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Liquid Crystal Displays

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Liquid Crystal Displays

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This paper reviews the present status and art of liquid crystal displays. It discusses the fabrication and operational principles of dynamic scattering, twisted nematic, guest-host, dye phase change, tunable birefringence, thermally addressed smectic A mode, etc. displays. The potentialities of applications of these displays are examined critically. Twisted nematic mode displays, which capture over 99% of today's LCD market, is discussed in detail. Molecular engineering, materials, and fabrication processes have been described. Addressing of liquid crystal displays, multiplexing and criteria for high level multiplexing are also discussed in detail. The use of nonlinear active devices (like varistor, MIM, TFT) for high level multiplexing are pointed out.

1. INTRODUCTION

Displays, a means of providing interface between man and machine through man's most versatile and sophisticated sense—the vision, has become a field of tremendous importance during the last few decades. Out of two major types of displays, the electro-optical displays are becoming more popular over mechanical displays. Electro-optical displays allow direct indication and reading of symbols, letters and numbers and can display more information in less space compared to analogue meters and mechanical devices. As data processing and other information based industries develop and adopt visual methods, display devices will assume greater significance. During the last decade the growth of this industry has been nothing short of phenomenal. It has paralleled the growth of the semiconductor industry and the trend is expected to continue in the future. However, there is a significant difference between the semiconductor and electro-optical display industries. The semiconductor industry is essentially based on a single technology, silicon, whereas the electronic display industry uses many different techniques, both emissive and passive.

A large number of displays such as, vacuum fluorescent, incandenscent lamps, nixie tube, plasma, light emitting diodes, electroluminescent, liquid

TABLE I

Relative importance of display features for various applications

Low interest = 0 Moderate interest = + High interest = + + +	Instrument	Business/pos	Appliances	Consumer	Watch/clock	Calculator	Automotive	Avionics	Military	Government	Distributor
Low cost	+	+	+ + +	+ + +	+ + +	+ + +	+ +	0	0	0	+
Readability	+ + +	+ + +	+	+	+ +	+ +	+ + +	+ + +	+ + +	+	+
Brightness uniformity	+ + +	+ + +	+	+	+ +	+ +	+ + +	+ + +	+ + +	+	+
Viewing angle	+ +	+ + +	+ +	+ +	+ +	+ +	+ +	+ + +	+ + +	+	+
Available decoder drivers	+ + +	+	+	0	0	0	+	0	0	+ +	+ +
Power requirement	+ +	+	+	+	+ + +	+ + +	+	+	+	+	+
Colour	0	+	0	0	0	0	+	+	0	+	+
Multiplex-ibilty	+	+ + +	+	+	0	+ + +	+	+	+	+	+
Special symbols	+ + +	+	+	+	+	0	+ + +	+ +	+	+	+
Decimal point	+ + +	+ +	+	+	+ +	+ + +	+	+	+	+	+
Reliability	+ +	+ +	+	+	+ +	+	+ + +	+ + +	+ + +	+	+
Installation ease	+ +	+ +	+	+	+	+	+	+	+	+	+ + +
Accessory availability	+ + +	+ + +	+	+	+	+	+	+	+	+ + +	+

crystal, etc., are available presently in the market.[1-4] Each of these displays has its own special characteristics and the proper choice of display, for a particular use, depends on a number of factors such as cost, size, brightness, life, power consumption, temperature range, operating voltage, drive circuits, etc.[1-4] Table I shows the relative importance of display features for various applications. Table II compares the display characteristics of various types of displays.

Of all these displays, the liquid crystal display has emerged as the most promising display during the last decade. Starting from almost scratch in the seventies, LCDs have captured 30% of the market for displays, excluding CRTs, in 1981 and are expected to have a tremendous growth rate in coming years.[2] The extremely low power consumption, low voltage operation, readability in glaring sunlight, compactness and flexibility of size, are just some of the distinctive features which make LCDs preferable over other types of displays. Liquid crystal displays consume the least amount of power ($\sim \mu W/cm^2$) amongst all of the displays and thus are the natural choice for portable and battery operated equipment. Another important factor contributing to this rapid growth is the capability of liquid crystal displays to interface directly with the integrated circuits which have revolutionized the electronics industry and substantially cut the cost and size of consumer and professional equipment. LCDs are truly flat panel and do not emit any harmful radiation which are their additional advantage over CRTs. The tremendous success of LCDs in watches and calculators has been alluring for use in various flat panel displays exhibiting more complex information and demanding stringent requirements.

The following table (Table III) shows the LCD market and its growth rate in comparison to other types of displays.[2] The table also indicates that while the high power emissive area is shared by so many types of displays, the low power or nonemissive area is unchallengingly occupied by LCDs. Table IV shows the current and future market for various segments of liquid crystal displays.[2] Besides its unchallenged and established dominance in watch and calculator markets, LCDs are gaining a major business in industrial and consumer electronics. The principal market in these areas are test and measuring equipment, analytical instrumentation, process control equipment, on line process analysers, domestic appliances, clocks, petrol pumps, etc. Other major sectors include automobile, military, telecommunications and avionics industries.[2] Moreover, the ever increasing capability of LCDs to display more information in less cost, due to recent developments in intrinsic and extrinsic multiplexing, is making them the most promising and favourable display for personal computer and similar high information content displays.

TABLE II

Characteristics of various types of displays

Characteristics	CRT	Nixie tube	LED	Vacuum fluorescent	Plasma or gas discharge	Incandescent
Brightness	Excellent	Good to Excellent	Good	Good	Good to Excellent	Excellent
Contrast ratio	40 : 1	10 : 1	40 : 1	20 : 1	40 : 1	20 : 1
Operating voltage (V)	5–25 K	175	2–8	12–60 (filament voltage of 1–12 V)	150–250	25–30
Temperature range (°C)	0–55	0–70	−55 to 100	−55 to 100	0–55	−55 to 100
Switching speed (sec) on	0.01–1 μ	150 μ	10 n	< 1 μ	20 μ	20 m
off	100 μ	150 μ	10 n	< 1 μ	10–100 μ	
Appearance	V. Good	Fair	Good	Excellent	Excellent	Good
Power consumption per picture element	Not applicable total power consumption ~ 60 W	350 mW	10–140 mW	100 mW	100 mW	100 mW
Life (in hours)	200,000	200,000	100,000	100,000	30,000	10,000
Colours	All colours with combination of phosphors	Neon Orange	Red, Orange Yellow, Green	Blue, Green others by filters	Orange, others by filters	All with filters
Viewing angle (°)	85	± 50	± 60	± 70	± 75	± 75
Character height (in.)	0.1	0.3–2	0.1–2	0.15–1.2	0.2 to 3.5	up to 1
Ruggedness	Good	Poor	Excellent	Good	Fair	V. Good
CMOS compatibility		Small	Yes	Yes	Yes	No
Safety factor	Harmful in long use due to radiation	No Special	No Special	Phosphor	No	No
Ease of mounting	V. Good	Good	V. Good	V. Good	Good	Good
Fonts	Individual	Numbers & Special Designs	7 Segment; 14/16 Segment; 4 × 7, 5 × 7 & other dot matrix; custom; graphic	7 Segment; 14/16 Segment; 5 × 7, 5 × 12 dot matrices; custom; graphics	7 Segment; 14/16 Segment; 5 × 7, 5 × 12 dot matrices; custom; graphics	Dot matrix Individual;
Multiplexing	V. Good, inherent multiplexibility	Not Applicable	V. Good, inherent multiplexibility	V. Good, inherent multiplexibility	V. Good, inherent multiplexibility	Fair
Maximum information content (p elements)	≃ 1000 K	Individual	≃ 50 K	≃ 65 K	≃ 250 K	Individual
Mode of operation	Active	Active	Active	Active	Active	Active

TABLE II (*Continued*)

Liquid crystal	Electrochromic	Electrophoretic	Electro luminescent	Suspended particle
Good	Good	Good	Good	Good
20 : 1 3–25	15 : 1 2–5	20 : 1 5–20	20 : 1 90–500	10 : 1 5–10
− 55 to 80 (DI Superfast Displays)	0–40	4–40	− 20 to 60	0–40
20 m 50 m Good 100 nW–1 μW	100 m 100 m Fair 10 mW	20 m 20 m Fair 10–100 mW	500 μ 500 μ Fair 50 mW	100 m 200 m Good 1–10 μW
50,000 to 100,000 All colours with filters, coloured polarizers and dichroic displays	Dev. Stage Blue and Mauve	Dev. Stage Many Colours	20,000 Yellow Orange Green	10,000 Blue
± 60 (Static mode) 85 (Dichroic) 45 (Multiplexed)	± 80	± 80	± 75	± 75
0.1–5	0.2–5	0.2–5	0.2–2	0.2–5
V. Good Yes, Direct	Good Yes	Good Yes	Good Yes	Good Yes
No	No	No	No Special	No Special
V. Good	Good	Good	Good	Good
7 Segment; 14/16 Segment 5 × 7, 5 × 8 dot matrices; custom; graphics	7 Segment (Dev. Stage)	7 Segment (Dev. Stage)	7 Segment (Dev. Stage)	7 Segment (Dev. Stage)
Good, inherent multiplexibility (~ 32 level for TN, ~ 100 for dual frequency mode) Excellent with external nonlinear devices like TFT ~ 500 lines	No inherent multiplexing	No inherent multiplexing	Fair	No inherent multiplexing
≤ 1–5 K with TN, ≃ 25 K with dual frequency ≃ 50–100 K with smectic, ≃ 50–100 K with TFT over 100 K with smectic and beam addressing	Up to 100	Up to 100	1–5 K	Up to 100
Passive	Passive	Passive	Active	Passive

TABLE III

Display market in U.S. and Japan

(A) Display market in U.S. (in million dollars). Total consumption in U.S. market as supplied by U.S. and Foreign manufacturers.

DISPLAYS	1975	1977	1979	1980	1981	1982	1983	1984	1985	1987
ACTIVE DISPLAYS										
Cathode Ray Tubes (CRTs)										
TV	496	633	792.5	833.4	898.1	1146.2	1198.3	1209.4	1217	1231
non TV	29	40	47.3	49.3	61.1	74.6	84.1	87.5	92.1	103
Light Emitting Diodes										
multicharacter displays	26	41	53.2	60.6	65.4	92	98.1	106.5	115.2	137
lamp or single character display	23	35	42	46.2	45	48.1	51.8	56.9	61.8	72
Gas Discharge	27	41.5	72	82.2	102.8	102.7	107.2	123.5	134.3	161
Vacuum Fluorescent										
single character	1.5	2.0	2.3	5.2	5.6	6.2	6.7	7.3	8	8.5
multicharacter	2.0	2.2	6.1	7.1	8.0	8.5	16.7	17.4	18.7	23
Incandescent	14.3	5.2	4.8	5.0	5.3	5.6	6.1	6.5	7.0	7.5
Electroluminescent	3.0	2.3	4.2	5.2	5.2	5.5	6.5	8.0	10	13
PASSIVE DISPLAYS										
Liquid Crystal Displays	4.3	25	31.6	40.9	54.5	61.3	69.4	77.3	99.5	166
Electrochromic Displays										
Electrophoretic Displays										
Dispersed Particles					In Development Stages					
Ferroelectric Displays										
Magneto-optic Displays										

(B) Display Market in Japan[2] (in Billion Yen, Approx 220 Yen—$1.00 U.S.)

	1979	1980	1981	1982	1983
Liquid Crystal Displays	30.4	35	44	55	65
Light Emitting Diode	23.4	32	40	45	50
Vacuum Fluorescent	21.1	28	32	38	42
Plasma Displays	3.1	5	6	7	12

2. WHAT IS LIQUID CRYSTAL?

It is commonly known that matter exists in three forms; solid, liquid and gas. Solid may be either crystalline or amorphous. In a crystalline solid, the molecules are well arranged in three dimensions over a large distance which is called a three dimensional long range order. When a crystalline solid is heated it transforms at its melting point into an isotropic liquid which has no long range order. Similarly on cooling, the isotropic liquid converts into crystalline solid. However, there are certain substances, like *p*-azoxyanisole

TABLE IV

The Worldwide Market for LCDs (millions of constant dollar 1982)

Applications	1981	1982	1983	1984	1985	1986	1990
Watches	115.9	110.6	111.7	112.8	113.9	114.8	117.4
Calculators	231.7	229.4	230.8	232.7	235.8	232.5	230.5
Clocks	36.7	38.1	38.7	35.3	32.1	32.5	33.2
Electronic Games and Toys	23.5	22.6	17.9	15.5	15.7	16.3	22.4
TV and Video	2.3	2.5	3.0	5.0	6.1	8.5	20.0
Electronic Data Processing	4.2	7.4	10.0	20.0	30.0	45.1	107.8
Telecommunications	0.7	1.2	3.0	5.9	8.0	15.0	28.0
Automobiles	0.5	5.9	8.8	12.0	23.8	29.2	37.0
Test and Measuring Equipments	1.6	1.8	2.3	2.8	3.2	3.9	5.5
Aircraft Cockpit	×	0.1	0.3	1.0	1.5	2.5	4.6
Petrol Pump	4.2	4.5	4.7	5.0	5.2	5.5	5.6
Radio, Camera etc.	1.9	2.2	2.4	2.5	2.7	3.2	4.4
Domestic Appliances	1.9	1.7	2.5	5.0	6.7	8.4	14.8
Business Systems	1.4	2.3	3.3	4.5	5.6	7.0	9.5
Marine Instruments	1.6	1.6	1.6	1.8	2.0	2.2	2.8
Agriculture	0.1	0.1	0.2	0.5	1.0	1.8	4.1
Others	0.8	1.1	2.4	3.7	4.8	9.3	15.5
Total:	427.6	433.2	443.9	466.0	497.9	537.7	663.1

(PAA) and *p-n*-pentylcyanobiphenyl (PCB), which do not directly pass from a crystalline solid to an isotropic liquid and vice versa, but adopt an intermediate structure which flows like liquids but still possesses the anisotropic physical properties similar to crystalline solids.[5-8] These types of phases are termed the liquid crystalline phase, mesophase or mesomorphic phase and the materials are called liquid crystals, mesomorphs or mesomorphic substances. Similar types of phases can also be obtained by dissolving some substances (like sodium or potassium salts of higher fatty acids) in a controlled amount of solvents (such as water). These types of materials are called lyotropic liquid crystals while those obtained by heating or cooling are called thermotropic liquid crystals. Lyotropic liquid crystals are more important from a biological point of view and hence will not be discussed here.

Liquid crystalline molecules are generally organic in nature and elongated in shape. These cigar shaped molecules are more or less parallel to each other in the mesomorphic phase and their long range orientational ordering is the cause of their anisotropic physical properties. A measure of the degree of this orientational ordering is termed the orientational order parameter. Depending on the molecular arrangement and ordering, liquid crystals are

classified into three types; nematic, smectic and cholesteric. In the following section a very brief description of liquid crystals is given. One may consult recent books and review articles to have more details.[5-8]

2.1 Nematic liquid crystal[5-8]

The name nematic is derived from the Greek word nematos meaning thread-like. Nematic liquid crystals, when viewed between crossed polarizers through a microscope, have threads distributed all over the area. The threaded structure appears because of the disclinations, an analogue of dislocation of crystals, in liquid crystals. In the nematic state the only restriction is that molecules should be more or less parallel to each other. This type of ordering is called orientational ordering. Molecules can move in all the three dimensions and can rotate freely along the long molecular axes. The average direction of the long axes of the molecules is called the director. Nematic liquid crystals are the most widely used liquid crystals in electro-optical displays.

2.2 Smectic liquid crystals[5-8]

The name smectic is derived from the Greek word 'smectos', meaning soap-like. The earlier smectic liquid crystals were mostly sodium or potassium salts of higher fatty acids (such as sodium palmitate) which were soaps. However, most of the later smectic liquid crystals are non-soaps, but the name has been retained. The smectic state is now used for the state of liquid crystals in which molecules have a layered structure. In the smectic state (except smectic D), the centre of gravity of the molecules are also ordered besides the orientational ordering and the molecules are arranged in layers. These layers can slide over each other and give rise to the flow characteristics. The viscosity of a smectic phase is much higher than that of a nematic. Smectics are divided into eight subclasses S_A, S_B, S_C, S_D, S_E, S_F, S_G, and S_H depending on the molecular arrangement inside the layers. Smectics are not as technologically important as nematics are. Recently the use of smectic A liquid crystals have been proposed in a thermally addressed mode.[2]

2.3 Cholesteric liquid crystal[5-8]

The earlier cholesteric liquid crystals were derivatives of cholesterol from which the name was derived. However, the work of Gray, Bahadur, Meyer and others layed the foundation for nonsteroidal cholesterics.[9-12] The cholesteric state can be visualized as the nematic state superimposed with the natural twist, i.e. the average direction of the molecules in every layer is unidirectionally skewed either clockwise or anticlockwise to the layer just

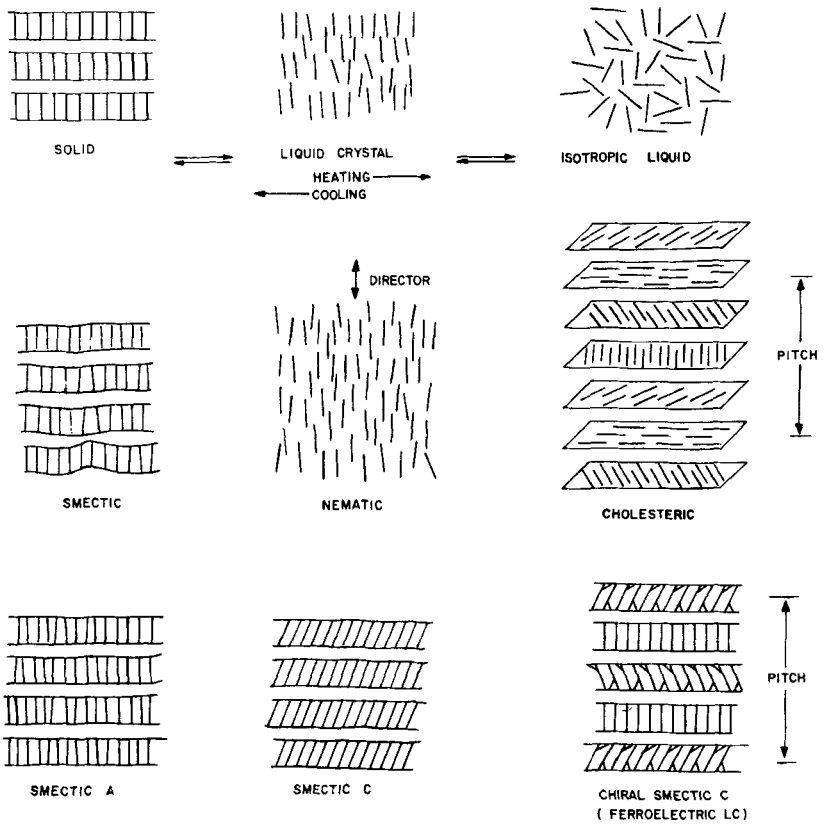


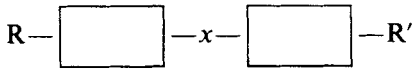
FIGURE 1 Molecular arrangement in various types of liquid crystals.

below it. Nowadays, cholesterics are not regarded as a separate phase but just as a nematic phase having a finite pitch. The chiral smectic C phase, a special type of cholesteric, resembles the smectic C phase. The molecular arrangement in various types of liquid crystals is shown in Figure 1.

2.4 Molecular structure and engineering

The most general structure of liquid crystals consists of two rigid aromatic groups (A, B) coupled with a central linkage group (—x—). R, R′ may be alkyl, alkoxy, aceloxy, nitro, amino, hydroxy, bromo, chloro, iodo, etc. groups. In most cases the two aromatic groups are benzene rings but in some cases either one or both of these rings are cyclohexane, pyrimidine, bicyclooctane etc. groups.[7,9] Besides these there are dienoic acids, cholesterol derivatives, discogenic phases, or naphthalene groups containing liquid crystals which do not have the above mentioned structure.[9] However, from

the molecular geometry, it is clear that most of the mesogenic molecules are elongated in nature. By replacing one or both of the alkyl groups with alkyl groups containing an asymmetric carbon atom, one can form a large number of nonsteroid chiral mesogens.[9-12] The name of the liquid crystal is generally termed on the central linkage group such as Schiff bases, esters, azoxy compounds, etc.[9,13,15] Some of the liquid crystals are mentioned below (Table V).



The earlier materials used in liquid crystal displays were Schiff bases, esters, azo and azoxy compounds etc.[9,13,14] Materials such as Schiff bases were found to be fairly unstable and a lot of care was needed in handling. Esters, azo and azoxy compounds were pretty stable but not extremely stable.[9,14] These materials are also having some colour. On the consideration of molecular engineering, it was found that the instability of these liquid crystals was linked with the central linkage which was breaking with moisture, temperature, UV light, etc. So, compounds having no central linkage like biphenyls, pyrimidine and phenylcyclohexanes were synthesized which are extremely stable[9,14] (Table V).

The display operation requires a chemically and photochemically stable liquid crystal material with wide temperature range around room temperature. Individual mesogens have limited liquid crystalline range and most of these have LC phase, above room temperature. This makes the use of individual mesogen unacceptable for displays. This problem was solved by making eutectic mixtures which have wider nematic range and hence giving wide operating temperature range to the LCDs.[13,14,16] Figure 2 shows the widening of the operating temperature range (i.e. nematic phase) by making eutectic mixtures. 5CB (*p-n* pentylcyanobiphenyl) and 80CB (*p-n* octyloxycyanobiphenyl) have nematic phase between temperatures 24–35.3°C and 67–80°C respectively. These nematic ranges are very limited, hence none of these materials are suitable individually for actual display. An eutectic mixture of these two has a nematic phase from 5 to 50°C which is much more acceptable. The nematic range can be further extended by taking proper components and making ternary, quaternary etc. mixtures. Most of the liquid crystalline mixtures, presently being used in display, generally have four to ten components. Sometimes these mixtures contain a small amount of nonmesomorphic constituents too.

Liquid crystals exhibit anisotropic physical properties. The anisotropy in the bulk physical properties in the liquid crystalline or mesomorphic state results because of the anisotropic distribution or long range ordering of the

TABLE V

Some of the Liquid Crystals and Mixtures

[A] Some Common Central Linkage and Group Name[9]

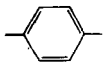
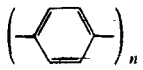
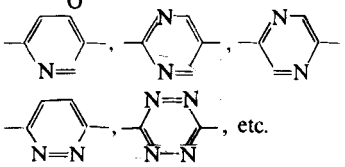
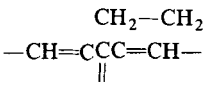
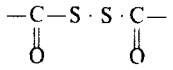
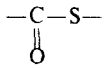
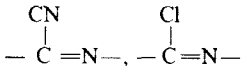
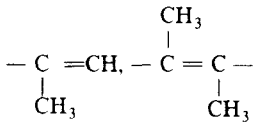
Central Linkage Group (—×—)	Name of the Liquid Crystal
—	biphenyl
	terphenyl
	tetraphenyl (n = 2), pentaphenyl (n = 3) etc.
$-CH_2-CH_2-$	diphenylethanes
$-CH=CH-$	trans stilbene
$-C\equiv C-$	tolanes
$-CH=N-$	Schiff base
$-CH=N(\rightarrow O)-$	nitrones
$-N=N-$	azobenzene
$-N=N(\rightarrow O)-$	azoxybenzenes
$-O-C(=O)-$	phenylbenzoate
	suitable heterocyclic compounds
	dibenzylcyclopentanone
$-O-CH_2-CH_2-O-$	glycol bis-(phenylether)

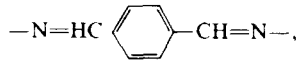
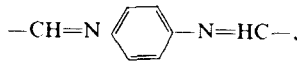
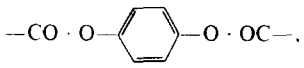
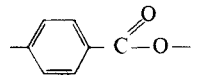
TABLE V (*Continued*)

Some of the Liquid Crystals and Mixtures

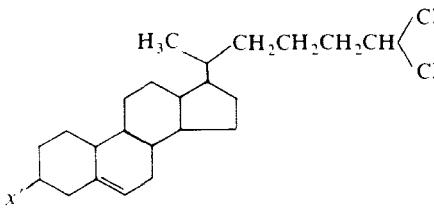
[A] Some Common Central Linkage and Group Name[9]

Central Linkage Group (—×—)	Name of the Liquid Crystal
	benzoyldisulphide
	phenylthiobenzoate
	Substituted Schiff bases (imidoyl cyanide and imidoyl chloride)
	Substituted stilbenes

Permutation and combinations of above mentioned groups generate new series such as

Some Other Common Structures



cholesterol derivatives

x' = Cl, Br, I for cholesteryl chloride, bromide, iodide.

x' = OR where R is the alkyl group for cholesteryl esters such as cholesteryl nonanoate, palmitate etc.

$RCOOx''$

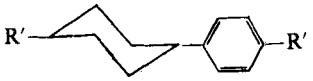
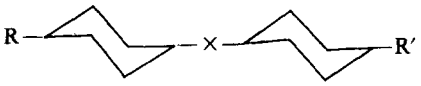
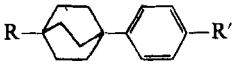
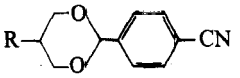
R = long alkyl group,

x'' = Na, K, etc. for Na, K, Rb, Cs salts of higher fatty acids.

