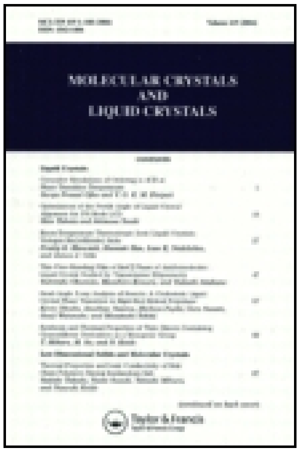

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Laser-Beam Addressed Liquid Crystal Display

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Laser-Beam Addressed Liquid Crystal Display

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The laser-beam addressed liquid crystal display is very attractive because of its very versatile display functions. Liquid crystal thermo- and electrothermo-optic effects on which the display functions are based are reviewed. Various display principles reported in the past are described, and technology to improve the write-in speed is surveyed. Recent display systems which can be used in practical fields are summarized. The paper emphasizes the liquid crystal aspects rather than the display electronics and system features.

Keywords: liquid crystal, thermo-optic effects, electrothermo-optic effects, high information content display, large-scale display, light valve

I. INTRODUCTION

Liquid crystals aligned in a molecular mono domain exhibit an anisotropic optical property. As it is not in a solid state but in a liquid state, the molecular alignment is easily altered. With this distinctive characteristic which cannot be obtained by any other materials except liquid crystals, a liquid crystal display cell can be operated with the lowest driving voltage and least power consumption. Thus, the liquid crystal cell has been widely accepted as the most compatible display device for low power and portable electronic equipment utilizing modern integrated circuits. This is the liquid crystal display utilizing the electro-optic effect: optical property variations by an externally applied electric field or voltage. The device function has rapidly progressed from a few digits of numerical data display for wrist watches and desk calculators to several-sentence display for word processors and, further, to a small-scale full-colour TV display.

However, the demand for a high information content display is growing. Such a display requires a high resolution over a reasonably large area. With the matrix arrangement of transparent electrodes, the resolution is very hard to improve upon beyond 200 μm and to extend the area further than 10 cm × 30 cm. The resolution becomes 2.5 pairs of lines per mm, and thus the total number of picture elements is, at most, 0.19×10^6.

The laser-beam spot can be focused to less than 10 μmϕ, and the matrix arrangement of electrodes can be avoided by the addressing of a laser beam onto the liquid crystal cell. In the laser-beam addressed liquid crystal display, the thermo-optic effects are utilized rather than the electro-optic effects. Although there are time delays in response due to thermal effects, the small power consumption for the change in liquid crystal molecular alignment reduces the problem of a slow response in display operation.

In this paper, first the liquid crystal thermo-optic effects on which the laser-beam addressed display are based are reviewed. Then, various display principles are briefly described and technology to improve display functions is surveyed. Finally, recent display examples are summarized. The paper emphasizes the liquid crystal aspects rather than the display electronics and system features.

II. THERMO-OPTIC EFFECTS

Liquid crystal thermo-optic effects are understood in terms of the change in optical properties of liquid crystals by temperature variations. The variations in the light transmission through the liquid crystal, e.g., transparent or translucent, reversible or irreversible, and stored or non-stored, are mainly interesting from the aspect of display, and they are caused by the changes in molecular alignment or texture. Those of nematic, nematic-cholesteric mixed, smectic, and smectic-cholesteric mixed liquid crystals have been investigated. Both of the following experiments have been carried out in the study: the temperature of a whole cell is varied by the change in the ambient temperature, and the temperature of a part of the liquid crystal cell is varied by irradiation with a focused light of a laser beam.

2.1. Nematic

A thin layer, approximately 50-μm thick or less, of the nematic liquid crystal is transparent in a mesophase or liquid crystal state in a certain temperature range, e.g., from 20 to 39°C for para-anisylidene-parabutylaniline (PAPB)[2] and from 21 to 38°C for *p*-methoxybenzylidene-*p'*-*n*-butylaniline (MBBA).[1] However, in the cooling process this transparent mesophase remains below 21°C as a supercooling state and it lasts longer in a lower temperature, if the material purity is higher. This phenomenon has been demonstrated by the MBBA liquid crystal cell set in a fixed ambient temperature within the range from 6 to 18°C. A small part of the liquid crystal is heated to over 21°C by irradiation with the focused light. Thus, the part irradiated is in the transparent mesophase whereas the rest part remains in the opaque solid phase. The temperature of the small part is brought back to the ambient temperature by removing the light beam. The mesophase contacted in the solid phase is unstable and changes to the solid phase. A transparent or semitransparent solid phase grows, depending on the ambient temperature. These results are shown by triangle mark in Figure 1. As for the transmission reference, the light transmission through a cell in an isotropic state is taken as 100%. The display has been demonstrated by using the transparent and opaque solid phases.[1]

