

Electronic Display Devices

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Chapter 2

Liquid crystal displays (LCDs)

2.1 INTRODUCTION

2.1.1 What is a liquid crystal?

Most substances have a single melting point at which they change from a solid to a transparent liquid, but a group of materials, termed liquid crystals, first become an opaque and cloudy liquid at one temperature, and then turn to an ordinary transparent liquid at a somewhat higher temperature.* These phase changes in a liquid crystal substance with temperature can be shown externally as in Fig 2.1. The term liquid crystal has two uses: it is applied both to the liquid crystal phase, which as shown in the diagram is intermediate between the solid phase and the liquid phase, and also to any material that itself has a liquid crystal phase.

Within a certain temperature range, a liquid crystal substance behaves externally as a fluid, but at the same time has a crystalline structure which exhibits optical double refraction. This is the background to the term 'liquid crystal', and the liquid crystal phase was discovered by the Austrian biologist. F. Reinitzer in 1888, in benzoic acid and acetic acid esters of cholesterol [2].

The majority of liquid crystal substances are organic compounds which either have long thin rod-shaped molecules or flat molecules. In the liquid crystal phase, the molecular orientation takes up certain special organizations, as shown in Fig. 2.2, and based on differences in these spatial organizations liquid crystals are divided into three types: smectic, nematic, and cholesteric.[†]

In a smectic liquid crystal, the rod-shaped molecules are arranged in layers with the molecules parallel to each other and aligned typically perpendicular to the layers. The binding between the molecular layers is relatively weak, so they slip easily over each other, and for this reason a smectic liquid crystal behaves as a

*An ordinary liquid is optically isotropic, and is therefore termed an isotropic liquid. Liquid crystals, on the other hand, are termed anisotropic liquids.

[†]Specific substances showing these three variations of the liquid crystal phase are described in Section 2.4.

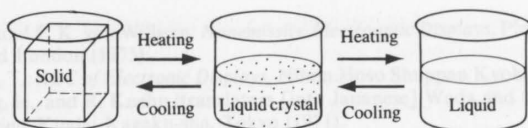
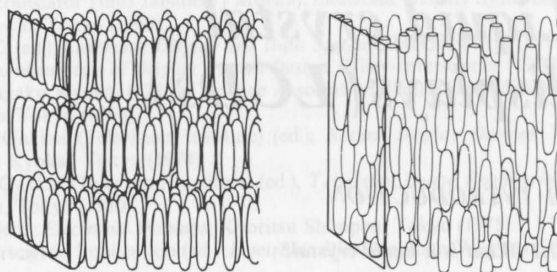
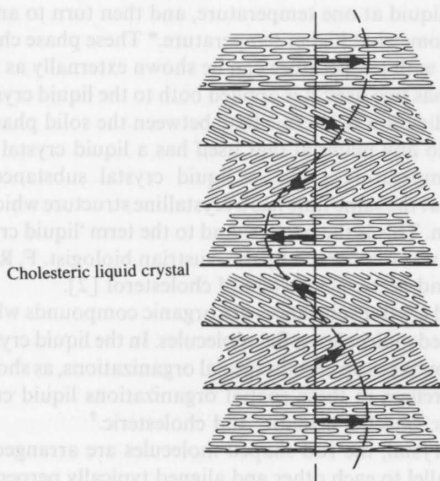


Figure 2.1 Phase changes with temperature in a liquid crystal substance [1]



Smectic liquid crystal

Nematic liquid crystal



Cholesteric liquid crystal

Figure 2.2 Molecular orientations in three types of liquid crystal [3]

two-dimensional fluid. Compared with an ordinary liquid, however, the viscosity is very high.

In a nematic liquid crystal, the rod-shaped molecules are also aligned parallel

to each other, but the individual molecules move relatively easily in the direction along their axis, so that there is no layering structure. The nematic substance is therefore very fluid, with low viscosity

A cholesteric liquid crystal has a layered structure like a smectic liquid crystal, but the axis of the molecules is in the plane of each layer, with a parallel orientation similar to that of a nematic liquid crystal. The axis of alignment of molecules in neighbouring layers slightly deviate one from another, and therefore overall the liquid crystal has a helical structure. The optical characteristics of a cholesteric liquid crystal, which include optical rotatory power, selective light reflection, and circular dichroism, are due to this helical structure.

2.1.2 Liquid crystals and displays

As will be seen from the preceding section, the structural organization of molecules in a liquid crystal is not rigid as in a crystalline structure. The molecules can therefore be easily reoriented as a result of an external stimulus such as an electric field, a magnetic field, temperature or mechanical strain, and thus the optical behaviour of the liquid crystal can be changed. It is precisely this flexibility in the molecule orientation in a liquid crystal that is the basis for the applications of liquid crystals in display devices, optoelectronic devices, sensors, and so forth.

In particular, in a liquid crystal display the molecules are in a particular initial orientation; this is changed to a different orientation by the effect of a voltage or heat, and the change in optical characteristics such as the double refraction, optical rotatory power, dichroism, light scattering, or optical rotatory dispersion in the liquid crystal cell, which occurs with the change in molecular orientation, is converted to a visible change. In other words a liquid crystal display utilizes the modulation of light by the liquid crystal cell, and is thus a passive (non-emitting) display. Generally the abbreviation LCD is used for a liquid crystal displays.

2.1.3 Characteristics of liquid crystal displays

The most important characteristics of LCDs, compared with other displays, are their unparalleled low power consumption and low voltage operation. They are therefore extremely suitable for use with LSI drive circuits, and are extremely valuable in practice. We now list these advantages individually:

1. Low power consumption (a few several tens of $\mu\text{W}/\text{cm}^2$) means that long-term battery drive is possible; energy saving.
2. Low drive voltage (10 V or less) enables direct IC drive, and drive circuits are both compact and simplified.
3. The device is thin and can be used for large displays (tens of square centimetres) and small displays (a few square millimetres), and so is particularly suitable for portable devices.

4. Because it is a passive display device, the display is clear even in a brightly lit position.
5. Making a colour display is easy, so the display functions can be enlarged and varied.
6. The display can be used for projection, so a large display (several square metres) is possible.

Set against these are the following disadvantages:

1. Since the display is a non-emitting type, it is not clear in a dark place.
2. The display contrast often depends on the viewing angle, which is therefore restricted.
3. The response depends on the ambient temperature, so low temperature operation is inadequate (approximately -20°C).

2.2 PHYSICAL CHARACTERISTICS OF LIQUID CRYSTALS

2.2.1 Anisotropy of physical characteristics

There are various principal types of liquid crystal (see Fig. 2.2), but all of these share the fact that molecules are aligned with their long axes parallel. It is for this reason that various physical characteristics such as refractive index n , dielectric constant ϵ , magnetic susceptibility η , conductivity σ , and viscosity of the liquid crystal substance have different values in the direction parallel to the molecular axis ($\parallel$) and orthogonal to the molecular axis ($\perp$), or in other words anisotropy ($n_{\parallel} \neq n_{\perp}$, $\epsilon_{\parallel} \neq \epsilon_{\perp}$, $\chi_{\parallel} \neq \chi_{\perp}$, $\sigma_{\parallel} \neq \sigma_{\perp}$, $\eta_{\parallel} \neq \eta_{\perp}$).

It is the combination of this anisotropy in physical characteristics in the liquid crystal and the ease of reorienting the molecular axes by applying a voltage or heat that opens up the possibility of applications for liquid crystals, in particular for displays.

In considering the anisotropy of the liquid crystal physical characteristics, it is very important to discover to what extent the liquid crystal molecules are properly aligned with each other. The degree of orderliness of liquid crystal molecular orientations may be represented by the molecular alignment order parameter S defined by the following expression [4]:

$$S = \frac{1}{2} \langle 3 \cos^2 \theta - 1 \rangle \quad (2.1)$$

Here a unit vector in the predominant molecule axis orientation when the liquid crystal is considered as a whole is termed the director $\mathbf{n}$, the angle of deviation of the molecular axis orientation $\mathbf{a}$ for individual liquid crystal molecules from $\mathbf{n}$ is φ (Fig. 2.3), and the symbols $\langle \rangle$ represent averaging over the whole space.

When the molecular axis orientation is unordered, as in an isotropic liquid, then $S = 0$, whereas when all the molecules are perfectly parallel aligned, as in an

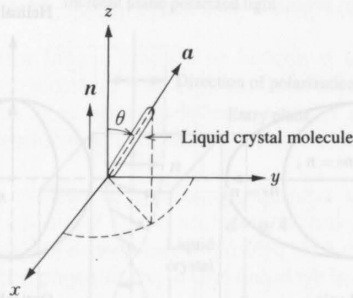


Figure 2.3 Spatial orientation of the liquid crystal director $\mathbf{n}$ and the molecular alignment direction $\mathbf{a}$ [1]

ideal liquid crystal, $S = 1$. In a typical nematic liquid crystal, S is in the range 0.3 to 0.8, depending on temperature.

2.2.2 Refractive index anisotropy and optical characteristics

1. Anisotropy of refractive index

A liquid crystal has an anisotropy of refractive index similar to that of an optical uniaxial crystal and exhibits double refraction. A uniaxial crystal has two different principal refractive indices n_o and n_e . These are the refractive indices of ordinary rays in which the axis of oscillation of the electrical vector is orthogonal to the optical axis of the crystal and extraordinary ray for which it is parallel.

In nematic and smectic liquid crystals the direction of the liquid crystal director $\mathbf{n}$ corresponds to the optical axis of a uniaxial crystal, and therefore the refractive indices are $n_{\perp}$ and $n_{\parallel}$ for rays whose oscillation is respectively orthogonal and parallel to the director $\mathbf{n}$ i.e.

$$\begin{aligned} n_o &= n_{\perp} \\ n_e &= n_{\parallel} \end{aligned} \quad (2.2)$$

Thus the refractive index anisotropy Δn is given by

$$\Delta n = n_e - n_o = n_{\parallel} - n_{\perp} \quad (2.3)$$

Thus the refractive index of these liquid crystals in three-dimensional space is realized, as shown in Fig. 2.4(a), as a spherical surface with respect to n_o and an ellipsoidal surface with respect to n_e . n_o is never greater than n_e and the two coincide only on the direction of the director $\mathbf{n}$. Therefore always $n_{\parallel} > n_{\perp}$ and Δn is positive. For this reason nematic and smectic liquid crystals are said to be optically positive.

For cholesteric liquid crystals the helical axis orthogonal to the director $\mathbf{n}$ corresponds to the optical axis, so the principal refractive indices n_o and n_e are

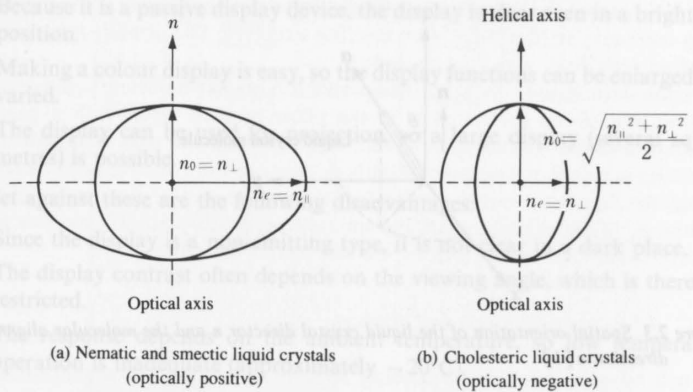


Figure 2.4 Refractive index anisotropy of a uniaxial liquid crystal [1]

given by [5]

$$\begin{aligned} n_0 &= [\tfrac{1}{2}(n_{\parallel}^2 + n_{\perp}^2)]^{1/2} \\ n_e &= n_{\perp} \end{aligned} \quad (2.4)$$

Since in a cholesteric liquid crystal the relation $n_{\parallel} > n_{\perp}$ holds, $\Delta n (= n_e - n_0) < 0$ holds. Therefore a cholesteric liquid crystal is termed optically negative. The distribution over space of the magnitude of the refractive indices of ordinary ray and extraordinary ray is shown in Fig. 2.4(b).

(2) Optical characteristics

Because of the anisotropy of refractive index, liquid crystals exhibit the following useful characteristics, which form the basis of liquid crystal displays:

1. Deflection of the direction of travel of light to the direction of the director $\mathbf{n}$ (molecular long axis)
2. A change in the polarization state (linearly polarized light, elliptically polarized light, circularly polarized light) or the direction of polarization
3. Reflection or transmission of incident polarized light according to whether the optical rotation is to right or left

The direction of travel of light incident on a liquid crystal in the direction of the director $\mathbf{n}$ is due to the fact that within the liquid crystal $n_{\parallel} < n_{\perp}$ holds, and the speeds of light $v_{\parallel}$ and $v_{\perp}$ are inversely proportional to the refractive indices $n_{\perp}$ and $n_{\parallel}$ so that $v_{\parallel}$ in the $\mathbf{n}$ direction is higher than $v_{\perp}$ in the orthogonal direction.

Next, considering a liquid crystal in which the director $\mathbf{n}$ is uniformly aligned with the x axis, we consider the case where linearly polarized light with its axis of oscillation at an angle θ to the x axis impinging in the direction of the z axis. When

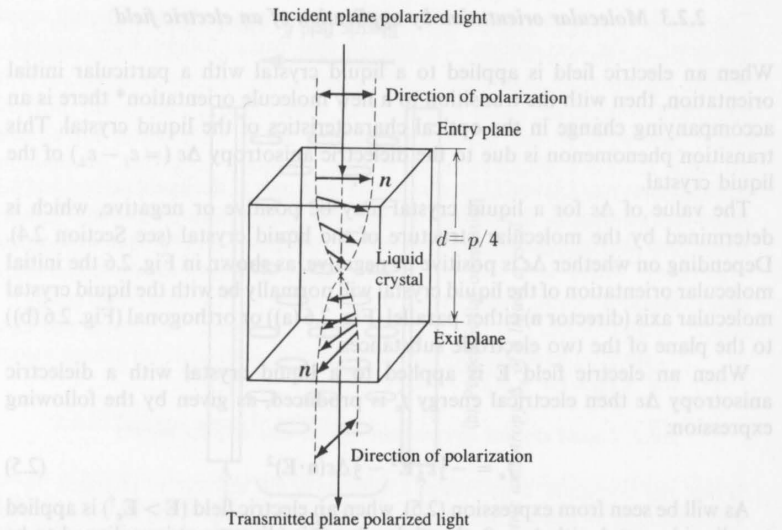


Figure 2.5 Rotation of the plane of polarization of incident light by a liquid crystal with twisted orientation [1]

$\theta = 0$ or $\pi/2$, the polarization of the linearly polarized light is not affected at all, but in other cases, for example when $\theta = \pi/4$, as the incident linearly polarized light proceeds along the z direction, the polarization changes in order from linear, to elliptical, to circular, to elliptical, to linear polarization, and at the same time the direction of the linear polarization is changed. What happens when linearly polarized light is incident on a liquid crystal with a twisted director $\mathbf{n}$ will be seen by considering Fig. 2.5. When the pitch p of the liquid crystal twist is sufficiently greater than the wavelength λ of the incident light, then light that is incident with its direction of oscillation parallel to $\mathbf{n}$ at the entry surface rotates together with the twist of $\mathbf{n}$, and emerges at the opposite side with its direction of oscillation still parallel to $\mathbf{n}$. Light that is incident with its direction of oscillation orthogonal to $\mathbf{n}$ emerges with its oscillation still orthogonal to $\mathbf{n}$ at the plane of emergence, but light incident with any other direction of oscillation will emerge with its polarization either elliptical, circular, or linear according to the phase difference $(n_{\parallel} - n_{\perp})\omega d/c$ from the incident surface to the surface of emergence, where ω is the angular frequency of the light, c is the speed of light, and d is the thickness of the liquid crystal layer.

If the pitch p of the twist is of the same order of magnitude as the wavelength λ of the light, as in an ordinary cholesteric liquid crystal, the component of incident polarized light in the same direction as the optical rotation direction of the liquid crystal is reflected and the rotation component in the opposite direction only is transmitted. This phenomenon is termed selective optical scattering.

2.2.3 Molecular orientation by application of an electric field

When an electric field is applied to a liquid crystal with a particular initial orientation, then with the transition to a new molecule orientation* there is an accompanying change in the optical characteristics of the liquid crystal. This transition phenomenon is due to the dielectric anisotropy $\Delta\epsilon (= \epsilon_{\parallel} - \epsilon_{\perp})$ of the liquid crystal.

The value of $\Delta\epsilon$ for a liquid crystal may be positive or negative, which is determined by the molecular structure of the liquid crystal (see Section 2.4). Depending on whether $\Delta\epsilon$ is positive or negative, as shown in Fig. 2.6 the initial molecular orientation of the liquid crystal will normally be with the liquid crystal molecular axis (director $\mathbf{n}$) either parallel (Fig. 2.6 (a)) or orthogonal (Fig. 2.6 (b)) to the plane of the two electrode substances.

