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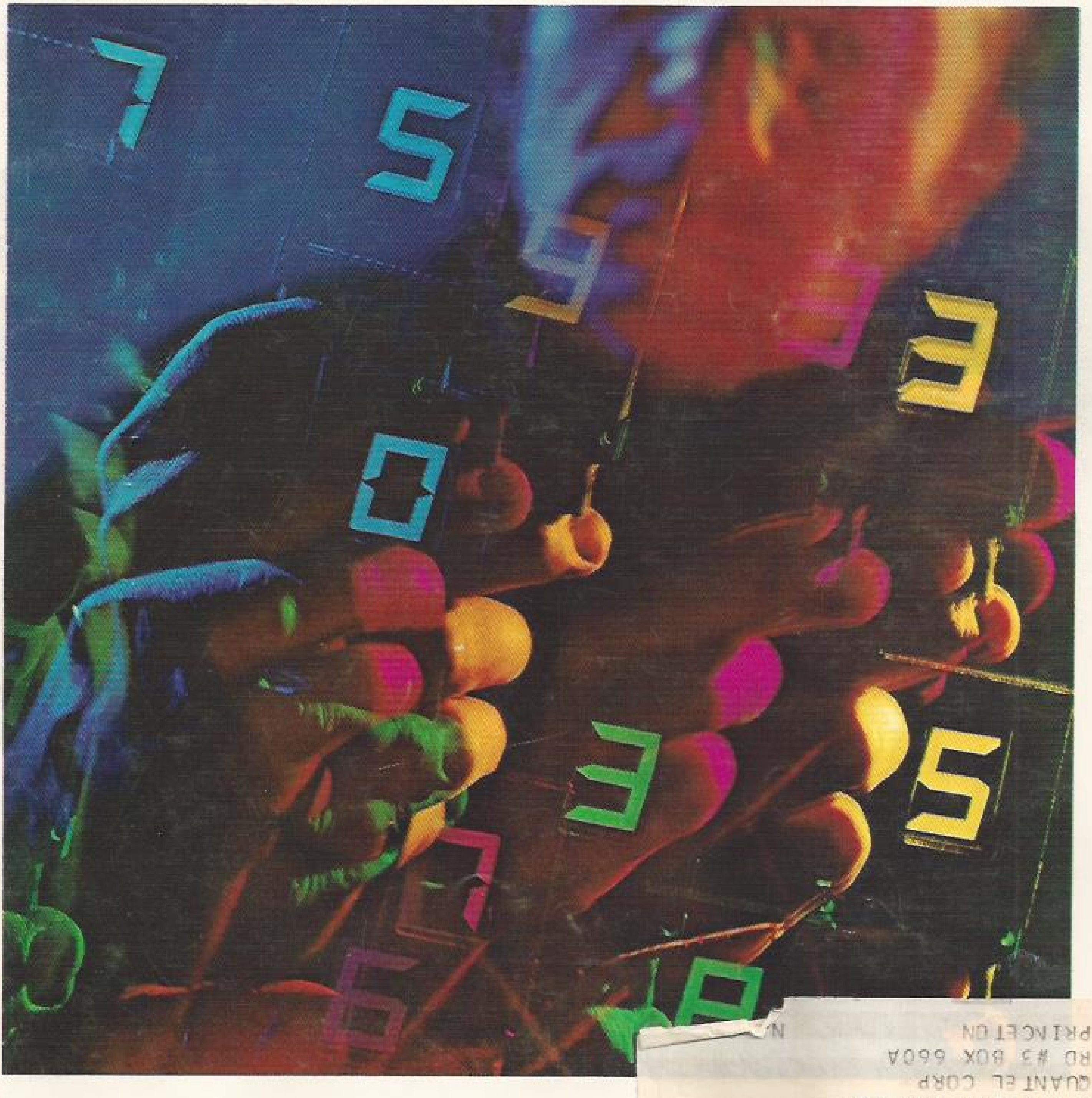
Liquid crystals — material with an unlimited future. New uses are pointing toward alphanumeric readouts that could operate on millimicrowatts, pilot lights that cost about one-hundredth of a cent, a flat-screen color TV, an inexpensive thermal mapper and a cancer detector. For details on this unique material, see p. 76.