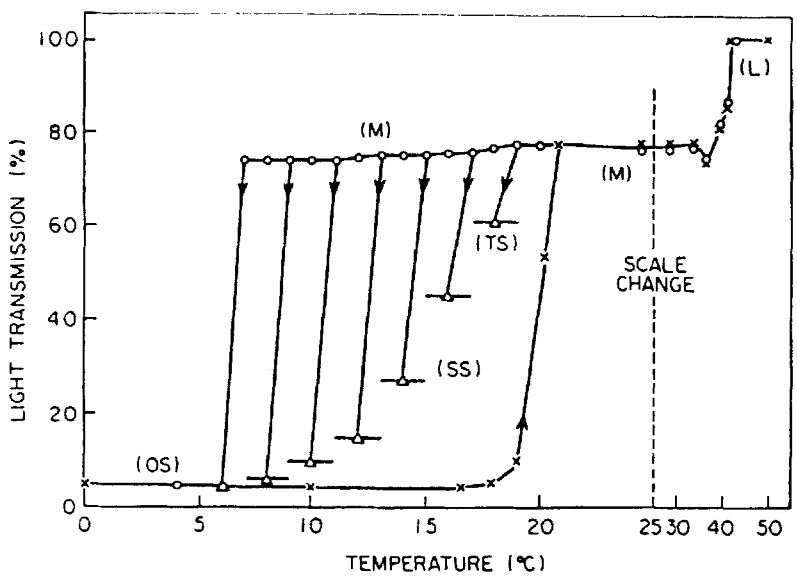


FIGURE 1 The thermo-optic effect of MBBA with changing temperature of a part of the liquid crystal in a cell. The letters TS, SS, and OS stand for transparent, semitransparent, and opaque states in the solid phase, respectively, M for the mesophase and L for the liquid phase.[1]

2.2. Nematic-cholesteric mixtures

When a cholesteric liquid crystal, even a few percent in weight, is mixed with a nematic liquid crystal, the molecular alignment is twisted and, in a spiral state, becomes a cholesteric alignment. The thermo-optic effects of a nematic-cholesteric mixture have also been measured and are shown in Figure 2, where a mixture of 90% PAPB and 10% cholesteric erucate (CE) was used as sample material. Here, the percentages are in weight.

The main characteristic feature is that the cell is in a focal conic texture of a liquid crystal state and always translucent, unless it is well and forcibly aligned to the planar texture by an applied electric field. Starting at the A state yielded by the sinusoidal voltage, the cell runs between the I (isotropic) and the B_1 states with the temperature change between 20 and 50°C. Again, starting at the A state

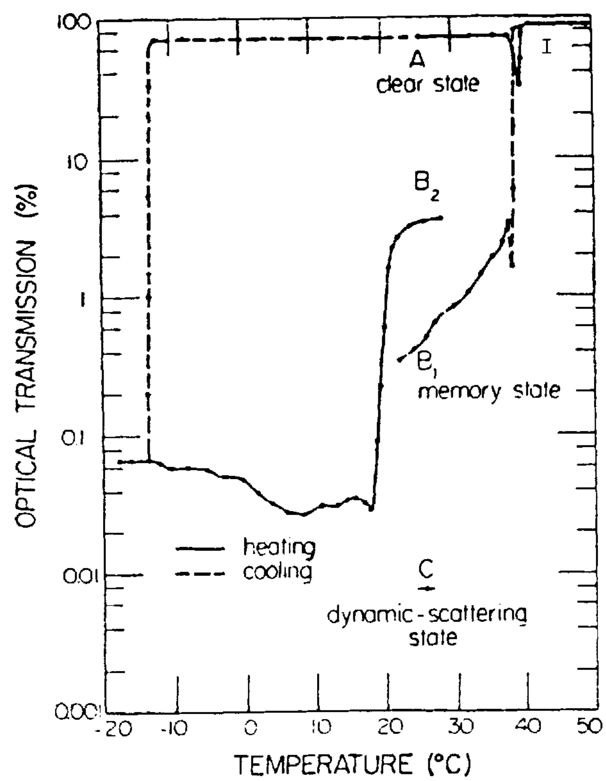


FIGURE 2 The transmission versus temperature for a 90% PAPB and 10% CE mixture. Results of two runs are shown.[2]

and lowering the temperature, the cell transits back to a translucent solid state near $-13.5°C$. By raising the temperature, the solid state changes to the liquid crystal state. The molecular alignment is in a loosely-packed texture, the B_2 state, and cannot revert back to the clear planar texture of the A state. However, the B_2 state can be erased back to the A state by a sinusoidal voltage application. The C state can be produced by a dc voltage application of 130 V, and the state is in a dynamic scattering mode.

Although the translucent B_1 state, i.e., light-scattering disordered state is metastable, it can coexist in the transparent ordered A state. It lasts longer than a year, provided the ambient temperature is not close to the transition temperature to the isotropic state. These two possible states can be utilized for the display with the memory function. Another example of this characteristic is given in Figure 3, where the liquid crystal is a mixture of MBBA : EBBA : CN = 45 : 45 : 10 (in weight percent). Here, EBBA and CN denote *p*-ethoxybenzyli-

