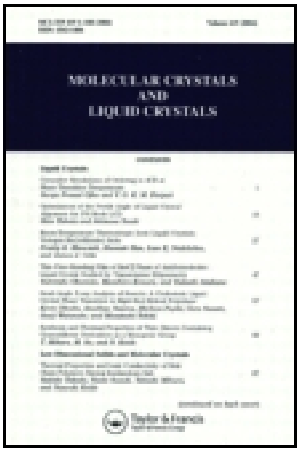

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl16

Liquid Crystal Shutters for Printers

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Version of record first published: 20 Apr 2011.

To cite this article: M. Nagata & H. Nakamura (1986): Liquid Crystal Shutters for Printers, Molecular Crystals and Liquid Crystals, 139:1-2, 143-160

To link to this article: http://dx.doi.org/10.1080/00268948608079603

Mol. Cryst. Liq. Cryst., 1986, Vol. 139, pp. 143–160
0026-8941/86/1392-0143/$20.00/0

Liquid Crystal Shutters for Printers

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(Received November 19, 1985; in final form December 24, 1985)

This paper describes two-frequency driven liquid crystal shutters (LCSs) for electrophotographic printers utilizing liquid crystals which show dielectric relaxation phenomenon in the audio-frequency range. A "one steady state operation" concept is adopted to realize high speed response time. The ECB mode is used for optical switching. Properties required for the liquid crystal materials and the practical uses of the materials are explained. Optical switching is performed by combining an initializing signal, a state-changing signal and a state-holding signal. Two examples of multiplex drive waveforms and their optical responses are given. Finally, specifications for electrophotographic printers using two-line multiplex-driven LCSs are shown.

Keywords: liquid crystal, nematic phase, dielectric relaxation, two-frequency addressing, liquid crystal shutter, printer

I. INTRODUCTION

With the increase in information processing by the personal computer, the printer is also realizing ever-wider applications as an output device indispensable for such information processing.

Today wiredot-impact printers are widely used because of their excellent cost performance, but they have such drawbacks as slow printing speed and high noise level. The electrophotographic printer features, on the other hand, not only high printing speed and low noise, but also the capacity to process "text" and "figure" at the same time. Thus, there are great hopes for this device as the printer of the coming generation.

According to the types of "writing" head, electrophotographic printers are classified into laser beam printers, LED printers, LCS (liquid crystal shutter) printers, etc. The LCS printers,[1–3] featuring a more compact head (than other types) and lower cost, are expected to become the mainstream of low-end page printers.

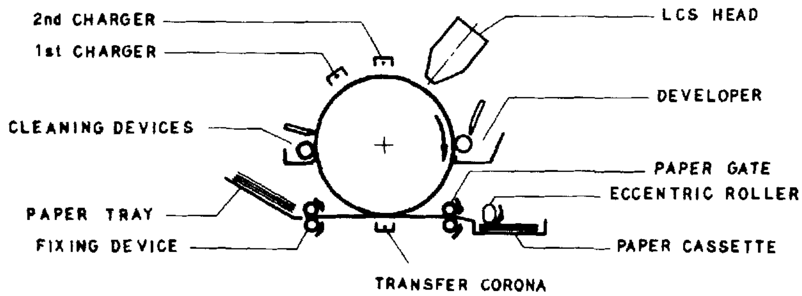


FIGURE 1 Conceptual diagram of an LCS printer.

Figure 1 shows a conceptual diagram of an LCS printer, and Figure 2 the internal structure of the LCS head. The printer structure shown in Figure 1 is identical to that of an ordinary copier with the exception of the LCS head. In a copier, a latent image is formed on the surface of the photo sensitive drum within the area between the 2nd charger and the developer as the image of the original copy is formed there. The latent image is turned into a real image by the developer, transferred to a paper by the transfer corona and fixed to the paper by the fixing device.

With the LCS printer, the latent image is formed on the photosensitive surface by irradiation of light from the LCS head that has a structure as shown in Figure 2. The LCS panel shown in Figure 2 is a shutter array with liquid crystal shutters arranged one-

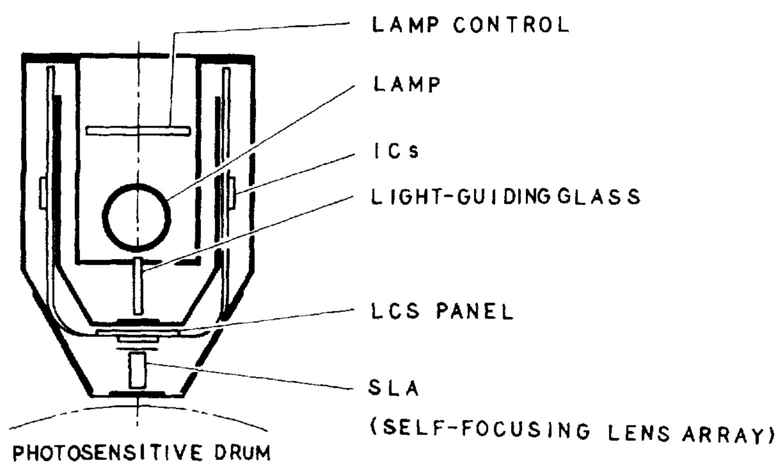


FIGURE 2 Cross-sectional drawing of LCS head construction.

dimensionally in the normal direction of Figure 2. Each shutter opens and closes independently by the operation of its driving IC. Accordingly, some of the light from the lamp, having reached the LCS panel through the light-guiding glass, passes through the open shutters and, upon passing the SLA (self-focusing lens array), forms an image on the photosensitive drum surface, while the rest of the light is arrested by the closed shutters. Thus, by opening and closing independent shutters adequately, desired patterns can be "written" on the photosensitive surface.

