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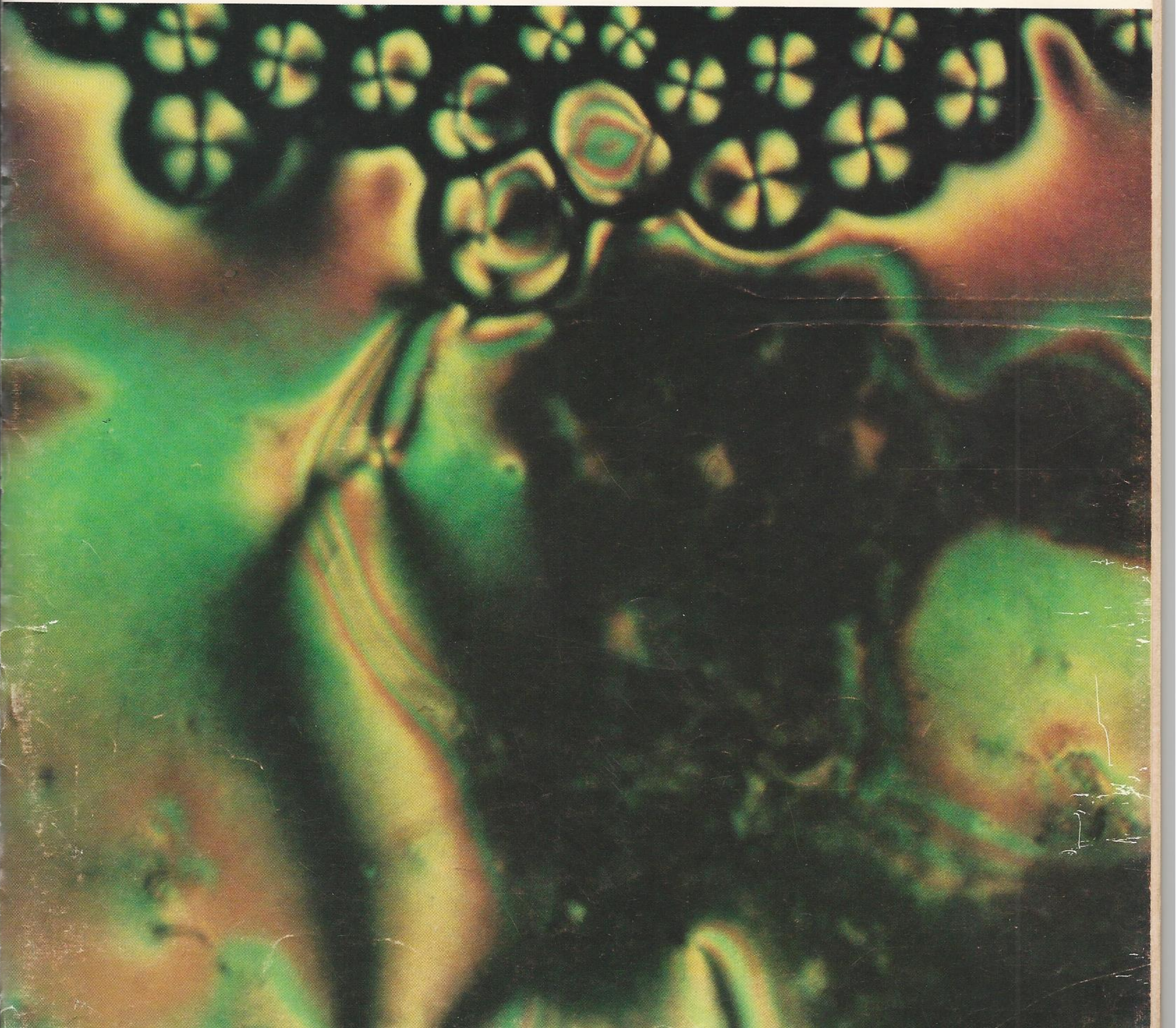

LIQUID CRYSTALS:
Perspectives, Prospects, and Products

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Until the right materials came along, the great potential of liquid crystals could not be fully realized. Now liquid crystal displays are popping up all over: in wrist watches, clocks, calculators, panel meters, multimeters, and industrial controls. And because they can store images and provide color effects, liquid crystals will make a significant impact on graphic and TV displays.

About five years ago, liquid crystals were only a well-publicized laboratory curiosity, seemingly of no great practical consequence. Today, liquid crystal technology has been reduced to practice and promises to make a significant impact on the marketplace, particularly in numeric readout displays. Companies announcing the use of liquid crystal displays in pocket-size calculators, wrist watches, multimeters, and electronic instrumentation have multiplied greatly in recent months.

Liquid crystals are finding applications from the smallest (the electronic wristwatch) to the largest displays (electronic outdoor and advertising displays); from the most immediate and practical (numeric readouts) to the most far out and pie-in-the-sky (flat screen TV and computer terminal displays).

This continuous tone, color image projected on a cholesteric-phosphor screen (6"x9") shows feasibility of laser-scanned color TV display (See p. 28). (Photo courtesy of Bell Labs)

Why have liquid crystals moved so suddenly into the forefront of displays after years of being on the backburner? The discovery of compounds that have liquid crystal phases and hence, electro-optical properties in a room temperature range has been crucial. Previously, electro-optical effects such as dynamic scattering were only observed at 100 C and above in liquid crystals. Now there are liquid crystals that exhibit these effects below 0 C; thus, high temperature heating is no longer required to make the liquid crystals work.