TABLE V (*Continued*)

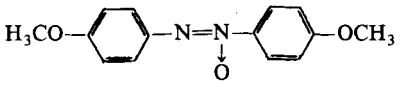
Some of the Liquid Crystals and Mixtures

[A] Some Common Central Linkage and Group Name[9]

Central Linkage Group (—X—)	Name of the Liquid Crystal
RCH=CH—CH=CHCOOH	2,4 dienoic acids R is normal alkyl group containing more than 4 carbon atoms.
	phenylcyclohexanes
	bicyclohexanes
	bicyclo[2,2,2]octanes
	cyanophenyl 1,3 dioxane

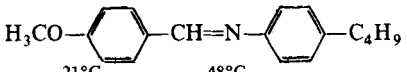
[B] Some of the Common Liquid Crystals

1. *p*-azoxyanisole (PAA)



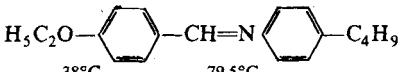
solid $\overset{117.4°C}{\longrightarrow}$ nematic $\underset{}{\overset{134.4°C}{\rightleftharpoons}}$ isotropic

2. *p*-methoxybenzylidene-*p*-*n*-butylaniline (MBBA)



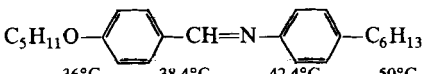
solid $\underset{}{\overset{21°C}{\rightleftharpoons}}$ nematic $\underset{}{\overset{48°C}{\rightleftharpoons}}$ isotropic

3. *p*-ethoxybenzylidene-*p*-*n*-butylaniline (EBBA)



solid $\underset{}{\overset{38°C}{\rightleftharpoons}}$ nematic $\underset{}{\overset{79.5°C}{\rightleftharpoons}}$ isotropic

4. *p*-*n* pentyloxybenzal-*p*'-*n*-hexylaniline



solid $\underset{}{\overset{36°C}{\rightleftharpoons}}$ S_G $\underset{}{\overset{38.4°C}{\rightleftharpoons}}$ S_F $\underset{}{\overset{42.4°C}{\rightleftharpoons}}$ S_B $\underset{}{\overset{50°C}{\rightleftharpoons}}$

S_C $\underset{}{\overset{51.8°C}{\rightleftharpoons}}$ S_A $\underset{}{\overset{60.3°C}{\rightleftharpoons}}$ nematic $\underset{}{\overset{72.8°C}{\rightleftharpoons}}$ isotropic

TABLE V (*Continued*)

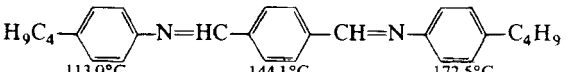
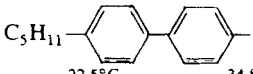
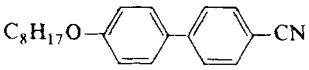
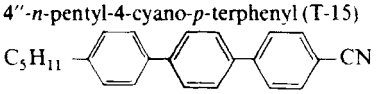
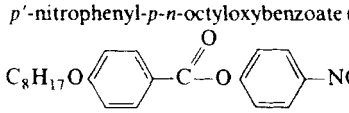
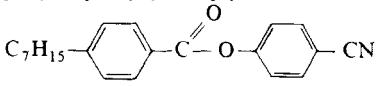
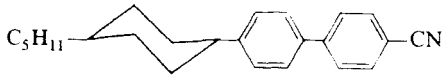
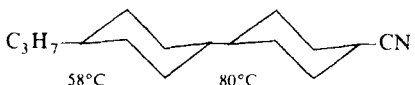
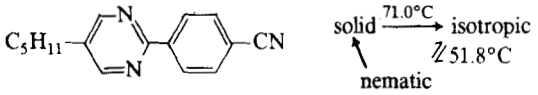
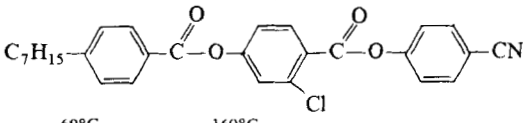
[B] Some of the Common Liquid Crystals	
5.	Terephthal-bis-4-*n*-butylaniline (TBBA)  solid $\overset{113.0°C}{\rightleftharpoons}$ smectic B $\overset{144.1°C}{\rightleftharpoons}$ smectic C $\overset{172.5°C}{\rightleftharpoons}$ smectic A $\overset{199.6°C}{\rightleftharpoons}$ nematic $\overset{236.5°C}{\rightleftharpoons}$ isotropic
6.	*p*-*n*-pentyl-*p*′-cyanobiphenyl (PCB)  solid $\overset{22.5°C}{\rightleftharpoons}$ nematic $\overset{34.8°C}{\rightleftharpoons}$ isotropic
7.	*p*-*n*-octyloxy-*p*′-cyanobiphenyl (8OCB)  solid $\overset{54.5°C}{\rightleftharpoons}$ S_A $\overset{67.0°C}{\rightleftharpoons}$ nematic $\overset{80°C}{\rightleftharpoons}$ isotropic
8.	4″-*n*-pentyl-4-cyano-*p*-terphenyl (T-15)  solid $\overset{129.8°C}{\rightleftharpoons}$ nematic $\overset{238.5°C}{\rightleftharpoons}$ isotropic
9.	*p*′-nitrophenyl-*p*-*n*-octyloxybenzoate (NPOB)  solid $\overset{49°C}{\rightleftharpoons}$ smectic A $\overset{61.0°C}{\rightleftharpoons}$ nematic $\overset{67.9°C}{\rightleftharpoons}$ isotropic
10.	*p*′-cyanophenyl-*p*-*n*-heptylbenzoate  solid $\overset{43.5°C}{\rightleftharpoons}$ nematic $\overset{56.0°C}{\rightleftharpoons}$ isotropic
11.	4 cyano-4′(trans-4 pentylcyclohexyl)biphenyl trans 4-pentyl 1-(4′cyanobiphenyl-4yl)cyclohexane (BCH-5)  solid $\overset{96°C}{\rightleftharpoons}$ nematic $\overset{222°C}{\rightleftharpoons}$ isotropic
12.	trans-4-heptyl(4-cyanophenyl)cyclohexane (PCH-7)  solid $\overset{30°C}{\rightleftharpoons}$ nematic $\overset{57°C}{\rightleftharpoons}$ isotropic
13.	 solid $\overset{58°C}{\rightleftharpoons}$ nematic $\overset{80°C}{\rightleftharpoons}$ isotropic

TABLE V (*Continued*)
[B] Some of the Common Liquid Crystals

14. 5-*n*-pentyl-2-(4 cyanophenyl)pyrimidine

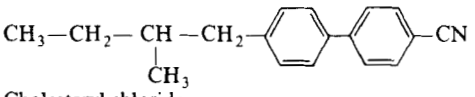


15.

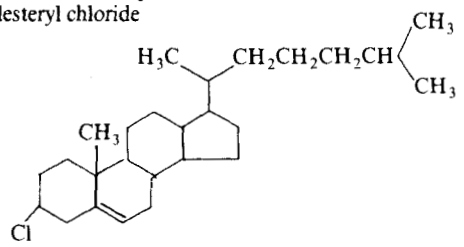


solid $\overset{69°C}{\rightleftharpoons}$ nematic $\overset{160°C}{\rightleftharpoons}$ isotropic

16. *S*-(-)-2methylbutyl-*p'*-cyanobiphenyl



17. Cholesteryl chloride



(C) Some of the Common Mixtures

(i) Biphenyls + Terphenyls

E_7	solid $\overset{-10°C}{\rightleftharpoons}$ nematic $\overset{60.5°C}{\rightleftharpoons}$ isotropic η = 40 cps, Δn = 0.225, $V_{90,0°,20°C}$ = 1.49 V. η = 161 cps (at 0°C); $V_{10,0°,20°C}$ = 1.96 V
E43	solid $\overset{-10°C}{\rightleftharpoons}$ nematic $\overset{84°C}{\rightleftharpoons}$ isotropic η = 39 cps Δn = 0.234 $V_{90,0°,20°C}$ = 1.67 V. η = 165 cps (at 0°C) $V_{10,0°,20°C}$ = 2.27 V
E100	solid $\overset{-20°C}{\rightleftharpoons}$ nematic $\overset{78°C}{\rightleftharpoons}$ isotropic η = 43 cps, Δn = 0.187 $V_{90,0°,20°C}$ = 1.43 V. $V_{10,0°,20°C}$ = 1.89 V
E120	solid $\overset{-20°C}{\rightleftharpoons}$ nematic $\overset{61°C}{\rightleftharpoons}$ isotropic η = 44 cps, Δn = 0.146 $V_{90,0°,20°C}$ = 2.01 V, $V_{10,0°,20°C}$ = 2.66 V
E140	solid $\overset{-20°C}{\rightleftharpoons}$ nematic $\overset{63°C}{\rightleftharpoons}$ isotropic η = 54.1°C, Δn = 0.147, $V_{90,0,20}$ = 3.80 V. $V_{10,0°,20}$ = 5.02 V

TABLE V (*Continued*)

(C) Some of the Common Mixtures

(ii) Phenylcyclohexanes + Biphenylcyclohexanes	
NP 1132 TNC	solid $\overset{-6°C}{\rightleftharpoons}$ nematic $\overset{70°C}{\rightleftharpoons}$ isotropic η = 28 cps, Δn = 0.14, $\Delta\epsilon$ = 10.1 η = 97 cps (at 0°C)
NP 1291 TNC	solid $\overset{-10°C}{\rightleftharpoons}$ nematic $\overset{107°C}{\rightleftharpoons}$ isotropic η = 46 cps Δn = 0.15, $\Delta\epsilon$ = 8.6 η = 199 (at °C)
NP 1694	solid $\overset{-20°C}{\rightleftharpoons}$ nematic $\overset{86°C}{\rightleftharpoons}$ isotropic η = 20 cps Δn = 0.13 $\Delta\epsilon$ = 6.5 $V_{90,0°,20°C}$ = 2.14 V, $V_{10,0°,20°C}$ = 2.93 V
NP 1957/5	Solid $\overset{-16°C}{\rightleftharpoons}$ nematic $\overset{85°C}{\rightleftharpoons}$ isotropic η = 18 cps Δn = 0.13, $\Delta\epsilon$ = 4.5 η = 48 cps(°C) $V_{90,0°,20°C}$ = 2.62 V η = 600 cps (−30°C) $V_{10,0°,20°C}$ = 3.57 V
(iii) Schiff Base	
ROTN 200	Solid $\overset{-20°C}{\rightleftharpoons}$ nematic $\overset{65.2°C}{\rightleftharpoons}$ isotropic η = 84 cps, Δn = 0.276, $\Delta\epsilon$ = 18.3 $V_{90,0°,20°C}$ = 1.40 V, $V_{10,0°,20°C}$ = 1.95 V
(iv) Biphenyl + Pyrimidine	
ROTN 403	nematic–isotropic = 81.5°C η = 66 cps, $\Delta\epsilon$ = 19.2, Δn = 0.258 $V_{90,0°,20°C}$ = 1.60 V, $V_{10,0°,20°C}$ = 2.20 V

anisotropic mesogenic molecules.[5-10,17,18] The mesogenic molecules are mostly anisotropic individually because of their elongated shape. Due to the cylindrical symmetry, the bulk properties are expressed in terms of two components, one along the director and the other perpendicular to the director (the two components mutually perpendicular to each other and orthogonal to the director are nearly equal in magnitude). These components can be measured easily by aligning the director (and hence the liquid crystal), by external forces such as electric field, magnetic field, surfactants, shear etc.[5-8,17,18] However, the magnetic field is generally preferred for alignment as its interaction with the internal field of the liquid crystal is negligible.[5-8] Some of these properties are listed in Figure 3.

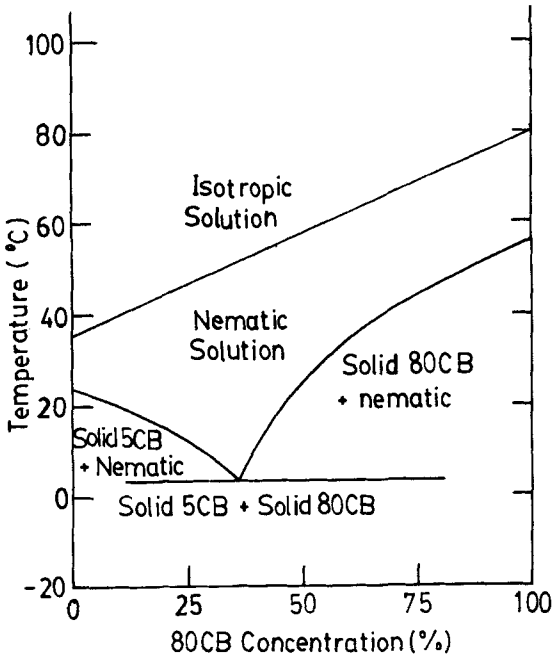


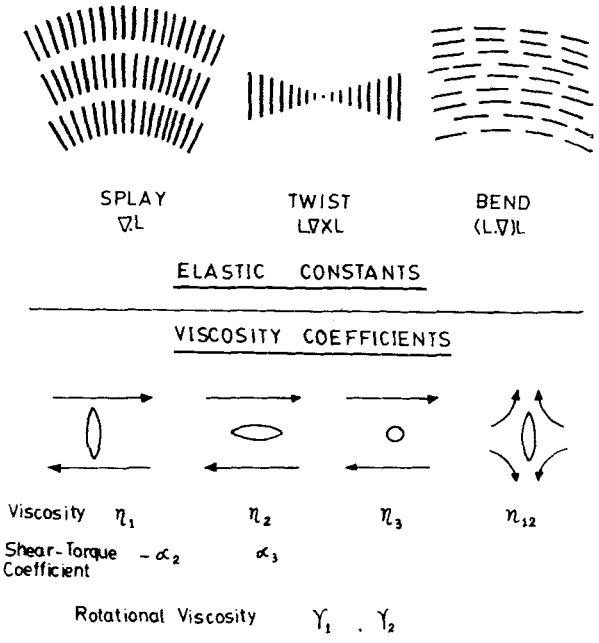
FIGURE 2 Phase diagram of the mixture of two biphenyls, *p-n* pentylcyanobiphenyl (5CB) and *p-n* octyloxy cyanobiphenyl (80CB).

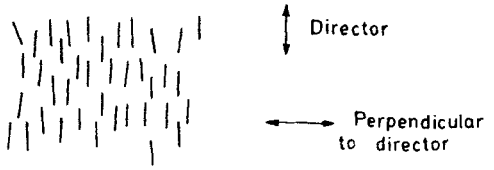
The bulk physical properties bear relation with ordering as well as with molecular structure of the individual mesogen.[5-10,17-20] For example the dielectric ansiotropy ($\Delta\epsilon$) in nematic phase is dependent on the dipole moment (μ) and the angle (ϕ) which it makes with the long molecular axis.

$$\frac{\Delta\epsilon}{4\bar{\Lambda}} = Nhf\left\{\Delta\alpha + \frac{F\mu^2}{2kT}(3\cos^2\phi - 1)\right\}S \qquad (1)$$

where S is order parameter and $\Delta\alpha$ is the polarizability anisotropy. The dipole moment is the vector sum of the individual group moment. Hence, by incorporating a strong group such as CN, NO_2 along the para axis, one may form a liquid crystal having a high positive dielectric anisotropy.

The birefringence (Δn) is also dependent on the molecular structure. It has been shown by Bahadur *et al.*[21] that Δn is proportional to $\Delta\alpha$, which in turn is dependent on the polarizability of individual groups. Phenyl-cyclohexanes have lower Δn compared to the other two phenyl groups containing liquid crystals as one of the phenyl groups in it is replaced by saturated cyclohexane group.[17,21,22] Similarly bicyclohexanes have much





Property	Parallel component	Perpendicular component	Anisotropy
Dielectric constant	$\epsilon_{\parallel}$	$\epsilon_{\perp}$	$\Delta\epsilon = \epsilon_{\parallel} - \epsilon_{\perp}$
Refractive index	$n_{\parallel}$	$n_{\perp}$	$\Delta n = n_{\parallel} - n_{\perp}$
Magnetic susceptibility	$\chi_{\parallel}$	$\chi_{\perp}$	$\Delta\chi = \chi_{\parallel} - \chi_{\perp}$
Dipole moment	$\vec{\mu}_{\parallel}$	$\vec{\mu}_{\perp}$	$\vec{\mu}_{\parallel} - \vec{\mu}_{\perp}$

FIGURE 3 Some of the physical properties of liquid crystals.

lower value of Δn.[17] The bulk elastic properties associated with the curvature of the director L of a nematic liquid crystal can be described by three elastic constants.[5-8] These constants are associated with the restoring torque opposing the splay (k_{11}), twist (k_{22}) and bend (k_{33}) of the director pattern (Figure 3). The elastic distortion free energy density is given by:

$$F = \tfrac{1}{2}\left[k_{11}(\nabla \cdot L)^2 + k_{22}(L \cdot \nabla \times L)^2 + k_{33}(L \cdot \nabla L)^2\right]. \qquad (2)$$

Studies are being made to determine the correlation of the elastic constants with molecular structure.

Viscosity, too is dependent greatly on molecular structure and order parameter. A globular molecular like phenylcyclohexane has less viscosity. Of course, there are only very scanty measurements on various components of viscosity $\eta_1, \eta_2, \eta_3, \eta_{12}$. Generally the viscosity measured by Ostwald viscometer are quoted by the liquid crystal manufacturers. In some cases a fair approximation to a twisted nematic cell behavior may be obtained by ignoring flow and considering only the viscosity opposing the director orientation without flow.

Elastic constants, dielectric anisotropy, birefringence and viscosity are the material parameters on which the performance of display is greatly dependent. The mixtures presently being used in LCDs are eutectic mixtures of chemically and photochemically stable mesogens. The material properties of these mixtures are also being tweaked by taking proper components from the structural point of view and by varying the composition.

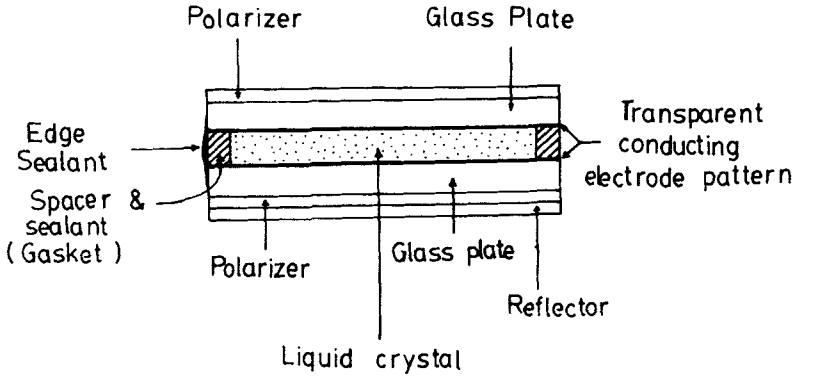
3. LIQUID CRYSTAL DISPLAYS

Now I will describe some of the features of liquid crystal displays. The first generation of liquid crystal displays were dynamic scattering mode displays. This type of display has become more or less obsolete with the advent of twisted nematic displays, except for some special applications. The dynamic scattering mode display is based on the principle of dielectric as well as on conductivity alignment while the rest of LC displays including twisted nematic mode are based on purely dielectric effect. Liquid crystal displays are passive electro-optical displays i.e. they do not generate light but only modulate the light. On application of the voltage on desired segments these areas become visibly different from the rest of the background giving rise to numeric, alphanumeric, dot matrix etc. characters. For the sake of simplicity, description is divided in three parts—1st materials and assembling process, 2nd operational principles and 3rd addressing of liquid crystal displays.

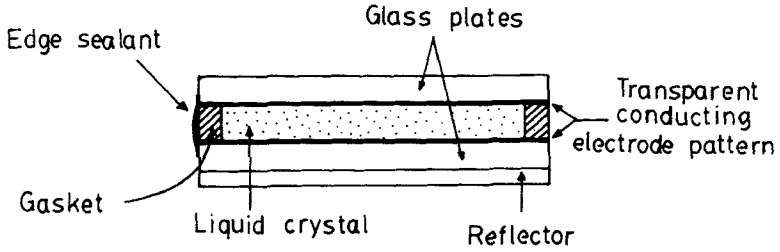
3.1 Materials and assembling process

In this section we will briefly describe the materials, technique and fabrication processes of LCDs. Most of the materials and fabrication processes are common to all types of LCDs such as twisted nematic, dichroic, dynamic scattering, smectic, bistable, etc. The fabrication process and materials will be discussed mainly in light of twisted nematic mode LCDs as it comprises over 99% of LCD market section. However, mention will be made in the text especially for other types of displays where their material and assembling procedures differ from those of TN mode.

The schematic diagram for standard LCD cell is shown in Figure 4. All types of LCDs contain glass plates with desired electrode patterns, alignment coating, liquid crystal material, spacer, sealant and reflector in reflective displays. TN displays, in addition to these, require polarizers.



(a) TWISTED NEMATIC DISPLAY



(b) DYNAMIC SCATTERING & DYE PHASE CHANGE DISPLAYS

FIGURE 4 Schematic diagram of a liquid crystal display.

3.1A Substrate Glass

For most of the LCDs, specially those operating in normal room conditions, the properties of substrate glasses are not especially demanding. In fact, most of the commercial LCDs are fabricated with sodalime glasses having composition similar to normal window glasses. However, flat glass surface is needed to maintain the thickness uniformity of the liquid crystal film in the cell and hence vertically drawn glasses are preferred over standard sheet or float glasses.

Sodalime glasses contain a lot of Na and other alkali ions which have a tendency to migrate on the surface. In adverse conditions (such as high temperature, high humidity inside the cell, imperfect hermetic sealing allowing the moisture to penetrate inside the cell), the migration of Na ions from interior to the surface is greatly enhanced and it forms a conducting layer with moisture on the surface of the glass. This migration of Na ion and conducting layer formation causes the problem of (i) blooming or fattening of the digits due to voltage sharing between the conducting glass surface in between the electrode patterns (ii) loss of alignment (iii) a little increase in power consumption. The first two problems become very serious for outdoor displays operating in severe conditions (high humidity and high temperature) and thereby shorten life of displays drastically. These problems can be greatly overcome by using a blocking layer of SiO_2. SiO_2 blocking layer is coated on the substrate glass either by dip and fire method or by sputtering technique. Mostly SiO_2 layer is put underneath the indium tin oxide coating which is preferable also to get better blocking. However, in some cases it is being put on the electrode patterns. The sputtered SiO_2 undercoated glasses are normally recommended for vacuum filling only. In drop filling method air bubbles are found in the cell frequently when sputtered SiO_2 undercoated glasses are used. The exact mechanism is not known and subject needs some basic research work to be done. However, author feels it is absorbed gases by SiO_2 which are released. In drop filling it remains inside the cell. In vacuum filling most of the absorbed gases are already evacuated in the chamber and remaining little portion is absorbed by the liquid crystal in the cell which is unsaturated with gases in vacuum filling. SiO_2 barrier coated glass plates by dip and fire method are not found to create such problems. Another way of removing the problems caused by alkali ion migration is to use borosilicate glasses containing least amount of Na ions (such as Corning 7740, 7059, etc).[23]

Watch industry generally uses SiO_2 barrier coated sodalime glasses with thickness 0.012″ to 0.020″. Calculators generally use sodalime glasses or SiO_2 undercoated sodalime glasses with thickness 0.020″–0.048″. Large area displays generally use glasses with thickness 0.020″ to 0.062″. An increasing practice is to use thicker glass on the front to provide the mechanical

strength and support and to use thinner glass on the back to reduce the parallax caused by the shadow.

Borosilicate glasses, containing no or least amount of sodium and other alkali ions, provide longer life to display compared to those using SiO_2 barrier coating and hence, in spite of their cost, their use is increasing in displays requiring stringent operating conditions. Use of plastic sheet substrate in place of glass plates have been proposed recently.[24,25] Though still in laboratory stage, plastic sheets have several advantages over glass plates such as no alkali ions, flexibility of moulding in any form, surface uniformity, low cost, less breakability, etc. and may eventually become a commercial reality. The main problem at present is to get nonbirefringent, nonreactive (with liquid crystals) rigid plastic sheets with commercial availability at low cost.

3.1B Transparent and Electrically Conducting Electrode Patterns

The electrode patterns in LCDs are required to be in the form of a thin transparent electrically conducting coating well adhering to the glass. Out of the three most commonly known materials indium oxide, tin oxide and cadmium stanate, only first two are being used in LCD industry. Both tin and indium oxides are degenerate *n* type semiconductor. SnO_2 is either deposited in pure form or containing some percentage of lower element like Sb^{++++}. Indium oxide contains generally 2–20% of Sn in Sn^{++++} form and the coating is generally termed as ITO (indium tin oxide). The thickness of these coatings is ~ 100–500 Å.

These thin, transparent and electrically conducting films can be deposited in a variety of ways: (i) Thermal evaporation[26] (ii) reactive sputtering[27] (iii) chemical vapor deposition[28] and (iv) pyrolytic decomposition.[29] Indium tin oxide generally has lower sheet resistance (10–300 Ω/cm^2) than tin oxide (150–1000 Ω/cm^2). Both have high light transmission (> 80%) throughout the visible region with ITO being slightly better. ITO is most commonly used electrode film for LCD industry. However, tin oxide films are less expensive, more durable and chemically resistant. The pyrolytic deposition of tin oxide lends itself to continuous processing in belt furnace. However, high temperature (400–550 °C) deposition of SnO_2 results in some nonuniformity in surface structure, more migration of Na ion on surface, etc. Consequently, SnO_2 approach has been adopted by few manufacturers who have very high volume throughputs of low complexity watch and calculator displays. The etching procedure of ITO is easy compared to tin oxide which requires a reduction reaction by nascent hydrogen using Zn dust + dilute hydrochloric acid. ITO can be easily etched in a hot aqueous HCl + HNO_3

bath. Mechanical agitation or bubbling by nitrogen or hydrogen of acid results in a better, uniform and consistent etching. Sometimes (generally in glass frit sealing method), partially oxidized ITO is used which is extremely convenient in etching.[30] The patterns turn in fully oxidized ITO at high temperature baking during sealing.

