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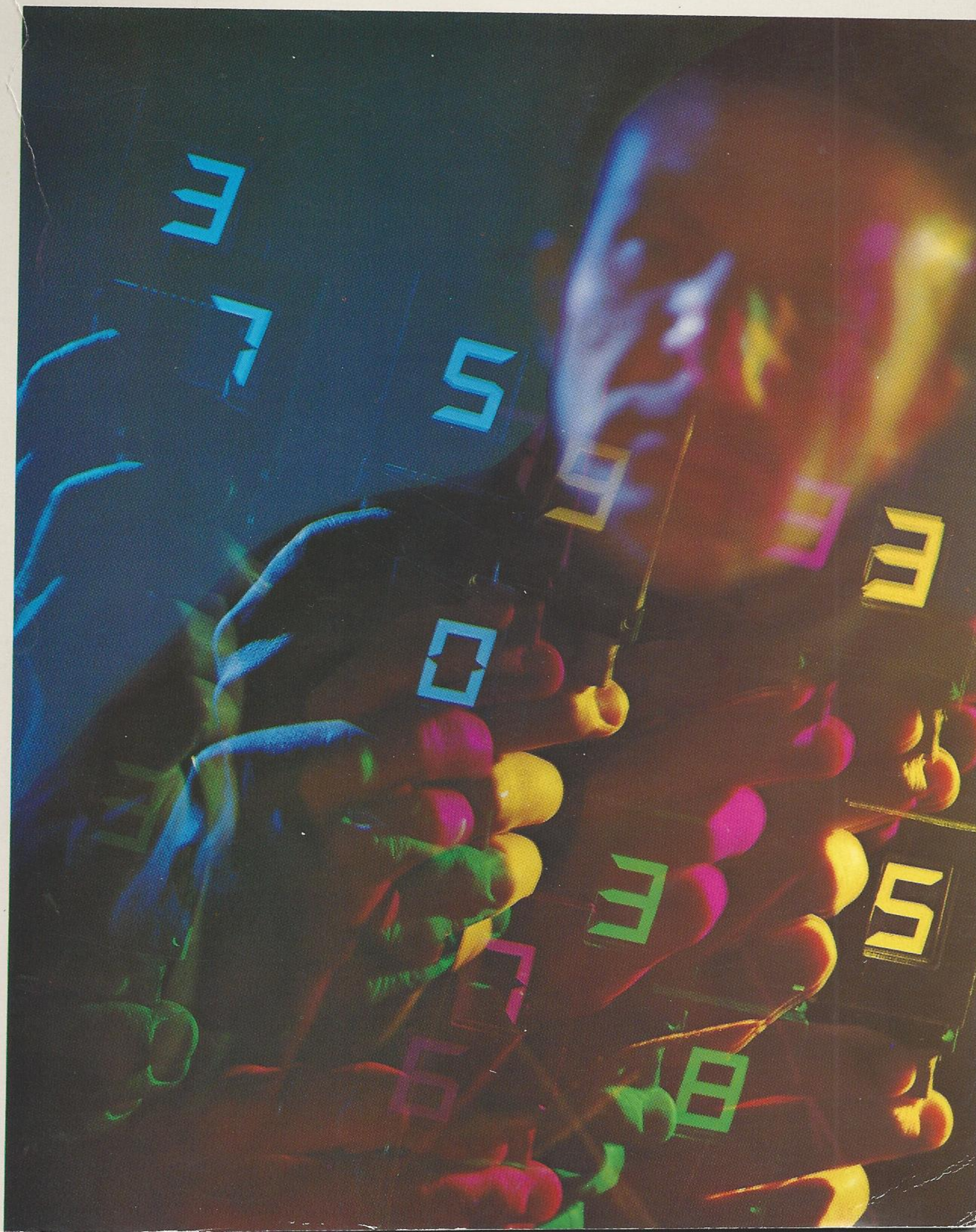

Liquid crystals—the first electronic method for controlling the reflection of light