The rapid development and availability of MOS circuits, particularly complementary MOS, have played no small part in the accelerating interest in liquid crystal displays. Many applications, where liquid crystals will find their greatest use (such as the electronic wrist watch and the pocket-size calculator), would hardly even exist without MOS integrated circuits. Why do the fortunes of liquid crystal displays seem to be so closely tied to MOS? The answer is simple. Liquid crystal displays can be directly driven off MOS IC chips, because they require little power and operate at relatively low supply voltages (15-30 volts).

What are Liquid Crystals?

Liquid crystals are materials whose molecules arrange themselves in ordered groupings, having many of the characteristics of crystals. For example, some crystalline materials have properties which vary along different axes of the crystal and are therefore anisotropic. Liquid crystals also have anisotropic properties. In the sense that these molecular arrangements display a crystalline-like order and the material does actually flow, these arrangements are called liquid crystal phases. There are three liquid crystal phases: nematic, cholesteric, and smectic **(Fig. 1)**. It should be remembered that these liquid crystal phases exist only over a limited range of temperature. Below this temperature range the liquid crystal material may become a solid without crystalline properties and above it, the material may cease to be a crystalline liquid and may become an ordinary liquid with isotropic properties. All of the interesting electro-optical and optical effects attributed to liquid crystals arise from the particular arrangement of the molecules in their crystalline liquid state.

According to Dr. Glen Brown, Director of the Liquid Crystal Institute at Kent State University, there are three characteristics of the structure of a molecule that enhance its ability to form liquid crystal phases: length, rigidity, and planarity. All these characteristics increase the molecules' tendency to align or stack themselves in ordered groups like pieces of cordwood.

The existence of electric dipoles in the molecular structure is required if electro-optical effects are going to occur in liquid crystals. The direction of the electric dipole moment determines whether a molecule will have positive or negative dielectric anisotropy, a property which controls the electro-optical behavior of the molecule. For positive anisotropy, the component of the electric dipole moment parallel to the molecular axis is greater than that perpendicular to it. For negative anisotropy the component of the dipole moment perpendicular to the molecular axis is greater.

Although the cholesteric is treated as a distinct phase, it really is a special case of the nematic phase. According to Dr. Alfred Saupe of the Liquid Crystal Institute, the cholesterics are thermodynamically the same phase as the nematic and the same order principle is involved in both phases. The difference between the nematic and cholesteric phases is that the parallel alignment of molecules in the nematic phase now has a continuous twist superimposed on it for the cholesteric phase (Fig. 1). Because of the continuous twist of the molecular alignment, cholesterics are very optically active and the plane of polarization of transmitted light is strongly rotated. A rotation angle of 18° per μm of thickness has been observed for one cholesteric.

Electro-Optical Effects in Liquid Crystals

Up to the present time five electro-optical effects have been observed in nematic liquid crystals: dynamic scattering, guest-host interactions, voltage-controlled optical activity, the fast turn-off mode, and deformation of vertically aligned phases. Electro-optical effects have also been observed in cholesterics, mixed cholesterics and nematics, and smectics.

By far the most useful effect in current display applications is dynamic scattering. Dynamic scattering is the well-known phenomena of the scattering of light by the turbulent motion of nematic liquid crystals in an electric field. With no applied field, the liquid crystals assume their crystalline alignment and are essentially transparent to light, when an electric field is applied, the liquid crystals become milky white and opaque. The dynamic scattering mode accounts for about 90% of the application of liquid crystals to the display market. Because of its importance dynamic scattering will be more fully discussed in a separate section.

A potential "sleeper" in display applications is the effect called voltage-controlled optical activity. One way this effect has been observed is to sandwich a thin layer of twisted nematic liquid crystals between two plates of glass, each provided with a conductive coating. The surface of the two glass plates is prepared in a special way, such that the orientation pattern of the molecules turns 90° in going from one glass plate to the other with no electric field applied. Now, if linearly polarized light is perpendicularly incident on one side, the direction of its plane of polarization will rotate along the twist axis of the nematic molecules a total of 90° as the light is transmitted to the other side.

When an electric field is applied across the cell, the nematic liquid crystal molecules are rearranged so that their orientation no longer shows a continuous twist of 90°. Hence, light will now pass through the nematic liquid crystals without a change in the plane of polarization.

Two variations of the effect can be obtained by viewing the light passing through the liquid crystals, either with a pair of parallel polarizers or with a pair of crossed polarizers **(Fig. 2)**.

The guest-host interaction effect opens the door to color in liquid crystal displays. In this effect, another kind of molecule, called the "guest", is introduced into the crystalline order of a nematic liquid crystal (the "host"). The "guest" is a dichroic dye molecule whose optical absorption of polarized light depends on the orientation of the dye molecule. The orientation of the dye molecules and their optical absorption can be controlled by aligning the nematic molecules in an electric field **(Fig. 3.)**

Another important effect in nematic crystals is the fast turn-off mode. The effect is similar to that of dynamic scattering except that the decay or turn-off times are much shorter. In the fast turn-off mode, first observed by Heilmeir and Helfrich at RCA, the milky-white appearance, which is the result of dynamic scattering, is achieved by oscillating domains of liquid crystal molecules instead of conduction-induced turbulence of the molecules themselves. In dynamic scattering the turn-off times are relatively long due to the highly disordered orientation in the turbulent state and are of the order of 100 to 200 ms. In the fast turn-off mode, a strong electro-optical effect is obtained but with faster turn-off times (less than 5 ms.).

The fast turn-off mode requires that the frequency of excitation be in a critical frequency range (600 Hz in Heilmeier and Helfrich's experiments). Below this frequency range the decay times increase very strongly; above it the electro-optical effect vanishes. The contrast achieved by this particular type of effect is not as great as it is for dynamic scattering, for oscillating domains do not scatter light as strongly as intense turbulence.

