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FEATURES

DEPARTMENTS

Dynamic scattering in liquid crystals

by Dr. George H. Heilmeier · RCA Laboratories

A new electronically controlled reflective display concept has recently been discovered based on an effect in certain classes of nematic liquid crystals. This concept offers for the first time reflective operation, flat construction, and low power and voltage operation which suggests the use of integrated cirucits in the addressing function. The effect has been called "dynamic scattering" because scattering centers are introduced in the liquid crystal by the disruptive effects of ions in transit through the ordered fluid. Since the active layer of liquid is only of the order of one mil thick and held between two pieces of glass by capillary action, none of the conventional problems in handling liquids are experienced. Several crude prototypes of devices using the new effect have been fabricated. These include a numeric indicator, an all-electronic clock with no moving parts, and an electronically controlled window.

By way of introduction, we note that basically 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 a photograph. There are many physical effects by which one can electronically control the emission of light, but relatively few, if any, are known that can be used 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 an electro-optic effect in certain classes of nematic liquid crystals. We have called this new effect *dynamic scattering*.

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 purpose of this discussion, the liquid is considered to be made up of cigar-shaped molecules as shown in Fig. 1. In an isotropic liquid, the cigar-shaped molecules are oriented at random with respect to one another. In a nematic liquid crystal, the cigar-shaped molecules align with their axes 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 (60 X), one would see tiny threads throughout the liquid. Materials which are liquid crystals exhibit this behavior only over very specific temperature ranges. Below the

Dr. George H. Heilmeier *received his PhD in solid state materials from Princeton University in 1962. He has published 24 papers in the areas of microwave devices, molecular crystals, thin films and liquid crystals, and has 12 patents issued or pending in these areas. He received RCA Laboratories Achieve awards in 1960, '62 and '65, and has been head of the Solid State Device Research Group there since 1966. Dr. Heilmeier is a member of Tau Beta Pi, Sigma Xi, Eta Kappa Nu and IEEE. He is listed in* American Men of Science *and* Who's Who in the Electronics Industry, *and this past year was recipient of one of the "Outstanding Young Electrical Engineer" awards of Eta Kappa Nu.*

liquid crystalline range, they are solids. They melt sharply, reversibly and reproducibly to form the nematic state or liquid crystal state, and at higher temperatures they make a transition to the isotropic liquid state. This transition temperature is also sharp, reversible, and reproducible.

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. The second class of liquid crystals is called the smectic state. Smectic comes from the Greek word meaning "soap-like." This class of liquid crystals is characterized by a layered structure as is seen in the illustration. The cigars in this class are once again parallel, but the molecules are not free to slide with respect to one another. The third class is the so-called cholesteric class. In this particular 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 among 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.[1]

Liquid Crystal Cell Structure

We now consider the structure used to demonstrate dynamic scattering. The structure consists of two pieces of glass, one with an inner coating of transparent conducting material (i.e. tin oxide), the other with a coating of reflecting, metallic material (i.e. nickel or aluminum). To fabricate the cell, one simply places a drop of the liquid crystal material on one of the plates and forms a sandwich by placing another plate on top of it.

Since the layer of the liquid crystal material is roughly only 1/1000 in. 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 one applies a dc voltage 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 scattering centers is approximately five microns, white light is scattered as white light[2] (there is no wavelength dependence in the scattering process for visible radiation).

Fig. 2 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. 2. 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. 3. 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 five microns in diameter that most of the light is forward scattered;[2] 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 Parameters

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 a resistor ($\sim$1 megohm/cm^2) in parallel with a capacitor ($\sim$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 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.

The maximum power necessary to operate the display is approximately 1 mw/sq in. of display area. The operating voltages are between 6-60 vdc. The 60 v level is that which one must use to obtain maximum contrast; the 6 v level being the threshold level for the effect. Since the contrast varies between 6-60 v, there is gray scale capability.