Dr. G. H. Heilmeier

Few technological advances cause one's imagination to wander quite as far as the liquid-crystal display concept. Such displays allow, for the first time, electronic control of the transmission and reflection of light. Further, the display itself is a flat, rugged, low-power device that is economical and easily fabricated. Obvious applications are electronic windowshades, numeric displays (see the front cover), and all-solid-state television; and, although this concept is barely beyond the laboratory-development stages, RCA already has several proprietory contracts to study further applications for customers in the Petroleum, Advertising, Automotive, and Avionics industries. This paper describes the dynamic light scattering effects in certain classes of nematic liquid crystals which make these applications possible. Several applications are also described along with the basic characteristics of the display itself.

There are two main classes of displays: those that emit light, such as the cathode ray tube or the neon bulb; and those that reflect or modify light, such as the printed page or the photograph. There are many ways to electronically control the emission of light but few, if any, to control the reflection of light. Reflective displays might be expected to have at least two obvious advantages: first, since the contrast is a constant independent of the ambient light intensity, they should be viewable in a wide range of ambients including direct sunlight; second, since the addressing circuitry does not have to supply the power necessary to emit light, the potential addressing power requirements are much lower. In this paper, a new reflective display concept is presented based on a new electro-optic effect in certain classes of nematic liquid crystals.[1] We have called this new effect *dynamic scattering*.

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Liquid crystals

The subject of liquid crystals is sufficiently esoteric that perhaps some introductory material is required. A liquid crystal is defined as an organic material that has the mechanical properties of a liquid, that is, it pours like a liquid and fills its container as a liquid does, and yet possesses the optical properties of a crystalline solid. For the purposes of this discussion, the liquid is considered to be made up of cigar-shaped molecules as shown in Fig. 1.

Isotropic and nematic states

In an isotropic liquid state, the cigar-shaped molecules are oriented at random with respect to one another. As a nematic liquid, the cigar-shaped molecules align with their axis in a common direction. The term nematic comes from the Greek word meaning "thread-like". If one were to look at the nematic liquid crystal under a moderate power microscope (60X), one would see tiny threads throughout the liquid. Materials which are liquid crystals exhibit this behavior only over very specific temperature ranges. Below the liquid crystalline range they are solids; they melt sharply, reversibly, and reproducibly to form the nematic (or liquid cyrstal) state, and at higher temperatures they make a transition to the isotropic liquid state. This transi-

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received the BSEE with honors from the University of Pennsylvania in 1958, and the MSE, MA, and PhD in solid state materials and electronics from Princeton University in 1960, 61, 62, respectively. His work at Princeton University was done under the sponsorship of the RCA Laboratories. In the past, he worked in the general area of the solid state microwave devices for amplification, generation, and conversion with emphasis on distributed parametric and tunnel diode structures. He has published six papers in this area. He has also studied the electrical, optical, and electro-optical properties of molecular crystals and thin films having also done his PhD dissertation in this area. He is the author of 13 publications in this field. In 1963, he initiated work at RCA Laboratories on thin film ferroelectric field effect devices. His current interests lie in the field of liquid crystals and he has published eight papers on the physical properties of these materials. His work in this area has resulted in the discovery of three new-electro-optic effects and the development of the first electronically controlled reflective displays. Dr. Heilmeier has twelve U.S. Patents issued or pending in the areas of adaptive thin-film ferroelectric devices, solid-state devices, optical modulators and displays. In 1960 he received the RCA Laboratories Achievement Award for his work in parametric and tunnel diode devices; in 1962 for pioneering work in the field of crystalline organic semi-conductors; and in 1965 for research in the area of liquid crystalline phenomena. In 1969, he was part of the team that received a David Sarnoff Outstanding Achievement Award in Science "for basic studies of liquid crystals with imaginative ideas for their application to practical displays." Dr. Heilmeier is a member of Tau Beta Pi, Sigma Xi, Eta Kappa Nu, and a senior member of the IEEE. He is also listed in American Men of Science and Who's Who in the Electronics Industry. In March of 1968 he was the recipient of one of the "Outstanding Young Electrical Engineer" awards of Eta Kappa Nu. In March of 1969, he received the Eta Kappa Nu Award as the "Outstanding Young Electrical Engineer in the USA."