When an electric field $\mathbf{E}$ is applied to a liquid crystal with a dielectric anisotropy $\Delta\epsilon$ then electrical energy f_e is produced, as given by the following expression:

$$f_e = -\frac{1}{2}\epsilon_{\perp}E^2 - \frac{1}{2}\Delta\epsilon(\mathbf{n} \cdot \mathbf{E})^2 \quad (2.5)$$

As will be seen from expression (2.5), when an electric field ($E > E_c^{\dagger}$) is applied to a liquid crystal with $\Delta\epsilon > 0$, the molecular axis (director $\mathbf{n}$) is realigned to be parallel with the direction of the electric field $\mathbf{E}$, whereas in the case of a liquid crystal with $\Delta\epsilon < 0$, $\mathbf{n}$ is reoriented to be orthogonal to $\mathbf{E}$. The reason for this is that in the reoriented state, the electrical energy f_e of the liquid crystal reaches a minimum.

However, the total free energy F of the liquid crystal when the molecule orientation in the initial state has undergone a deformation by the application of the electric field is the volume integral of the sum of the electrical energy f_e as given by expression (2.5) and the elastic energy f_d :[‡]

$$F = \int (f_e + f_d) d\Gamma \quad (2.6)$$

The electric field threshold value E_c at which the transition from the initial molecule orientation of the liquid crystal begins can be determined from a computation of the value at which the total free energy F given by expression (2.6), under appropriate boundary conditions, is a minimum [6]:

$$E_c = \frac{\pi}{d} \left(\frac{k_{11}}{|\Delta\epsilon|} \right)^{1/2} \quad (2.7)$$

*Termed the Freédricksz transition.

[†]The threshold electric field value where the transition from the original molecule orientation to the new molecule orientation begins.

[‡]A liquid crystal is an elastic body, and shows three types of basic strain under an external force: splay, twist, and bend. The elastic coefficients showing the relationship between these strains and the external force are called respectively k_{11} , k_{22} , and k_{33} , and the elastic free energy f_d of a liquid crystal under a certain deformation is given by the following [7]:

$$f_d = \frac{1}{2}k_{11}(\text{div } \mathbf{n})^2 + \frac{1}{2}k_{22}(\mathbf{n} \cdot \text{rot } \mathbf{n} + t_0)^2 + \frac{1}{2}k_{33}(\mathbf{n} \cdot \text{rot } \mathbf{n})^2$$

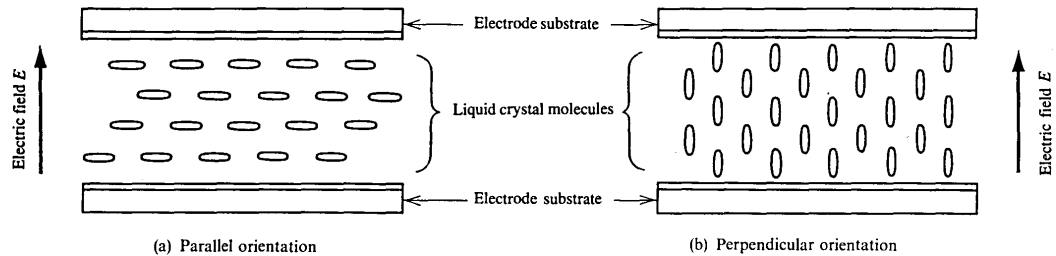


Figure 2.6 Relationship between the sign of the dielectric anisotropy Δ_ϵ of a liquid crystal and the initial molecule orientation

The threshold voltage V_{th} for the various electrooptic effects of liquid crystal described in the next section, 2.3, may be obtained as follows from expression (2.7):

$$V_{th} = \pi \left(\frac{k_{ii}}{|\Delta\epsilon|} \right)^{1/2} \quad (2.8)$$

In expressions (2.7) and (2.8), d is the cell thickness of the liquid crystal and k_{ii} is the elastic coefficient. When the initial molecule orientation is parallel, $k_{ii} = k_{11}$, when it is the orthogonal orientation $k_{ii} = k_{33}$, and in the case of a twisted orientation which is a deformation of the parallel orientation $k_{ii} = k_{11} + (k_{33} - 2k_{22})/4$.

2.3 LIQUID CRYSTAL DISPLAY MODES

2.3.1 Liquid crystal electrooptic effects and display modes

When the molecule orientation within a liquid crystal is changed by the application of an electric field, the optical characteristics of the liquid crystal cell change; this phenomenon of an electrically induced optical modulation is termed an electrooptic effect of the liquid crystal.

Of the many electrooptic effects of liquid crystals, the most important from the point of view of application to liquid crystal displays are shown in Table 2.1. Historically, the phase change (PC) effect [8] was discovered first in 1968 by J. Wysoki *et al.*, and then in the same year the dynamic scattering (DS) effect [9] and the guest–host (GH) effect [10] were announced by G. Heilmeyer *et al.* Then in 1971 the twisted nematic (TN) effect [11] was announced by M. Schadt *et al.* and the electrically controlled birefringence (ECB) effect [12, 13] was announced at almost the same time by groups represented by M. Schiekel and M. Hareng.

Table 2.1 Classification of electrooptic effects of liquid crystals

Liquid crystal electrooptic effect
Current effects
Dynamic scattering effect (DS)
Electric field effects
Twisted nematic effect (TN)
Guest–host effect (GH)
Electrically controlled birefringence (ECB)
Phase change effect (PC)
Thermal effects
Smectic effect
Cholesteric effect

Of the electrooptic effects in Table 2.1, the twisted nematic, guest–host, electrically controlled birefringence, and phase change effects are caused by the effect of a dielectric torque due to the anisotropy of the dielectric constant, and are therefore called electric field effects. On the other hand, the dynamic scattering effect is due to the effect of the conductivity torque, due to anisotropy of the conductivity, becoming dominant, and is therefore called a current effect. In addition to these types of effects, there are also electrooptic effects termed thermal effects which require the application of heat in addition to an electric field. These thermal effects can be classified into smectic and cholesteric effects by differences in the liquid crystal materials used.

Typical display principles based on the electrooptic effects of liquid crystal described above are shown in Table 2.2, with various characteristics. These display modes are described in more detail in the following sections.

2.3.2 Twisted nematic (TN) type

A layer of nematic liquid crystal (N_p , liquid crystal) for which $\Delta\epsilon$ is greater than 0, of thickness approximately $10\text{ }\mu\text{m}$, is sandwiched between transparent electrode substrates, and a cell is constructed so that the molecular axis of the liquid crystal rotates continuously through 90° between the two substrates (see Section 2.5.3); this is a twisted nematic (TN) cell. Since the pitch of this twist is sufficiently large compared with the wavelength of visible light, the direction of polarization of linearly polarized light incident vertically on one of the electrode substrates is rotated through 90° by the twist of the liquid crystal molecules as it passes through the cell (see Section 2.2.2).^{*} Therefore this twisted nematic cell shuts off light when placed between two parallel polarizers and transmits light when placed between two orthogonal polarizers.

Next, when a voltage is applied to a twisted nematic cell, from a certain threshold voltage V_{th} the molecule axes begin to align themselves with the electric field. When the voltage applied is about twice V_{th} the majority of molecules have their axes realigned in the direction of the electric field, and the 90° optical rotatory power is eliminated. In this case, in completely the opposite fashion to the case when a voltage is not applied, between parallel polarizers light will be transmitted and between orthogonal polarizers light will be shut off.

In Fig. 2.7 the principle of a twisted nematic display is illustrated: it is based on the electrooptic effect when a twisted nematic cell is placed between orthogonal polarizers. In this case light is transmitted when the voltage is not applied and light is shut off when the voltage is applied. Between parallel polarizers, however, the relationship of transmitting or shutting off light is reversed. Currently the most widely used LCD devices are based on this twisted nematic principle and provide a black display on a white background or a white display on a black background.

^{*}The direction of polarization of incident light coincides with the direction of the liquid crystal director at the electrode substrate on the entry side.

Table 2.2 Typical liquid crystal display modes

DISPLAY TYPE	PRINCIPLE	LIQUID CRYSTAL MATERIAL		NUMBER OF POLARIZERS	THRESHOLD VOLTAGE (V)	OPERATING VOLTAGE (V)	POWER CONSUMPTION ($\mu\text{W}/\text{cm}^2$)	LIQUID CRYSTAL MOLECULAR ORIENTATION CHANGE	
		TYPE	SIGN OF $\Delta\epsilon$					INITIAL ORIENTATION $\rightarrow$ VOLTAGE (HEAT) APPLIED ORIENTATION	OPTICAL PHENOMENON
Twisted nematic (TN)	Optical rotation	N	Positive	2	1-3	2-5	a few to several tens	Twisted $\rightarrow$ perpendicular	Brightness change
Guest-host (GH)	Dichroism	N with dye additive	Positive Negative	1	1-6	4-10		Homogeneous $\rightarrow$ perpendicular Homeotropic $\rightarrow$ parallel	Colour intensity change
		Ch with dye additive	Positive Negative	Not necessary	2-8	3-15		Focal conic $\rightarrow$ homeotropic Homeotropic $\rightarrow$ focal conic	

Electrically controlled birefringence (ECB)	Optical interference	N	Negative Positive Positive (negative)	2	1-5	1-10		Homeotropic → parallel Homogeneous → perpendicular Hybrid → perpendicular (parallel)	Colour change
Phase change (PC)	Light scattering	Ch	Positive	Not necessary	3-10	5-20		Focal conic → perpendicular	Turbid to transparent transformation
Dynamic scattering (DS)	Light scattering	N with electrically conductive additive	Negative	Not necessary	5-10	7-30	few hundred	Homeotropic → random Homogeneous → random	Transparent to turbid transformation
Thermal effects	Light scattering	S Ch	Positive Positive	Not necessary	10-20	15-40	a few to several tens	Homeotropic → focal conic	Transparent to turbid transformation

Note: N = nematic liquid crystal; S = smectic liquid crystal; Ch = cholesteric liquid crystal.

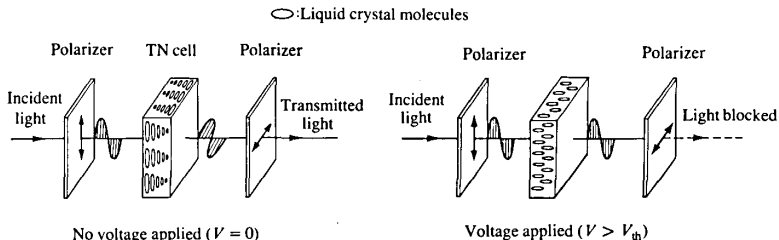


Figure 2.7 Principle of twisted nematic (TN) display [1]

The threshold voltage V_{th} of this type of liquid crystal display is given, following expression (2.8), by the following expression, which includes the dielectric anisotropy $\Delta\epsilon$ of the N_p liquid crystal and the elastic moduli k_{11} , k_{22} , and k_{33} .

$$V_{th} = \pi \sqrt{\frac{k_{11} + (k_{33} - 2k_{22})/4}{\epsilon_0 \Delta\epsilon}} \quad (2.9)$$

From expression (2.9) it will be seen that V_{th} can be varied by choosing appropriate dielectric anisotropy and elastic moduli. Generally for twisted nematic LCDs the value of V_{th} is between 1 and 3 V.

Super-twisted nematic LCDs, called STN or SBE type LCDs, have a twisting angle larger than about 180° , and are based on the optical interference effect.

2.3.3 Guest–host (GH) type

When a dichroic dye* (the guest) that has anisotropy in the absorption of visible light in the molecular long axis and short axis directions is in solution in a liquid crystal (the host) with a certain molecule orientation, the molecules of the dichroic dye align themselves parallel to the liquid crystal molecules. Thus, if the molecule orientation of the host liquid crystal is changed by the application of an electric field, the molecule orientation of the guest dye will change in the same way, and thus the amount of visible light absorbed by the dichroic dye can be controlled electrically. A display using this type of electrooptic effect is termed a guest–host type. This type can be subclassified into a number of types depending on the combination of molecular orientation type, liquid crystal material, and dye used, and also cell construction.

Figure 2.8 shows the principle of a guest–host display based on the electrooptic effect of a guest–host cell of homogeneous orientation (see Section 2.5.3) in which a p -type dichroic dye dissolved in an N_p liquid crystal is sandwiched between

*A dye that has a transition moment for light absorption in the molecular long axis direction is termed a p (positive) type dichroic dye and one with a transition moment in the molecular short axis direction is termed an n (negative) type dichroic dye.

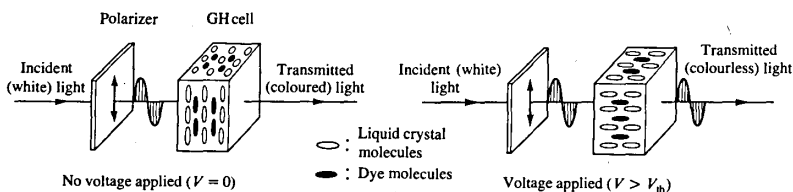


Figure 2.8 Principle of guest–host (GH) display [10]

transparent electrode substrates. When a voltage is not applied, the direction of oscillation of white linearly polarized light from the polarizer coincides with the light absorption axis of the dye, so that light is absorbed and the transmitted light is coloured. When, on the other hand, a voltage is applied, the direction of oscillation of the linearly polarized light is orthogonal to the absorption axis of the dye, and in principle there is no light absorption and the transmitted light is not coloured.

In Fig. 2.8, if a nematic liquid crystal (N_n liquid crystal) for which $\Delta\epsilon < 0$ is used in place of the N_p liquid crystal and an n -type dichroic dye is used in place of the p -type dichroic dye, then when a voltage is not applied the transmitted light is not coloured, whereas when the voltage is applied the transmitted light is coloured. On the other hand, if a smectic liquid crystal or cholesteric liquid crystal is used in place of the nematic liquid crystal as the host, or if a two-layer construction for the nematic liquid crystal cell is used, then the polarizer can be dispensed with.

The threshold voltage V_{th} for a colour LCD using the guest–host principle is shown in expressions (2.13) and (2.12) below in the cases respectively that the host liquid crystal is an N_p liquid crystal or an N_n liquid crystal. When a cholesteric liquid crystal is used, then V_{th} is given by a transform of expression (2.8) as follows [14]:

$$V_{th} = \frac{d\pi^2}{p_0} \sqrt{\frac{k_{22}}{\epsilon_0 |\Delta\epsilon|}} \quad (2.10)$$

where p_0 is the helical pitch length of the cholesteric liquid crystal, k_{22} is the twist modulus of elasticity, $\Delta\epsilon$ is the dielectric anisotropy, and d is the cell thickness.

2.3.4 Electrically controlled birefringence (ECB) type

This display technique is based on controlling the birefringence of a liquid crystal cell by the application of an electric field, and is very important as a multicolour liquid crystal display technique. There are a number of types of this display depending on the molecule orientation of the liquid crystal cell used; these include the DAP type, homogeneous type, and HAN type.

A cell with homeotropic (DAP) orientation is made with an N_n liquid crystal sandwiched between transparent electrode substrates (see Section 2.5.3). This

DAP cell is placed between crossed polarizers, and light impinges perpendicularly on it as in the construction shown in Fig. 2.9. When an electric field is not applied, the incident linearly polarized light does not undergo birefringence when passing through the cell, so that it cannot pass through the second polarizer. On the other hand, when a voltage is applied, the molecular axis of the liquid crystal is inclined through an angle ϕ , so that the linearly polarized incident light becomes elliptically polarized by the effect of birefringence (see Section 2.2.2) and a portion of the light is able to pass through the second polarizer (the detector), and the light passing through is coloured.

The intensity I of the light passing through the detector is given by [12]

$$I = I_0 \sin^2 2\theta \sin^2 \frac{\pi d \Delta n(V)}{\lambda} \quad (2.11)$$

where I_0 is the intensity of incident light, θ is the angle between the direction of polarization of the incident light and the direction of oscillation of the ordinary light within the cell, d and $\Delta n(V)$ are respectively the cell thickness and the double refractive index at the applied voltage V , and $d\Delta n$ is the optical phase difference, and λ is the wavelength of the incident light. As will be seen from expression (2.11), the intensity of light transmitted depends on the magnitude of the voltage applied, and also on the wavelength of the incident light. Therefore, when the incident light is white light the light passing through the detector will be coloured by the interference effect variously, according to the magnitude of the applied voltage.

The threshold voltage V_{th} for a multicolour LCD using the DAP technique is found, following expression (2.8), as follows:

$$V_{th} = \pi \sqrt{\frac{k_{33}}{\epsilon_0(-\Delta\epsilon)}} \quad (2.12)$$

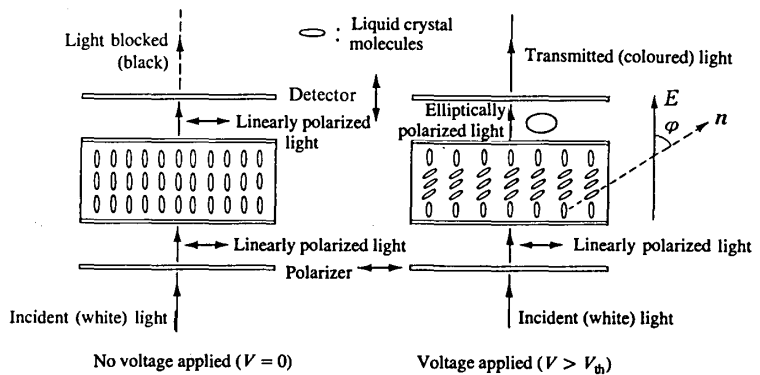


Figure 2.9 Principle of ECB (DAP) display [1]

Here $\Delta\epsilon$ is the dielectric anisotropy of the N_n liquid crystal and k_{33} is the bending elasticity coefficient.