The electrode patterns on front and rear glass plates are designed in such a way that in assembled cell they overlap each other only in a desired information format. In rest of the visible area of the cell, the connecting leads and patterns of front and rear electrodes do not overlap each other. A simple electrode pattern for $3\frac{1}{2}$ digit display is shown in Figure 5. The sheet resistivity of transparent conducting electrode patterns for short leads is not very critical for direct drive or low level (2–4 level) multiplexed display as the resistance of liquid crystal ($> 10^{10}\ \Omega/\text{cm}$) is much higher compared to

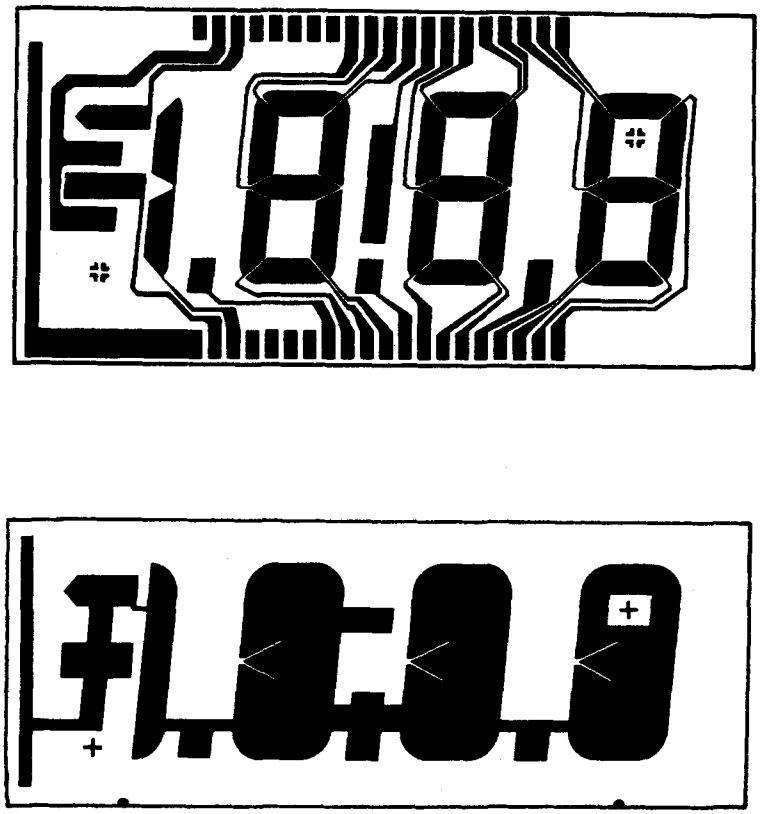


FIGURE 5 Electrode patterns for a $3\frac{1}{2}$ digit display.

ITO or SnO_2 (sheet resistivity ~ 200 Ω/cm^2). However, for dot matrix displays with long narrow leads, the low sheet resistivity is advantageous. Generally seven segment, 14 or 16 segmented alphanumeric, dot matrix and enunciator type electrode patterns are formed. 7″ × 7″ and 14″ × 14″ ITO coated glass plates, suited for LCDs, are available commercially.[30]

The electrode patterns on the substrate glass plates can be formed (i) by screen printing or photolithographically covering the desired portion of the ITO coating on glass and chemically etching the unwanted portion, (ii) by deposition of transparent conducting coating materials like ITO, SnO_2 on desired portion of the glass by covering rest of the portion either by mask or some ink (iii) by fixing suitable screen printed organometallic materials on glass and curing it at high temperatures. Almost 100% LCDs electrode patterns are being made using technique (i) i.e. by using photolithography or screen printing and then etching out the undesired portions of the ITO. Photolithography, using UV curable positive or negative photoresists, gives better and finer line definitions.

3.1C Alignment and Aligning Materials

Some of the alignments commonly adopted by the liquid crystals are shown in Figure 6. These alignments are achieved by the cooperative ordering of the liquid crystal molecules locally affected by the surface forces. A lot of research has been made to understand the physical phenomena but still it is largely empirical.[31-33] In most of the liquid crystal displays, either homogeneous or homeotropic alignment is needed. In homogeneous alignment the liquid crystal molecules remain parallel to the glass plates while in homeotropic alignment the molecules are perpendicular to the electrode surfaces. In most of the cases like twisted nematic displays, the homogeneous alignment should be unidirectional i.e. all the local directors should be oriented in the same direction.

The earliest homogeneous alignment generating materials were dilute solutions of long chain polymers such as polyvinyl alcohol (PVA), polynuclear dicarboxylate chromium complexes, proper silanes (such as *N*-methyl-3 aminopropyl trimethoxysilane, phenyl and diphenyl tri alkoxy or chlorosilanes). A thin layer of these materials is applied on the glass substrates having electrode patterns and then buffed unidirectionally.[31,32,34-36] Janning first demonstrated that oblique evaporation of variety of materials such as gold, SiO, MgF_2 could create homogeneous alignment.[37,38] This approach was followed very enthusiastically in watches and calculators as SiO alignment layer was compatible with hermetic glass frit sealing which was badly needed for the long life of display due to nonavailability of extremely stable liquid crystal mixtures at that time.

However, evaporated alignment film procedures suffered from three limitations: (i) process does not produce unidirectional low tilt geometries of LC molecules, crucially needed for multiplexed displays, unless two stage complex evaporation process is employed,[31,39,40] (ii) the process is not suitable for high manufacturing throughputs and (iii) because of the oblique evaporations at critical angles, process is not suitable for large area displays. The polymer coating and unidirectional buffing procedure generates a low tilt (2–5°) unidirectional alignment of liquid crystal molecules and is extremely useful for mass scale production. With the advent of very stable liquid crystal mixtures such as biphenyl and phenylcyclohexanes, the need of perfect hermetic sealing by glass frit has been relaxed and nowadays most of the displays have homogeneous alignment by polymeric coatings, buffed unidirectionally. PVA produces good homogeneous alignment but is susceptible to moisture. Silane makes only a monolayer alignment film and so is not extremely reliable. In later period of seventies polyimides have been introduced as alignment layer. Nowadays most popular alignment material is polyimide.[41,42] SiO is still being used in most of the watch displays and PVA is still being continued by some companies in large area displays. Homeotropic alignment in nematics and smectics is obtained by treating the glass surface by lecithin, suitable carboxylatochromium complexes, silanes containing long alkyl chains (such as DMOAP, steryltriethoxysilane, steryltrichlorosilane, etc.)[31,34] However, in most of the LCDs where homeotropic alignment is needed (i.e. phase change type dichroics, dynamic scattering, etc.), the degree of perfection of homeotropic alignment is not

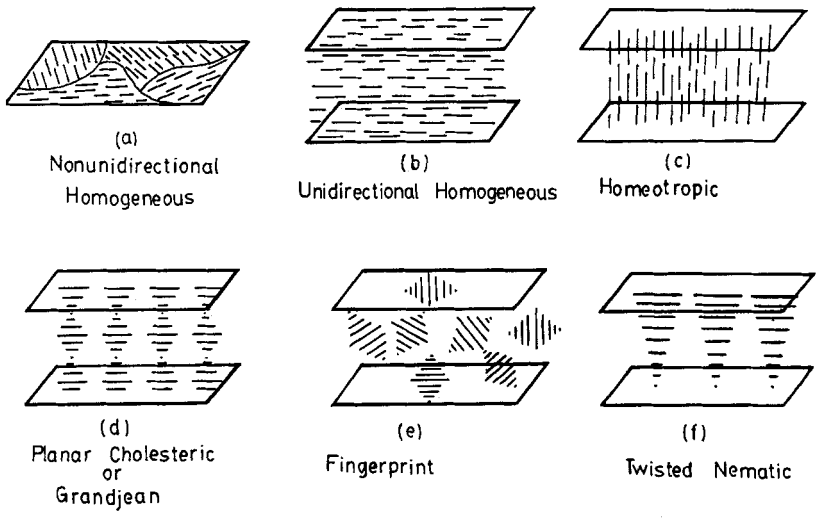


FIGURE 6 Various types of alignments for liquid crystal displays.

extremely critical. Quasi homeotropic alignment can also be achieved by oblique evaporation of some dielectrics and then treating with suitable surfactants.[31,43] Glass plates also generate weak homeotropic alignment if they are pretreated with strong acids.

Out of many textures of cholesterics,[44] the important textures from display point of view are finger print and Grandjean (also called as homogeneous or planar). In the Grandjean texture, the helix axis is perpendicular to the electrode surface and long molecular direction in each layer is oriented parallel to the surface with its orientation varying in helical fashion from one layer to other.[6-10,44] This type of texture in cholesterics is obtained by treating the surface with homogeneous aligning surfactants. In the fingerprint texture, local helix axes are randomly oriented. This is achieved by treating the electrode surfaces by homeotropic aligning agents.

The alignment is particularly dependent on the surface structure of the substrate and nature of liquid crystal material.[31] Usually liquid crystal mixture adopts only one type of texture on the uniformly treated substrate in the entire nematic, smectic or cholesteric phase except in the vicinity of transition temperature.

3.1D Sealing and Spacer Materials

LCDs contain a thin layer of liquid crystal material sandwiched between two substrate glasses containing electrode patterns and alignment layer. The thickness of the LC layer controlled by the spacing in between the substrate glasses varies from ~ 3–50 μm, with a commonly used value of ~ 5–25 μm, depending on LCD. In most of the TN cell the spacing is kept ~ 6–10 μm depending on the birefringence of the LC mixture. However, in high level multiplexed displays spacing as low as 2.5 μm have been utilized.

Presently in most of the direct drive and low level multiplexed displays, the sealing material acts as a sealant as well as the spacer. This approach occasionally leads to significant thickness nonuniformity in the cell causing coloured fringes, zones of different response and contrast in the cell. Hence, nowadays use of dispersed spacers (glass fibres, glass beads) inside the cell, to control and maintain the thickness of LC layer and its uniformity, is increasing even in simple LCDs. In case of high level multiplexed displays where the performance of the cell is critically dependent on the thickness of the LC layer and its matching with the birefringence of liquid crystal (usually $d\Delta n = 2\lambda$ but in some cases first minima of circularly polarized light),[45,46] the use of glass fibre or glass bead is a must. The glass fibres are preferred over glass bead due to better thickness uniformity and low cost.

The choice of sealing materials are limited by the need for compatibility with liquid crystal and a fairly hermetic, strong and moisture tight seal. Moisture penetration not only increases the current drain, deteriorates the

alignment (in few cases like PVA) and liquid crystals (like Schiff bases, esters, etc.) but also increases the fattening of digits. The best hermetic sealing is glass frit sealing. So after the failure of early LCDs because of the noncompatibility of Schiff base and ester based LCs with epoxy sealing for high performance, glass frit sealing with SiO alignment approach was favoured. However, with the advent of extremely stable liquid crystals, improved organic sealing, SiO_2 barrier coated or low sodium glasses, the pendulum has swung back to the inherently lower cost thermoplastic or thermosetting type organic seal approach which also puts fewer constraints on the rest of fabrication processes.

A typical glass seal is formed by screen printing a thick film paste of fritted lead borosilicate glass dispersed with organic binder and printing vehicle.[47] The organic material is evaporated and charred first before cell plates could be sealed. Both of these processes are done in conveyor belt furnaces.

Organic polymer seal materials are also printed by screen printing. They require a brief curing (~ 10 minutes) at 180–200 °C to drive off the solvents before sealing at 120 °–150 °C.[41,48] The low temperature operation of organic polymer sealing is advantageous in not only cost but also from many other ways such as compatibility with polymeric alignment, no deformation of the glass substrate, less Na ion migration, etc. Usually the organic seal compositions are in-house developments, proprietary to the LCD manufacturers.

3.1E Crossover Materials

To take all the electrode leads on one plate, it is usual practice to screen print or dot a conducting internal interconnect or crossover which connects the electrode traces of back plane electrodes to the front glass. Either a silver powder + glass frit conducting paste or a silver loaded epoxy is used, depending on the peripheral seal material. Recently, use of conducting gasket material as interconnect as well as spacers is increasing. Fine silver powder is dispersed in thermoplastic material in a small proportion and conductivity of the gasket is kept such that it makes a good contact in between the interconnects and offers very high resistance in between the electrode patterns of the same plate. The use of low percentage of conducting particles (silver powder or glass fibre coated with conducting material) with the exact diameter of desired spacing of the cell leads to extremely satisfactory results.[41]

3.1F Polarizers and Reflectors

Polarizers are the weakest link in TN LCDs subject to bleaching, delamination and air bubbling at high temperature, high humidity levels which can

be easily tolerated by other parts of the device. Moreover, they are subject to scratches and other cosmetic blemishes and represent an appreciable portion of both materials and device assembly expense.[49] They also reduce the brightness of the LCDs by over 50%. In fact an ideal polarizer (100% of polarization efficiency) cannot transmit more than 50% of the light. The efficiency of the polarizer decreases significantly when transmission increases over 40–45%.[50,51] The contrast ratio of the display is greatly dependent on the polarization efficiency of the polarizer and brightness is dependent on transmission of polarizers both of which are to some extent contradictory.

Most of the polarizing films used in LCDs are a multi-layer sandwich of iodine containing stretched PVA between sheets of cellulose acetate.[50,51] In case of coloured polarizers, dyes are embedded in place of iodine. Dyes are also being used in place of iodine to enhance the life of neutral gray polarizers. However, the polarization efficiency of dye based polarizers are low compared to iodine based polarizers. In most of the cases polarizers contain an acrylic adhesive and protective plastic layer on the top of cellulose acetate. Reflective polarizers contain a brushed or beaded aluminum foil and transreflective polarizers contain a transreflective aluminum film on the back of the polarizers. There are only four major suppliers of polarizers; namely Nitto, Sansitsu, Polaroid (without glue) and Hoeschst; whose product has essentially not changed during the last few decades.[52] However, during the last few years some improvements have been made by these companies to enhance the life of the polarizers. New high humidity temperature resistant, high reliability polarizers (such as with life ~ 1,000 hours at 80°C/95 RH and ~ 10,000 hours at 90°C in dry air) are available.[52] These polarizers are now being used in LCDs operating in stringent conditions such as automobile, gas pumps, military, etc. Sansitsu has also developed multicolour polarizers for use in coloured displays.[52]

Phase change type dichroics do not need polarizer but need a diffuse white reflector (in some cases transreflectors). This is done by either using diffuse white reflectors available commercially[52] or putting a paste of TiO_2, $BaSO_4$, etc.

Dynamic scattering displays also do not require polarizers. They require a diffuse aluminum reflector or transreflector. The recent psychometric studies on polarizers are also resulting in development of improved and optimized polarizers for LCDs.[53,54]

3.1G Liquid Crystal Material Requirements

Liquid crystal material is the heart of display. Generally used commercial LC materials contain ~ 4–10 individual compounds, mostly mesogens, mixed in certain proportions to satisfy the display requirements. The

physical properties of the mixture depends on the properties of the components. General material requirements are:

(i) Chemical and photochemical stability.[14,55,56]

This is achieved by taking stable mesogens to form the mixture. As mentioned in earlier section it has been found that compounds having no unstable central linkage such a biphenyl, terphenyls, dioxane, phenylcyclohexane, bicylohexane, biphenylcyclohexanes, pyrimidines, etc. are extremely stable. So present day mixtures contain mostly these components.

(ii) Wide temperature range

Display operation requires wide temperature range mixtures. This is achieved by making eutectic mixtures. Now commercial mixtures are available operating from $-40°$ to $+85°C$ or $-20°C$ to $+110°C$.[56]

(iii) Pitch

Liquid crystal materials in TN mode are nematic. However, to avoid the reverse twist problem, nematic mixtures are doped with a small amount of cholesteric to make them long pitch cholesteric.[14,56] The amount of doping (0.5–1% by C-15 and 0.05–0.2% by CB-15 or cholesteryl esters) is not extremely critical. However, it has been found that proper relation of pitch with cell spacing results in faster display.[57,58] It has been also found that lowering the amount of cholesteric and keeping it at absolute minimum is advantageous for multiplexed displays.[55] Moreover, the matching of the sense of pitch with tilt directions results in a tilt free wide viewing angle display. However, dichroic displays require much smaller pitch compared to TN.

(iv) Dielectric Anisotropy

TN mode and phase change type dichroics require a material of positive dielectric anisotropy ($\sim$ 4–15) while dynamic scattering display requires a material of negative dielectric anisotropy (-0.5 to -5.0). Most of other type of LCDs also require a material of high positive dielectric anisotropy. A LC mixture of positive or negative dielectric anisotropy can be made by taking constituents mesogens mostly of positive or negative dielectric anisotropy respectively. A mixture of positive dielectric anisotropy can be also made by taking an eutectic mixture of small negative (or small positive) $\Delta\epsilon$ and then doping it with desired amount (generally $\sim$ 5–15%) of a material of very strong positive dielectric anisotropy (such as PEBAB, cyanoesters, cyanobiphenyls, etc.).[59] Up to small amount (0–20%) of doping, the dielectric anisotropy of the mixture increases almost linearly with the % of

dopant[59] after which it starts getting saturated. The dielectric anisotropy of mixture can be easily adjusted to desired value of operating voltage by using this approach. Nowadays the use of two bottle system, each mixture having different $\Delta\epsilon$, is increasing for multiplexed displays to make desired intermediate mixtures suitable for a particular drive circuitry.[56] In a multicomponent mixture, some components may have negative dielectric anisotropy and this may favour in fact a good device performance.[55] In multiplexed displays it has been found that low $\Delta\epsilon/\epsilon_\perp$ leads to better performance of display.[55,60]

(v) Birefringence

The birefringence of liquid crystal mixture plays an important role in TN mode. This parameter is specially sensitive in multiplexed displays where it should be matched to the thickness of liquid crystal layer (i.e. cell spacing, d) by the relation of $d \cdot \Delta n = 2\lambda$ where λ is the wavelength of the visible light (0.4–0.7 μm). $d \cdot \Delta n < 2\lambda$ leads to colour while $d \cdot \Delta n > 2\lambda$ leads to the narrow viewing angle especially in multiplexed displays. Attempts have been also made to use low birefringence material and apply the relation $d \cdot \Delta n = \sqrt{3/4}\lambda$ for high level multiplexed displays.[46] Generally for direct drive display, matching is not very critically assured and $d \cdot \Delta n$ is kept $\geq 2\lambda$..

Low birefringence materials with high positive dielectric anisotropy and order parameter are needed for dye phase change type displays.[61]

(vi) Viscosity

Viscosity of LC mixtures (as measured by Ostwald viscometer and most commonly cited) lies ~ 15–100 cps at room temperature. As response time of cell is directly proportional to the viscosity,[62,63] low viscosity materials are preferred.[64] Author also feels that low viscosity also reduces the threshold and operating voltage though there exists no direct mathematical relationship.

Viscosity, η, increases exponentially with $1/T$ i.e. $\eta = \eta_0 \exp(-E/kT)$. Hence for operating displays at low temperatures, it is important that it should be filled with a mixture which not only has low viscosity at room temperature but also small temperature coefficient of viscosity (i.e. low activation energy E).[64] It is rotational viscosity, γ_1, which is important for display operation.[60,64,65] However, as γ_1 is usually proportional to $\eta_{\parallel}$ measured by Ostwald viscometer and measuring γ_1 is cumbersome,[64,65] generally $\eta_{\parallel}$ is referred for all practical purposes.

A less viscous mixture can be made by taking low viscous components. It has been found that globular molecules such as phenylcyclohexanes, bi-

cyclohexanes have lower viscosity compared to esters, biphenyls, pyrimidines, etc.[56] Most of liquid crystal mixtures having biphenyl, pyrimidines, Schiff base, ester, etc. work pretty well up to $-10\,^{\circ}C$. However, their viscosity increases drastically at low temperature side making displays too sluggish to operate. Hence for low temperature operation phenylcyclohexane, bicyclohexane, cyclohexane esters, dioxane based mixtures are preferred.[56,60,64]

(vii) Elastic Constants

Liquid crystals possess weak elastic constants ($\sim 10^{-6}$ dynes cm^{-1}) leading to their easy orientation by low fields.[17] For multiplexed operation it has been found that low value of K_{33}/K_{11} is beneficial.[55,64,66] This is achieved by doping liquid crystals by long chain alkyl group containing molecules (such as dialkylbenzoate esters).[56]

(viii) V_{th}, V_{op} and Its Temperature Dependence

Nowadays, liquid crystal mixtures are tuned according to the drive circuitry available (drive circuitry and chips also have some flexibility). The easiest way of doing it is to adjust V_{th} and V_{op} of the mixture according to the voltage available from the drive circuit.[56] This is done by adjusting $\Delta\epsilon$ (mainly) and other physical parameters.

By proper blending the mixtures various properties critical for display operation such as $\Delta\epsilon$, Δn, pitch, η, etc. could be adjusted to desirable extent.[56,67,68] K_{33}/K_{11} could be adjusted to some extent. However, each of these parameters cannot be adjusted fully independently i.e. usually improvement in one parameter results in some adverse effect in other parameters.[67,68] So compromises have to be made. The adjustment in these physical properties ultimately result in adjusting V_{th}, V_{op} and their viewing and temperature dependence. For multiplexed displays, nowadays the use of two bottle system is increasing.[56]

(ix) Dichroic Dyes.[69-80]

Dichroic dyes are needed for guest host and phase change type dichroic displays. Sometimes they are also used in S_A displays. The requirements, from dyes point of view, for a good operating display are (i) high order parameter (0.75–1) (ii) high solubility and compatibility in liquid crystal host (iii) nonionic nature (iv) high chemical and photochemical stability (v) high absorption coefficient and pleasant colour. The order parameter of dye depends on its elongated structure, as well as on the order parameter of the host material. Therefore LC material used in dichroic displays are generally taken to have higher nematic–isotropic transition temperature giving rise to

higher order parameter at room temperature. Besides high order parameter of LC mixture, its low birefringence and high $\Delta\epsilon$ are advantageous.

The two families of dyes used in GH LCDs are azo[69,74-79] and anthraquinone.[69-71,79,80] Azo dyes have all the advantages over anthraquinone dyes except for chemical and photochemical stability which is extremely critical for life of display. Hence azo dyes are losing the ground. A lot of research is being made on anthraquinone dyes to improve their performance. Still azo dyes, with the use of UV lacquer, find some applications in GH LCDs.[75,79]

3.1H Connectors

For making the electrical contacts with PCB, either snap-in pin connectors or zebra connectors are being used.[81,82] Pin connectors are generally used when electrode density is not much (generally 10 pin per inch, in some cases 20 pins per inch) and zebra connectors are used when electrode density is large.

Though not very popular, in some cases to avoid the contact problems and PCB, driving chip is directly mounted on the substrate glass itself (chip on glass approach).[83]

Spring action snap-in connectors, firmly held in plastic base, do not require conductive dotting electrode patterns. They firmly hold the glass, but contact electrode patterns are exposed to environment. Lead frame type of connectors need additional silver epoxy dotting and fixation by putting epoxy layer. However, in this case electrode patterns are covered by epoxy and not exposed to environment.[84]

3.1I Antiglare, Refractive Index Matching, etc. Materials

Antiglare and refractive index matching materials are not required for normal LCDs. However, their use leads to better optical performance of the displays.

Specular reflections result because of the reflection of incident light from various layers of LCDs having significantly different refractive index from adjacent layer. To reduce the specular reflections (especially in dichroics) from air glass interface either spraying of antiglare material or vacuum deposition of desired thickness of MgO (generally called high efficiency antiglare coating or HEA) is done on the front glass. Glasses are also commercially available with HEA coating on front or HEA on one side and ITO on other side. In case of TN LCDs, HEA coating is generally not needed as impact of glare is reduced considerably because of reduction of brightness by polarizers (by over 50%). In some cases mitten or antiglare coated polarizers are used. For military applications HEA coating is demanded even in TN mode.[84]

Another interface which reflects significantly and differentially is glass ITO, sometimes strongly reflecting the electrode patterns. This can be reduced by using an undercoating material having refracting index in between glass and ITO (1.5 for glass and 1.7 to 2.0 depending on ITO). To reduce the specular reflections of electrode patterns, sometimes a coating of Si/Ti liquicoats is used on the top of electrode patterns and is then fired.[41]

3.1J Fabrication Process

Figure 7 shows almost all the possible routes by which LCDs can be fabricated. However, still LCD fabrication is an art and different manufac-

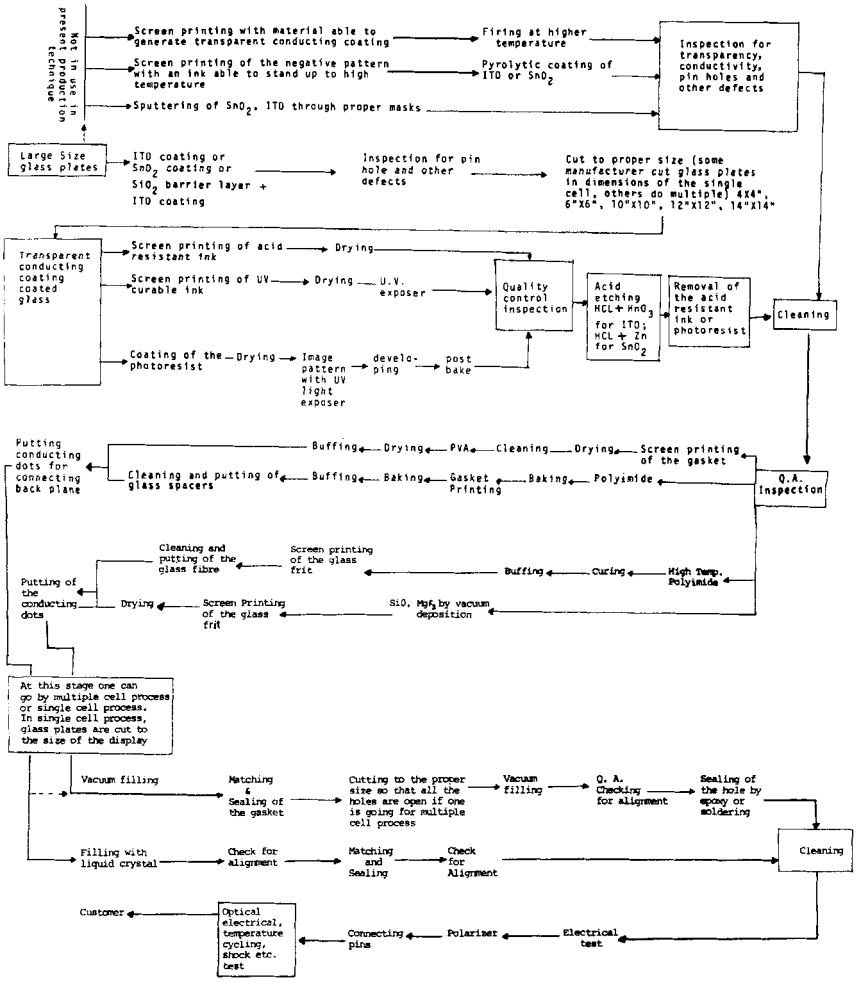


FIGURE 7 Flow chart for manufacturing of liquid crystal displays.

turers use different techniques. Some of the processes shown in Figure 7 may be slightly alternated in single cell and multiple cell approach. Multiple cell and automated batch processing approach eliminates human handling at several stages and not only reduces cost and increases yield but also improves the quality of the display. So multiple cell batch processing of $7'' \times 7''$ and $14'' \times 14''$ plates (also called as quarter and full plate) is gaining favour over single cell approach.[85]

All the Japanese and far east companies use multiple cell batch processing approach.[49,85] Although Japanese did not originate the concept of multiple cell batch processing fabrication approach of LCDs, they have advanced it and automated handling to a far greater degree than manufacturers in US, Europe or other far east countries. However, still some small companies in Europe and North America are following single cell approach because of low initial capital cost and flexibility for handling several sizes of custom displays.