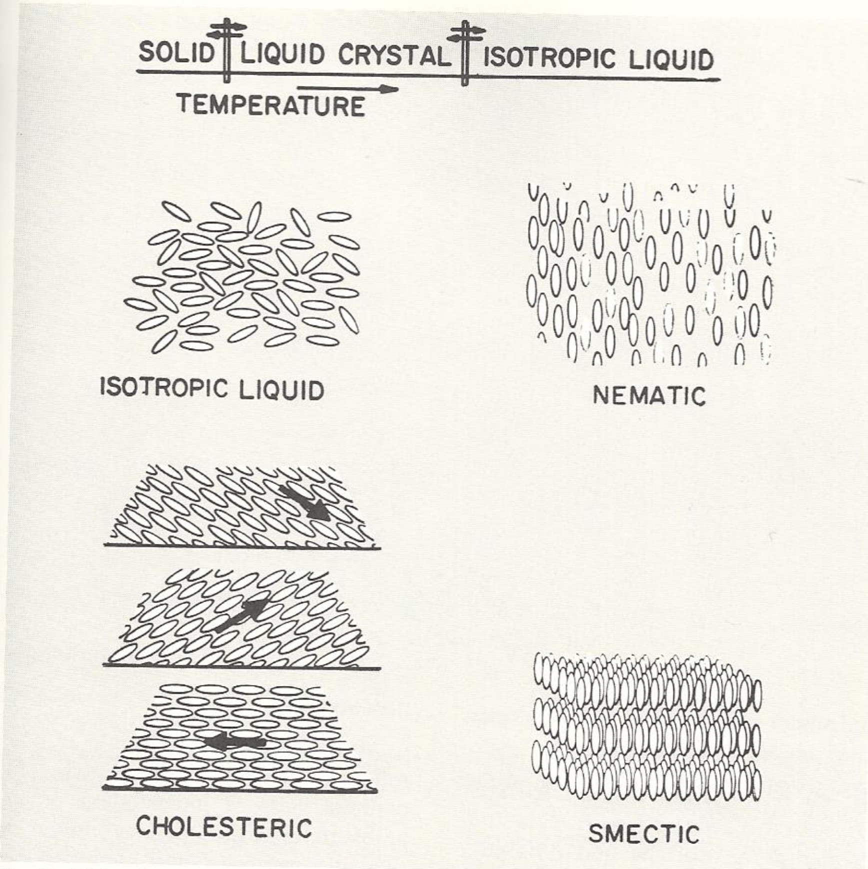

Fig. 1—Molecular arrangements in the liquid crystalline state.