The maximum reflection efficiency for this effect is 40-45 percent 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 1-5 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 milliseconds to 1 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 of 1/1000 in. 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 proprietary material is 20° and 212°F. While the materials are nematic below 20°F, the response is sluggish.

The resolution for the effect is roughly 500 TV lines/in. 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. Life studies are presently in progress. Results do look encouraging, and we have obtained over 3000 hrs of continuous life to date.

Experimental Models

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.

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 v are applied, the window becomes opalescent, as is shown on page 21. 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.

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

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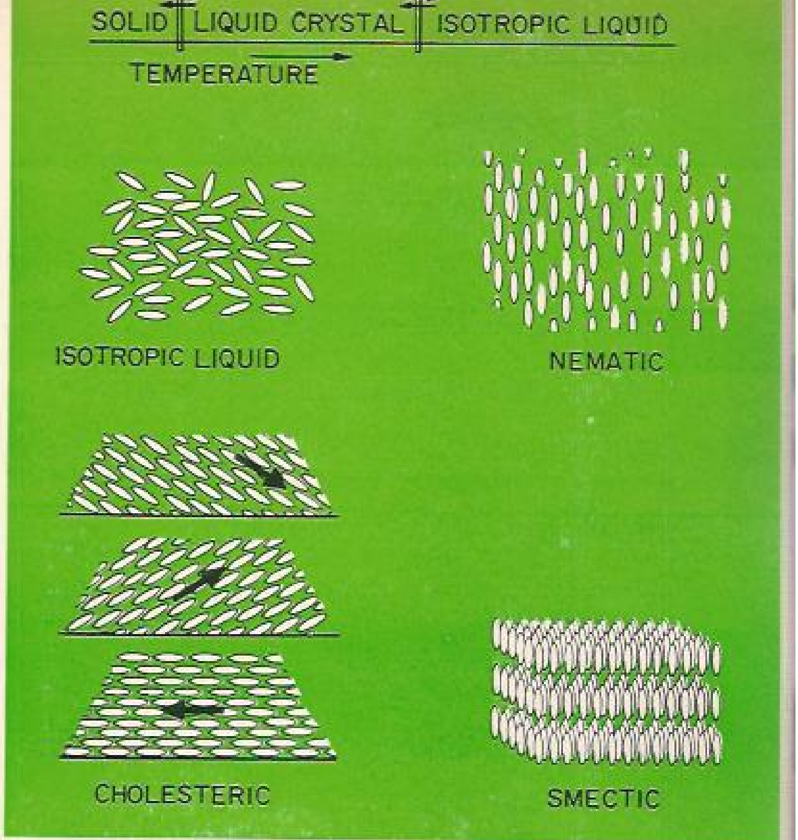


