CHAPTER 2

LIQUID CRYSTAL DISPLAYS - A REVIEW

2. LIQUID CRYSTAL DISPLAYS - A REVIEW

Of the various flat panel displays available at present, viz., Liquid crystal, Electrochromic, Electroluminescent, Vacuum Fluorescent, Gas Discharge Plasma, etc., **Liquid Crystal Displays** (**LCDs**) require the lowest power to operate and are economical. LCDs became commercially available in 1970 and since then, their technology has progressed rapidly and they have replaced CRTs in several applications. At least twenty models of portable, lap-top computers using LCDs are available now. This clearly indicates their usefulness. Considerable scientific and technical efforts are currently devoted towards further development of LCD technology. As this thesis is devoted to matrix addressing of LCDs, important aspects of liquid crystal materials, electro-optic effects and the addressing techniques are reviewed in this chapter.

2.1. LIQUID CRYSTAL MATERIALS

2.1.1. Liquid Crystals

The liquid crystalline phase was discovered by an Austrian botanist, Friedrich Reinitzer in 1888. He found that **cholesteryl benzoate,** unlike many of the organic compounds known at that time exhibited two distinct melting points [1]. Later, it was found that many organic materials melt from the solid state to form a turbid liquid, which on further heating undergo a second transition leading to a clear isotropic liquid. The intermediate state between the solid and the isotropic liquid has some properties of both crystalline and liquid phases as given in Table 2.1. This was therefore termed as the liquid crystalline phase. This phase is often called a meso-

Table 2.1. Crystal, Liquid Crystal and Isotropic Liquid - A Comparison

Characteristics	STATE		
	CRYSTAL	LIQUID CRYSTAL	ISOTROPIC LIQUID
Molecular shape anisotropy	Not essential	Essential	Not essential
Orientational order	Present when molecules have shape anisotropy	Present	Not present
Positional Order	Present in three dimensions	May be present in one or two dimensions	Not present
Flow properties	Rigid and does not flow	Flows and takes the shape of the container	Flows easily and takes the shape of the container
Physical properties	Some of them are anisotropic	Generally anisotropic	Isotropic

morphic phase or mesophase. The materials which exhibit this phase are called liquid crystals, mesomorphic substances or mesomorphs.

Liquid crystals are broadly classified into two types as given below:

- ***Thermotropic liquid crystals,*** *which are obtained either by heating or cooling certain organic materials;*
- ***Lyotropic liquid crystals,*** *which are obtained by dissolving certain solids in appropriate solvents.*

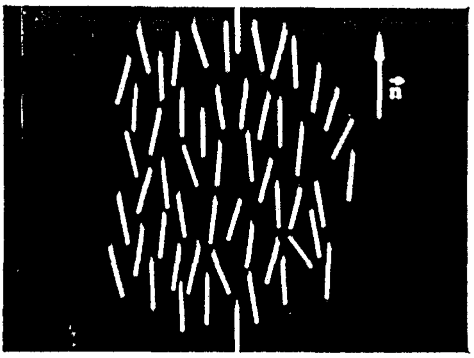
Of these, the thermotropic liquid crystals are used in display applications.

Liquid crystal molecules have shape anisotropy. They are mostly made up of rod-like molecules. Liquid crystals with disc-like molecules were discovered recently [2], but, their applications in display devices are not known so far. In the liquid crystalline phase, the molecules exhibit an orientational order. The average preferred direction of the molecules in a small volume of liquid crystal is described by an unit vector (of arbitrary sign) called the director as shown in Fig. 2.1.

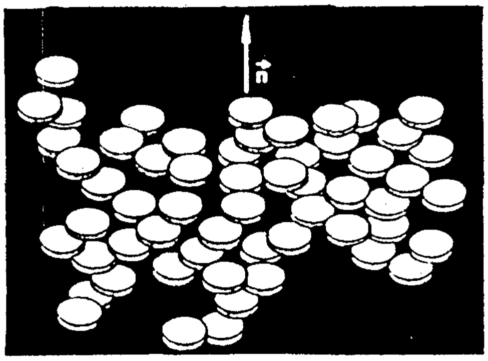
2.1.2. ***Classification***

Thermotropic liquid crystals are classified into four main categories depending on the molecular arrangement as given below; and as shown in Fig. 2.2.

- ***Nematic liquid crystals.*** *They are the simplest and widely used in practical applications. The rod-like molecules are approximately parallel to one another and hence exhibit orientational order. But, they do not have positional order.*

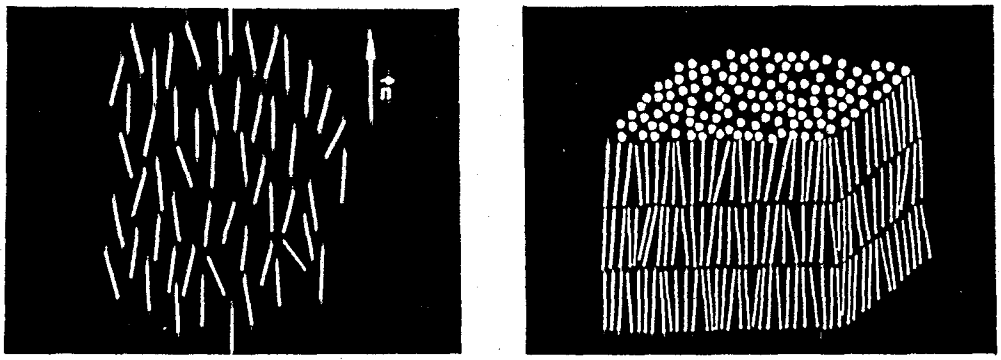


a) Rod-like molecules

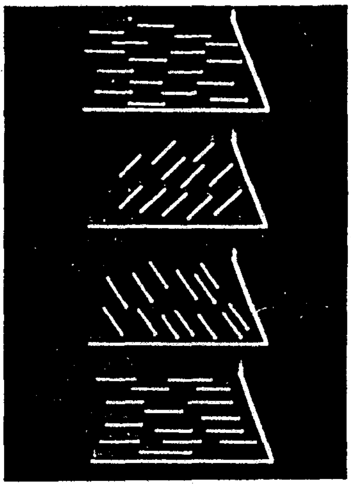


b) Disc-like molecules

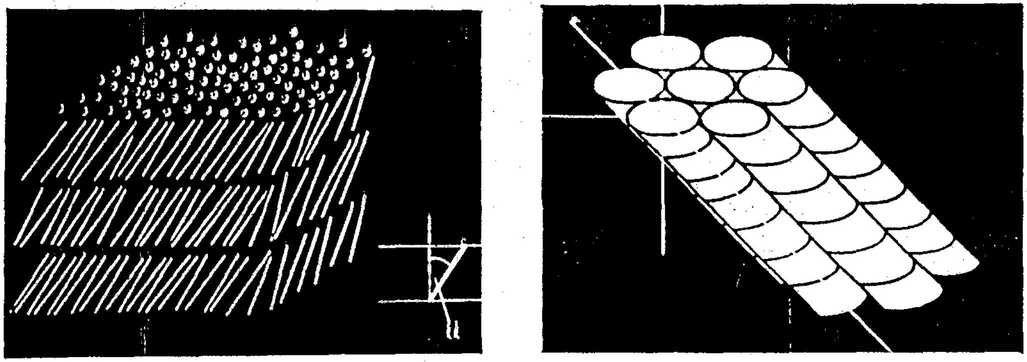
Fig. 2.1. Director direction in nematic liquid crystals.



a) Nematic   c) Smectic-A



b) Cholesteric



d) Smectic-C   e) Columnar

Fig. 2.2. Classification of thermotropic liquid crystals.

- **Cholesteric liquid crystals.** They exhibit orientational order. However, the director rotates continuously about a helical axis with a characteristic pitch. This rotation is due to the presence of one, or more chiral centers within the molecules. The nematics can be considered as a special case of cholesteric liquid crystals with an infinite pitch.
- **Smectic liquid crystals.** They are closer to solids as they exhibit one dimensional positional order as well as orientational order. Smectics are further classified into subgroups, viz., smectic-A to smectic-H, depending on the ordering within and between the layers.
- **The columnar liquid crystals.** They exhibit a two-dimensional positional order leading to a closely packed flexible columnar structure. The disc-like molecules are piled on each other to form the columns.

2.1.3. **Physical Properties**

Liquid crystals exhibit anisotropy in many of their physical properties. The two principal components of the macroscopic properties of these materials are as given below:-

- Along the direction of the director; and
- Perpendicular to the direction of the director.

The bulk properties of the liquid crystals depend on the molecular structure and the ordering of the molecules. The physical properties that are relevant to display applications are given in Appendix 1.

2.1.4. **Liquid Crystal Materials for Displays**

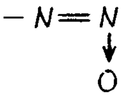
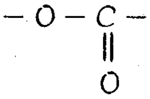
The liquid crystal materials should have a proper combination of physical properties for a satisfactory operation of the display. Hence, only a small percentage of the thousands of liquid crystal materials is suitable for display devices. Moreover, none of the **single** liquid crystal materials known so far, has all the physical properties required for a display. Hence, it is a common practice to use mixtures of a number of liquid crystal materials (i.e., single components). A typical liquid crystal mixture may need four to seven components to achieve the desired characteristics.

A typical Nematic Liquid Crystal (NLC) material consists of two rings (phenyl or cyclohexyl) connected by a bridging group and two end groups. Typical end groups are -CN, $-NO_2$ or short alkyl chains. NLC materials are classified according to the nature of the bridging group. Table 2.2 lists the structure of some important liquid crystals [3,4]. NLC materials like Schiff bases are unstable when exposed to moisture, temperature, ultraviolet light, etc., for a long time. Materials like cyanobiphenyls have better chemical and photochemical stabilities and are well suited for use in displays. The NLC mixtures should have a stable composition over a wide temperature range. This calls for a eutectic mixture or a composition very close to it.

2.2 ELECTRO-OPTIC EFFECTS IN LIQUID CRYSTALS

Liquid crystal materials exhibit anisotropy in many of their physical properties. Moreover they are sensitive to relatively weak external stimuli. Hence, electric field, magnetic field or thermal energy can be utilized to induce optical effects in liquid crystals. These effects are mainly due to the reorientation of the molecules resulting in absorption, reflection or scattering of light. Practical displays need uniformly oriented and stable layers of molecules with appropriate electrical, optical, elastic and thermal

Table 2.2. Common Central and End Groups in Liquid Crystals

Central Group		End Group	
Structure	Name	Structure	Name
$-CH=N-$	Azomethane (Schiff base)	$-C_nH_{2n+1}$	Alkyl
$-N=N-$	Azo	$-O-C_nH_{2n+1}$	Alkoxy
 $-N=\underset{\overset{\downarrow}{O}}{N}$	Azoxy	$-COOH$	Carboxylic acid
 $-O-\underset{\overset{\Vert}{O}}{C}-$	Ester	$-O-CO-R$	Acyloxy
$-CH=CH-$	Stilbene	$-CN$	Cyano
	Aromatic ring	$-NO_2$	Nitro
—	direct coupling	$-CHO$	Aldehyde

properties. LCDs require a very low power to operate, since they do not emit light and small external stimuli can induce a large change in the orientation of the liquid crystal molecules. Salient features of the electro-optic effects in liquid crystals are given below :-

- Low voltage operation ;
- Low power consumption;
- Legibility in high ambient light;
- Flexible format;
- Flat panel construction; and
- Choice of size.

2.2.1. Display Cell

A display cell consists of a thin layer of liquid crystal material sandwiched between two glass plates. Most of the electro-optic effects in liquid crystals require a uniformly aligned liquid crystal cell. This is achieved by aligning the molecules at the inner surfaces of the cell and can be one of the following types:-

- **Planar or Homogeneous** alignment. Here, the director is oriented parallel to the surfaces of the glass plates. This is obtained by coating the surface with a thin layer of polyimide and buffing the surface unidirectionally with a cloth or tissue paper.

- **Perpendicular or Homeotropic** alignment. Here, the director is oriented perpendicular to the surface of the glass plate and is obtained by chemical treatment of the glass surface.

- **Tilted** alignment. Here, the director is at an angle to the surface of the glass plate. A tilted alignment can be obtained by coating the surface with SiO or MgF_2 at a suitable oblique angle in a vacuum coating unit.

Fig. 2.3 illustrates these alignments at the surface of the cell.

The following major steps are involved in the fabrication of a liquid crystal display:-

i) Indium Tin Oxide (ITO) coated glass plates which are electrically conducting and transparent are used to make the display cell. The electrode patterns are printed on the ITO layer using photolithography.

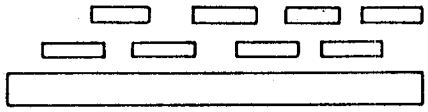
ii) The electrodes are obtained by etching the unwanted portions in the ITO layer.

iii) The inner surfaces of the glass plates are treated for alignment as mentioned earlier.

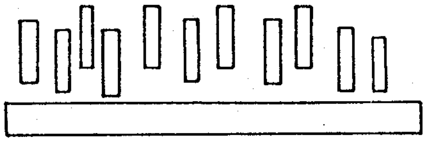
iv) The cell is assembled using the two glass plates, with the treated surfaces facing each other. The gap between the two plates is typically 5-15 μm and is usually controlled by spacers distributed uniformly all over the area. The spacers are either glass fibres or glass beads with a uniform diameter. The two plates are held together by a sealant.

v) The liquid crystal material is filled into the cell and the fill holes are closed by a sealant.

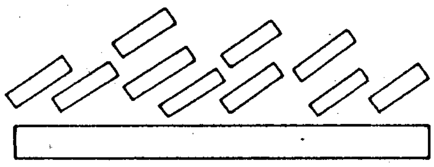
Fig. 2.4 gives the cross-section of a display cell.



a. Planar alignment.



b. Perpendicular alignment.



c. Tilted alignment.

Fig. 2.3. Types of surface alignment

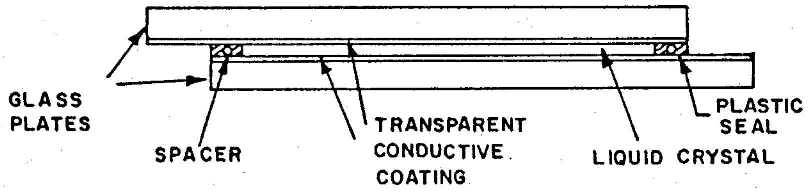


Fig. 2.4. Cross-section of a display cell.

The liquid crystal display can be made using transparent plastic films instead of glass plates [5]. Polarizers are required in visualising many of the electro-optic effects in liquid crystals. The glass plates or the plastic films can be eliminated by having the electrode pattern on the polarizers [6].

2.2.2. **Important Electro-Optic Effects**

a) Dynamic Scattering Effect

The dynamic scattering effect is the result of flow induced in liquid crystals due to electro-hydrodynamic processes. A liquid crystal material with a negative dielectric anisotropy and doped with ionic impurities is used here. This develops a periodic spatial modulation of the director orientation with a definite spatial frequency above a threshold voltage. The flow becomes turbulent at higher voltages leading to **Dynamic Scattering** [7]. The application of electric field leads to a scattering state, while the background is clear. This results in a contrast between the selected and unselected pixels. Dynamic scattering is the first electro-optic effect, discovered in liquid crystals. This mode of operation is no longer popular due to the following reasons:-

- High voltage and current requirements, and
- Insufficient contrast under certain lighting conditions.

b) Field Effects

Application of electric field induces a change in the molecular orientation of a selected pixel. The Twisted Nematic Field Effect (TNFE), Guest-Host Effect (GHE), Electrically Controlled Birefringence (ECB), Cholesteric-Nematic Phase Change (CNPC), Cholesteric-Nematic Phase Change Guest-Host (CNPC-GH) or Dye Phase Change (DPC), Super twisted Birefringence

Effect (SBE) and Ferro Electric Effect (FEE) are some examples of field effects [8-14].

c) Smectic Storage Effect

A liquid crystal material in the smectic phase is taken to the nematic or isotropic phase by external heating. A scattering state is obtained if the cooling is effected in the absence of electric field. Application of electric field while cooling, aligns the liquid crystal molecules resulting in a clear state. Dye materials can be added to the liquid crystal to improve the contrast [15]. A similar electro-optic effect in smectics with electrical addressing, without heating or cooling is also possible [16].

The choice of the electro-optic effect depends on its characteristics and the applications. The resulting display should have a high contrast and a wide viewing angle. Moreover multiplexing is used to address a display, when the number of pixels in a display is large. A non-linear electro-optic characteristic is essential for multiplexing. The characteristics in favour of multiplexing are given below:-

- Steep electro-optic response curve with a threshold. (Ideally a brick-wall characteristics is desired) ;
- Hysteresis ; or
- Short time or long time memory.