For simple lab demonstration, one can use thermoplastic sheet or spacer, PVA alignment, unidirectional rubbing by cotton swab, silver epoxy dotting, drop filling, clamping with ordinary paper clip and sealing in oven, cleaning and then putting polarizers. Most common mass scale (far east watch LCDs and Japanese manufacturers)[49,85] production employs the following procedure:

$7'' \times 7''$ or $14'' \times 14''$ ITO coated glass → cleaning → pattern designing by photolithography → cleaning → alignment film deposition (polyimide) → gasketing → crossover → buffing → glass fibre spacer → sealing → cutting in strips of displays or single displays → vacuum filling → plugging of hole → cleaning → lamination of polarizer → mounting of pin connectors → visual and electrical testing → customer.

Some of these processes are discussed below:

(i) Glass Cleaning

Glass cleaning operation is most critical. Poorly cleaned and contaminated glass surfaces not only reduce the yield but also compromise the performance and life time of the display devices.

$7'' \times 7''$ or $14'' \times 14''$ cut glasses are put in racks. These racks are loaded into cassettes and sequenced through a series of cleaning baths (i.e. aqueous solutions of detergent and alkali, deionized water, organic solvents and sometimes vapour degreasing too in addition of these). Use of strong ultrasonic agitation facilitates the cleaning.

(ii) Electrode Film Patterning

For low resolution displays screen printing of acid resistant ink or positive photoresist (sometimes even negative photoresist) on substrate glass is

preferred. Glass is dried and then immersed in etchent (usually the temperature of bath and acid concentration is kept fixed) which removes the unprotected film. A stripping and cleaning process follows leaving behind the desired electrode patterns on the glass.

For high resolution and complex displays, photolithography, using positive or negative photoresist, is preferred. Because of easy cleaning and handling, the use of positive photoresist is increasing for LCD manufacturing (in screen printing as well as in photolithography).

The batch processing means that each glass plate will bear an X-Y array of many cell patterns. These arrays consist of only one pattern (i.e. front or rear electrode pattern) or both.

(iii) Alignment Film

After patterning, glass plates have to be cleaned thoroughly. It is extremely essential for good sticking of alignment layer on the glass. Sometimes glasses also go through a silane adhesion promoter treatment. Polyimide resins or PIQ are put either by spin coating, dip coating or offset printing. A thick polyimide causes bonding problem. So either a thin polyimide is used or photodefinable polyimides are used and removed from peripheral seal area.[41] A thin polyimide layer is being preferred to avoid the voltage drop on the liquid crystal layer due to polyimide dielectric layer. Polyimides are then cured to remove the organic solvents.

(iv) Gasketing and Crossover

An array of peripheral seal patterns are screen printed using thermoplastic or epoxy sealing materials. After precuring to remove the solvents, dots of silver loaded epoxy is printed as crossover on complementary plate and then it is baked.

(v) Buffing

To give unidirectional low tilt alignment, the alignment film is rubbed or buffed unidirectionally by cotton or polyester roller. Some companies prefer rubbing first and then printing gasket and crossover materials. Some buff after gasketing and then autodot crossover materials.

(vi) Cell Spacers

In order to maintain thickness uniformity of LC layer, glass fibres or ceramic spheres are distributed on the glass plates.[86] They may be either spun in a fluid dispersion or may be put by dipping in a solution containing fibres.

(vii) Assembling Front and Rear Glass Plates

The two cell plates arrays (containing complementary electrode patterns) are registered by mechanical or optical alignment techniques secured in fixtures and then sealed under pressure and temperature. Generally several pairs of such glasses are piled over each other and then a calculated clamp pressure is applied uniformly over the glass surface. Curing of seal takes place between 125–200 °C depending on the thermoplastic material and may take half an hour to several hours. Pressure forces the cell plates down to a separation of 5–10 μm (depending on the diameter of the spacer).

(viii) Cell Separation and Liquid Crystal Filling

Glasses are then cut in form of strips of displays, keeping the end holes open and on one side, or in form of individual cells. For large area displays (i.e. only a couple of displays per 7″ × 7″ plate) displays are not separated at filling time but after filling and end seal. Usually the cutting is done by a programmable single head scriber with step and repeat capability (such as VPI scriber)[87] or a ganged array. Generally a carbide wheel scriber is used and cell array is scribed on both sides to increase the yield in breaking and separating.

These cells are then stacked properly and put in a vacuum chamber evacuating the atmosphere (up to 10^{-2}–10^{-3} torr) and then submerging the fill hole portions of the cells in a tray of liquid crystal material. In place of tray, some companies use sharp V-shaped LC trough or foam material soaked with liquid crystal to reduce the sticking and wastage of LC materials on the sides of displays. In some older techniques liquid crystal was filled through a plastic fine tubing coming out of the hole in rear plate. Slow back filling of the chamber (sometimes with an inert gas) drives the fluid in evacuated cell and fills it. Generally the filling is done at room temperature but in some cases chamber is heated to reduce the viscosity of LC material for fast filling.

(ix) Visual Inspection

Displays are cleaned and inspected between cross polarizers on a light table. The usual practice is to check by wearing polaroid sunglasses and placing the cells on a polarizer sheet mounted on a light table. Reject cells (due to bad alignment, sealing, etc.) are taken out. Generally the cells are also checked electrically at this stage.

(x) Polarizers and Reflector Lamination

Glued surface of polarizers have protective plastic films. It is peeled off and then polarizers are applied under some combination of temperature and

pressure in multiple fixtures. In case of phase change type of dichroic and dynamic scattering displays only reflector is pasted. Following this, the finished displays are printed or pasted with product and code identification labels and then go for final visual and electrical inspection.

(xi) Electrical and Visual Inspection

Before sending to the consumer, displays are checked visually and electrically. For large area displays, usually the checking is done by individually testing the display on text fixture.[88] However, for small area and very large volume displays testing is automatized.[89]

3.2 Operational principles of LCDs

3.2A Dynamic scattering mode displays

In DSM display[90] the liquid crystal filled is of negative dielectric anisotropy with certain conductivity ($> 10^{-9}$ mhos cm^{-1}). This conductivity is achieved either by doping liquid crystal with certain organic conductors or charge carriers or by the intrinsic impurity in the liquid crystal itself such as moisture etc. Extremely pure liquid crystals do not exhibit dynamic scattering. Either there is no alignment or homeotropic alignment is given. In absence of the field the thin layer of liquid crystal looks transparent. When a low field is applied all the molecules take homogeneous alignment as the dipoles get aligned in the direction of the electric field. Further increase of voltage exhibits Williams domain—a comb type of pattern because of the flow of the charges.[91] On further increase of the voltage, the charge motion becomes turbulent and molecular structure is broken in micron size domains each having different director orientation varying with time and space both. These domains act as scattering centres and the light is scattered strongly in the forward direction. This type of scattering was termed as dynamic scattering.[90] Dynamic scattering mode display operates at slightly higher voltage (10–20 volts) and consumes more power ($\sim$ mW). The back reflector is generally diffuse aluminum reflector. An antiglare coating is sometimes needed on the front surface. As the operation is dependent on charge flow, DSM displays operate only up to low ac frequency ($\sim$ 1 kHz) due to the relaxation of the charged carriers at higher frequencies.[92–95] More details on dynamic scattering displays can be obtained from early literature on LCDs.[96–98]

The next generation of displays is based on purely dielectric effects. It contains twisted nematic mode, tunable birefringence, guest-host, cholesteric–nematic phase change, dye-phase change etc. type of displays. Twisted nematic mode displays are the most popular displays while others are just knocking the door.[2]

3.2B *Twisted Nematic Mode Displays*

(i) General Principle

In twisted nematic liquid crystal cell[99] a thin layer (~ 5–15 μm) of liquid crystal material of positive dielectric anisotropy is sandwiched between the two glass plates containing transparent conducting electrode patterns. These two glass plates are already treated for unidirectional homogeneous alignment, (having alignment directions orthogonal to each other), before sealing and filling the liquid crystal. The top and bottom layers take the alignment according to the surface treatment and intermediate layers adopt the intermediate arrangement according to the distance from these two glass surfaces. The arrangement is such that on going from top to bottom, each layer is skewed unidirectionally (either clockwise or anticlockwise) to its preceding layer such that final (bottom) layer is skewed 90° from the initial

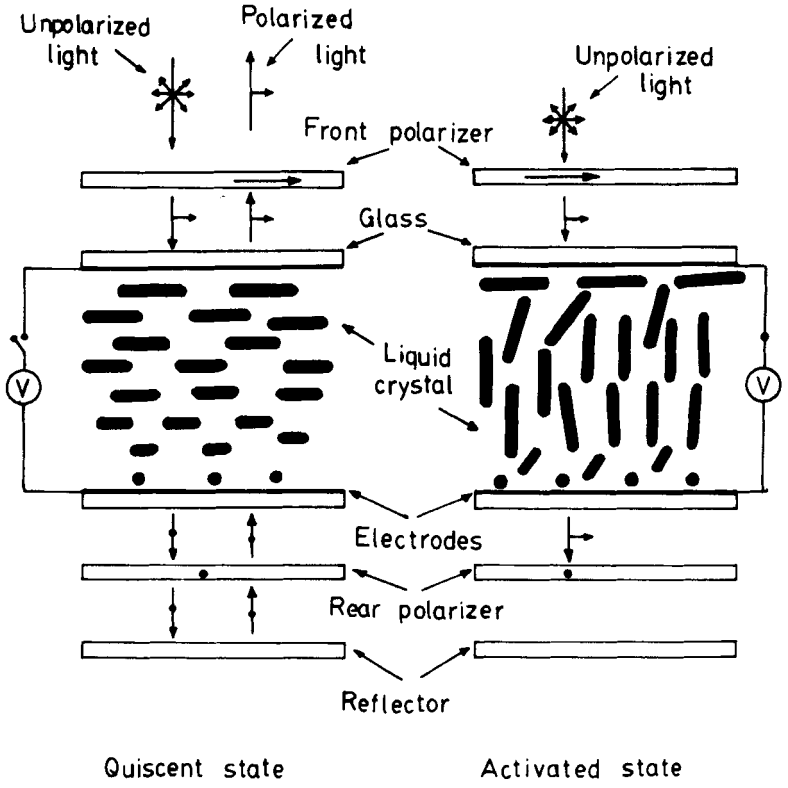


FIGURE 8 Structure and operational principle of a twisted nematic cell.

(top most) layer. Liquid crystals are birefringent so each layer will act as birefringent sheet. This structure consisting of birefringent piles, each pile skewed unidirectionally compared to its preceding layer, can rotate the plane of polarization of light. The structure and the operational principle of the twisted nematic cell is shown in Figure 8.

The unpolarized beam of light after passing through the front polarizer, gets polarized along its polarization axis. The plane of this polarized beam of light rotates as its traverses through the twisted nematic cell. The total rotation of the plane of polarization of the light inside the cell is 90°. If the plane of polarization of the second polarizer is 90° to the first polarizer, the light beam, coming out of the cell, passes through the second polarizer as it has the same direction of polarization as that of the second polarizer and the cell looks clear. In reflective type cell, a reflector is put on the back of the second polarizer to reflect this outgoing light in forward direction. On application of the voltage, liquid crystal molecules align themselves in the direction of the field because of the positive dielectric anisotropy and hence lose the property of guiding or rotating the plane polarized light by 90°. In this case light is transmitted directly without any rotation of the plane of polarization. As the plane of polarization of this light is orthogonal to that of second polarizer, it cuts the passage of light and the area where the electric field is applied looks black. The voltage from the circuitry is applied on the segments which are to be selected to form the desired character and it appears as black character on colourless or neutral gray background. By changing the direction of polarizer i.e. by keeping both the polarizers in the same direction one may get transparent digits on black background.

There are three types of twisted nematic cells (i) transmissive (ii) reflective and (iii) transreflective. In transmissive cell no reflector is used. Depending on orientations of the two polarizers one may get black digits on neutral gray background or transparent characters on black background. In transmissive cells generally transparent character over black background is preferred. In reflective cells a reflector is put on the back of the second polarizer. Nowadays, reflectors are coming laminated with the second polarizer. There are two types of reflectors, aluminum and glass bead. Aluminum reflector is a plane reflector while glass bead is a diffuse. Contrast at 90° viewing is more with aluminum but viewing angle is more with glass bead. Again depending on the orientation of the polarizers with respect to each other, black digits on light background or transparent digits on black background are obtained. Generally, in reflective cells the dark or black digits on light (neutral grey) background are preferred. The transreflective displays are operated as reflective in sufficient ambient light and backlighted in insufficient ambient light. Various types of polarizers are available, 38%, 42%, 45%, 48% and 55% transmission.[52] The polarization

efficiency decreases with increasing transmission[50,51] and characters look dark blue instead of black with high transmission polarizers.

(ii) Threshold, Contrast and Contrast Ratio

The voltage at which the molecules start turning in the central layer is termed as threshold voltage and is given by the mathematical expression,

$$V_{th} = \bar{\Lambda}\sqrt{\frac{k_{11} + (k_{22} - 2k_{33})/4}{\epsilon_0 \Delta\epsilon}}. \tag{3}$$

The above expression is for the capacitative or dielectric threshold. The optical threshold is generally higher (~ 1.5 to 2 times) than the capacitative threshold.[100] The operating voltage is generally ~ 1.2–5 times the optical threshold.

The detection of a particular information by the eye and hence its readability depends on the factor how much contrast is there in between the information and the background. Contrast may be defined as the ratio of the difference in between the symbol and background luminance (or brightness), ΔB, to the luminance (or brightness) of the symbol (or background, whichever is brighter), B,[1,101,102]

$$C = \frac{\Delta B}{B}. \tag{4}$$

In LCDs the more popular term is contrast ratio. Contrast ratio is the ratio of brightness (or luminance) of the symbol, Bs, and background, Bo,

$$CR = \frac{\text{Bo}}{\text{Bs}} \quad \text{(For LCDs exhibiting dark symbol on light background)}$$
$$= \frac{\text{Bs}}{\text{Bo}} \quad \text{(For LCDs exhibiting light or transmissive symbol on dark background)} \tag{5}$$

So

$$C = 1 - \frac{1}{CR}$$

The contrast and contrast ratio both in LCDs are viewing angle and voltage dependent.

The background can be taken as either the off situation of the activated segment or electro-optically inactivated portion of the cell. Usually there is a

small difference in contrast in these two situations. So the contrast ratio of the activated segment is defined as the ratio of the brightness of the segment at V_{90} and V_{th} where V_{90} is the voltage at which symbol gets the 90% of the contrast.

(iii) Viewing Angle and Threshold Characteristic

The optical characteristic of a twisted nematic cell is shown in Figure 9. Depending on the parallel or crossed arrangements of the polarizers in TN

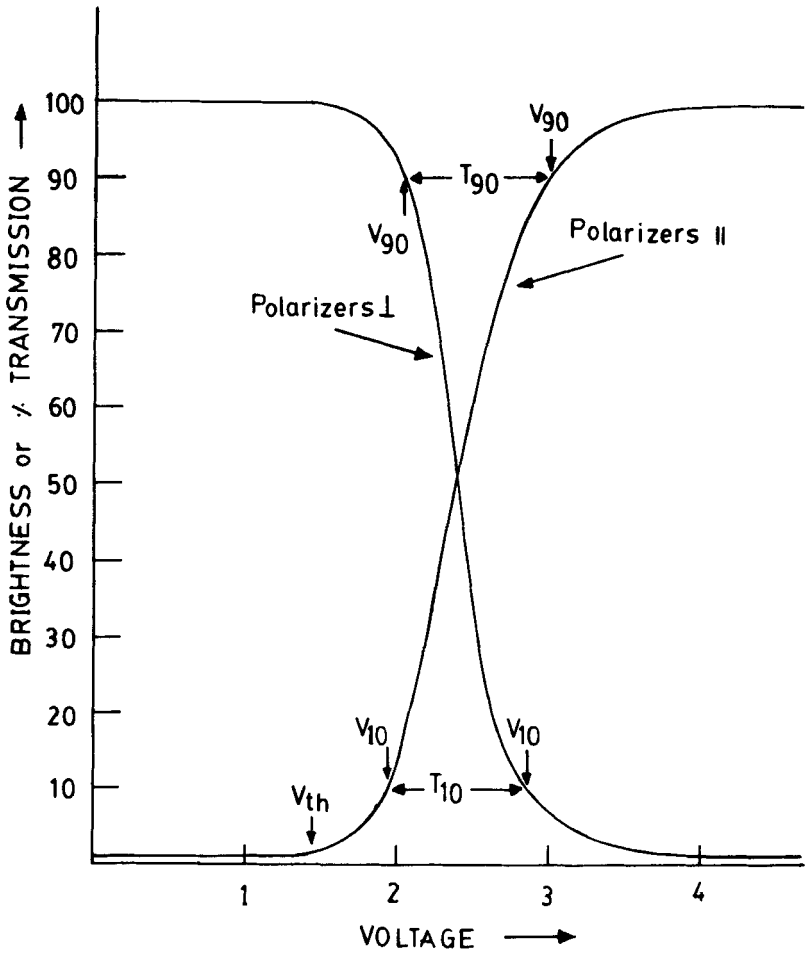


FIGURE 9 Optical characteristic vs applied voltage of a twisted nematic cell.

cell, the transmission increases or decreases with increasing electric field and gets almost saturated near operating voltage. For intermediate voltages between the threshold and the operating voltage, the molecules in the centre of the cell are oriented at a significant angle to the normal of the cell. In a display this generates a principal viewing cone with an off normal axis. If a calculator or watch display is viewed at 45° from the plane of the cell, one will find the principal viewing cone to be in 4:30, 6:00 or 7:30 (o'clock) direction. At 10:30, 12:00 or 1:30 (o'clock) only a shadow image cast on the

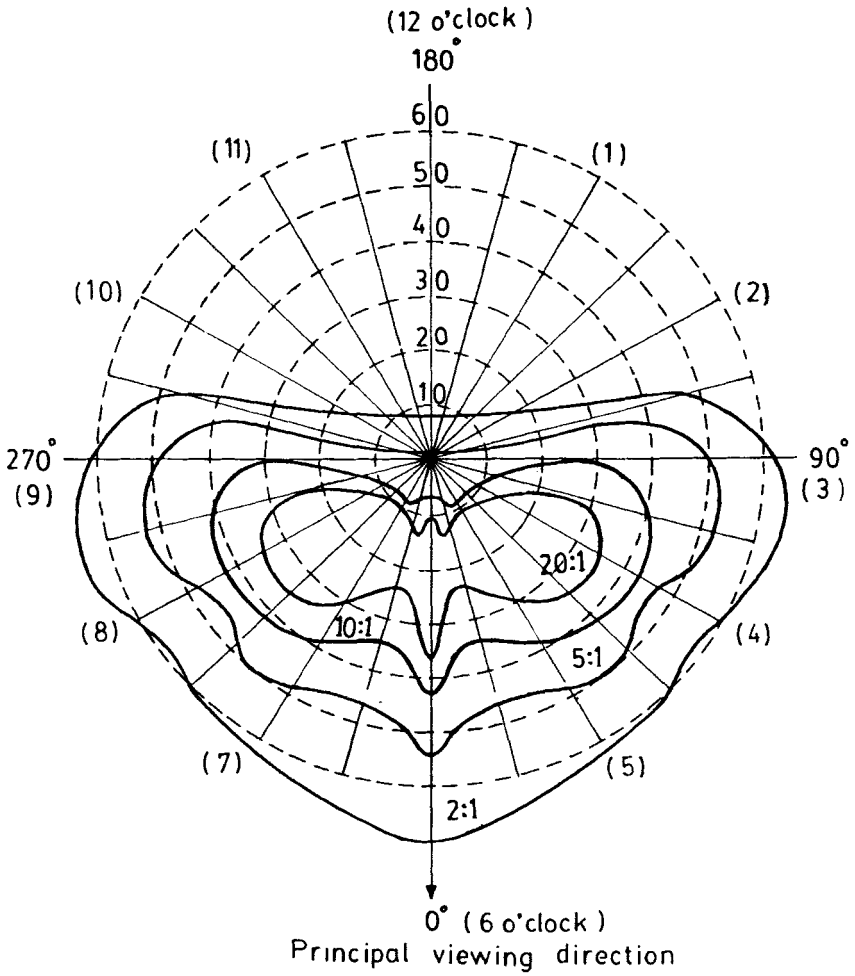


FIGURE 10 Polar plot of a TN mode display for viewing angle and contrast.

reflector would be seen. Figure 10 shows the polar plot of a display (for its contrast and viewing) having the principal viewing direction directed towards 6 o'clock. With increasing electric field not only the molecules in the central layer become orthogonal to the cell but more and more layers, closer to the glass plates, also get aligned in the direction of the field. This increases the viewing angle as well as the contrast (Figure 11). With very high electric field (~ 2–5 times threshold voltage), the viewing becomes more symmetrical to the normal and the display can be seen in all the four quadrants in a significantly wider viewing cone. However, in multiplexed display where operating voltage cannot be kept very high due to cross talk, this principal viewing cone and preferred quadrant become very important. By proper choice of the alignment directions on front and rear plates and the chiral material imbedded in nematic, the preferred quadrant can be generated in a way to give the display the best look.[103]

The threshold characteristic of a TN cell varies with viewing angle as well as with temperature[55] (Figures 12 and 13). The threshold and operating voltages generally decrease as the viewing angle increases from normal in the best viewing quadrant and increase as the viewing angle increases from the normal away from the best viewing quadrant. Threshold and operating both voltages have a negative temperature coefficient i.e. both of these decrease on going above room temperature and increase on going below room temperature. Generally these values lie between -5 to -20 mV/°C depending on the mixture. Temperature variation of the threshold and operating voltages for a mixture are nearly equal though they need not be the same. Recently Gerber have reported some mixtures where dV_{th}/dt is zero over a considerable temperature range.[67,104]

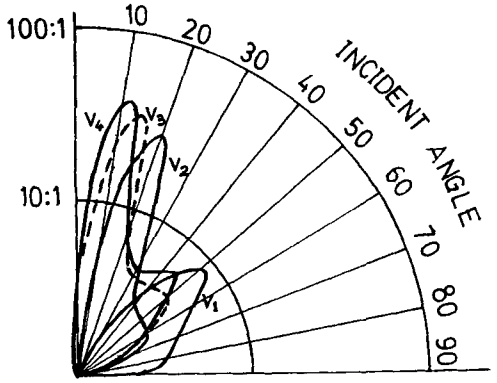


FIGURE 11 Effect of voltage on viewing angle and contrast of a TN mode display in principal viewing quadrant.

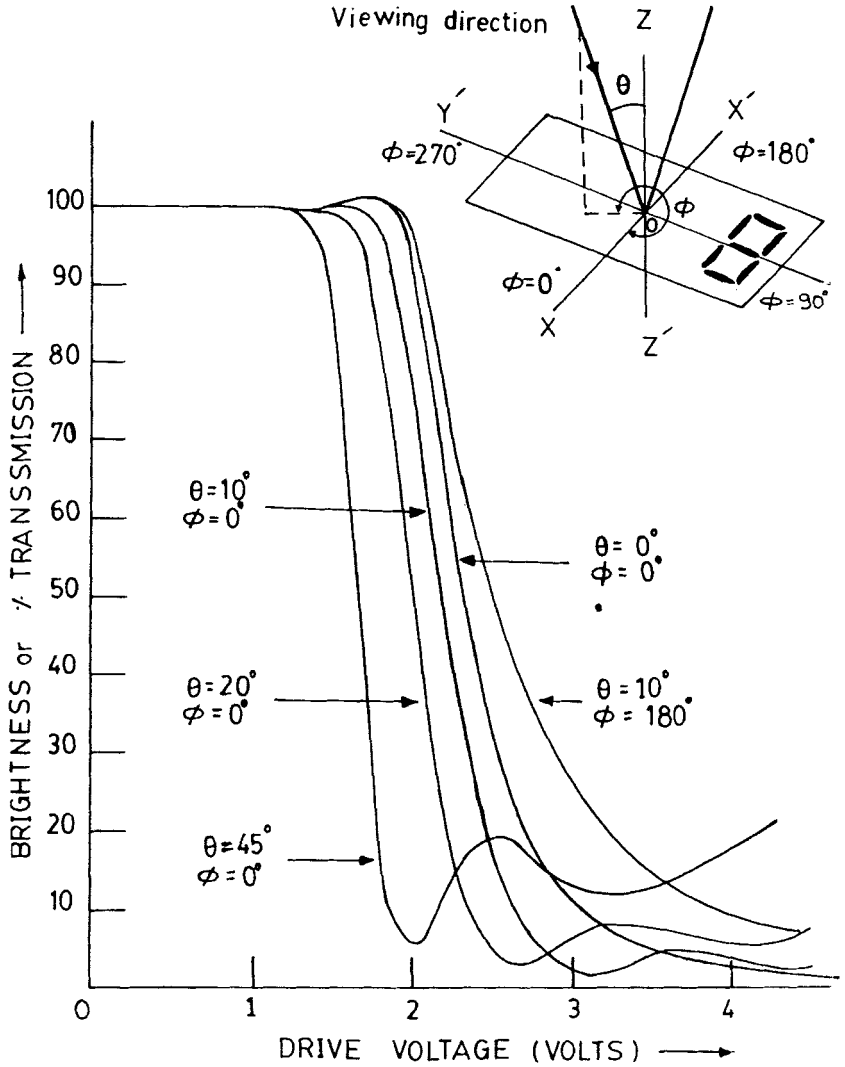


FIGURE 12 Variation of threshold characteristic of a TN mode cell with respect to viewing angle.