In liquid crystal displays employing dynamic scattering, the liquid crystal acts like a light valve, controlling the transmission and reflection of light. Other electro-optical effects can be used to perform this function. One of these effects is the deformation of vertically aligned phases, observed by Schiekel and Fahrenschon of AEG-Telefunken (West Germany). In this effect the transmission of light is controlled by a specially prepared nematic liquid crystal cell located between crossed polarizers. The liquid crystal cell is prepared so that the long axis of the nematic molecules is perpendicular to the electrode surface over large areas. This effect uses the birefringent properties

Dynamic scattering is not a field effect . . .

of the specially prepared liquid crystal cell. Contrast ratios of 1000:1 have been achieved with voltage requirements of only 7 to 8 volts.

The storing of information or of an image in liquid crystals is a capability that has hardly been explored, but will probably become important in the future. The storage effect occurs in a mixture of nematic and cholesteric crystals, the nematic crystal being of the type that exhibits dynamic scattering. With no applied field, the mixture of the two is transparent. The effect is the same as that of dynamic scattering except that when the low-frequency field that is applied to create dynamic scattering is removed, the mixture remains milky white instead of returning to the clear state. The mixture can be made transparent again by applying an ac field of several KHz and about 50 volts. Without applying a high-frequency field, the mixture regains its transparency only after several weeks have elapsed.

Dynamic Scattering In Displays

About 90% of the displays that are being developed today are using the effect of dynamic scattering in liquid crystals. Dynamic scattering will occur only if the nematic liquid crystal has a negative dielectric anisotropy. This means that the electric dipole moment of the molecule has a larger component perpendicular to the molecular axis than it does parallel to it. Since an electric dipole generally tries to line up parallel to an applied field, having negative dielectric anisotropy insures that the nematic molecules will line up perpendicular to or across the applied field at some angle **(Fig. 4)**. Electrical conduction through the crystals is a necessary condition for dynamic scattering, for it is the interaction of charge carriers and the dipole moment of the nematic liquid crystal molecules that gives rise to the light-scattering turbulence in the liquid crystal film. Therefore, dynamic scattering is *not* a field effect.

Pure nematic compounds have resistivities on the order of 10^{12} ohm-cm and are not sufficiently conductive to give good contrast ratios* in a display. Hence, a dopant is added to the pure nematic material to make it more conductive. To see any contrast at all, the resistivity of the material must be dropped down below 10^{11} ohm-cm. Contrast ratios continue to improve as the resistivity is lowered, but there is a limit to this improvement. To get a resistivity of 10^8 ohm-cm or less, 1 to 3% of dopant must be added to the pure nematic liquid crystal and the nematic temperature range starts to narrow. One benefit of operating at the lower resistivities is that the response time of the crystals is considerably shortened. A detrimental effect of the lower resistivities is that current and therefore power consumption increase and can become excessive, especially for battery-powered applications.

Dynamic scattering is not observed until the applied voltage exceeds a certain value, the threshold for the material. Threshold voltages for dynamic scattering in most nematic crystals is about 7 to 8 volts for a liquid crystal film thickness of about 10 to 15 μ. At the threshold voltage the contrast ratio is minimal (about 5:1). The contrast ratio keeps improving until at some voltage a saturation point is reached after which no further increase in contrast is observed. The contrast ratio-voltage curve for many manufacturers' nematic material exhibits a finite slope from the threshold to the saturation point, but Texas Instruments claims to have a material whose curve is almost a step function. Contrast ratios at saturation can be anywhere from 25:1 to 50:1.

Displays using the dynamic scattering mode are fairly easy to make. A few drops of nematic liquid crystal are placed between two parallel plates of glass, each plate having a coating or film of transparent electrical conductor, such as tin oxide, to provide an electric field across the thickness of the liquid crystal. Plastic or glass spacers are used to keep the liquid crystal layer uniformly thick. Thicknesses range from about 6 to 25 μ. If the display is to work by reflecting ambient light, then the rear electrode should be a highly reflecting film, such as aluminum. If on the other hand, the display is to work by controlling transmitted light, then both the rear and the front electrode should be transparent. The electrode can be shaped into patterns of segments so that when the display is "on", numbers or letters can be presented.

While a liquid crystal display can be put together fairly easily, there is more to a display than mere mechanical construction. Although the basic liquid crystal materials are readily available, the commercially available materials are not sufficiently pure to give good display properties, life, and stable temperature range. The crystals must be purified to remove from them all traces of water, oxygen, and unreacted components. The real problem of the doping of pure materials is that an impurity may be added inadvertently that will degrade the display properties of the material.

While most liquid crystal display manufacturers are reluctant to say what nematic liquid crystal systems they are using, it is a relatively sure bet that many of them are using either MBBA, EBBA, or a mixture of both.

What is the big attraction of MBBA and EBBA? First, these two compounds are readily available commercially and are relatively inexpensive, so that they are handy for companies who have no facility for synthesizing liquid crystal materials. Also, MBBA is one of the very few pure nematic crystals which has a freezing point at room temperature, i.e. the transition temperature from the

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*The contrast ratio is the ratio of the brightness of an activated segment of the display to the brightness of a non-activated segment. A minimum acceptable contrast ratio is 10:1.

nematic phase to the solid phase is at 22 C. MBBA also has a useful nematic temperature range from 20 C to 41 C, where it undergoes the transition from a nematic liquid crystal to an isotropic liquid. EBBA is a similar compound but has a nematic temperature range of 38 to 60 C. By mixing these two compounds together the freezing point can be depressed to —10C or a little lower, and the resulting temperature range for the nematic phase is from about —10 to 50 C. Both MBBA and EBBA have fairly good scattering properties and both compounds are easy to synthesize. It is not too difficult to use these compounds as starting points and develop new compounds by chemical substitution.