In addition to the above requirements, the following characteristics are desirable in any electro-optic effect:-

- Low voltage operation, so that standard ICs can be used as drivers;

- Low power consumption, to ensure a long battery life in portable products;
- Wide temperature range;
- Long life;
- Colour and grey scale capability, for displaying images and scenes.

Colour LCDs are possible by using one of the following principle [17]:-

- **Interference** (e.g., ECB displays);
- **Dichroism** (e.g., GH displays);
- **Absorption,** with colour filters or colour reflectors along with TNLCDs or black GH displays as light shutter.

The electro-optic response curve should not be very steep, if grey scale is to be included in the display. This requirement is directly in conflict with that of multiplexing. Hence, the choice of the electro-optic effect depends on the application. Table 2.3 gives the merits and demerits of some important electro-optic effects in liquid crystals. Most of these effects are slow (typical response time in the range 10-100 ms) and hence they respond to the rms voltage rather than to the instantaneous voltage. The TNFE, TN-GH, SBE, ECB, etc. exhibit rms response. Of these, TNFE is the most popular and is used in many applications. Displays based on SBE were first developed in 1985 [18] and are commercially available now. The technology of SBE displays is similar to that of TNFE, except for a few deviations. Displays based on SBE are likely to replace those based on TNFE for many applications in the future. The displays based on ferroelectric effect have a fast response time (typically 1-100 μs), good contrast

Table 2.3. Important Electro-optic Effects in Liquid Crystals - A Comparison

Electro-optic Effect	Merits	Demerits	Comments
Dynamic Scattering Effect [7]	No polarizers required V_{th} independent of temperature and viewing angle	Relatively high voltage (10- 15V) and power (mW/cm^2) required; Contrast depends on angle of incident light; slow response	First discovered electro-optic effect in liquid crystals. Not popular now
Twisted Nematic Field Effect (TNFE) [8]	Low voltage (1 - 3 V) Low power operation	Requires polarizers. Limited viewing angle; V_{th} depends on temperature. Slow response	Most widely used now; Colour is possible; Limited grey scale
Guest-Host Effect (GHE) [9]	Wide viewing angle	Low contrast ratio; single polarizer; Negative contrast; Slow response	Commercially available
Electrically Controlled Birefringence (ECB) [10]	Steep electro-optic characteristics Inherent colour	Limited viewing angle; Negative contrast; Slow response	Prototypes are available
Cholesteric to Nematic Phase Change (CNPC) [11,12]	Possesses Hysteresis. Good contrast ratio and wide viewing angle	High V_{th}. Requires uniform cell thickness (±0.2%). Slow response	Prototypes are available
Super twisted Birefringence Effect (SBE) [13]	Steep electro-optic characteristics; Low voltage and low power operation; Good contrast and wide viewing angle	Grey scale is not possible. Requires uniform cell thickness (±0.2%). Slow response	Likely to replace TNFE in many applications
Ferro Electric Effect (FEE) [14]	Polarity dependant electro-optic characteristics, Good contrast and wide viewing. Fast response.	Requires thin cell (1 - 2 µm)	Technology in infancy
Smectic Storage Effect (SSE) [15,16]	Good contrast ratio and wide viewing angle; Possesses memory	Requires heating; slow response	Electrical addressing possible

and wide viewing angle. But, the technology of these displays is not fully developed as yet. Prototypes of these displays are available and they are suitable for displays with a high information density.

Since the addressing techniques for rms responding devices is the theme of this thesis, only TNLCDs and SBE displays will be discussed in detail in the following sections.

2.2.3. **TNLCDs**

a) Principle

The Twisted Nematic Liquid Crystal Display (TNLCD) cell [8] is made up of two glass plates treated for planar alignment. The cell is assembled such that the direction of the alignment in the top plate is perpendicular to that in the bottom plate of the cell. This display cell is filled with a NLC mixture having a positive dielectric anisotropy. The liquid crystal molecules confined in the cell form a 90° twisted structure as shown in Fig.2.5. This twisted structure acts like a **waveguide** and gradually rotates the plane of polarization by 90°. Hence, a linearly polarized light incident on the cell emerges linearly polarized in an orthogonal direction when the following conditions are satisfied:-

- The plane of polarization of the incident light is parallel or perpendicular to the director at the surface of the cell; and

- The product of the optical anisotropy (Δn) and the pitch (P) is high compared to the wavelength of the incident light, where P is four times the thickness of the cell.

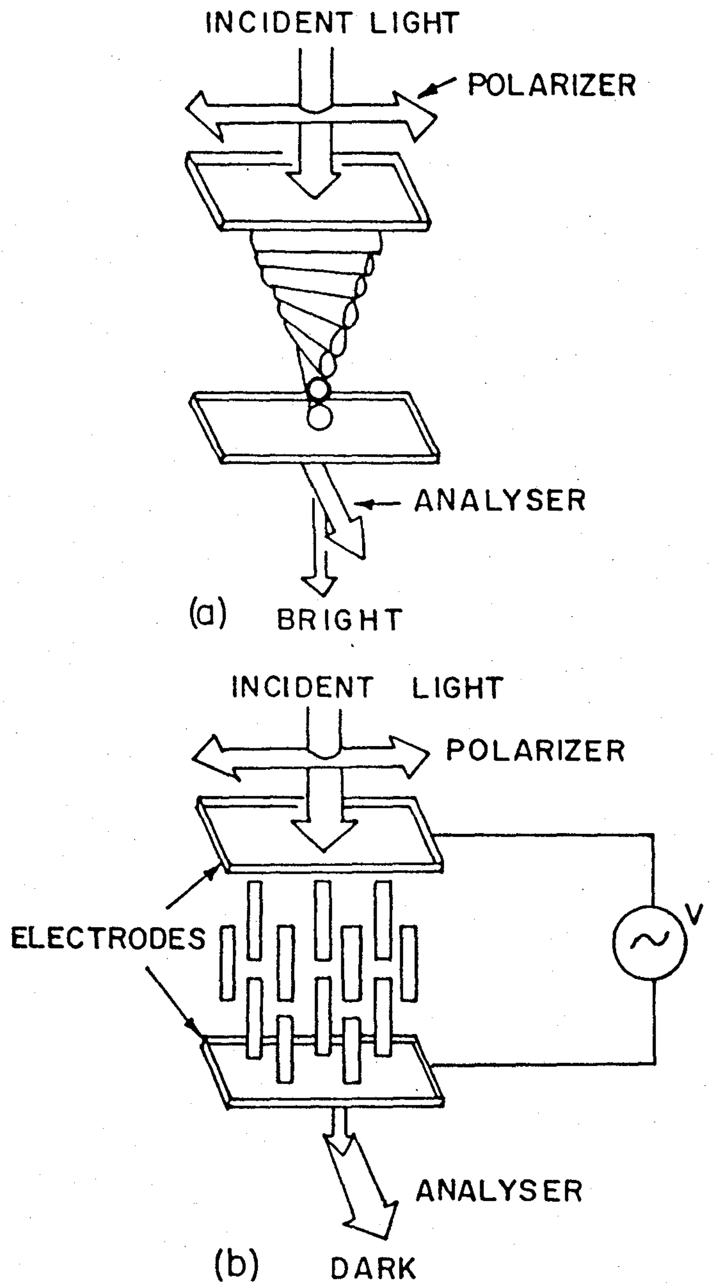


Fig. 2.5. Twisted Nematic Cell. a) OFF, b) ON states.

The cell in the unexcited state (OFF) rotates the plane of the polarization of the incident light by 90°. Hence, the cell appears -

- dark, when viewed between two polarizers parallel to each other; and
- transparent, when viewed between two polarizers perpendicular to each other.

The 90° twist in the cell is lost when a sufficiently strong electric field is applied to the cell (ON). Hence, the cell appears -

- transparent between two parallel polarizers; and
- dark between two perpendicular polarizers.

The difference in transmission between the unexcited and excited states is exploited in TNLCDs. Only one optical mode is excited here by placing the polarizers parallel or perpendicular to the director at the surface of the cell.

TNLCDs require a low power to operate; ($\sim 1 \mu w/cm^2$) since they modulate the incident light and do not emit light. A voltage in the range of 2-5 volts is adequate to excite the **ON** pixels. The TNLCDs can be of the following types [19]:-

- **Transmissive type** with the light source at the back and the observer in front of the display. This type of display is preferred for use in dark environments;
- **Reflective type** with both the light source and the observer in front of the display. A polarizer with a reflector is used at the back of

the display. This type of display is suitable for use in well lit, bright environment; and

- **Transreflective type** with a transreflector instead of reflector at the back. This type of display is suitable for both dark and bright environments. The transreflector allows sufficient light from the back illumination to fall on the display, for a good readability in a dark environment.

The displays can be operated in one of the following modes:-

- **Positive contrast mode** with dark symbols against a bright background. This is achieved by placing the top and bottom polarizers perpendicular to each other in TNLCDs; and
- **Negative contrast mode** with bright symbols against a dark background. This is achieved by placing the top and bottom polarizers parallel to each other in TNLCDs.

A positive contrast mode is preferred in a reflective type of display, while a negative contrast mode is preferred in a transmissive type of display [20].

b) Electro-optic Response of TNLCDs

The TNLCDs respond equally well to both positive and negative voltages. However, the life of the displays is reduced due to irreversible electrochemical reactions if they are driven with a dc field. Hence, the TNLCDs are normally driven with an ac field. They are slow responding devices with the response time in the range of 10-100 ms. This has an integrating effect. Hence, the electro-optic response is determined by the rms voltage rather than the instantaneous voltages. Typical electro-optic response of a TNLCD is shown in Fig. 2.6. The electro-optic response is described by the following parameters:-

- Threshold voltage (V_{th}),
- Saturation voltage (V_{sat}),
- Sharpness parameter (γ), and
- Response times.

These parameters are discussed in detail in Appendix 2.

V_{th} decreases with an increase in temperature (typically -5 to -20 mV/°C). V_{th} is also a function of the viewing angle, and it decreases with an increase in the viewing angle, measured from the normal to the display cell. The sharpness parameter gives an idea of the number of lines that can be multiplexed using the NLC mixture. The value of γ should be close to 1 for the material to be useful in a large matrix display. V_{th} and γ depend mainly on the NLC mixture used in the display. The response time depends on the NLC mixture, the display cell thickness (d) and the applied field.

The performance of a display is determined by the contrast ratio and the viewing angle. Fig. 2.7 shows the viewing angle characteristics of a typical TNLCD [21], when the number of lines multiplexed is 100. The contrast ratio, viewing angle and the response time can be optimised by controlling the display cell parameters [17] as given below:-

- **Cell thickness** (d). A large cell thickness is desirable for a good contrast ratio. But the response time is directly proportional to d^2. The condition $\Delta n.d = 0.5\ \mu m$ results in a good contrast ratio and a fast response time.

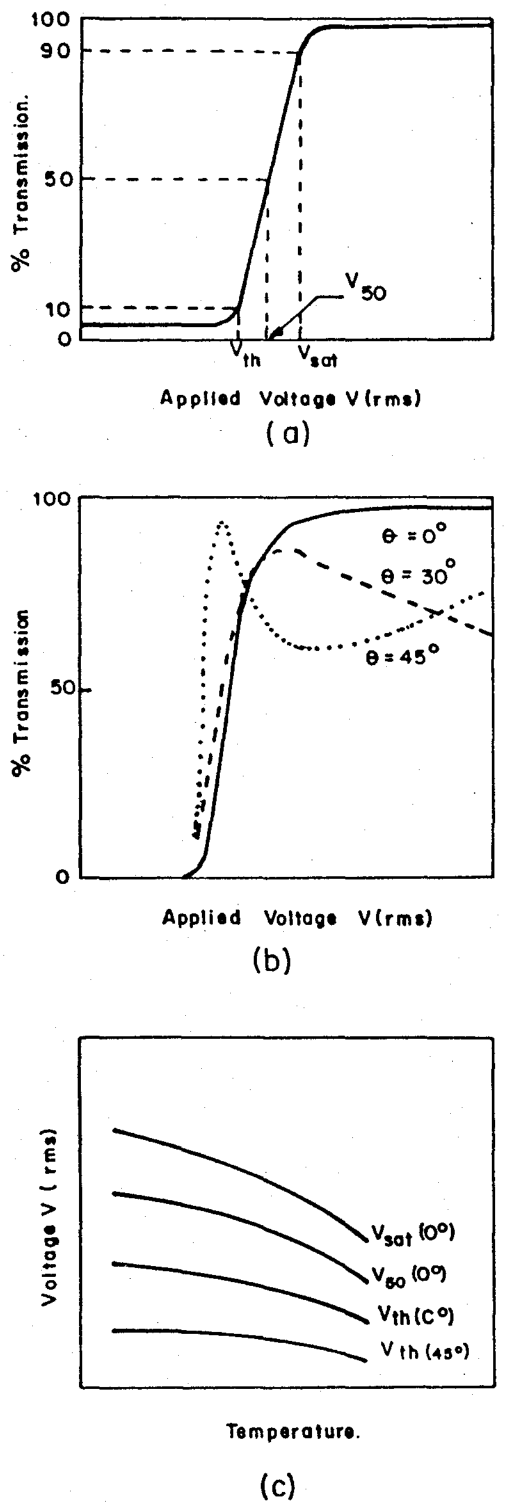


*Fig. 2.6. Typical electro-optic response of TNLCDs.
a) Threshold characteristics, b) variation with
viewing angle, and c) variation with temperatuure.*

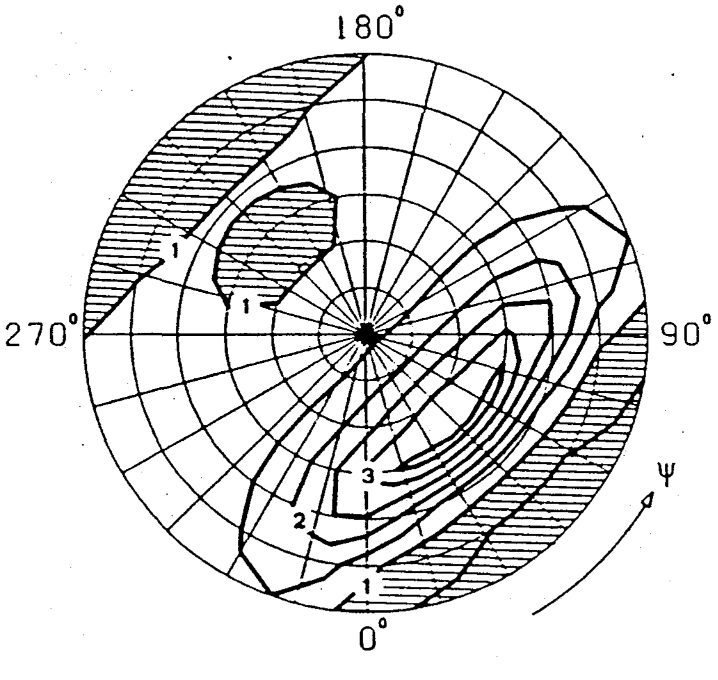


Fig. 2.7. Viewing angle characteristics of a typical TNLCD.

However $\Delta n.d$ = 1.1 μm is preferred, since the contrast ratio is less sensitive to thickness variations and the resulting display has a uniform appearance.

- **Tilt angle.** The director at the surface is oriented at a pre-tilt angle of 2 to 5° from the surface of the cell. This eliminates the non-uniform appearance of the display arising from the reverse tilt in the director configuration in the **ON** state.
- **Twist sense.** A non-splay configuration with the twist sense matching the tilt direction is required. This avoids the non-uniform appearance of the display arising from the reverse twist even in the **OFF** state.
- **Director direction at the surface of the cell.** The axis of symmetry of the viewing angle characteristics lies at 45° to the director at the surface of the cell. Hence, the best viewing quadrant can be chosen depending on the application. The director direction is usually at 45° to the edges of the display.
- **Efficiency of the polarizers.** Typical values of polarization efficiency and the transmittance of the polarizers used in displays are 95% and 45% respectively. The contrast ratio is doubled when the polarization efficiency is 95.5% and the transmittance is 46% [22].

2.2.4. **SBE Displays**

a) Principle

The SBE display cell [13] requires -

- a twist angle between 180° and 270° ;

- a tilted alignment with the director at 20 to 30° to the surface of the glass plates; and
- the polarizers placed in unconventional directions.