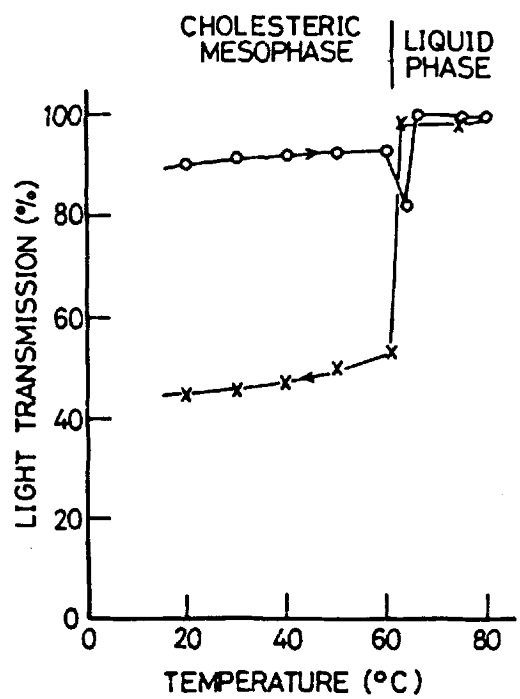


FIGURE 3 The transmission versus temperature for MBBA : EBBA : CN = 45 : 45 : 10 (in weight percent) mixture.[3]

dene-*p*′-*n*-butyl-aniline and cholesteryl nonanoate, respectively. The liquid crystal textures have been observed at each state of the light transmission.[3]

2.3. Smectic

Molecular alignment in the smectic liquid crystal is more tightly bound than the nematic-cholesteric mixed liquid crystals, and thus the disordered state caused thermally can last longer, i.e., a longer memory operation can be expected in display. In compensating for the tight binding, the smectic liquid crystal hardly responds to the applied voltage for erasing. The smectic materials for the thermal aspect have been thoroughly investigated.[4–8] Based on reliable property and near room-temperature application, the smectic liquid crystals used for the thermal display are of the 4-cyanobiphenyl class, such as cyano-octyl-4-4′-biphenyl (COB) and cyano-octyloxy-4-4′-biphenyl (COOB).

The thermo-optic characteristic of COB is shown in Figure 4, where the light transmission varies very little in all of the smectic, nematic, and isotropic phases. However, the temperature variation in a part of the liquid crystal cell creates light scattering centers. When the temperature is increased by the laser beam spot, the central portion and the periphery become the isotropic and the bent nematic phases, respectively, and they are surrounded by the smectic phase. With the removal of the laser beam, the portion which has been irradiated is rapidly cooled. During the cooling process, the random alignment in the isotropic phase is transformed to a honeycomb texture through the bent nematic phase.[10] The texture is frozen in the smectic phase and scatters the incident light. It becomes a dark spot in a clear smectic phase of the cell.

2.4. Smectic-cholesteric mixture

The thermo-optic characteristic of COB : CN (90 : 10 in weight) mixture has been measured and the result is shown in Figure 5. In contrast to the smectic case, the light transmission is fairly decreased in a cholesteric phase due to the light scattering by the focal conic texture. In the rapid cooling from the cholesteric phase, this texture is frozen in the smectic phase and becomes the dark spot. During the cooling process from the isotropic phase, the heterogeneity of the honeycomb and focal conic textures would be frozen and retained in the smectic phase. The thermo-optic effects of some other smectic-cholesteric mixtures have been investigated.[9]

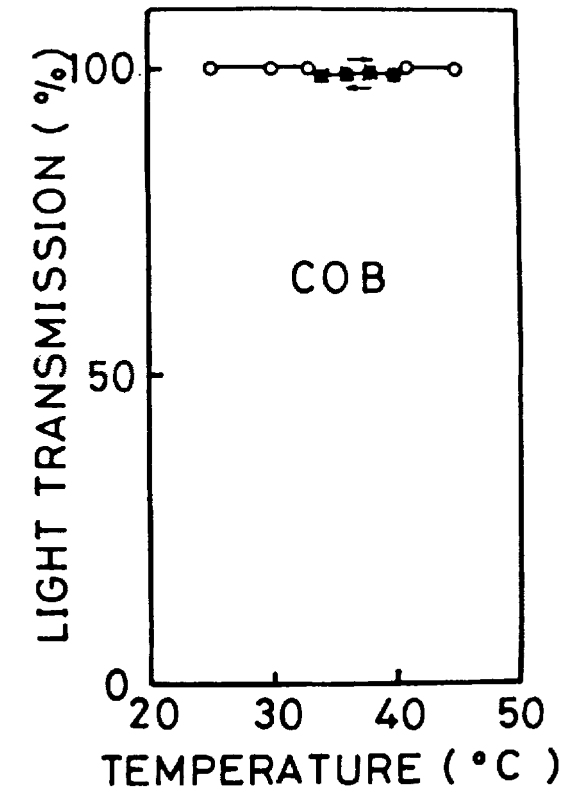


FIGURE 4 Transmission characteristic in thermo-optic effect of COB.[9]

III. ELECTROTHERMO-OPTIC EFFECTS

The voltage application in the thermo-optic phenomenon is important in the display operation. A low frequency application causes dynamic scattering and reduces the light transmission in a nematic or cholesteric phase which increases the contrast ratio, whereas a high frequency application extinguishes the light scattering centers and restores to a clear smectic phase which produces the figure-erasing function in display.