In the case of the homogeneous technique [15], the liquid crystal cell of Fig. 2.9 uses an N_p liquid crystal of homogeneous orientation. Therefore, with this method the value of V_{th} is obtained as follows, by replacing the k_{33} in expression (2.12) by the splay elasticity coefficient k_{11} :

$$V_{th} = \pi \sqrt{\frac{k_{11}}{\epsilon_0 \cdot \Delta\epsilon}} \quad (2.13)$$

There is no difference in principle between the homogeneous type and the DAP type, but compared with the DAP type, the order of the colour change is in the reverse direction when a voltage is applied, and additionally the threshold voltage value can be substantially reduced.

The HAN (hybrid aligned nematic) technique [16] is characterized by using a hybrid orientation cell (see Section 2.5.3) in which the molecules of the liquid crystal are aligned perpendicularly to one substrate, but parallel to the other substrate. Therefore for a colour LCD based on this technique, both N_p and N_n types of liquid crystals can be used, and since there is no clear threshold voltage, they have the advantage that a very low drive voltage can be used.

2.3.5 Phase change (PC) type

The phase change display technique is based on a change in molecular orientation from the helical cholesteric phase to the homeotropic nematic phase, and vice versa. For this technique cholesteric liquid crystals with long helical pitch and $\Delta\epsilon > 0$ or $\Delta\epsilon < 0$ (Ch_n or Ch_n liquid crystals) can be used.

Figure 2.10 illustrates the principles of the phase change type display using a Ch_p liquid crystal focal conic orientation cell (see Section 2.5.3). When a voltage is not applied, the incident light passing through the cell is optically dispersed in a focal conic orientation, and the cell appears cloudy. When, however, a voltage of at least a certain threshold value V_{th} is applied, the helical structure of the cholesteric phase disintegrates, and a nematic phase of homeotropic orientation appears. Therefore when a voltage is applied the cell becomes transparent.

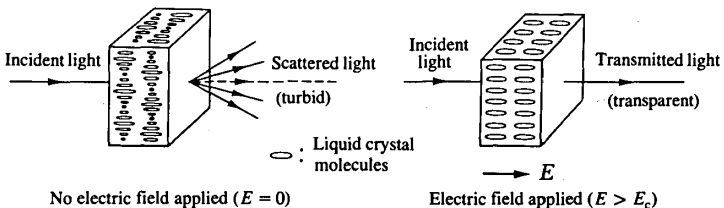


Figure 2.10 Principle of phase change (PC) display [1]

It is also possible to use a Ch_p liquid crystal planar orientation cell (see Section 2.5.3), but in any case the value of V_{th} is given by expression (2.10).

2.3.6 Dynamic scattering (DS) type

A homogeneous orientation liquid crystal cell (see Section 2.5.3) is made by sandwiching a layer of thickness approximately $10\text{ }\mu\text{m}$ of an N_n liquid crystal, which has a resistivity not more than approximately $5 \times 10^{10}\text{ }\Omega\cdot\text{cm}$ and in which is dissolved an electrically conductive substance, between transparent electrode substrates. When a voltage V , which is either d.c. or is a.c. of not more than a certain frequency f_c^* is applied to the cell, as shown in Fig. 2.11, when V is not more than a certain voltage V_w ((a) in the figure), then incident light is transmitted straight through the cell which is thus transparent. When V exceeds V_w ((b) in the figure) then eddy currents occur in the liquid crystal, and a pattern of fine lines termed Williams domains is observed.

Next, when the applied voltage increases so that $V \gg V_w$ ((c) in the figure), the eddy currents give way to turbulence, and the orientation of the liquid crystal molecules then becomes random. Thereby a very large number of very small birefringent domains are produced, with orientations different from surrounding domains, and light is strongly scattered at the boundaries of these domains in the so-called dynamic scattering phenomenon. This electrooptic effect is also found in homeotropic orientations, and is the operating principle of dynamic scattering LCD.

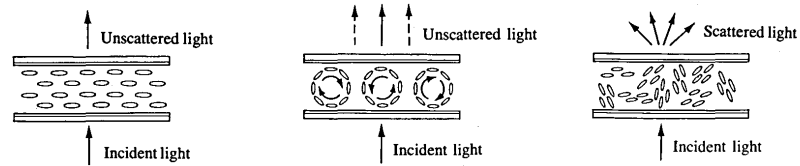
2.3.7 Thermal effect types

When the temperature of a liquid crystal is changed, phenomena whereby the optical characteristics change are called thermooptic effects, and are due to the change in molecular orientation in the liquid crystal when it is heated or cooled. We discuss an example with smectic liquid crystals.

A smectic A (S_A) liquid crystal is sandwiched between transparent electrodes that have been subject to vertical orientation processing (see Section 2.5.3) to form a liquid crystal cell. If this cell is heated until the isotropic liquid phase is reached, and is then cooled, then if the cooling is sudden the whole cell will become cloudy, whereas if the cooling is gradual the whole cell will become transparent. This cloudy state and transparent state correspond respectively to the focal conic orientation and homeotropic orientation of the S_A liquid crystal. This thermooptic effect of an S_A liquid crystal cell can be used as the principle for a large-capacity display in which a laser beam is used to write the image

* f_c is termed the cut-off frequency for the dynamic scattering effect, and is proportional to the conductivity of a liquid crystal.

[†] V_w indicates the threshold voltage (of the order of 10 V) for Williams domains.



(a) Homogeneous molecule orientation $V < V_w$ (b) Williams domains $V > V_w$ (c) Dynamic scattering (DS) $V > V_w$

Figure 2.11 Dynamic scattering (DS) phenomenon and changes in liquid crystal molecule orientation [17]

thermally, and can also be used as a principle for a memory type display in which one of the transparent electrodes of the cell is treated as the heating electrode and the other as the signal electrode, and an electric field is applied at the same time as heating (see Section 2.6.5).

2.3.8 Response times of LCDs

For an LCD based on one of the display modes using nematic liquid crystals—twisted nematic, guest–host, electrically controlled birefringence, and dynamic scattering types—the rise time response speed τ_r and decay time response speed τ_d are given as follows [18]:

$$\tau_r = \eta_i d^2 (\epsilon_0 \cdot |\Delta\epsilon| V^2 - k_{ii} \pi^2)^{-1} \quad (2.14)$$

$$\tau_d = \frac{\eta_i d^2}{\pi^2 k_{ii}} \quad (2.15)$$

where η_i and k_{ii} are the appropriate viscosity parameter and elasticity parameter, $\Delta\epsilon$ is the dielectric anisotropy, d is the cell thickness, and V is the applied voltage.

For the phase change and other types of display mode using cholesteric liquid crystals, the values of τ_r and τ_d for an LCD are given as follows in the case that the

Table 2.3 Response times and parameters η_i and k_{ii} for different display modes [1]

DISPLAY TYPE	$\Delta\epsilon$	RESPONSE TIMES (ms)		PARAMETERS	
		τ_r	τ_d	k_{ii}	η_i
TN type	+ ve	20–80	60–150	$k_{11} + \frac{(k_{33} - 2k_{22})}{4}$	$\sim \eta_1$
GH type	+ ve	70–150	90–200	$\sim k_{11}$	$\sim \eta_1$
	– ve	100–200	150–300	$\sim k_{33}$	$\sim \eta$
ECB type	+ ve	10–30	30–100	k_{11}	η_1
	– ve	20–50	50–200	k_{33}	η_2
PC type	+ ve	10–40	60–200	k_{22}	η_2
DS type	– ve	10–50	30–150	k	η

helical pitch p_0 is shorter than the thickness of the cell d [18]:

$$\tau_r = \eta_i \left[\varepsilon_0 \cdot |\Delta \varepsilon| \left(\frac{V}{d} \right)^2 - \frac{\kappa_{ii} \pi^2}{p_0^2} \right]^{-1} \quad (2.16)$$

$$\tau_d = \frac{\eta_i p_0^2}{\pi^2 \kappa_{ii}} \quad (2.17)$$

The viscosity parameter η_i and elasticity parameter κ_{ii} in expressions (2.14) to (2.17) vary depending on the display type. Table 2.3 shows the η_i and κ_{ii} for individual display types, together with approximations to the response times τ_r and τ_d .

2.4 LIQUID CRYSTAL MATERIALS

2.4.1 Practical liquid crystal materials

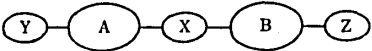
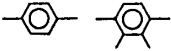
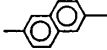
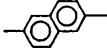
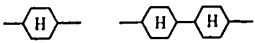
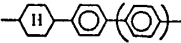
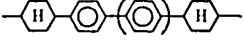
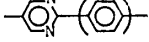
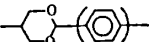
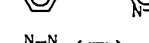
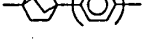
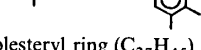
The most important requirement at the beginning of the development of liquid crystal materials for display purposes was for a liquid crystal material that could be used at room temperature. Thereafter, as liquid crystal displays entered the tactical phase, the range of applications widened and a variety of new liquid crystal display modes were developed; in addition to the liquid crystal temperature criterion the following items were the principal criteria in making practical liquid crystal materials:

1. Exhibit the liquid crystal phase from low temperatures to high temperatures, giving a wide working temperature range.
2. Good chemical and photochemical stability, and long life.
3. Low viscosity and high response speed.
4. Large dielectric anisotropy; applicable to low-voltage operation.
5. The magnitude of the double refraction index is appropriate for increased display contrast.
6. The elasticity coefficients are balanced to allow multiplex driving.
7. The degree of ordering of molecule orientation is high, allowing increased display contrast.

These objectives are common to all the modes of liquid crystal display devices, but naturally depending on the display technique there will be variations in the type of liquid crystal used, whether the dielectric anisotropy is positive or negative, the magnitude of the double refraction index, and the necessity or not for additives (refer to Table 2.2).

Thus various characteristics, functions and qualities are required of practical liquid crystal materials, and in order to answer these requirements a wide variety of liquid crystal compounds have been synthesized to date (refer to Sections 2.4.3

Table 2.4 General molecular structures for liquid crystal compounds

		
CENTRAL GROUP X	TERMINAL GROUPS Y, Z	RING GROUPS A, B
$-\text{CH}=\text{N}-$	R—	
$-\text{N}=\text{N}(\text{O})-$	RO—	
$-\text{N}=\text{N}-$	RCO—	
$-\text{CO}-\text{O}-$	ROCO—	
$-\text{CO}-\text{S}-$	RCO—O—	
$-\text{CH}=\text{N}(\text{O})-$	ROCO—O—	
$-\text{CH}=\text{C}(\text{CN})-$	$-\text{COOH}$	
$-\text{CH}=\text{C}(\text{Cl})-$	$-\text{CN}$	
$-(\text{CH}_2)_n-$	$-\text{NO}_2$	
$-\text{CH}=\text{CH}-$	$-\text{Cl}$	
$-\text{C}\equiv\text{C}-$	$-\text{Br}$	
—	$-\text{I}$	
$-\text{CO}-\text{CH}_2-$	$-\text{F}$	
$-\text{CH}_2-\text{O}-$	R*—	
$-\text{O}-(\text{CH}_2)_2-\text{O}-$	R*O—	
$-\text{CH}=\text{CH}-\text{CO}-\text{O}-$		

Cholesteryl ring ($\text{C}_{27}\text{H}_{45}$)R: alkyl group, : benzene ring, : trans-cyclohexane ring, R*: optically active alkyl group

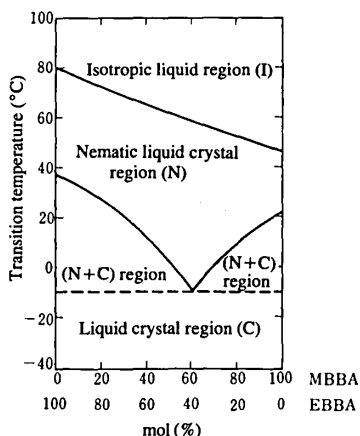


Figure 2.12 Phase diagram for MBBA-EBBA composite liquid crystal material [19]

to 2.4.5) [1]. The general molecular structures of these basic liquid crystal compounds are summarized in Table 2.4. By trying various combinations of the central group, terminal groups, and ring groups, practical liquid crystal compounds can be designed and synthesized.

2.4.2 Composite liquid crystal materials

In practice it is difficult to find a single liquid crystal compound that has all the characteristics required for a display. Therefore, for application purposes, rather than a single liquid crystal material, a composite blend of materials is used to provide the characteristics and qualities required for a particular display mode. Depending on the type of display, electrically conductive materials, dichroic dyes, chiral materials, and so forth may also be added.

This technique of using a blended composition is necessary not only to obtain the sum of the characteristics of individual liquid crystal materials but also in order to produce characteristics that cannot be obtained by the use of a single liquid crystal material. A good example of this is the increase in the temperature range for the liquid crystal phase that can be obtained from a composite material, which is described next.

Figure 2.12 shows the phase diagram for a composite liquid crystal material formed from MBBA* and EBBA† liquid crystals. This composite material has a eutectic point at a mol composition where MBBA/EBBA = 60/40, and for this composition the nematic liquid crystal range extends from -10 to $+60^{\circ}\text{C}$.

* *p*-Methoxybenzylidene-*p*-butylaniline (see Section 2.4.3).

† *p*-Ethoxybenzylidene-*p*-butylaniline (see Section 2.4.3).

2.4.3 Nematic liquid crystal materials

(1) Schiff bases

MBBA (*p*-methoxybenzylidene-*p*'-butylaniline) was the first room temperature liquid crystal material; this is a typical example of the Schiff base compounds shown in Table 2.5. Liquid crystal substances of the same family such as MBBA and EBBA (*p*-ethoxybenzylidene-*p*'-butylaniline) have negative dielectric anisotropy ($\Delta\epsilon$ approximately -0.5), large birefringence (Δn approximately 0.25), and medium viscosity (η approximately 35 cSt, and are used for dynamic scattering and electrically controlled birefringence type LCD devices. For a twisted nematic LCD, a liquid crystal material with $\Delta\epsilon > 0$ is required, and the first liquid crystal compositions used for this were Schiff base compounds with cyano terminal groups. Although their viscosity is high, their dielectric anisotropy is large ($\Delta\epsilon = 15$ – 20), so they are appropriate for low-voltage operation. However, all of the Schiff base compounds are unstable in the presence of moisture, which is an obstacle to practical implementation.

(2) Benzoate esters

These liquid crystal compounds have benzene rings joined by an ester group, and as shown in Table 2.6 encompass a large number of materials with widely varying characteristics. Since they also have good chemical stability, they are used in a range of LCD techniques as components of composite liquid crystal materials. Compounds with both terminal groups being alkyl groups or alkoxy groups show changes in the sign of the dielectric anisotropy with a small difference in these terminal groups, and the absolute value of $\Delta\epsilon$ is less than 1. When both terminal groups are alkyl groups then the viscosity is low (η approximately 20 cSt), but in other cases the viscosity is always high (η at least 45 cSt).

The temperature dependency of physical characteristics of these liquid crystal compounds is low, so various N_p liquid crystals and mixtures thereof are useful

Table 2.5 Schiff base liquid crystal compounds

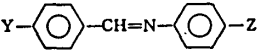
<div style="text-align: center;">  </div>				
TRANSITION TEMPERATURE (°C)				
Y	Z	C-N	N-I	$\Delta\epsilon$
CH ₃ O—	C ₄ H ₉ —	22	47	—
C ₂ H ₅ O—	C ₄ H ₉ —	37	80	—
C ₃ H ₇ —	—CN	65	77	+
C ₄ H ₉ O—	—CN	65	108	+

Table 2.6 Benzoate ester liquid crystal compounds

$\text{Y}-\text{C}_6\text{H}_4-\text{CO}-\text{O}-\text{C}_6\text{H}_4-\text{Z}$				
TRANSITION TEMPERATURE (°C)				
Y	Z	C-N	N-I	$\Delta\epsilon$
CH ₃ O—	C ₆ H ₁₃ O—	55	77	—
CH ₃ O—	C ₅ H ₁₁ —	29	42	+
C ₅ H ₁₁ —	C ₅ H ₁₁ —	(33)	(12)	+
C ₆ H ₁₃ —	—CN	45	47	+
C ₅ H ₁₁ — 	—COO—C ₅ H ₁₁ —	78	179	+
C ₄ H ₉ —	—  —CN	108	225	+

Note: Figures in () are monotropic transitions.

for multiplex driving. Liquid crystal compounds with a terminal cyano group have $\Delta\epsilon$ positive and very large ($\Delta\epsilon > 20$), and are used as liquid crystal material for low-voltage drive. On the other hand, liquid crystal compounds having three or more benzene rings show high viscosity, and the N-I transition temperature is very high. They are therefore useful as components in liquid crystal mixtures for increasing the liquid crystal temperature range.

(3) Biphenyl and terphenyl compounds

Cyanobiphenyl liquid crystal compounds that have an alkyl or alkoxy terminal group are colourless and have extremely good chemical stability and photochemical stability. Furthermore, they have balanced characteristics for dielectric anisotropy ($\Delta\epsilon$ approximately 13), viscosity (η approximately 35 cSt), and birefringence (Δn approximately 0.2), and are representative N_p liquid crystal materials for use in a wide range of LCD devices (Table 2.7).