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West Coast Editor

Liquid crystals:

Imagine an alphanumeric readout that requires only microwatts of drive power and is totally insensitive to ambient light level. Consider a transducer that can take an image transmitted at any frequency and convert it to an optical image. Or how about a pilot light that costs one-hundredth of a cent, an inexpensive thermal mapping device, a cancer detector, a smog sniffer or a flat-screen color TV set?

These are a few of the present and envisioned applications of a state of matter called liquid crystals.

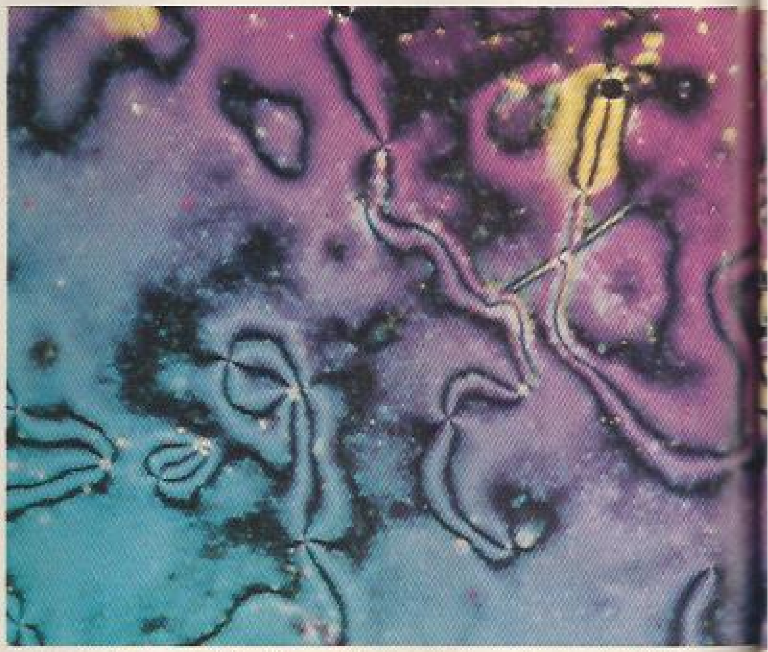
Dr. George H. Heilmeier, head of device concepts research at RCA Laboratories in Princeton, N.J., describes a liquid crystal as an organic material that has the physical properties of a liquid. It pours as a liquid does and assumes the shape of its container as a liquid does. But over specific temperature ranges liquid crystals possess a degree of molecular order that is more characteristic of solid state. The molecules have a definite spatial relationship to each other.

Liquid crystals change their optical properties when subjected to certain stimuli. Depending on the particular molecule, the stimuli can include heat, an electric or magnetic field, shear force, pressure, ultraviolet light, acoustic energy and certain gases. The optical property most often considered is the ability of the liquid crystal to reflect light. Heilmeier notes:

"With liquid crystals, we see, for the first time, the ability to control the reflection of light by electronic means."

Brighter the day, brighter the display

Liquid crystals are expected to have their greatest impact on displays. Although three different phases of liquid crystals exist, it is the nematic phase which will be used in most displays. The nematic phase is a condition where the molecules, which are roughly shaped like a cigar, tend to line up in a random fashion, with their long axes all parallel to one another. The optical effect that allows nematic liquid crystals to be used in displays is called dynamic scattering. Dynamic scattering is an effect in which the application of an electric field makes all of the molecules align parallel to a pair of electrodes. A controlled flow of ions is then generated by the applied voltage from electrode to electrode. The ions disrupt the crystal alignment, causing a scattering of light that impinges upon the liquid crystal film. Scattering turns the normally transparent film white and causes light to be reflected off it. The amount of light reflected can be controlled by the voltage across the electrodes.



Heated nematic liquid crystal viewed through a polarizing

According to Heilmeier: "Since the effect is reflective, contrast is independent of ambient light level. Hence the brighter the light, the brighter the display."