The display cell is filled with a NLC mixture with a positive dielectric anisotropy. The director at the centre of the cell responds more freely to the applied field as compared with the director at the surface of the cell. Hence the variation of the tilt angle at the mid-plane gives an idea of the steepness in the electro-optic characteristics. Fig. 2.8 gives the mid-plane tilt angle as a function of the applied voltage for various twist angles [21]. From this Figure, it is evident that the steepness increases with the twist angle upto 270°. The curve has a negative slope above 270° and exhibits bistability [23]. The SBE display is based on the birefringence mode, wherein the ordinary and extraordinary waves of light interfere in the field of view to give rise to colour. The SBE displays are also referred to as Super-twisted Nematic Liquid Crystal Displays (STNLCDs).

b) SBE Display with 270° Twist (SBE-270)

The SBE display cell requires a tilted alignment with the director at 20-30° with the surface of the cell. This is essential to suppress the formation of two-dimensional striped domains found in the 270° twisted cell with planar alignment [24]. The following parameters are optimised in the SBE-270 [25] :

- $\Delta n . d . \cos^2 \theta = 0.8$ μm, where Δn is the optical anisotropy of the NLC mixture, d-the cell thickness and θ- the average tilt angle of the molecules in the unexcited state.

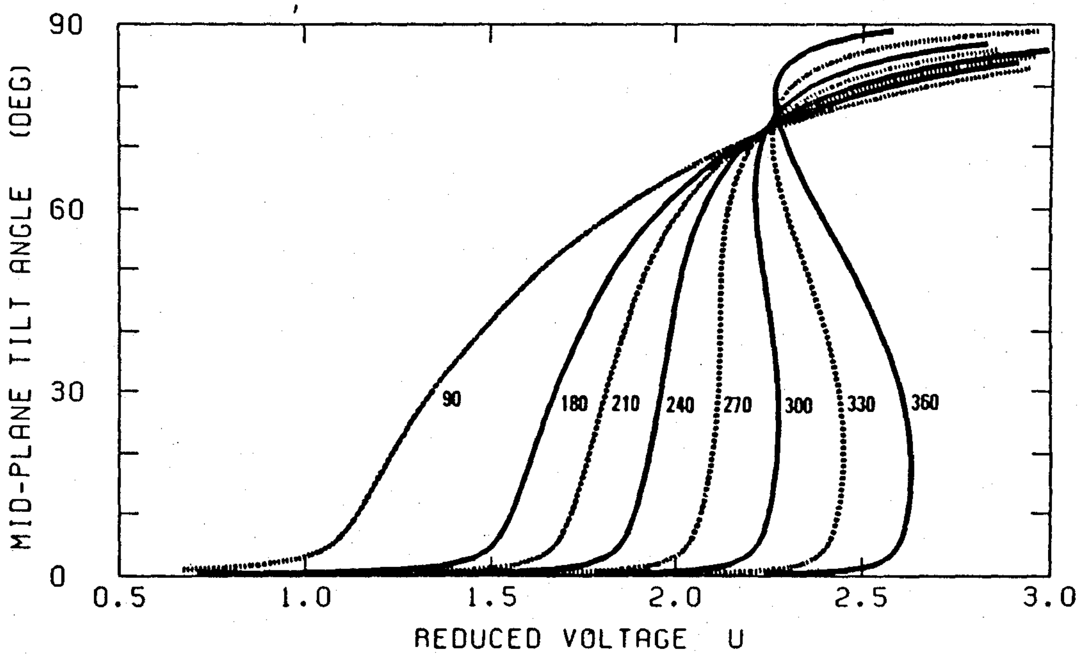


Fig. 2.8. Mid-plane tilt angle vs. Applied voltage and its dependence on twist angle.

- The **ratio** (d/P) = 0.75, where P is the pitch of the doped NLC mixture.
- **The direction of the polarizers** with reference to the direction of the director at the surface of the cell. The top and bottom polarizers are set at angles β = 32.5° and γ = 57.5° respectively, with reference to the projection of the director at the surface of the cell for a left-handed twist. This results in a positive contrast mode.
- **Cell thickness** (d) should be uniform and the variation in thickness should not exceed ±2%, for a uniform appearance of the display.

The following modes are possible in the SBE display with 270° twist:-

- **Positive contrast mode**, when the polarizers are placed as given above and is referred to as **Yellow mode**. The selected pixels are black against a yellow colour of the unselected pixels and the background.
- **Negative contrast mode**, when one of the polarizers is rotated by 90° from that corresponding to the positive contrast mode. This mode is referred to as **Blue mode**. The selected pixels are transparent (colourless) against a dark purplish-blue of the unselected pixels and the background.

The SBE display with 270° twist exhibits a good contrast ratio and wide viewing angle characteristics. The response times are in the range of 200 - 400 mS. The electro-optic characteristics of a typical SBE-270 display cell are shown in Fig. 2.9. The viewing angle characteristics of a multiplexed (100 lines), SBE-270 display are shown in Fig. 2.10.

The SiO coating which was originally used to obtain the tilted alignment

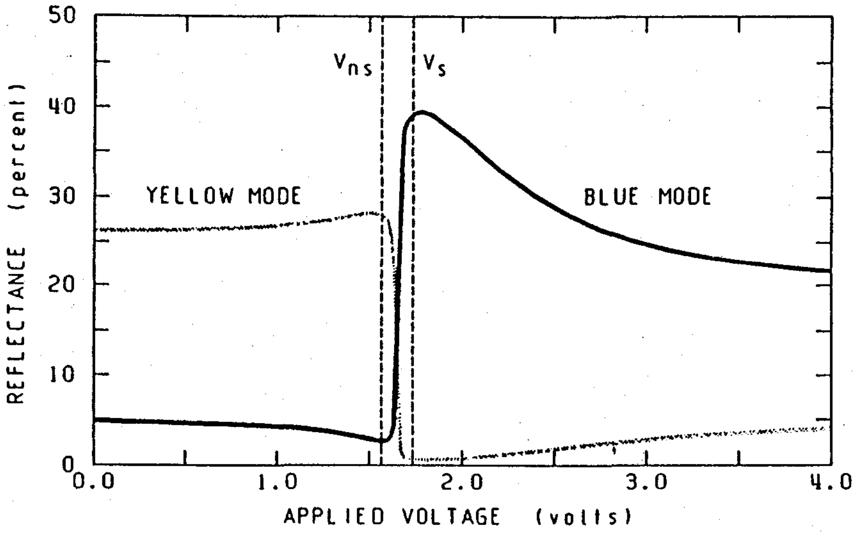


Fig. 2.9. Electro-optic characteristics of a typical SBE-270 display cell.

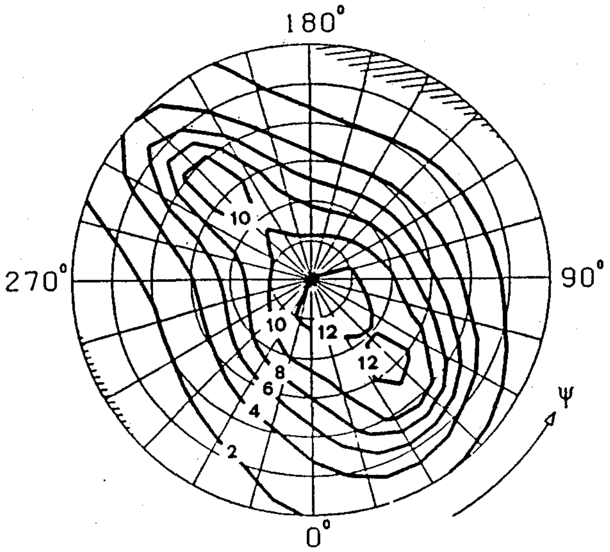


Fig. 2.10. Viewing angle characteristics of a typical SBE-270 display cell.

in the SBE cell is an expensive process as compared to the polyimide coating and buffing required in TNLCDs. A buffing process to obtain a tilted alignment has also been reported recently [26,27].

c) SBE Display with 180° twist (SBE-180)

SBE displays with 180° twist are preferred as a compromise, since they do not require alignment with a high tilt angle. The inner surfaces of the display cell are treated for alignment with a small tilt angle. The cell is assembled such that the director at the top and bottom glass plates are parallel to each other. A 180° twist is achieved by doping the NLC mixture with the right amount of cholesteric material. The following parameters are optimized in the SBE-180 [21,28]:-

- $\Delta n.d. = 1\ \mu m$.
- **The ratio** (d/P) = 0.3 to 0.5.
- **The direction of the polarizers.** The top and bottom polarizers are set at an angle of 45° to the director at the surface of the cell.
- **Cell thickness** (d) should be uniform and the variation in thickness should not exceed ±2%, for a uniform appearance of the display.

Only a positive contrast mode is found suitable for practical applications. The selected pixels and unselected pixels exhibit different colours depending on the cell parameters.

The electro-optic characteristics of SBE-180 display cell are shown in Fig. 2.11. Although the steepness is less than that of SBE-270, it is better than that of TNLCDs.

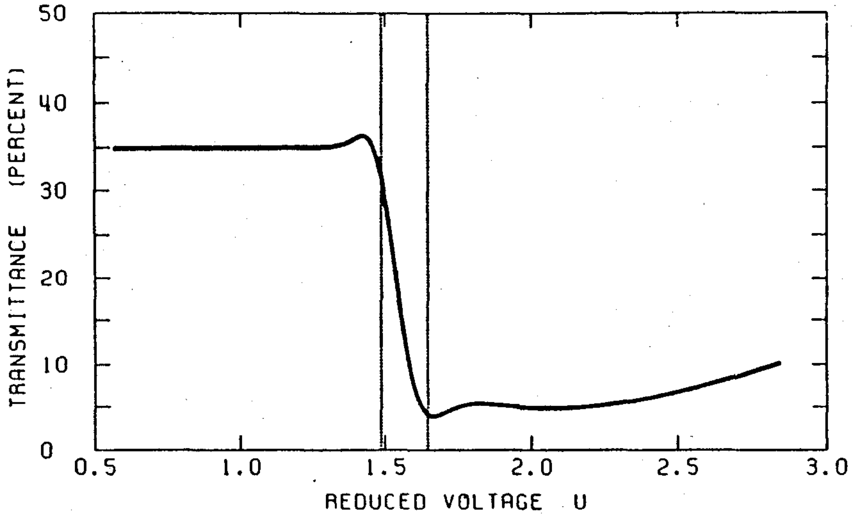


Fig. 2.11. Electro-optic characteristics of a typical SBE-180 display cell.

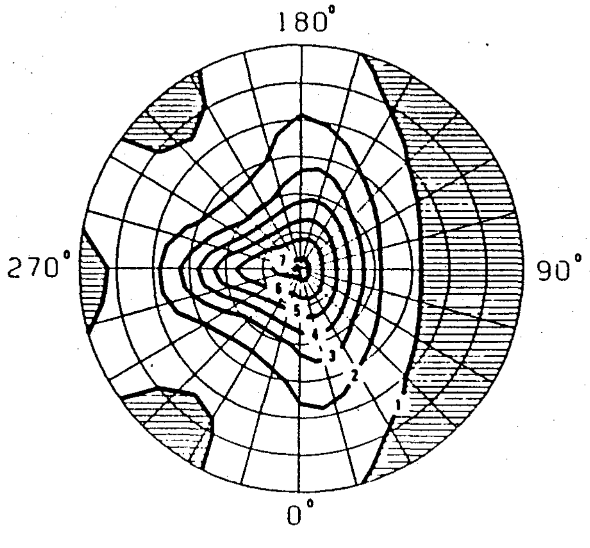


Fig. 2.12. Viewing angle characteristics of a typical SBE-180 Display Cell.

Typically, the response time is in the range of 200-400 mS. The viewing angle characteristics of a multiplexed (100 lines) SBE-180 display are shown in Fig. 2.12. A contrast ratio of 5 has been reported for a multiplexed display with 200 lines [29].

The following display types are possible in SBE display, as in the case of TNLCDs:

- **Transmissive type,**
- **Reflective type**, and,
- **Transreflective type.**

A black and white SBE display has been reported recently [30,31]. The display cell here is optimised for Δn.d in the range 0.4 to 0.6 μm. The thickness tolerance is less critical here as compared to the SBE-270 and SBE-180 displays.

2.3 MATRIX DISPLAYS AND MULTIPLEXING

2.3.1 Matrix Display

A display is made up of a number of picture elements (pixels). The information being displayed depends on the collective state of the pixels. A matrix display is made up of an array of display elements (either emissive or non-emissive types) arranged in the form of a matrix. Most of the electronic display elements require at least two terminals to activate them. The individual pixels can be directly connected to the drive electronics, when the number of pixels in the display is small. However, it becomes more and more difficult to connect them directly to the display drivers as the number of pixels in a display increases. Hence a group of pixels is made to share a common lead or address line. Every pixel in the matrix display is connected to a row address line and a column address line [32]. Therefore the row and column address lines form a matrix with the individual pixels at their inter-sections. These pixels can be uniquely addressed as in the case of a two dimensional memory array. A matrix display with N rows and M columns can have (N x M) pixels, while the number of connections is just (N + M). The number of connections to a display is minimum when :

- the pixels in the display are organized as a square : the number of address lines in the row and column of the matrix is the same, and equal to the square-root of the number of pixels.

The number of connections to the display can be further reduced by using one of the following schemes :

- An unconventional interconnection scheme, wherein N_l leads can address $N_l(N_l-1)$ polarity dependent devices like LED [33] and $N_l(N_l-1)/2$ pixels in LCDs [3,4], or
- Multilevel Addressing scheme, wherein a number of matrix displays are stacked one above the other. While electrical addressing is employed to drive each matrix panel, optical addressing is used in the third dimension [35,36].

2.3.2 **Fonts and Formats**

The resolution required in a display is a function of the viewing distance. A person with an average eye-sight can easily resolve two points subtending an angle of 1 minute of arc at the eye [32]. This demands at least 12 pixels/mm at a viewing distance of 250 mm. Such a high density of pixels is not only difficult to achieve in most of the display technologies, but will be too expensive for many applications. Around 900 pixels are required to display a single character with the size and resolution as found in a printed text. The cost of the display, drive electronics and the associated circuits will be high to achieve this resolution. Numeric and alphanumeric displays in most of the practical applications use simpler fonts for technical and economic reasons [37].

The various display fonts used in practice are given in Table 2.4. These character fonts are designed to reduce the number of pixels. Any failure in the display or the drive electronics can lead to reading errors. A single fault is serious in a font using bars and can lead to erroneous reading. A dot-matrix font can accommodate a single fault without causing any reading errors. However, an error due to a wrongly activated dot is more prominent as compared to a missing dot [37]. While the number of pixels can be reduced in numeric and alphanumeric applications, no such reduction is possible in graphic displays.

Most of the character fonts given in Table 2.4 [32,37] are suitable for LCDs. The pixels in the LCDs are formed by the intersection of electrode patterns on the top and bottom glass plates of the display cell. Hence the electrode patterns must be designed such that they intersect only at the pixel and not anywhere else in the active area. The character fonts in LCDs can easily be improved, since the pixel shape can be changed by altering the electrode patterns. Apart from the character fonts, special symbols like kHz, mV, Ω , etc., can be included with a high resolution in

Table 2.4. Various Character Fonts used in Displays

Font	No. of Pixels/ Character	Format	Purpose	Comments
Seven numeric segment	Seven bars and a decimal point	tilted to right	0-9 and few characters like A, E, H, L, P	widely used in displays
Star burst pattern	13 - 16 bars	tilted to right	0-9, A-Z and special characters	Not popular
3 x 5 dot matrix	15 dots	5 rows and 3 columns	0-9	Numeric application not as popular as seven segment display
5 x 7 dot matrix	35 dots	7 rows and 5 columns	0-9, A-Z and special characters	Most popular in Alphanumeric applications
7 x 9 dot matrix	63 dots	9 rows and 7 columns	0-9, A-Z (both upper and lower case) and special characters	Has better character representation compared to 5 x 7 dot matrix.
5 x 5 dot matrix	48 dots	5 rows and 5 columns may be tilted to right	0-9, A-Z and special characters	Not popular
6 x 8 dot matrix	48 dots	8 rows and 6 columns	""	""
Random position	13-30 strokes	bars randomly	0-9, A-Z and special characters	used in CRT and plotters only

LCDs, without any additional cost. The pixels in these numeric and alphanumeric displays are usually interconnected to form a matrix display, if the number of pixels is large. The electrode patterns on the glass plates form the pixels as well as the address lines.

2.3.3 **Multiplexing**

A display should be capable of displaying any information. Hence it should be possible to activate the selected pixels without altering the state of the other pixels. The process of transmitting information to all the pixels and hence activating the appropriate ones is called **addressing**. A line-by-line addressing is used in matrix displays based on many technologies including LCDs. The information to be displayed in a column (or row) is time multiplexed through a single column (or row) address line. This is similar to the time division multiplexing in communication engineering. Hence the addressing technique is commonly referred to as Multiplexing or Matrix addressing. A signal applied to a column for activating a pixel in a selected row appears across all the pixels connected to that column. Hence the display elements should have nonlinear characteristics, if they are to be multiplexed [38], e.g., LED is a polarity dependent device with a nonlinear V-I characteristics. The main advantages of multiplexing are as follows :

- A reduction in the number of connections to the display ;
- A reduction in the number of display drivers ; and,
- Increase in the reliability.

