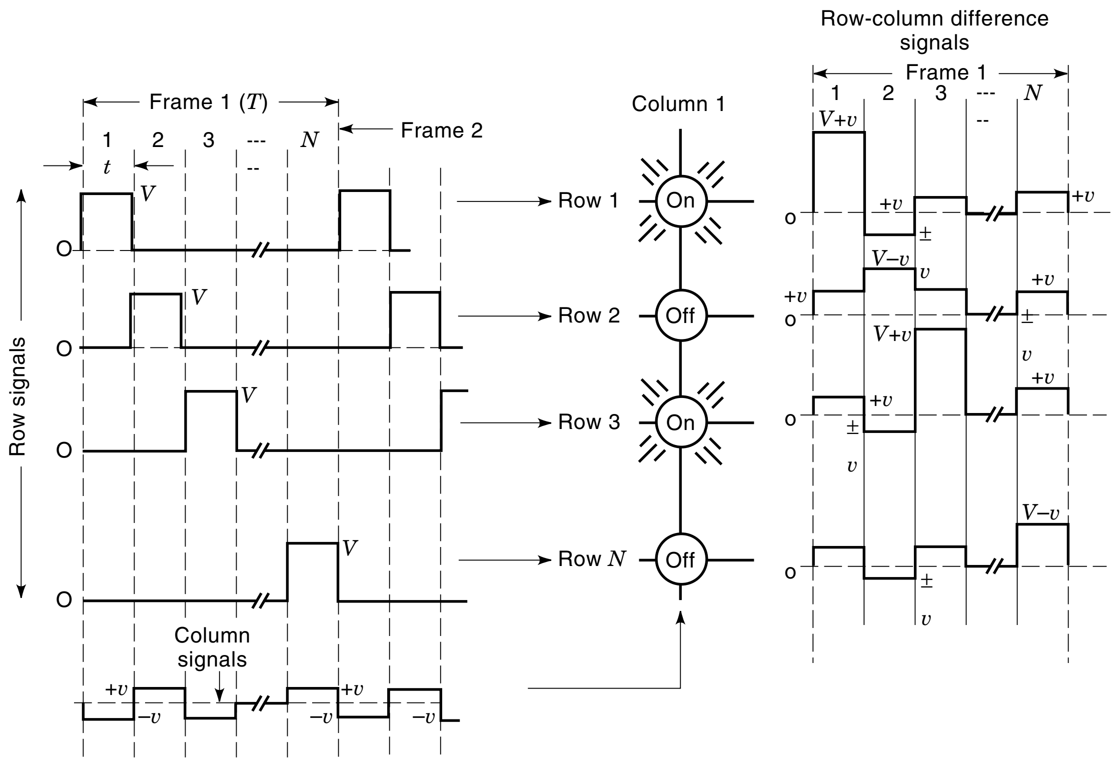


Figure 11. Principle of driving a matrix of N rows and 1 column.

large as possible. Alt and Pleshko (16) have shown that the optimum value for the selection ratio, obtained when $V/v = \sqrt{N}$, is given by

$$\langle S_{\text{on}}\rangle/\langle S_{\text{off}}\rangle = \sqrt{\frac{\sqrt{N}+1}{\sqrt{N}-1}} \quad \text{where}\ \sqrt{N} = V/v \tag{6}$$

Figure 12 shows the selection ratios for different number of rows (N) for both the 3 : 1 scheme and Alt-Pleshko scheme. As N increases the selection ratio asymptotically approaches unity. This means the voltage of the "on" pixel gets close to the voltage of the "off" pixel. For the "off" pixel (with nonzero voltage) to be strictly "off," the electrooptical characteristics of the LC [Fig. 7(a)] should be steep. For the TN-LCD, it is

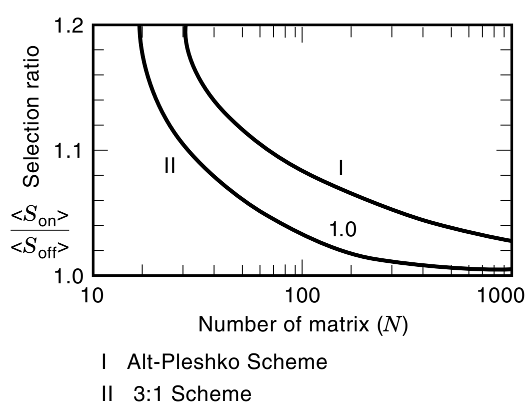


Figure 12. Graphical illustration of the optimized selection ratios for the number of matrix rows.

very difficult to achieve. However, the Alt-Pleshko scheme demands less stringent requirement from the LCD because of its higher selection ratios at higher values of N than the 3 : 1 scheme. Hence, for large number of rows (high information content) Alt-Pleshko scheme has a better performance than 3:1 scheme. Addressing an LCD with 100 rows/lines (N = 100) with this technique is termed as 100 : 1 multiplexing and with increasing number of lines the multiplexing ratio also increases. The waveforms shown in Fig. 11 impose a net dc voltage on the pixel (and hence on LC film). The presence of dc voltage on the LC film, for a prolonged period, results in irreversible electro-decomposition of the LC, thus deteriorating the LCD. Hence the waveforms illustrated in Fig. 11 merely serve to explain the principle of amplitude modulation. To eliminate the dc component, the row and column voltages are simply inverted in the alternating frames. As the number of addressable rows (lines) increase, the contrast and the angle of view of the LCD deteriorate. As N increases it is easy to apply the desired voltage on the pixel one desires to be "on," but it is very difficult to avoid the voltage on the pixels where one does not want. Cross-talk known as "ghosting" occurs due to the optical response of the LC being different for the same rms voltage with different frequencies. Below 500 Hz and above 20 kHz the optical response of LC changes despite the fact the rms voltage is the same. The frequency change arises from the Fourier components of the column signals. Further, the column voltage which carries image signals induces voltage on the row electrodes. All these effects contribute to unwanted cross-talk. Increase in N also affects the contrast and viewing angle of the LCD. When N = 200, the selection ratio becomes 1.07. At this low selection ratio the "off" pixels are not strictly "off." To increase the contrast ratio, still preserving the same number of lines, LCD matrix electrode lay-outs have been modified and operated successfully with additional column drivers. For a clear understanding of these schemes and effects, see Refs. 15 and 16.

Gray Shades with Amplitude Selection Method. Various intensity levels (gray levels/shades) are required in presenting graphical information. Two methods (15) are in use to display gray levels through LCD. These methods are (1) frame rate control (FRC) and (2) pulse width modulation (PWM). In FRC method, several regular frames (say 16) form a *super frame.* Pixels can be turned "on" during certain regular frames and turned "off" during certain other regular frames. The optical intensity level of a pixel depends on the rms voltage averaged over the super frame. A shading alogrithm performs the job of turning "on" and "off" of the pixels. In PWM method, the intensity level of the pixel is changed by modulating the data voltage (column voltage) pulse width during the selection interval.

Multiple Line Addressing. The addressing scheme discussed so far is for displaying static images or information data. The scheme assumes that the response time of the display is many times longer than the duration of the addressing signals. The LCDs that display moving images at video rates do not satisfy this criterion. Hence new addressing schemes have been developed. Basic principle involves the near constancy of the pixel rms voltage during a narrow window which is smaller than both the 60 Hz frame period and the response time of the fast LCD. A generalized matrix addressing scheme (17) for all LCDs and novel addressing scheme for fast LCDs (18,19) are creating big impacts in LCD address electronics.