A display (see illustration) can therefore be constructed by:

- Depositing transparent conductive electrodes on two pieces of glass.
- Sandwiching a 1-mil-thick layer of nematic liquid crystal between the two panes of glass and holding it there by capillary action.

Voltage then applied appropriately across the electrodes can yield a visible pattern, determined by the physical configuration of the electrodes. Tin oxide is the most popular electrode material. About 25 V is typical of the required voltage.

In addition to the constant-contrast feature, liquid-crystal displays are also small, flat, light, inexpensive and users of very little power.

James L. Fergason, associate director of the Liquid Crystal Institute at Kent State University in Kent, Ohio, explains the power requirements this way: "There is very little force involved in reorientation of liquid-crystal molecules. For

Material with a hot future

microscope. Colors respond to variations in thickness.

comparison, you could think of mosquitos doing pushups or leaves fluttering on a tree. Nematic liquid crystals require energy on the order of microwatts per square inch."

Dr. H. Barry Bebb, director of the Advanced Technology Laboratory at Texas Instruments in Dallas, says: "You can drive a liquid crystal display directly from the logic without an additional driver." Bebb notes that the "turn-on time of the display is about 2 milliseconds, and the turn-off time is about 20 milliseconds."

Texas Instruments has built seven-segment numeric readout displays. However, Bebb feels that "most people prefer a display which is a 5 x 7 dot matrix type rather than a seven-segment type." TI sees no reason why a 5 x 7 dot matrix display could not be made easily with liquid-crystals.

If the constant-contrast feature is not considered a major consideration, dynamic scattering displays can be back-lighted. They then operate in a transmissive mode, where most of the light is scattered forward rather than backward. Dynamic scattering always results in more light being scattered forward than backward. For reflective operation, the rear electrode is made reflective rather than transparent.

Dr. Richard A. Reynolds, manager of the applied optics branch of the Advanced Technology Laboratory at Texas Instruments, says: "We have been able to make more pleasing displays in the transmissive mode than in the reflective mode. However, it is necessary to provide a light bulb behind the panel."

RCA uses the reflective mode in its displays. Thomson-CSF in France has made alphanumeric displays in the transmissive mode. Collins Radio in Cedar Rapids, Iowa, is also building back-lighted liquid-crystal displays. The Collins displays are for aircraft cockpits.

Only a few problems remain

Only two major areas of study remain before liquid-crystal readouts find their way to the marketplace. One is temperature stability and the other lifetime or reliability.

Liquid-crystal displays must operate within a fairly limited temperature range. At limits of the particular range, contrast tends to drop off a bit. Materials research is currently going on at many different companies to extend the usable temperature range.

Due to the newness of the developmental displays, a sufficient amount of time has not yet been spent studying failure mechanisms. Donald C. Batesky, a technical associate in new product development with Eastman Kodak in Rochester, N.Y., notes:

"The main failure mechanism in most nematics is that over a period of time the electric field can break a carbon-nitrogen double bond in the liquid-crystal molecule. However, there are nematics that don't have the double-bond problem. The carbon-nitrogen materials are, however, the easiest to manufacture."

Life-testing in the industry to date has shown that 5000 to 6000 hours of constant dc operation can be achieved with liquid-crystal displays.

Dr Frederic J. Kahn, a member of the technical staff at Bell Telephone Laboratories, Murray Hill, N.J., points out some other areas of current study: "They include organic molecule instability, photochemical deterioration and electrochemical deterioration."

When a display is desired with more than just letters and numbers, liquid crystals can fill the bill. Werner Haas, senior scientist at Xerox in Rochester, N.Y., points out: "Liquid crystals can be thought of as image converters. Images transmitted at any frequency can be converted into optical images."

Imaging can be accomplished with either the nematic phase or the cholesteric phase. There is disagreement among scientists as to what constitutes the cholesteric phase. It can be thought of as a stack of discrete layers of molecules in which all of the molecules in each layer are aligned in the same direction, and the direction of each layer is offset from the direction of the adjacent layers. If one were to plot the angular direction of the molecules as they moved in a vertical direction through the stack, a helix would be traced out.