If the cycle time of each liquid crystal shutter becomes less than 2 msec, then the system as shown in Figure 1 can create a page printer that can copy several pages per minute. And an element most crucial in realizing such an LCS printer is the LCS, or a one-dimensionally arranged liquid crystal shutter array capable of operating at high speed.

The following five performance items are required of an LCS:

1. quick response time
2. large light transmission
3. high contrast
4. high multiplexibility
5. wide-band light switching

We have successfully developed an LCS that satisfies all the above requirements by adopting the two-frequency drive of liquid crystal whose dielectric anisotropy changes from positive to negative because of its dielectric relaxation phenomenon in the audio-frequency range. The following is a detailed discussion of this LCS.

II. OPERATION CONCEPT ON LCS

In the following, the technical features of the LCSs are clarified through comparison with an ordinary liquid crystal display (hereafter abbreviated as "LCD").

In the operation of an LCD, the on state and off state are both determined by the effective voltage of the voltage applied. In other words, they have little to do with the instantaneous changes of applied voltage. And both the on state and off state are steady states corresponding to the respective effective voltages being applied.

The response time of an LCD is the time for transition from one to the other of the two steady states. In the conventional system, the rise time could be shortened but the fall time could not be changed.

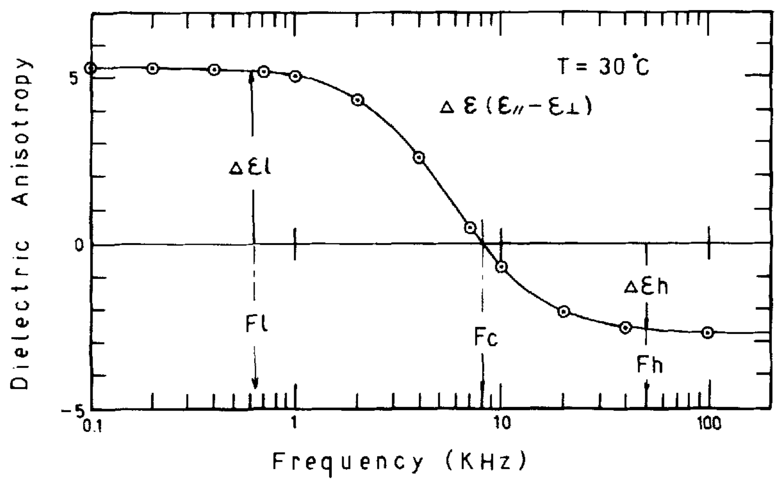


FIGURE 3 Frequency dependence of dielectric anisotropy of the liquid crystal used for LCS. (temperature: 30°C) Relations of $\Delta\epsilon l$, Fl, Fc, $\Delta\epsilon h$ and Fh are shown.

Thus, a two-frequency drive using liquid crystals characterized by the dielectric dispersion as shown in Figure 3 was proposed to compensate for this shortcoming.[4-9] However, the response speed fast enough for an LCS printer was not realized.

The performance requirements for an LCS, on the other hand, are as follows:

1. The repetitive cycle corresponding to the scanning time, which is always constant, is very short (2 msec or less).
2. The light transmission is constant, irrespective of the history of opening and closing.

Condition 1 above requires a high-speed response of the LCS of 1 msec or less both in rise and fall time. Condition 2 implies that the contrast of the LCS must not have any dependence on the effective voltage. Hence, the LCD concept can not satisfy requirements 1 and 2.

In our method, therefore, the two steady states were reduced to one[10-12] and an initializing signal is applied to bring about the said steady state at least once in a repetitive cycle. We call this concept a "one steady state operation." In addition to this concept, the adoption of the two-frequency drive of a liquid crystal material characterized by dielectric dispersion as shown in Figure 3 has satisfied not only the above conditions 1 and 2 but also the five requirements mentioned in the previous section.

Actual LCSs are produced as follows:

1. Liquid crystal material showing dielectric dispersion in the audio-frequency range is used. (See Figure 3.)
2. The above material is placed into a cell in a homogeneous orientation.[13] (See Figure 4(a).)

The orientation can be a hybrid orientation;[14] the following discussion, however, concerns only the homogeneous orientation.

The basic operation of the shutters comprises the following four steps:

(1) A low-frequency (*Fl* in Figure 3) electric field is applied as an initializing signal to create an initial state. (See Figure 4(b).)
(2) A high-frequency (*Fh* in Figure 3) electric field is applied as a state-changing signal to tilt the liquid crystal molecules. (See Figure 4(c).)
(3) A state-holding signal is applied to hold the initial state.
(4) An initializing signal is applied again to create an initial state.