The practical use of cyanobiphenyl liquid crystal is often in combination with cyanoterphenyl liquid crystals as an additive in order to expand the nematic liquid crystal temperature range, increase the birefringence, and improve the multiplex drive characteristics.

(4) Cyclohexylcarboxylic ester compounds

The cyclohexylcarboxylic ester liquid crystal compounds shown in Table 2.8 have a fairly low viscosity and a relatively wide range of liquid crystal temperatures. N_n liquid crystal compounds having a terminal group Z which is an alkyl group or alkoxy group have a very low viscosity ($\eta < 20$ cSt), so that they

Table 2.7 Biphenyl and terphenyl liquid crystal compounds

$\text{Y} - \text{C}_6\text{H}_4 - \text{C}_6\text{H}_4 - \text{Z}$				
TRANSITION TEMPERATURE (°C)				
Y	Z	C-N	N-I	$\Delta\epsilon$
$\text{C}_5\text{H}_{11}-$	$-\text{CN}$	24	35	+
$\text{C}_6\text{H}_{13}-$	$-\text{CN}$	14	29	+
$\text{C}_5\text{H}_{11}\text{O}-$	$-\text{CN}$	48	68	+
$\text{C}_7\text{H}_{15}\text{O}-$	$-\text{CN}$	54	74	+
$\text{C}_6\text{H}_5-\text{C}_6\text{H}_4-$	$-\text{CN}$	182	257	+

Table 2.8 Cyclohexylcarboxylic ester liquid crystal compounds

$\text{Y} - \text{C}_6\text{H}_{11} - \text{CO} - \text{O} - \text{C}_6\text{H}_4 - \text{Z}$				
TRANSITION TEMPERATURE (°C)				
Y	Z	C-N	N-I	$\Delta\epsilon$
C_4H_9-	$\text{C}_6\text{H}_{13}-$	26	31	—
$\text{C}_5\text{H}_{11}-$	$\text{C}_3\text{H}_{11}-$	37	47	—
C_3H_7-	$\text{C}_5\text{H}_5\text{O}-$	47	78	—
C_4H_9-	$\text{C}_5\text{H}_{11}\text{O}-$	29	66	—
C_3H_7-	$-\text{CN}$	54	69	+
C_2H_5-	$-\text{C}_6\text{H}_4-\text{CN}$	85	229	+

are used as a constituent of low viscosity liquid crystal mixtures. They can also be used as constituents to improve the multiplex drive characteristics. The N_p liquid crystal compounds having a cyano terminal group have low birefringence (Δn approximately 0.12) and low dielectric anisotropy ($\Delta\epsilon$ approximately 8).

On the other hand, liquid crystal compounds with a terminal group that is a cyanophenyl group have a wide liquid crystal temperature range and low viscosity, and so are often used to extend the temperature range of an N_p liquid crystal material.

(5) Phenylcyclohexane and biphenylcyclohexane compounds

These liquid crystal compounds shown in Table 2.9 combine the stability shown by biphenyl liquid crystals with the low viscosity shown by cyclohexylcarboxylic

Table 2.9 Phenylcyclohexane and biphenylcyclohexane liquid crystal compounds

Y	Z	TRANSITION TEMPERATURE (°C)		
		C-N	N-I	$\Delta\epsilon$
C ₃ H ₇ —	—CN	43	45	+
C ₃ H ₁₁ —	—CN	30	55	+
C ₃ H ₁₁ —	—CN	95	219	+
C ₃ H ₇ —	C ₂ H ₅ O—	(41)	(37)	—
C ₃ H ₇ —	C ₂ H ₅ —	(0)	(- 70)	+

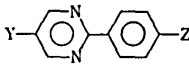
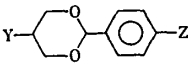
Note: figures in () are monotropic transitions.

ester liquid crystal and are therefore extremely useful as materials for liquid crystal displays. The series of cyanophenylcyclohexane liquid crystal compounds have reasonable dielectric anisotropy and extremely low viscosity, and so are useful to liquid crystal displays requiring high response speed. Cyanobiphenylcyclohexane liquid crystals have a high N-I transition temperature, and are therefore used to extend the liquid crystal temperature range. Phenylcyclohexane liquid crystal compounds which have both end groups that are alkyl or alkoxy groups are monotropic transition liquid crystals, but have extremely low viscosity, and are therefore very important as viscosity-lowering additives for composite liquid crystal materials.

(6) Pyrimidine and dioxane compounds

Typical examples of these liquid crystal compounds are shown in Table 2.10. The cyanophenylpyrimidine liquid crystal compounds having a cyano group at one end have a high dielectric anisotropy ($\Delta\epsilon$ approximately 25) and a wide liquid crystal temperature range, so are used as liquid crystal materials for wide temperature range and low-voltage operation. On the other hand, phenylpyrimidine liquid crystal compounds which have both terminal groups that are alkyl groups or alkoxy groups have a very low elastic coefficient ratio (k_{33}/k_{11}), and therefore are used as principal components of liquid crystal materials for multiplex drive. Cyanophenyldioxane liquid crystal compounds generally have a monotropic transition and high viscosity (η approximately 70 cSt), but show high dielectric anisotropy ($\Delta\epsilon$ approximately 18) and relatively small elastic coefficient ratio (k_{33}/k_{11}); again they are useful as liquid crystal materials for multiplex drive.

Table 2.10 Pyrimidine and dioxane liquid crystal compounds

<div>  </div>				
Y	Z	TRANSITION TEMPERATURE (°C)		
		C-N	N-I	$\Delta\epsilon$
$C_7H_{15}-$	$-\text{CN}$	44	50	+
C_4H_9- 	$-\text{CN}$	94	246	+
$C_6H_{13}-$	$C_6H_{13}O-$	31	60	+
$C_6H_{13}-$	$C_9H_{19}O-$	37	61	+
<div>  </div>				
C_4H_9-	$-\text{CN}$	(42)	(35)	+
$C_6H_{13}-$	$-\text{CN}$	(47)	(40)	+
$C_6H_{13}-$ 	$-\text{CN}$	84	151	+

Note: figures in () are monotropic transitions.

2.4.4 Cholesteric liquid crystal materials

Cholesteric liquid crystal compounds are divided, as seen from Table 2.11, into two main groups: cholesterol derivative compounds, which have a cholesteryl group ($C_{27}H_{45}-$), and chiral nematic liquid crystals, which are ordinary nematic liquid crystal compounds with a terminal group replaced by an optically active branching alkyl or alkoxy group such as 2-methylbutyl (2MB) or 2-methylbutoxy (2MBO) groups. These cholesteric liquid crystals have characteristic optical properties such as optical rotatory power, selective light reflection, and circular dichroism, and these optical properties are very sensitive to changes in temperature and applied voltages. Such phenomena have therefore been used to develop various applications such as colour displays.

The following two purposes are important applications which make direct use of the helical structure of cholesteric liquid crystals:

1. By adding a very small amount of cholesteric liquid crystal to a nematic liquid crystal in a twisted nematic LCD, reverse twist molecular orientation defects are prevented.

Table 2.11 Typical cholesteric liquid crystal compounds

MOLECULAR STRUCTURE	TRANSITION TEMPERATURE (°C)	
	C-Ch	Ch-I
Cholesterol acetate $\text{CH}_3\text{COO}-(\text{C}_{27}\text{H}_{45})$	114	(90)
Cholesterol palmitate $\text{C}_{15}\text{H}_{31}\text{COO}-(\text{C}_{27}\text{H}_{45})$	77	146
Cholesterol benzoate $-\text{COO}-(\text{C}_{27}\text{H}_{45})$	150	182
$\text{C}_2\text{H}_5\text{O}-\text{C}_6\text{H}_4-\text{CHN}-\text{C}_6\text{H}_4-2\text{MB}$	25	58
$2\text{MB}-\text{C}_6\text{H}_4-\text{CO}-\text{O}-\text{C}_6\text{H}_4-\text{OC}_6\text{H}_{13}$	24	30
$3\text{MBO}-\text{C}_6\text{H}_4-\text{C}_6\text{H}_4-\text{CN}$	53	(9)

Note: figures in () are monotropic transitions; 2MB = 2-methylbutyl group; 3MBO = 3-methylbutoxy group.

- By adding a small quantity of cholesteric liquid crystal to a normal nematic liquid crystal, a liquid crystal material with long helical pitch can be fabricated for use in a phase change type LCD.

2.4.5 Smectic liquid crystal materials

Smectic liquid crystals are classified on the basis of very fine differences in molecular orientation structure as A, B, C, ..., H variants. Of these, smectic A liquid crystals and smectic C liquid crystals are relatively susceptible to external fields; the former is particularly used as an LCD based on a thermo-optic effect. Table 2.12 shows examples of smectic A (S_A) liquid crystal compounds.

Some kinds of chiral smectic liquid crystals, typically chiral smectic C materials, show a spontaneous polarization phenomenon, so they are useful as ferroelectric LCDs based on the interactive force between spontaneous polarization and electric field.

2.5 STRUCTURE AND MANUFACTURE OF LIQUID CRYSTAL DISPLAYS

2.5.1 LCD structure

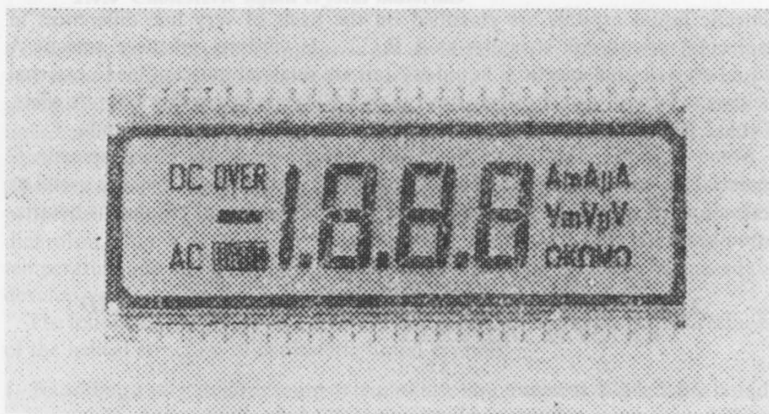
Liquid crystal displays have a wide range of dimensions depending on the applications; these range from an area of a few square millimetres or a few square

Table 2.12 *Smectic liquid crystal compounds*

MOLECULAR STRUCTURE	TRANSITION TEMPERATURE (°C)		
	C-S _A	S _A -N	S _A [N]-I
C_8H_{17} —  —  —CN	21	33	(40)
$C_{10}H_{21}$ —  —  —CN	44	—	50
$C_9H_{19}O$ —  —  —CN	64	77	(80)
$C_{11}H_{23}O$ —  —  —CN	71	—	87

centimetres for wrist watches or pocket calculators to hundreds of square centimetres for vehicle instrumentation panels or computer terminals. Figure 2.13 is an external view of a typical reflection type twisted nematic LCD for use as a numeric display in an industrial meter or other measuring instruments. The external dimensions of this LCD are overall length 71 mm, overall width 31 mm, and overall thickness 3 mm, with an effective display area of $16 \times 63 \text{ mm}^2$.

Figure 2.14 shows the sectional construction of this LCD. A liquid crystal layer of thickness about $10 \mu\text{m}$ is sandwiched between two glass substrates which have transparent electrodes and molecular orientation layers (see Section 2.5.3), and

**Figure 2.13** *Exterior view of reflective TN type LCD*

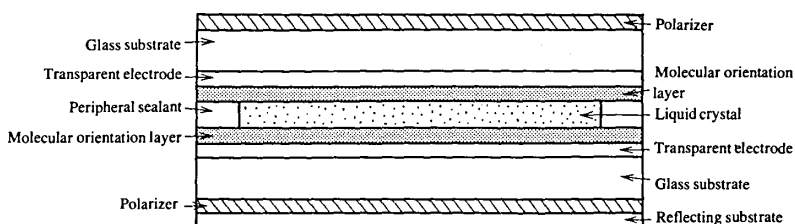


Figure 2.14 Sectional structure of reflective TN type LCD

the cell construction is completed by an air-tight sealing material around the periphery of the liquid crystal layer. Then a polarizer film is adhered to both sides of the cell, and a thin reflective layer is added to one side.

In displays using techniques that make polarizers unnecessary, or in LCDs for use with transmitted light, the polarizers or reflective layers can be omitted from the construction of Fig. 2.14.

2.5.2 Material and parts for LCDs

The principal constituents of a LCD are the liquid crystal material, the molecular aligning material, the transparent electrodes, the sealant, the spacer, the polarizers, the reflecting layer, and then various filters and connectors.

Liquid crystal materials have already been discussed in detail in Section 2.4 above. Molecular alignment materials needed to form the molecular alignment layers are described in the next section 2.5.3.

The transparent electrode substrates are usually glass plates with a film of indium oxide or tin oxide. Generally their optical transmission coefficient is at least 90 per cent and the surface resistivity is some tens or hundreds of ohms. The formation of the display pattern electrodes is mostly done by photoetching the whole transparent electrode substrate.

Thermosetting epoxy adhesive is widely used as a sealant, and in cases where reliability is particularly important glass soldering, for example, can be used. For spacing purposes, in order to control the cell gap, glass or plastic in granule or fibre form can be used.

For the polarizers that are necessary for the majority of LCD devices, a stretched polyvinyl alcohol film dyed with iodine or a dichroic dye is used, in sheet form and sandwiched between protecting layers of cellulose acetate. The optical transmission coefficient is between 40 and 50 per cent and the degree of polarization is approximately 90 per cent. The reflecting layer is often made integral with the polarizer.

The filters used are ultraviolet cut-off filters and coloured filters for colour displays. The electrical connections between the liquid crystal display and the drive circuits are provided by pin connectors, elastic connectors, or flexible connectors.

Table 2.13 *Classification of liquid crystal molecular orientations*

MOLECULAR ORIENTATION TYPE	HOMEOTROPIC	HOMOGENEOUS	TILT	HYBRID	TWIST	PLANAR	FOCAL CONIC
Orientation (diagrammatic)							
Substrate arrangement processing combination	$\perp/\perp$	$\parallel/\parallel$	$\perp/\perp$	$\perp/\parallel$	$\parallel/\parallel$	$\parallel/\parallel$	$\perp/\perp$

Note: $\rightleftharpoons$ liquid crystal molecules, $\rightarrow$ director orientation, $\hookrightarrow$ helical axis orientation

2.5.3 *Liquid crystal molecular orientations and molecular alignment techniques*

(1) Types of molecular orientation and their roles

A uniform and stable liquid crystal molecular orientation is essential for an LCD. This is because all LCD techniques depend on the liquid crystal having an initial molecular orientation which is changed to a new orientation under the effect of an external field such as an electric field or heat.

There is a wide range of liquid crystal molecular orientations, but seven typical examples are shown in Table 2.13, and we list them here:

1. Homeotropic: the liquid crystal molecules are arranged perpendicular to both substrates.
2. Homogeneous: the liquid crystal molecules are parallel to both substrates and aligned in one fixed direction.
3. Tilt: the liquid crystal molecules are tilted at a certain angle to both substrates, and are aligned in one fixed direction.
4. Hybrid: the liquid crystal molecules are perpendicular to one substrate, and are parallel to the other substrate, all in the same direction; the overall molecular orientation curves continuously through 90° between the two substrates.
5. Twist: the liquid crystal molecules are arranged parallel to both substrates, but the alignment orientations on the two substrates are 90° apart, so that overall the molecular orientation twists continuously through 90° between the substrates.
6. Planar: the liquid crystals are aligned such that the helical axis is perpendicular to both substrates.
7. Focal conic: the orientation is such that the liquid crystal molecule helical axis is parallel to both substrates.