Cholesterics reflect light at different wavelengths when they are stimulated. Each type of stimulus tends either to wind or unwind the helix. When the helix winds, the colors that are reflected move from red towards blue. When it unwinds, the reflection wavelength gets longer. Therefore, while nematics yield a white display, cholesterics yield a color display.

Although images can be transmitted at any frequency, the mechanism of imaging is frequency-dependent. Haas of Xerox notes: "Different wavelengths have different effects upon liquid crystals. At light frequencies, you have heating and can detect a color change. Acoustics will change the birefringence or the reflection colors as well, by changing the angular pitch of the cholesteric molecules. Ultraviolet produces a chemical decomposition, resulting in a color change."

Experiments in imaging have been varied. According to Dr. James E. Adams, a scientist at Xerox, ultraviolet imaging can be done by shining the light through a mask onto a plane of cholesteric liquid crystals. Where the ultraviolet gets through, chemical bonds are broken, resulting in a color change of the plane at those points.

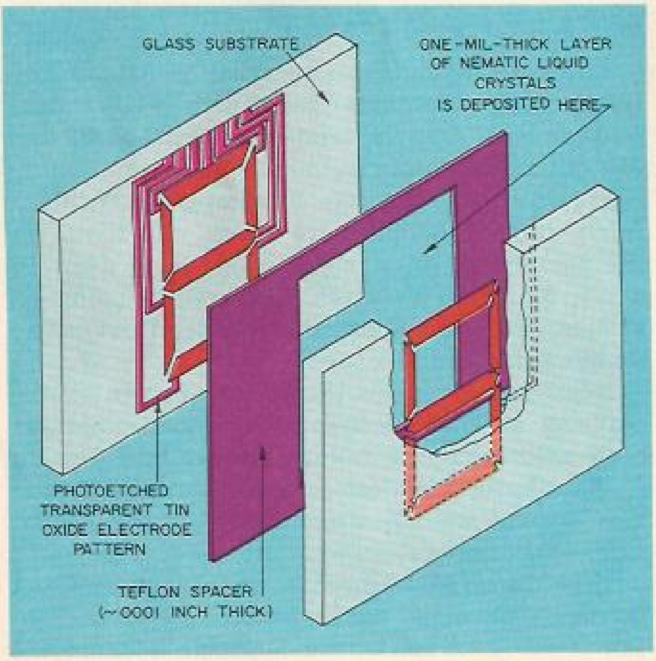
The difference in reflectivity between those areas that were shielded from the ultraviolet and those areas that were not shielded creates the image.

Dr. James H. Becker, manager of exploratory device development at Xerox, describes another imaging experiment.

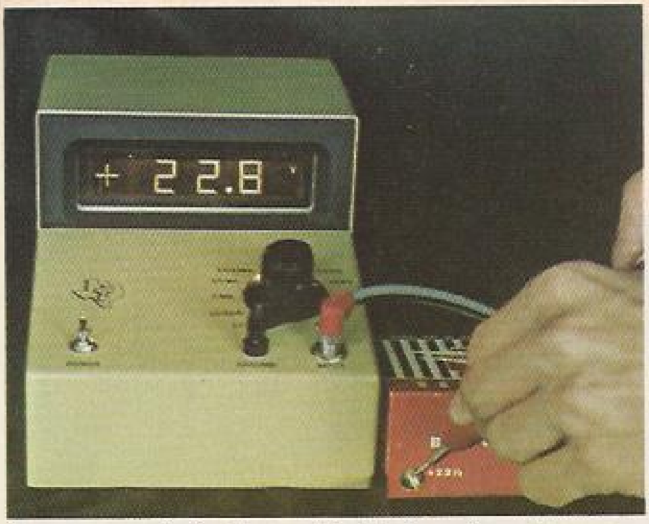
"We place a liquid-crystal layer on top of a photoconductor [selenium]," he reports. "The combination of liquid-crystal layer and photoconductor is uniformly charged. Light is reflected off the object to be copied and imaged onto the photoconductor. Where the light is incident on the photoconductor, electron-hole pairs are generated. These migrate in the influence of the original electric field. The motion of the electrons and holes is such that where the light hits, the original field is removed—that is, the voltage goes down to practically zero. In the regions where the light does not hit—the dark line that you are trying to copy—the voltage pattern remains on the photoconductor. This voltage pattern on the photoconductor is the same as the image pattern. A large voltage exists where the original image is dark, and a small voltage where it is light. This latent image field pattern then interacts with the liquid crystal to cause a rearrangement of molecules. As a result of this rearrangement of the liquid-crystal molecules, a visual pattern is created."