3.1. Nematic-cholesteric mixtures

The electrothermo-optic characteristic of Figure 2 (90% PAPB and 10% CE mixture in weight) has been measured by applying 120 Vrms at 1500 Hz to a 25-μm thick layer and is shown in Figure 6. In the

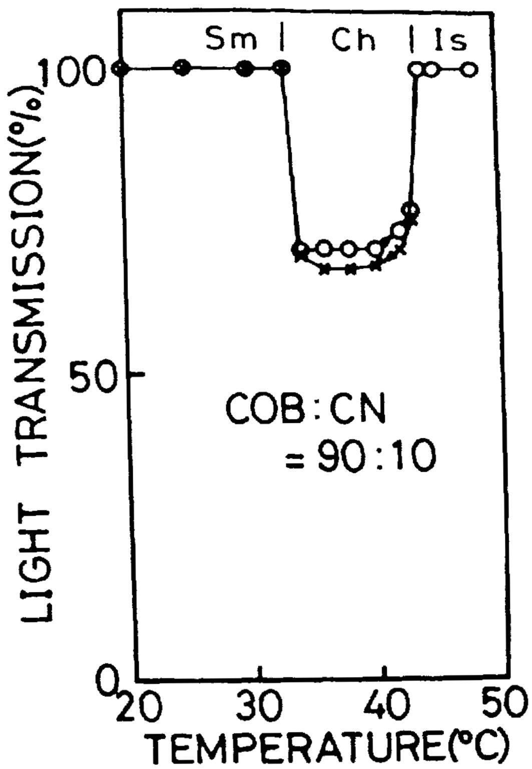


FIGURE 5 Transmission characteristic in thermo-optic effect of COB : CN = 90 : 10 (in weight percent) mixture.[9]

cooling process, the dynamic scattering continues, until the liquid crystal becomes solid. In the heating process, a clear liquid crystal is restored at the transition temperature from the solid to the liquid crystal state. This restoration function can be used for the erasure of figures in display.

3.2. Smectic-cholesteric mixture

The electrothermo-optic characteristic has been measured by applying 12 V at 100 Hz to a 12-μm thick layer, and is shown in Figure 7. It does not differ much from the thermo-optic characteristic, but the light transmission is lowered in the cholesteric phase due to the dynamic scattering rather than the scattering by the focal conic texture. The liquid crystal is restored to the clear smectic phase from the

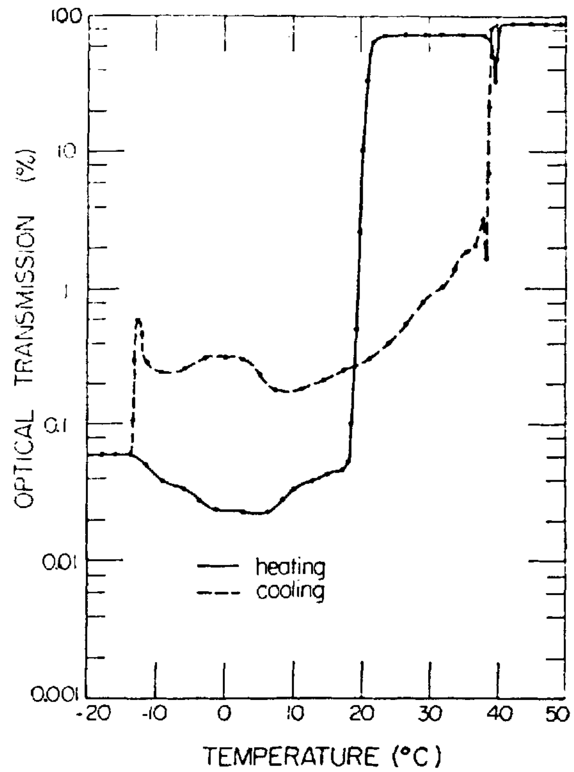


FIGURE 6 Transmission versus temperature for a 90% PAPB and 10% CE mixture. An erasure voltage was applied during heating from −18° to 24°C.[2]

opaque cholesteric phase, even if the temperature variation is rapid. This characteristic can be used for dynamic-figure display.

IV. PRINCIPLES OF LASER-BEAM ADDRESSED DISPLAYS

Materials and characteristics used for laser-beam addressed displays are summarized in Table I. Here, rapid cooling means that the freeze-in process of the light scattering centers in the smectic phase by rapid cooling from the isotropic or the cholesteric phase, described in the previous sections. Although thermally addressed liquid crystal displays originally used the thermo-optic effects of nematic or nematic-cholesteric materials, recent practical displays mainly use smectic or smectic-cholesteric materials, because of a high-contrast ratio and

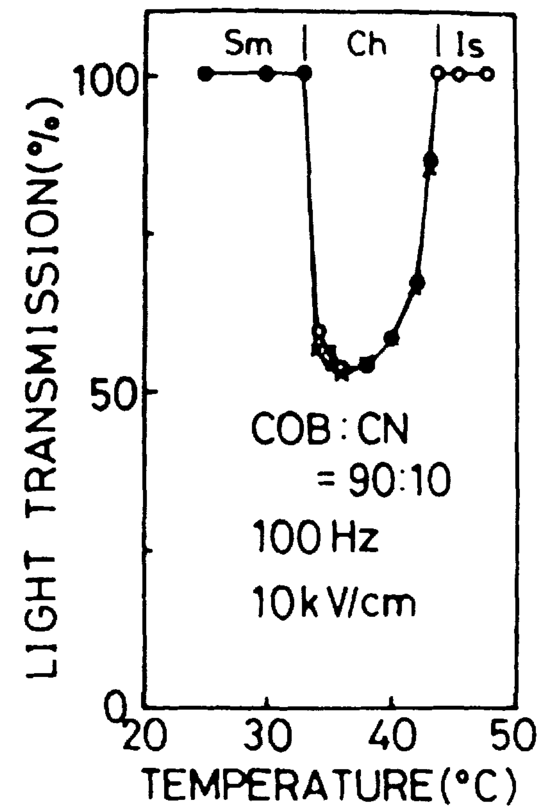


FIGURE 7 Transmission characteristic in electrothermo-optic effect of COB : CN.[9]

long lasting memory effect. A variety of principles of a laser-beam addressed display are shown in Figure 8.