However the performance of a multiplexed display may be limited by the shortcomings in the nonlinear characteristics of the display device.

But multiplexing becomes the natural choice when the number of pixels in a display is large, in spite of this drawback.

The matrix displays make use of the **intrinsic** nonlinearities present in a display device. This approach is not suitable when the nonlinear characteristics in a display device are :

- totally absent ; or
- not adequate for a given application.

Multiplexing is then made possible or enhanced by incorporating a nonlinear element with each pixel in the matrix display [39,40]. The nonlinear element can be one of the following devices :

- Varistor [41,42]
- Diode [43,44,45]
- Metal-Insulator-Metal (MIM) device [46,47]
- Thin Film Transistor (TFT) [48,49,50].

Matrix displays fabricated with such nonlinear elements are usually called Active matrix displays. The term **active** in this context refers to the presence of an **extrinsic** nonlinear element only. Table 2.5 gives a comparison between the matrix addressing (multiplexing using the intrinsic nonlinearity) and the active matrix addressing. The active matrix approach is becoming popular now-a-days because of the following developments:

- Reduction in the number of steps required for the fabrication of the nonlinear devices [51] ; and,
- Introduction of redundancy techniques to improve the yield [52].

Table 2.5. Matrix Addressing and Active Matrix Addressing - A Comparison

Parameters	Characteristics of		
	Matrix Addressing (multiplexing with the intrinsic nonlinearity)	Active Matrix Addressing (using extrinsic nonlinearity) with	
		Two terminal devices	Three terminal devices
Nonlinearity in the display device characteristics	Essential	Not essential	Not essential
Display performance (contrast ratio and viewing angle)	Highly dependent on the number of lines multiplexed (N)	Less dependent on N	Independent of N
Drive requirements	Depends on N	Depends on N	Independent of N
Duty cycle	1/N	Can be enhanced with a storage element	100% with a storage device
Supply voltage	Increases with N	Increases with N	Independent of N
Display fabrication	Simple	Requires several steps	Requires several steps
Grey levels	Limited	Limited	Unlimited
Yield	Good	Poor	Poor
Cost	Economical	Expensive	Expensive

However, **multiplexing using the intrinsic nonlinearity is still attractive** due to its inherent simplicity and cost effectiveness. The characteristics in favour of multiplexing TNLCDs are given in Table 2.6. Most of the liquid crystal displays use the voltage threshold and the rms response for multiplexing. Displays using the dielectric relaxation in liquid crystals (two frequency addressing) are not popular due to the drawbacks listed in Table 2.6.

Most of the electro-optic effects in liquid crystals exhibit rms response, which is independent of the polarity of the voltage. The problem of cross-talk encountered in a matrix display is illustrated using a 2 x 2 matrix shown in Fig. 2.13. A voltage V is applied to the row X_1 and the column electrode Y_1 is grounded. The remaining electrodes, viz., X_2 and Y_2 are left floating. The following states are defined in this arrangement:

- Selected state (P_{11}) ;
- Half-selected state (P_{12} and P_{21}) ; and,
- Non-selected state (P_{22}) .

As the voltage V is increased from zero, the selected pixel is activated first. When the amplitude of V is increased further, pixels in the half-select and non-select state are also activated. This phenomenon is referred to as cross-talk and is mainly due to the bidirectional characteristics of LCDs. The applied voltage is divided among the half-select and non-select pixels depending on their impedances. The cross-talk in the actual matrix is more complicated due to the large number of rows and columns, and is easily

Table 2.6 Characteristics in favour of multiplexing TNLCDs

Characteristics	Points in favour of multiplexing	Critical parameters	Shortcomings	Comments
Electro-optic response with a well defined threshold voltage(V_{th})	A voltage below V_{th} across the elements does not active them	$\Delta\varepsilon$, Δn, d $\Delta\varepsilon/\varepsilon_\perp$ K_{33}/K_{11} Pre-tilt angle	The electro-optic response curve is not steep (a brick wall chs. is desired). V_{th} and steepness are functions of viewing angle and temperature	V_{th} is essential for multiplexing
rms response (response is independent of the shape of the addressing wave-forms)	Presence of an instantaneous voltage above V_{th} does not turn ON an OFF pixel, if V_{rms} is less than V_{th}	Cell thickness and viscosity	Response time is large	Allows a greater freedom in the choice of the addressing wave-forms
Dielectric relaxation in some of the NLC mixtures	Change in sign of the dielectric anisotropy at high frequency	$\Delta\varepsilon$ and f_c	f_c and dielectric anisotropy is a function of temperature	Not popular due to the temperature dependence of anisotropy. Requires high voltage pulses for addressing and power consumption is high

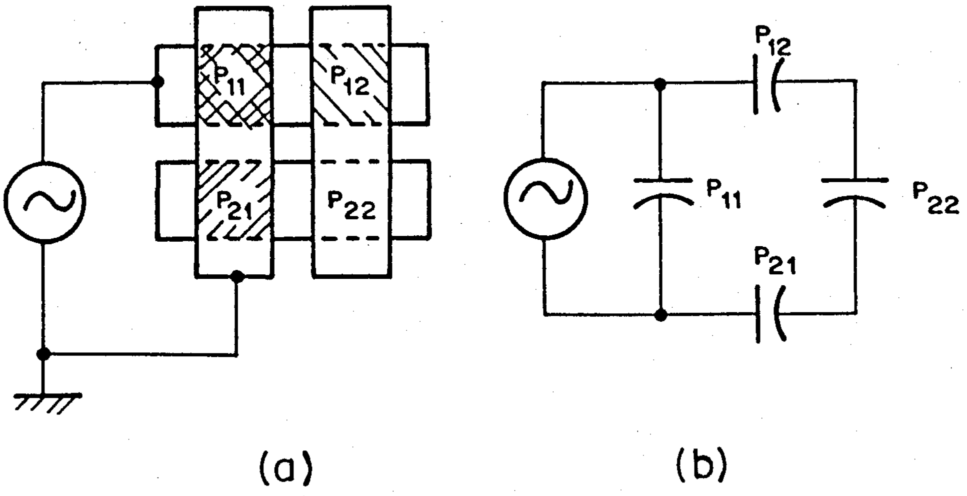


Fig. 2.13. Illustration of cross-talk in a matrix display .
a) 2×2 matrix, and b) its equivalent circuit.

visible in a device with a poor threshold characteristics [3]. The effect of cross-talk can be minimized by connecting the electrodes to low driving impedances [53].

2.3.4 Desirable Characteristics of Addressing Techniques

The following characteristics are desired in any addressing technique for driving matrix displays with an rms response. The addressing techniques are based on the intrinsic nonlinearities in LCDs with a special reference to TNLCDs :

- The cross-talk should be minimized.
- The rms voltage across all the **ON** pixels and similarly the rms voltage across all the **OFF** pixels should be equal for a uniform appearance of the display. Considering the nonlinear transmission characteristics of TNLCDs (Fig. 2.6), ideally the

  i) voltage across the **OFF** pixels, i.e., V_{OFF} (rms) $\leq V_{th}$; and,

  ii) voltage across the **ON** pixels, i.e., V_{ON} (rms) $\geq V_{sat}$.

But, in practice, the rms voltage across pixels in identical states should be the same for the reasons given below :

i) The threshold characteristic of TNLCDs varies considerably with viewing angle ; and

ii) The voltage margin between V_{ON} (rms) and V_{OFF} (rms) is not wide, especially when the number of lines multiplexed is large.

- The selection ratio, i.e., $R = [V_{ON}\ (\text{rms})/V_{OFF}\ (\text{rms})]$ should be high. This ensures a good discrimination between the **ON** and **OFF** pixels, resulting in a good contrast ratio of the display ;

- The addressing technique should lead to a dc-free operation, in order to ensure a long life of the display ;
- The supply voltage requirement should be low for the following reasons: -

  i) LCDs are mostly used in portable products ; and

  ii) Regular CMOS ICs can be directly used without any need for development of high voltage drivers, leading to considerable economy.

  iii) An addressing technique requiring a lower supply voltage is preferable even when the supply voltage is determined by other considerations since NLC mixtures for TNLCDs with a steep electro-optic characteristic usually have a high V_{th}.
- The addressing technique should be simple. Apart from the elegance, this leads to a simple control circuit and hence will be reliable and economical.
- The addressing technique should have the flexibility to match the display characteristics. For example the dielectric relaxation in liquid crystals demands that all the frequency components of the waveform across the pixels to lie within the flat region of the curve (Fig. A1.2).

2.4 MATRIX ADDRESSING OF LCDs - CURRENT APPROACHES

The performance of a multiplexed LCD depends on -

- **the liquid crystal material** used in the display, i.e., its physical parameters ;
- **the electro-optic effect** employed including the cell parameters ; and
- **the addressing technique** used to drive the display.

While some important aspects of liquid crystals and the electo-optic effects were reviewed earlier, the various addressing techniques for multiplexing **rms responding LCDs** are critically reviewed here. These addressing techniques can be broadly classified as follows :-

- **Techniques for displaying general patterns;** and
- **Techniques for displaying restricted patterns** [54].

Basics of matrix addressing, the Direct driving, the Half-Select Technique, the One-third Select Technique, the Alt and Pleshko Technique (APT), the Improved APT (IAPT), the Switching Bias Voltage Addressing Technique (SBAT) and the Two Frequency Addressing Technique are covered under the first category. Basics of restricted pattern addressing and some special addressing techniques for oscilloscope displays are covered next. This is followed by practical considerations applicable to matrix addressing and some techniques for reducing the lead count in matrix displays.

2.4.1 **Displaying General Patterns**

a) Basics of Matrix Addressing

The line-by-line addressing is the basis of all the addressing techniques for multiplexing rms responding LCDs. One set of address lines (row or column) is used for the scanning, while the other set (column or row) is used for the signals. The choice between the row and column address lines for scanning depends on the matrix. The set with a small number of address lines is preferred for scanning, since the performance of a matrix display deteriorates with the number of address lines. However, the scanning is considered to be row-wise in this review for the sake of convenience. The N address lines to be multiplexed are sequentially selected one at a time. The selected row gets a voltage V_r while the unselected rows are grounded. The column voltage V_c depends on the data to be displayed in the selected row and is in-phase with V_r for an OFF pixel and is out-of-phase for an **ON** pixel. Both the row-select and column voltages are simultaneously applied to the display. A cycle is completed when all the rows are selected once. The display should be refreshed sufficiently fast to avoid flicker, since rms responding LCDs have short time memory only. The polarity of the row and column voltages are reversed periodically in order to ensure a dc-free operation.

b) Direct Driving

Direct driving is employed, when the number of pixels in a display is small (less than 20-30). The electrode patterns on one of the glass plates are interconnected to form a common **back-plane** and brought out as a single connection. The connection for each pixel is brought out independently on the other glass plate. Hence a display with M pixels will require (M+1) external connections. This is equivalent to a matrix with a single row and M columns. The **ON** pixels here can be driven as hard as required, while the **OFF** pixels get a zero voltage across them. CMOS logic gates are well suited for driving such LCDs. The main advantages of using CMOS gates as drivers are listed in Table 2.7. **Biphase addressing** is the most popular technique for directly driving TNLCDs since the supply voltage requirement of this technique is low. Here, an Exclusive-OR gate, used as a controlled inverter is the driver (Fig. 2.14). A square wave with 50% duty cycle is applied to the back-plane and as one of the inputs of the gate. The data is connected as the other input of the gate. The driver functions as follows:

- The output of the gate is 180° out-of-phase with the back-plane waveform, when the data input is logic 1. Hence an **ON** pixel gets an rms voltage equal to the supply voltage;- OR
- The output of the gate will be in-phase with the back-plane waveform, when the data input is logic 0. Hence the voltage across an **OFF** pixel is zero. The frequency of the square waveform is usually low (32-100 Hz) in order to conserve power. The supply voltage is chosen to be at least three times V_{th}, in order to get a good contrast ratio in the display.

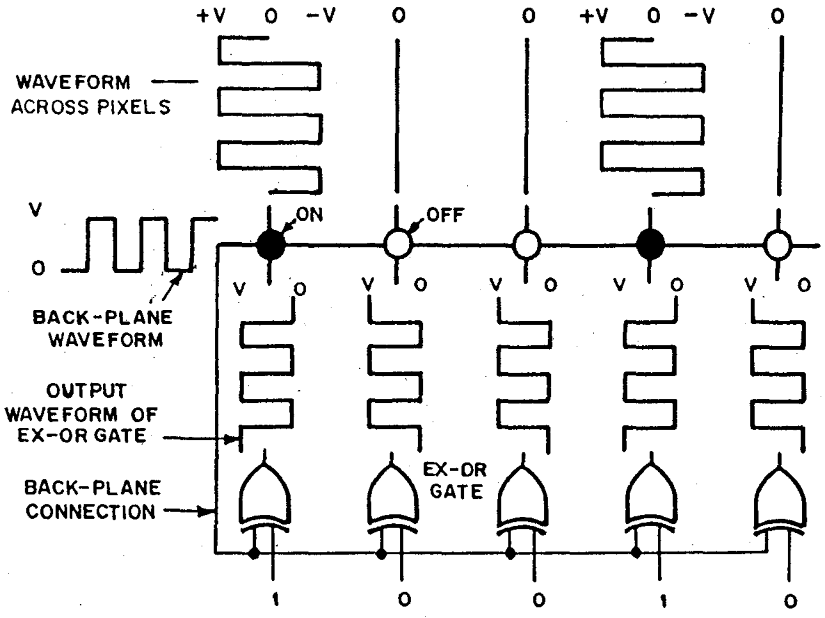
The problem of cross-talk appears even in a directly driven display, when the display size is large [55]. The back-plane waveform gets distorted for the following reasons :

- The distributed resistance of the back-plane electrode; and
- The large capacitance (700 - 7000 PF) of the pixels.

The cross-talk can easily be observed by increasing the amplitude and fre-

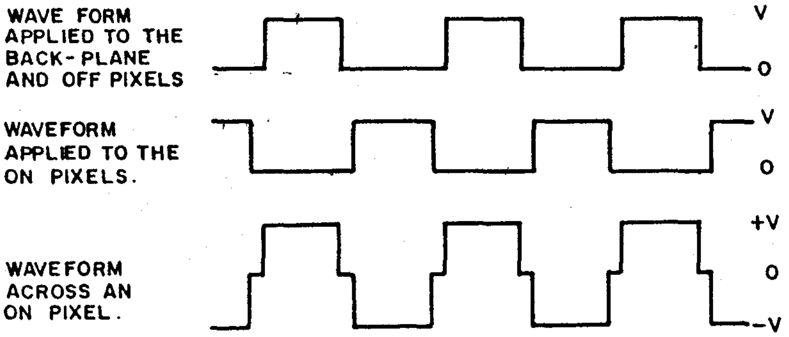
Table 2.7. Advantages of CMOS gates as LCD drivers

- They are low power devices
- They operate over a wide voltage range
- They have symmetrical characteristics
- They can sink or source equally well.



(a)

Fig. 2.14. Biphase addressing of directly driven displays



(b)

Fig. 2.15. Modified addressing waveforms to reduce power consumption.

quency of the addressing waveform. The effect of cross-talk in a large area, directly driven display can be reduced by taking the following steps:

- Decreasing the resistance of the back-plane electrode;
- Using an NLC mixture with a high V_{th} ; or
- Delaying the segment waveform (~ 300 μs) with reference to the back-plane waveform.

The power required in the directly driven display can be reduced by modifying the addressing waveforms as given in Fig.2.15. All the drive lines are momentarily grounded here, to allow the charge across the **ON** pixels to discharge without using the supply current. While a 50% reduction in the power is expected theoretically, an actual reduction of 33-43% is reported in literature [56].

c) Half-select Technique [HST]

This technique is based on line-by-line addressing and was the first technique ever used for multiplexing LCDs [57]. The row-select voltage here is $\pm V/2$ and the column voltage V_c is as given below :

- $V_c = \pm V/2$, i.e., in-phase with the row-select voltage, for an **OFF** pixel in the selected row; and
- $V_c = \mp V/2$, i.e., out-of-phase with the row-select voltage, for an ON pixel in the selected row.