A somewhat similar experiment is by Dr. J. David Margerum, head of the photochemistry section of the Chemical Physics Dept. at Hughes Research Laboratories, Malibu, Calif.

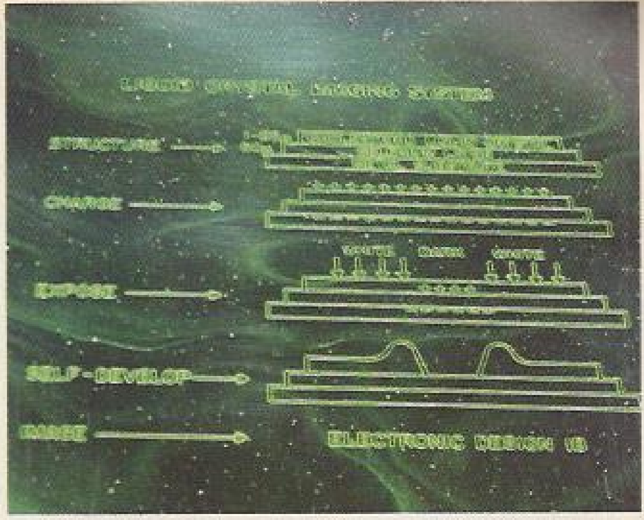
"We have a liquid-crystal cell that is photosensitive," he notes. "You can record an image on it which can be displayed, by either reflection or projection techniques, on a large screen. The cell consists of a layer of zinc sulphide photocon-



Liquid-crystal displays can be constructed very simply. Etch the desired electrode pattern—in this case a seven-segment numeric readout—in transparent conductive material that has been deposited on two pieces of glass. Using a spacer of about one mil in thickness to confine it, deposit some nematic liquid crystal on one of the pieces of glass. Complete the sandwich by covering the liquid crystal with the other piece of glass. Now, when an electric field is impressed across any segment of the display, the liquid crystal will be stimuated into a dynamic scattering mode, and that segment of the display will reflect light.



Seven-segment liquid crystal displays from Texas Instruments are incorporated into an experimental digital volt-ammeter. These readouts are back-lighted. Turn-on time is about 2 milliseconds.



Imaging with cholesteric liquid crystals is achieved by Xerox. The liquid crystals are coated on a layer of selenium. After exposure, the crystals take on a permanent image.

ductor and a layer of nematic liquid crystal, sandwiched between a pair of transparent electrodes. The electrodes are deposited on a pair of glass plates, which complete the sandwich.

"When a voltage is applied across the cell in the absence of ultraviolet light, there is no occurrence of dynamic scattering. This is because the ZnS is a high resistivity material, and it holds off the transport of current to the liquid crystal. When the ultraviolet light falls upon the photoconductor, it opens the circuit and allows current to flow at the point at which it is activated. In this way an image is impressed on the liquid-crystal layer in the form of dynamic scattering. If white light is now reflected off the cell onto a screen, the UV image is seen as a visual image.

"Variable persistence can be achieved in the display by adding a little bit of cholesteric material to the nematic. Although ultraviolet was chosen and ZnS used, any wavelength can be imaged using the appropriate photoconductor."

Cholesteric imaging in the infrared has been achieved by Fergason at Kent State. "We are focussing an infrared image through an optical system onto a liquid-crystal film. We use very highly temperature-sensitive cholesteric liquid crystal. By controlling the temperature of the film, we get an image of the object that is being viewed. It has the following advantages over other techniques:

"It works at room temperature rather than at liquid nitrogen temperature. It has a field imaging capability—that is, it takes a total image and converts it to a visible pattern. It has much higher sensitivity than other room-temperature bolometric devices. And there is no need for an electronic readout such as an electron gun.