Display Quality in Matrix Addressing. As the multiplexing ratio employing Alt-Pleshko scheme increases the display quality diminishes. This is due to the selection ratio being small at high values of N. In terms of the LC molecules, this amounts to the partial untwisting of the structure in the "off" pixel. The "off" pixels will be partially "on" when viewed off-axis. This results in poor contrast and narrow viewing angle in addition to contrast reversal (20). Figure 13 shows an iso-contrast diagram (15) for a 100 : 1 multiplexed TN-LCD with a selection ratio of 1 : 1. The polar plot depicts the curves of equal contrast ratio with viewing angle in all the four quadrants. The radial distance is a measure of the viewing angle and the "on" axis viewing corresponds to 0° viewing angle and the outer-most circle corresponds to an off-axis viewing angle of 60°. The best viewing region is in the first quadrant around 30° with a maximum contrast of 5 : 1. Improvements in the contrast and viewing angle have been made by synthesizing new LC materials by altering their elastic constants and dielectric parameters such that the electro-optical characteristics [Fig. 7(b)] is steeper. But, the improvements were not enough for a satisfactory performance beyond $N \simeq 10$. High information content LCDs like those employed in personal computers (PCs) contain 640 × 480 ($M \times N$) pixels (a typical TV contains 250,000 pixels). To successfully drive these LCDs to obtain good display quality, there were many attempts to find new driving schemes with innovative modes of LC operation. The most successful among them is the thin-film-transistor (TFT) driven LCDs. TFT was invented in 1933 by J. E. Lilienfield (21) and the first working TFT matrices were made by P. K. Weimer (22). In 1971 Lechner et al. (23) proposed the TFT-LCD but the first TFT-LCD was indeed made by Brody et al. (24). For nearly a decade, the progress on TFT-LCD was insignificant until Morozumi et al. demonstrated (25) 1.5 in. diagonal pocket color TV using TFT-LCD. What follows is a description of this so-called TFT-LCD.

THIN-FILM-TRANSISTOR LIQUID CRYSTAL DISPLAY WITH TWISTED NEMATIC STRUCTURE

In the multiplexed driving scheme, the "on" pixel gets the peak voltage during the selection interval. During the re-

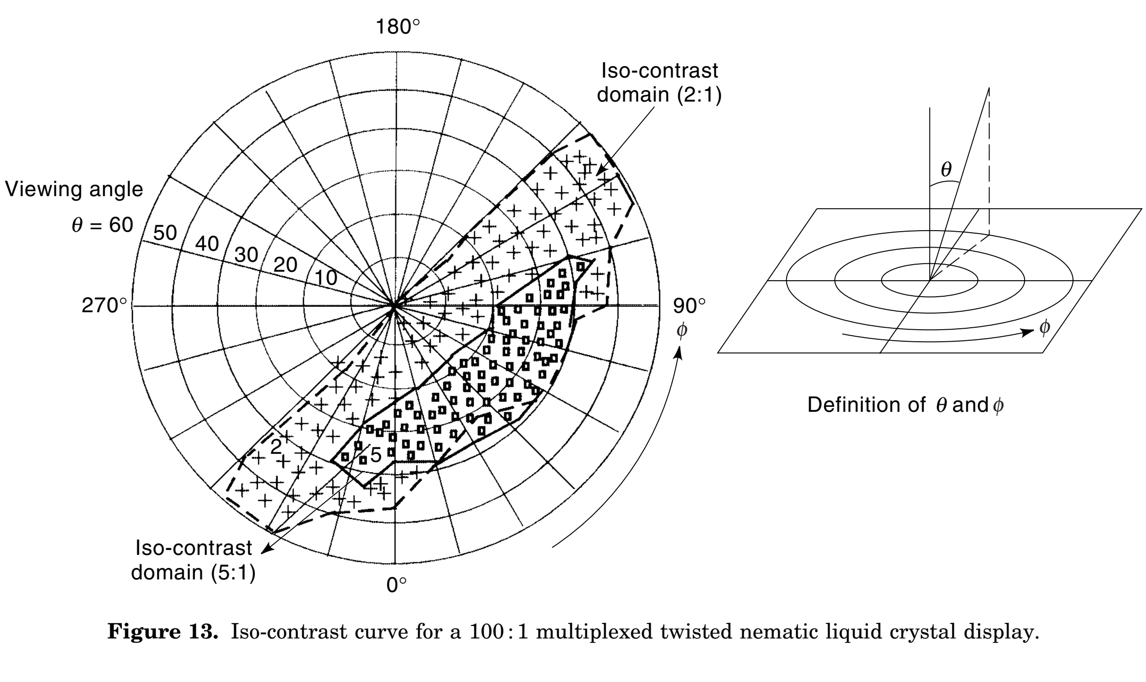


Figure 13. Iso-contrast curve for a 100 : 1 multiplexed twisted nematic liquid crystal display.

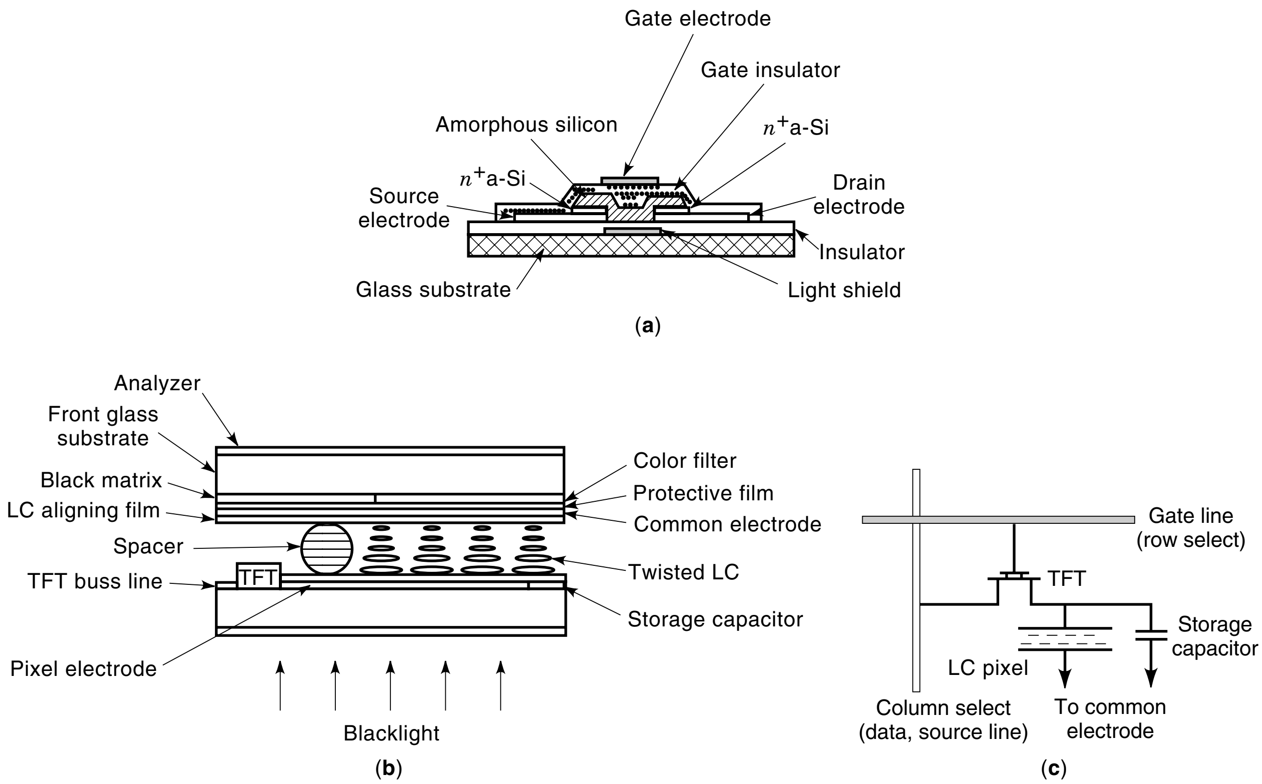


Figure 14. (a) Cross-section of amorphous silicon thin film transistor. (b) Cross-section of thin film transistor liquid crystal display in the vicinity of a pixel. (c) Equivalent circuit of a single pixel thin film transistor liquid crystal display.