4.1. Smectic

The texture changes in a smectic display cell are shown as (a)⟼(b)⟼(c) and they are based on the thermo-optic effects caused by the laser-beam irradiation and removal. The honeycomb light scattering centers remain as a trace of a laser-beam address, and thus figures can be written in the cell by the addressing of a beam. They can be erased by AC voltage application.

4.2. Smectic-cholesteric mixture

Two different texture changes in smectic-cholesteric mixed liquid crystal cell are shown as (a′)⟼(b)⟼(d)⟶(e) and (a′)⟼(f)⟼(g). First,

TABLE I

Materials and characteristics used for laser-beam addressed liquid crystal displays

Materials	Characteristic used
Nematic	Figure 1
Nematic-cholesteric	Figure 3, Figure 6
Smectic	Figure 4 (rapid cooling)
Smectic-cholesteric	Figure 5 (rapid cooling), Figure 7

the light scattering centers, possibly the heterogeneous texture of the honeycomb and the focal conic, are created by the cooling process from the isotropic through the cholesteric phase. Second, the light scattering centers are of the focal conic texture created by the cooling process from the cholesteric phase. The second process has the advantage of improving the write-in speed, since irradiation time is not required to produce the isotropic phase but only the cholesteric phase existing in a lower temperature side of the isotropic phase. These light-scattering centers are also erased by the AC voltage application. The light-scattering centers remain in the cell as in Figures (c), (e), and (g), and thus they display static figures.

With the use of the electrothermo-optic effect, a dynamic figure can be displayed. In the texture change of (a')→(f) {or (b)→(d)}→(h), the light is scattered in a cholesteric phase. The light scattering centers are erased in the cooling process to the smectic phase which is now a clear texture. The light is scattered only during the period of the beam irradiation, as the bright light spot makes an optical contrast on the CRT from the electron beam impinging on the face plate.

With these effects, simultaneous display for static and dynamic figures has been demonstrated. Further, a locally selective erasure has also been shown by using the electro-optic effects. Thus, multi-functions such as (i) display for static figures, (ii) display for dynamic figures, (iii) total erasure by applied voltage, (iv) locally selective erasure, and (v) simultaneous display for static and dynamic figures have been operated in the laser-beam addressed display.[15]

V. ADDRESSING SPEED

Laser-beam addressed liquid crystal display has attracted great interest as display with stored image capability, high resolution (50 pairs of lines/mm), large scale[16] (2.4×2.4 m^2), and a reasonable

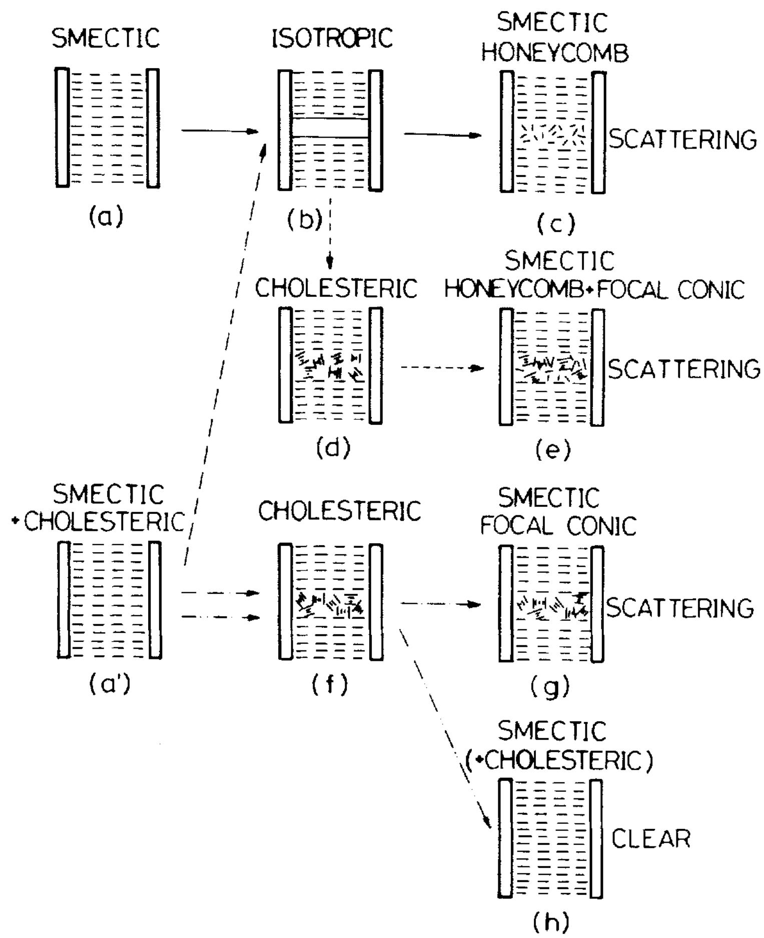


FIGURE 8 Various processes of write-in and erasure of laser-addressed liquid crystal display.

contrast ratio.[17] However, the addressing speed remains to be improved, since it takes about several seconds to write figures in a display frame. Further, addressing improvement is required to increase the cell size for high information content and to use a semiconductor laser as a writing beam for a compact size of display system.