(iv) Switching Times

Figure 14 shows the switching characteristic of the display. After application or removal of the voltage, there is certain delay in action which is called the delay time. T_{rise} is the time during which the display gets 90% contrast from 10% level and T_{decay} is the time in which contrast falls from 90% level to 10% level. In actual display operation the rise and decay times are also associated with delay times. Delay time in decay is very small while in rise it

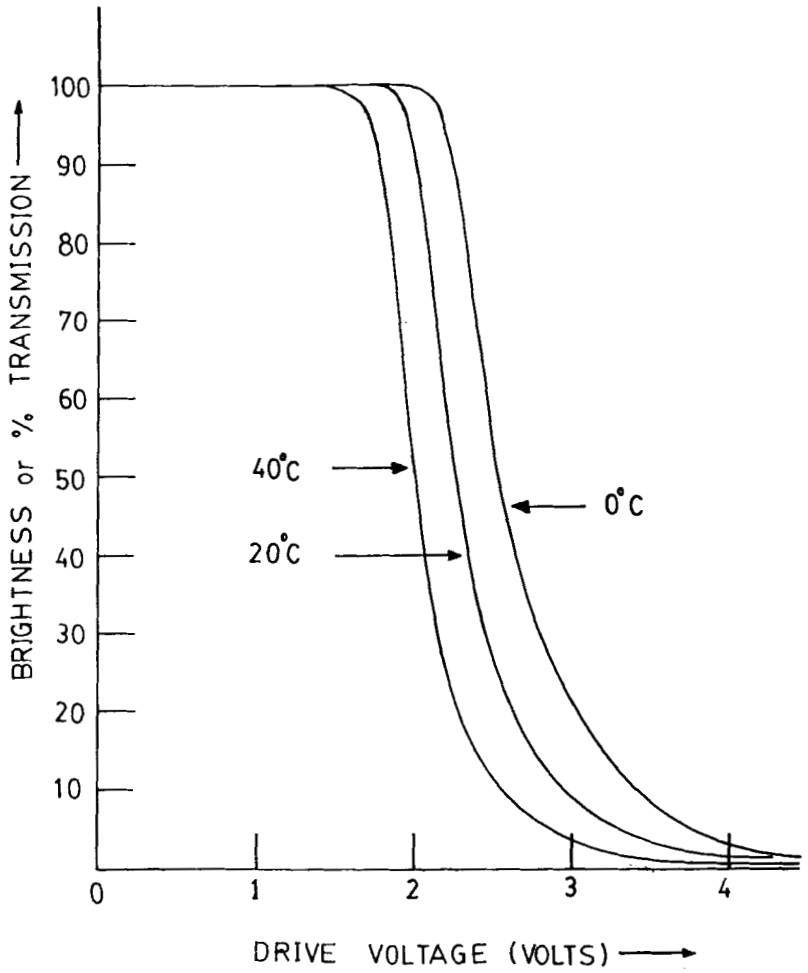


FIGURE 13 Variation of threshold characteristic of a TN mode cell with respect to temperature.

is significant. Hence actual on and off times of displays are (T_{rise} + $T_{\text{delay in rise}}$) and (T_{decay} + $T_{\text{delay in decay}}$) respectively. Rise, decay and delay times, all of them, increase almost exponentially with decrease in temperature, mainly due to exponential increase in viscosity of the LC material (Figure 15).

The rise and decay time of the display may be given by the mathematical expression:

$$t_{\text{switching}} \propto \frac{\eta d^2}{\epsilon_0 \Delta\epsilon V^2 - k\overline{\Lambda}^2} \tag{6}$$

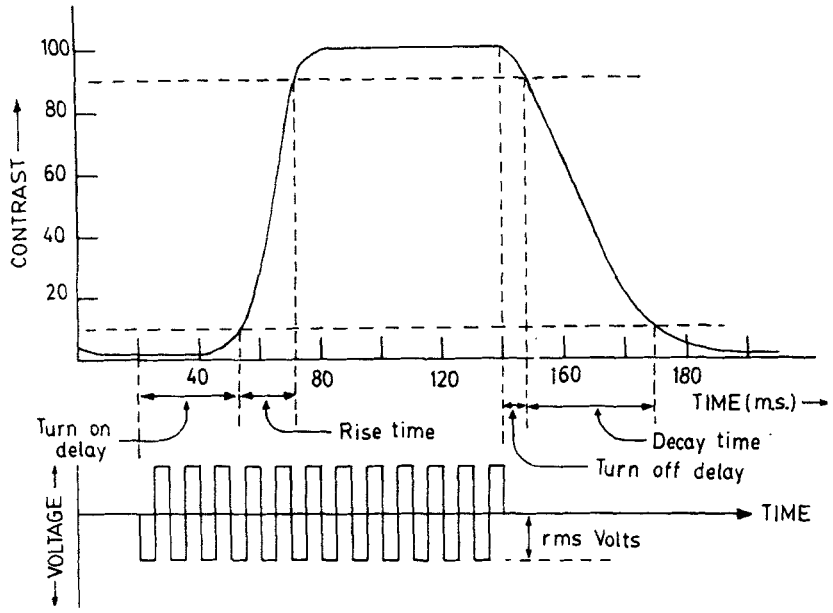


FIGURE 14 Switching times of a liquid crystal display.

where η is the viscosity, d is the thickness of the cell, $\Delta\epsilon$ is the dielectric anisotropy and k is the elastic constant. As $k\overline{\Lambda}^2$ is very small compared to $\epsilon_0\Delta\epsilon V^2$, T_{rise} and T_{decay} are given mainly by,

$$T_{\text{rise}} = C_1\eta d^2/\epsilon_0\Delta\epsilon V^2$$
$$T_{\text{decay}} = C_2\eta d^2/k\overline{\Lambda}^2 \tag{7}$$

where C_1 and C_2 are constants. A good display needs faster switchings which can be achieved by decreasing thickness and using liquid crystals of low viscosity. Moreover, T_{on} can be further decreased by increasing the voltage which affects the T_{off} a little bit adversely. However, there is practical limit for decreasing the thickness of the cell. The liquid crystal layers in the immediate vicinity of glass plate do not turn homeotropically on application of the electric field. This thickness is few hundred Å. Moreover, there is nonuniformity in commercial glass, some nonuniformity is also created during sealing etc. which limits the minimum thickness ~ 2.5 μm. Bigger cells need slightly more thickness. Another problem with drastic thickness reduction is that one gets colours in display due to imperfect guidance of the light. However, thinner cells give rise to wider viewing angle

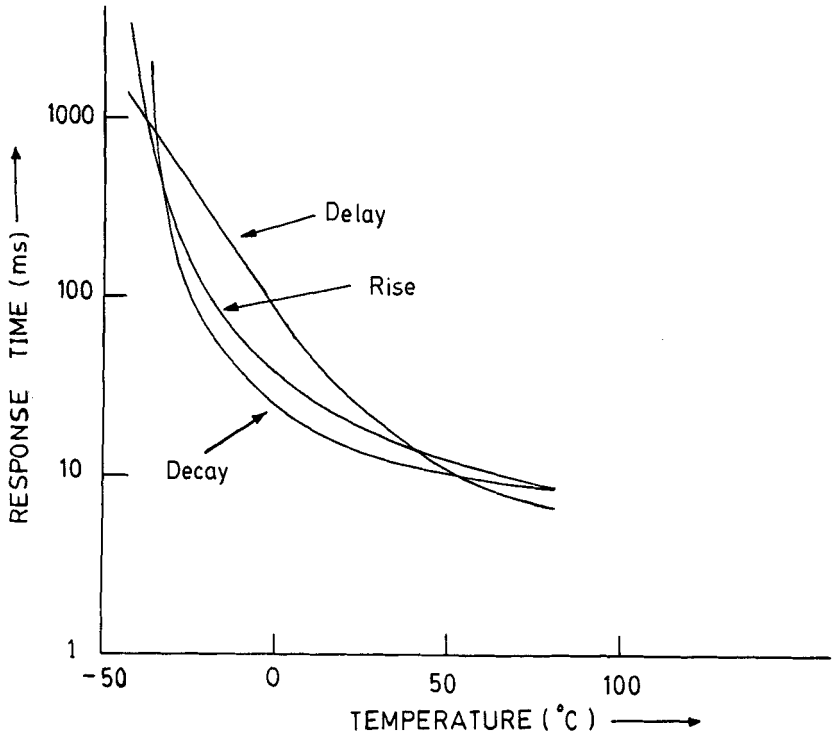


FIGURE 15 Effect of temperature on the rise and decay time of a display.

and sharper threshold characteristic but they also suffer from more colorations as both of these are proportional to $1/(d\Delta n)$. To get less colour $d \cdot \Delta n$ should be much more than 2λ. A compromise is obtained by selecting $d \cdot \Delta n = 2\lambda$. Generally a thin cell ~ 6–10 μm is preferred with a material having birefringence 0.13 to 0.25.

Typical rise and decay times of LCDs are respectively about 20 and 50 msec at room temperature and 200 and 350 msec at 0°C. The viscosity increases drastically at lower temperatures causing the sluggish response of the display. However, developing a special liquid crystal mixture of very small viscosity and thin cell assembling technique, author has been able to achieve the switching (total on and off including delay) times of around 500 msec at −30°C and 1 sec at −40°C which is more than enough for any practical use even in stringent environment. On low temperature side this display operates up to −55°C. The upper temperature is 80°C. The switching time of this display is ~ 15 msec at room temperature.[105]

Another way of reducing the switching time is dual frequency addressing.[106,107] Most of the liquid crystal mixtures show dielectric relaxa-

tion in radio frequency range. In some cases they exhibit positive dielectric anisotropy at low frequency and negative dielectric anisotropy at higher frequency.[19,108] The on of these displays is made by a voltage at lower frequency and for off the frequency is switched to higher. The operational voltage and power consumption both are higher than those of a normal twisted nematic display.

(v) Reverse Twist and Reverse Tilt

The two common visual defects in LCDs are reverse twist and reverse tilt. In cells having reverse twist certain areas will appear as having patchy appearances in quiescent state. However, reverse twist will be observable at off 90° viewing in activated mode of the display. In this case different parts of the segments will have different optical transmission and digit will look as having cut.

Reverse twist is generated if the whole area of the display does not have one sense of rotation of the molecules and different parts have different sense of rotation. The boundary area between two such rotations will have optical discontinuity and hence look as visual defect. Reverse twist is overcome in LCD cell by doping nematic material with a small amount of cholesteric.[109] Cholesteric materials have only one sense of rotation either clockwise or anticlockwise and this rotation forces the nematic molecules in the whole area of display to rotate only one way depending on the sense of cholesteric. In fact doping makes the nematic as a cholesteric with long pitch. It also increases the threshold voltage by a small amount.[109]

When a voltage is applied to a twisted nematic mode cell, irregular patches appear sometimes. These patches appear in the area where the sense of director tilt in the centre of the nematic film is opposite to that in the surrounding areas. These patches are called areas of reverse tilt. They were commonly observed in earlier TN mode cells when no preferential tilt biasing was given. The effect looks more pronounced at low voltage operation and viewing at obtuse angles. To remove this effect a small unidirectional tilt (2–20°) is given on the glass surface during alignment process. A small tilt (2–5°) is inherently generated during alignment by buffing technique while two evaporations have to be done at different obtuse angles to generate the homogeneous alignment with a small tilt by vacuum deposition technique.[31,39,40] However, the tilt directions on top and bottom plates should be matched with the sense of cholesteric such that in central layer the molecules should have nonzero tilt. The problem created by reverse tilt is called reverse tilt defects. The small tilt biasing created to remove reverse tilt defects has a beneficial side effect of reducing the turn off time.

In badly manufactured TN cell the sense of twist and sense of tilt may interact in a way that the application of voltage reverses the sense of twist.

The reverse twist areas revert slowly after the voltage have been removed.[110]

(vi) Effect of Frequency

Behaviourwise liquid crystal display can be regarded as a nonlinear voltage dependent lossy capacitor. Simple TN mode liquid crystal displays can be operated up to fairly high frequencies (i.e. below relaxation frequency of the material). The threshold and operating voltages almost do not change up to few tens of kHz above which they increase. However, the power consumption increases considerably at high frequency operation (Figure 16). So the low frequency ac operation is preferred.

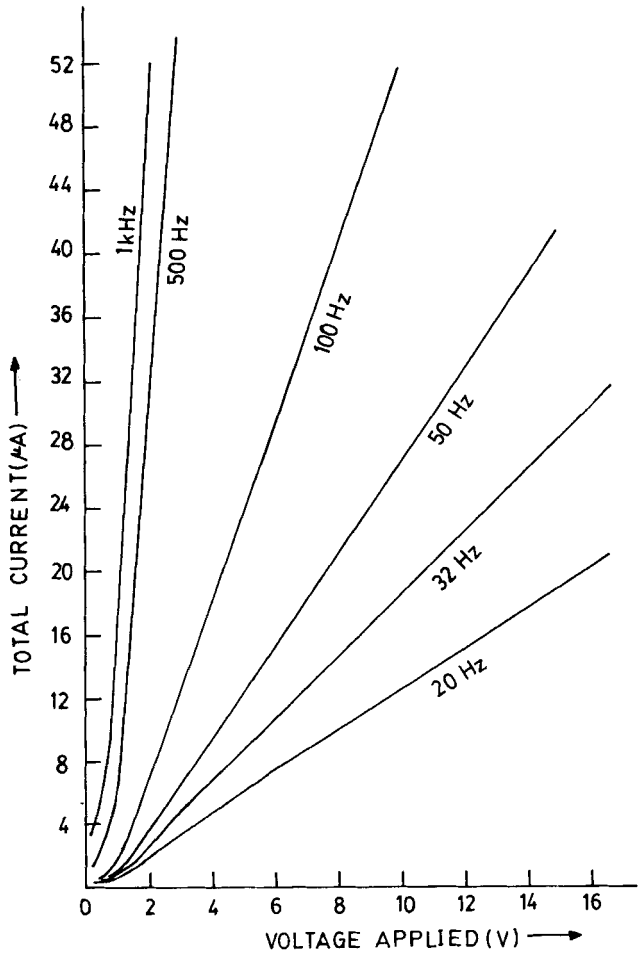


FIGURE 16 Effect of frequency on the power consumption of a TN mode display.

(vii) Coloured TN Mode Displays

By using one coloured polarizer and other neutral polarizer with TN mode display one can form coloured LCDs. Similarly by using two coloured polarizers at right angles on front and one neutral polarizer on back one can form two colour switching display. Coloured TN mode displays can also be formed by putting coloured filters or screen printing the coloured inks on the glass. These coloured TN mode displays have good eye appeal. The performance characteristics of these displays are identical with those of normal TN mode cell.

3.2C Displays based on selective interference.[111]

These types of displays are also based on dielectric principle. Liquid crystals are birefringent[21] and behave as uniaxial crystal i.e. a beam of light traversing through it, is divided in two components, ordinary light and extraordinary light, polarized in two different planes orthogonal to each other. The interference of these plane polarized light can be generated in the same way as in case of uniaxial crystals and one can obtain the interference colours. The optical transmission with respect to incident unpolarized light of a system composed of a retardation or birefringent sheet with its optic axis at 45° between the crossed polarizer is given by

$$T_{\perp} = \frac{1}{2}\sin^2\left(\frac{\overline{\Lambda}\Delta n \cdot d}{\lambda}\right) \tag{8}$$

where Δn is the birefringence and d is the thickness of the birefringent layer. If the source produces white light, this arrangement will transmit a characteristic colour since $T_{\perp}$ shows a strong wavelength (λ) dependence. If the polarizers are parallel, the transmitted colour will be complementary.

$$T_{\parallel} = \frac{1}{2}\cos^2\left(\frac{\overline{\Lambda}\Delta n \cdot d}{\lambda}\right) = \frac{1}{2} - T_{\perp}\,. \tag{9}$$

(i) Tunable birefringence LCDs[111-116]

The analysis in nematic liquid crystals is much more complicated as retardation factor, τ ($\Delta n \cdot d$ in the above case), is more complex being temperature, viewing angle, thickness and applied voltage dependent. However, in principle if we replace the birefringent sheet with a thin nematic layer, we have the same effect. By changing the voltage and thus adjusting Δn, one may get different colours in the same cell. These types of displays are called liquid crystal coloured displays based on tunable birefringence. Beautiful colours can be generated by using tunable birefringence but as the Δn varies with temperature and viewing angle, the display at the same

operating voltage will exhibit different colours at different temperatures and viewing angles.

Moreover, one has to maintain the thickness uniformity of the nematic layer very critically otherwise the different portions of the same display will give different colours. Because of strong temperature dependence of Δn the cell operates within a very limited range of temperature. These types of displays may be useful in projection displays where the same display is required to generate several colours. The threshold characteristic of these displays are steeper than those of twisted nematic and switching times are also less.

(ii) LCDs with external retardation sheet[111,117]

Solid birefringent sheet with very uniform thickness can be made easily. Their birefringence is also unaltered by the temperature for all practical purposes, so their retardation factor $\Delta n \cdot d$ remains constant. If we use the birefringence of such a uniform retardation sheet and liquid crystal material as a shutter in between two geometries given by formulae 8 and 9, one can form a good display switching between two complementary colours, governed by the thickness and birefringence of the sheet. Twisted nematic cell between two crossed polarizers acts as a switch for parallel or crossed geometries of the polarizers. Hence, a display can be made by putting a birefringent sheet between polarizer and twisted nematic cell (Figure 17). This type of display can operate over a wide temperature range and will look uniform throughout the display. Colours will also be independent of the thickness of the nematic layer and material. Of course there will be viewing angle dependence.

This type of coloured display works in a limited viewing angle for all practical applications in which TN mode displays are being put to. The operational characteristics of these displays are almost similar to those of TN mode. Only difference is that these are having much more viewing angle dependence compared to TN mode displays which limits its application.

By using multiple twisted nematic cells in conjunction with retardation sheets, one may switch several colours. In principle it is possible but as every polarizer cuts certain amount of the light falling on it, it would not be good for practical purposes.

3.2D Guest Host Displays

The contrast of twisted nematic mode display is strongly angle dependent i.e. it decreases with increasing angle of view. Moreover, it requires two polarizers for its operation and hence the brightness of the display suffers. These drawbacks of twisted nematic modes are at least in principle less pronounced or absent in guest host effect liquid crystal displays.

If a small amount of elongated dye is mixed in liquid crystal, the dye molecules get aligned in the liquid crystal matrix and hence can be oriented from one position to other along with liquid crystal molecules on the application of electric field. The phenomena of aligning the impurity or guest molecules is called the guest host interaction.[74-79,118-120] The dyes selected for display purposes should be highly dichroic i.e. they should absorb light maximum along its one axis and minimum along its other axis.[74-79,118-120]

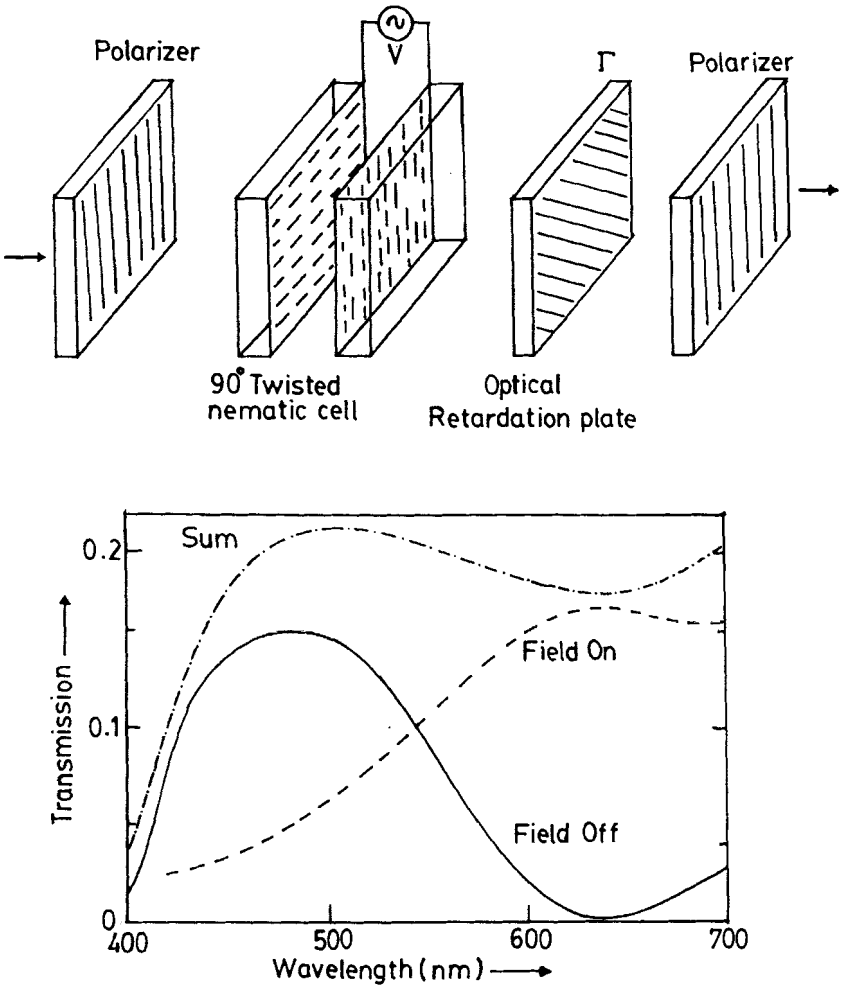


FIGURE 17 Two colour switching display using birefringent sheet and 90° twisted nematic cell.

The operational characteristics of the displays based on guest host interaction effect depend strongly on various dye related parameters such as its life, hue, solubility and compatibility with liquid crystals. There are two main types of guest host displays (i) with single polarizer and (ii) based on cholesteric–nematic phase transition.

(i) With Polarizer

By putting a neutral polarizer along the alignment direction and filling the liquid crystal mixture of positive dielectric anisotropy mixed with small amount of pleochroic dye in between the two transparent electrodes, one may form a display giving colourless digits on coloured background (Figure 18).[118–120] The alignment on the glass plates with respect to each other may be given either on the same direction or in perpendicular direction.[121]

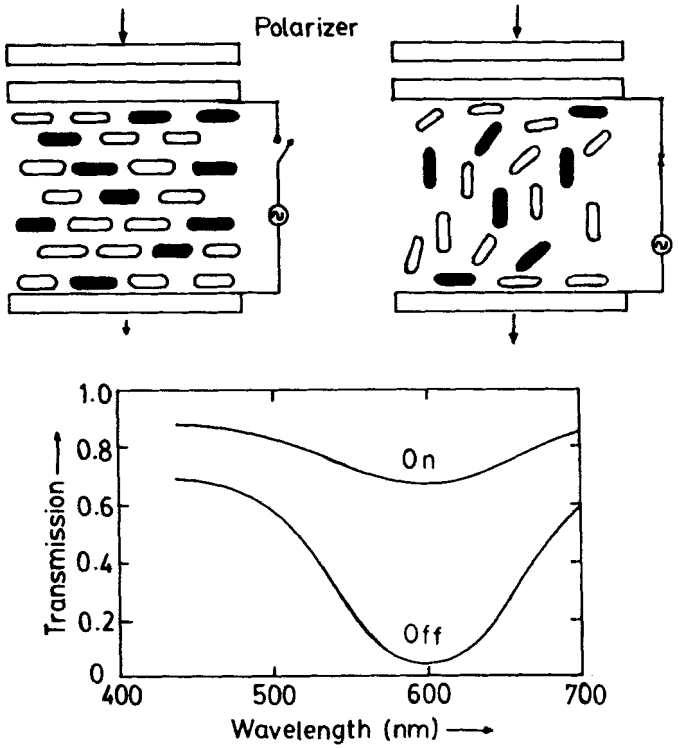
By filling a liquid crystal mixture of negative dielectric anisotropy mixed with pleochroic dye in initially homeotropic geometry, one can make a display having coloured digits on colourless background.

In another approach one can mix a dichroic dye of negative dichroism in a liquid crystal mixture of positive dielectric anisotropy in homogeneous geometry. On application of electric field coloured digits will appear on colourless background.[120]

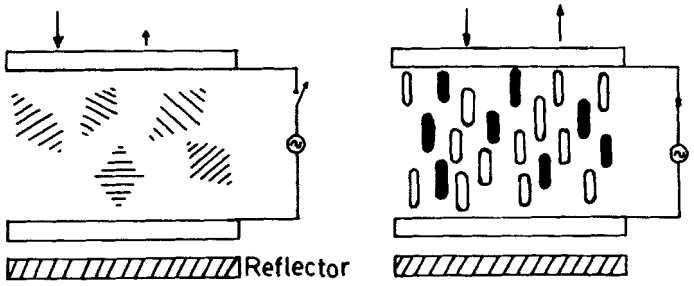
All these types utilize one neutral polarizer and the display may operate in transmissive as well as in reflective geometry. Front and rear plates in homogeneous alignment case may be treated in the same direction or similar to that in twisted nematic mode.

(ii) Dye Phase Change Effect Displays.[72,79,121–124] This type of display seems to be promising. It has some advantages over the TN mode displays. Theoretical analysis and experimental results show that if the pitch of the cholesteric in Grandjean texture is much greater than the wavelength of the light, λ, the polarized mode follows the twist. So using pleochroic dyes in twisted nematic mode without polarizer, one can get a maximum contrast of 2 : 1. Use of polarizer enhances the contrast, but it reduces the brightness and increases the cost. It has been shown recently that if pitch of the mixture, $p < \lambda/\Delta n$, the absorption of the unpolarized light may be more than 50% and one may get the contrast much more than 2 : 1.

White and Taylor[72] have shown that a mixture of high pitch cholesteric (pitch $\lesssim 3\ \mu$m) containing pleochroic dye absorbs both the components of unpolarized light in homogeneous or finger print texture. On application of the electric field above the cholesteric–nematic phase transition voltage, materials become nematic and dye molecules stand perpendicular to the glass surface along with the nematic molecules. In this case no absorption takes place. By putting a diffuse white reflector one may get white digits on



Guest-host displays with one polarizer.



Dye phase change type display.

FIGURE 18 Dichroic displays.

coloured background. The threshold voltage V_{th} is given by:

$$V_{th} = \frac{\overline{\Lambda}^2 d}{p}\left(\frac{k_{22}}{\epsilon_0 \Delta\epsilon}\right)^{1/2} \tag{10}$$

where p, k_{22}, $\Delta\epsilon$, and d are respectively the pitch, twist elastic constant, dielectric anisotropy and thickness of the material.