Note that (1) and (4) are exactly the same step, so that (1) can be considered the end of a foregoing step. Each shutter repeats one or

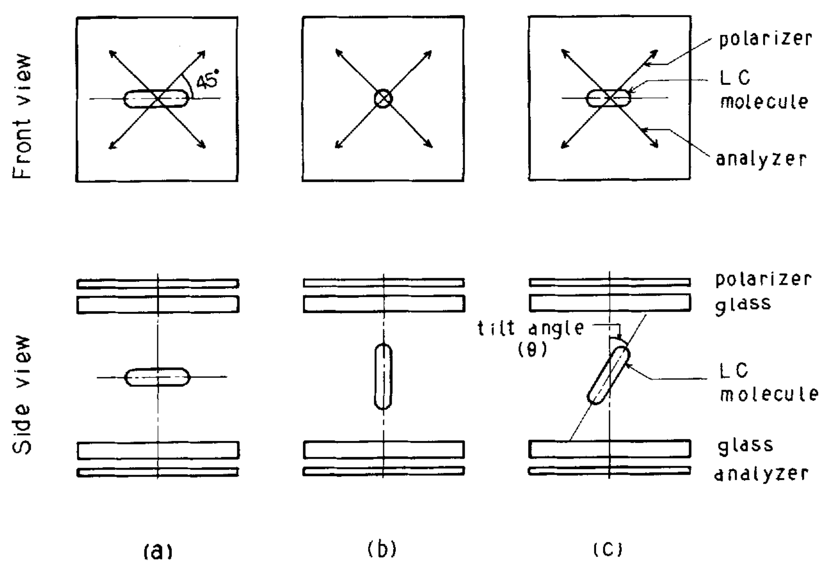


FIGURE 4 Conceptual diagram of optical switching by the ECB mode. The upper half are front views of the cells and the lower half shows side views. (a) is the state with no electric field. (b) and (c) are the off state and on state respectively.

both of (2) → (4) and (3) → (4) steps. It can be decided at will whether the initial state be the state of transmission or no transmission. The following discussion, however, explains that the initial state is the state of no transmission (off state). Therefore, Figure 4(c) is the state of transmission (on state).

The initial state or off state is a steady state. That is, this state is a steady state corresponding to the initializing signal (*Fh* field). The on state (Figure 4(c)), on the other hand, is not a steady state but a transitional state. In other words, the on state is a whole process during which the tilt angle increases gradually from zero to the desired point and then gradually decreases to zero. Therefore, there is no steady state during all this process. This is the point that is basically different from the LCD. The state-holding signal represents either a state of *Fl* and *Fh* fields superimposed or a state where there is no electric field.

Thanks to the structure and operation of the liquid crystal cell as mentioned above, the LCSs were successfully put into practical application.

III. LIQUID CRYSTAL MATERIAL

The liquid crystal material to be used for the LCSs must display dielectric characteristics as shown in Figure 3.[15] *Fc* in Figure 3 is a crossover frequency at which $\Delta\epsilon = 0$. *Fl*, which is lower than *Fc*, is a frequency at which the dielectric anisotropy $\Delta\epsilon l$ is positive. *Fh*, which is higher than *Fc*, is a frequency whose corresponding dielectric anisotropy $\Delta\epsilon h$ is negative. The above relationships of *Fl*, *Fh*, $\Delta\epsilon l$ and $\Delta\epsilon h$ must be kept in mind in the following discussion.

The response time,[16] when the twisted nematic cell[17] filled with liquid crystals of Figure 3 is driven at frequency *Fl*, can be written

$$\tau_r = \frac{\eta d^2}{\epsilon_0 \Delta\epsilon l V^2 - K\pi^2} \tag{1}$$

$$\tau_d = \frac{\eta d^2}{K\pi^2} \tag{2}$$

where η is viscosity, d is cell thickness, ϵ_0 is the vacuum dielectric constant, V is the applied voltage and K is the elastic constant. From Equation (2), we know that the fall time τd can not be changed by external means. But, with an electric field of frequency *Fh* applied at fall time,[4,5] we obtain

$$\tau_d = \frac{\eta_d^{\,2}}{\epsilon_0 |\Delta\epsilon h| V^2 + K\pi^2} \tag{3}$$

From Equations (1) and (3), we see that both the rise time and fall time are dependent on the applied voltage. Accordingly, high-speed switching can be realized by raising the voltage.

Also, from Equations (1) and (3), it is apparent that the larger the values of $\Delta\epsilon l$ and $|\Delta\epsilon h|$, the higher the response speed is. Therefore, the liquid crystal material must have a larger $\Delta\epsilon l$ and $|\Delta\epsilon h|$.

Now, the liquid crystal element is a capacitive load, the lower the drive frequencies Fl and Fh, Fh in particular, the lower the power consumption will be. Since Fh is higher than Fc, the lowering of Fc as much as possible leads, in turn, to the lowering of Fh. Supposing Debye's theory[18] can be applied to the relaxation time of the liquid crystal τ_{LC}, we obtain

$$\tau_{LC} = \frac{4\pi\eta L^3}{kT} \tag{4}$$

$$Fr \propto \tau_{LC}^{\;-1} \tag{5}$$

where L is molecular length, k is the Boltzmann constant, T is temperature (°K) and Fr is the relaxation frequency. Since $Fc \approx Fr$, a greater molecular length L proves very effective in lowering Fc.