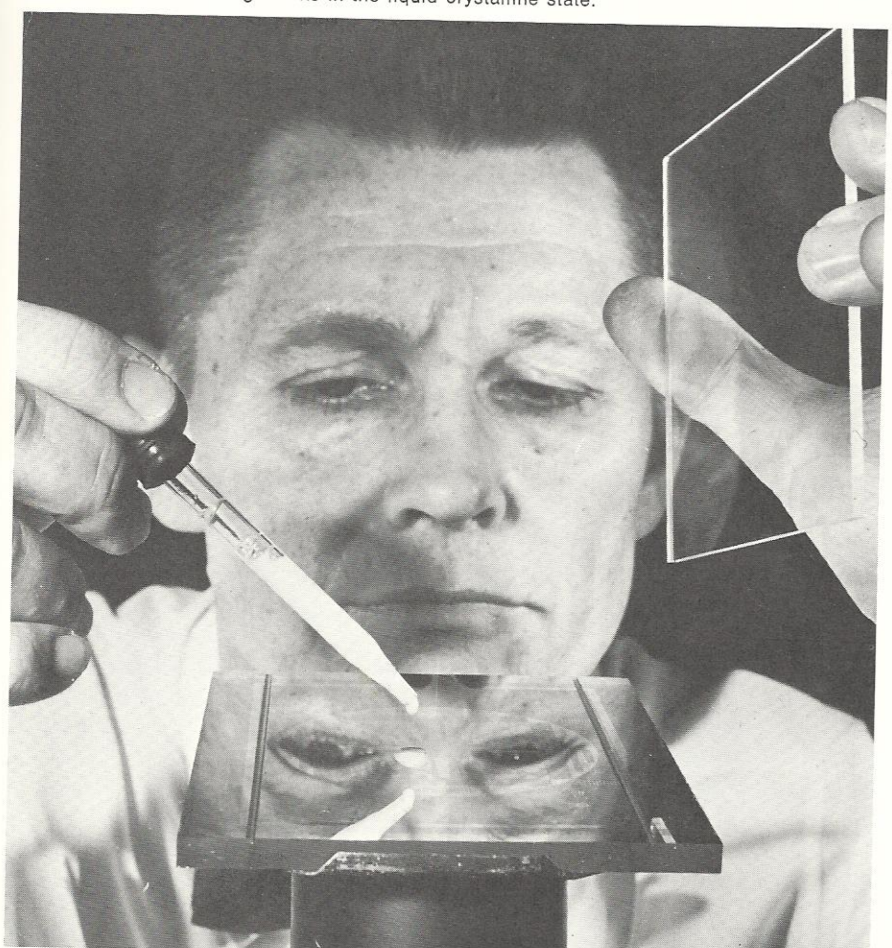

Fig. 2—Fabrication of liquid-crystal display.

tion temperature is also sharp, reversible, and reproducible.

Smetic and cholesteric states

For the sake of completeness, it is appropriate to mention that there are two other classes of liquid crystals. These are also shown in Fig. 1. In the nematic state, the molecules are free to slide with respect to one another; however, this is not true of liquid crystals in the smectic state (smectic comes from the Greek word meaning "soap-like"). This class of liquid crystals is characterized by a layered structure. The cigar-shaped molecules in this class are once again parallel, but are not free to slide with respect to one another. In the liquid crystals of the so-called cholesteric class, the molecules are once again found in layers. Within each layer, however, the axes of the molecules are parallel, and there is a twist in this preferred axis as we go from one layer to another. Unfortunately, when the term liquid crystals is found in the trade literature, no distinction is made between the classes and the term refers almost exclusively to the cholesteric class. These materials have been of recent interest, because they possess the property of being able to change their color as a function of temperature, thus they have been used as temperature indicators of various kinds.[2]

Dynamic scattering

The structure used to demonstrate dynamic scattering consists of two pieces of glass, one with an inner coating of transparent conducting material (tin oxide), the other with a coating of reflecting, metallic material (nickel or aluminum). To fabricate the cell, a drop of the liquid crystal material is placed on one of the plates and a sandwich is formed by placing another plate on top of it (Fig. 2). Since the layer of the liquid is only roughly 1/1000 of an inch thick and is maintained between the plates by capillary action, the conventional problems of handling liquids are not experienced. With no field applied, the structure is transparent; when a DC voltage is applied it becomes milky white. This is *not* due to a chemical change. It is due to the scattering of light. The sample returns to its transparent state when the voltage is removed. Since the size of the

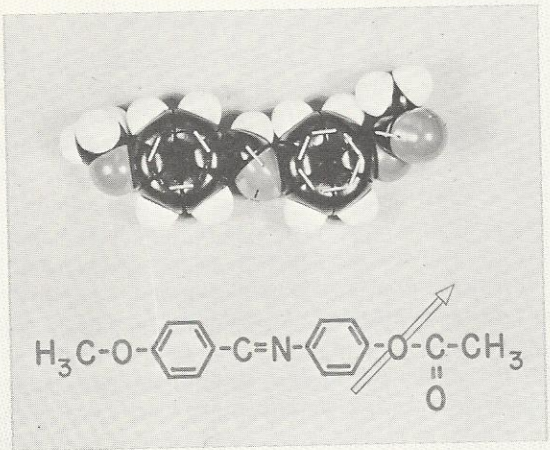

Fig. 3—Anisylidene-p-aminophenylacetate—a material that exhibits dynamic scattering.