The absorption of both the components of light in off state by the dyes in cholesteric liquid crystal matrix increases with decrease in pitch of the cholesteric and therefore the contrast increases. However, decreasing pitch increases the operating voltage. For an acceptable contrast i.e. for $p \lesssim \lambda/\Delta n$, the operating voltage is ~ 15 V for a cell of 10–12 μm thickness. For aesthetic reason, homeotropic treatment is preferred though it has slightly lesser contrast. The display looks very bright and operates faster as the decay time is governed by the cholesteric centres inside the liquid crystals and not by the surface forces. These displays have large viewing angle (up to 180°) compared to TN mode (limited to 50°).

Besides these guest-host displays some other modes have been proposed.[111,125-129] In one such type, double cell construction each GH cell having 90° twist, is used.[129] This does not need any polarizer. In another approach the unidirectional homogeneous alignment is given and pitch of the mixture is taken such that total rotation of the molecules in the cell is $\sim 360°$.

3.2E Smectic Displays

In smectic state, liquid crystals generally do not respond to electric or magnetic field. However, if a smectic material is cooled from nematic or isotropic state to smectic state in the presence of an electric or magnetic field, one can get aligned smectic. In smectic materials, smectic A is the most easy to align by the field.[130] If a smectic A material of high positive dielectric anisotropy is cooled from its nematic or isotropic phase to smectic A phase in presence of electric field, molecules will be aligned in the direction of the field with layers parallel to the plates. This homeotropic structure would look clear. If the material is cooled in absence of the field, it adopts focal conic texture which is scattering. Generally the structure in smectic A phase has a long memory and this memory could be erased by heating it to isotropic phase. Thomson CSF[131-134] and Kylex[135,136] both group adopted the same basic principle. The physical phenomena is shown in Figure 19.

In Thomson CSF dot matrix displays[133,134] the heating is done by applying the pulsed voltage on rows and the electric field is simultaneously

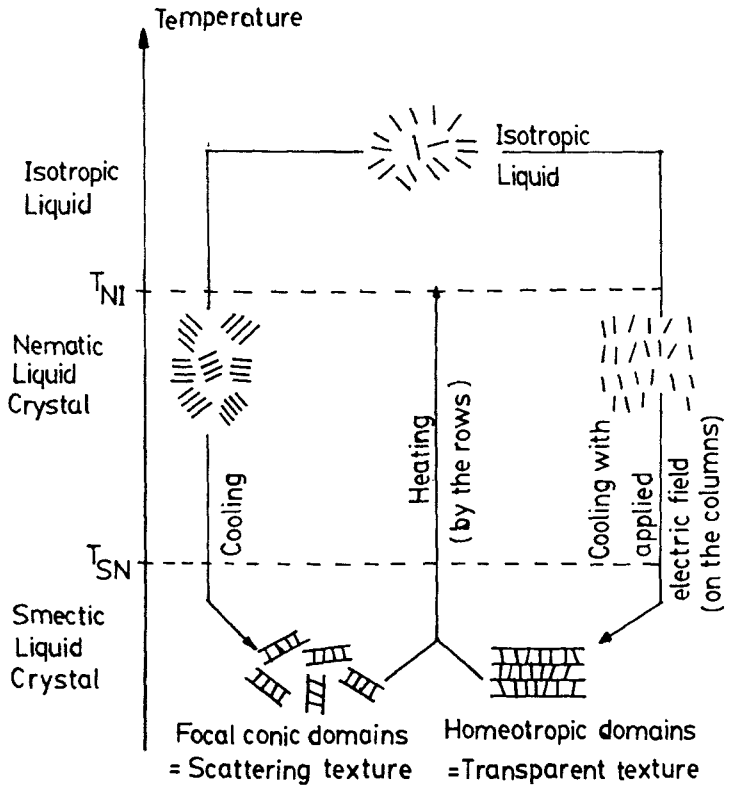


FIGURE 19 Physical principle of a thermally addressed smectic A display.

applied on the segments through columns. The information can be written by heating the rows one by one and applying the voltage simultaneously on all the desired segments of that row through the columns. The segments on which the voltage was applied (i.e. segments in which the smectic material was allowed to cool from isotropic or nematic state to smectic A state in presence of electric field) look clear while the rest of the area (areas on which electric field was not applied or was applied in smectic A state and the areas which were cooled in absence of electric field), look scattering or milky white. Generally the front or column electrode patterns are made up with indium tin oxide coating. Rear or row electrode patterns are made from metallic coating which acts as a heater as well as a reflective mirror. In Kylex approach the idea is the same but they use pleochroic dyes imbedded in smectic A matrix.[135,136]

Besides these types of smectic displays the use of smectics has been proposed as ferroelectric displays[137] and laser addressed projection

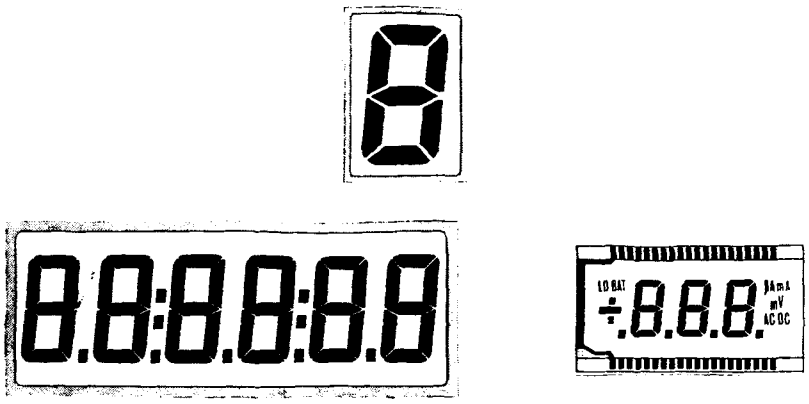
displays.[138-142] Ferroelectric bistable chiral smectic C displays can provide microsecond switchings. As these ferroelectric displays are based on purely dielectric effect and do not require thermal addressing they will consume power comparable to TN mode displays. However, the research is still at the laboratory state. Smectic displays do not have the limitation of multiplexing, so a large number of lines can be multiplexed. Because of their memory effect, they do not need fast refreshing. However, in thermally and laser addressed smectic A mode displays, significant power is consumed in heating which restricts the uses of smectic A displays.

Recently a lot of interest has been created in bistable displays.[143-146]

4. ADDRESSING OF LIQUID CRYSTAL DISPLAYS

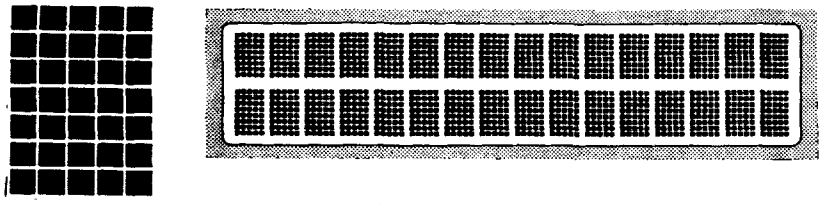
The presentation of visual information by a display requires a method or methods of activating multiple positions in display medium. The act of transmitting signal information throughout the display and exciting the different positions in display medium is called addressing. Addressing may be achieved in five ways, beam, grid, direct, shift and matrix. Beam and grid addressings are not applicable to true flat screen displays and are being widely used in CRTs and other displays.[1] However, some work is being made in liquid crystals to utilize laser beam addressing of smectic A displays.[138-142] Direct wiring or driving is applicable when number of picture elements is small and in fact is widely used in liquid crystal displays in meters, watches and industrial equipments. Shift addressing is unique to certain gas discharge configurations and is not used in liquid crystal displays. Matrix addressing is widely used in flat panel displays when number of picture elements are large and is becoming more and more popular in liquid crystal displays.

Several types of electrode patterns are in practice for displaying the numeric and alphanumeric information. Some of these patterns are shown in Figure 20. In designing the patterns, the consideration is taken that front and rear electrode patterns should overlap each other only on information displaying areas. In numeric displays seven segment patterns are more common while in alphanumeric displays 14 & 16 segment and 5×7 dot matrix are most common. In most of the equipment one row of information is sufficient, but for some applications like computer terminals etc., several rows of informations are needed. This increases the number of picture elements. The number of picture elements needed in some common applications are given in Table VI.

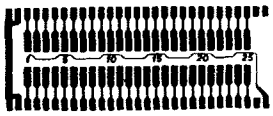


SEVEN SEGMENT NUMERIC

14 SEGMENT ALPHANUMERIC



5X7 DOT MATRIX



BARGRAPH

FIGURE 20 Some electrode patterns for liquid crystal displays.

TABLE VI

Approximate number of picture elements for some displays

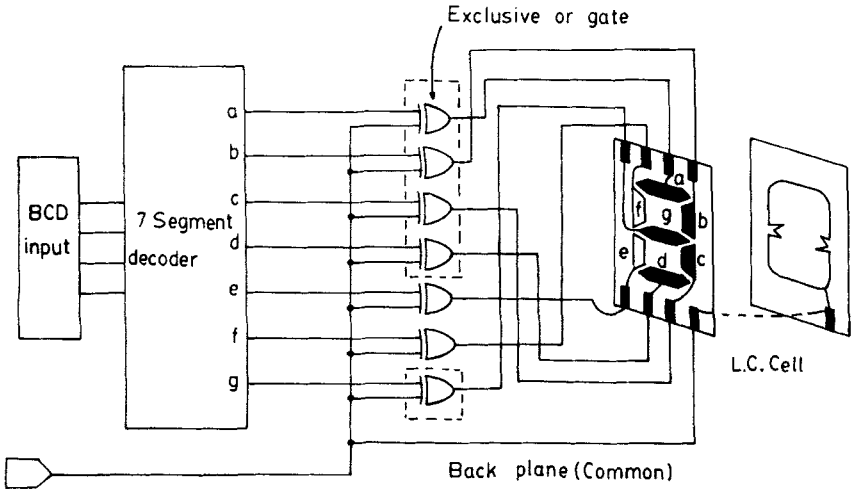
Application	Type of display	Picture elements
Domestic	Indicators	1–50
	Watches	23–50
	Clocks	23–50
	TV Indicators	15
	TV	300,000 +
Retail	Weighing Machines	100 +
	Cash register	100–150
	Petrol pump	100
Telephone	Dial indicator	100–250
	Exchange display	2000
Automobile	Taxi meter	30–60
	Dash board	500 +
Instruments	Digital meters	50–150
	Calculators	60–150
	On line Process Analysers and controllers	5000
Computer	VDU	5000 +
	Minigraphics	25,000 +
	Graphics	100,000
	Teletype	2000 +
	Data Entry	500 +
	Programme Keys	50–100
Word Processing	Memory typewriter	2000 +
	Full page edition	30,000
Military	Mobile ratio	500 +
	Cockpit display	200 +
	Large area displays (radar map etc.)	2,000–2,000,000
Public Information	Moving sign	250–2000
	Sign boards	5000 +

4.1 Direct driving

When the number of picture elements or segments in liquid crystal cell are small, these are driven directly. In this case separate connections are made for each segment. These static or direct driven displays are used in clocks, watches and some industrial equipment. In principle LCDs can be operated with dc, ac or electric pulses of any shape provided the rms voltage applied is more than the operating voltage of the cell and refreshing is faster than the decay time of the cell to make it flicker free. The cell remains off if the rms voltage applied is less than the threshold of the cell. However dc voltage gives rise to irreversible electro-chemical reactions which drastically shorten the life of the display. Hence LCDs are commonly driven by alternating field. The dc offset in output drive voltage affects the life of the cell so it is necessary to minimise its instability. The symmetrical driving characteristic and low power of CMOS are ideally suited for LCD driving.

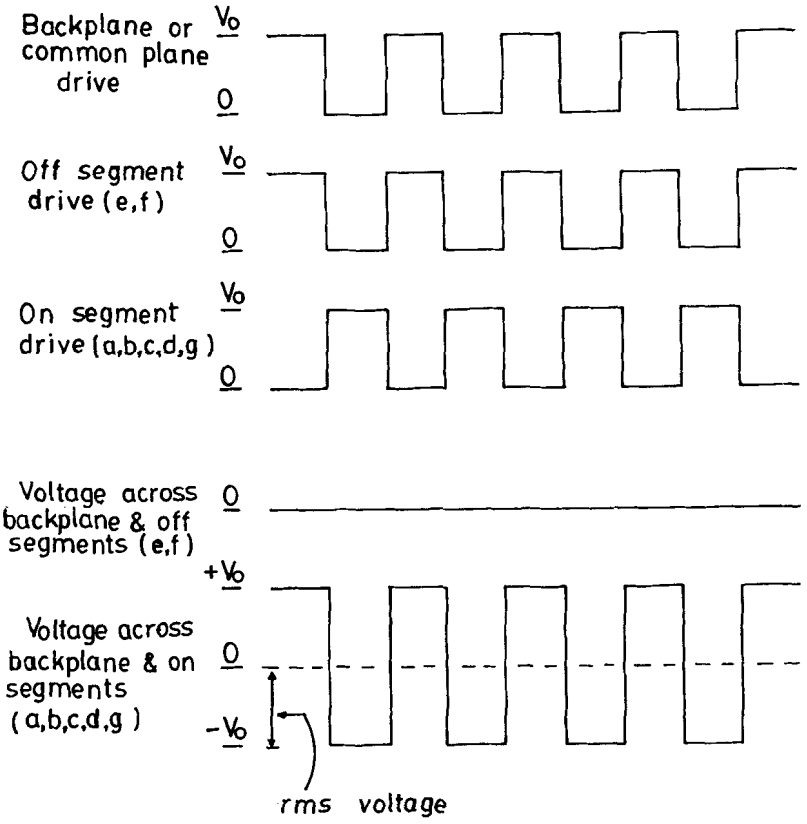
The driving of the seven segment numeric pattern is shown in Figure 21. Each LCD segment and its associated back plane can be regarded as lossy, nonlinear voltage dependent capacitor. The contrast of the segment is dependent on the rms voltage applied on it. For displaying 3, the segments a, b, c, d and g (Figure 21a) should be on and others should be off. The voltages applied to each electrode are shown in Figure 21b. The rms voltage applied to a, b, c, d and g is $V_{\text{operating}}$ ($V_{\text{op}} \gtrsim$ saturation voltage) while it is on e and f is zero. This driving method is called phase shift addressing and results in a symmetrical waveform with almost zero dc component. dc component should be less than 50 mV so that electro-chemical reactions can be prevented.

LCD driving from a single sided power supply needs a bridge as shown in Figure 21c. Switches Q_1 to Q_4 must be able to sink current as well as deliver current. Complementary NMOS and PMOS drivers of CMOS logic family are very nicely suited to this application. All of the other logic families are designed to sink current but only marginally deliver the current resulting in considerable asymmetry and dc offset. The basic logic element used to generate ac waveform is the exclusive OR gate or similar gate where one input is encoded data signal and other is a symmetrical, 50% duty cycle square wave as shown in Figure 21b. The square wave also drives the backplane. The turn on and turn off conditions are selected by applying a



(a)

FIGURE 21 Driving of a static mode display (a) Application of proper ac voltages to on, off segments and backplane. (b) Driving waveform. (c) Driving of LCD from a single polarity supply. Driving the display requires closing switches Q_1 and Q_4 or Q_3 and Q_2 during alternate half cycles. Switches Q_3 and Q_4 should be capable of sinking the current.



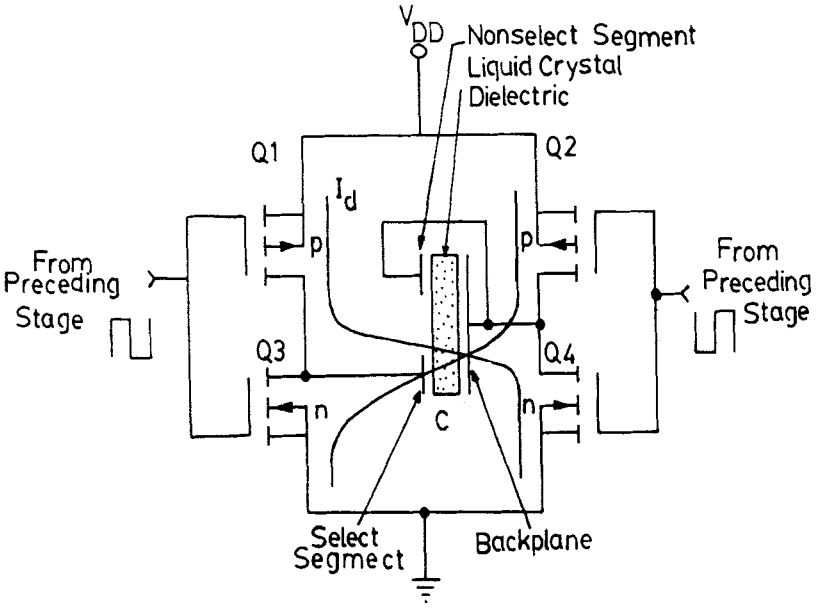
(b)

FIGURE 21 (*Continued*)

data signal out of phase and in phase with the backplane respectively. The voltage appearing across the selected segment will be twice the peak to peak voltage of the supply and will have an rms voltage equal to supply voltage. Unused segments of the display should always be connected to the backplane to ensure that they are not partially turned on due to capacitative coupling between adjacent leads and segments.

During switching, when the display capacitance in the output circuit must be charged to power supply voltage through the on *p*-channel transistor, power is being delivered by the supply. Similarly when the voltage is reversed across the display, the previously stored charge must be removed and display must again be charged to power supply voltage. If display has relatively small series resistance and low conductivity, then the dynamic power P required for switching is given by,

$$P = 4CV_{DD}{}^2 f \tag{11}$$



(c)

FIGURE 21 (*Continued*)

where C is the capacitance of the display, V_{DD} is the supply voltage and f is the operating frequency. Actual power is somewhat higher than given by above equation because of conductance and polarization currents.

For direct addressing, various kinds of CMOS ICs are available by various LC manufacturers.[147,148] Besides the general purpose logic packages like CD4070, and 54C86, which provide four dual input X-OR gate, there are forty pin display drivers with 32-X-OR outputs. Some such as HLCD 0438, MM 58438 include an onward oscillator for backplane squarewave and can be cascaded. Once the data has been loaded serially, it is displayed continuously on LCD with no further attention. Other LCD drivers incorporate decoding logic; the CD 4055 and 4056 drive a single seven segment digit from BCD input; the ICM 7211 MM 5452, MM 74C946, Mitel MD 4330, HD 44100 and CD 22104 need no extra components to decode and drive a four digit LCD.

Twisted nematic and dynamic scattering both types of displays are driven by direct or multiplexed mode depending on their applications. Most of the watches, multimeters, industrial and test equipment LCDs are direct driven. High information displays are multiplexed addressed. The Heilmeier type and dye phase change type display are almost solely driven by direct addressing because of the lack of sharpness in their threshold characteristic.

4.2 Multiplexed addressing

4.2A General

In complex displays requiring more information, it is not possible to provide separate connections for each element because of large number of picture elements and the display has to be addressed by multiplexing or matrix addressing. Multiplexing is essentially a technique employed to reduce the number of interconnections or leads for each signal. This can be achieved either by time division multiplexing or frequency division multiplexing. In liquid crystal displays only time division multiplexing is used. Besides reducing the number of individually independent interconnections, multiplexing also simplifies the drive electronics, reduces the cost and provides direct interface with the microprocessors. The term multiplexing and matrix addressing carry the same meaning. The term multiplexing is generally used when the number of picture elements are small to medium and matrix addressing is used when number of picture elements are large.

Multiplexing in liquid crystal displays is limited because of the complex electro-optical response of the cell. However, by properly choosing the liquid crystal mixture and cell designing, a fairly good level of multiplexed LCD can be formed. Major adjustments are birefringence,[55] thickness of the cell, ratio of the elastic constants k_{33}/k_{11},[55,149] alignment directions, pitch and the sense of the cholesteric imbedded,[150] tilt angle,[151] ratio of the dielectric constants,[55] viscosity, operating temperature range, temperature coefficient of the threshold and operating voltage of the liquid crystal.[55,63,64,66–68,149–152] Nowadays 4 level multiplexed numeric and alphanumeric and seven and sixteen level multiplexed alphanumeric dot matrix LCDs are commonly available in the market. Recently some LCD companies have developed 32 and 64 level multiplexed dot matrix displays.[153] Instead of using intrinsic multiplexing characteristic of liquid crystal material in TN mode displays, one may couple it with nonlinear devices like TFT or use thermally addressed smectic A displays and can go to very high limit of multiplexing.

4.2B Full and Intermediate Multiplexing

In liquid crystal displays full mutiplexing and intermediate multiplexing both schemes are popular. In full multiplexing scheme $M \times N$ picture elements can be driven by $M + N$ connections. In intermediate multiplexing schemes the number of interconnections will vary between $M + N$ to $M \times N$ depending on the level of intermediate multiplexing scheme. This can be easily understood by taking an example of eight digit seven segment calculator. In calculators each digit requires one more segment as dot or

decimal besides seven segments to show numerals. The total number of picture elements would be 8(number of digits) × 8(number of picture elements or segments per digit) = 64. In nonmultiplexed or direct driven form it will require 64(total number of picture element) + one(backplane) = 65 connections. In multiplexed display, the various segments of different symbols are not independent but are interconnected. In fully multiplexed scheme all the segments which are at the same location in every digit are joined together to form row which are sequentially addressed and each backplane behaves as a column (Figure 22) so the number of total connections required would be 8(number of rows) + 8(number of columns) = 16. In fully multiplexed scheme whole system (i.e. all picture elements) is considered as a single matrix. In intermediate multiplexed scheme each digit itself is considered as a matrix. In this approach, picture elements or segments are wired so that interconnected segments do not share the same symbol backplane. Figure 23 shows how pairs of segments of different digits may be interconnected even though each member of a given pair belongs to a different half of the digit backplane. In seven segment numeric displays 3 × 3 and 4 × 2 patterns are most widely used. In 3 × 3 pattern, each digit is divided in a matrix of 3 × 3 i.e. in three rows and three columns. These three rows of a digit are joined with corresponding three rows of other digits while the columns remain independent. In 4 × 2 pattern each digit is divided in a matrix of 4 × 2 i.e. 4 rows common to all digits and two independent columns per digit. In alphanumeric displays (14 or 16 segmented) each digit is divided in a matrix of 4 × 4. As the level of multiplexing is assigned by the number of sequentially addressed rows,

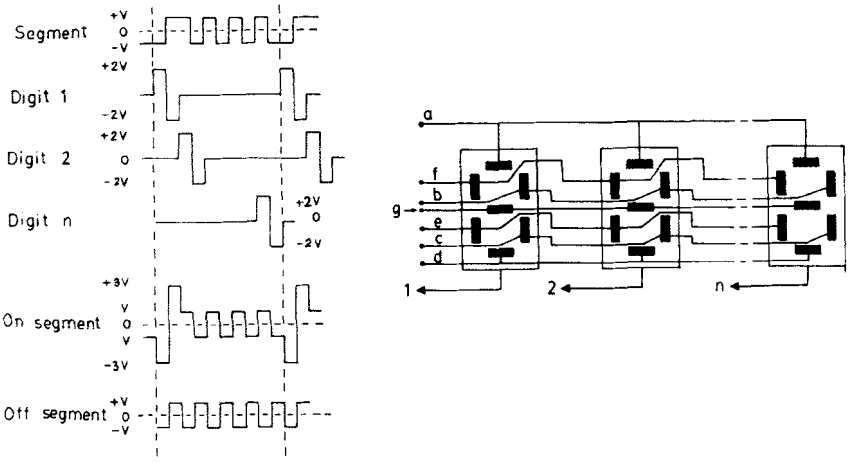


FIGURE 22 Driving of a calculator display by fully multiplexed scheme generally used in LED.

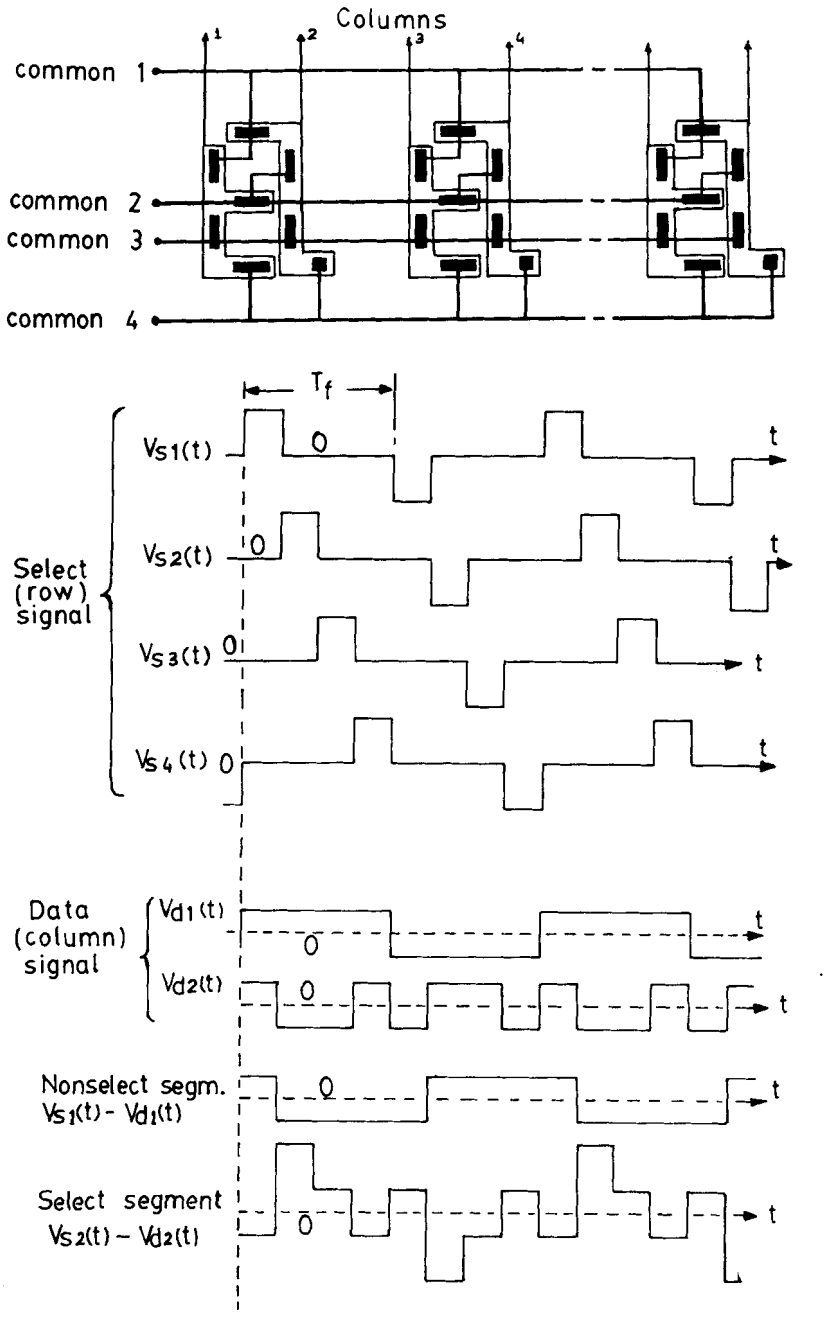


FIGURE 23 Driving of an intermediate level (4 level) multiplexed liquid crystal display.