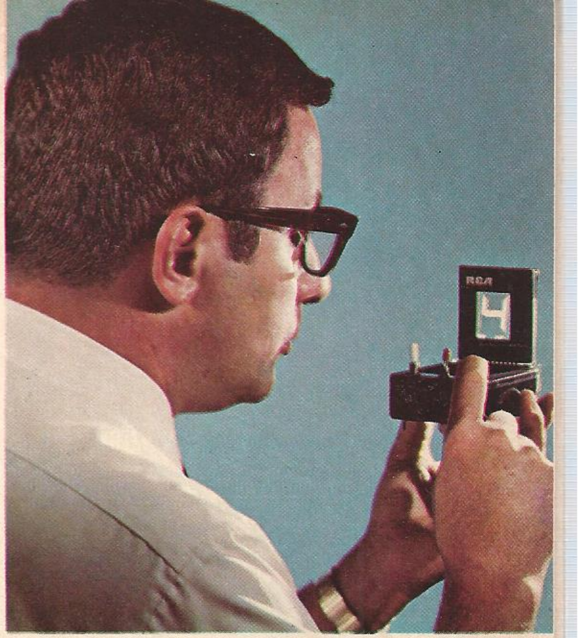
A disadvantage of this family of nematic liquid crystal compounds is that they hydrolyze in the presence of moisture, acids, or bases. They decompose at the carbon-to-nitrogen double bond and form an aldehyde and an amine, neither of which have liquid crystal properties. Decomposition by hydrolysis is a problem common to all Schiff-base materials such as MBBA and EBBA. While hydrolysis is no problem once the liquid crystals are hermetically sealed, it could be a problem during the assembly of the display devices. Ultraviolet and sunlight can also decompose the Schiff-base materials.

The Pluses and Minuses of Liquid Crystal Displays

The big pluses of liquid crystal displays can be summed up in the words: low power, low cost, low voltage, and great flexibility in size. The reflective type of liquid crystal display requires little power to operate compared to other types of displays such as LEDs and glow-discharge tubes. They do not emit light themselves but use the ambient light to derive their contrast. Typically, the power consumption is about 1 mW/digit compared to about 100 mW/digit for glow-discharge tubes, and several hundred mW/digit for LEDs. Using ambient light to achieve contrast provides an additional bonus: the brightness of the display is a function of the ambient light. Hence, the displays do not "wash out" in high ambient light levels as other displays do, and input power does not need to be increased to operate in a higher ambient light.

Because of the low cost of the liquid crystal material and the simplicity of the display cell structure, the cost of liquid crystal displays are expected to be below those of other types of displays in the near future, especially when systems costs (i.e. the cost of all components including decoder/driver electronics) are compared. Although current prices are somewhat higher for liquid crystal displays because they have just been put into production, the cost per digit is expected to come down to about $0.50 to $1.00/digit by 1973, exclusive of the decoder/driver circuits.

With operating voltages of liquid crystal displays being in the range of 15-35 volts, the displays in many cases can be driven directly off an MOS chip. This means that in some applications such as the calculator, there will be no need for a separate decoder/driver module, for the decoder/driver function can put onto the same chip along with the other calculator functions. Hence, the cost of the decoder/driver circuits need not increase the overall cost of liquid crystal displays significantly.



Guest-host interaction creates a blue liquid crystal display. Almost-white "4" is the result of aligning blue dye molecules with nematic molecules in applied field. (Photo courtesy of RCA)

Liquid crystal displays can be made as large as a billboard and as small as a watch face. The great flexibility in size and configuration will open up a wider range of display applications than is possible for any other type of display.

Liquid crystal displays, of course, are not without their disadvantages. The operating temperature range is rather limited compared to other displays, 0 C to 60 C, for most of the presently available displays.

For applications such as outdoor displays and automobile

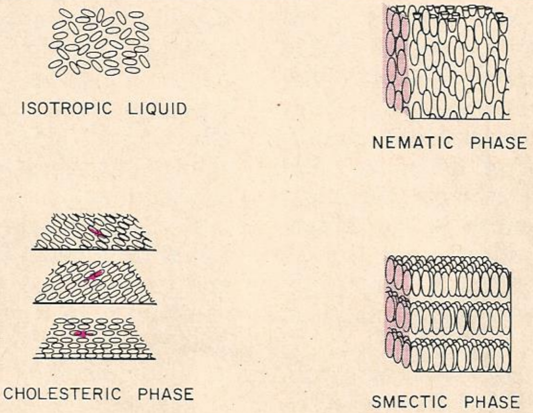


Fig. 1. The molecular axes of isotropic liquids are randomly oriented. By contrast in the nematic phase, molecules all have their long axes parallel to each other, but are free to move in any direction. In the smectic phase, molecules exist in parallel layers and any two layers are free to slide over each other so long as the individual molecules do not move out of their layers. In the cholesteric phase, molecules lie parallel in layers with the alignment axis shifting in each successive layer so that a helix is traced out through the layers.

Operating life has been one of the biggest concerns . . .

dashboard indicators, the inability to operate much below 0 C will be a liability for liquid crystal displays. The prospects for finding new materials with lower operating temperatures and wider ranges are not encouraging. George Graham of Optel puts it bluntly: "It just is not in the chemical cards to get a nematic operating range of —50 C to 125 C." The only practical solution is to incorporate a heating element in the liquid crystal display to keep the temperature of the liquid crystal in its operating temperature range.