maining period the voltage is below the threshold and overall the pixel responds to the rms voltage. In TFT-LCD, the "on" pixel has approximately the same voltage from the instant of selection to the end of the frame. It is as though the LCD is driven continuously as illustrated in the preceding section [Fig. 10(a)]. Figure 14(a) shows the structure of a typical TFT made from amorphous silicon. Figure 14(b) depicts the cross-section of a TFT-LCD in the vicinity of a pixel. There are nearly a million pixels in high information content TFT-LCD. As the LCD matrix also contains the matrix of active TFTs, the TFT-LCD is also termed an *active matrix LCD* (AM-LCD). The equivalent circuit of a single pixel TFT-LCD [Fig. 14(c)] shows that the row select voltage is applied to the gate of the TFT and the column voltage (video signal) is applied to the source electrode of the TFT. The drain electrode of the TFT connects the pixel electrode and the storage capacitor. A common electrode connects the storage capacitor and LC in parallel.

An application of a gate pulse turns the TFT "on" and allows the LC to be charged to the voltage at which the column line is at that particular instant. At the termination of the gate voltage pulse, the TFT isolates the LC which sustains the voltage with additional help from the storage capacitor till the next gate pulse. Figure 15 illustrates schematically the driving principle of TFT-LCD for 2×1 matrix. The gates of the TFT are connected to the rows and the source electrodes are connected to the columns. Row scan voltage turns on the TFT and the LC is charged to the voltage on the column at that instant of time. When the row voltage is turned "off," the TFT isolates the LC which holds the voltage until the next row cycle commences. At this refresh cycle the column voltage reverses and the LC is charged inversely. At the termination of the gate pulse, the LC holds the charge in this reversed state. Thus the LC gets ac voltage continuously, independent of the selection time (gate pulse width) and the duration of column voltage. To accomplish this task, the TFT should satisfy two basic requirements namely, (1) it must conduct sufficiently in the "on" state to charge the LC to the full column voltage during the row voltage pulse in one frame (2) it must be least conductive in the "off" state to isolate the LC so as to hold the charge till the frame period. These two requirements, for a 1% error in the charging voltage can be mathematically expressed by the relation (26), $G_{on}/G_{off} \geq 500\ N$, where N is the number of rows. The amorphous silicon (a-Si) TFT with 20% hydrogenation has good electrical characteristics to satisfy on/off current ratio of 10^7 and has been widely used. Figure 14(b) shows that there needs to be a light shield layer at the bottom of the TFT to minimize photo-induced leakage as a result of the backlighting. A typical TFT-LCD has superior on-axis contrast ratio compared with a multiplexed non-TFT LCD and the values are between 150 : 1 to 200 : 1. Figure 16 shows the iso-contrast curve of such an LCD.

Color Thin Film Transistor-Liquid Crystal Display

LCDs do not generate light and hence they need ambient light (reflective LCDs) or light from the back of the LCD

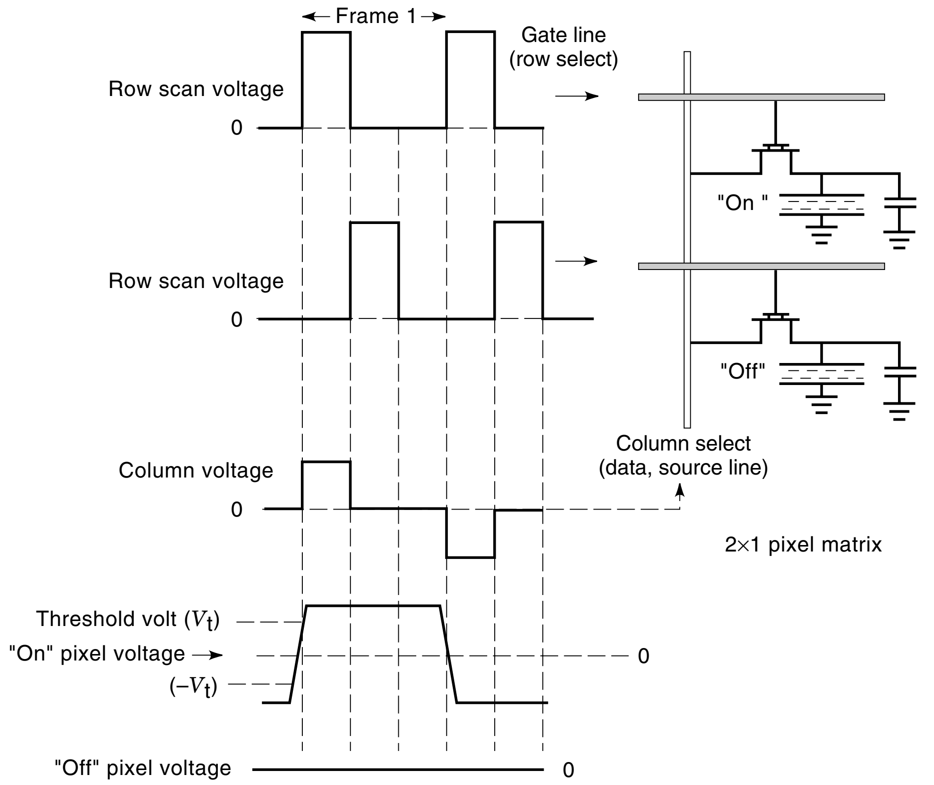


Figure 15. Driving principle of a thin film transistor liquid crystal display.

(transmissive LCDs). There are certain types of LCDs called *trans-reflective LCDs* which can be operated in both modes depending on the intensity of available ambient light. Many laptop computer LCDs operate in this manner. However, TFT-LCDs employed for color video applications like TV need a backlight source. The backlighting source contains the primary colors and the color filters employed inside the LCD are tuned to these colors for obtaining maximum efficiency and color purity. The video signal at the data line (source line) regulates the color and brightness. Figure 17 shows a schematic of the structure of color TFT-LCDs employed in color display system. A backlighting system consisting of linear fluorescent lamps and a light guide collimates the light on to the polarizer of the LCD. The polarized light travels through the LC. The bottom glass substrate has pixel electrodes of thin film ITO which are connected to the TFTs and the column electrodes in the matrix. Usually the ITO employed on the pixel electrodes has a sheet resistivity of 15 Ω/square.