From Equation (4), we know that τ_{LC} is in proportion to the viscosity. The viscosity, which is experimentally given by

$$\ln(\eta) = \ln(\eta_0)\exp[W\eta/kT] \quad \eta_0,\ W_\eta : \text{constant} \tag{6}$$

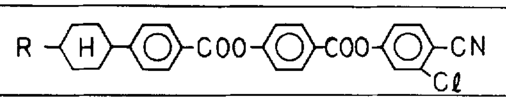
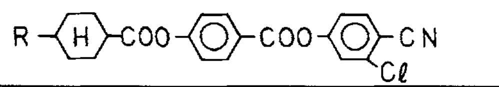
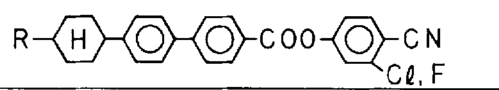
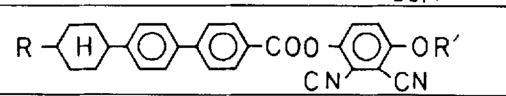
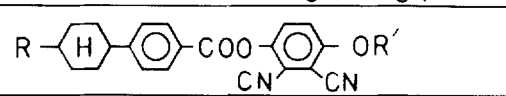
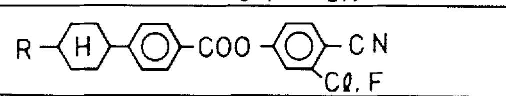
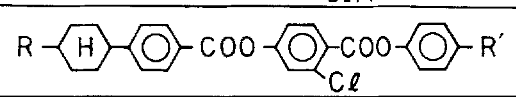
is greatly influenced by temperature. Therefore, Fc, too, shows considerable temperature dependence, and temperature compensation is an important problem to be solved in practical application.

Equations (1) and (3) indicate that the response speeds τ_r and τ_d are proportional to viscosity η. This means the response can be quickened by reducing the value of η. From Equations (4) and (5), however, we know that a smaller η brings about a higher Fc, thus necessitating a higher Fh. All considered, the value of η must be determined by balancing the response speed against the drive frequency Fh.

Table I shows examples of liquid crystal materials actually used in

TABLE I

Examples of liquid crystal materials used in LCS. Molecular formulae marked with a circle (○) in the columns corresponding to $\Delta\epsilon l$, $\Delta\epsilon h$ and Fc are effective in enlarging $\Delta\epsilon l$, making $|\Delta\epsilon h|$ bigger and decreasing Fc, respectively.

No.	Molecular Formula	$\Delta\epsilon l$	$\Delta\epsilon h$	Fc
1		○		
2		○		
3		○		○
4			○	○
5			○	○
6		○		
7				○

LCSs. Note that all the materials shown in Table I are tricyclic or quadricyclic and there are no bicyclic materials that are used in ordinary TN–LCDs. All this is to realize a lower Fc, and the materials 3, 4, 5 and 7 are particularly effective in lowering Fc.

The material with a large dipole moment in the director direction proves effective in enlarging $\Delta\epsilon l$. Materials 1, 2, 3 and 6 are examples of such material. Material with a large dipole moment in the vertical directions of the director can enlarge $|\Delta\epsilon h|$. Materials 4 and 5 are examples. Practically usable liquid crystal mixtures (e.g., the ones shown in Figure 3) with a sufficient nematic range, can be produced by properly mixing the materials shown in Table I.

IV. OPTICAL SWITCHING

The method of switching the tilt angle of the liquid crystal layer was outlined in Section II. And the discussion in this Section concerns how the change in tilt angle is converted into the change in optical transmission.

The methods of converting tilt angle change into optical change include the G.H. (guest-host) mode using a dichroic dye and the ECB (electrically controlled birefringence) mode. Though both modes can be used for LCSs, the ECB provides a better contrast ratio.

Figure 4 shows a conceptual diagram of optical switching by the ECB. The upper half of Figure 4 shows front views of the liquid crystal cell from the incident direction. The lower half shows side views of the liquid crystal cell. In this figure, (a) represents the steady state with no electric field while (b) and (c) represent the off state and on state, respectively. In the steady state (a) and on state, the director is set at 45 degrees to both the polarizer and analyzer. This can be accomplished by a parallel orientation treatment in which the liquid crystal cell is subjected to rubbing in advance.

The optical transmission T in this setup can be written

$$T = T_0 \sin^2\left[\frac{\Delta N \cdot d}{\lambda}\pi\right] \tag{7}$$

where d is cell thickness, λ is wavelength, T_0 is incident light intensity. ΔN, which is the apparent birefringence anisotropy, can be given by

$$\Delta N = \frac{\mathrm{n}_\parallel \cdot \mathrm{n}_\perp}{(\mathrm{n}_\parallel^2 \cdot \cos^2\theta + \mathrm{n}_\perp^2 \cdot \sin^2\theta)^{1/2}} - n_\perp \tag{8}$$

and is a function of the tilt angle θ as shown in Figure 4(c). In the above equation, $\mathrm{n}_\parallel$ and $\mathrm{n}_\perp$ are the parallel refractive index and the perpendicular refractive index, respectively.

In the off state (Figure 4(b)), the tilt angle θ is zero. At this time, $\Delta N = 0$. So from Equation (7), transmission $T = 0$. That is an off state. The off state can be caused by an application of an electric field of frequency *Fl*. And the on state can be brought about with an electric field of frequency *Fh* applied to the cell in the off state. In the on state, $\Delta N \neq 0$, which usually means $T \neq 0$, or an on state.

Figure 5 shows a static relationship between transmission and applied voltage when an electric field of 1.6 kHz is applied as *Fl* to the liquid crystal as shown in Figure 3. In Figure 5, the maximum value of transmission stands at about 3.5 V. At this maximum value, $\Delta N \cdot d/\lambda = 1/2$ and then with an increase in applied voltage, $\Delta N \cdot d/\lambda$ decreases toward zero—an approach toward an off state.