"This device can be used for medical thermal mapping of a subject. There are also some military applications."

A new liquid-crystal display element has been developed at Bell Laboratories. It uses the polarization properties of cholesterics and was developed by Dr. Kahn.

"Cholesteric materials," says Kahn, "are sensitive to the polarization of the incident light. Incident light of different polarizations result in different colors being reflected.

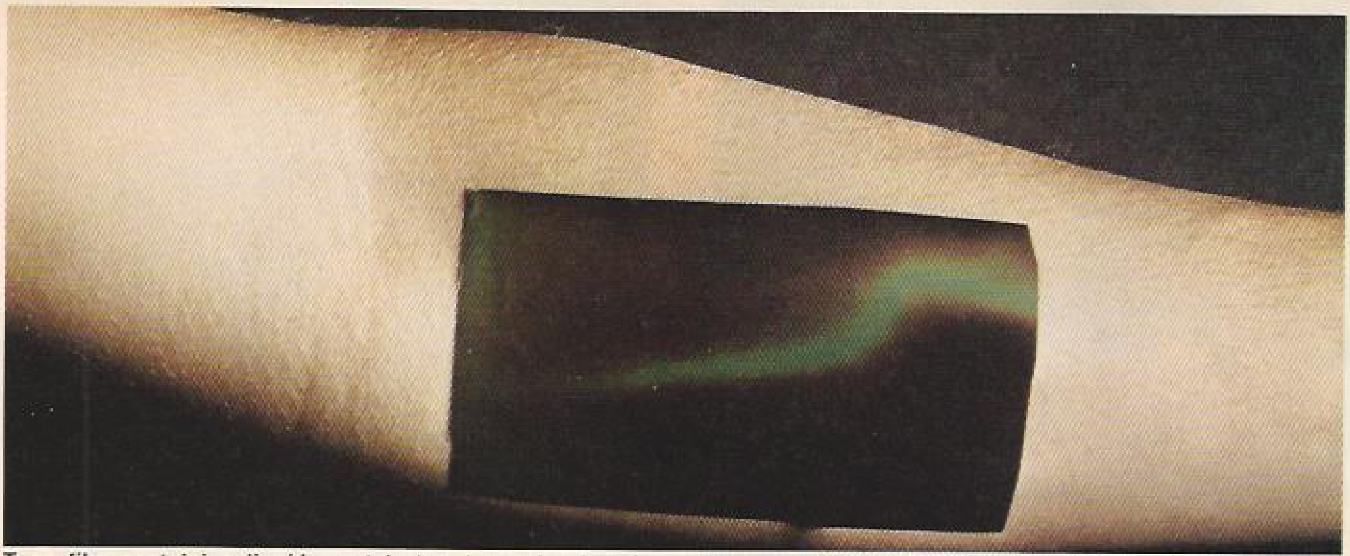
"We have made a passive, polarization-switched, two-color display element. It is called cholophor. The cholophor is composed of one or more layers of room-temperature cholesteric liquid crystals and one or more layers of photoluminescent phosphors. This element is of particular interest for large-screen, optically scanned, laser applications.

"The color of the cholophor element is determined by the sense of circular polarization of the illuminating light. For example, a typical cholophor, which appears blue-green when illuminated with 4880 Å of right circularly polarized light, turns red [the color of the illuminated phosphor] when the sense of polarization is switched to left circular."

Flat-screen applications sought

Peering into the future, liquid-crystal experimenters see such things as flat-screen or even 3-D TV. But Heilmeier of RCA points out that this will be a long time in coming. It's not the liquid crystals' fault though. "Flat-screen TV," says Heilmeier, "requires a 500-by-500-line matrix. The problem is: How do you address a quarter of a million elements? It's an electronics problem, not a liquid-crystal problem."

Fergason believes that a flatscreen oscilloscope may not be too far off. "I believe that it will be possible to make a flat-screen oscilloscope many years before a flat-screen TV," he says. "In an



Tape film containing liquid crystals has been developed by Hoffman-La Roche for thermal analysis. In this case the main vein in an arm can be seen. Since the blood is hotter than the surrounding medium, it shows up blue. Similar techniques have been used to determine breast cancer more accurately than with X-ray techniques. It is through monitoring of thermal patterns on the breast that abnormalities can be observed. Estimated cost of one breast-cancer check using liquid crystals is $1. No side effects have been found.

oscilloscope you can use a cross-grid drive rather than having to address every element in a large matrix."