The instantaneous voltage across a pixel for all the combinations of row and column voltages are given in Table 2.8. The voltages within the parenthesis include polarity inversion, for a dc-free operation. This technique as

Table 2.8. Pixel voltages in the Half-select techniques

Applied Voltage		Resultant voltage across the pixels
Row	Column	
+V/2, (-V/2) Selected	-V/2, (+V/2) Selected	+V, (-V) ON pixel
+V/2, (-V/2) Selected	+V/2, (-V/2) Unselected	0, (0) OFF pixel
0, (0) Unselected	-V/2, (+ V/2) selected	+V/2, (-V/2) both ON and OFF pixels
0, (0) Unselected	+V/2, (-V/2) Unselected	-V/2, (+V/2) both ON and OFF pixels

it was originally used did not take the rms response of LCDs into consideration. Hence the instantaneous voltage ($\pm V/2$) *was maintained below* V_{th}, *so that the* **OFF** *pixels are not activated. A display with a fast response time is required if the technique is based on instantaneous response rather than the rms response. The rms voltage across the pixels and the selection ratio of this technique are however given below for the sake of completeness.*

$$V_{ON}\,(\text{rms}) = \left[\frac{V^2 + (N-1)\left(\frac{V}{2}\right)^2}{N}\right]^{1/2} = \left[\frac{N+3}{4N}\right]^{1/2} V \qquad (2.1)$$

$$V_{OFF}\,(\text{rms}) = \left[\frac{(N-1)\left(\frac{V}{2}\right)^2}{N}\right]^{1/2} = \left[\frac{N-1}{4N}\right]^{1/2} V \qquad (2.2)$$

and

$$\text{The selection ratio} = R = \left[\frac{N+3}{N-1}\right]^{1/2} \qquad (2.3)$$

where N *is the number of lines multiplexed.*

d) One-third Select Technique (OST)

This technique is a line-by-line addressing technique and is based on the rms response of LCDs [58,59]. The rows are selected with a voltage $\pm\frac{2V}{3}$, *while the unselected rows are grounded. The column voltage* V_c *is* $\pm\frac{V}{3}$ *and depends on the data to be displayed in the selected row as given below :*

- $V_c = \pm V/3$, *i.e., in-phase with the row-select voltage for an* **OFF** *pixel, and*
- $V_c = \mp V/3$, *i.e., out-of-phase with the row-select voltage for an* **ON** *pixel.*

The instantaneous voltages across the pixels in the OST are given in Table 2.9. The rms voltage across the **ON** and **OFF** pixels are given below :

$$V_{ON}\ (rms) = \left[\frac{V^2 + (N-1)\left(\frac{V}{3}\right)^2}{N} \right]^{1/2} = \left[\frac{N+8}{9N} \right]^{1/2} V \tag{2.4}$$

$$V_{OFF}\ (rms) = \left[\frac{\left(\frac{V}{3}\right)^2 + (N-1)\left(\frac{V}{3}\right)^2}{N} \right]^{1/2} = \left[\frac{N}{9N} \right]^{1/2} V = \frac{V}{3} \tag{2.5}$$

The selection ratio here is

$$R = \left[\frac{N+8}{N} \right]^{1/2} \tag{2.6}$$

where N is the number of lines multiplexed.

The supply voltage for this technique is obtained as follows :

$$V_{OFF}\ (rms) = V_{th} = \frac{V}{3} \tag{2.7}$$

or

$$V_{supply} = V = 3V_{th} \tag{2.8}$$

Although the supply voltage here is independent of N, the selection ratio is not the maximum for **all** values of N. This is because the rms response of LCDs is not exploited fully here. The selection ratio is maximum, only when $N = 4$. Hence, this technique is no longer used due to its poor selection ratio, especially for higher values of N.

e) Alt and Pleshko Technique (APT)

Alt and Pleshko were the first to **maximize** the selection ratio by

Table 2.9. Pixel voltages in the One-third selection technique

Applied voltage		Resultant voltage across the pixels
Row	Column	
$+\frac{2V}{3}$, $(-\frac{2V}{3})$ Selected	$-\frac{V}{3}$, $(+\frac{V}{3})$ Selected	$+V$, $(-V)$ ON pixel
$+\frac{2V}{3}$, $(-\frac{2V}{3})$ Selected	$+\frac{V}{3}$, $(-\frac{V}{3})$ Unselected	$+\frac{V}{3}$, $(-\frac{V}{3})$ OFF pixel
0, (0) Unselected	$-\frac{V}{3}$, $(+\frac{V}{3})$ Selected	$\frac{V}{3}$, $(-\frac{V}{3})$. both ON and OFF pixels
0, (0) Unselected	$+\frac{V}{3}$, $(-\frac{V}{3})$ Unselected	$-\frac{V}{3}$, $(+\frac{V}{3})$ both ON and OFF pixels

taking the rms response of LCDs into consideration [60]. The instantaneous voltage across an OFF pixel can exceed V_{th} as long as the following constraints are satisfied :

- Its duration is small as compared to the response time of the display; and
- The rms voltage across the pixel is below V_{th}.

This technique is a line-by-line addressing technique. The rows are sequentially selected with a row-select voltage $\pm V_r$, while the unselected rows are grounded. The column voltage depends on the data to be displayed in the selected row as given below :

- It is $\pm V_c$, i.e., in-phase with the row-select voltage for OFF pixels; or
- It is $\mp V_c$, i.e., out-of-phase with the row-select voltage for ON pixels. The instantaneous voltages across the pixels for the various combinations of row and column voltages are given in Table 2.10.

The instantaneous voltage $|V_r - V_c|$ appearing across the OFF pixels can be higher than V_{th}. The column voltage $|V_c|$ appearing across the pixels, when the corresponding row is not selected, does not have any relevance to the data to be displayed in these pixels. Hence, the duty cycle is 1/N.

The rms voltages across the ON and OFF pixels are given below :

$$V_{ON}\ (rms) = \left[\frac{(V_r + V_c)^2 + (N-1)V_c^2}{N}\right]^{1/2} \qquad (2.9)$$

and

Table 2.10. Voltages across the pixels in APT

Applied Voltage		Resultant voltages across the pixels
Row	Column	
$+V_r$, $(-V_r)$ Selected	$-V_c$, $(+V_c)$ Selected	V_r+V_c, $-(V_r+V_c)$ ON pixels
$+V_r$, $(-V_r)$ Selected	$+V_c$, $(-V_c)$ Unselected	V_r-V_c, $-(V_r-V_c)$ OFF pixels
0, (0) Unselected	$-V_c$, $(+V_c)$ Selected	$+V_c$, $-(V_c)$ Both ON and OFF pixels
0, (0) Unselected	$+V_c$, $(-V_c)$ Unselected	$-V_c$, $+(V_c)$ Both ON and OFF pixels

$$V_{OFF}\,(\text{rms}) = \left[\frac{(V_r - V_c)^2 + (N-1)\,V_c^2}{N} \right]^{1/2} \tag{2.10}$$

The selection ratio is a maximum for

$$V_r = N^{1/2}\,V_c \tag{2.11}$$

The maximum selection ratio is as given below :

$$R = \frac{V_{ON}\,(\text{rms})}{V_{OFF}\,(\text{rms})} = \left[\frac{N^{1/2}+1}{N^{1/2}-1} \right]^{1/2} \tag{2.12}$$

A dc-free operation is ensured by reversing the polarity of the row and column voltages simultaneously in a periodic manner [60,61] as given below:

- Within the row-select time; or
- After selecting N rows .

Both these schemes are shown in Figs.2.16 and 2.17 respectively.

The rms voltages across the **ON** and **OFF** pixels for a maximum selection ratio are as given below :

$$V_{ON}\,(\text{rms}) = \left[\frac{2(N + N^{1/2})}{N} \right]^{1/2} V_c \tag{2.13}$$

and

$$V_{OFF}\,(\text{rms}) = \left[\frac{2(N - N^{1/2})}{N} \right]^{1/2} V_c \tag{2.14}$$

The **OFF** pixels in the display are usually biased to V_{th} in order to get a good contrast ratio. Hence, the voltage V_c can be determined in terms

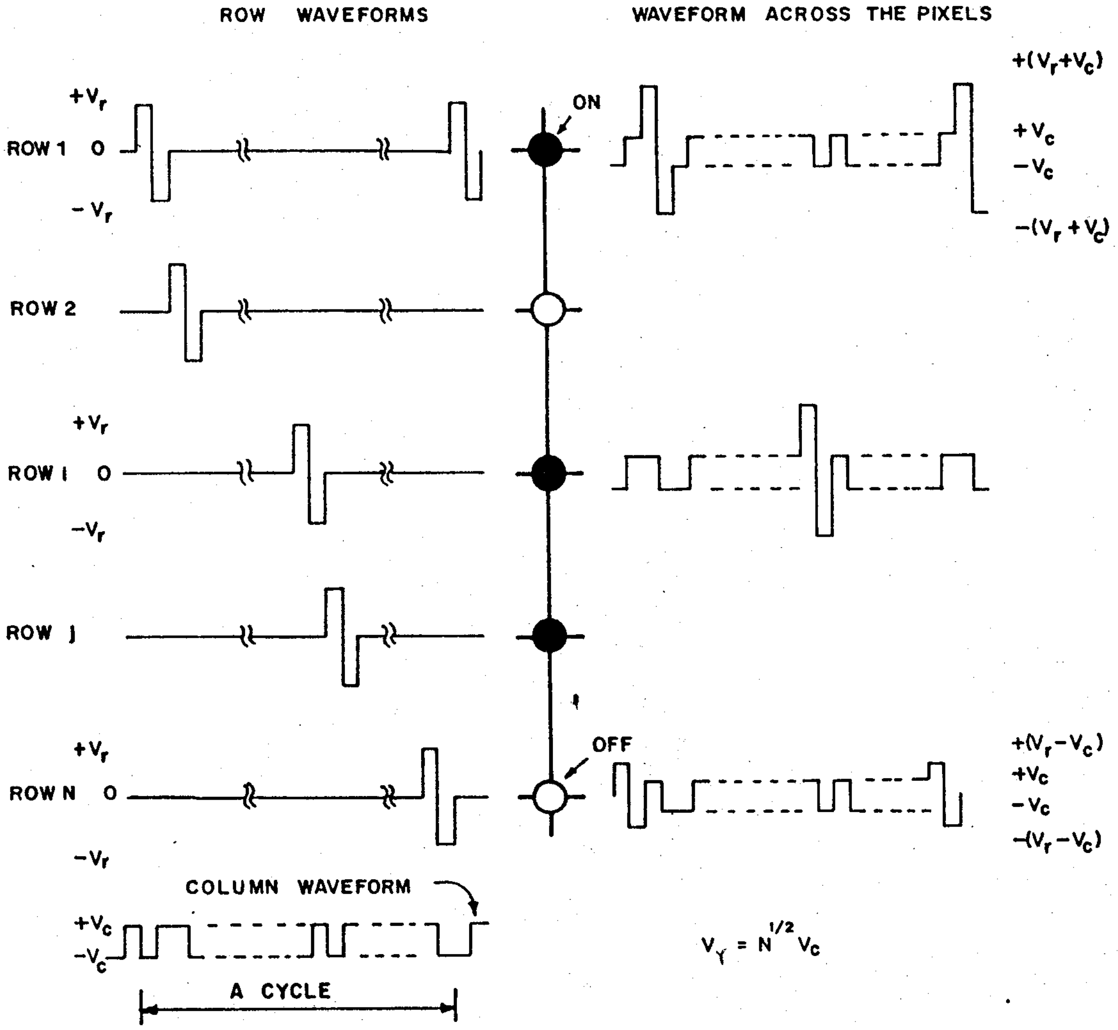


Fig. 2.16. APT with polarity reversal within the row-select time.

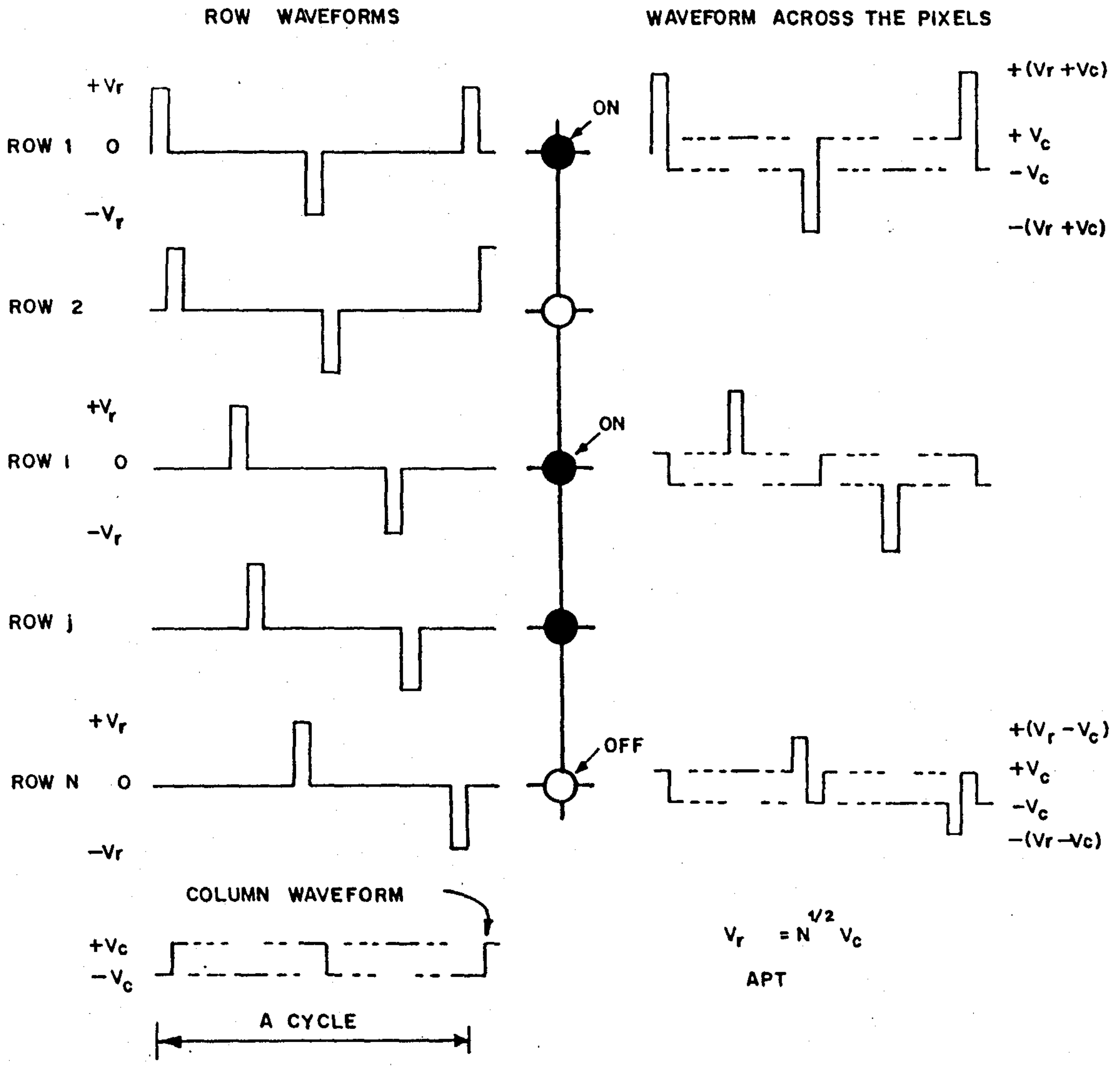


Fig. 2.17. APT with polarity reversal after selecting N rows.

of V_{th} as follows :

$$V_{OFF}\,(rms) = V_{th} = \left[\frac{2(N - N^{1/2})}{N}\right]^{1/2} V_c \qquad (2.15)$$

or

$$V_c = \left[\frac{N}{2(N - N^{1/2})}\right]^{1/2} V_{th} = \frac{V_{th}}{[2(1 - N^{-1/2})]^{1/2}} \qquad (2.16)$$

The supply voltage is determined by the maximum voltage swing in the addressing waveforms. Hence,

$$V_{supply}\,(APT) = 2V_r = 2N^{1/2}\, V_c = \left[\frac{4N}{2(1 - N^{-1/2})}\right]^{1/2} V_{th} \qquad (2.17)$$

This technique is simple and it provides the maximum selection ratio. The maximum instantaneous voltage across any pixel is $(V_r + V_c)$. But the maximum voltage swing in the addressing waveform is $2V_r$. It is possible to reduce this swing to (V_r+V_c) by using a technique proposed by Kawakami et al [62]. This technique with a low supply voltage will be referred to as Improved Alt and Pleshko Technique (IAPT) in this Thesis.

f) Improved Alt and Pleshko Technique (IAPT)

The addressing waveforms of APT can be modified from the following observations in the addressing waveforms of Figs. 2.16 and 2.17 :

- The instantaneous voltage across any pixel does not exceed $|V_r + V_c|$, i.e., $(N^{1/2} + 1)\, V_c$; and
- The voltage V_r is either positive or negative at a given instant.

The modified addressing waveforms of IAPT are obtained from that of APT as given below :

- The row and column voltages are shifted by $+V_c$ when the polarity of the row-select voltage is positive; and
- The row and column voltages are shifted by $+V_r$, i.e., $N^{1/2}\ V_c$ when the polarity of the row-select voltage is negative.

The above transformation does not alter the rms voltage across the pixels since, both the row and column voltages are shifted by an equal amount.