Actually, however, $\theta = 0$, or $T = 0$, does not result, no matter how high a voltage is applied. Nevertheless, the ratio of the trans-

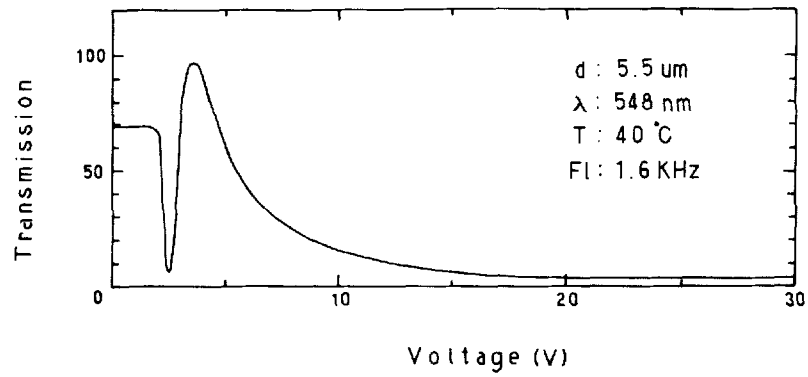


FIGURE 5 Static characteristics of voltage versus optical transmission of LCS panel. Cell thickness is 5.5 μm, wavelength is 548 nm, temperature is 40°C, and the frequency of applied voltage is 1.6 KHz.

mission at voltages of 25 V or above to the maximum transmission at 3.5 V is 1 : 25 or more. By use of these two points as off state and on state, an adequate contrast ratio can be obtained for the LCS. As was described in Section II, an actual on state is a dynamic state in which the tilt angle of the liquid crystal or the transmission is constantly changing. However, as will be shown in Section VI, the value of θ remains generally in the neighborhood of the maximum transmission, so that a considerable light transmission can be obtained on average.

V. LCS PANEL STRUCTURE

As shown in Figure 2, the LCS panel is a tiny one-dimensional shutter array. Figure 6 shows an example of actual LCS panel construction. The left side is the front view and the right side the cross-sectional view at $K-K'$ in the front view. In the front view, both the electrode pattern on the data substrate and the electrode pattern on the common substrate are shown only between two-dot chain lines.

The example of Figure 6, having two common electrodes, represents an electrode pattern suited to two-line multiplex drive. Common electrodes are composed of transparent ITO (Indium Tin Oxide) and opaque nickel electrodes. The nickel electrodes work as the optical masks and form the shape of micro shutters. Nickel electrodes are also useful in reducing resistances of common electrodes.

Data electrodes are mostly made of ITO. But they have small nickel

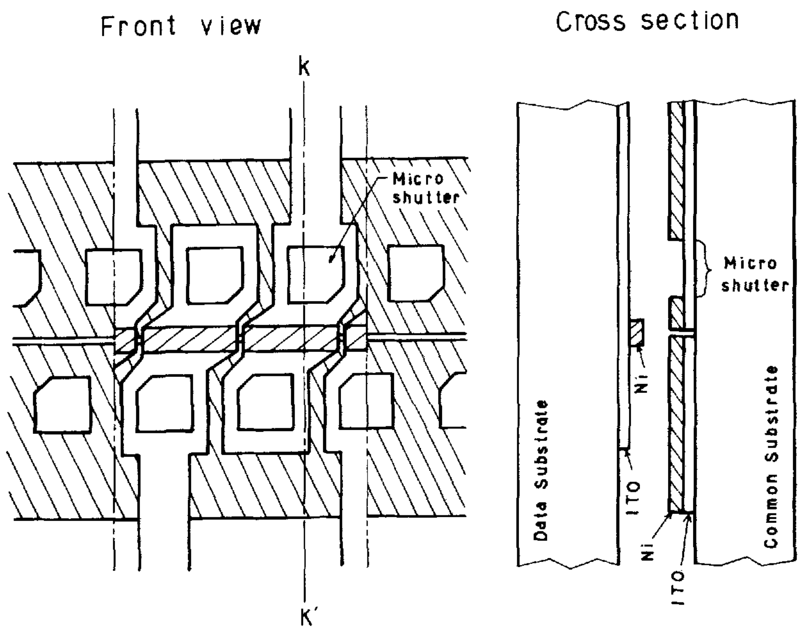


FIGURE 6 LCS panel structure. The left side is front view and the right side is cross section at $K-K'$ in the front view.

electrodes facing on the border of the two common electrodes. They also work as an optical mask to prevent light leakage between the common electrodes. Consequently, incident light can only pass through micro shutters. There are, however, little apertures surrounded by two common electrodes and the data electrodes which allow a negligible amount of light leakage. The pitch of the micro shutter array is 211.6 μm on each common electrode. It corresponds to 240 D.P.I. (dots per inch). The micro shutter is 110 μm square with one corner cut at an angle of 45°.

VI. DRIVING WAVEFORMS

The concept of the LCSs driving was already discussed in Section II. That is, the drive consists of the following four steps:

(1) First an initializing signal is applied to create an initial state (off state).
(2) For an on state, a state-changing signal (*Fh*) is applied.
(3) For an off state, a state-holding signal is applied.
(4) An initializing signal is applied again to create an initial state.