(2) Techniques for molecular alignment

A cell with any of the molecular orientations described above may be formed by using a suitable combination of two substrates and the three-molecule alignment processing techniques described next (see Table 2.13):

1. Perpendicular processing: the substrate surface is processed so that the liquid crystal molecule long axis is aligned perpendicular to the substrate ($\perp$).
2. Parallel processing: the substrate surface is processed so that the liquid crystal molecule long axis is aligned parallel to the substrate ($\parallel$).
3. Inclined alignment processing: the substrate surface are processed so that the liquid crystal molecule long axis is inclined at a constant angle to the substrate surface (V, IV)

Table 2.14 shows actual techniques for carrying out these three types of alignment processing [1]. In direct methods of substrate processing, the substrate

Table 2.14 *Molecular alignment processing methods*

TYPE	PROCESS	ALIGNMENT MATERIAL	ORIENTATION TYPE
Direct processing of substrate surface	Coating	Chromium perfluorononanoate complex, organic silane DMOAP, lecithin	Perpendicular
		Chromium brassylate complex, organic silane MAP, polyvinyl alcohol, polyimide	Parallel
Indirect processing of substrate surface	Solution	CTAB ammonium salt, octadecyl malonic acid	Perpendicular
		Dicarboxylic acid, varsamide 125	
Substrate surface transformation	Rubbing	Parallel alignment material	Parallel
—	Oblique evaporation	Silicon monoxide SiO ₂ , metals Au, Pt	Tilted (small evaporation angle) Parallel (large evaporation angle)

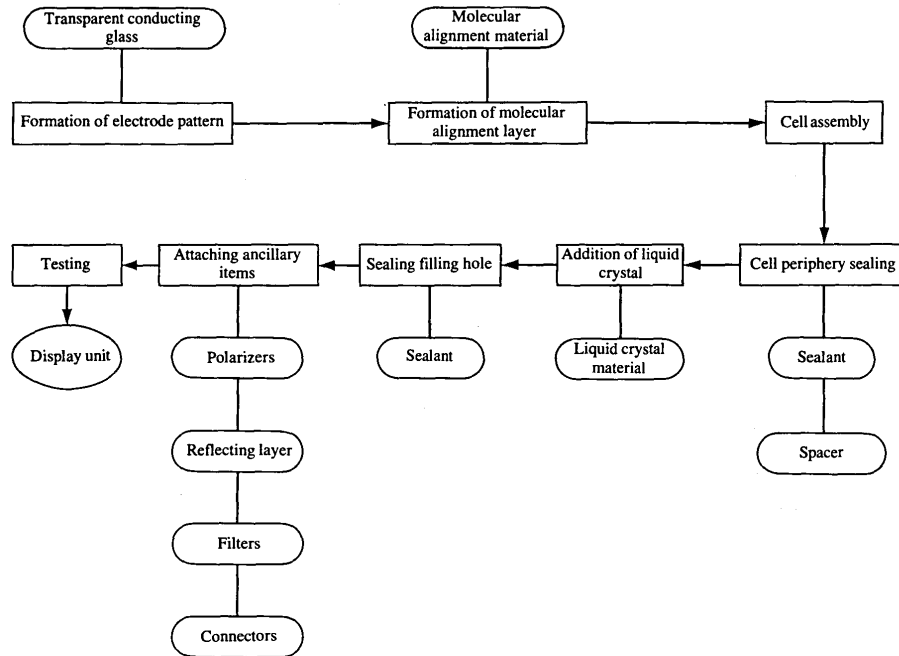


Figure 2.15 Stages in manufacture of an LCD

surface is coated with a solution of an aligning agent, the solvent is removed by heat drying or similar, and a thin film of the aligning agent is formed on the surface. In indirect methods of processing, the aligning agent is dissolved in the liquid crystal. When the liquid crystal is introduced into the cell the aligning agent is adsorbed onto the substrate surface from within the liquid crystal, thus forming the alignment layer.

One substrate surface transformation processing method consists of rubbing the surface of the substrate lightly in a single direction with a cotton cloth. Generally, after direct processing of the substrate surface with a parallel aligning agent, rubbing processing is carried out. This technique ensures that the parallel orientation of the liquid crystal molecules is definitely in a fixed direction. Another substrate surface transformation processing method consists of oblique evaporation of an aligning agent such as silicon monoxide on the substrate surface. When the angle of vapour evaporation θ^* is shallow (θ from 5° to 20°) inclined orientation is obtained, while when the angle of vapour deposition is deep (θ between 20° and 45°) parallel orientation is obtained.

2.5.4 LCD manufacture

Figure 2.15 shows an outline of the stages in manufacture of a LCD. Of these stages, that which affects most greatly the device characteristics and quality is the formation of the liquid crystal molecular alignment layer. As described in Sections 2.3 and 2.5.3, different molecular orientations and molecule aligning methods are needed for different display types, and the surface processing for a particular orientation is carried out on the patterned electrode substrate surface.

The cell gap between electrodes is normally set to be approximately $10\ \mu\text{m}$, and this cell gap can be controlled either by dispersing some spacer material between the electrodes during the assembly of the cell or by mixing a spacer material in with the sealant. The introduction of the liquid crystal material to the empty cell is done under reduced pressure in a bell jar, and either the filling aperture of the empty cell is immersed in the liquid crystal or the liquid crystal material is introduced by a dropping method. After the various ancillary parts are fitted, the liquid crystal display device will undergo external inspection, display operation testing, reliability testing, mechanical strength testing, and other checks before becoming a finished product.

2.6 DRIVE TECHNIQUES FOR LIQUID CRYSTAL DISPLAYS

2.6.1 Drive electrode structure

The electrode constructions used in liquid crystal displays are classified in Table 2.15, together with their principal applications. The most common

*Angle of the vapour deposition beam to the surface of the substrate.

Table 2.15 LCD electrode constructions and their principal applications

LCD electrode constructions	
Segmented electrodes	(numeric displays, analogue bar graph displays)
Fixed pattern electrodes	(symbol and pattern displays)
Matrix electrodes	(character, graphics, and video displays)

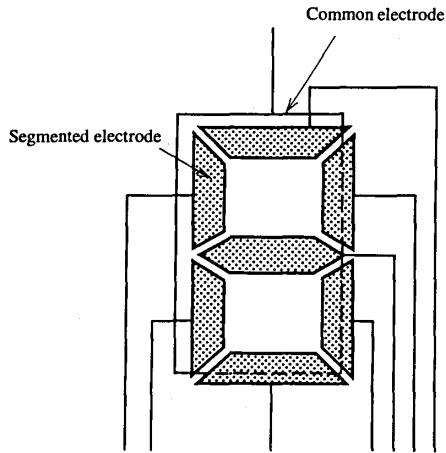


Figure 2.16 Seven-segment electrode construction

segmented electrode is the seven-segment pattern shown in Fig. 2.16, which has seven individual segment electrodes on the front substrate and a common electrode on the back substrate. A voltage is applied selectively to each of the segments so that any of the digits 0 to 9 can be displayed. For an analogue bar graph display a number of segment electrodes are arranged in a line. When a special pattern or symbol is to be displayed an electrode of the appropriate shape is used.

Next, Fig. 2.17 shows the matrix electrode construction which is used when the display is to be capable of an arbitrary pattern. One substrate has strip (scan) electrodes X_n and the other substrate strip (signal) electrodes Y_m , so by means of selectively applying a voltage to one scan electrode and one signal electrode, any intersection point (pixel) can be activated, and character displays, graphic displays, and video displays can be obtained.

The principal drive techniques actually used for liquid crystal displays using

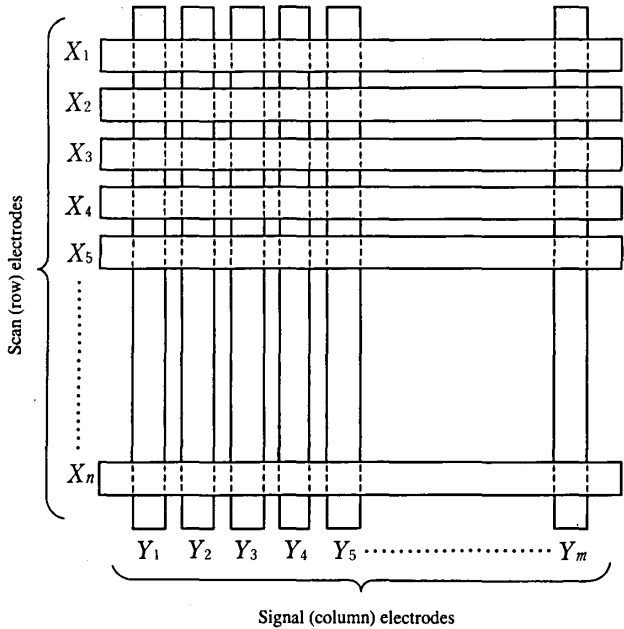


Figure 2.17 Matrix electrode construction

Table 2.16 Principal LCD drive techniques

LCD drive techniques
Static drive
Multiplex drive
Active matrix drive
Thermal addressing drive
Optical addressing drive

the above electrode constructions are listed in Table 2.16, and we then discuss these individually.

2.6.2 Static drive

In the static drive method each electrode segment to be displayed is driven separately and simultaneously. Therefore each segment requires an independent drive circuit element and a voltage is applied continuously to the display segment

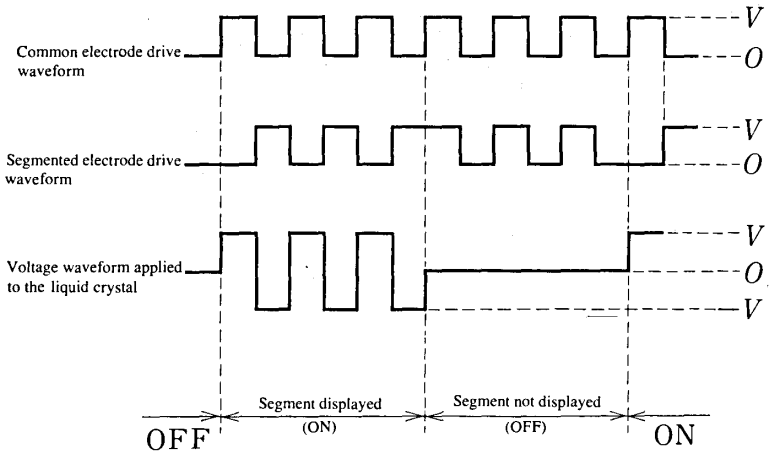


Figure 2.18 Static drive waveform examples

and the common electrode while the segment is to be displayed. Figure 2.18 shows the waveforms of a typical static drive. Both the segment electrode and the common electrode are supplied with a pulse wave form of the same polarity, and when the display is to be on these are put out of phase by 180° . The voltage applied to the liquid crystal is therefore actually an a.c. waveform, and the deterioration of the liquid crystal due to direct current operation is avoided.

Since in a static drive separate drive circuit elements are required for each

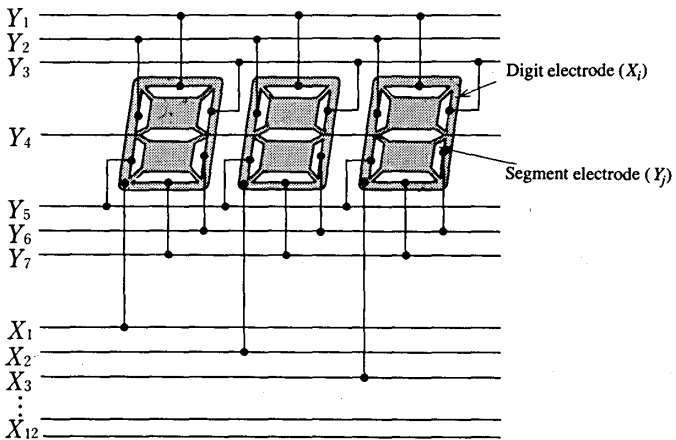


Figure 2.19 Combination of segment electrodes for multiplex drive

electrode segment, for a numeric display with a large number of digits the number of drive circuit elements and the number of lead connections is inconveniently large. The multiplex drive method described next alleviates this problem.

2.6.3 Multiplex drive

This technique is used for cases with a relatively large number of segments, such as multidigit numeric displays, and also for matrix displays; it is also referred to as time-division drive or dynamic drive.

Consider, for example, a twelve-digit seven-segment numeric display that is using a multiplex drive; as shown in Fig. 2.19, there will be twelve common

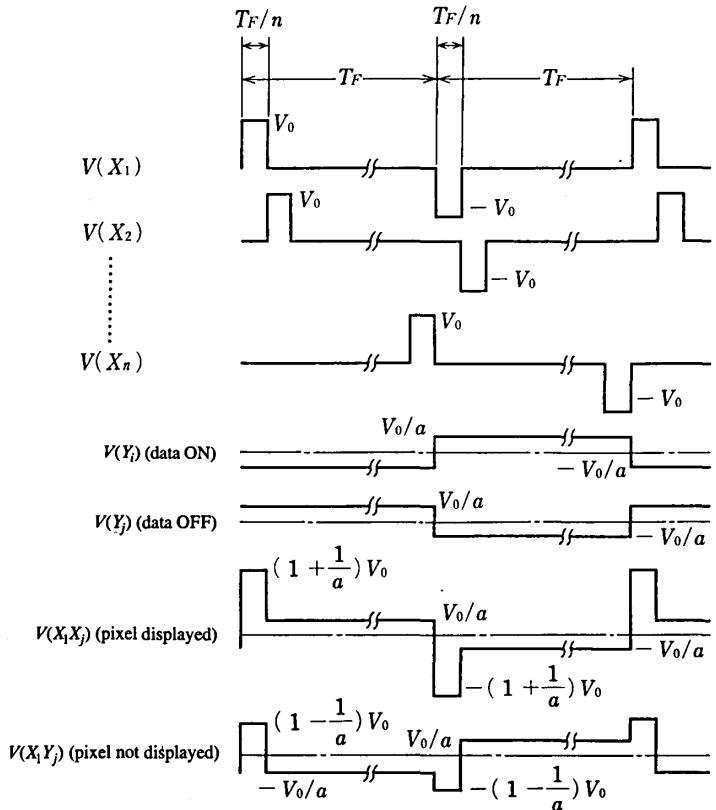


Figure 2.20 Drive waveforms using the voltage-averaging method (T_F : frame time)

electrodes, one for each digit, and all of the segment electrodes will be connected together in seven sets. Thus the drive operates by operating the twelve-digit electrodes $X_1, X_2, \dots, X_{12}$ in time sequence and selectively driving the displayed segment electrodes $Y_1, Y_2, \dots, Y_7$ for each digit in turn. Thus, in this example the number of necessary connections and drive elements is nineteen, which is very much less than if the static drive technique is used.

Since, however, the segment electrodes are connected in common, various partial voltages will be applied to segments other than those to be displayed, so that the display contrast will be reduced. This phenomenon is called crosstalk, and arises because the response of the liquid crystal to voltage is bipolar and because the electrooptic response (voltage to display contrast) characteristics are not steep. In order to avoid this crosstalk phenomenon the following technique, termed voltage averaging, is usually used with a liquid crystal multiplex drive.

In a multiplex drive using a voltage-averaging method by line sequential drive and the XY matrix electrode construction* shown in Fig. 2.17, the drive waveform is designed to satisfy the following conditions (Fig. 2.20):

1. In order to eliminate the crosstalk phenomenon, the effective voltages V_s and V_{us} applied to the liquid crystal of a group of pixels for which the display is on and a group of pixels for which the display is off are the same for the respective groups of pixels.
2. In order to increase the display contrast, V_s is set to be a maximum limit exceeding the operating threshold voltage of the liquid crystal.
3. V_{us} is set to be a size that does not exceed the threshold voltage.

As shown in Fig. 2.20, the scanning pulse for time-division driving and the signal pulse for data input are set to V_0 and V_0/a respectively, and if the number of scanning electrodes is n , then the effective voltage values V_s and V_{us} are given as follows:

$$V_s = \frac{V_0}{a} \sqrt{\frac{a^2 + 2a + n}{n}} \quad (2.18)$$

$$V_{us} = \frac{V_0}{a} \sqrt{\frac{a^2 - 2a + n}{n}} \quad (2.19)$$

The value a in expressions (2.18) and (2.19) is found from the condition that the display contrast should be maximum or, in other words, that the ratio α of V_s/V_{us} (the voltage operating margin) should be maximum, and thus $a = \sqrt{n}$. This means that in Fig. 2.20, when the scanning pulse has the value V_0 , if the signal pulse is set to a value of $V_0/\sqrt{n}$ the maximum display contrast will be obtained.

At this time the margin $\alpha_{\max}$ of the operating voltage is given by the

*The segmented electrode construction of the twelve-digit numeric display shown in Fig. 2.19 is exactly the same electrically as the matrix electrode construction of Fig. 2.17, with $n = 12$ and $m = 7$.

following expression:

$$\alpha_{\max} \left(\frac{V_s}{V_{us}} \right)_{\max} = \sqrt{\frac{\sqrt{n} + 1}{\sqrt{n} - 1}} \quad (2.20)$$

Expression (2.20) shows that as the number of scanning electrodes n is increased, it is necessary to have a liquid crystal that can produce adequate display contrast for a smaller voltage difference ($V_s - V_{us}$), and for a particular liquid crystal the display contrast will fall as n increases.

A current practical limit on the number of scanning electrodes appears to be about 200.

2.6.4 Active matrix drive

Using the multiplex drive technique described in the previous section, when a voltage averaging technique is used to prevent crosstalk the number of the scanning electrodes that will allow time-division driving is restricted, and therefore the technique cannot be applied to applications such as a video display where more than 200 scanning electrodes are required. The active matrix drive technique is applicable to large display capacity applications such as this.

In this technique, a switching element and if necessary a capacitor is added for the pixel corresponding to each matrix intersection point of the scanning electrodes and signal electrodes, in order to improve display characteristics such as contrast and response. The switching element and capacitor for each pixel have the roles of preventing crosstalk and storing the signal charge. In this way restrictions on the number of scanning electrodes are practically removed, and in principle a liquid crystal display by a static drive with nearly 100 per cent duty factor can be obtained.