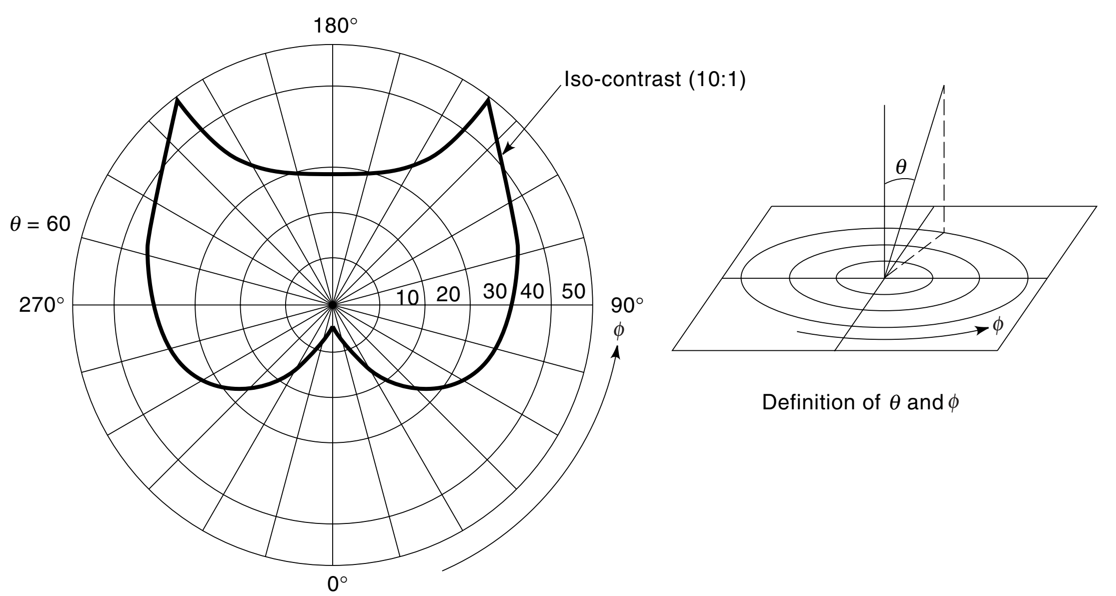


Figure 16. Iso-contrast curve for a conventional thin film transistor liquid crystal display.

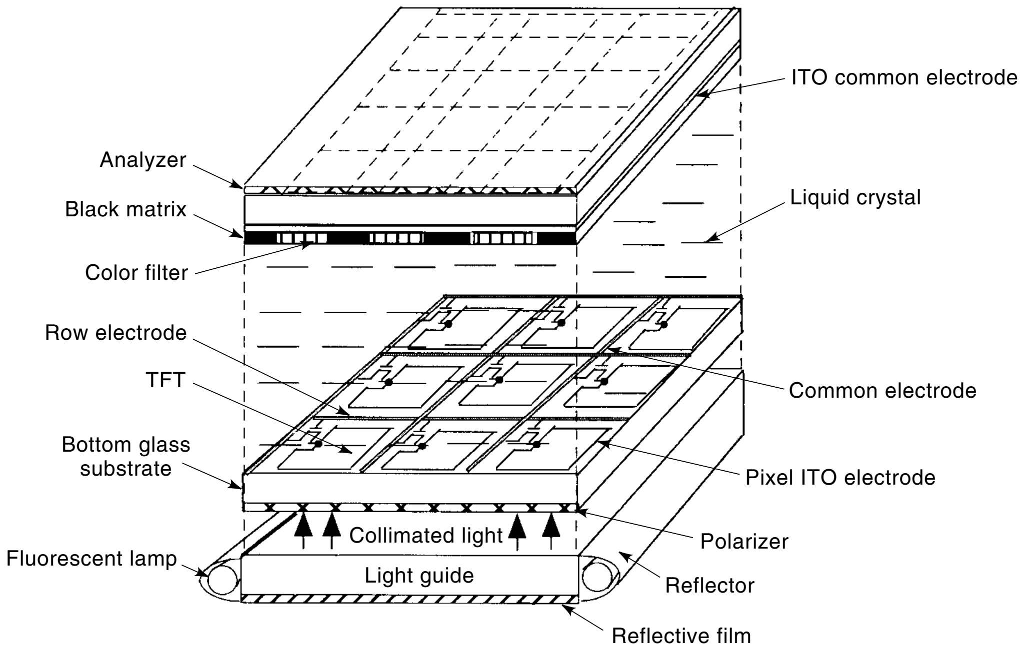


Figure 17. Exploded view of a color thin film transistor liquid crystal display.

The materials for gate/row electrodes and column electrodes are very critical for preserving voltage wave forms and rapid charging of the pixel. Typically either Mo or Cr are employed for this purpose and the resisitivities are in the range of 15 μ ohm-cm. The TFTs are either made from a-Si or polysilicon (p-Si) material depending on the charge mobility and process temperature requirements. The liquid crystal cell gap is usually maintained around 6 μm. For maintaining the cell gap over a large area, spacers are employed (not shown in the figure). The top substrate contains the black matrix to prevent light leakage, and thus a good contrast, and the black matrix is usually made of either a black resin of 1.2 μm or Cr of 0.12 μm. Color filters (CFs) between the black matrix filter the required color from the backlight passing through the selected cell. For this purpose, the filter characteristics of the CF must have a good selective window of transmission for the primary colors of the backlight. The CF is made photolithographically from the color pigments dispersed into the polyimide. An ITO film whose sheet resistivity is in the range of 50 to 100 Ω/square forms the common electrode. Thus the color information in the form of moving images or static display is obtained through the data (column) signals which contain the information and which also controls the transmission of the pixels to allow the appropriate colors with various brightness levels (gray shades), in synchronization with the row scanning and TFT switching. This is a very highly simplified description of the operation of TFT-LCD. For a broad description of TFT-LCD, the most successful display device in recent years, see Ref. 28.

Amorphous Silicon Thin Film Transistor versus Polysilicon Thin Film Transistor. Both these materials are in use today although the material of choice seems to be hydrogenated amorphous silicon (a-Si:H). Poly silicon (p-Si) has higher electron mobility than a-Si:H but it is very difficult to fabricate TFTs over large areas. Further, it becomes costly to produce them. In contrast, a-Si:H has lower leakage current than p-Si but lower mobility as well. It is not difficult to produce a-Si:H-TFTs in large areas at a lower cost. However, a-Si:H requires a light-shield layer on the TFT to prevent the photo-induced leakage current whereas p-Si TFT does not require this additional layer. Amorphous Si process is a low temperature (300°C) process and is preferred over the high temperature (600 to 1000°C) process of p-Si. A glass substrate will be less expensive for use in temperature around 300°C than quartz for use around 600°C. Hence, p-Si TFTs are employed in small high resolution displays used in the "view-finders" and projection TV, whereas a-Si:H-TFTs are used in displays for notebook personal computers and pocket TVs. Table 1 summarizes the technology comparison between a-Si:H and p-Si TFTs. The electron mobility and the "on" current of the TFT control the quick charging of the pixel to the data voltage. After the charging, the pixel is isolated to retain the charge and the extent of isolation is decided by the "off" current (intrinsic leakage) of the TFT. The parasitic capacitors and line

Table 1. TFT Technology for LCD

Parameter	Amorphous Silicon (a-Si:H)	Polycrystalline Silicon
Electron mobility (cm^2/V-s)	0.5–1.0	25–100
On/Off current ratio	10^7	10^6
Transistor drive	poor	fair
Transistor leakage	low	fair
Process temperature	300°C	>600°C
Stability under illumination	requires light shield	does not require
Achievable dot pitch/inch	300	500–1000
Achievable feature size (μm)	5–10	3–5
Existing infrastructure	good	fair

resistors also play a role in the charging and discharging of the pixel.