Table 2.11 gives the instantaneous voltages across the pixels for various combinations of row and column voltages. The voltages within the parenthesis include phase reversal for a dc-free operation. The maximum voltage swing in the addressing waveforms of IAPT is $(N^{1/2} + 1)V_c$. Hence, an expression for the supply voltage is determined by substituting for V_c from eqn. 2.16:

$$V_{supply}\,(\mathrm{IAPT}) = (N^{1/2} + 1)V_c = \frac{(N^{1/2} + 1)}{[2(1 - N^{-1/2})]^{1/2}}\,V_{th} \qquad (2.18)$$

The supply voltage requirement of IAPT is compared with that of APT, as given below :

$$\frac{V_{supply}\,(\mathrm{IAPT})}{V_{supply}\,(\mathrm{APT})} = \frac{N^{1/2} + 1}{2N^{1/2}} \qquad (2.19)$$

From the above equation, it is evident that IAPT requires a lower supply voltage as compared to APT. For example IAPT requires only 55% of the

Table 2.11 Voltages across the pixels in IAPT

Applied voltage		Resultant voltages across the pixels
Row	Column	
$(N^{1/2}+1)V_c$, $[0]$ **Selected**	0 , $[(N^{1/2}+1)V_c]$ **Selected**	$+(N^{1/2}+1)V_c$, $[-(N^{1/2}+1)V_c]$ **ON pixels**
$(N^{1/2}+1)V_c$, $[0]$ **Selected**	$2V_c$, $[(N^{1/2}-1)V_c]$ **Unselected**	$+(N^{1/2}-1)V_c$, $[-(N^{1/2}-1)V_c]$ **OFF pixels**
V_c , $[N^{1/2} V_c]$ **Unselected**	0 , $[(N^{1/2}+1)V_c]$ **Selected**	$+ V_c$, $[- V_c]$ **ON and OFF pixels**
V_c , $[N^{1/2} V_c]$ **Unselected**	$2V_c$, $[(N^{1/2}-1)V_c]$ **Unselected**	$- V_c$, $[+ V_c]$ **ON and OFF pixels**

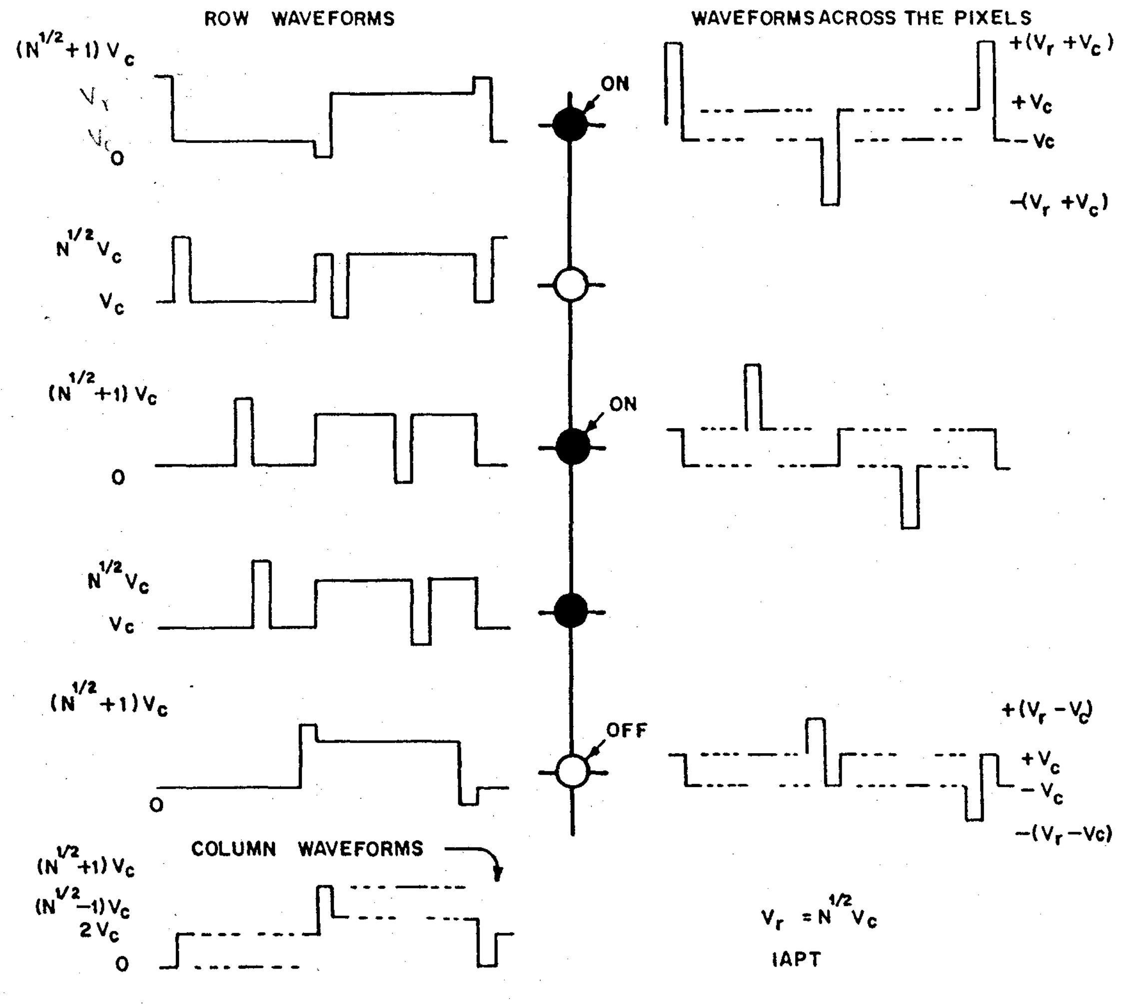


Fig. 2.18. Typical addressing waveforms of IAPT .

supply voltage of APT, when $N = 100$.

Typical addressing waveforms of IAPT are shown in Fig.2.18. Both the row and column waveforms have four voltage levels. The IAPT is used to multiplex almost all the matrix LCDs available at present, since it requires a lower supply voltage as compared to APT. Thus, it is a very popular technique.

g) Switching Bias Voltage Addressing Technique (SBAT)

The SBAT [63] is based on the following observations in APT and IAPT :-

- The APT, without the polarity reversal requires only two voltage levels for the row and column voltages; and
- The IAPT requires four voltage levels in the row and column waveforms, since both row and column drivers are connected to a common ground; but, the row and column drivers have only two voltage levels at a given instant. In SBAT, a bias voltage is applied between the ground of the row, column drivers and the common ground between them as shown in Fig.2.19. Both the row and column drivers require only two voltage levels as given below :
- The voltage swing in the row drivers is $V_r = N^{1/2} V_c$; and
- The voltage swing in the column drivers is $2V_c$.

The bias voltages are switched as given below :

- The row drivers are biased to $+V_c$, while the column drivers have

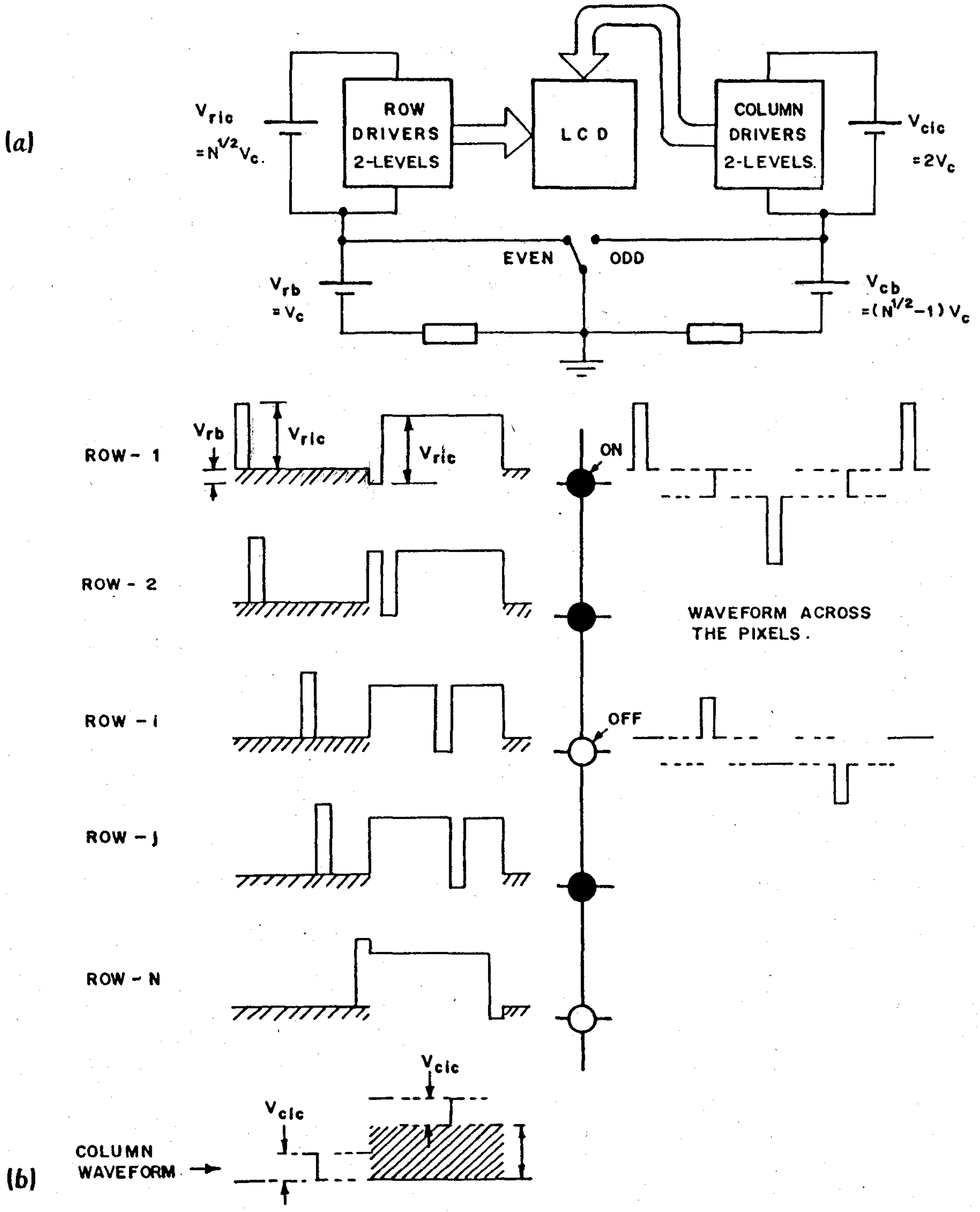


Fig.2.19. SBAT. a) Schematic, and (b) typical addressing waveforms.

no bias voltage in one frame; and

- The column drivers are biased to $(V_r - V_c) = (N^{1/2} - 1)V_c$, while row drivers have no bias voltage in the other frame.

The resultant waveform across the pixels is the same as in the case of APT and IAPT as shown in Fig. 2.19. The SBAT is attractive from practical points of view since standard CMOS ICs can be used as row and column drivers. However, the following points must be taken into consideration while using SBAT for driving LCDs :

- The supply voltage for the row and column drivers are different, i.e., V_r and $2V_c$ respectively; and
- The data and the control signals must be made compatible to the driver logic circuits by including proper level shifts to these signals.

h) Two Frequency Addressing Technique (TFAT)

This technique is based on the dielectric relaxation of a positive NLC mixture [59,64,65]. The cross-over frequency f_c should be low, i.e., in the range of a few KHz. A low frequency signal applied to the cell aligns the molecules so that the director is parallel to the electric field. A high frequency signal however aligns the molecules perpendicular to the electric field. Hence, the application of both low and high frequency signals to the cell increases V_{th}. Consequently, the effective steepness of the electro-optic response curve is increased. The following alternatives are possible in TFAT :

- Low frequency addressing waveforms with a fixed high frequency bias; OR
- High frequency addressing waveforms with a fixed low frequency bias.

The latter is found to give better results [66]. A display using TFAT has the following characteristics :

- Good contrast ratio ;
- Wide viewing angle; and
- Fast response.

Yet, this technique is not popular due to the following drawbacks :

- The cross-over frequency f_c is highly sensitive to temperature;
- The amplitudes of the addressing waveforms are high, leading to a high supply voltage;
- The power consumed is high due to the high frequency and the large amplitudes of the addressing waveforms.

A prototype of a display based on two frequency addressing with temperature compensation is reported in literature [67].

i) Ultimate Limits for rms Matrix Addressing

The ultimate limits on the value of the selection ratio in a matrix display with an rms response was analyzed by Kmetz and Nehring [68,69] and also by M.G.Clark et al [70]. From a generalized definition of multiplexing, the following conclusions have been drawn when a general pattern is to be displayed :-

- No other orthogonal strobe functions, viz., sinusoids of different frequencies or Walsh functions can lead to a better performance as compared to the pulsed waveform of APT ;

- No addressing technique exists which improves the selection ratio substantially as compared to that of APT, except when $N = 2$. A selection ratio of 3 is obtained by using a special addressing technique [68,69], when $N = 2$.

A comparison of the addressing techniques based on the rms response and threshold characteristics of LCDs is given in Table 2.12. Here N_{eq} is used to compare the selection ratio of the other techniques with that of APT. N_{eq} gives the number of lines to be multiplexed using APT in order to get the same selection ratio as that of the technique being compared [71]. Hence, N_{eq} is obtained by equating the selection ratio (R) of the technique being compared to the standard expression for the selection ratio of APT as given below :

$$R = \left[\frac{N_{eq}^{1/2} + 1}{N_{eq}^{1/2} - 1} \right]^{1/2} \qquad (2.20)$$

Hence, the technique with a lower selection ratio as compared to APT has a higher value of N_{eq} .

j) Contrast Improvement

The selection ratio is less than 1.1, when the number of lines multiplexed is more than 100. The NLC mixtures available for TNLCDs, at present are just adequate for multiplexing a maximum of 128 lines only. However, there are applications, wherein the matrix size is larger, viz., 200 x 480, 400 x 640, etc. Although active matrix displays are suitable for such applications, simpler techniques are adopted for technical and economic reasons. All these techniques are based on the following observation :

- The selection ratio is independent of the number of columns and depends

Table 2.12. Matrix Addressing Techniques for LCDs - A Comparison

Parameter	Addressing techniques for displaying general patterns				
	Half-Select Technique [HST]	One-third Select Technique [OST]	Alt and Pleshko Technique [APT]	Improved Alt and Pleshko Technique [IAPT]	Switching Bias Voltage Addressing Technique [SBAT]
Selection ratio (R)	Low	Intermediate	High	High	High
N_{eq}	$[(N+1)/2]^2$	$[(N+4)/4]^2$	N	N	N
Maximum number of lines multiplexed for $R = 1.1$	20	38	110	110	110
Supply voltage	Low	Low	High	Intermediate	Intermediate
Duty cycle	$1/N$	$1/N$	$1/N$	$1/N$	$1/N$
Ratio of row-select voltage to column voltage (V_r/V_c)	1	2	$N^{1/2}$	$N^{1/2}$	$N^{1/2}$
Comments	Oldest Technique Not popular now a days	Not popular now-a-days	Can be used	Most popular due to its low supply voltage	Driver ICs for directly driven display can be used

only on the number of rows multiplexed.

Hence the structure of the matrix panel can be modified to reduce the number of lines multiplexed. Even though the number of columns is increased, such a modification is justified for the following reasons :

- The contrast ratio of a matrix display of a given size can be improved;
- The display fabrication is easy as compared to that of an active matrix;
- The various structures of LCD matrix panels, resulting in a contrast improvement are compared in Table 2.13.

  The split signal electrode type of matrix panels are used even in displays based on SBE, in order to obtain a good contrast ratio [18,29,31].