Operating life has been one of the biggest concerns about liquid crystal displays. Manufacturers of liquid crystal displays are currently quoting lifetimes of 10,000 hours as a typical operating life for liquid crystal displays under ac excitation, and either quoting no figure or a figure much less than 10,000 hours for dc operation. The problem for dc operation is that driving the display continuously in one direction results in electrochemical process that degrade the liquid crystals and shorten the life.

A life of 10,000 hours is an acceptable minimum for many applications, but other applications will require considerably longer life (50,000 hours). Although few manufacturers have performed statistically significant life testing for more than 15,000 to 20,000 hours, there is a general consensus in the industry that an operational life of 50,000 hours or more is not only feasible but will be attainable in the near future.

To avoid the handling problems of the Schiff-base materials, a group at IBM, under the direction of Marvin Freiser, Manager of the Physical Sciences Dept., is synthesizing a family of room temperature nematic compounds called trans-stilbenes. In the trans-stilbenes, the carbon-to-nitrogen double bond of the Schiff-base materials is replaced by a carbon-to-carbon double bond. This chemical class of compounds is much more resistant to degradation by moisture, oxygen, and ultraviolet than the Schiff bases are. Another advantage is that they are intrinsically colorless, whereas the Schiff bases are yellowish in color. One binary mixture of trans-stilbene derivatives which IBM is developing has a nematic temperature range of 8 C to 59 C.

The contrast ratio of a liquid crystal display does change with viewing angle, particularly for the reflective displays, where at certain angles front surface reflection off the front glass panel can compete with rear-surface reflected light. However, this is not a serious problem for transmissive displays. If the ambient light level is too low to get good contrast with the reflective display, then the transmissive display must be used with an auxiliary light source to backlight the display. For the transmissive display, some of the advantages of low power consumption and size are negated by the addition of the light source.

It should be noted that many of the advantages of the dynamic-scattering liquid crystal display also apply to the type of display that relies on the voltage-controlled optical activity of a twisted nematic crystal. This type of display is currently manufactured only by the International Liquid Crystal Company (Ilixco). Voltage-controlled optical activity is a field effect and does not require charge carriers and therefore any current.

Because the threshold voltage for this display is only 3 volts and the contrast ratio saturates at about 7 to 8 volts, the power consumption is even lower than it is for displays using dynamic scattering. A leakage current does flow through the liquid crystals but it is a factor a 10 to 100 times smaller than current levels in dynamic scattering displays. Because fewer charge carriers are around to cause electrochemical degradation of the material, dc life as well as ac life should be greatly improved.

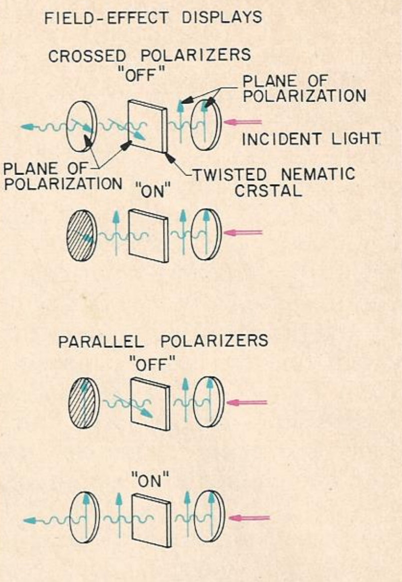


Fig. 2. Contrast Effects with Voltage-Controlled Optical Activity. With parallel polarizers light transmission through the cell will be a minimum with no applied field and a maximum with an applied field. With crossed polarizers, maximum transmission occurs with no applied field. An "on" segment appears white on a black background with parallel polarizers and black on a white background with crossed polarizers.

The disadvantage of the display is that the contrast ratio changes strongly with viewing angle, going from 25:1 to 4:1 as the viewing angle increases to 40° for the reflective display and 85° for the transmissive display. Because these displays are relatively slow in response, sequential scanning will be as difficult as for the dynamic scattering displays. Lower voltages, lower power, and potentially greater life make this type of liquid crystal display a dark horse in the display market.

Is Ac in the Driver's Seat?

Since dc driving of present generation liquid crystal displays considerably shortens their life, dc operation is a real hang-up for most manufacturers. Even in battery-powered applications, many of the manufacturers are converting the dc supply voltage to an ac excitation voltage, in many cases by using complementary MOS. As

Walter Lawrence, Manager of the Liquid Crystal Display Product Department of RCA, puts it: "We're all for ac". He explains that with complementary MOS available, it is very easy to drive the displays ac, and that to drive them dc is unnecessary and not worth the effort. Other product engineers echo a similar sentiment, and it appears that ac operation will be the accepted practice for many of the displays being marketed today.

Going counter to prevailing opinion, Richard Reynolds, Manager of Display Technology at Texas Instruments, is not ready to write off dc operation. He contends that, provided lifetime is acceptable, dc is still the most convenient method of operation, especially if sequential scanning or multiplexing of the display is desired. In displays with a string of 5 or more digits, applying power to each of the digits in sequence instead of all of them simultaneously considerably reduces the power consumption of the display. Reynolds feels that the simplest way to scan sequentially is with dc using a diode in series with each segment of the digit.