As illustrated in Table 2.17, there are two main types of this drive, depending

Table 2.17 Classification of active matrix drive methods

Active matrix drive methods
Field effect transistor (FET) type
MOS transistor type
TFT transistor type
a-Si type
p-Si type
CdSe type
Te type
Non-linear two-terminal device type
Varistor type
MIM type
Diode type

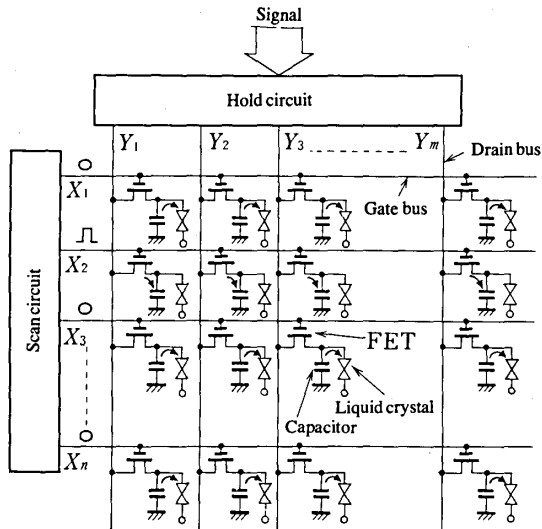


Figure 2.21 Operating principle of active matrix drive LCD

on whether a field effect transistor (FET) is used as the switching element or non-linear two-terminal element. Figure 2.21 shows the operating principle of an active matrix drive LCD using FETs. Using a line scan technique, the row electrodes (gate buses) $X_1, X_2, \dots, X_n$ are scanned sequentially, so that all of the FETs on one gate bus are turned on (conducting) simultaneously, and the signals for the current row are supplied from the hold circuit through the drain buses $Y_1, Y_2, \dots, Y_m$ through the conducting FETs to the capacitors. The liquid crystal elements are sustained in their current state by the charge on the capacitor until the next scan.

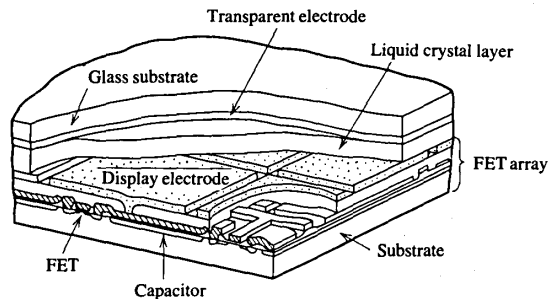


Figure 2.22 Construction of an active matrix drive LCD [20]

There are two types of FET drive: the MOS transistors type, which uses a silicon single-crystal substrate, and the thin-film transistor (TFT) type, which uses a thin film of α -Si, β -Si, CdSe, or Te formed on a transparent substrate of glass or quartz. The construction of an active matrix drive LCD using either type of FET is basically as shown in Fig. 2.22. For some of these drive techniques, the peripheral drive circuitry can be integrated on the same substrate as that for the FET array for the display, which simplifies the connection between the drive circuit and the display. Since the TFT type allows a transmissive display, a multicolour display or a full-colour display can easily be implemented.

Active matrix drive techniques using non-linear two-terminal elements as the switching elements are all designed with the objective of simplifying construction and reducing cost. The MIM type uses a three-layer construction for the switching array, consisting of metal-insulator-metal layers (M-I-M), typically Ta/Ta₂O₃/Cr. The varistor type uses a sintered ZnO varistor as the switch element and capacitor element.

2.6.5 Thermal and optical addressing

The thermal addressing drive method uses a thermo-optic effect (see Section 2.3.7) of a smectic or cholesteric liquid crystal. The liquid crystal may be heated either by an infrared laser beam or by an electrical resistive heater. In the former case a

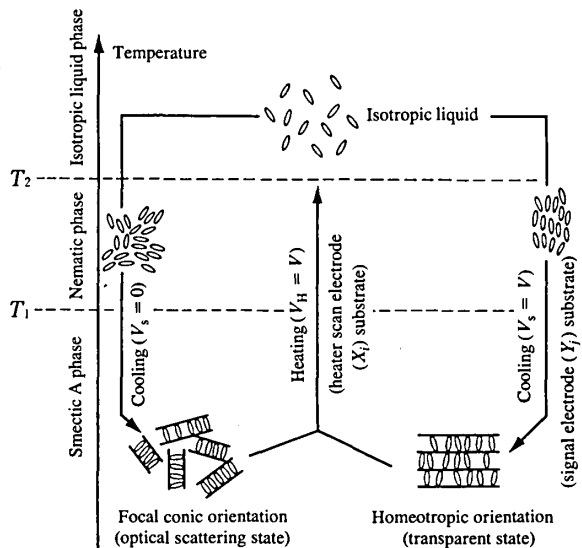


Figure 2.23 Principle of thermal addressing drive display [21]

liquid crystal cell is used which has an infrared absorbing layer and the display image is written directly by scanning with the laser beam. This laser beam technique is principally used for large projection displays (see Section 2.7.5) and is characterized by a large-display capacity, high resolution, and a memory function.

In the latter case, an XY matrix electrode construction is used, and the scanning electrodes (X) are the heater resistance electrodes. In the display principle illustrated in Fig. 2.23 a smectic A liquid crystal (S_A) is used which has a nematic phase in a high-temperature region. The S_A liquid crystal is progressively heated ($V_H = V$) by the heater scan electrode (X_i) to the isotropic (I) phase, and then as it cools through the N phase the presence or absence of a voltage signal ($V_s = V$ or $V_s = 0$) on the signal electrode (Y_j) determines whether the clear state or the cloudy state (scattering texture) is reached. These two states are strongly retained by the smectic A phase. Therefore this technique gives in principle no crosstalk, and no limit to the number of scanning electrodes. It can therefore be applied to large-capacity displays which cannot be implemented using the normal multiplex drive technique (see Section 2.7.2). The difficulty is, however, that a fast write speed is not possible.

The optical addressing drive method uses a layer of a photoconductive material such as CdSe on one substrate and a liquid crystal cell construction in which the other substrate is a whole surface electrode. The display image is projected on the liquid crystal cell as an optical image, and an electric field corresponding to the optical intensity of the image is applied to the liquid crystal layer. This technique is principally used for large-scale projection displays (see Section 2.7.5).

2.7 APPLICATIONS OF LIQUID CRYSTAL DISPLAYS

The first stage in the development of liquid crystal displays as practical devices came in 1973 with the implementation of the numeric display panel for watches and calculators. These applications exploited to the full the advantages of liquid crystal displays, which are incomparably low operating voltages and power consumption, together with compact, lightweight, and thin construction. Building on the success of these first implementations, the second stage of applications came in about 1977 when liquid crystal displays began to appear in a wide range of applications such as measuring instruments, domestic electrical and audio equipment, office equipment, game machines, and vehicle instruments. These became established by 1980 or 1981. In this second stage the application broadened from digital displays to analogue displays, small character displays, and colour displays.

In order to reach the third and fourth stages of applications the development of

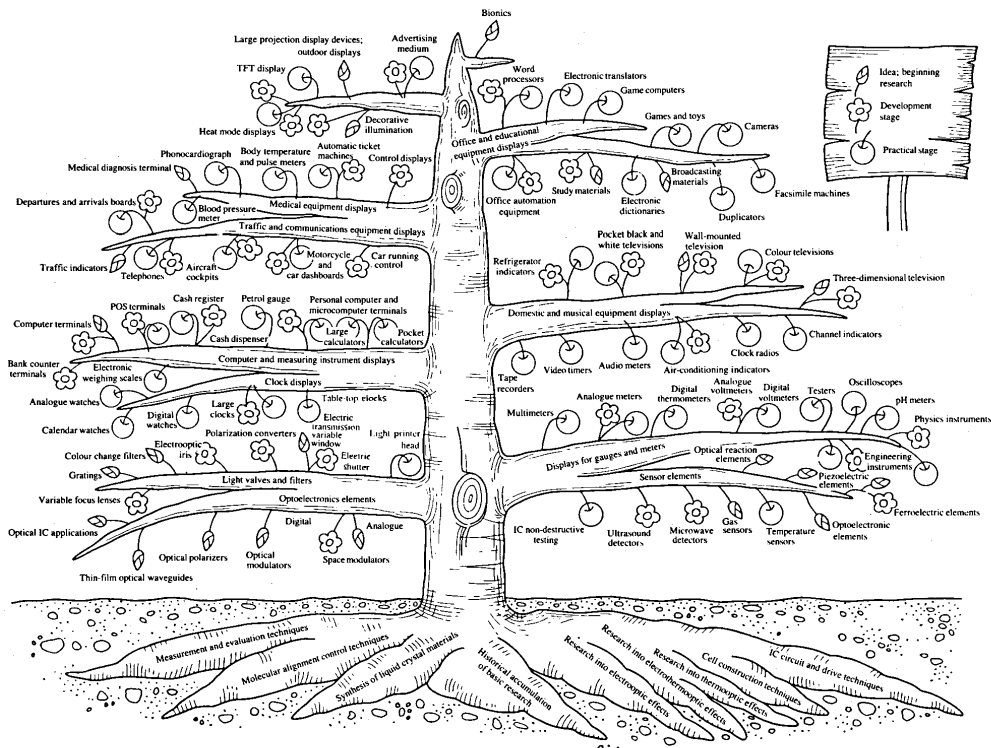


Figure 2.24 The 'tree' of OR liquid crystal display (LCD) applications

liquid crystal displays in the 1980s has aimed next at large-capacity character displays, graphic displays, large-area displays, and then colour video displays, and in 1982 medium-capacity character displays and black and white television displays entered the stage of practical implementation. Following on from this the implementation of LCDs as the large-capacity character displays and colour television displays which will compete with CRT displays is approaching.

Figure 2.24 shows the liquid crystal display application 'tree' which shows the current development states of the liquid crystal displays described above; these are now described in more detail.

2.7.1 Digital displays and analogue displays

The majority of domestic devices such as watches clocks, calculators, household electrical and audio equipment, and also industrial equipment such as measuring instruments, to which liquid crystal displays are applicable are digital, but analogue displays are also needed. In this type of application the display capacity is relatively small, and most of the demand is for displays of about ten digits, so that a segment electrode drive can be adopted. For applications such as clocks where the number of segments is small a static drive technique can be used, but



Figure 2.25 Colour liquid crystal display digital clock (Toshiba)

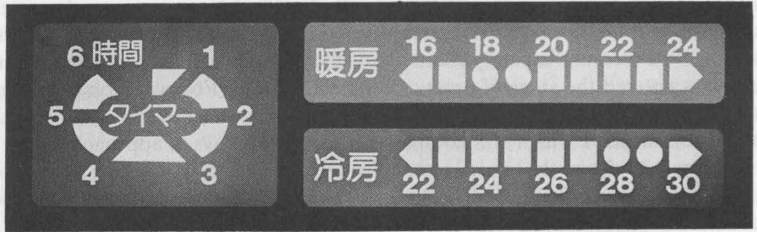


Figure 2.26 Multicolour liquid crystal display air conditioning indicator (Stanley)

when the number of segments increases as in, for example, calculator displays a multiplex drive technique is used. Figure 2.25 shows a digital clock using a guest-host type color liquid crystal display with static drive, and Fig. 2.26 shows an air conditioner indicator panel using a multicolour liquid crystal display combining digital and analogue displays.

2.7.2 Character displays and graphic displays

Character and graphic displays for computer terminals, word processors, and so forth require a large display capacity, and therefore a matrix electrode drive is

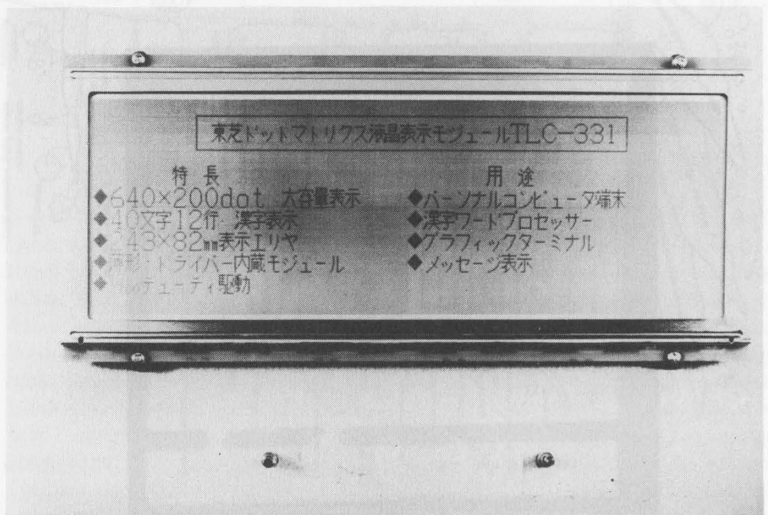


Figure 2.27 Character display using multiplex matrix drive twisted nematic LCD (Toshiba)

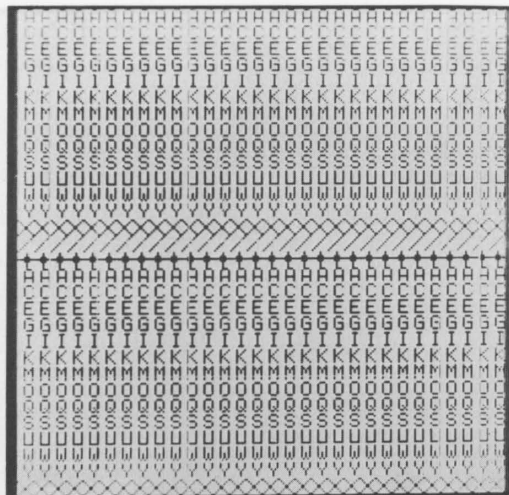


Figure 2.28 Character display using MOS type active matrix drive guest-host LCD (Toshiba)

adopted. For a number of scan electrodes N up to approximately 200 a multiplex matrix drive technique which relies on the multiplex capability of the liquid crystal material itself can be adopted, but for a higher number of scan lines an active matrix drive technique is used in which switching elements are added. For the former drive technique twisted nematic, super-twisted nematic and dynamic scattering displays are used, and for the latter technique also a guest-host type.

Figure 2.27 shows a twisted nematic liquid crystal display module of full-dot type which uses a multiplex matrix drive. This has a multiplexing number $N = 100$ and can display alphanumeric characters, Chinese characters and graphics.

A high-density large-capacity character display that uses an active matrix drive and guest-host LCD is exemplified in Fig. 2.28. It uses a MOS matrix array (480×480 pixels/3 inch-diagonal screen), and displays 30 rows of 30 characters. As well as the MOS type, the active matrix drive displays of the varistor type, MIM type, diode type, and TFT type have been developed, and of these the first three, which use two-terminal switching elements, appear to be appropriate as simple and inexpensive drive methods for character and graphic displays that do not require grey tones.

For large-capacity displays the thermally-addressed multiplex matrix/drive method using smectic A liquid crystals is also used (see Section 2.3.7). In Fig. 2.29 a character display with black characters on a white background is shown which uses a smectic guest-host matrix liquid crystal cell using a black dissolved dye.

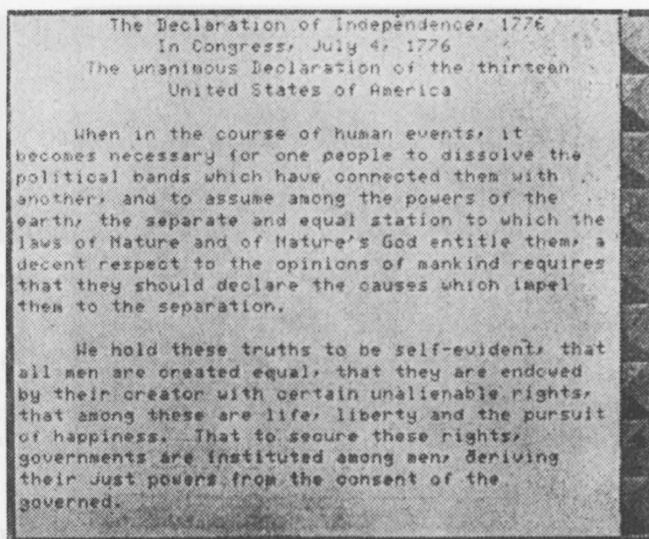


Figure 2.29 Thermal drive multiplex matrix guest-host LCD (Kylex) [22]

2.7.3 Video displays

A television display requires high resolution, good half-tone resolution, fast response, high contrast, and other high-grade characteristics. The principal display types that have been used are dynamic scattering, twisted nematic, and guest-host types, and the drive techniques are active matrix drive and multiplex matrix drive.

Figure 2.30 shows a liquid crystal TV set of dynamic scattering type using a MOS active matrix drive. It has a fast response time (< 30 ms), high contrast ($> 20:1$), high resolution (220×240 pixels/2 inch-diagonal screen), and is conveniently small, thin, and light. A wristwatch including a guest-host liquid crystal TV using the same MOS drive method has been marketed by Seiko. The TV screen size is 2 inches diagonal and the number of picture elements is 210×152 .

Figure 2.31 shows an α -Si type TFT active matrix drive colour liquid crystal TV set. The display type is twisted nematic, and a red, green, and blue mosaic colour polarizer film is incorporated into the cell so that a colour image is generated by light transmission. A colour television using p -Si type TFT active matrix drive has been marketed by Seiko. It has a resolution of 240×43 pixels/ 32 mm^2 and uses the same twisted nematic display technique, but the colour image is produced by a mosaic of red, green, and blue colour filters.