A standard reflection type of cell is shown in Figure 9. The liquid crystal is not heated directly but by the laser power absorption through an indium-tin oxide film electrode, and cooled down by removing the laser beam. In the past, the improvement has been demonstrated

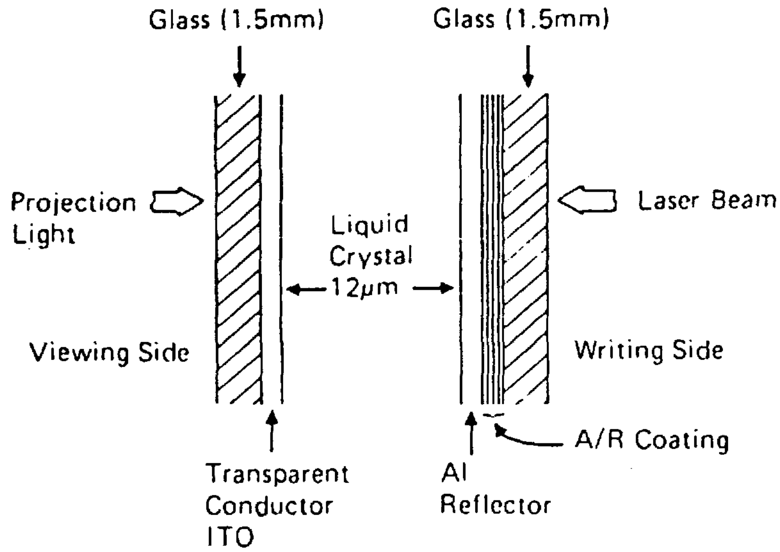


FIGURE 9 Structure of the reflection type of liquid crystal cell.[18]

by several methods, such as an aluminum film,[19] a cold filter,[20] smectic-cholesteric mixed liquid crystal,[21] a laser-absorption dye,[22] and dopants for a contrast ratio which improves the speed with the same level of contrast ratio.[23]

One successful method (not physical but chemical) is to dope the dichroic dye into a smectic[24] or smectic-cholesteric liquid crystal.[25] With the laser-power absorption by the dichroic dye doped into the liquid crystal rather than by the indium-tin oxide electrode on the cell glass plate, the thermal spread is suppressed, and thus the resolution also is improved.[24] In the experiment, the NK-1575 (Nippon Kanko Shikiso Co.) was doped into cyanononyl biphenyl (CNB) by 0.05 ~ 0.2 wt.%, for the He–Ne laser. In other experiments,[25] *p*-nitro-*p*′-dimethyl amino azobenzen for the Ar-laser and D-16 (BDH Chemical) were used. The results are summarized in Table II.[25] Here, the energy required for the write-in spot is reduced to COB, #1/COB = $13/10^3 = 0.013$ and COB : CN, #1/COB : CN = $5/130 = 0.038$. In other words, the same addressing speed could be expected with a small percentage of laser power. It is desired to achieve the response improvement by the liquid crystal materials themselves which are able to absorb the laser power directly and effectively.

TABLE II

Energy required for write-in spot

Cell #	LC & dye	Pulse width (ms)	Spot area ($\times 10^{-3}$ mm^2)	Power (mW)	Energy for write-in (mJ/mm^2)
a	COB	20	1.2	60	10^3
b	COB:CN	20	9.3	60	130
c	COB, #1	5 10	6.8 8.5	18 18	13 21
d	COB:CN, #1	10	20	10	5
e	COB, #3	10	2.3	5.8	25
f	COB:CN, #3	10	4.5	5.6	12

VI. DISPLAY SYSTEM

Liquid crystal display on the basis of the thermo- and electrothermo-optic effects were initiated in 1972,[1,10,13] and since then have been pioneeringly developed in several places, such as Bell Laboratories,[13] Kyoto University,[15,26] Western Electric,[27] and Thomson-CSF.[14] The laser-addressed liquid crystal display was at first considered for the