Fergason dreams of the day of the 3-D home display. "You can write," he says, "the information that's in a hologram, with an infrared laser, on a liquid-crystal screen and get a truly three-dimensional display. Instead of using a regular optical system, you use a laser-illuminated scene. You convert your camera tube so that instead of seeing a normal image, it sees a phase modulation, due to the laser light. It transmits the phase information to a liquid-crystal screen, which in turn modulates a source in the home, and you have a projected three-dimensional image."

Fergason expects liquid crystals to find wide use first as indicators or pilot lights. A small cell constructed of two pieces of glass coated with transparent electrodes, and a drop of nematic material sandwiched in between, is all that is required. The pilot light or indicator would be a dynamic scattering device. One industry source feels that in large quantities these indicators could be produced for a fraction of a cent a unit.

Thermal maps come in pretty colors

Beyond displays and readouts, most other applications of liquid crystals make use of the temperature-sensing capabilities of the cholesteric phase. A coating of liquid crystals on any surface can give an immediate thermal map of that surface. Dr. Kahn at Bell Laboratories notes: "You can make liquid crystals which would change from red to blue in about 0.1°C."

Fergason says it's even possible to do better. "Cholesterics," he reports, "can change state with temperature changes on the order of one-ten-thousandth of a degree." As the temperature increases, the helix winds, and the reflected color moves from red towards blue.

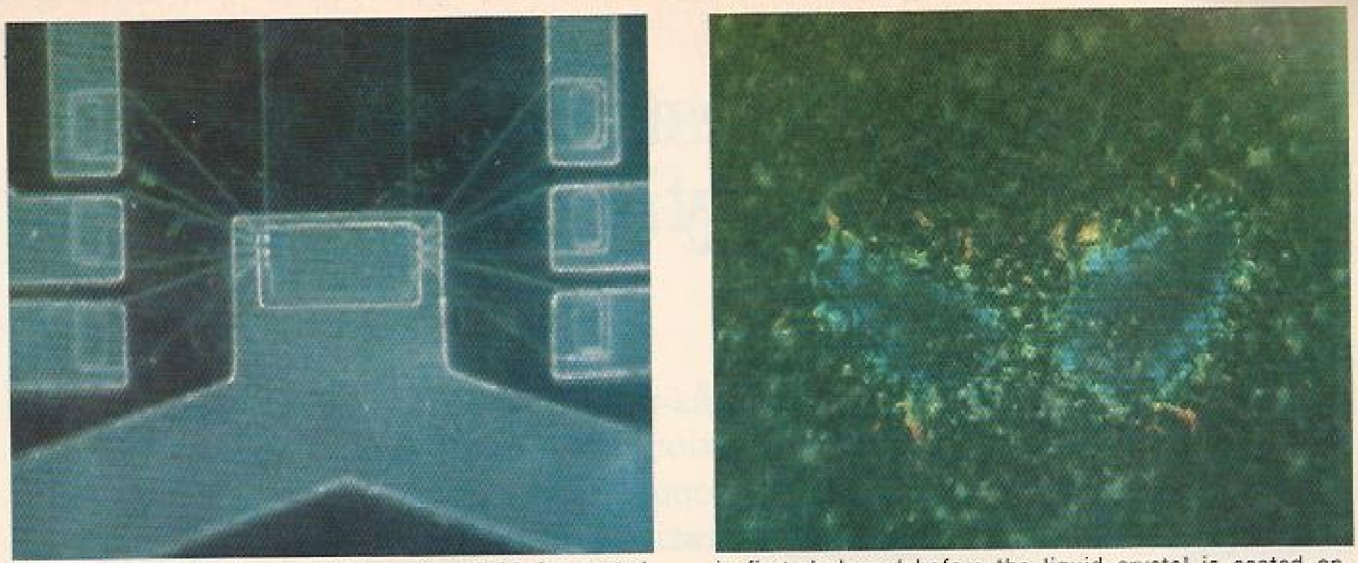
Nondestructive testing is an important application of liquid crystals. They have been used to test integrated circuits—looking for hot spots, checking thermal gradients, etc. And they have hunted the structural imperfections in such things as honeycomb structures. In any situation where a thermal pattern is important, liquid crystals can play a role.