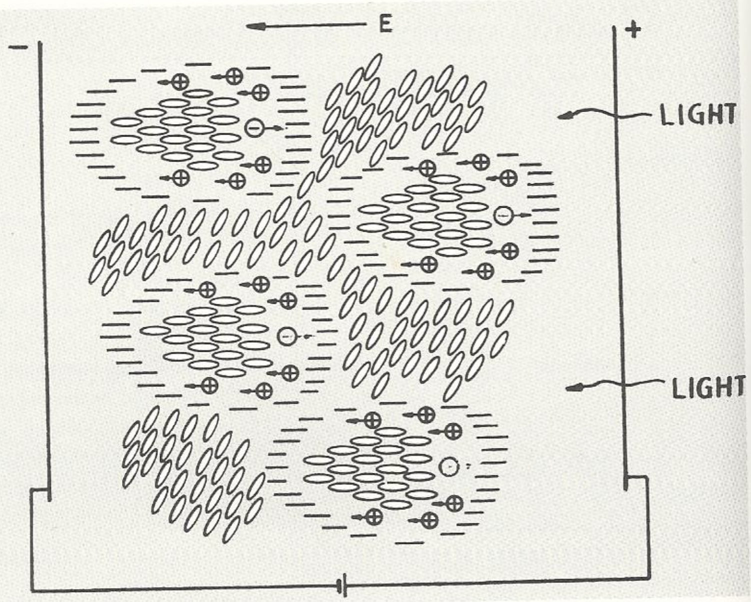

Fig. 4—Schematic representation of dynamic scattering.

scattering centers are approximately 5 microns, white light is scattered as white light[3] (there is no wavelength dependence in the scattering process for visible radiation).

Fig. 3 illustrates a particular compound which exhibits dynamic scattering. The material in question is anisylidene-p-aminophenylacetate. This material is nematic between the temperatures of 82° and 110°C although we have developed proprietary materials which are nematic at room temperature. There is something very specific about the structure of this molecule. The main electric dipole moment does not lie along the main molecular axis. This can be seen also in the model which appears in Fig. 3. Note the cigar-shaped character of the molecule and note also the appendage which represents the main molecular moment which finds itself at an angle with respect to the main molecular axis, With this as background, it is now possible to discuss the mechanism of dynamic scattering.

Consider once again a plate electrode (planar electrode) structure: basically, a parallel plate capacitor with a liquid-crystal dielectric as shown in Fig. 4. When one applies a DC voltage, the initial tendency of the molecular swarms of the nematic state is to align with their permanent moment in the direction of the field. For the materials in question, the main dipole moment does not lie along the main molecular axis. Consequently, the axes of the cigar-like molecules find themselves at an angle with respect to the electric field and the electrodes.

If we now permit an ion to move through this ordered structure, it tends to disrupt the ordering, and in its wake it tends to produce an alignment with the main molecular axis along the direction of ion transit. Since these molecules are highly birefringent, a region of discontinuity exists between those molecules inside the wake and those molecules outside the wake. This discontinuity, since it represents a region of changing index of refraction, can effectively scatter light. It is characteristic of scattering centers which are of the order of 5 microns in diameter that most of the light is forward scattered[3]—that is, scattered in the same general direction in which the light was initially traveling. Hence, if the effect is to be maximized for reflected light, a specular reflecting back electrode must be used to redirect the light back toward the viewer.

Display characteristics

It is appropriate to review briefly some display-related parameters of which this new effect is capable. The equivalent circuit of the device is that of resistor (~1 megohm/cm^2) in parallel with a capacitor (~200 pF/cm^2). The mode of operation can either be reflective or transmissive depending on whether the back electrode is a specular reflector or a transparent conductive coating.

Contrast

Contrast ratios greater than 15:1 in reflection have been obtained. This contrast ratio is independent of the ambient light, thus displays based on dynamic scattering will not wash out even in direct sunlight.