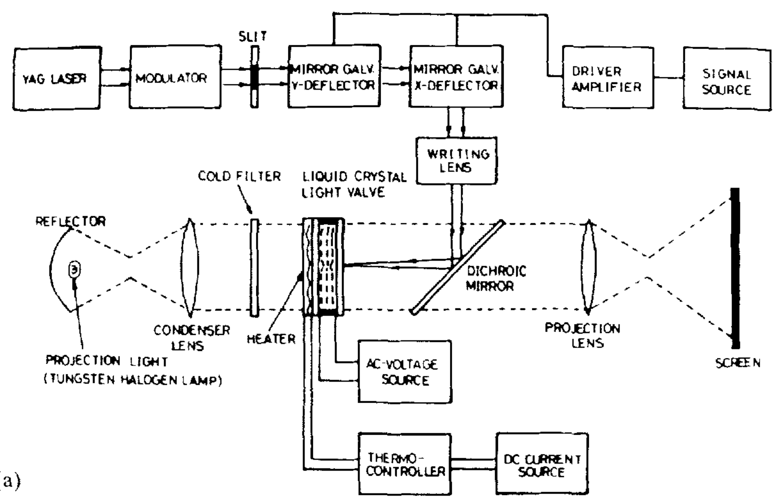
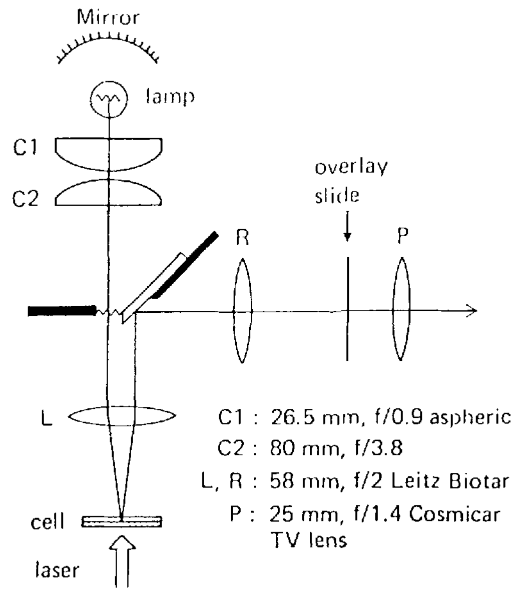


FIGURE 10 Projection display systems for laser-addressed liquid crystal light value. (a) transmission type[15] (b) reflection type.[18]



(b)

FIGURE 10 Continued

video-telephone and the electronic black board.[27] However, once it had been recognized that display possesses many versatile functions, such as high resolution, high information display capacity, large-scale display, storage capability, full-page erasure, selective erasure, gray-scale display, and further dynamic figure display, considerable effort was made to develop the display system for other practical uses.

The display systems are shown in Figure 10. Here, (a) is for the transmission type of cell and (b) for the reflection type of cell in which the projection light is reflected at the dielectric mirror in the cell.[18] The cell structure is simple in the former, and the laser beam can be sharply focused in the latter. In both systems, the laser beam is deflected and addressed by the mirror galvanometers, and the cell temperature is held just below the transition from the smectic to the nematic or the cholesteric phase by the electric current flow through the cell electrodes. The transition temperature is normally higher than room temperature, and thus the temperature bias is for the reduction of temperature increase which improves display response. By the combination of colour filter, the colour display has been demonstrated.[18,28] Recent display systems which can be used in practical fields are summarized in Table III.

The display could be divided into two categories: the high-information content display and the compact type of display. The

TABLE III

Laser-beam addressed liquid crystal display systems

	Cell size [cm²]	Laser [mW]	Spot size [μm]	Numbers of pixel (×10⁶)	Speed [μs/PXL]	Projection lamp [W]	Screen size [cm²]	Contrast ratio	Brightness	Reference	Notes
IBM	1 × 1	GaAs[1] 15 ~ 25	10	0.25	280[2]	Halogen lamp, 50	25.4 × 25.4	8 : 1	8 lm	18	Table-top display
	1.8 × 1.8	Ar 1000	15	1.05[3]	1.5	Xenon 150	38.1 × 38.1			18	Four-colour display Half-tone display
Singer	2.54 × 2.54	YAG : Nd	10	8.39	5		120 × 120	60 : 1		28	Four-colour display 12-level gray scale
Laser-scan	3 × 3	He–Ne 7	30	1.0	500[4]	Hg Arc lamp 350	50 × 50			29	Dye doped cell
	3 × 3	GaAs 10	10	9[5]	~50[4]	Halogen lamp, Arc lamp	75 × 75	7 : 1 50 : 1		29	Dye doped cell
NEC	3 × 3	Ar		9	1.5	Xenon 1000	240 × 240	10 : 1	100 ft-L	16	Two cells Teleconference display
	2 × 2	GaAs 80	10	4	5	Halogen lamp, 650	50 × 50[6]	10 : 1	400 lm[7]	30	Printing function System size 0.5 m³
Sony		GaAs 10	10	1.05 3.53	~8	Halogen lamp		9 : 1		24	

[1] 2 ~ 3 mW on the cell
[2] 20 μs/PXL with 10 mW
[3] Extended to 2.4×10^6, 0.8 μs/PXL
[4] Equivalent writing rate for a line in any direction
[5] Addressable pixels = 144×10^6
[6] Adjustable up to 500×500 cm²
[7] Comparable to OHP

first one is a system with a large number of display picture elements, about 10×10^6 or more. The display can be used for integrated circuit pattern design, newspaper page editing, cartographic editing, command-and-control application, and teleconference display. The other is the compact or table-top type of display to which the GaAs semiconductor or He–Ne rather than the Ar or YAG:Nd laser is adopted for the addressing laser. The number of picture elements is about 1M pixels, which is still very large compared with other types of liquid crystal display. The display examples are shown in Figures 11