The difficulty with ac operation, according to Reynolds, is that they have not found a cost effective circuit which not only gives an ac drive on the liquid crystal segments but also scans the digits. The problem is with electrical isolation and the lack of a sharp voltage threshold for dynamic-scattering nematic materials. Each segment of a character in a liquid crystal display electrically looks like a large-value resistance (hundreds of megohms) shunted by some value of capacitance (hundreds of picofarads). As a result, when a display is driven with ac in a scanning or multiplexing mode, the capacitive coupling between segments produces parallel current paths, and because there is no sharp voltage threshold, segments that have not been selected can be partially turned on. Isolation can be improved by going to higher frequencies, but if the critical frequency of the liquid crystal (usually several kilohertz) is exceeded, the dynamic scattering effect is lost. Hence, Reynolds concludes that the only way to drive and scan the display is dc.

If liquid crystals are ever going to have a significant impact on graphic and TV displays, an adequate scanning or multiplexing scheme to address the display matrix will have to be developed. Presently the status of multiplexing schemes is not encouraging. Walter Lawrence of RCA reveals that many multiplexing schemes have been proposed and tried at RCA, but that they have not seen any scheme which is practical and cost effective.

The recently announced two-frequency coincidence addressing scheme developed by Stein and Kashnow at General Electric has offered renewed hope that the multiplexing problem can be solved. The GE scheme capitalizes on the fact that dynamic scattering is restricted to relatively low-frequency regimes below a certain critical frequency (about 500-1000 Hz), and that moderate voltages above the critical frequency prevent dynamic scattering.

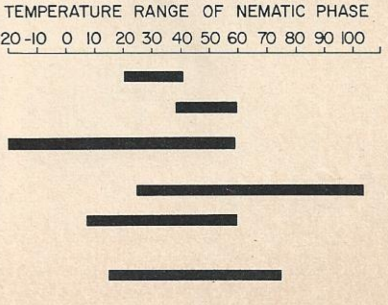
By simultaneously applying two signals or pulse trains, one below the critical frequency at 30 Hz and one above the critical frequency at 2000 Hz to the eight-segment electrodes, Stein and Kashnow were able to turn on segments where the two different pulses did not coincide and turn off segments where the two different pulses did coincide. The GE development reduces the number of electrical leads needed to activate the display. For an 8 digit long display, the two-frequency coincidence scheme requires only 16 electrical leads compared to the 65 required by previous methods.

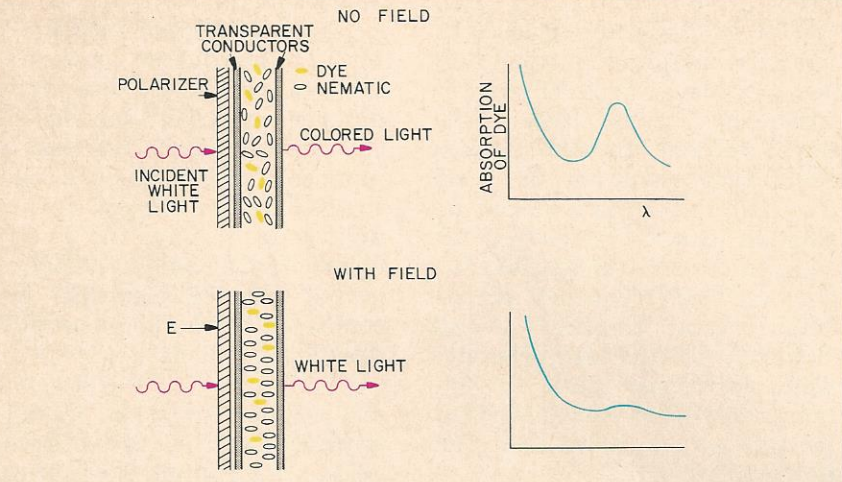
There are some drawbacks to the scheme. Stein and Kashnow noticed that it takes several cycles of scanning to reach peak response. The number of cycles that must be applied and the peak response is a function of the amount of voltage available. To get good contrast and a fairly snappy response time, the display must be operated at about 50 volts. This is fairly high voltage compared to the normal driving voltage of 15-30v. Another limitation of the scheme is that, since the liquid crystal material is heavily doped for the special application of the matrix addressing scheme, the nematic temperature range was correspondingly reduced to about 40 degrees (13 to 53 C) compared to the usual 50 to 60 degrees. Finally, the necessity for a high refresh rate to minimize display flicker will limit the number of characters or elements in the matrix that can be addressed without replication of circuitry. Charles Stein, a co-developer of the GE matrix addressing scheme, readily admits that a liquid crystal TV display will require a matrix addressing scheme that is much better than the present coincident addressing scheme. A 16×16 matrix would be possible with the present scheme but a TV matrix of

TABLE 1

Some Commonly Used Nematic Liquid Crystals for Dynamic Scattering Displays

Liquid Crystal	Chemical Name
MBBA	N-(p-methoxybenzylidene)-p-n-butylaniline
EBBA	N-(p-ethoxybenzylidene)-p-n-butylaniline
55 mole % MBBA and 45 mole % EBBA	--
Ternary mixtures	p-alkoxybenzylidene-p'-aminophenylacylates
Binary mixtures of substituted trans stilbenes	Example: d,1-4(2-methylhexyl)-4'-ethoxy-α-chloro-trans-stilbene
Merck NLC N4	Azoxybenzene derivatives





COLOR DISPLAYS USING DICHROIC DYES

Fig. 3. The Guest-Host Interaction Effect. A dichroic dye absorbs light differently along two perpendicular axes. The nematic crystals used must have positive dielectric anisotropy. When a field is applied, the nematic molecules line up parallel to the field, and if the concentration of the guest molecule is small enough (around 1%), they will also help align the guest molecules to the field.