2.4.2 **Displaying Restricted Patterns**

a) Basics of Restricted Pattern Addressing

A matrix display is usually designed to display general patterns. Hence, it is possible to display 2^N different patterns in each column, in a matrix with N rows. However there are several applications, wherein many of these 2^N combinations do not occur. For example, a pointer type display has only one pixel selected in the matrix at a given instant. Similarly, in an oscilloscope display, only one pixel per column is selected when a single waveform is displayed. It is possible to improve the selection ratio when such restricted patterns are displayed. The magnitude of the column voltage V_c need not be the same for **ON** and **OFF** pixels, when the number of selected pixels in a column is a constant. The selection ratio as a function of

Table 2.13. Structure of LCD matrix panel - A comparison

Parameter	Structure of LCD matrix panel				
	Simple X-Y type (Fig. 2.20a)	Split signal electrode type [3] (Fig. 2.20b)	Double matrix type [72] (Fig. 2.20c)	Quad matrix type [73] (Fig. 2.20d)	Double layer matrix type [74] (Fig. 2.20e)
Number of pixels in the matrix	$N \times M$	$N \times M$	$N \times M$	$N \times M$	$N \times M$
Number of scanned lines	N	$2 \times (\frac{N}{2})$	$\frac{N}{2}$	$\frac{N}{4}$	$2 \times (\frac{N}{2})$
Number of signal lines	M	$2 \times M$	$2 \times M$	$4 \times M$	$2 \times M$
Number of row drivers	N	$\frac{N}{2}$	$\frac{N}{2}$	$\frac{N}{4}$	N
Number of column drivers	M	$2 \times M$	$2 \times M$	$4 \times M$	$2 \times M$
Number of lines scanned from the point of view of selection ratio (R)	N	$\frac{N}{2}$	$\frac{N}{2}$	$\frac{N}{4}$	$\frac{N}{2}$
Comments	Standard	Simple. No compromise on the pixel size. Most popular	The pixel size is reduced. Requires metalization to reduce the electrode resistance. Pixels are displaced and have a zig-zag structure	Same as Double matrix panel Pixel size is smaller than that of double matrix	Equivalent two LCDS stacked on one another. Requires thin glass plates to avoid parallax. Not economical for large area displays

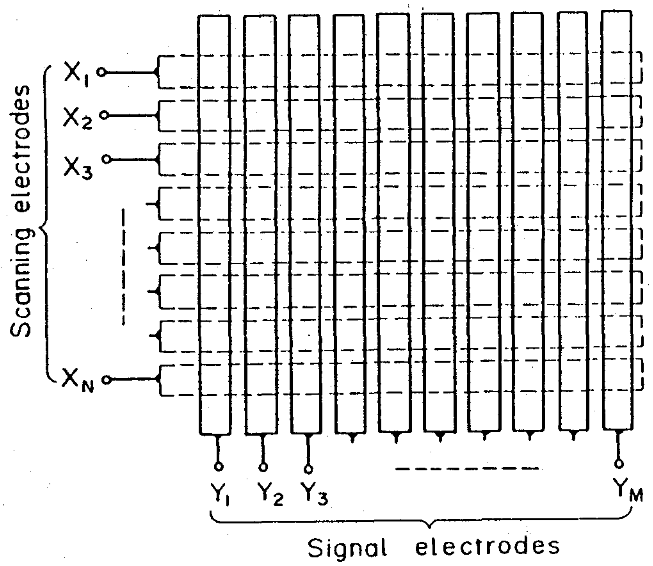


Fig. 2.20a. Schematic of a simple X-Y type matrix LCD panel.

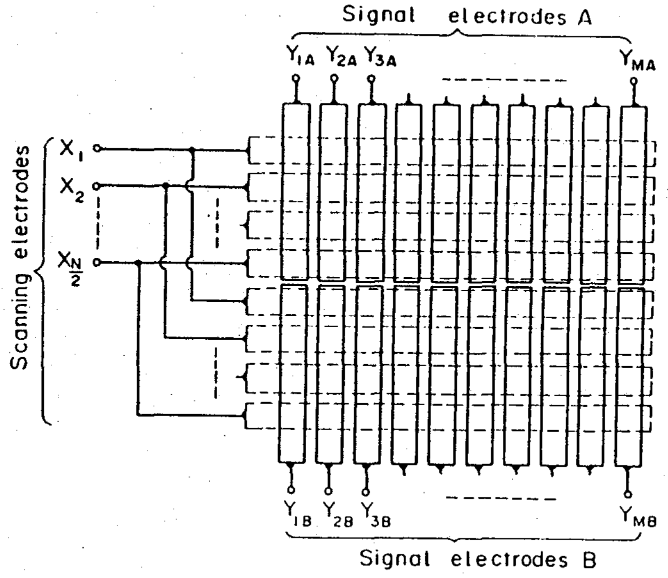


Fig. 2.20b. Schematic of a split signal electrode type matrix LCD panel.

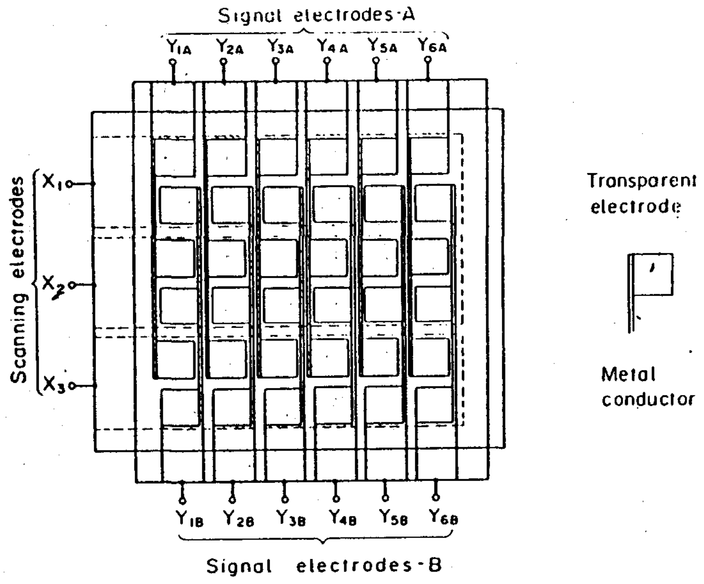


Fig.2.20c. Schematic of a double matrix type LCD panel.

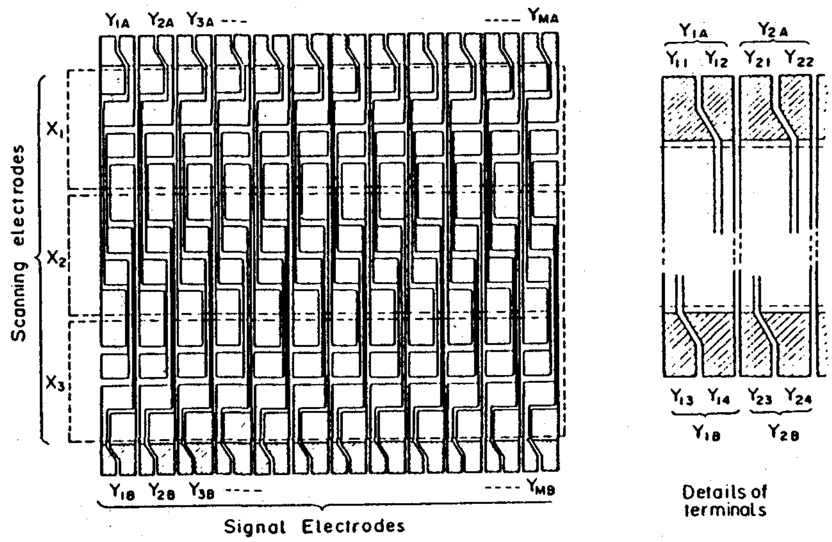


Fig. 2.20d. Schematic of a Quad matrix type LCD panel.

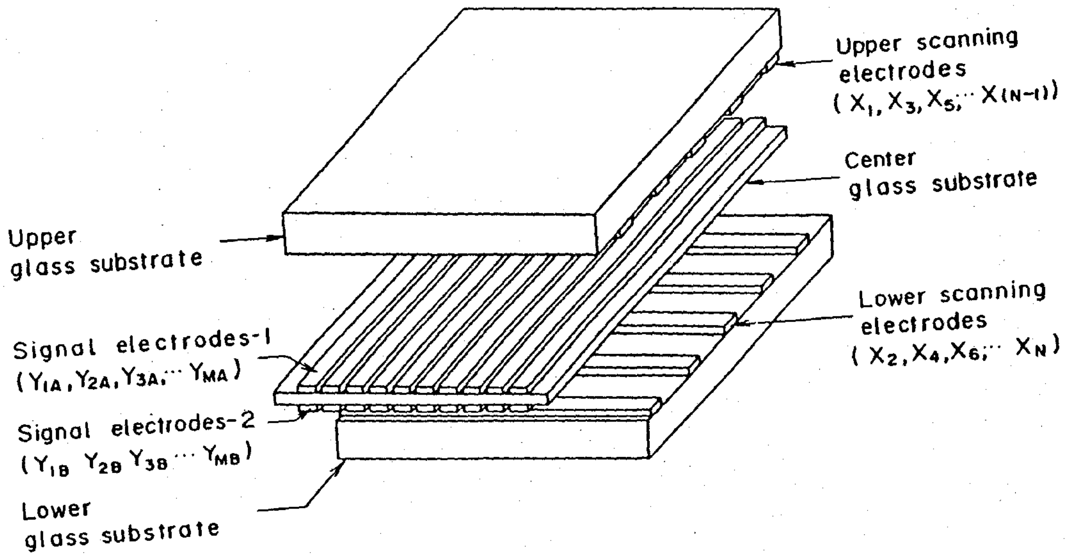


Fig.2.20e. Schematic of a double layer matrix type LCD panel.

number of **ON** pixels in a column (n) was arrived at by Kmetz and Nehring [69]. The technique is similar to APT, except for the choice of the column voltage and is referred to by them as Non-Multiplexed Addressing.

The choice of the column voltage V_c here, is as given below :

- The amplitude of the column voltage is V_1 and is out-of-phase with the row- select voltage, for an **ON** pixel in the selected row.
- The amplitude of the column voltage is V_0 and is in-phase with the row-select voltage, for an **OFF** pixel in the selected row. The rms voltages across the **ON** and **OFF** pixels in a matrix display with N rows and n **ON** pixels in each column are as given below :

$$V_{ON}\ (rms) = \left[\frac{(V_r + V_1)^2 + (n-1)V_1^2 + (N-n)V_0^2}{N} \right]^{1/2} \qquad (2.21)$$

and

$$V_{OFF}\ (rms) = \left[\frac{(V_r - V_0)^2 + nV_1^2 + (N-n-1)V_0^2}{N} \right]^{1/2} \qquad (2.22)$$

The optimum selection ratio is

$$R = \left[1 + \frac{N}{[n(N-n)(N-1)]^{1/2} - n} \right]^{1/2} \text{for } 0 < n \leq (N-1) \qquad (2.23)$$

The selection ratio as a function of n for various values of N are shown in Fig. 2.21.

The column voltages normalized with respect to the row-select voltage V_r are as given below :

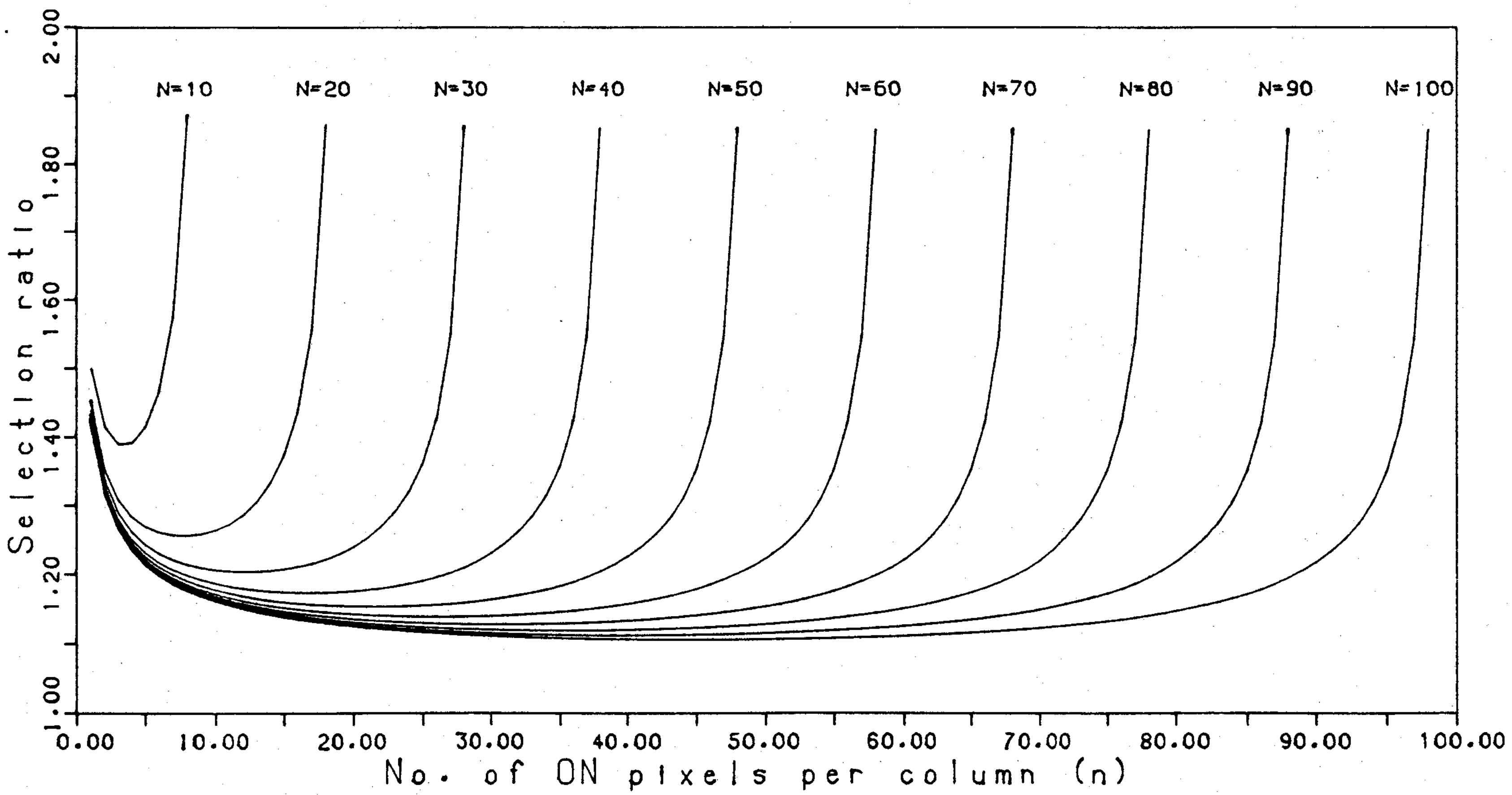


Fig. 2.21. Selection ratio vs. n as a function of N.

$$\frac{V_1}{V_r} = \frac{[n(N-n)(N-1)]^{1/2} - n}{Nn} \qquad (2.24)$$

and

$$\frac{V_0}{V_r} = \frac{[n(N-n)(N-1)]^{1/2} + (N-n)}{N(N-n)} \qquad (2.25)$$

The following observations are important as they form the basis of restricted pattern addressing :

- The selection ratio is infinite for $n = (N - 1)$ which is useful for several special-purpose displays like pointers [75,76] and oscilloscopes [77,78]
- The selection ratio is a minimum for $n = (N - N^{1/2})/2$. The minimum value is the same as that of APT.
- The selection ratio is higher when most of the pixels are **ON** as compared to the case when most of the pixels are **OFF**.

The waveforms that are displayed in an oscilloscope are mostly single valued functions of time. Hence only one pixel per column is selected in the matrix. Two addressing techniques were developed by Shanks et al [77,78] for displaying a single waveform, viz., Pulse Coincidence Technique and Pseudo Random Technique, which are briefly described below.

b) Pulse Coincidence Technique (PCT)

This addressing technique can be treated as a line-by-line addressing technique (Fig. 2.22). The rows are selected with a row-select voltage $\pm V_r$. The column voltage V_c is chosen depending on the data to be displayed in the selected row as given below :

- $V_c = 0$, for an **ON** pixel; and
- $V_c = +V_r$, i.e., the same as the row-select voltage for an **OFF** pixel.

The rms voltage across an **OFF** pixel is zero, since the row and column waveforms are identical in this case. An **ON** pixel gets a voltage V_r once when the corresponding row is selected. All the **ON** pixels in a column get a voltage V_r again, when the row corresponding to the **OFF** pixel in that column is selected. The rms voltage across the **ON** pixels is as given below:

$$V_{ON}\,(\mathrm{rms}) = \left[\frac{2V_r^2}{N}\right]^{1/2} = \left[\frac{2}{N}\right]^{1/2} V_r \qquad (2.26)$$

The selection ratio is infinite, since the **OFF** pixels have no voltage across them. Here, the selected pixels (i.e., the points on the displayed waveform) get a lower voltage as compared to the background (ON) pixels. Hence the resulting display has a negative contrast in the case of TNLCDs and a positive contrast in GH displays. This technique has an inherent dc-free operation and does not require the polarity reversal in the addressing waveforms. Hence, standard CMOS gates can be used as drivers. The supply voltage is determined as follows :

$$V_{ON} = V_{sat} = [\tfrac{2}{N}]^{1/2}\, V_r \qquad (2.27)$$

The maximum voltage swing in the addressing waveform is V_r and hence,

$$V_{supply} = V_r = \left[\frac{N}{2}\right]^{1/2} V_{sat} \qquad (2.28)$$

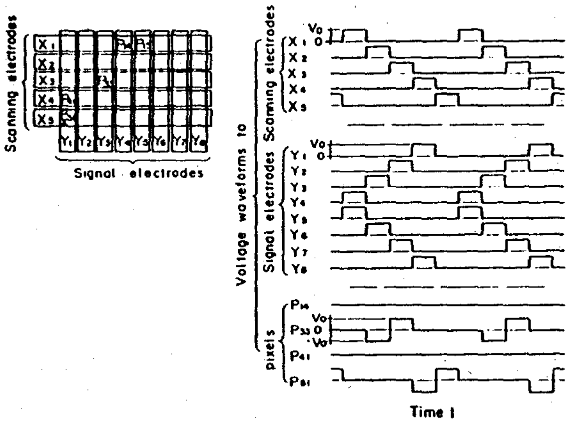


Fig. 2.22. Typical addressing waveforms of PCT.