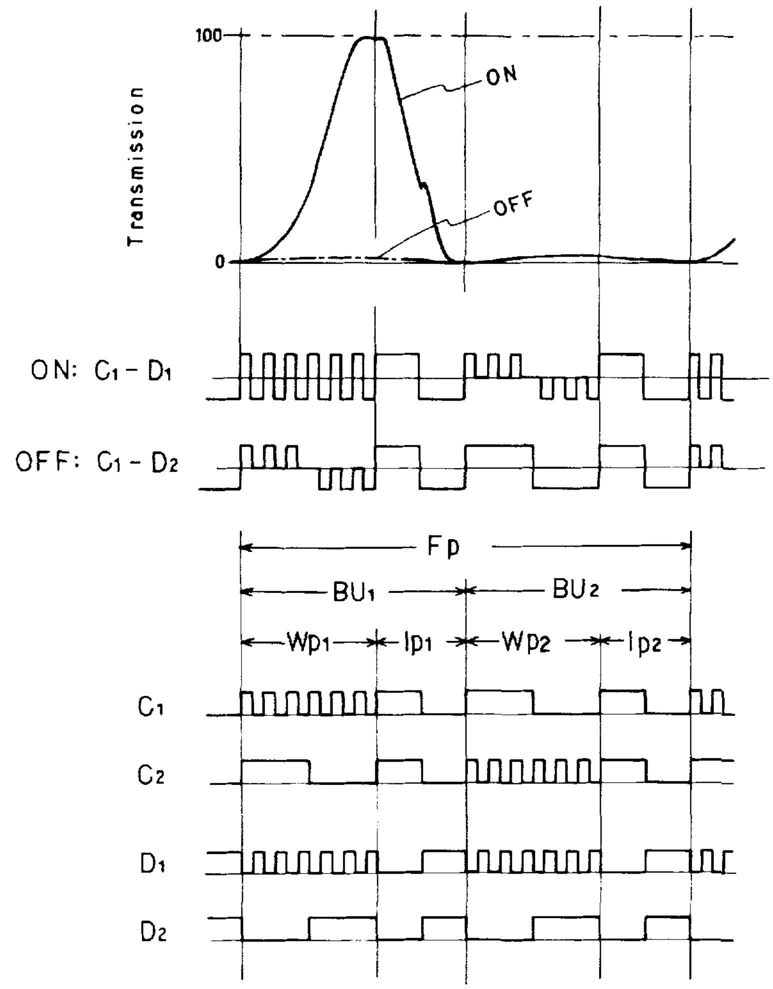


FIGURE 7 Example of two-line multiplex drive waveforms and the optical responses of LCS.

Here the step of (2) → (4) or (3) → (4) is called a basic unit (BU). For a multiplex drive, BUs are combined in accordance with the multiplexity, thus constituting the frame period.

There are various methods proposed for the LCS drive using the three basic signals of initializing signal, state-changing signal and state-holding signal.[10–11,20–22] Figure 7 and Figure 8 show examples of the waveform of two-line multiplex drive and the optical characteristics of the liquid crystal shutters.[21–24] In these figures, *C1* and

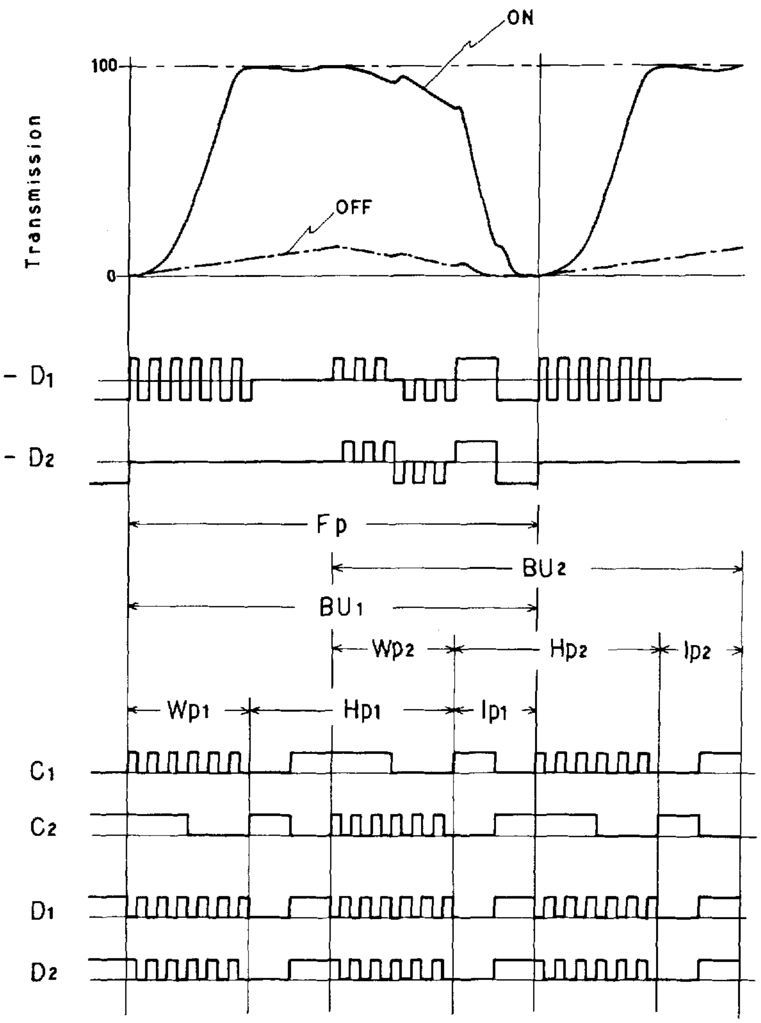


FIGURE 8 Example of two-line multiplex drive waveforms and the optical responses of LCS.