Power required

The maximum power necessary to operate the display is approximately a milliwatt per square inch of display area. The operating voltages are between 6 and 60 volts DC. The 60-volt level is that which one must use to obtain maximum contrast; the 6-volt level is the threshold level for the effect. Since the contrast varies between 6 and 60 volts, there is gray scale capability.

Response

The maximum reflection efficiency for this effect is 40 to 45% of the standard white ($MgCO_3$). The addressing time or the time necessary to impart information to the display is less than 60 microseconds. The response time of the effect is in the range of 1 to 5 milliseconds. The natural image decay time, or the period which it takes for the display to revert back to its initial state after the field is removed, can be varied from 30 ms to one second depending on the temperature, the specific materials used, and the method of fabrication. Since the active layer of the liquid is only of the order 1/1000 of an inch thick, the total thickness of a liquid crystal display panel can be less than a quarter of an inch. The temperature range of useful operation using RCA-proprietary material is 20°F and 212°F. While the materials are nematic below 20°F, the response is sluggish.

Resolution

The resolution for the effect is roughly 500 TV lines/inch. There are field-of-view restrictions due to the necessity for a specular-reflecting back electrode but these seem to be tolerable for a wide range of applications.

Reliability

Life studies are presently in progress. Results do look encouraging, and we have obtained over 3,000 hours of continuous life to date.

Applications

Several experimental devices that could lead to important new electronic products have been fabricated to demonstrate the versatility of this new display concept. These include a simple numeric indicator, an all-electronic clock with no moving parts, and an electronically controlled window.

Electronic window

The electronically controlled window is perhaps the simplest device. Basically, it is a parallel plate capacitor with transparent electrodes (tin oxide on glass). With no voltage applied the window is clear. When approximately 50 volts is applied the window becomes opalescent (Fig. 5). It is possible that this opalescent effect could be used to provide glass door panels and windows that could be frosted at the touch of a button to insure privacy for the users. A step away from that is the possibility that liquid crystals can be used to provide electronic curtains that will automatically control the amount of sunlight admitted into our homes.

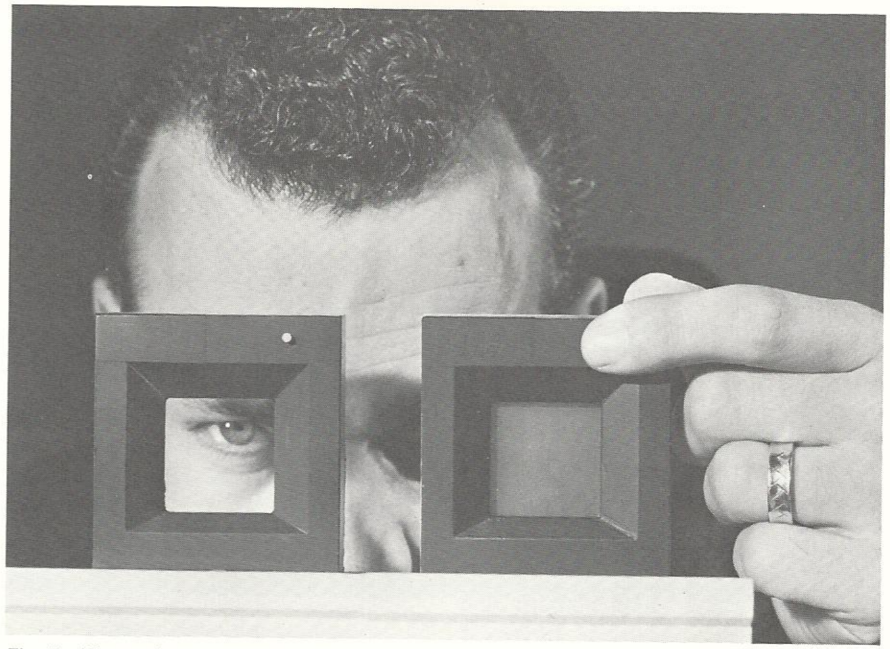
Fig. 5—Electronically controlled window.