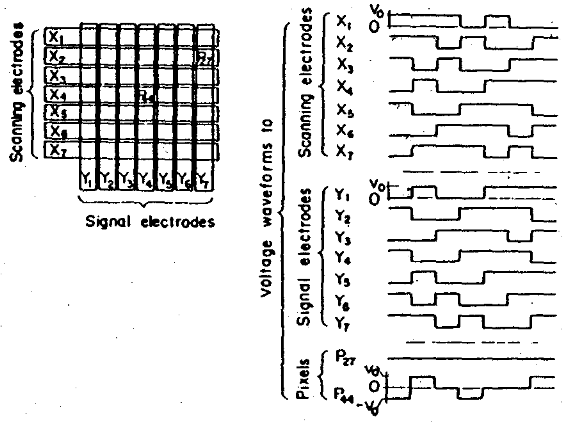


Fig. 2.23. Typical addressing waveforms of PRT .

Although the selection ratio is independent of the matrix size, the supply voltage increases with N, i.e., the number of scanned lines.

c) Pseudo Random Technique [PRT]

The Pseudo Random Binary Sequences (PRBS) are used here to reduce the supply voltage requirements. These sequences can easily be generated using shift registers with a linear feedback [79]. The maximum length of these sequences is $(2^L - 1)$ when an L-bit shift register is used to generate them. The feedbacks required to generate the maximum length sequence are readily available [80], One of the many interesting properties of the PRBS is the nature of its autocorrelation function. The autocorrelation is unity for zero delay and a constant value for any other delay. Similarly, the difference between a PRBS and its delayed versions have the following properties :

- The rms value is independent of the number of delays, except for a zero delay; and
- The rms value is zero for a zero delay.

The PRBS chosen for this technique should have a sequence length greater than or equal to the number of rows in the matrix. Here, the PRBS and its delayed versions are applied as row waveforms (Fig.2.23). No two rows should have the same delay, so that the rows are uniquely defined. The column waveform is chosen such that the row and column waveforms are identical as in the case of PCT. This ensures a zero voltage across the **OFF** pixels. The rms voltage across the **ON** pixels is as follows :

$$V_{ON}\,(rms) = \left[\frac{2^{(L-1)}}{2^L - 1}\right]^{1/2} V \qquad (2.29)$$

wherein $2^{(L-1)}$ gives the number of anticoincidences between a PRBS and its delayed version and V is the amplitude of the pulses, i.e., the supply voltage in this case. Here, the supply voltage is independent of N. An ON pixel gets approximately an rms voltage of 0.707 V. Here again, the selection ratio is infinite, since **OFF** pixels get no voltage across them. The background (**ON**) pixels get a higher voltage as compared to the selected (OFF) pixels. This leads to a negative contrast, i.e., bright waveform against a dark background in the TNLCDs.

d) Multi-trace Displays

There are practical applications, viz., Logic analyzers and multi-trace oscilloscopes wherein more than one waveform have to be displayed. The following approaches have been proposed for the same :

- By using the interleaved vertical electrodes. A dual trace display using odd columns for one waveform and even columns for the other has been demonstrated [3]. The horizontal resolution is sacrificed here, without any compromise in the selection ratio.
- By displaying the waveforms one after the other in a sequential manner, i.e., W waveforms to be displayed being multiplexed in sequential frame periods (referred to as SFMT). The selection ratio here is $[W/(W-1)]^{1/2}$, without any compromise in the horizontal resolution [3].

These two techniques are illustrated in Fig. 2.24.

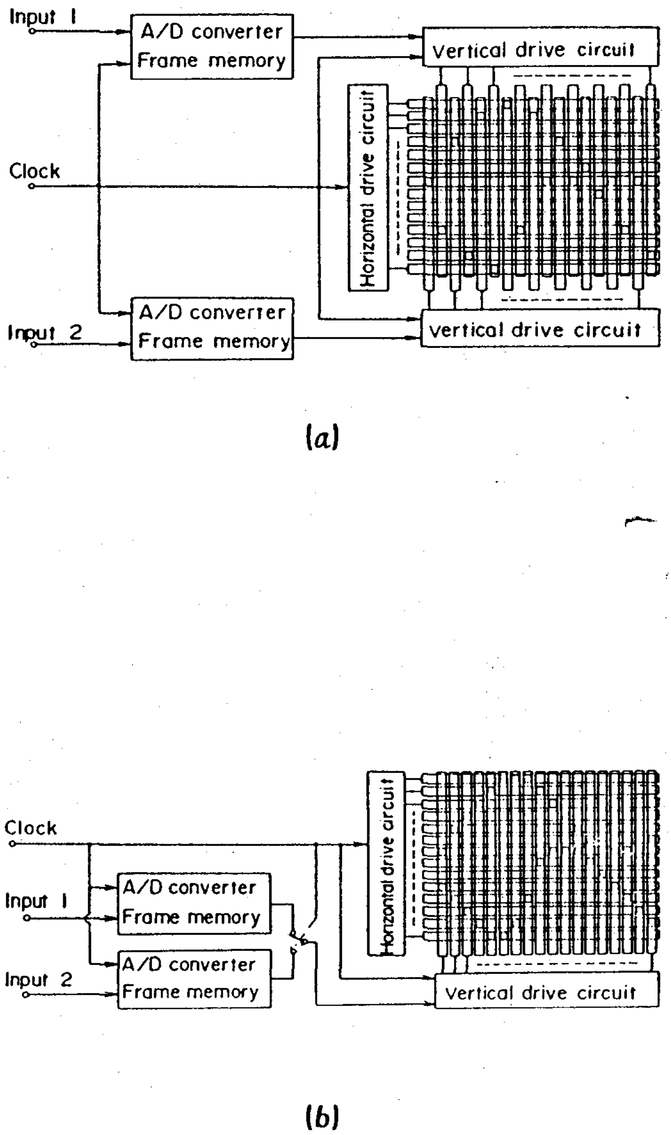


Fig. 2.24. Techniques for displaying multi-trace waveforms.
a) by using interleaved vertical electrodes, and
b) by using SFMT.

e) Addressing Technique for Analog Displays

Displays simulating the mechanical motion of a pointer is of interest in some applications. The pointer display and the analog watch display fall under this category. The patterns to be displayed are restricted and some addressing techniques for such applications, discussed by Penz [36] are given below for the sake of completeness :

- A technique proposed by Fukumoto used a square waveform with 50% duty cycle and its phase shifted versions to address an analog watch display using a pointer and bargraph to display the time. The selection ratio of this technique is $(3)^{1/2}$.
- A technique proposed by Gruebal et al. to address an analog watch display. This technique is also suitable for multiplexing a matrix display with two rows. The selection ratio of this technique is $(5)^{1/2}$, which is less than that of APT.

2.4.3 **Practical Considerations**

Important practical aspects common to both the general and restricted pattern matrix LCDs are briefly covered in this section.

a) Choice of scanning frequency

Each pixel in an LCD can be considered as a lossy variable capacitor and the power consumed in the display is dependent on the following factors:

- Display area ;
- Number of lines multiplexed (N); and
- Frame frequency (scanning rate).

It has been shown by Marks [81] that the power consumed in a large matrix (N x M) is proportional to N^2M. However, the power consumed is still low and will not be a limiting factor for LCDs. While a slow scanning rate is desirable to minimise the power consumed, the scanning must be fast enough to ensure the rms response and to avoid flicker.

b) Large Area Display

Here, the distributed resistance of the electrode patterns and the distributed capacitance of the pixels form transmission lines. Hence, the higher frequency components in the addressing waveforms get attenuated as they travel from one end to the other end of the display. The rms voltage across the pixels in identical states (ON or OFF) are not the same here. This leads to a brightness nonuniformity of the pixels which can be reduced by decreasing the resistance of the electrode patterns in the display [82].

c) Dielectric Relaxation

Ideally the NLC mixture used in the display should have a high f_c, so that $\Delta\varepsilon$ is a constant in the frequency range of operation. However, in practice, the choice of the NLC mixture depends on a number of considerations, viz., temperature range, V_{th}, steepness of the electro-optic response, optical anisotropy, viscosity, etc. Hence, the actual NLC mixture used may exhibit a slight droop in the value of $\Delta\varepsilon$ in the frequency range of operation due to low f_c of some of the components in the mixture. The decrease of f_c with decrease in temperature also contributes to this problem.

The effective rms voltage across a pixel is a weighted sum of the rms voltages of the frequency components across the pixel. This takes care of the variation of $\Delta\varepsilon$ with frequency. However the exact waveform across a pixel depends on the

- data to be displayed in the column ;
- addressing waveforms ;
- polarity reversal scheme; and
- scanning rate.

The effective rms voltage across a pixel is lower when the high frequency components are dominant as compared to the case when they are weak. The brightness non-uniformity of the pixels arising due to the dielectric relaxation can be reduced or eliminated by using addressing waveforms resulting in predominantly low frequency components across the pixels. The effect of the polarity reversal scheme in APT or IAPT, on the pixel brightness nonuniformity has been studied [83] by using the following approaches :

- Polarity reversal within the row-select time interval (Bipolar Monopulse Strobe or BPMS), and
- Polarity reversal at the end of each cycle. (Two Field Monopulse Strobe or TFMS).

It has been shown that the contrast variation (brightness non-uniformity of pixels) is less in BPMS as compared to TFMS.

In another approach to reduce this nonuniformity, a new method is proposed

[84]. The polarity of the addressing waveforms are reversed after scanning L^* lines, where $L^* < N$. The polarity signal with a period of $2L^*$ is modulated with another macro polarity signal with a polarity reversal after M^* lines. A dc-free operation is ensured only when M^*/L^* is odd and M^* is a least common multiple of N and L^*. The dominant frequency components of this technique are in between those of TFMS and BPMS. This technique reduces the contrast variation arising from the dielectric relaxation and the transmission line characteristics of the display. Psuedo Random Binary Sequences (PRBS) have been used to reverse the polarity of the addressing waveforms. This improves the brightness uniformity of pixels in displays addressed with IAPT [85].

2.4.4 Techniques for reducing the lead count

In a matrix display with N_ℓ external connections, the maximum number of pixels that can be addressed is $(N_\ell/2)^2$. An unconventional interconnection scheme wherein N_ℓ leads can address $N_\ell(N_\ell-1)/2$ pixels is possible in LCDs. An addressing technique for a display with this interconnection scheme was proposed by Kmetz [34], and is shown in Fig. 2.25. The pixels are addressed sequentially one after the other. There is no distinction between the row-address and column-signal lines. The reduction in the lead count is achieved with a substantial sacrifice in the selection ratio. However they are useful for displaying restricted patterns as in the case of pointer and bargraph displays. The Multilevel addressing technique proposed by Sherr [35] for LCDs achieves a good reduction in the lead count. Here a number of display panels are stacked one behind the other. Various areas in each panel is activated electrically using the regular matrix type of electrodes. Optical modulation is used in the third dimension. The display is partitioned into large areas in the first panel and only one of them is selected at a given instant of time.

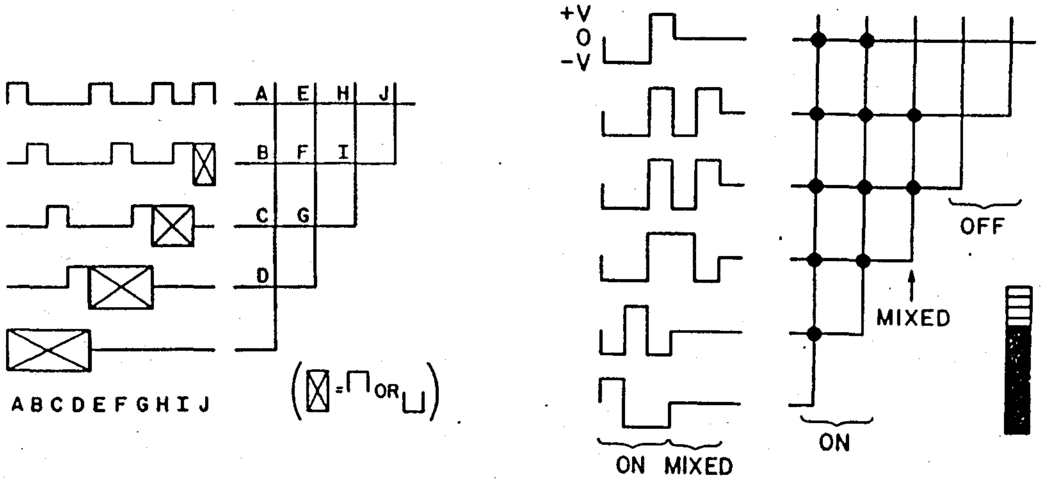


Fig. 2.25. Typical addressing waveforms for a display with reduced lead count. (a) general patterns, and (b) restricted patterns (bargraph).

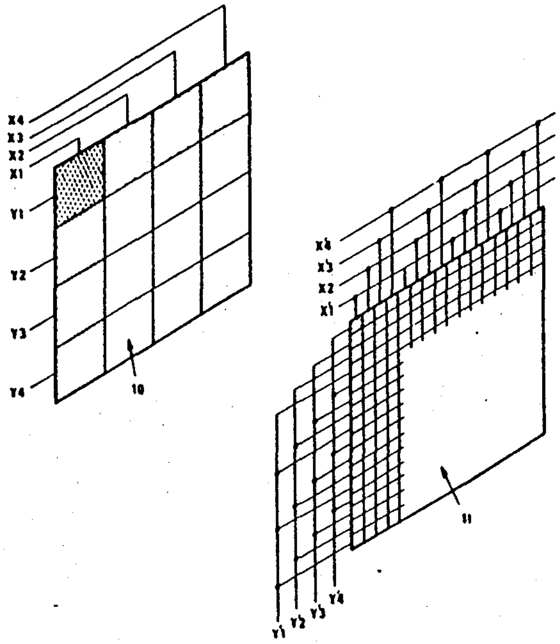


Fig. 2.26. Schematic of multilevel addressing .

The subsequent panels select smaller areas with increasing resolution. The selected pixel is the intersection of the selected pixels in all the panels. Fig. 2.26 illustrates this technique for a 16 x 16 matrix display with two panels stacked one behind the other. The number of external connections is reduced since the high resolution electrode patterns belonging to different areas with respect to the area selected in the first panel are interconnected. Threshold characteristics is not essential here since -

- *optical modulation is used in the third dimension; and*
- *areas in each panel can be selected with infinite selection ratio using direct driving.*

The drawbacks of this technique are as given below :

- *Requires LCD with a fast response time, since the pixels (and not rows) are selected sequentially to minimize the number of external connections.*
- *A substantial reduction in the transmission, since a number of matrix panels are stacked one behind the other for the optical modulation.*

A special case of this technique for a bargraph display was also proposed by Sherr [36] using two displays stacked one behind the other.

2.5 NEED FOR NEW ADDRESSING TECHNIQUES

A number of addressing techniques for multiplexing matrix displays with an rms response were reviewed in the previous section. It is clear from this that the IAPT is suitable for displaying general patterns. This technique is used in almost all the matrix LCDs because of the following reasons :-

- *The selection ratio is maximum for displaying general patterns; and*

- The supply voltage requirement is low.

However the IAPT has the following limitations :-

- The supply voltage requirement increases with N ;
- The brightness uniformity of the pixels is poor ; and
- The addressing waveforms are complex, with four voltage levels in the row and column waveforms.

Considering the growing demand for LCDs in a wide range of applications, it would be useful if the addressing technique has the following characteristics:-

- Supply voltage requirement lower than that of IAPT ;
- Improved brightness uniformity of the pixels ; and
- Simple addressing waveforms.

This calls for the development of new addressing techniques for displaying general patterns on LCDs.

In the case of restricted pattern displays it is seen that the PRT reviewed in the previous section is well suited for displaying a single waveform in an oscilloscope display. However it has the following limitation for displaying multiple waveforms; as in a multichannel oscilloscope, logic state analyzer, etc. :

- The selection ratio or the horizontal resolution is reduced.

This again calls for the development of new addressing techniques with higher selection ratio, without any compromise in the horizontal resolution for displaying multiple waveforms.

With these factors in view, some new addressing techniques are proposed for use with LCD matrix displays in the next chapter. An analysis of these techniques, their merits, demerits and a comparison of their performance in relation to the conventional techniques are also presented in the same chapter.