$C2$ are timing select signals, $D1$ and $D2$ are data signals, the axis of abscissa represents the time axis, and Fp is the frame period.

In Figure 7, the Fp is comprised of two basic units, $BU1$ and $BU2$. Each of the BUs consists of "writing" period Wp and initializing period Ip. By combining these waveforms, an initializing signal, a state-changing signal and a state-holding signal are created. For example, through a combination of $C1$ and $D1$, the $C1-D1$ signal is

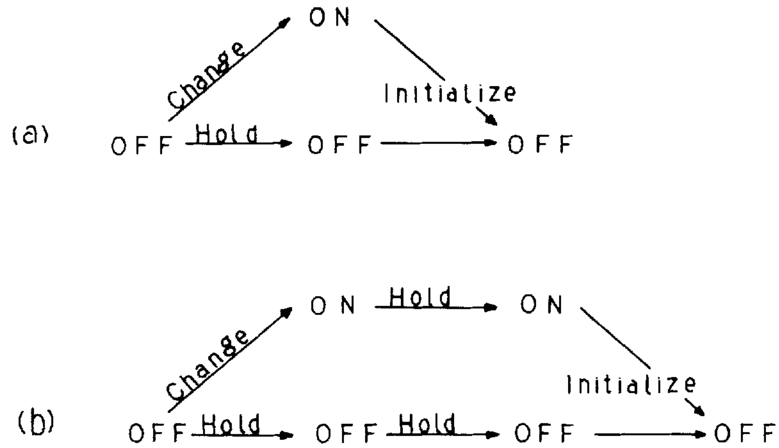


FIGURE 9 Schematic representations of driving processes. (a) corresponds to Figure 7 and (b) to Figure 8.

applied to the liquid crystal. During the $Wp1$ of $C1-D1$, a high-frequency field is applied, which is a state-changing signal. During this period, the liquid crystal molecules keep tilting, with the optical transmission rising, as shown at the top of Figure 7. Then during $Ip1$, a low-frequency field is applied. This is an initializing signal. Thus, the transmission is reduced until an off state is reached. Next, during $Wp2$, a high-frequency signal and a low-frequency signal are applied at the same time. This is a state-holding signal, which maintains the off state. Finally, during $Ip2$, an initializing signal is applied again to create an off state.

In the case of $C1-D2$, an off state is maintained throughout the frame period Fp because a state-holding signal is applied during the $Wp1$ of $BU1$.

It is evident that the system as represented in Figure 7 can realize a multiplex drive of 3 lines or more simply by adding a necessary number of basic units (BUs).

Figure 8 shows another example of drive waveforms. It differs from Figure 7 in that $BU1$ and $BU2$ overlap each other by one half. Each of the BUs consists of three periods, namely a "writing" period Wp, a holding period Hp and an initializing period Ip. In other words, they have an addition of a holding period Hp over those of Figure 7. The differences between Figure 7 and Figure 8 are represented schematically in Figure 9. Figure 9(a) corresponds to Figure 7 and Figure 9(b) to Figure 8. The combination of Wp and Hp in Figure 8 corresponds to Wp in Figure 7.

The optical response by $C1-D1$ and $C1-D2$ is shown at the top. In the case of Figure 8, the light transmission in the on state is larger than that in Figure 7. However, its light leakage in the off state is greater. Therefore, the case of Figure 7 features a better contrast ratio.

In either case of the representative drive systems described above, the "writing" period Wp ("writing" period + holding period for Figure 8) must be of such a length that an initial state can be restored by an initializing signal to be applied subsequently.

VII. LCS PRINTER

A conceptual diagram of the LCS Printer was already shown in Figure 1, and a cross-sectional drawing of the LCS head construction is shown in Figure 2. Figure 10 shows the LCS head. Figure 11 shows the inner construction of the LCS head, including the LCS panel and the driver *IC*s. Two-line multiplex drive, shown in Figure 7, is used for this LCS head. The appearance of the LCS printer is shown in Figure 12. The LCS head shown in Figure 10 and Figure 11 is built into this printer. The specifications of this printer are given in Table II.

VIII. SUMMARY

It was most important for making a technical breakthrough on the LCSs to use liquid crystals that show dielectric relaxation phenomenon in the audio-frequency range and to adopt a two-frequency

FIGURE 10 LCS head.

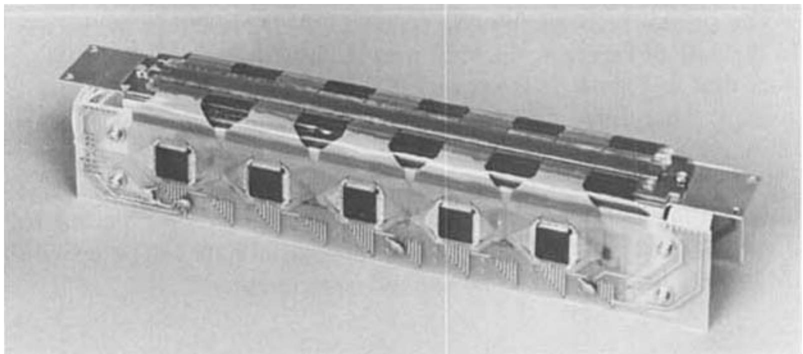


FIGURE 11 Inner construction of LCS head.

drive. However, the "one steady state operation" concept is no less important than the above. The "one steady state operation" concept, which represents one steady state, that is, an initial state or an off state, and one transitional state or an on state, makes the LCSs possible.