Backlights for Liquid Crystal Display. Most full color TFT-LCDs are of the transmissive type and hence they rely totally on the backlighting arrangement for the display quality. The backlighting devices employed in these LCDs have to satisfy stringent requirements. For avionic LCDs the specifications are very rigorous. A good backlight arrangement should meet the following requirements:

1. Uniformity of light output over the entire area
2. Well collimated light
3. Flat geometry and light weight for compatibility with the flat display
4. High luminous efficiency
5. Performance independent of the operating temperature range
6. Emission wavelengths for a good color quality
7. High dimming ratio of $>10000:1$

The only successful backlight device for a direct view TFT-LCD that optimally meets these requirements is the fluorescent lamp. Projection display systems incorporating TFT-LCDs employ Xe arc lamps or halogen lamps for backlighting. The phosphor employed for fluorescent lamps emit primary colors around the wavelength peaks of 610 nm (red), 540 nm (green), and 450 nm (blue). These wavelengths are known to offer good color performance. However, the final quality is dependent on the color filters employed. The color filters should have the characteristics to transmit these wavelengths. Figure 18 shows the transmission characteristics of the three color filters. The vertical dotted line depicts the peak wavelengths of the backlight device. It is important that the characteristics of the color filters and the backlight device match very well. This satisfies the color performance requirement of the LCD. Most commercial fluorescent lamps are either linear or "serpentine." Special shapes can also be custom made. For example it is not uncommon to find integrated serpentine lamps with a flat shape. However, these lamps can not be used as they exist behind the LCD because of the gross nonuniformity of light output. Elaborate optics needs to be employed for obtaining uniformity of luminance and collimation. Figure 19 shows one such optical arrangement (29). The collimation is necessary to make the direction of light propagation to be along the optic axis (long axis) of the LC in the "on" state. In the absence of collimation, the rays incident at off-axis will undergo birefringence and the resulting display quality will suffer. The arrangement clearly shows the conversion of the line source (linear fluorescent lamp) of light into a sheet source of light. During this conversion process, an enormous amount of light loss occurs. It is therefore meaningful to obtain a direct sheet source of light. There have been several attempts to develop a truly flat fluorescent lamp for backlighting LCD. One such attempt (30) is the development of a multichannel flat fluorescent lamp employing thick-film hollow cathodes. Figure 20 is a schematic representation of such a lamp. This lamp, in addition to being flat and thin, has a luminance uniformity of $>90\%$ over the entire area of the lamp. The uniformity is the result of the multichannel design. It is clear from the figure that there are six channels of discharge corresponding to the six sets of hollow electrodes, which operate as cathodes and anodes in the alternating cycles of the impressed ac voltage. The light output is the result of the ultraviolet (UV) produced in the Hg discharge and the conversion of UV to visible light by the phosphor. Despite the existence of six discrete channels, the light output is a continuous sheet and the uniformity of light output over the entire area can be externally adjusted by changing the current through individual channels, as needed. Both the space between the substrates and the length of the positive column of the discharge need to be increased to augment the efficiency of this lamp. The present day LCDs use either linear lamps or serpentine shaped lamps because of light weight and low cost. All Hg based fluorescent lamps have high luminous efficiency (80 lumen/W) but they are highly temperature dependent. Lamps based on field emission and inorganic electro-

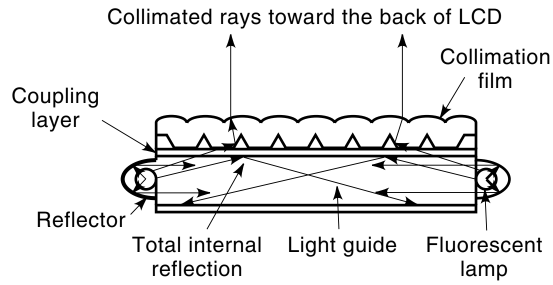


Figure 19. Backlighting arrangement for liquid crystal display.

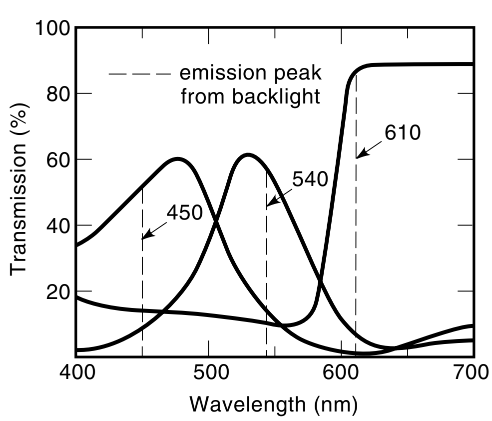


Figure 18. Color filter characteristics of a thin film transistor liquid crystal display.

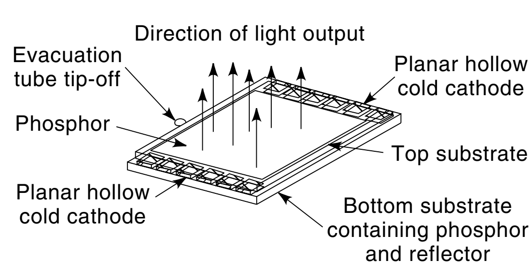


Figure 20. True flat fluorescent lamp for liquid crystal display backlighting.

luminescence are also being considered for backlighting due to their temperature independent characteristics. In the conventional backlighting arrangement (Fig. 19), there is a light loss of 30% from the lamp to the back of the LCD and 95% from the lamp to the front of the LCD. Maximum light loss occurs at the color filters and this will be a major problem for all types of LCDs employing backlighting.

Limitations of Thin Film Transistor-Driven Liquid Crystal Display.

1. The yield of TFTs fabricated over large area >14 in. diagonal is between 30% and 50%
2. Distortion of the gate pulse, due to the associated resistance and capacitance of the line, as it travels down the gate line in a large area LCD and the consequent pixel voltage error
3. The capacitance between the gate and pixel electrode induces voltage error on the pixel electrode when the TFT is turned off at the end of a charging period
4. Due to the source drain capacitance and LC capacitance, the cross-talk increases as resolution increases
5. In spite of TFT, the TN-LCDs viewing angle of 60° is still not enough
6. A drift in TFT performance is noticed with fluorescent backlighting
7. Cost is high

Due to the foregoing limitations, much effort has been made to develop LCDs based on different modes of operation.

OTHER TYPES OF LIQUID CRYSTAL DISPLAYS

Super-Twisted Nematic Liquid Crystal Display

In the preceding sections on multiplex addressing of TN-LCDs (without TFT), it has been made clear that due to the lack of the steepness of the electrooptical characteristics of the TN-LCD, high multiplex ratios required for high information content displays, for good display quality, can not be employed. It was extremely challenging to synthesize special LC mixtures to obtain the steepness required for even the 100 : 1 multiplex ratio. This led to the development of a TFT-LCD which has its own complexity. However, it was found (31) that the twist angle has a dominant role in increasing the steepness and a twist angle of 270° yielded an infinite slope. As the magnitude of the twist is always compared with the conventional 90° twisted TN-LCDs, the LCDs based on a 180° to 270° twist are termed a super-twist nematic liquid crystal display (STN-LCD). A reflective STN-LCD with black information on yellow background was demonstrated (32) for high multiplex driving. See Ref. 33 for more details on STN-LCD. The required steepness of the electrooptical characteristics is achieved by STN-LCDs for use in notebook computers and other high resolution displays with 1024 × 768 ($M \times N$) pixels. Figure 21 illustrates the principle and the electro-optical characteristics of STN-LCD based on reflective mode. Figure 21(a) is the cross-section of the STN cell and Fig. 21(b) illustrates the effect of twist angle on the steepness of the electro-optical characteristics. At a twist angle of 270° the slope is very steep, thus yielding the advantage of high multiplex ratios not possible with 90° twisted TN-LCDs. To obtain and sustain a twist angle exceeding 90° a normal nematic LC is doped with a cholesteric LC and the resulting "chiral nematic" has an intrinsic twisted structure. The amount of twist is determined by the pitch p which is the distance along the helical axis traversed for one full rotation of the director (i.e., 360°). The gap between the substrates d and the aligning directions at the substrates also decide the twist angle. Generally the relation $d/p = \varphi_0/2\pi$, where φ_0 is the twist angle, is valid and for a twist angle of 270°, $d/p = 0.75$. The pitch can be adjusted by varying the concentration of the dopant for the designed d. STN-LCDs typically have the cell gaps in the range of 5 to 8 μm with a tolerance of ± 0.05 μm. To avoid a "striped" distortion (34) in the structure of the super-twist, a pretilt angle of 5 to 8° for the LC molecules at the surface is required. Figure 21(a) shows, in the "off" state, an STN cell with a pretilt angle for LC molecules at the boundaries (saw-tooth structure at the bottom substrate and hidden at the top substrate) and a twist angle of 270°. In the "on" state the LC molecules align themselves along the electric field due to the positive dielectric anisotropy. In STN-LCD, the polarizer axes are not assembled either parallel or perpendicular to the alignment direction of the LC molecules at the substrate boundaries, as in TN-LCD. Instead, the axes are assembled at an angle with the LC alignment direction for maximum contrast.