A means that has been proposed to increase the number of scanning electrodes

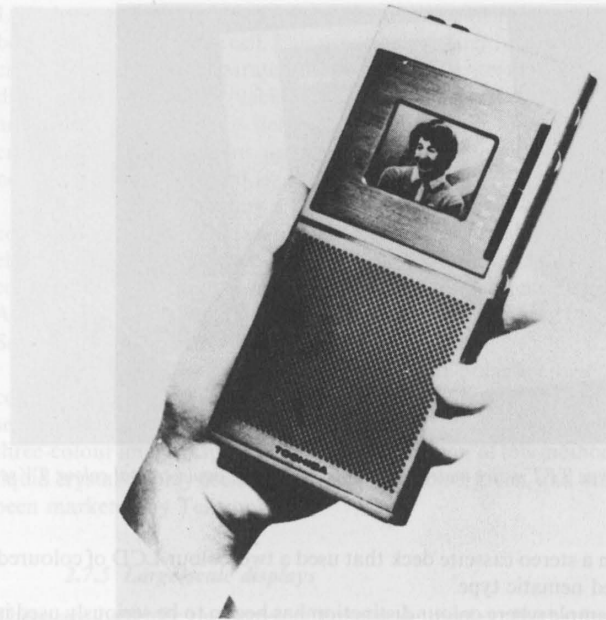


Figure 2.30 MOS type active matrix drive dynamic scattering liquid crystal TV set (Toshiba)

in the multiplex matrix drive arrangement is the multiple electrode matrix technique which has a number of signal electrodes scanned simultaneously. A test version of a twisted nematic liquid crystal TV of this type has been made [23], with a quadruple electrode matrix drive, 120×160 picture elements, and 3 inch-diagonal size, and a double-electrode matrix type black and white display liquid crystal TV set has been marketed by Casio.

2.7.4 Colour displays

Single-colour liquid crystal displays have been marketed for clocks, calculators, measuring instruments, and so forth, but in these cases the principal object is simply novelty of design. The first example of using a colour display where different colours discriminated functions was a peak programme meter made by

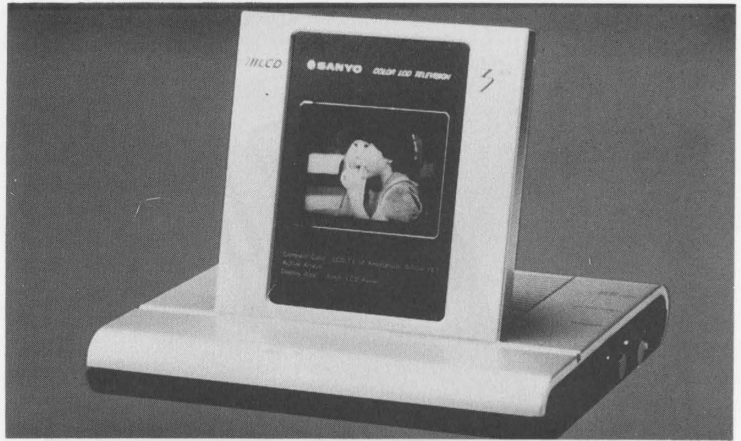


Figure 2.31 α -Si type TFT active matrix drive twisted nematic liquid crystal colour TV set (Sanyo)

Sony provided in a stereo cassette deck that used a two-colour LCD of coloured polarizers twisted nematic type.

One recent example where colour distinction has begun to be seriously used is in coloured LCD instrument panels for cars. Figure 2.32 shows a multicolour

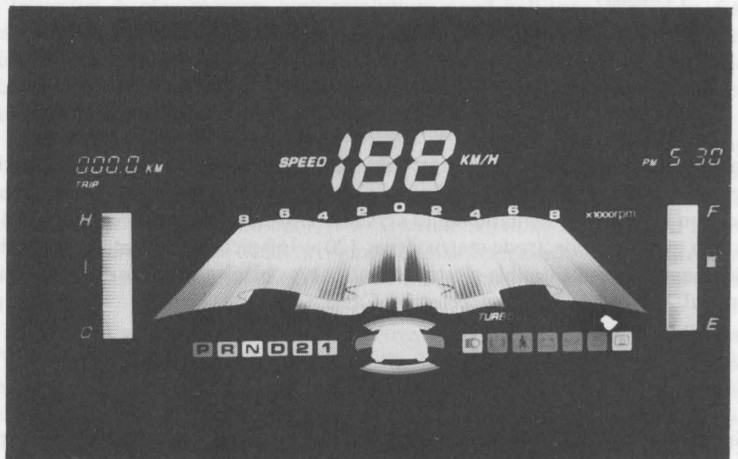


Figure 2.32 Multicolour guest-host type liquid crystal vehicle instrumentation panel (Toshiba)

LCD instrument panel in which all of the instruments from the dashboard have been integrated into one cell. This uses a colour filter type black guest–host liquid crystal cell, and has separate functions for blue, green, red, and yellow colour displays. In this case the black guest–host liquid crystal cell acts as a light shutter and the display colour is determined by a colour filter. A multicolour liquid crystal vehicle instrument panel has also been implemented using a twisted nematic liquid crystal cell as an optical shutter.

As a means of providing a full-colour display, the method of laminating a coloured layer with a mosaic of the primary colours red, green, and blue onto the electrode surface of a black and-white liquid crystal cell and effecting a natural colour display by additive colour light mixing has been attracting attention [24]. A colour TV display based on this method has already been described above (see Section 2.7.3).

Another technique is to place a two-colour polarizer type twisted nematic colour liquid crystal display panel in front of a monochrome CRT for field sequential colour display and to utilize the integrating effect of vision to provide a three-colour image display [25]. In an application of this method, a three-colour liquid crystal display oscilloscope, providing blue, green, and orange images, has been marketed by Tektronix.

2.7.5 Large-scale displays

There are basically two types of large-scale display. In the first a small liquid crystal cell, playing the same role as a slide, has a display image drawn on it by thermal, optical, or electric field methods, and the image is projected onto a large screen by a projector. In the other method, a large array of liquid crystal cells of a fixed size corresponding to an image element are integrated together to make a large screen, and this integrated display image is viewed directly by back lighting.

In an optical addressing projection type of display one electrode of the liquid crystal cell is replaced by the photoconductive layer of, for example, CdSe, and by directing a beam of light onto this layer a corresponding electric field will be applied to the liquid crystal layer. A projection colour television system has been marketed by the Hughes Corporation which uses three monochrome CRTs to provide the image source separated into red, green, and blue images and three light bulbs each combined with a liquid crystal cell of the above type. The three independently modulated images are projected in superimposition on a large screen in the system.

In the thermal addressing projection method, a smectic A liquid crystal is sandwiched between electrode substrates, one of which has a thermal absorption layer, and the image is produced by a laser beam (see Section 2.3.7). IBM, for example, have built a projection system in which a semiconductor laser array head writes an image of 8000×8000 pixels on a liquid crystal cell $10 \times 10 \text{ mm}^2$ in 62.5 seconds, and this image is then projected on a $1 \times 1 \text{ m}^2$ screen with a display contrast of 10:1 [26].

One example from the many large display systems in which small liquid crystal

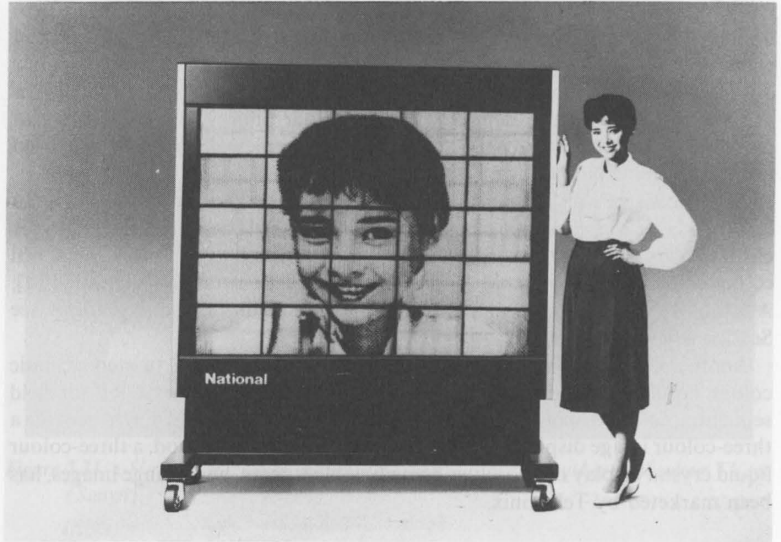


Figure 2.33 Large-scale full-colour liquid crystal video display system using liquid crystal cell integration (Matsushita)

cells are integrated together is the full-colour video system made by Mitsubishi. With the three primary colours of red, green, and blue as the pixel units, the basic element is a transmission type of twisted nematic liquid crystal cell of 8×46 pixels and size $6 \times 46 \text{ cm}^2$, and by combining these in an array, a full-colour video display of area up to $2.9 \times 4.6 \text{ m}^2$ is obtained. The Matsushita Group has also marketed a full-colour display device of this type (Fig. 2.33) with a display area of $1 \times 1.2 \text{ m}^2$ which consists of units that combine black and white guest-host type liquid crystal cells with red, green, and blue colour filters and have good half-tone resolution and wide viewing angle.

2.8 OUTLOOK

The development of liquid crystal display applications has been startling, and although these applications only began about ten years ago LCD production is approaching 1 billion panels per year. The range of application of liquid crystal displays is still widening rapidly (see the liquid crystal display application 'tree' in Fig. 2.24).

Even so, LCDs for the new applications other than watches, clocks and calculators have still not reached the 50 per cent level overall. The widening of the market for LCDs will of course continue, but to enable LCDs to expand their

contribution to the field of electronic display devices development is still needed for high performance and high quality LCDs that can meet the new applications.

In Sections 2.6 and 2.7 developments were described in multiplex displays, active matrix displays, colour displays, video displays, large-scale displays, and so forth to enable the display capacity to be increased, to improve the display functions, and to give higher quality, and performance so that we can see that these requirements are being worked on.

BIBLIOGRAPHY

- Chandrasekhar, S.: *Liquid Crystals*, Cambridge University Press, Cambridge (1977).
 de Gennes, P. G.: *The Physics of Liquid Crystals*, Clarendon, Oxford (1973).
 de Jeu, W. H.: *Physical Properties of Liquid Crystalline Materials*, Gordon and Breach, New York (1980).
 Gray, G. W.: *Molecular Structure and the Properties of Liquid Crystals*, Academic, New York (1962).
 Kelker, H., and R. Hatz: *Handbook of Liquid Crystals*, Verlag Chemie, Weinheim (1980).
 Kobayashi, S. (ed.): *Liquid Crystals—Nature and Applications*, Nikkan Kogyo Shinbunsha, Tokyo (1970).
 Matsumoto, S., and I. Tsunoda: *Latest Liquid Crystal Technologies—Physical Properties, Materials and Applications*, Kogyo Chosakai, Tokyo (1983).
 Meier, G., E. Sackmann, and J. G. Grabmaier: *Applications of Liquid Crystals*, Springer, Berlin (1975).
 Nakada, I., and F. Hori: *Synthesis and Applications of Liquid Crystals*, Sachishobo, Tokyo (1974).
 Sasaki, A. (ed.): *Foundations and Applications of Liquid Crystal Electronics*, Ohm-sha, Tokyo (1979).
 Tachibana, T., et al.: *Liquid Crystals*, Kyoritsu Shuppan, Tokyo (1972).

REFERENCES

- [1] S. Matsumoto and I. Tsunoda: *Latest Liquid Crystal Technologies—Physical Properties Materials and Applications*, Kogyo Chosakai, Tokyo (1983).
- [2] F. Reinitzer: *Z. physik. Chem.*, **4**, 462 (1889).
- [3] J. L. Fergason: *Sci. American*, **211**, 77 (1964).
- [4] V. Tsvetkov: *Acta Physicochim. (USSR)*, **16**, 132 (1942).
- [5] W. H. de Jeu: *Physical Properties of Liquid Crystalline Materials*, Gordon and Breach, New York (1980).
- [6] P. G. de Gennes: *The Physics of Liquid Crystals*, Clarendon, Oxford (1973).
- [7] K. Kobayashi: Ch. 2 in *Liquid Crystals*, T. Tachibana et al. (eds.), Kyoritsu Shuppan, Tokyo (1972).
- [8] J. J. Wysoki, A. Adams, and W. Haas: *Phys. Rev. Lett.*, **20**, 1024 (1968).
- [9] G. H. Heilmeyer, L. A. Zanoni, and L. A. Barton: *Proc. IEEE*, **56**, 1162 (1968).
- [10] G. H. Heilmeyer and L. A. Zanoni: *Appl. Lett.*, **13**, 91 (1968).
- [11] M. Schadt and W. Helfrich: *Appl. Phys. Lett.*, **18**, 127 (1971).
- [12] M. F. Schiekol and K. Fahrnschon: *Appl. Phys. Lett.*, **19**, 391 (1971).
- [13] M. Hareng, G. Assouline, and E. Leiba: *Electron Lett.*, **7**, 699 (1971).
- [14] R. B. Meyer: *Appl. Phys. Lett.*, **12**, 281 (1968).

- [15] J. Borel, J. Robert, and F. Gharadjedaghi: *The International Conference on Alphanumerical Display Device and Systems*, B-3, p. 61 (1973).
- [16] S. Matsumoto, M. Kawamoto, and K. Mizunoya: *J. Appl. Phys.*, **47**, 3842 (1976).
- [17] P. A. Penz and G. W. Ford: *Phys. Rev.*, **A6**, 414 (1972).
- [18] E. Jakeman and E. P. Raynes: *Phys. Lett.*, **39A**, 69 (1972).
- [19] D. L. Fishel and Y. Y. Hsu: *J. Chem. Soc.*, **23**, 1557 (1971).
- [20] F. Hori and Kasahara: *Television Gakkai-shi (Journal of the Television Institute)*, **37**, 32 (1983).
- [21] M. Hareng, S. Le Berre, R. Hehlen, and J. Perbet: *1981 SID International Symposium Digest*, p. 106 (1981).
- [22] S. Lu, D. H. Davies, R. Albert, D. Chung, A. Hochbaum, and C. Chung: *1982 SID International Symposium Digest*, p. 238 (1982).
- [23] E. Kaneko, H. Kawakami, H. Hanmura, and S. Saito: *Proc. SID*, **23**, 3 (1982).
- [24] Uchida, TV Gakkai Giho (Report of the Television Institute), IPD 63-2, p. 7 (1981).
- [25] M. G. Clark and I. A. Shanks: *1982 SID International Symposium Digest*, p. 172 (1982).
- [26] A. G. Dewey et al.: *1982 International Symposium Digest*, p. 36 (1983).

DECLARATION OF JUNE ANN MUNFORD

1. My name is June Ann Munford. I am over the age of 18, have personal knowledge of the facts set forth herein, and am competent to testify to the same.
2. I earned a Master of Library and Information Science (MLIS) from the University of Wisconsin-Milwaukee in 2009. I have over ten years of experience in the library/information science field. Beginning in 2004, I have served in various positions in the public library sector including Assistant Librarian, Youth Services Librarian and Library Director. I have attached my Curriculum Vitae as Appendix CV.
3. During my career in the library profession, I have been responsible for materials acquisition for multiple libraries. In that position, I have cataloged, purchased and processed incoming library works. That includes purchasing materials directly from vendors, recording publishing data from the material in question, creating detailed material records for library catalogs and physically preparing that material for circulation. In addition to my experience in acquisitions, I was also responsible for analyzing large collections of library materials, tailoring library records for optimal catalog

search performance and creating lending agreements between libraries during my time as a Library Director.

4. I am fully familiar with the catalog record creation process in the library sector. In preparing a material for public availability, a library catalog record describing that material would be created. These records are typically written in Machine Readable Catalog (herein referred to as “MARC”) code and contain information such as a physical description of the material, metadata from the material’s publisher, and date of library acquisition. In particular, the 008 field of the MARC record is reserved for denoting the date of creation of the library record itself. As this typically occurs during the process of preparing materials for public access, it is my experience that an item’s MARC record indicates the date of an item’s public availability.
5. Typically, in creating a MARC record, a librarian would gather various bits of metadata such as book title, publisher and subject headings among others and assign each value to a relevant numerical field. For example, a book’s physical description is tracked in field 300 while title/attribution is tracked in field 245. The 008 field of the MARC record is reserved for denoting the creation of the library record itself. As this is the only date reflecting the inclusion of said materials within the library’s collection, it is my experience

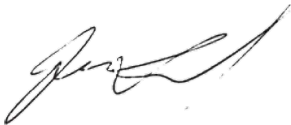
that an item's 008 field accurately indicates the date of an item's public availability.

6. I have reviewed Exhibit 1008, Electronic Display Devices by Shoichi Matsumoto.
7. Attached hereto as Appendix MATSUMOTO01 is a true and correct copy of the MARC record for Electronic Display Devices as held by the Penn State University Library. I secured this record myself from the library's public catalog. The MARC record contained within Appendix MATSUMOTO01 accurately describes the title, author, publisher, and ISBN number of Electronic Display Devices. In comparing Exhibit 1008 to Appendix MATSUMOTO01, it is my determination that Exhibit 1008 is a true and correct copy of Electronic Display Devices by Shoichi Matsumoto.
8. The 008 field of the MARC record in Appendix MATSUMOTO01 indicates the date of record creation. The 008 field of Appendix MATSUMOTO01 indicates the Penn State University Library first acquired Electronic Display Devices as of September 17, 1990. Considering this information, it is my determination that Electronic Display Devices was made available to the public shortly after its initial acquisition as of September 17, 1990.