3×3 numeric format is a three level multiplexed display while 4×2 numeric and 4×4 alphanumeric both formats are example of 4 level multiplexed display. If in a seven segment numeric pattern each digit is taken as a matrix of 2×4 i.e. two rows common to all digits and 4 independent columns per digit, it would be an example of biplexed display. So in biplexed eight digit seven segment numeric display independent connections required would be 2(rows) + $4 \times$ 8(columns) = 34. In triplex it would be 3(rows) + $3 \times$ 8(columns) = 27. In quarterplex, the independent connections required would be 4(rows) + $2 \times$ 8(columns) = 20. In fully multiplexed displays, connections required are 16 and in nonmultiplexed form it is 65. The example shows to which extent multiplexing reduces the number of independent interconnections.

4.2C Analysis of Multiplexed Driving in LCDs

In a matrix addressed display each row or common backplane is sequentially addressed (Figure 23) by scan or select pulses ($\pm V_s$) and segments or columns are addressed by data pulses ($\pm V_d$). If the number of rows or common backplane is N, the pulse will be applied on each row for $1/N$ fraction of the frame time T. Duty cycle will be $1/N$ and display will be N level multiplexed display. The simultaneous application of select and data signals on rows and column determines the on and off state of any particular segment. At the intersection of row and column, the voltage that appears across an LCD segment is difference between the select and data signals. The waveforms V_s and V_d are chosen such to give zero or very low dc offset on the segment. On average for a period of time T, a segment will be on if the voltage during the interval T/N is $V_s - (-V_d)$ and off if the voltage is $V_s - V_d$. For rest of the frame period the segment sees only $\pm V_d$. LCDs are sensitive to root mean square voltage between their segments and backplane and their contrast is independent of wave shape so long as the rms value of the applied voltage remains constant and refreshing time is less than the decay time of the cell to avoid the flicker.[154-156]

The rms voltage on select and nonselect segments would be:[154,155]

$$V_{\text{on}}^2 = \frac{1}{T}\left[(V_s + V_d)^2 \frac{T}{N} + \left(T - \frac{T}{N}\right)V_d^2\right] \tag{12}$$

$$V_{\text{off}}^2 = \frac{1}{T}\left[(V_s - V_d)^2 \frac{T}{N} + \left(T - \frac{T}{N}\right)V_d^2\right] \tag{13}$$

Solving (12) and (13) we get

$$N = 8V_d^2 \frac{\left(V_{\text{on}}^2 + V_{\text{off}}^2 - 2V_d^2\right)}{\left(V_{\text{on}}^2 - V_{\text{off}}^2\right)^2} \tag{14}$$

For maximum value of N, $\partial N/\partial V_d = 0$ and we get

$$V_d = \tfrac{1}{2}\left(V_{on}^2 + V_{off}^2\right)^{1/2} \tag{15}$$

Putting it in (12) we get

$$N_{max} = \left[\frac{V_{on}^2 + V_{off}^2}{V_{on}^2 - V_{off}^2}\right]^2 \tag{16}$$

In multiplexed operation voltages are chosen such that $V_{off} \leq V_{th}$ and $V_{on} \geq V_{th} + \Delta V$ where $V_{th} + \Delta V$ is the voltage (V_{op}) for the acceptable contrast of the on element. A device parameter $p = \Delta V/V_{th}$ is defined which is the measure of sharpness of the threshold characteristic.[154] Putting these values in 16 we get:

$$N_{max} = \left[\frac{(1+p)^2 + 1}{(1+p)^2 - 1}\right]^2 \tag{17}$$

A low value of p will result in high level of multiplexing. For $p = 0$ $N_{max} = \infty$. $p = (V_{op} - V_{th})/V_{th}$ is the most important parameter for multiplexing in liquid crystals. Small p or sharp threshold characteristic is essential for multiplexing. However, it is not possible to make threshold curve very sharp similar to LEDs. For high level multiplexing it is advantageous to increase V_{th} of the mixture keeping the $V_{op} - V_{th}$ same which results in high voltage driving of the display and in low value of p, a must for high level multiplexing.

In liquid crystal cell the threshold characteristic is not very sharp, so to avoid crosstalk, it requires more margin, $V_{on} - V_{off}$, from the circuit compared to other displays having sharper threshold. The ratio V_{on}/V_{off} and hence the margin is not always maximum in 3 : 1 voltage selections scheme commonly employed in LED and other displays (Figure 22). However, it can be maximized by taking proper amplitude selection scheme for the desired level of multiplexing. When the drive waveform has $\frac{1}{2}$ of the voltage it is called $\frac{1}{2}$ bias or $\frac{1}{2}$ voltage selection scheme. Similarly $\frac{1}{3}$ bias has $\frac{1}{3}$ and $\frac{2}{3}$ voltage levels (Figures 22, 23) and $\frac{1}{4}$ bias has $\frac{1}{4}$, $\frac{2}{4}$ and $\frac{3}{4}$ voltage levels (Figure 24). $\frac{1}{5}$ voltage selection scheme (Figure 25) or bias will have $\frac{1}{5}$, $\frac{2}{5}$, $\frac{3}{5}$ and $\frac{4}{5}$ voltage levels. The proper biasing or voltage selection scheme for a

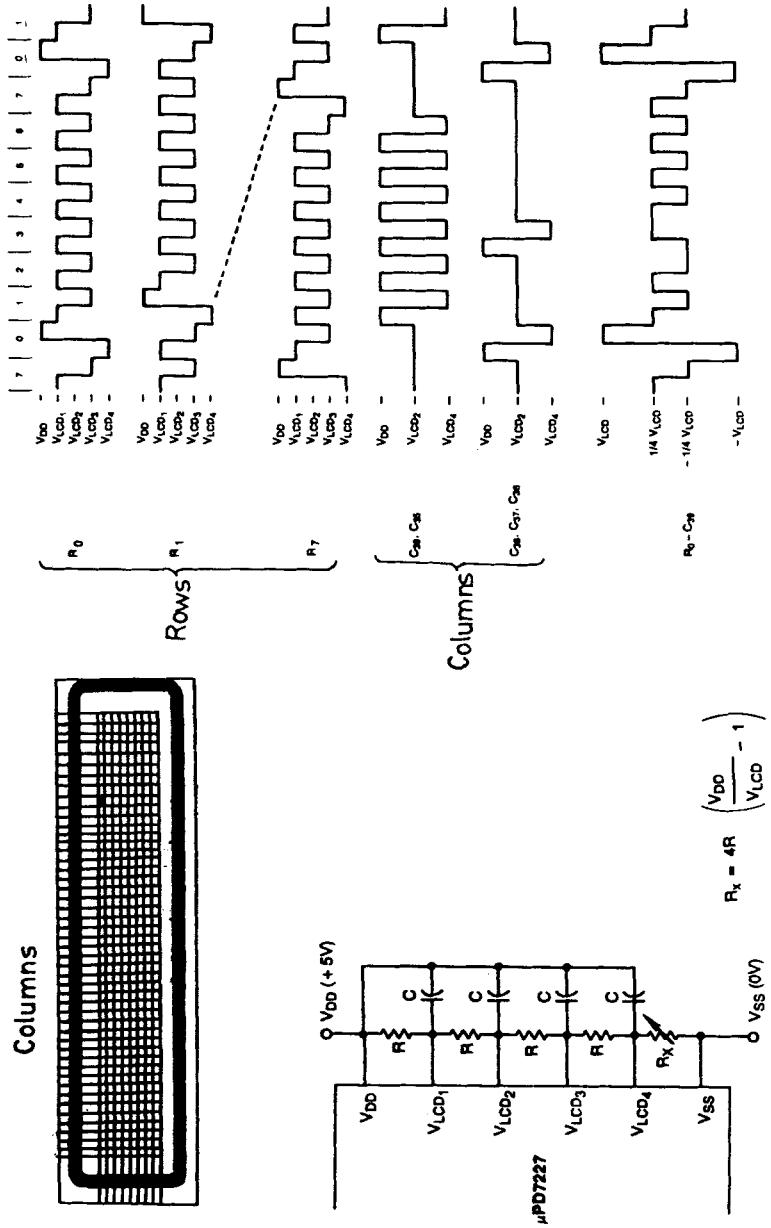


FIGURE 24 Waveform for an 8 level multiplexed display.

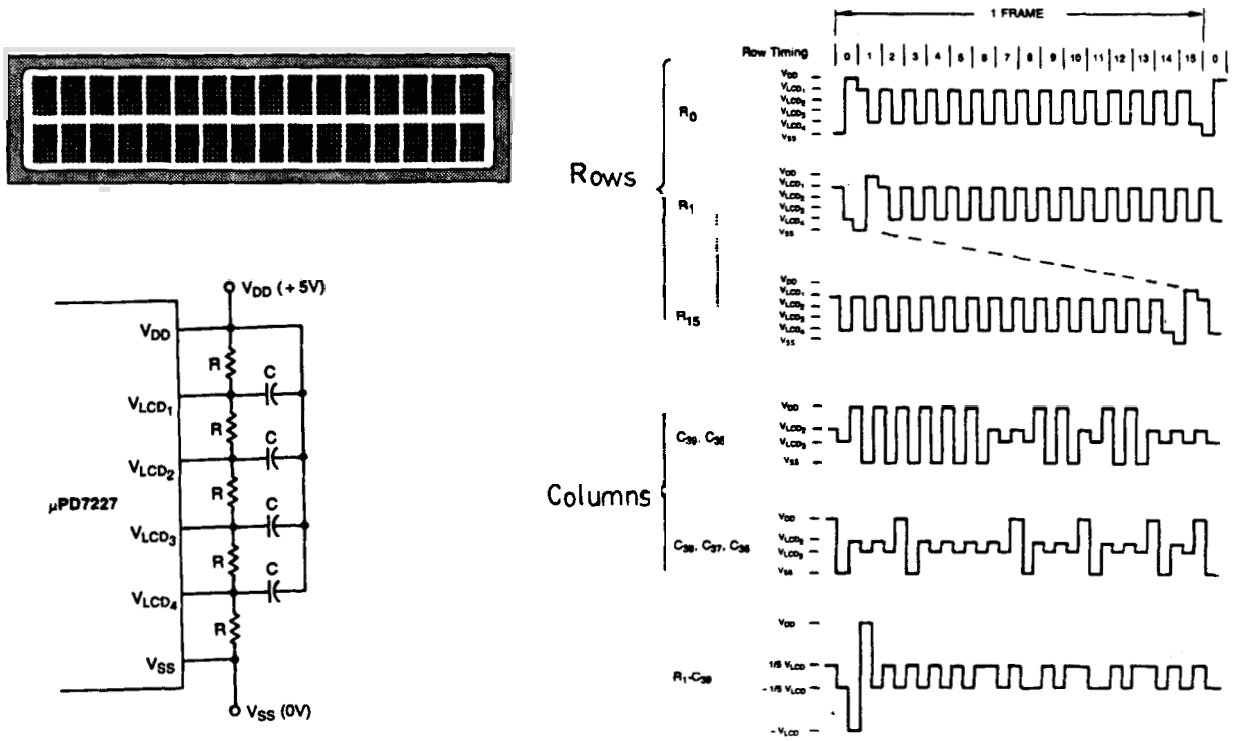


FIGURE 25 Waveform for 16 level multiplexed display.

desired level of multiplexing can be obtained from following basic equations:

$$V_{\text{on}}^2 = \frac{1}{N}(V_s + V_d)^2 + \left(1 - \frac{1}{N}\right)V_d^2 \tag{18}$$

$$V_{\text{off}}^2 = \frac{1}{N}(V_s - V_d)^2 + \left(1 - \frac{1}{N}\right)V_d^2 \tag{19}$$

V_{on}^2 can be written as

$$V_{\text{on}}^2 = V_d^2\left[\frac{(N-1) + (V_s + V_d)^2/V_d^2}{N}\right]^2 \tag{20}$$

By putting $(V_s + V_d)/V_d = V_b/V_d = s$, where V_b is the battery voltage applied on LCD ($V_{DD} - V_{\text{LCD}}$) from chip and s is the voltage selection level (for $\frac{1}{4}$ biasing it is 4), we get

$$V_{\text{on}} = \frac{V_b}{s}\left(\frac{N - 1 + s^2}{N}\right)^{1/2} \tag{21}$$

Similarly V_{off}^2 can be written as

$$V_{\text{off}}^2 = V_d^2\left[\frac{(N-1) + \{(V_s + V_d)/V_d - 2\}^2}{N}\right]$$

or

$$V_{\text{off}} = \frac{V_b}{s}\left[\frac{(N-1) + (s-2)^2}{N}\right]^{1/2} \tag{22}$$

Hence

$$\frac{V_{\text{on}}}{V_{\text{off}}} = \left[\frac{N - 1 + s^2}{N - 1 + (s-2)^2}\right]^{1/2} \tag{23}$$

The ratio of $V_{\text{on}}/V_{\text{off}}$ can be maximized by taking $\frac{\partial}{\partial s}(V_{\text{on}}/V_{\text{off}}) = 0$ which yields

$$s = 1 + \sqrt{N} \tag{24}$$

Therefore, to have maximum margin from the circuit for N level multiplex-

TABLE VII

Voltage margin V_{on}/V_{off} for various levels of multiplexing

N	$s = 2$	$s = 3$	$s = 4$	$s = 5$	$s = 10$	$s = 1 + \sqrt{N}$
2	2.236	2.236	1.844	1.612	1.246	2.414
3	1.732	1.915	1.732	1.567	1.243	1.931
4	1.528	1.732	1.648	1.527	1.240	1.732
5	1.414	1.612	1.581	1.493	1.237	1.618
6	1.342	1.528	1.528	1.463	1.234	1.543
7	1.291	1.464	1.483	1.438	1.230	1.488
8	1.254	1.414	1.446	1.414	1.228	1.447
9	1.225	1.374	1.414	1.393	1.225	1.414
10	1.202	1.342	1.387	1.374	1.222	1.387
12	1.168	1.291	1.341	1.341	1.217	1.346
14	1.143	1.254	1.306	1.314	1.211	1.315
16	1.118	1.225	1.277	1.291	1.207	1.291
18	1.105	1.202	1.253	1.271	1.202	1.272
20	1.095	1.183	1.233	1.253	1.197	1.255
24	1.083	1.155	1.202	1.224	1.189	1.230
28	1.071	1.134	1.177	1.201	1.181	1.211
32	1.062	1.118	1.159	1.183	1.174	1.196
40	1.050	1.095	1.131	1.155	1.162	1.173
48	1.042	1.080	1.111	1.134	1.151	1.156
50	1.039	1.077	1.107	1.129	1.148	1.153
56	1.036	1.069	1.096	1.118	1.141	1.144
64	1.031	1.061	1.086	1.105	1.133	1.134
72	1.028	1.054	1.077	1.095	1.125	1.126
80	1.0260	1.0488	1.070	1.0871	1.1188	1.1188
88	1.0227	1.0444	1.0638	1.0801	1.1128	1.1129
96	1.0208	1.0408	1.0588	1.0755	1.1074	1.1078
100	1.0200	1.0392	1.0566	1.0715	1.1043	1.1055
128	1.0156	1.0307	1.0448	1.0572	1.0901	1.0926
256	1.0078	1.0156	1.0229	1.0298	1.0549	1.0646

ing, the voltage selection s or biasing should be equal to $s = 1 + \sqrt{N}$. Putting this value of s in (23) we get maximum value of V_{on}/V_{off}

$$\frac{V_{on}}{V_{off}} = \left[\frac{\sqrt{N} + 1}{\sqrt{N} - 1}\right]^{1/2} \tag{25}$$

The voltage margin or V_{on}/V_{off} vs number of multiplexed lines (or 1/duty cycle) is given in Table VII and is plotted for different value of s in Figure 26. For 4 level multiplexed display, 3 : 1 voltage selection is the best while for 16 level 5 : 1 selection scheme yields better result. For 3 : 1 selection scheme

$$\frac{V_{on}}{V_{off}} = \left(\frac{N + 8}{N}\right)^{1/2} \tag{26}$$

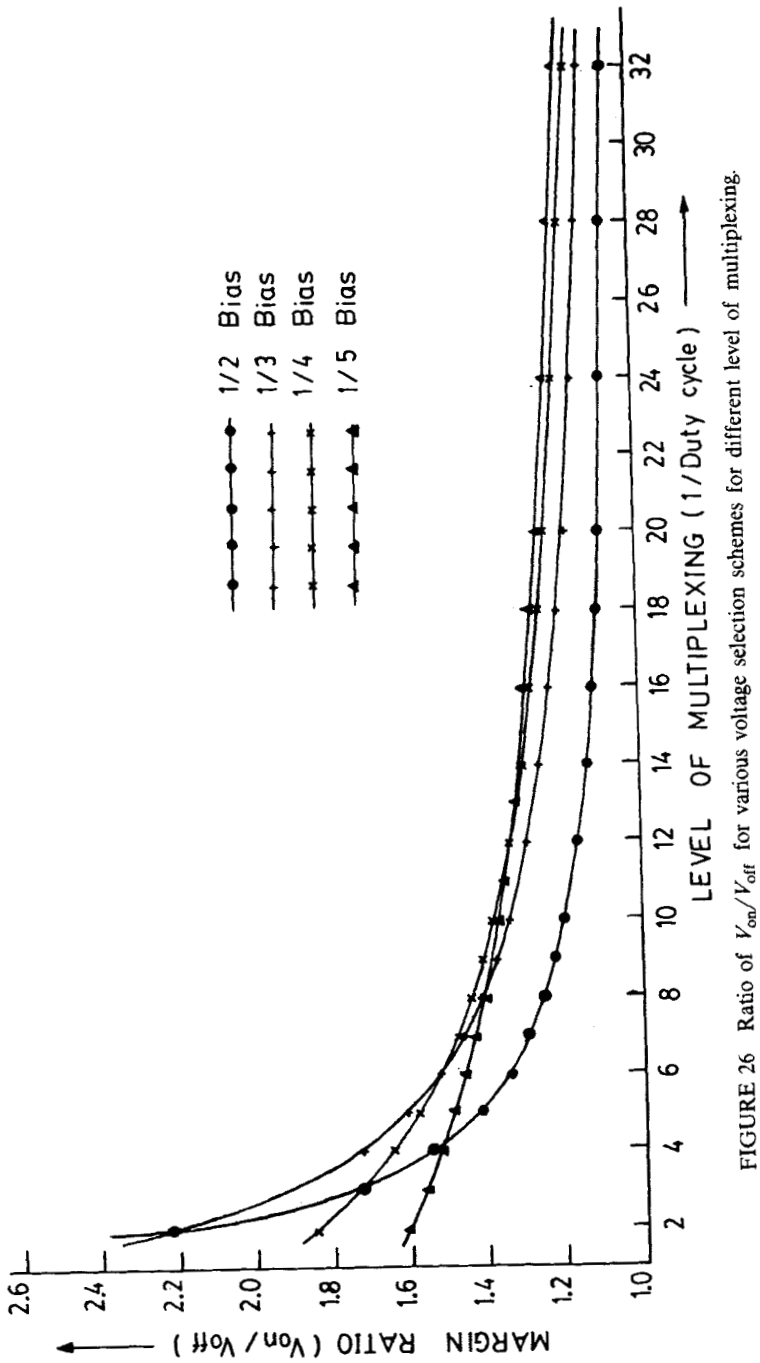


FIGURE 26 Ratio of V_{on}/V_{off} for various voltage selection schemes for different level of multiplexing.

In 3 : 1 selection scheme $V_{off} \leq V_{th} = V_d$ and putting $V_{on} = V_{th} + \Delta V = V_d + pV_d$ in equation (14) we get N_{max} for 3 : 1 scheme

$$N_{max\,3:1} = \frac{8}{p^2 + 2p} \tag{27}$$

4.2D Cell Designing and Material Requirement for Multiplexing

The threshold characteristic of a select (on) and nonselect (off) segment vs voltage applied on select segment (V_{on}) is shown in Figure 27. In multi-

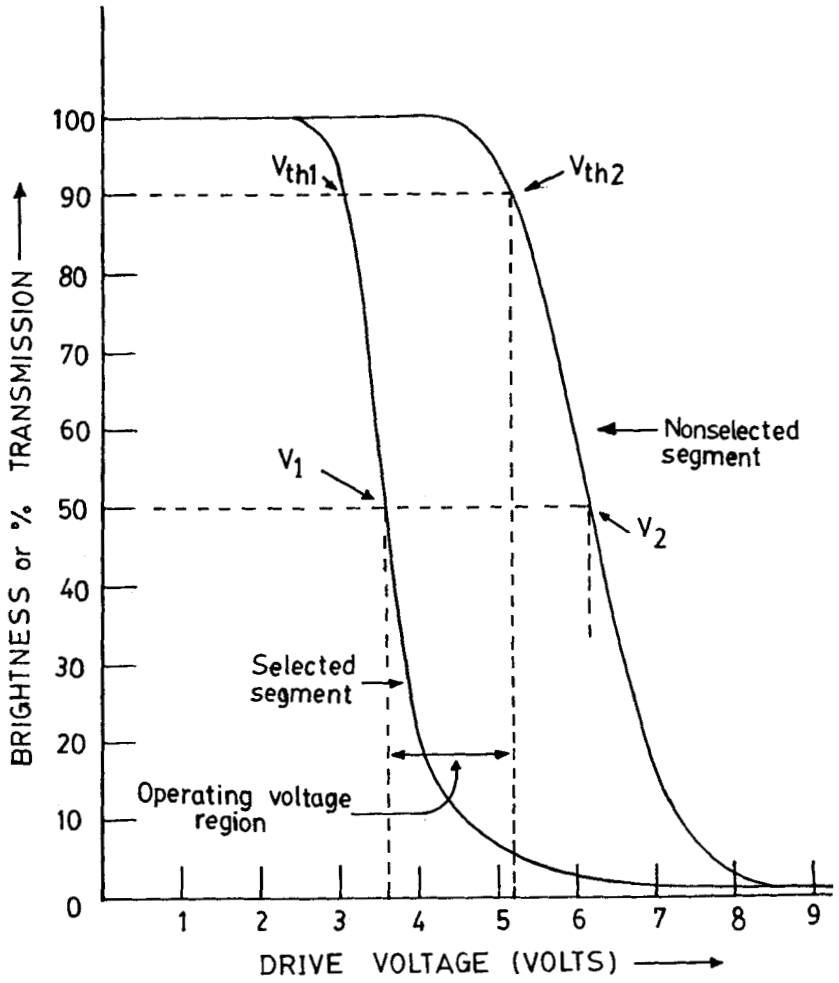


FIGURE 27 Threshold characteristic of select (desired) and nonselect segment.

plexed display the nonselect segment always experiences a nonzero voltage which is a function of level of multiplexing and voltage applied on the select segment. As the voltage on the select segment increases, the corresponding voltage on the nonselect segment also increases resulting in glowing of nonselect segment. The ghosting or getting the contrast of nonselect segment is called cross talk. As the number of multiplexed lines (or duty cycle) increases, the margin between V_{on} and V_{off} decreases and the threshold characteristic of nonselect segment shifts towards that of on segment implying the tendency for more ghosting or cross talk. To eliminate the cross talk, the operating voltage V_{on}, in multiplexed display, is normally not allowed to exceed the voltage producing 90% contrast but is taken somewhere between the voltages required to generate 50% (V_{50}) and 90% (V_{10}) contrast. The threshold characteristic is also temperature and viewing angle dependent. V_{th} and V_{op} both have negative temperature coefficient meaning therefore the cell will require higher voltage for proper contrast at low temperature side and will require less voltage above room temperature. The threshold and operating voltage both decrease as one moves away from normal in best viewing quadrant and increase when one moves away from normal in other quadrant. Operating voltage is chosen in such a way so that display could be operated in wide temperature range and wide viewing angle with maximum contrast and no cross talk. Figure 28 shows the margin for the operating voltage in a multiplexed mode LCD in wide viewing angle and wide temperature range. If the voltage applied on LCD is obtained from a battery one has to give certain margin for the battery voltage too as it has a positive temperature coefficient. The figure of merit of a multiplexed cell (M) with a temperature compensated circuit and viewing angle 0 to θ is given by (as shown in Figure 27)

$$M = \frac{V_{th\,2}(\theta) - V_1(0)}{V_{th\,2}(\theta) + V_1(0)} \tag{28}$$

In mass production of displays a certain margin is also given to $V_{th2}(\theta)$ and $V_1(0)$ due to thickness variation, degradation etc.