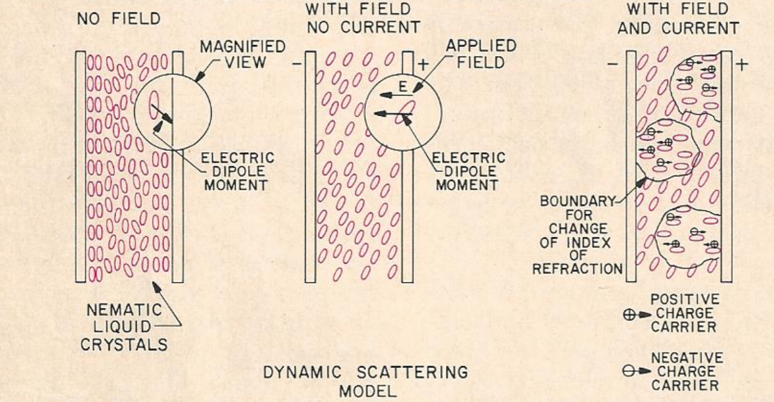
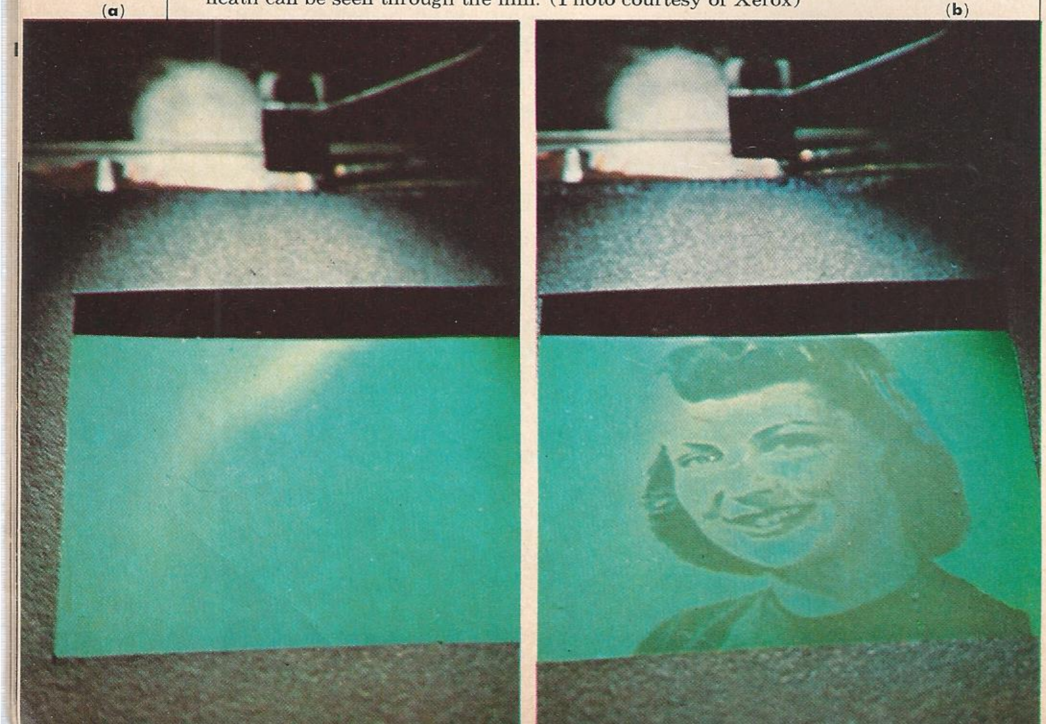


Fig. 4. With no applied field, nematic molecules are generally randomly oriented. With an applied field but no current, the molecules assume a parallel orientation such that their dipole moment lines up with the field. As current starts to flow, the charge carriers disturb the aligned molecules and create regions of changing index of refraction.

Fig. 5. Semi-permanent image-storing display in cholesteric crystals. Before exposure (a), the liquid crystal film has uniform green reflection color. After exposure (b), lighted areas lose their reflection color and the dark photoconductor underneath can be seen through the film. (Photo courtesy of Xerox)


(a)

(b)

. . . the biggest market could be the electronic wrist watch.

over 300×500 elements would be out of the question.

The Marketplace

For the near term, at least, three potentially strong market areas are shaping up for the liquid crystal displays. They are the watch and clock market, the pocket-size and desk calculator market, and the digital panel meter market.

One of the biggest markets for liquid crystal displays could be the all electronic wrist watch using a digital output. Conservatively estimated this could be a 50 million dollar market by 1975. If both liquid crystal displays and MOS circuits realize their full potential and costs come down to the point where the liquid crystal display-electronic watch can sell for about $20 to $40, it could mean the rebirth of an American watch industry, an industry which has been steadily declining under the pressure of foreign imports for decades.

Another potentially big market for liquid crystal displays is the calculator market, particularly the pocket-size calculator market which is just starting to boom. Ragen Precision Industries, for example, is already in production on a mini-calculator using an eight-digit liquid crystal numeric readout. The size of this market will depend greatly on the overall cost of the calculator. If the cost of the mini-calculator comes down around $50 to $75 for the consumer, then a very large potential market could open up, this market could be as large as 25 million dollars by 1975.

The third big market for liquid crystal displays will be in digital panel meters. The market for digital panel meters will probably be limited to those re-

. . . TV displays will depend on an effective matrix addressing scheme.

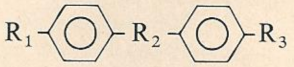
quiring 1% accuracy or better, an accuracy for which the digital panel meter is superior to the analog panel meter. The biggest application for the digital panel meter could be the familiar multimeter (volt-, ohm-, ammeter). When the cost of the electronic multimeter itself gets down around \$50-\$100, then the whole multimeter market could open up for liquid crystal digital panel meters. This amounts to some 300,000 units per year. There are many other applications of digital panel meters and one of them, industrial controls, is receiving the concentrated interest of Industrial Electronic Engineers, Inc., who plan to go into production of liquid crystal digital panel meters and indicators by early summer.