9. I have been retained on behalf of the Petitioner to provide assistance in the above-illustrated matter in establishing the authenticity and public availability of the documents discussed in this declaration. I am being compensated for my services in this matter at the rate of \$200.00 per hour plus reasonable expenses. My statements are objective, and my compensation does not depend on the outcome of this matter.

10. I declare under penalty of perjury that the foregoing is true and correct. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

Dated: 7/29/2025

A handwritten signature in black ink, appearing to read 'June Ann Munford', with a stylized flourish at the end.

June Ann Munford



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264 4 c| ©1990

300 a| xii, 380 pages, 4 unnumbered pages of plates : b| illustrations (some color) ; c| 24 cm

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337 a| unmediated b| n 2| rdamedia

338 a| volume b| nc 2| rdacarrier

500 a| Translation of: Denshi disupurei gijutsu.

504 a| Includes bibliographical references and index.

650 0 a| Information display systems.

700 1 a| Matsumoto, Shōichi.

700 1 a| Ōta, Isao.

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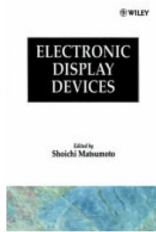


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Uniform Title

Denshi disupurei gijutsu. English

Published

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June A. Munford
Curriculum Vitae

Education

University of Wisconsin-Milwaukee - MS, Library & Information Science, 2009
Milwaukee, WI

- Coursework included cataloging, metadata, data analysis, library systems, management strategies and collection development.
- Specialized in library advocacy, cataloging and public administration.

Grand Valley State University - BA, English Language & Literature, 2008
Allendale, MI

- Coursework included linguistics, documentation and literary analysis.
- Minor in political science with a focus in local-level economics and government.

Professional Experience

Researcher / Expert Witness, October 2017 – present
Freelance ● Pittsburgh, Pennsylvania & Grand Rapids, Michigan

- Material authentication and public accessibility determination. Declarations of authenticity and/or public accessibility provided upon research completion. Experienced with appeals and deposition process.
- Research provided on topics of public library operations, material publication history, digital database services and legacy web resources.
- Past clients include Alston & Bird, Arnold & Porter, Baker Botts, Fish & Richardson, Erise IP, Irell & Manella, O'Melveny & Myers, Perkins-Coie, Pillsbury Winthrop Shaw Pittman and Slayden Grubert Beard.

Library Director, February 2013 - March 2015
Dowagiac District Library ● Dowagiac, Michigan

- Executive administrator of the Dowagiac District Library. Located in Southwest Michigan, this library has a service area of 13,000, an annual operating budget of over \$400,000 and total assets of approximately \$1,300,000.

- Developed careful budgeting guidelines to produce a 15% surplus during the 2013-2014 & 2014-2015 fiscal years while being audited.
- Using this budget surplus, oversaw significant library investments including the purchase of property for a future building site, demolition of existing buildings and building renovation projects on the current facility.
- Led the organization and digitization of the library's archival records.
- Served as the public representative for the library, developing business relationships with local school, museum and tribal government entities.
- Developed an objective-based analysis system for measuring library services - including a full collection analysis of the library's 50,000+ circulating items and their records.

November 2010 - January 2013

Librarian & Branch Manager, Anchorage Public Library ● Anchorage, Alaska

- Headed the 2013 Anchorage Reads community reading campaign including event planning, staging public performances and creating marketing materials for mass distribution.
- Co-led the social media department of the library's marketing team, drafting social media guidelines, creating original content and instituting long-term planning via content calendars.
- Developed business relationships with The Boys & Girls Club, Anchorage School District and the US Army to establish summer reading programs for children.

June 2004 - September 2005, September 2006 - October 2013

Library Assistant, Hart Area Public Library

Hart, MI

- Responsible for verifying imported MARC records and original MARC cataloging for the local-level collection as well as the Michigan Electronic Library.
- Handled OCLC Worldcat interlibrary loan requests & fulfillment via ongoing communication with lending libraries.

Professional Involvement

Alaska Library Association - Anchorage Chapter

- Treasurer, 2012

Library Of Michigan

- Level VII Certification, 2008
- Level II Certification, 2013

Michigan Library Association Annual Conference 2014

- New Directors Conference Panel Member

Southwest Michigan Library Cooperative

- Represented the Dowagiac District Library, 2013-2015

Professional Development

Library Of Michigan Beginning Workshop, May 2008

Petoskey, MI

- Received training in cataloging, local history, collection management, children's literacy and reference service.

Public Library Association Intensive Library Management Training, October 2011

Nashville, TN

- Attended a five-day workshop focused on strategic planning, staff management, statistical analysis, collections and cataloging theory.

Alaska Library Association Annual Conference 2012 - Fairbanks, February 2012

Fairbanks, AK

- Attended seminars on EBSCO advanced search methods, budgeting, cataloging, database usage and marketing.

Depositions

2019 • Fish & Richardson

Apple v. Qualcomm (Case No. IPR2018-001281, 39521-00421IP, IPR2018-01282 and 39521-00421IP2)

2019 • Erise IP

Implicit, LLC v. Netscout Systems, Inc (Case No. 2:18-cv-53-JRG)

2019 • Perkins-Coie

Adobe Inc. v. RAH Color Technologies LLC (Case No. IPR2019-00627, IPR2019-00628, IPR2019-00629 and IPR2019-00646)

2020 ● O'Melveny & Myers

Maxell, Ltd. v. Apple Inc. (Case No. 5:19-cv-00036-RWS)

2021 ● Pillsbury Winthrop Shaw Pittman LLP

Intel v. SRC (Case No. IPR2020-1449)

2022 ● Perkins-Coie

Realtek v. Future Link (Case No. IPR2021-01182)

2023 ● Fish & Richardson

Neuroderm Ltd. v. Abbvie, Inc (Case No. PGR2022-00040)

2023 ● Fish & Richardson

Nearmap US Inc. v. Pictometry International Corp. (Case No. IPR2022-00735)

2023 ● Fish & Richardson

Samsung Electronics v. MemoryWeb LLC (Case No. 39843-0136PS1)

2023 ● Pillsbury Winthrop Shaw Whitman LLP

Gravel Rating Systems v. Costco Wholesale Corp. (Case No. 4:21-cv-149-ALM)

2024 ● Willkie-Farr

Netflix, Inc. v. VideoLabs. Inc. (Case No. IPR2023-00628)

2024 ● Quinn Emanuel Urquhart & Sullivan

Purdue University v. Wolfsped (Case No. 1:21-CV-840)

2024 ● Fish & Richardson

Dish Network v. Entropic Communications (Case No. IPR2024-00393)

2025 ● Perkins Coie

Amazon.com, Inc. v. Nokia Technologies Oy (Case No. IPR2024-00572)

2025 ● Fish & Richardson

Dish Network v. Entropic Communications (Case No. IPR2024-00373)

Limited Case and Clientele History

Alston & Bird

- Ericsson

v. Collision Communications (Case No. IPR2022-01233)

- Nokia

v. Neptune Subsea, Xtera (Case No. 1:17-cv-01876)

- Universal Electronics Inc

v. Roku Inc (Case No. IPR2022-00818)

Alavi & Anaipakos PLLC

- Stingray Group Inc. and Stingray Music USA, Inc.

v. Edwin A. Hernandez-Mondragon and Eglia Corp. (Case No. 1:24-cv-21226-RAR)

Arnold & Porter

- Ivantis

v. Glaukos (Case No. 8:18-cv-00620)

- Samsung

v. Jawbone (Case No. 2:21-cv-00186)

Benesch Friedlander Coplan & Aronoff

- Voyis
v. Cathx (Case No. 5:21-cv-00077-RWS)

Buchanan, Ingersoll & Rooney PC

- Google LLC, AT&T Service Inc., T Mobile USA Inc., Cellco Partnership, Ericsson Inc. & Nokia of America Corp.
v. KT Corp & Pegasus Wireless Innovation LLC (Case No. IPR2025-00293)

Deschert LLP

- Smaxtec Animal Care
v. ST Reproductive Technologies, LLC (Case No. IPR2024-00885)

Duane Morris

- Kangxi Communication Technologies
v. Skyworks Solutions Inc. (Case No. IPR2025-00373)
- Microsoft
v. Edge Networking Systems LLC (Case No. 1:24-cv-00215)

Erise I.P.

- Apple
v. Ericsson Inc. (Case No. IPR2022-00715)
v. Future Link Systems (Case No. IPRs 6317804, 6622108, 6807505, and 7917680)
v. INVT (Case No. 20-1881)
v. Navblazer LLC (Case No. IPR2020-01253)
v. Qualcomm (Case No. IPR2018-001281, 39521-00421IP, IPR2018-01282, 39521-00421IP2)

- v. Quest Nettech Corp (Case No. 2:19-cv-00118-JRG)
- v. Telefonaktiebolaget LM Ericsson (Case No. IPR2022-00275)
- v. Theta IP, LLC (Case No. IPR2024-00818)
- v. THL Holding Company LLC (Case No. 1:23-cv-00548)

- Fanduel

- v. CGT (Case No. 19-1393)

- Garmin

- v. Phillips North America LLC (Case No. 2:19-cv-6301-AB-KS)

- Netscout

- v. Longhorn HD LLC (Case No. 2:20-cv-00349)
 - v. Implicit, LLC (Case No. 2:18-cv-53-JRG)

- Sony Interactive Entertainment LLC

- v. Bot M8 LLC (Case No. IPR2020-01288)
 - v. Infernal Technology LLC (Case No. 2:19-CV-00248-JRG)

- Tesla

- v. Charge Fusion Technologies LLC (Case No. IPR2025-00032)

- Unified Patents

- v. GE Video Compression (Case No. 2:19-cv-248)

Fish & Richardson

- Apple

- v. AliveCor (Case No. 3:21-cv-03958)
 - v. LBS Innovations (Case No. 2:19-cv-00119-JRG-RSP)
 - v. Koss Corporation (Case No. IPR2021-00305)

v. Masimo (Case No. IPR 50095-0012IP1, 50095-0012IP2, 50095-0013IP1, 50095-0013IP2, 50095-0006IP1, 50095-0135IP1)

v. Neonode (Case No. 21-cv-08872-EMC)

v. Qualcomm (Case No. IPR2018-001281, 39521-00421IP, IPR2018-01282, 39521-00421IP2)

v. Resonant Sys. (Case No. 7:23-cv-00077-ADA)

- AsusTek Computer Inc.

v. Videolabs, Inc. (Case No. 22-CV-00720-ADA)

- Dell

v. Neo Wireless (Case No. IPR2022-00616)

- Dish Network

v. Entropic Communications, LLC (Case No. 2:2023-CV-01043)

v. Entropic Communications LLC (Case No. IPR2024-00393)

v. Realtime Adaptive Streaming (Case No. 1:17-CV-02097-RBJ)

v. TQ Delta LLC (Case No. 18-1798)

- Evapco Dry Cooling

v. SPG Dry Cooling (Case No. IPR2021-00688)

- Genetec

v. Sensormatic Electronics (Case No. 1:20-CV-00760)

- Huawei

v. Bell Northern Research LLC (Case No. IPR2019-01174)

- Kianxis

v. Blue Yonder (Case No. 3:20-cv-03636)

- LG Electronics
 - v. Bell Northern Research LLC (Case No. 3:18-cv-2864-CAB-BLM)
- MediaTek
 - v. MOSAID (Case No. IPR2024-00718)
- Metaswitch
 - v. Sonus Networks (Case No. IPR2018-01719)
- Microsoft
 - v. Throughputer Inc (Case No. IPR2022-00757)
- Mom Enterprises
 - v. Ddrops Company (Case No. 1:22-cv-00332)
- MLC Intellectual Property
 - v. MicronTech (Case No. 3:14-cv-03657-SI)
- Nearmap Inc
 - v. EagleView Technologies (Case No. IPR2022-01009)
- Neuroderm Ltd.
 - v. Abbvie, Inc (Case No. PGR2022-00040)
- Posco Co Ltd.
 - v. Pascal Drillet et al. (Case No. IPR2025-00370)
- Realtek Semiconductor
 - v. Future Link (Case No. IPR2021-01182)

- Quectel
 - v. Koninklijke Philips (Case No. 1:20-cv-01710)
- Samsung
 - v. Aire Technology (Case No. IPR2022-00877)
 - v. Bell Northern Research (Case No. 2:19-cv-00286-JRG)
 - v. Communication Technologies Inc (Case No. IPR2022-01221)
 - v. Jawbone Innovations (Case No. IPR2022-00865)
 - v. MemoryWeb LLC (Case No. IPR2022-00885)
 - v. Dodots Licensing Solutions (Case No. IPR2023-00701)
 - v. Telefonaktiebolaget LM Ericsson (Case No. IPR2021-00615)
- Texas Instruments
 - v. Vantage Micro LLC (Case No. IPR2020-01261)
- Xilinx
 - v. Sentient Sensors LCC (Case No. 1:22-cv-00173)

Goodwin Proctor

- Intel
 - v. Proxense, LLC (Case No. 6:24-cv-00283)
- Samsung Electronics
 - v. Mobile Data Technologies (Case No. 2:24-cv-00435)
- Taiwan Semiconductor Manufacturing Company Ltd.
 - v. Advanced Integrated Circuit Process LLC (Case No. 2:24-cv-00623)

Groombridge Wu

- Nearmap

v. Eagle View Technologies Inc. and Pictometry International Corp. (Case No. 2:21-cv-00283-TS-DAO)

Irell & Manella

- Curium

Latham & Watkins LLP

- Apple

v. Advanced Coding Research LLC

Leydig, Voit & Mayer, Ltd.

- Public Availability Consultancy

O'Melveny & Myers

- Apple

v. Maxell (Case No. 5:19-cv-00036-RWS)

- Disney Media & Entertainment Distribution LLC

v. Digital Media Technology Holdings, LLC (Case No. 2:22-cv-01642)

- Micron Technology Inc.

v. Besang Inc (Case No. IPR2023-00900)

- Samsung

v. Daedalus Prime LLC (1335 Investigation)

Perkins-Coie

- Amazon
 - v. Nokia (Case No. IPR2024-00847 and IPR2024-00848)
 - v. Nokia Technologies Oy (Case No. IPR2024-00572)
- Heru Industries
 - v. The UAB Research Foundation (Case No. IPR2022-01148)
- Intel Corporation
 - v. BeSang Inc. (Case No. IPR2023-00991)
 - v. BitMICRO (Case No. 5:23-cv-00625)
 - v. Telefonaktiebolaget L M Ericsson (Case No. IPR2024-00610)
- Realtek Semiconductor
 - v. Future Link (Case No. IPR2021-01182)
- r-pac
 - v. Adasa, Inc. (Case No. 1:2024cv06102)
- Twitter Inc
 - v. VOIP-Pal.com (Case No. 3:20-cv-02397-JD)
- TCL Industries
 - v. Koninklijke Philips NV (Case No. IPR2021-00495, IPR2021-00496 and IPR2021-00497)
- VusionGroup
 - v. Hanshow (Case No. IPR2024-00857)

Pillsbury Winthrop Shaw Pittman

- Intel

v. FG SRC LLC (Case No. 6:20-cv-00315)

- Gravel Rating Systems

v. Costco (Case No. 4:21-cv-149)

v. Lowe's Home Centers (Case No. 4:21-cv-150)

v. T-Mobile USA (Case No. 4:21-cv-152)

v. Kohl's Inc. (Case No. 4:21-cv-258)

v. Under Armor (Case No. 4:21-cv-356)

Quinn Emanuel

- Exact Sciences Corporation

v. Geneoscopy, Inc. (Case No. IPR2024-00459 and IPR2024-1330)

- ServiceNow, Inc.

v. InQusient, Inc. (Case No. 22-900-CJB)

- Wolfsped

v. The Trustees of Purdue University (Case No. 1:2021-cv-00840)

Sheppard, Mullin, Richter & Hampton LLP

- Advanced Micro Devices, Inc and Pensando Systems, Inc.

v. Concurrent Ventures LLC and Xtreamedge, Inc. (Case No. IPR2025-00478)

- Cadence Design Systems Inc.

v. Semiconductor Design Technologies (Case No. 3:23-cv-01001)

Shook, Hardy & Bacon LLP

- HP Inc.

v. Universal Connectivity Technologies (Case No. 1:23-cv-01177)

Stern, Kessler, Goldstein & Fox

- Preliminary Research

Wilmer, Cutler, Pickering, Hale and Dorr

- Apple

v. Shunock (Case No. 1:23-cv-08598)

- Quest Diagnostics Inc., Haystack Oncology Inc. and Haystack Oncology GmbH

v. Natera, Inc. (Case No. 1:23-cv-08598)

- Roche Diabetes, Inc.

v. Trividia Health, Inc. (Case No. 1:24-cv-00668)

Willkie, Farr & Gallagher LLP

- Lenovo, Dell, HP

v. Universal Connectivity Technologies Inc. (Case No. 2:2023cv00449)

- Neurent

v. The Foundry, LLC (Case No. IPR2024-00669)

- Netflix, Inc.

v. VideoLabs, Inc. (Case No. IPR2023-00628)