Fig. 1—*Schematic representation of liquid crystals.*

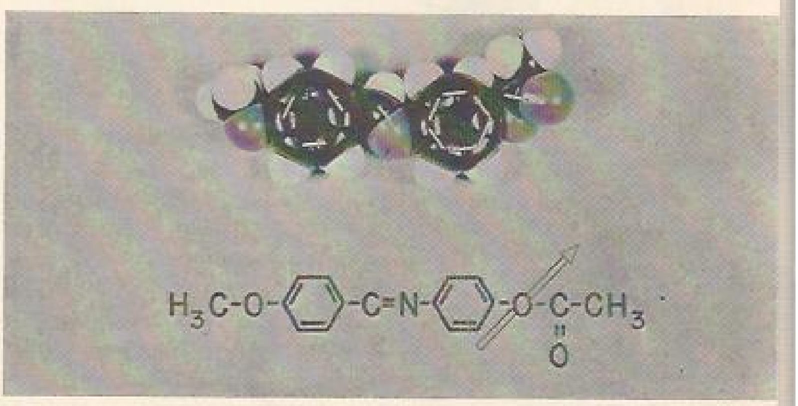
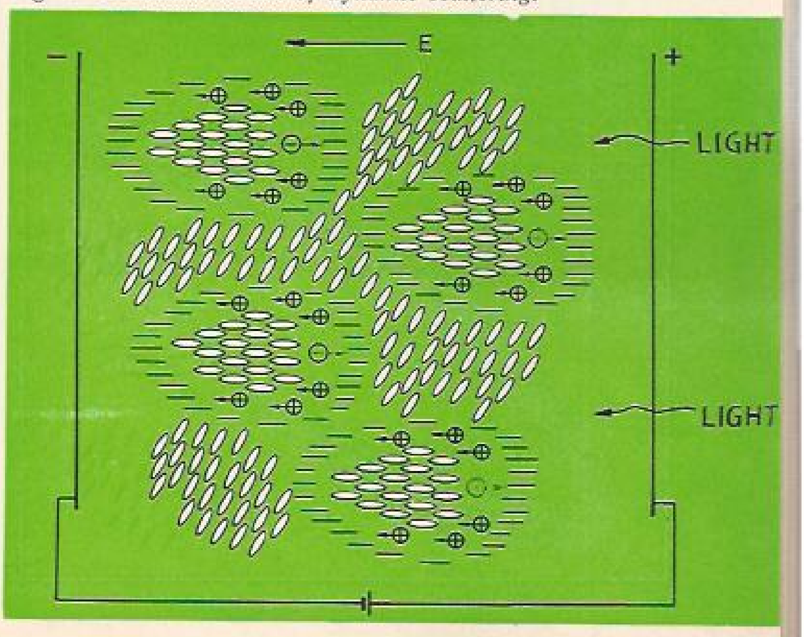


Fig. 2—*Anisylidene-p-aminophenylacetate is nematic between 82° -110° C.*

Fig. 3—*Molecular model of dynamic scattering.*



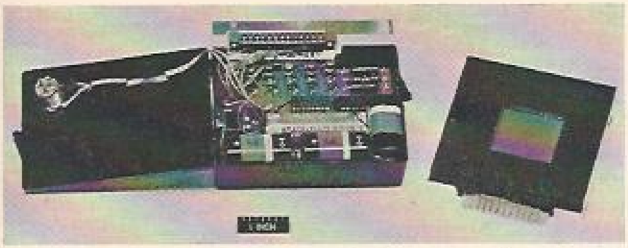


Fig. 4—*Device and associated electronics for numeric indicator.*

integrated circuits for the clock, counter and decoder. Discrete transistors 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 are shown in Fig. 4.

Basis for an 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 can then be used to present the time in hours and minutes or, with two additional cells, the seconds can also 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 10's of seconds information. The output of the counters used in this clock occurs in binary coded decimal 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 10's of minutes. Likewise the minutes counter is divided by 10 to 2 to produce the hours and 10's 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.

Initial setting of the clock display is accomplished 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. The low power, 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.

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.

Similarities to Electroluminescent Cells

The circuit characteristics of liquid crystal devices are similar to that of a field electroluminescent cell. Both liquid crystal cells and EL cells behave essentially as a linear capacitor in parallel with a high resistance. In fact, the same techniques employed as switching elements of an EL cell, e.g. ferroelectric, gas discharge and piezoelectric and photoconductive switching elements, may be similarly employed in liquid crystal cells. In addition, liquid crystal analogs to the well known photoconductor-electroluminescent image converters and light amplifiers can be prepared by similarly coupling a photoconductive layer in series with a liquid crystal cell. The resultant image converter and/or light amplifier will differ from its EL-PC 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 luminescence of the EL 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. DC operation simplifies the addressing function (audio frequency used in EL cells for best results).
5. One is not restricted to a specific color for the display.

To summarize, liquid crystal displays based on dynamic scattering offer: reflective operation, hence a contrast ratio that is independent of the ambient light; low power and low voltage operation, making them attractive for solid-state addressing schemes; rugged flat construction; potential low cost (the liquid crystal material costs less than a tenth of a cent per square inch of display). ———————— **AE**

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