The script for the general market scene for liquid crystal displays up to 1975 could read as follows. For 1972, the liquid crystal displays are not expected to chalk up more than a few hundred thousands dollars sales total, because they have been on the market for such a short time. However, by 1973, the volume should start rising significantly, and by 1974-75 the total market should be in the vicinity of 10 million dollars.

Cracking the Chemical Code

To the non-chemist the long and bewildering chemical names of the nematic liquid crystal compounds can leave the erroneous impression that all these compounds are structurally very different. This is not the case, for when the known nematic compounds are written in symbolic form, one recognizes the great similarity between them. In all of the compounds listed below, there are two co-planar benzene rings separated by a central group, and each benzene ring is flanked on the outside by two end groups, one group of which is an alkoxy group ($CH_3(CH_2)_n0$-). The benzene rings give the molecule a flatness or planarity that facilitates the stacking of the molecules. Central groups typically have carbon-to-carbon or carbon-to-nitrogen double bonds to give the molecule rigidity. The dipole moment can be displaced off the molecular axis to achieve negative dielectric anisotropy by using an end group, for example, that has an oxygen-to-carbon double bond. A liquid crystal molecule can be lengthened by makin the end group on one side a longer alkyl or branched alkyl group ($CH_3(CH_2)_n$-).

The basic skeletal molecule for known room temperature nematic liquid crystals is



where the end (R_1 & R_3) and center groups (R_2) are given in the following table.

	R_1	R_2	R_3
MBBA	CH_3O-	$-CH=N-$	$-C_4H_9$
EBBA	CH_3CH_2O-	$-CH=N-$	$-C_4H_9$
trans stilbene derivative	CH_3CH_2O-	$-CH=\underset{\underset{Cl}{\vert}}{C}-$	$-CH_2CH(CH_3)C_4H_9$
Alkoxybenzylidene aminophenylacylate derivatives	$CH_3(CH_2)_nO-$	$-CH=N-$	$-O-\overset{\overset{O}{\Vert}}{C}-(CH_2)_nCH_3$
Merck NLC N4	CH_3O-	$-N=\overset{\overset{O}{\vert}}{N}-$ and $-N=\overset{\overset{O}{\vert}}{N}-$	$-C_4H_9$

Looking beyond the near term market to 1975, a tremendous market for liquid crystal displays could develop in the automobile industry. Any or all of the automobile dashboard meters and indicators could be well served by liquid crystal displays. In addition liquid crystal devices could be used to automatically dim automobile headlights or to dim the rear view mirror to reduce night blindness. Automobile manufacturers have already been approached and are receptive to the concept. For the distant future, there could be a potentially significant market in graphic displays. Graphic displays include computer terminal displays, specialized flat panel displays, commercial TV displays, and billboard and advertising displays. Each of these displays depends on the development of a good and inexpensive matrix addressing scheme to activate the multi-element display.

The Future

Significant as it is, the application of dynamic scattering to numeric or alphanumeric readout displays is not the sole measure of the potential of liquid crystals. Liquid crystals will probably have an even broader impact on display technology. As an indication of what directions liquid crystal applications may be taking in the future, two laboratory developments that use liquid crystals quite differently in display devices will be cited.

The first development is a laser-scanned display, using a display medium called the cholophor by its developers, Frederic Kahn and John La Macchia of the Bell Telephone Labs. The cholophor is a screen formed by a thin layer of mixed nematic-cholesteric liquid crystals placed over a layer of phosphor. The nematic crystal was MBBA and the cholesteric crystal

. . . cholophor can produce a continuous-tone, color image.

was cholesteryl oleyl carbonate. This display uses a property of cholesteric crystals called circular dichroism. This property allows right-hand circularly polarized light incident on the liquid crystal layer to be transmitted through the liquid crystals down to the phosphor, and left-hand circularly polarized light to be reflected from the surface of the liquid crystal layer. By using the principal blue emission line (488 nm) of an argon ion laser and a phosphor which emits red light at 620 nm when activated by the blue light of the argon ion laser, they obtained a two-color display. The red light emitted by the phosphor is outside the reflection band of the cholesteric and will be transmitted back through the liquid crystal layer. Hence, by controlling the circular polarization and the amplitude of the laser beam, a continuous tone, color-image can be produced. Although the image on the cholophor screen was projected and not laser-scanned, the photograph (p. *20*) demonstrates the feasibility of the concept.

An image-storing display was developed by James Adams and Werner Haas of the Xerox Research Labs. The display employs "texture changes" in cholesteric liquid crystals. The texture change causes a change in the light scattering properties of the crystal. The liquid crystal layer is formed over a photoconductor layer and the combination is sandwiched between conductive transparent electrodes. In the dark, a voltage applied to the electrodes will have no effect on the texture of the cholesteric crystals, because very little current can flow through the photoconductor. Now, when the panel is illuminated by an image, current will flow through the photoconductor in those regions where light is impinging, and the applied voltage will cause a change in the texture.

A photograph of a stored image is shown in **Fig. 5(b)**. A negative of the image is formed by the display. To get the positive image shown in **Fig. 5(b)** a negative of the picture was used to project the image. The stored image can be retained for days after exposure, and the image can be erased by moving the cover electrode or in certain cases, by the application of an electric field. The panel may be used again after erasure.

The two developments just described indicate new directions in electro-optical applications liquid crystals will be taking in the future; there will be others. In any event, liquid crystals will be filling the pages of the technical press with important new developments for some time to come. ☐

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