Optics of Super-Twisted Nematic Liquid Crystal Cell. An ordinary light entering the polarizer from the bottom is linearly polarized and it proceeds into the cell [Fig. 21(a)] and incident at the anchored LC molecules at the boundary at an angle with the long axes of the molecules. It undergoes birefringence, as it proceeds, and finally emerges at the top glass plate as an elliptically polarized light as a result of the phase difference between the ordinary and extraordinary rays. The polarizer at the top transmits that component of the elliptically polarized light parallel to the transmission axis of the polarizer. Due to the wavelength dependency of the birefringence and the optical rotation due to the large twist angle, the transmitted light in the "off" state is colored yellow and is termed *yellow mode.* In the "on" state, the linearly polarized light coming into the cell from the bottom polarizer does not undergo birefringence and optical rotation and hence is blocked by the top polarizer, leading to the black appearance. An STN-LCD operating under this arrangement will display a black pattern on a yellow background (yellow mode). However, as with the TN-LCD, if one of the polarizers is rotated through 90°, a complementary mode results. In the "on" state, the display appears bright and colorless and in the "off" state it appears dark blue. This is referred to as the *blue mode.* Both blue mode and yellow mode STN-LCDs are employed in notebook computer displays (640 × 480) for their simplicity without the use of TFT and the consequent cost advantage over TFT-LCDs. However, the users accustomed to TN-LCDs demand a black-and-white information display from STN-LCDs. So, the coloration caused by birefringence has to be compensated for to derive white appearance in place of yellow

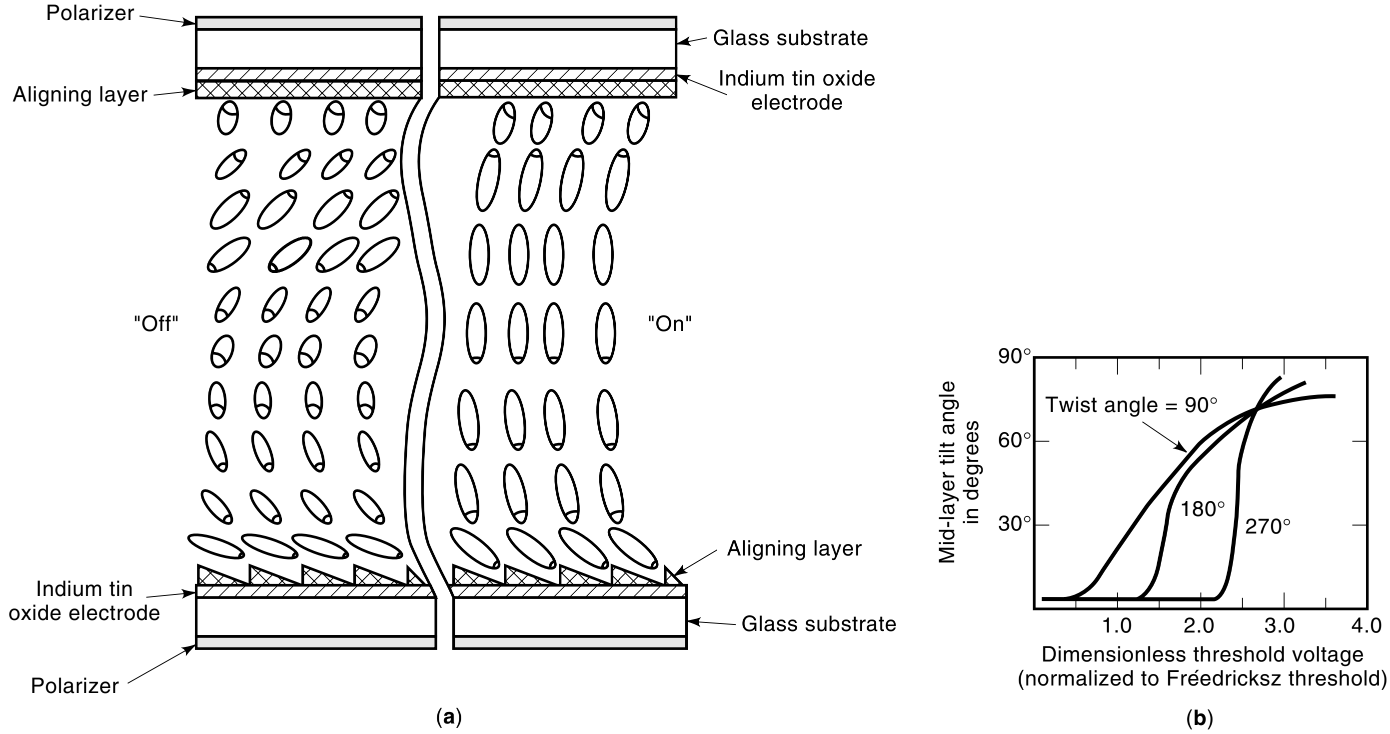


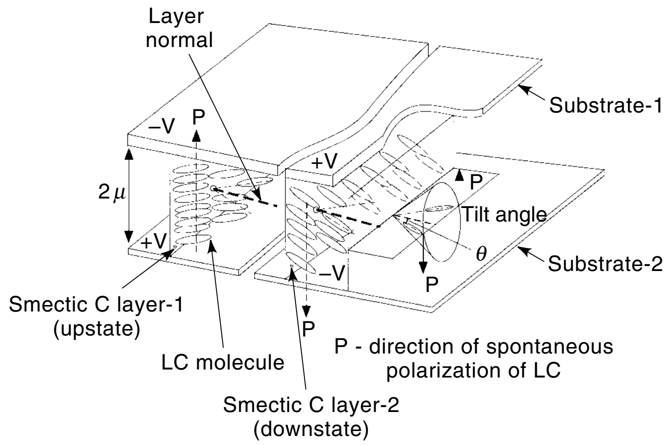
Figure 21. (a) Cross-section of a super-twisted nematic liquid crystal cell in the "off" and "on" state. (b) Applied voltage versus mid-layer tilt angle for various twist angles of twisted structure.

appearance and dark appearance in place of blue appearance. This has been accomplished (35) by the development of a double layer STN-LCD with a 180° twist. In this structure, a compensating reverse super-twisted structure without any electrodes is placed in front of the STN-LCD but inside the front polarizer. In the "off" state, this compensating layer nullifies the elliptically polarized light and turns it back to linearly polarized light which is blocked by the front polarizer. Thus, in the "off" state, the display appears dark. In the "on" state, however, the compensating layer allows the light (rotate the plane of polarization) to be passed by the front polarizer. Thus, the display appears bright in the "on" state. This arrangement is advantageous for assembling color filters to make the STN-LCD display full colors. The double layer STN-LCD is considered thick and heavy for notebook computer application and hence efforts were made to develop lightweight and thin compensating layers. This resulted in the development of polymer film retardation layer (36) in combination with STN-LCD.