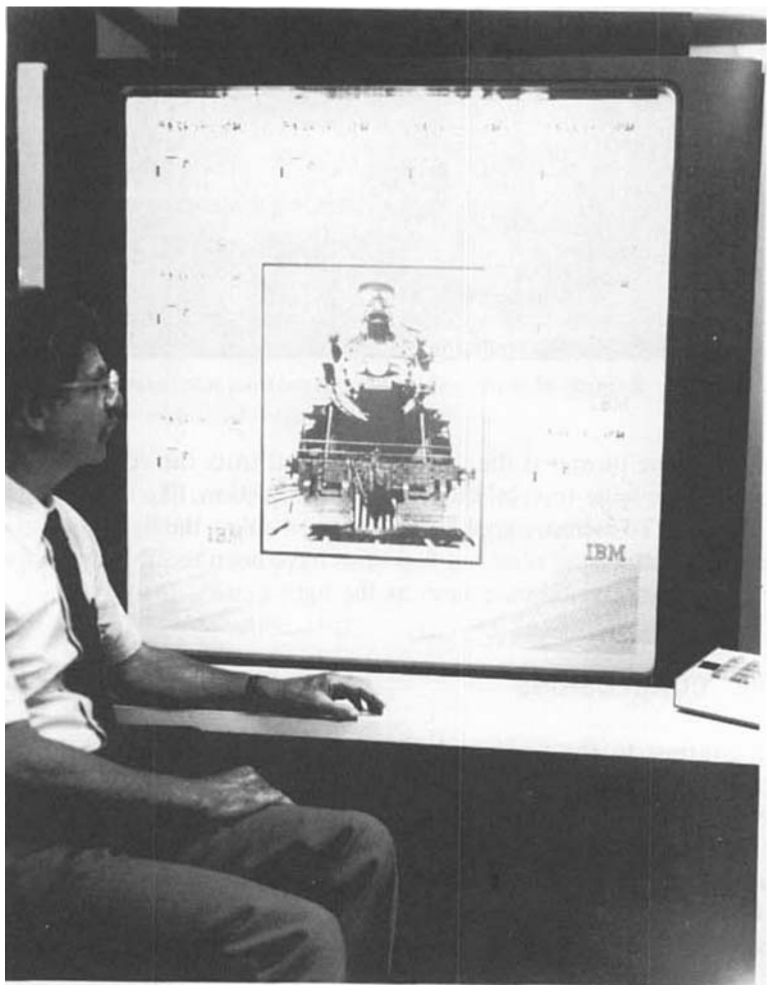


FIGURE 11 Example of display projected from the rear side (courtesy of IBM).

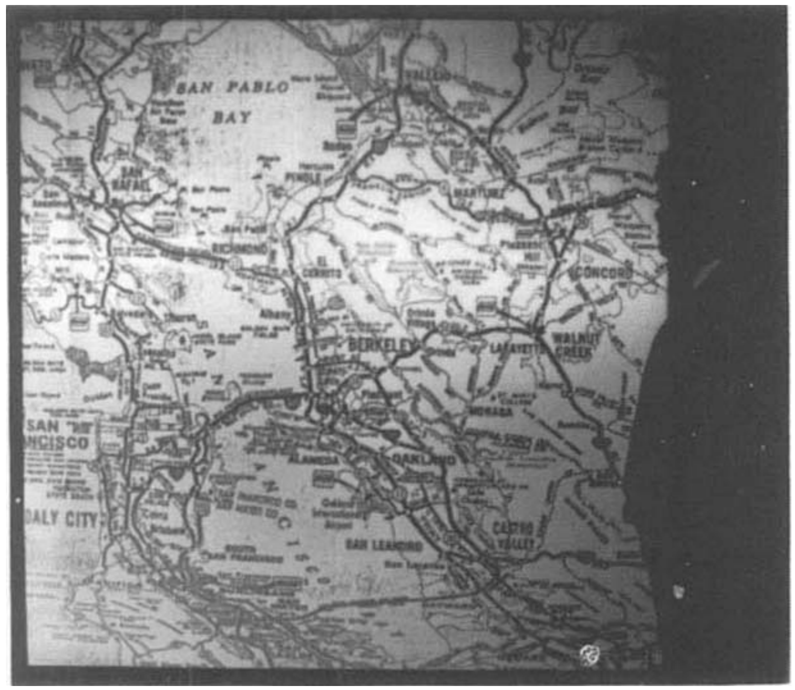


FIGURE 12 Example of display projected from the front side (courtesy of NEC).

and 12. The former is the display projected from the rear side. The latter is the table-top and the front-side projection, like an over-head projector. To increase applicability of the display, the light pen write-in and the electrical read-out functions have been recently developed by using a semiconductor laser as the light pen.[31]

VII. CONCLUSIONS

In contrast to the small-scale flat panel of the conventional liquid crystal display, the laser-beam addressed liquid crystal display has such features as 1) a large scale, 2) memory capability, 3) a selective erasure, and 4) a high resolution. The display can be expected to be used in many applications of high-information content display for IC mask composition, page lay-out, cartography, and scientific data presentation. However, further effort is needed to improve the addressing speed.

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