Liquid crystal materials are required to have a large absolute value for both $\Delta\epsilon l$ and $\Delta\epsilon h$. The longer molecular length results in a lower relaxation frequency.

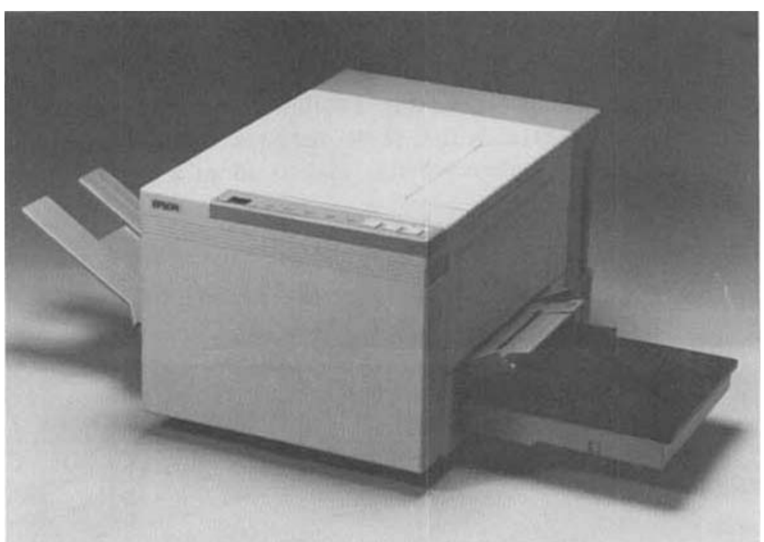


FIGURE 12 LCS printer.

TABLE II

Specifications of the LCS printer

1. **Printing Specifications**	
Printing Method	: Electrophotographic and liquid crystal shutter system
Printing Speed	: 7 PPM
Dot Density	: 240 DPI
2. **Paper**	
Paper	: Plain paper
Paper Supply	: Cassette type (250 sheets in one cassette)
Paper Handling	: Friction feed
3. **Life**	: Approximate 1 million sheets
4. **Noise Level**	: 55 dB (A range)
5. **Interface**	: 8 bit parallel and RS-232C as standard
6. **Electrical Specifications**	
Power Line Voltage	: 4 different voltage options are available
Power Consumption	: 1.2 KVA
7. **Physical Specifications**	
Dimensions	: 436 mm(H) × 607 mm(W) × 350 mm(D)
Weight	: 45 kg

Both the ECB mode and the G.H. mode are applicable for use in optical switching of the LCSs. However, when the ECB is used, there is better contrast.

Driving waveforms used in the LCSs consist of an initializing signal, a state-changing signal and a state-holding signal. By a combination of these signals, the operation cycle of LCSs starts from an initial state and ends in the same state. Each cycle operates independently, neither giving nor receiving any influence from the neighboring cycle.

By adopting the above mentioned techniques, the LCS printer has been developed.

Acknowledgment

The authors would like to express their thanks to Dr. Y. Yamazaki, general manager of the fundamental technology research division, for his encouragement.

References

1. J. Tults, *Proceeding of the S.I.D.*, **12**, 199 (1971).
2. K. Aoki, et al., U.S. Patent 4386836.
3. K. Aoki, et al., Japan Patent Application 54-171799.

4. T. S. Chang and E. E. Loebner, *Appl. Phys. Lett.*, **25**, 1 (1974).
5. C. S. Bak, K. Ko and M. M. Labes, *J. Appl. Phys.*, **46**, 1 (1975).
6. C. J. Gerritsma, Japan Patent 1018345.
7. Marvin J. Freiser, U.S. Patent 3857629.
8. H. Nakamura, Japan Patent 1268314.
9. H. Nakamura, Japan Patent 1264769.
10. H. Nakamura, et al., Japan Patent Publication 60-40608.
11. H. Nakamura, et al., Japan Patent Publication 60-40609.
12. H. Nakamura, et al., Japan Patent Publication 60-42456.
13. H. Nakamura, Japan Patent Application 57-59327.
14. H. Nakamura, Japan Patent Application 57-202565.
15. M. Schadt, *J. Chem. Phys.*, **56**, 1494 (1972).
16. E. Jakeman and E. P. Raynes, *Phys. Lett.*, **39A**, 69 (1972).
17. M. Schadt and W. Helfrich, *Appl. Phys. Lett.*, **18**, 127 (1971).
18. P. Debye, "*Polar Molecules*," Reinhold Publishing, New York (1929), Chap. 5.
19. Y. Matsushita, et al., Japan Patent Application 56-7046.
20. K. Aoki, et al., Japan Patent Publication 60-40611.
21. Y. Matsushita, et al., Japan Patent Publication 60-42457.
22. H. Nakamura, Japan Patent Application 57-202568.
23. H. Nakamura, et al., Japan Patent Publication 60-40612.
24. H. Nakamura, K. Aoki and M. Yonekubo, The 2nd international congress on advances in non-impact printing technologies, p. 213, Arlington, Virginia, U.S.A., (1984).