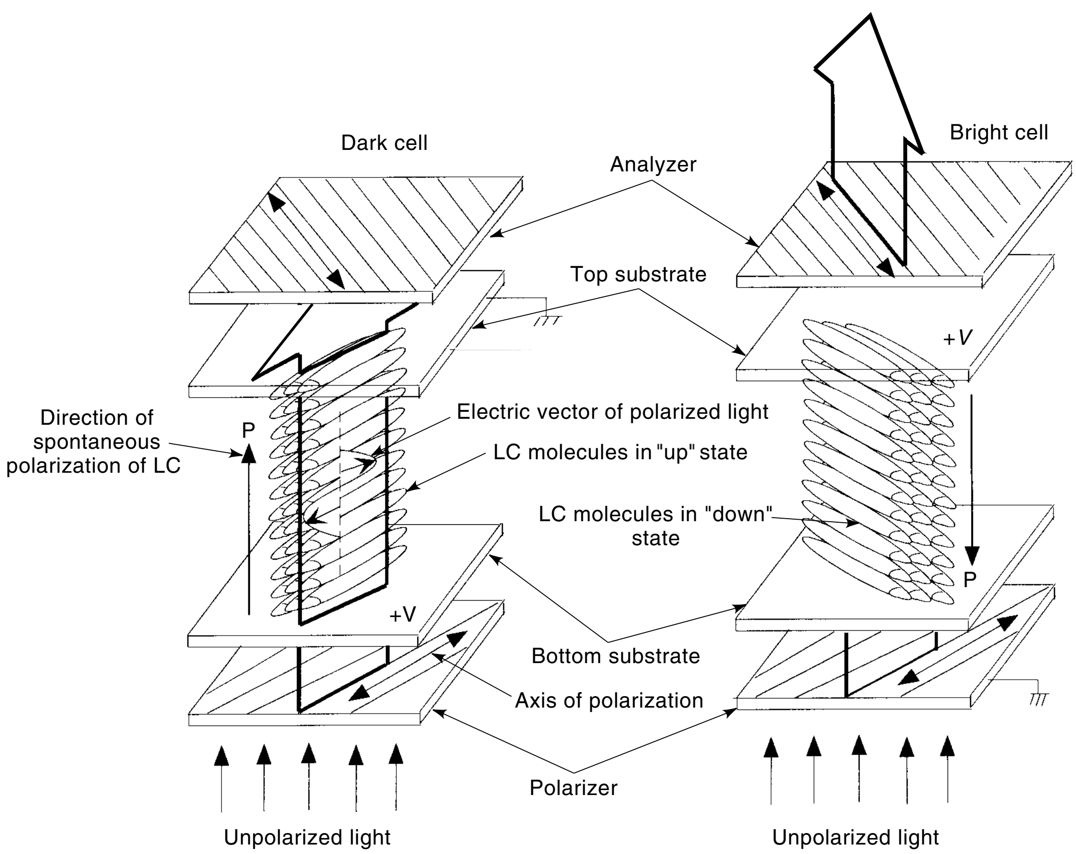
Advantages and Disadvantages of Super-Twist Liquid Crystal Displays. The simplicity of fabrication compared to the complex TFT-LCD is the main reason for the STN-LCD to be cost effective. Driving with high multiplex ratios (480 : 1) employing rms response scheme yields reasonable viewing angle and contrast. For this reason, STN-LCDs are finding increasing applications in notebook computer displays and in portable equipment display applications requiring a bright reflective LCD without backlight. However, STN-LCDs still suffer from low on-axis contrast ratio of 20 : 1 as against 200 : 1 for TFT-LCDs. The best viewing angle in any quadrant is <50° as against 60° for TFT-LCD. The quality of full color display of STN-LCDs is lacking. The surface irregularities of STN-LCD substrate demand more stringent tolerance (<0.05 μm) compared to the TN-LCD (0.1 μm).

Ferro-Electric Liquid Crystal Display

All the twisted structures of the liquid crystal, be it 90° or 180° or 270°, have response times in the range of tens of milliseconds and hence they require multiplexing drive schemes based on rms response. The ferroelectric liquid crystal display (FLCD), in a specific mode of operation, has response time in the range of microseconds. A permanent or spontaneous polarization exists in FLCs and this property is exploited in FLCDs. If a chiral smectic C phase is sandwiched between two substrates whose surfaces are treated with alignment layer and the space between the substrates is 1 μm–3 μm, a surface stabilized FLC phase is formed. Figure 22(a) shows the structure of the surface stabilized ferro-electric liquid crystal (SSFLC) phase, known as *book-shelf* geometry. In practice, a more complicated configuration known as *chevron* structure may occur (which implies that the layers are no more perpendicular to the cell walls, instead bending in a wedge pattern between the cell walls). For simplicity let us assume the book-shelf geometry in which the layers are normal to the substrates. In this example pixel-1 has a spontaneous polarization P in the upward direction (upstate) when a positive voltage is impressed on the bottom plate and a negative voltage on the top plate and the pixel-2 has P in the downward direction (down state) when the polarity of the voltage is reversed. The LC molecules in the layer are tilted by an angle θ with respect to the layer normal. The molecules freely rotate around the cone [Fig. 22(a)] during the change-over from one state (down state or $-\theta$) to the other (up state or $+\theta$). However, the molecules at the substrate boundary are anchored. The time taken for changing over from one state to the other is fast and is on the order of microseconds. The dominant factors for response time seem to be the viscosity and polarization. Figure 22(b) shows the operating principle of the surface stabilized ferroelectric liquid crystal display (SSFLCD). The cell on the left is impressed with a suitable polarity of the voltage to create an electric field from the bottom toward the top. The direction of spontaneous polarization P of the LC molecules align along the direction of the field and this imposes a tilt to the LC molecules about the layer normal as indicated in the figure. Under this condition the unpolarized light traveling from the bottom is incident on the polarizer and changes to the linearly polarized light. This polarized light has its electric vector parallel to the long axes



(a)



(b)

Figure 22. (a) Structure of surface stabilized ferro-electric liquid crystal display. (b) Principle of operation of a surface stabilized ferro-electric liquid crystal display.

(optic axis) of the LC molecules and hence propagates with a single velocity unaffected by the LC medium. On incident at the polarizer at the top, the polarized light is absorbed as the axis of the polarizer is placed at right angles to the direction of the linearly polarized light. Thus, the cell appears dark. The LC molecules will remain in this state even if the voltage is removed, signifying the existence of memory. Considering the cell on the right, the voltage on the cell is reversed to create an external electric field from the top toward the bottom. This imposes a tilt to the LC molecules in the opposite direction as the result of the spontaneous polarization P aligning itself along the direction of the external electric field. Under these circumstances, the linearly polarized light entering the cell has its electric vector interacting at an angle with the optic axis (long axis of LC) of the LC medium. Hence, the polarized light undergoes birefringence and emerges as an elliptically polarized light. The top polarizer transmits that component of the polarization of the elliptically polarized light which is parallel to the polarization axis of the polarizer. Thus, the cell appears bright.