Numeric indicators

If one wishes to operate the liquid crystal panel as a reflective display, a specular reflecting back electrode is needed as previously mentioned. Edge lighting is possible for viewing under conditions of complete darkness. A seven-segment numeric indicator (capable of displaying the numerals 0 through 9 by application of excitation voltage to the proper segments of the cell) has been constructed which uses commercially available integrated circuits for the clock (TIS43), counter (TISN7490) and decoder (Fairchild L930759). Discrete transistors (2N40084) were used for the segment drivers. The panel consisted of the glass/liquid-crystal/glass sandwich discussed previously with segmented electrode defined by photoresist techniques. The device and associated electronics is shown in Fig. 6.

All-electronic clock

The liquid crystal display concept could lead to quite different approaches for some fairly conventional commercial products. One such product which falls into this classification is the familiar time indicator or clock. A clock has been constructed which has no mechanical moving parts. The basis of this clock is the seven-segment liquid crystal numeric display cell. Four of these cells arranged in a row

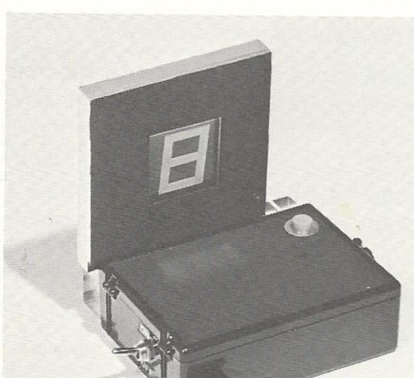

Fig. 6a—Battery operated liquid-crystal numeric indicator.

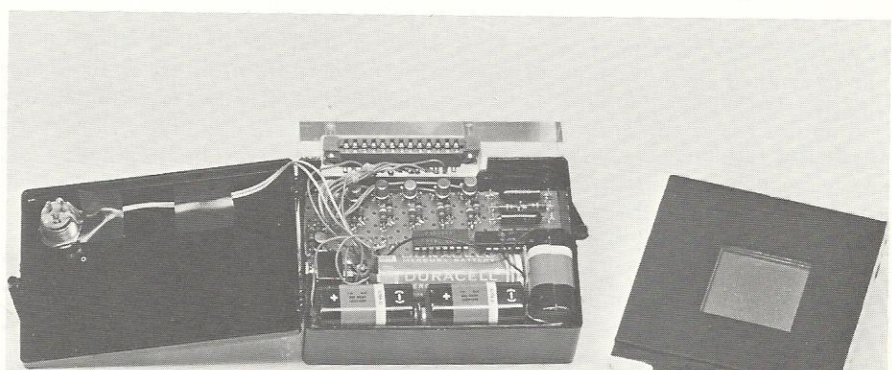

Fig. 6b—Electronics for the numeric indicator.