The sharpness of the threshold characteristic and good operation of the display in wide viewing and temperature range depends on many factors such as birefringence, thickness of the cell, tilt angle and its direction, sense and pitch of the cholesteric, ratio of the elastic constants K_{33}/K_{11}, viscosity, ratio of the dielectric constants $\Delta\epsilon/\epsilon_\perp$, temperature range of the material, temperature coefficient of the threshold and operating voltages, etc.[55,66-68,149-152] These parameters are dependent on material and packaging techniques of the display. The third important thing for multiplexed

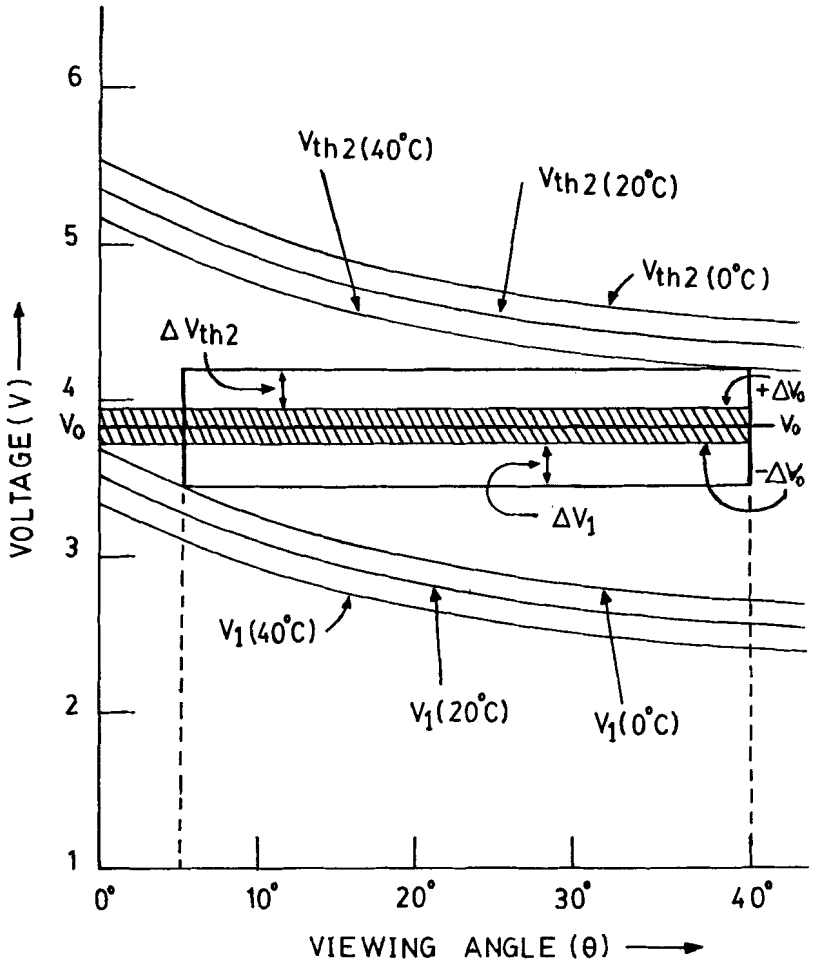


FIGURE 28 Voltage selection and margin for the proper operation of a multiplexed display in wide viewing and temperature range.

driving is the selection of compatible and proper chip. These days the increasing practice is to use temperature compensation in circuitry itself.[157]

The physical properties of liquid crystal mixture have great impact on multiplexibility.[55] The material should have wide temperature range and low viscosity. With low viscosity (specially the rotational viscosity γ_1),[60] the response of the display would not be sluggish on lower end of the operating temperature. Low tilt is advantageous for multiplexed operation as the threshold characteristic becomes less sharp with high tilt. By properly matching the tilt directions and sense of the cholesteric, one may generate

the best viewing quadrant to suit the display and its mounting in the equipment.[103] It has also been found experimentally that the threshold characteristic becomes sharper with decreasing k_{33}/k_{11}.[55] This can be achieved by doping the mixture with compatible materials having longer alkyl groups.[56] According to author's feeling reduction in $\Delta\epsilon/\epsilon_\perp$ does not make the threshold characteristic that much sharper as it increases the threshold voltage. The increase in threshold voltage keeping ΔV almost same, decreases p and hence increases multiplexing. The low birefringence (Δn) increases the viewing angle but the value of $d\Delta n$ should be kept equal to 2λ, otherwise it will show a lot of colour. The contrast of the display also decreases due to imperfect guidance of the polarized beam of light if $d\Delta n \ll 2\lambda$. A thin cell has slightly sharper threshold characteristic which is advantageous in multiplexing.[49] Recently Gerber has reported that by incorporating suitable chiral materials, the temperature variation of the threshold dV_{th}/dT can be kept almost equal to zero in a very wide temperature range.[104] These types of mixtures are good for low level of multiplexing in wide temperature range without using any temperature compensation circuitry.[104] However, the addition of cholesteric reduces the threshold sharpness and hence is no good for high level multiplexing. For high level multiplexing the mixture is used containing lowest amount of chiral to remove reverse twist.[56,103] A temperature compensated circuit is preferred and in most cases is essential. The temperature variation of the threshold can be sensed and compensated either by external means such as thermistor or intrinsically by using the capacitance or resistance of a portion of the cell.[157] As V_{on} and V_{off} both are proportional to the battery voltage, it is better to operate high level multiplexed cells with higher voltage to get more margin. However, if one wants to use all the advantages of CMOS technology, one has to restrict maximum battery voltage up to 15–18 V. Moreover, with low level of multiplexing, it is desirable to keep operating voltage low (~ 3–7.5 V). High voltage operation can be achieved by using materials of high threshold. However, all material requirements cannot be fully and simultaneously met by molecular engineering. The incorporation of a proper group or component for improving one material characteristic sometimes makes another worse. So optimization and compromises have to be made.

As regards the operating frequency, it should be higher than 1/(decay time) of the cell to avoid the flickering. For higher end, one can go to few hundred kHz or isotropic frequency. However, the power consumption increases with higher operating frequency and driving voltage too to some extent.

The best analysis of the performance of a display can be done by analyzing the polar plots (Figure 9). In crude way for simplicity it can be divided into two angles—horizontal and vertical (as shown in the Figure

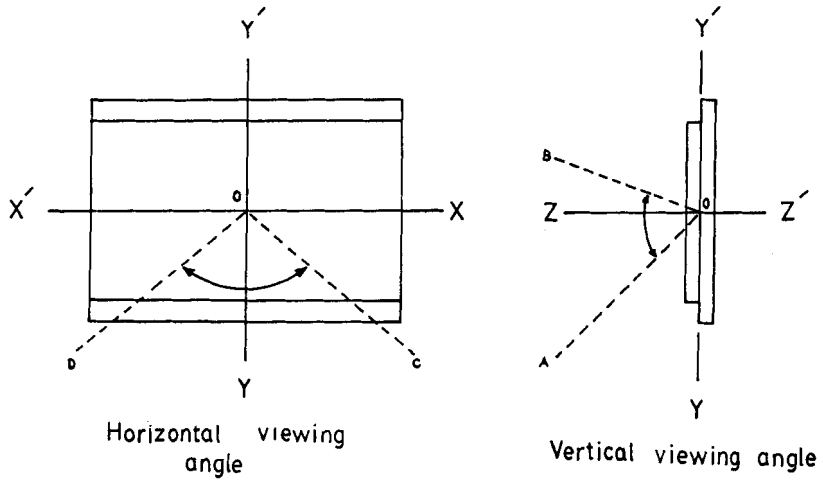


FIGURE 29 Horizontal and vertical viewing angles of a multiplexed display.

29). The horizontal viewing angle is governed more by packaging technique while vertical is governed more by material characteristic. However, material characteristic has also significant impact on horizontal viewing angle. The packaging technique too has significant effect on vertical viewing angle.

The viewing angle of these displays are made centred in best viewing quadrant. Above *ZOB*, the contrast of display would be less or poor but there would be no cross talk. Below *ZOA*, contrast of display would be more but there would be cross talk. Viewing angle *AOB* can be rotated to some extent towards *OY* or *OY'*, by voltage. A lower voltage would bring it towards *OY* and higher away from it. However, there is only a limited room for variation of voltage in multiplexed displays.

4.2E Driving ICs and Alternative Ways

There are several chips in the market which can drive the multiplexed displays. Besides cost, functions, intelligence and quality, the three main factors in selection of the chip are the output voltage from the chip, its voltage variation limits and voltage selection scheme. Other factors for consideration are low value of average dc component and frequency of operation. A three level voltage selection scheme would be best for 4 level multiplexed displays while 5 level will be best for 16 level multiplexed displays. The LCD drivers having voltage selection scheme (s) according to Alt and Pleshko scheme $s = 1 + \sqrt{N}$ where N is the level of multiplexing would yield the best performance. Now a days, a lot of semiconductor manufacturers are designing their LCD chips to suit best the LCD requirements.[148] For example three level multiplexed Data Images displays can be driven by COP 472 and ICM 7231. Four level multiplexed DI displays can

be driven by either of NEC 7225, Hughes HLCD 0607, HLCD 0539, Motorola MC 145000, or Hitachi HD 44790. Eight level multiplexed displays can be driven by NEC 7227; Hughes HLCD 0515, HLCD 0538, HLCD 0541, HLCD 0550, HLCD 0551 and Hitachi HD 44780. Sixteen level multiplexed DI displays have the choice of NEC 7227, Hitachi HD 44780, Hughes HLCD 0488, HLCD 0548, and HLCD 05040.

Besides the above mentioned approaches of getting more information by increasing the level of multiplexing, approaches have been also made to get more information without loading the level of multiplexing. One approach is to rotate the rows backwards i.e. top most row taking a U turn at the end, reversing as bottom most row, and other rows taking similar turn.[147] The upper half of the displays are being addressed from the columns at top and lower half being addressed from columns at bottom. Another pure mechanical approach is suggested in which a matrix of $M \times N$ (M rows and N columns) is broken in $(M/2) \times 2N$ or $(M/4) \times 4N$.[158] This decreases the number of sequentially addressed rows but increases the number of columns. Hitachi has demonstrated a pocket size liquid crystal TV using this "quad matrix" electrode arrangement ($M/4 \times 4N$). Another technique to increase the number of picture elements is double or multiple layer cell approach. Up to this stage, we have assumed that the addressing scheme must be displaying any possible pattern on the matrix. Considerable improvements in performance can often be made by taking advantage of a priori restrictions on the set of allowable patterns. An excellent and extremely simple example is LCD oscilloscope, which though has several rows and columns but is actually driven in nonmultiplexed form.[159] Oscilloscope patterns, as single valued function of time, require selection of one element in each column. This can be done by applying the voltage on all the rows and columns thereby exciting all the picture elements and then removing the voltage from the selected segments.[159] This reverse contrast display thus has an infinite selection ratio regardless of the size of matrix. Similar driving schemes have been forwarded by other workers.[160,161] Another example is the well known hand held electronic game "Block Buster," which though is played on 16×16 LCD matrix, need not to have effective multiplexing level over 5, as only the five rows displaying paddle, ball and bricks are ever turned on.[147] Kmetz has recently proposed a new scheme of addressing[162,163] to reduce the number of interconnections compared to conventional matrix addressing.[1,154-155,164]

4.2F Multiplexing of Dynamic Scattering, Tunable Birefringence, Dual Frequency Addressed and Dichroic LCDs

In dynamic scattering mode displays the sharpness of the threshold characteristics (Figure 30) is nearly the same as in case of TN mode displays. So

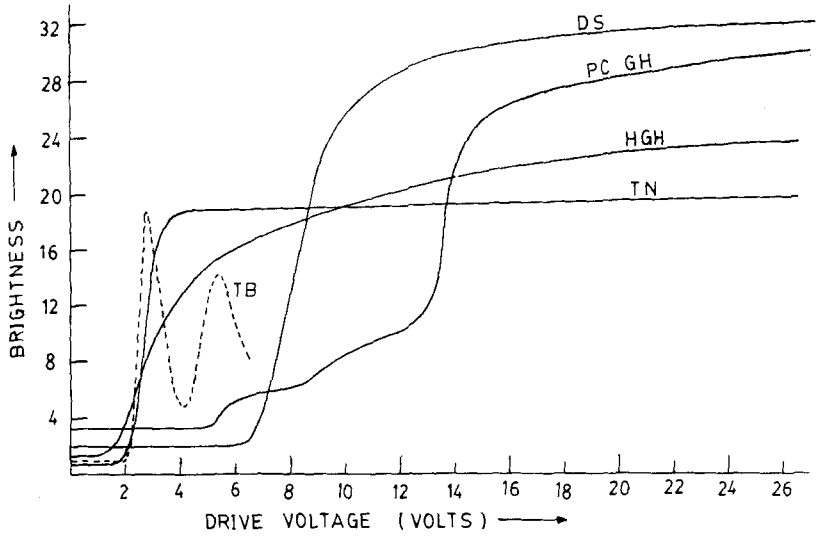


FIGURE 30 Threshold characteristic of dynamic scattering, Heilmeir type, dye phase change effect type and tunable birefringence type displays. The threshold characteristic of TN mode display is also plotted for comparison.

these displays have almost the same multiplexing potentiality as that of TN mode. The analysis which we have done for TN mode is also valid for dynamic scattering mode. A two frequency coincidence addressing scheme was also proposed for dynamic scattering mode displays.[165] Two major problems for driving them with CMOS are (i) higher threshold and operating voltage reducing the level of multiplexing in CMOS capability (~ 15–18 V) and (ii) much higher power consumption. In early period (1968–75) a lot of research was done for addressing dynamic scattering mode displays.[167,168]

Tunable birefringence has a much sharper threshold characteristic as compared to TN mode displays (Figure 30), so it has much higher multiplexing potentiality.[149] However, these displays suffer badly from viewing angle, thickness nonuniformity and temperature variation so their use is extremely limited. The analysis and circuits applicable for TN mode are also applicable to tunable birefringence displays.

Dual frequency switching TN mode LCDs have higher multiplexing capability compared to normal TN mode due to higher threshold and sharper threshold characteristic, thereby reducing p significantly.[60,108,169] A dual frequency multiplexed display may be operated either by applying a fixed high frequency bias with rms voltage V, and varying the low frequency signals so that all on segments experience a higher LF rms voltage and all

off segments experience a lower rms voltage (low frequency selection) or by applying a constant LF bias with rms voltage V and varying the high frequency signal that all on segment see one lower HF signal and off segments experience higher HF signal (high frequency selection) or even by modulating both high frequency and low frequency signal. A good analysis of these displays has been done by Clark.[108,169] The major drawbacks are higher voltage operation limiting the level of practical multiplexing up to 32 level in CMOS capability (~ 15–18 volts) which has already been achieved by normal TN mode display. Another drawback is much higher power consumption compared to TN mode, due to driving at higher frequencies and shorter operating temperature range due to temperature variation of isotropic frequency. Materials exhibiting high + $\Delta\epsilon$ at low frequency and high − $\Delta\epsilon$ at high frequencies are also limited. However, recent developments in these areas are making dual frequency addressed displays promising in future.[60]

The threshold characteristic of dichroic displays are broad and not as sharp as in the case of TN mode displays. One can understand the difference in dichroic displays and TN displays based on their operational principle. TN displays operate on the principle of rotation of light and as soon as the central layer stands due to application of sufficient field and loses light rotating property, TN mode gets almost saturated contrast though the liquid crystal layers in the vicinity of the glass plates are still unaffected. However, dichroic displays operate on absorption principle and contrast ratio is proportional to the number of layers aligned in the direction of field. As alignment of the liquid crystal molecules (especially in the vicinity of the glass plates) in field direction increases gradually with increase in field, the contrast ratio increases gradually with field and thereby making threshold characteristic less sharp compared to TN mode displays. Therefore, Heilmeir type dichroic displays containing the same LC host and geometry, have less sharp threshold characteristic and operate at higher voltage than TN mode displays. The broadness of threshold characteristic in White and Taylor type display is also due to this fact though their threshold voltage is dependent on the pitch of the mixture and alignment. The lack of sharpness in threshold characteristic forces dichroic displays to be direct addressed. At the most 2–3 level multiplexing can be done.[124,170]

4.3. Active matrix addressing

The problem of multiplexibility, arising due to lack of proper sharpness of threshold characteristic of LCDs, can be obviated if a control device is added at each picture element. These types of cells are often called as active matrix addressed LCDs. Control device can be two terminal nonlinear

devices (such as varistor, metal insulator metal) or three terminal switches (such as FET MOS, thin film transistor). They are placed in series with the liquid crystal element which acts as a capacitative load. Two terminal devices are generally restricted to fully on or fully off display elements since any variability in their conduction voltage results in a corresponding variation in liquid crystal voltage. Three terminal devices ideally act as a switch with a very low voltage drop across them and hence they are preferred in applications where gray scale is required. Important considerations in using nonlinear devices are nonlinearity, device uniformity, temperature effects, photoconductivity, capacitance, stability, life, etc. Yield should be very high. Factors affecting the yields are size of the display, resolution of the required lithography, redundancy and whether in process testing and repair is possible to eliminate the defects.[171] Figure 31 shows two terminal and three terminal active matrices addressed LCDs.

Zinc oxide varistors are attractive control elements as their high nonlinear IV characteristics is very less affected over a large temperature range. A $5'' \times 7''$, 36 lines per inch reflective dichroic display was demonstrated by GE.[171,172] Another two terminal control device is metal insulator metal (MIM).[173-176] A 128×160 lines, 40 lines per inch, TN display has been demonstrated by Bell Northern Research.[175] Fabricationwise MIM device is simpler due to use of thin film technology. Three terminal control devices include FET MOS,[177-183] CdSe TFT,[184-187] Te TFT,[188] Pb Te TFT, polycrystalline and amorphous silicon TFT.[188-200] Two important considerations of a three terminal device are: 1st, on resistance R_{on} should be low enough to get the LC capacitance fully charged during line addressing time, $R_{on}C_{lc} \lesssim T/N$; and 2nd, off resistance R_{off} should be high enough so that the voltage on the liquid crystal element does not appreciably fall before it is refreshed i.e. $R_{off}C_{lc} \gg T$. The approach of developing liquid crystal displays using FET arrays on silicon substrate[177-183] has been in use only in small size displays due to size and cost limitations of silicon wafer processing. Dynamic scattering and guest-host displays are preferred with FET MOS. The advantage of FET MOS active matrix approach is that driving circuit can be also made on the same substrate. Some improvements have been made in CdSe TFT.[186,189] Amorphous silicon TFT approach seems to be more promising and cost effective approach today.[190-195] Silicon is deposited by sputtering or glow discharge onto a low temperature substrate. Field effect transistors fabricated from this material have the low leakage current required for liquid crystal displays. A 240×240, lines per cm, display using amorphous silicon TFT has been announced in SID 82.[192] An even more useful display would include the scan and data drivers and their control circuits on the display panel and thereby eliminating the large interconnection problem to external drivers. Amorphous silicon is probably

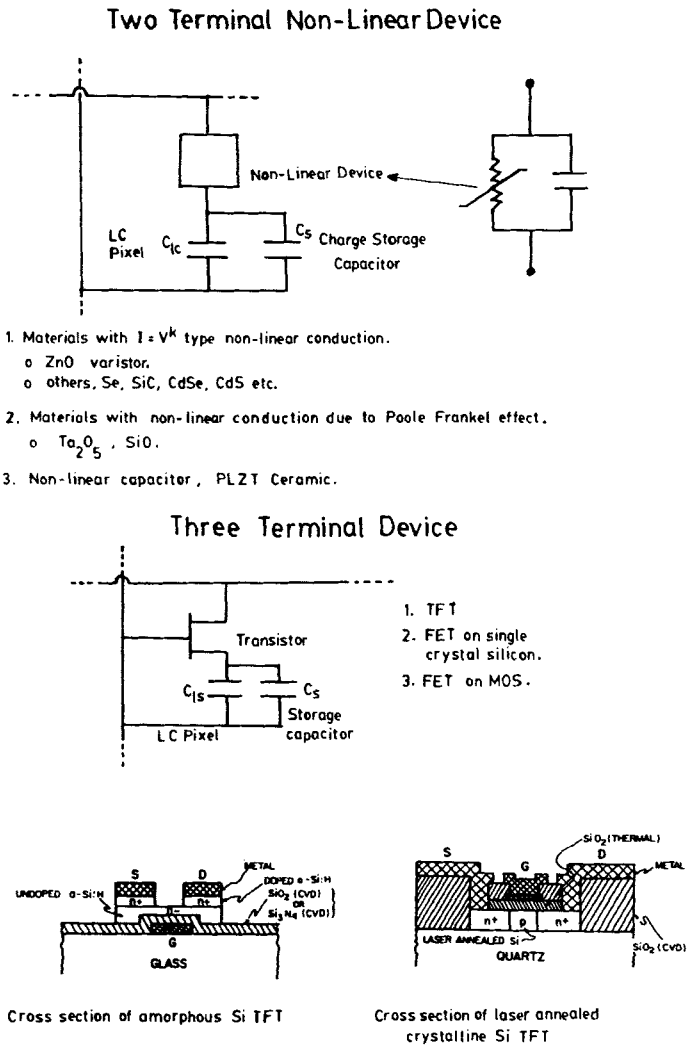


FIGURE 31 Active matrix operated liquid crystal cell.

not adequate for these high speed, high current devices. However, silicon can be transformed into large grain polycrystalline silicon by laser recrystallization. This approach is being investigated by various laboratories.[196–199] Recently, Suwa Seikosha has demonstrated coloured LCD TV using this polycrystalline silicon TFT and colour filters of red, blue and green patterns. The major problem in nonlinear devices is the yield which is being sorted out.

4.4. Addressing S_A displays

The addressing techniques discussed above are direct and matrix. Sometimes beam addressing (specially with smectic A) is used.[200] Laser addressed smectic A displays are used for large area projection. The information content is very high, probably the highest in all type of liquid crystal displays (up to 10^8 picture elements).[138-142] The writing is done by laser heating of the nonscattering smectic A texture to its isotropic state; the material cools to smectic A phase with scattering texture. To erase either high electric field is applied to align S_A phase or heating whole display and then cooling in presence of electric field is applied. The writing speed of these displays are limited and the associated laser and projection optics is complex and expensive. Another way of beam scanning is photoconductor coupled LCDs, in which a photoconductor, addressed by projector, CRT or laser, acts as a gate for the voltage applied to the liquid crystal.[201,202] These type of displays can exhibit very high information content but they need CRT or laser for addressing adding to their cost.

The most popular smectic A display is one in which heating is done by applying pulsed signal along the rows. The voltage is applied in between those columns and the heated row which is to be selected. So smectic A material on the desired segments, cooled to S_A state from its isotropic state in presence of electric field, get aligned in the direction of the field and therefore remains clear. The other segments on the row are cooled in absence of electric field and smectic adopts scattering texture. Sometimes a black reflector is provided to get black digits on white background. The information is written row by row. Because of the long memory, displays do not have to be refreshed. This way a large number of picture elements can be addressed. Both Thomson CSF approach and Kylex approach have some promise.

5. COMMENTS

The future of liquid crystal displays seems to be very bright. In the late sixties when I started my research in liquid crystals and displays, no stable room temperature liquid crystal was available for experiments and most of the liquid crystallographers had to synthesize even the materials for their studies. Most of the materials available at that time were having liquid crystalline phases at higher temperature and people were just murmuring about some possible applications of liquid crystals in electro-optical displays. During the last 15 years not only have LCDs made spectacular growth, but established itself as the second largest display industry behind

only to CRTs, in terms of the dollar value. They have not only captured almost the entire market of digital watches, pocket calculators and battery operated portable equipment, but also are appearing very aggressively in industrial and consumer equipment, military, avionics, portable computers, telecommunications, automobile, agriculture equipment, etc. In fact, some of the applications such as wrist watch TV, pocket TV battery operated portable computers could not have been feasible without LCDs.

Continued research and developments in liquid crystal material, glass, ITO coating, polarizers, thermoplastic sealing materials and mass scale production technique have not only improved the overall performance of LCDs, but also cut their cost. The life and reliability of LCDs have increased considerably. Now LCDs are available operating from $-55\,^{\circ}C$ to $+85\,^{\circ}C$ (or $-20\,^{\circ}C$ to $+110\,^{\circ}C$) with a life of 10 years. They can tolerate the harsh environment (high humidity and high temperature operation) and shocks. Though plastic substrate LCD is in laboratory stage, it may become a commercial reality soon. The switching speed has been improved by a factor of over 10 compared to first generation LCDs. The cost of a standard 3.5 digit standard watch display is now 25 cents compared to 6 dollars about 10 years ago. The mass scale production and drastic reduction in prices of LCDs coupled with those of ICs have resulted in tremendously lowering the cost of some consumer items such as digital watches, pocket calculators, pocket games, etc. LCD technology has now become mature, reliable, cost effective and established technology.

In the early stages of development, LCDs were considered unsuitable for multiplexing unless some control device (like TFT, MIM, etc.) is added with it. Later on 3 and 4 level intrinsically multiplexed LCDs were developed especially for calculators. Since then tremendous improvements have been made in inherent multiplexibility of LCDs due to developments in LC material, packaging technique and drive ICs. Nowadays, up to 32 level multiplexed LCDs, generating eight lines of text, are commonly available in market. These can display alphanumeric and graphics with over 20,000 pixels. Sharp has recently marketed 64 level multiplexed display. In laboratories 64–128 level multiplexed displays are under development. The limit of acceptable LCD multiplexing seems to be a "moving target." The welcome of 32 level multiplexed LCDs in Radio Shack TRS 100 portable computer and similar applications shows user acceptability of intrinsically multiplexed LCDs with its limited viewing angle. Moreover, the developments in active matrix addressed LCDs, giving rise to very wide viewing angle, have been made considerably and now these (MIM and TFTs) are going to market very soon.[203-205] In fact, some Japanese companies have already marketed small TV watches. Pocket TVs are going to come this year. These developments are making LCDs very useful and prime competi-

tor for high information content displays such as computer terminal, etc. High information content LCDs with MIM and TFTs are expected to come on the market by the end of 1984.

The problem of eye appeal of LCDs is also being sorted out by using coloured polarizers, coloured sheets, screen printed coloured inks with TN mode displays and dichroic dyes with cholesteric nematic phase change effect displays. For generating multicoloured pictures of TV quality, Japanese companies are utilizing interesting techniques such as selective electrodeposition of pigments,[206] vacuum evaporation of pigments on glass substrate,[194] photolithographically defining the pigments[194] etc. Suwa Seikosha has recently released 2″ coloured LCD TV screen. Other Japanese companies like Sanyo Electric Co, Toshiba Corporation etc. are also coming aggressively in coloured pocket TVs. The developments of larger coloured screens are not far away. The recent developments in synthesis of photochemically stable pleochroic dyes with high order parameter (anthraquinone dyes) have resulted in improved dichroic displays.

The overall growth rate of LCDs would be 5–10% in terms of constant dollars of 1982. The growth of LCDs is quite open and unchallenged as none of the passive display technology like electrochromic, electrophorectic, suspended particle, ferroelectric could come out of lab and make any dent to LCDs.[207–209] In fact, due to tremendous developments and several superiorities, LCDs may not only prove killer to some of these immature "babies" but also to some active displays in certain market sectors. Today more and more industrial and consumer products are using LCDs more than ever. The realization that a low cost, low voltage, extremely low power consuming display with good visibility, reliability and compatibility with microprocessors is available has prompted many manufacturers of electronic devices, systems and consumer products to incorporate LCDs in their equipment. This trend is expected to continue in the future also.

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