High speed switching in liquid crystal was first demonstrated (37) in 1980. Soon the tremendous advantage of driving large numbers of lines with high multiplex ratios has driven LCD manufacturers to exploit this mode of LCD operation. In the beginning, it was extremely difficult to obtain SSFLC mode even over an area of 1 mm^2. The technological difficulty is mainly in maintaining a cell gap of 3 μm over a large area. However, in 1992 a 15 in. diagonal SSFLCD was developed (38) with 1024 × 1280 pixels. Among the LCDs based on birefringence and multiplex driving SSFLCD has the widest viewing angle. The SSFLCD behaves as a uniform birefringent slab and the light transmitted through the slab is given by (39)

$$I = I_0 \sin^2 4\theta . \sin^2[\pi d \Delta n/\lambda] \quad (7)$$

where I_0 is the transmission through parallel polarizers, θ is the half cone angle of the FLC molecule, Δn is the birefringence of the liquid crystal, d is the cell gap and λ is the wavelength of the incident light. Maximizing for light transmission and contrast ratio (I/I_0 = maximum), the condition Δnd $\approx$ $\lambda/2$ is obtained (the optimum half cone angle of the FLC is 22.5°). On a practical 15 in. diagonal FLCD, with a pixel count of 1024 × 1280, an impressive contrast ratio of 40 : 1, a viewing angle of 50°, and a response time of <70 μs was achieved (38). The fast response of the FLCD was exploited in a novel display structure (40) in which the row function is transferred to a fast scanned backlight device and the FLCD is employed as a column shutter. Despite the fact that the FLCDs are the fastest responding devices in the family of LCDs, they have not become popular in commercial production due to three major problems, which are (1) the stringent requirement of spacing between the substrates around 2 μm over the entire area of the display and the permissible variation in this gap is $\pm$0.05 μm to maintain the SSFLC structure, (2) the external pressure effects on the display irreversibly damages the SSFLC structure, and (3) lack of gray scale for TV application.

Performance Enhancement Approaches to Liquid Crystal Displays

Display parameters such as viewing angle, contrast ratio, gray scale, brightness, efficiency, resolution, response time, ease of driving, and ease of fabrication to large sizes, require continuous improvement for enhanced performance. There are several approaches for enhancing the performance of LCDs in general, but specific details will not be described here. Many new structures and new modes of operation are always evolving. For example, the performance of the TFT-LCD is superior to other types of LCD considering the full color display capability in small sizes. But the TFT structure becomes complex and the production yield becomes low for sizes larger than 14 in. diagonal. Hence, for large sizes, plasma addressed LCD (PALCD) is proposed. In this novel driving method (41), the TFTs are replaced by plasma switches. Row scanning is accomplished through long plasma channels underneath the liquid crystal and the LC is isolated from the plasma by a thin dielectric sheet. LC pixel is sandwiched between the ITO column electrodes and plasma channels. One plasma channel replaces an entire row of TFTs in a conventional TFT-LCD. This novel technique replaces the costly TFT and scales up the size with high yields in manufacturing because the plasma channels are easy to fabricate. Already, 25 in. diagonal (42) PALCD has been commercially made for multimedia applications.

The LCDs, in general, do not have sufficient viewing angle compared to the conventional cathode ray tube (CRT) which people are accustomed to in their homes when viewing television. Hence, the efforts are relentlessly on-going to improve the viewing angle. There are several innovative techniques employed to accomplish this. One such technique is the *in-plane switching* of the TN-LCD driving. In this technique, coplanar electrodes are formed inside the LCD on one substrate exclusively as against the conventional plane parallel electrodes (on both substrates). The field produced by the coplanar electrodes untwist the LC molecules more toward the electrode-substrate than toward the opposite substrate to occupy a different orientation (different from the conventional untwisting) so as to yield a wide angle of view. On a TFT-LCD, the widest angle of view reported (27) is 80° both along X- and Y-axes. Recent TFT-LCDs (27) with 1024 × 768 × 3 pixels have on-axis contrast ratio of 150 : 1 and a viewing angle of 80° in all the four quadrants with lowest contrast of 10 : 1 at the extreme angle. The on-axis luminance is 120 cd/m^2. This extended graphic array (XGA) TFT-LCD has been made employing coplanar electrodes for the LCD and is driven by "in-plane" switching method (27). Typical high resolution (640 × 480) TFT-LCDs (10.4 in. diagonal size) employ pixel size of 100 μm × 300 μm (300 μm × 300 μm for one color pixel) with line spacing of 10 μm and a TFT area of 12 μm × 16 μm. The theory of in-plane switching is given in Ref. 43.

It is well known that the TN-LCD suffers from asymmetrical degradation of viewing angles, that is, viewing angles along the vertical viewing zones are worse than along the horizontal viewing zones. In addition, the reverse contrast and gray levels are also asymmetric. A multidomain approach for the LC alignment has been employed to overcome this problem. In this configuration, each pixel has two or more domains with opposite sense of twist and pretilt of LC molecules. In a two domain LCD, the divided domains mutually compensate for the asymmetric viewing characteristics. The fabrication procedure is complicated by way of additional lithographic and alignment steps (44). By employing this multidomain technique a 33 cm diagonal full color TFT-LCD has been developed (45) yielding a viewing angle of >40° along the vertical zone and >50° along the horizontal zone. Currently, LC alignment method employing polarized UV exposure technique (nonrubbing) is being developed to obtain 4 domains within a pixel.

Yet another technique used to widen the angle of view of the TN-LCD is a simple method of assembling a negative birefringence film outside the LCD. There is no need to change anything within the LCD. A normally white LCD (bright when no voltage is applied) appears dark when the voltage is applied. When viewed on-axis (zero angle of view) the LCD will have high contrast and appears dark in a bright background. However, when viewed off-axis at wide angle (>40°) the degree of darkness is reduced due to the birefringence the polarized light ray undergoes at that angle because of its incidence at an angle with the long axis (optic axis) of the LC molecule. Presumably, the negative birefringence film compensates for the birefringence the ray undergoes. By using this technique, the widest angle of view of 65° along the horizontal direction, 55° along the top vertical zone and 40° along the bottom vertical zone has been achieved (46).

It is well known that the transmissive TN-LCD in its full color capability transmits only 5% of the backlight intensity and the angle of view is limited due to the inherent birefringence at wide angle. The polarizers employed absorb appreciable amount of light. In certain applications like the projection display, high brightness on the screen is desired. LCDs based on the scattering mode have started reappearing. Although the origin of scattering is not the same as the Heilmeier type of scattering (2), nevertheless the scattering phenomenon resulted in a wide angle of view and the absence of polarizers increased the transmission of the LCD. There are two types of displays in this scattering mode. One type is based on a polymer dispersed in the LC and the polymer forming its own network in the absence of the voltage. The other type is based on a polymer encapsulating the LC in individual droplets. Both the types are generally called polymer dispersed liquid crystal (PDLC). In the polymer network type of display the polymer dispersed inside the liquid crystal has its own network to scatter light. When the voltage is applied the network is modified by the LC and the polymer transmits light. In polymer encapsulated type of display, the LC molecules inside the polymer assume a homogenous alignment (homeotropic alignment also can be designed). At this condition the display will scatter light. When the voltage is applied the LC molecules align themselves with their long axes along the field (for positive dielectric anisotropy). The display will transmit light and not scatter. By a suitable choice of the LC and the polymer, this function can also be reversed. The principle is illustrated in detail in Ref. 47. Usually these displays are operated in reflective mode under ambient light or frontlighting with increased efficiency. Another type of display termed *guest-host* display or *dichroic* display employs LC compatible color dyes doped in the LC and operated either in a homeotropic alignment or homogenous alignment. For example, in a homogenous alignment the dye molecules are aligned along with the LC and the dye absorbs one polarization of the backlight or the frontlight, thus giving its characteristic color. When a voltage is applied to the display, the LC molecules align along the field (for a positive dielectric anisotropy) and the display transmits the light. For more details on the dichroic type of display, see Ref. 48. There is a multiplicity of variations on different modes of operation of the LCD and some of these can be found in Ref. 49. The field of LCD is so extensive that it is impossible to cover the details of all types of LCDs in the limited space available.

Finally, the ever increasing LCD development will continue to reveal the marvels of the interesting phases of the liquid crystal which took display technology from the centenarian CRT.

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