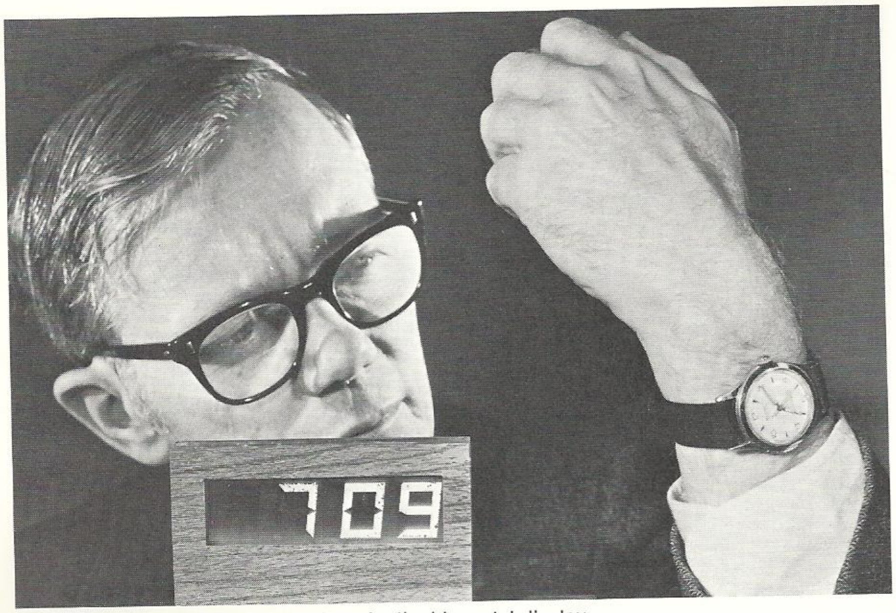

Fig. 7—All-electronic clock based on the liquid-crystal display.

can then be used to present the time in hours and minutes or, with two additional cells, the seconds can be displayed.

The electronics to control the display numerals are a rather straight-forward application of presently available integrated-circuit counters. The time reference can be either a crystal oscillator or, as in conventional clocks, the 60-Hz line frequency. In the case of the line reference, the 60 Hz is first divided by a 60-to-1 counter to produce pulses at 1 Hz. These 1-Hz pulses are then counted by 10 and 6 to produce the seconds and the tenths of seconds information. The output of the counters used in this clock occurs in binary-coded-decimal (BCD) form and therefore must be decoded into a form suitable for driving the seven-segment display. This can be accomplished with a series of binary gates or perhaps the easiest way is to use a commercially available BCD-to-seven-segment display integrated circuit mentioned previously.

In similar fashion, the output of the seconds counter is further divided by 10 and 6 to produce the minutes and the tenths of minutes. Likewise the minutes counter is divided by 10 and 2 to produce the hours and tenths of hours. Of course when the hour count reaches 12, it is necessary to include logic to recognize this condition and arrange to reset the hours to 1 rather than 13 upon receipt of the next count pulse.

Initially, the clock display is set by means of bypass switches which allow 1-Hz pulses to be fed directly into each numeral counter and thus index that particular numeral at a 1-Hz rate until the proper numeral is displayed. A crude prototype of such a clock is shown in Fig. 7. The low-power and flat construction characteristics of the liquid-crystal cell are such that in the future it may be possible to extend this concept to an all-electronic wrist watch.

Television

In years to come, the liquid-crystal display concept may yield a practical thin-screen competitor to the cathode ray tube used in radar and TV displays. The low voltage and power requirements certainly lend themselves to integrated circuitry for the complex addressing function instead of the electron beam. In this case, the electrodes would form an X-Y matrix with the selection of a given element performed by the scanning signals. The cost and complexity of the addressing circuitry, however, make this application impractical at the present time.

Liquid crystals versus electroluminescent cells

The circuit characteristics of liquid-crystal devices are similar to that of a field-effect electroluminescent cell. Both liquid-crystal cells and electroluminescent cells behave essentially as a linear capacitor in parallel with a high resistance. In addition, liquid-crystal analogs to the well known photoconductor - electroluminescent image converters and light amplifiers can be prepared by similarly coupling a photo-conductive layer in series with a liquid-crystal cell. The resultant image converter and/or light amplifer will differ from its electroluminescent-photoconductor analog mainly in that the liquid-crystal device operates by the reflection and/or scattering of light from an ambient light source while the electroluminescent device obtains its light by the luminescence of the electroluminescent material.

The liquid-crystal display, however, possesses several important advantages over electroluminescent phosphors:

1) Reflective or transmissive operation;
2) Contrast is independent of the ambient;
3) Lower voltage and power requirements;
4) The DC operation simplifies the addressing function (audio frequency used in electro-luminescent cells for best results); and
5) One is not restricted to a specific color for the display.

Conclusions

Liquid-crystal displays based on dynamic scattering offer:

1) Reflective operation—hence a contrast ratio that is independent of the ambient light;
2) Low-power low-voltage operation making them attractive for solid state addressing schemes;
3) Rugged flat construction; and
4) Potential low cost (the liquid crystal material costs less than a tenth of a cent per square inch of display).

Acknowledgments

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