Dr. Paul L. Garbarino, a project engineer with the Components Div. of International Business Machines in Hopewell Junction, N. Y., is using liquid crystals to check integrated circuits. To see the colors, it is necessary to provide a black background that will absorb any extraneous incident light.

"We spray on a 2 or 3-micron amorphous carbon coating for our black background," says Garbarino. "Carbon gives better uniformity and stability over a period of time than any other method. The layer of carbon is so thin that, even though it is somewhat conductive, it doesn't seem to change the circuit's electrical performance.

"We are interested in studying failure modes in ICs, such as electro-migration and shorts. Electro-migration in a stripe of aluminum occurs when a high current density bombards the metal atoms, sweeping them away and causing vacancies. Ultimately an open circuit can occur.

"Thermal mapping has been done at IBM on



Thermal analysis of monolithic and hybrid integrated circuits can be done with cholesteric liquid crystals. Temperature gradients will show up as color changes, thus allowing faults or hot spots to be located easily. For the colors to be easily seen, the surface of the circuit is first darkened before the liquid crystal is coated on. IBM uses a thin layer of amorphous carbon that does not allow the circuit to be seen any longer, but it brings out the color pattern well (left). At the right is the circuit coated, but with no black background.

both bipolar and MOS structures."

Garbarino admits to the following limitations:

- Thickness of the liquid-crystal film causes a good bit of light dispersion.
- Variations in the crystal thickness cause inconsistent color coverage.

Elliott Philofsky, head of the metallurgy and analytical services section at Motorola Semiconductor in Phoenix, Ariz., is skeptical about using liquid crystals instead of infrared microscopy in thermal mapping. "As I see it," he says, "liquid crystals have a couple of great disadvantages over IR microscopy. Since one usually has to provide a black background for the crystal coating and since the liquid crystal solvent may damage the device under test, liquid crystals may not be a totally nondestructive method of testing. Then there's the time involved in setting up a liquid-crystal test. In addition the ultimate resolution of liquid crystals doesn't appear to be that much better than IR microscopy is now. In time IR microscopy may give even better resolution than liquid crystals.

"Offhand, I can't see where liquid crystals will ever be used on a production-line basis. They will be more used for troubleshooting and as a design tool."

A boon for diagnostic medicine

Since the human body is a mass of thermal patterns, doctors have found that liquid crystals can help them in their diagnoses. Fergason at Kent State notes:

"We are doing studies of breast-cancer detection. Out of 65 patients, we have determined malignancy more accurately than X-ray techniques. It costs us only about $1 to do a breast-cancer check. We have found no side effects yet in all of our experimentation. It is through monitoring of thermal patterns on the breast that abnormalities can be observed.

"We have also seen some relation of thermal patterns on the breast to the degree of fertility of the subject. The effect is in preliminary investigation at present."

When used as a simple liquid, liquid crystals are difficult and messy to handle. A great deal of work is going on at several companies to develop a convenient way of working with the crystals. At Hoffman-LaRoche, Inc., in Nutley, N. J., Peter G. Pick, head of the liquid crystal chemistry section, has developed a good approach. He explains:

"The key to the whole thing is the delivery system. The liquid crystals are contained within a multilayer film, which can be easily applied to a surface. The film has a useful lifetime of years. It can be torn, bent or twisted and still be usable."

This tape can be applied to a person's skin to observe the patterns of the blood vessels near the surface. It can be used as a body-temperature monitor. Or it can be used to monitor the temperature in an electronic enclosure.

Kahn at Bell Laboratories, sums up the potential of liquid crystals by saying:

"Research is in such an early stage that it is not yet quite clear which effect will prove to be most useful. Liquid-crystal research is at about the same stage today that solid-state physics was at 20 years ago." ■■