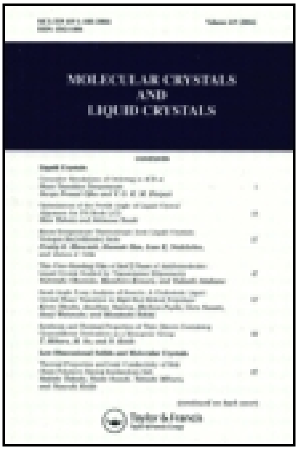

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Liquid Crystal Display Applications: The First Hundred Years

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Liquid Crystal Display Applications: The First Hundred Years

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Although liquid crystal materials have been known for 100 years, large-scale applications for the materials in the form of electronic displays did not occur until the mid-1970s when compact, attractive calculators and watches with liquid crystal displays (LCDs) reached the marketplace and soon became household items. Now, some 12 years later, low cost LCDs are being made by the hundreds of millions. Today, we see more sophisticated LCDs appearing in such products as portable computers and hand-held color TV sets; the fabled liquid crystal TV on a wall appears to be only a few years in the future.

This paper deals with a review of the liquid crystal applications which have resulted from research carried out over the past 25 years. It presents a liquid crystal research pioneer's assessment of how applications were envisioned in the past, how they actually developed and what we might expect in the future.

I. INTRODUCTION

Although liquid crystallinity was first observed in 1888 by Reinitzer, it was more than 30 years before Mauguin[1] discovered and described the twisted-nematic structure which later became the basis for liquid crystal display (LCD) technology, now the major application for liquid crystal materials. During the 1920s and 1930s work on liquid crystal materials and the electro-optic effects which they produced was conducted in France, Germany, the U.S.S.R. and Great Britain. Perhaps the first patent on a light valve device which used liquid crystals was awarded to the Marconi Wireless Telegraph company (now part of GEC) in 1936.[2] Then in the mid-1950s, researchers at the Westinghouse Research Laboratories discovered that cholesteric liquid crystals could be used as temperature sensors. It was not until the nineteen-sixties, however, that serious studies of the materials and the effects of electric fields on them were carried out. One reason for this was that liquid crystals were little known materials and, in fact, the first book in English to treat the subject was not published until George W. Gray's "Molecular Structure and the Properties of Liquid Crystals" appeared in 1962.[3] This excellent book quickly became the definitive work on the subject. Before its publication, students of organic chemistry in most U.S. universities were not even taught that liquid crystals existed!

The early work on applications of liquid crystals was carried out in research laboratories in the U.S.A., Eastern and Western Europe and Japan. During this period, a great deal of research and development was performed; theories were formulated and tested, a number of electro-optic effects were discovered, materials with broader operating temperature ranges were prepared and rudimentary fabrication techniques were developed.

II. EARLY OBSERVATIONS & DEVELOPMENTS

The idea of using liquid crystal materials for display applications was probably first conceived by Richard Williams and George Heilmeier at the David Sarnoff Research Center (then the central research arm of RCA Corporation) in Princeton, New Jersey in 1963.[4] Later, a larger group, headed by G. H. Heilmeier and including Louis Zanoni, Joel Goldmacher, Lucian Barton and myself, spearheaded the work to develop liquid crystal displays for application to the fabled "TV-on-a-wall" concept, a dream of the late TV pioneer David Sarnoff. During the period from 1964 to 1968, this group discovered many of the effects which were later to be commercialized including dynamic scattering,[5] dichroic dye LCDs,[6] and phase change displays.[7] One of the major breakthroughs was our discovery that by mixing various pure nematic liquid crystalline compounds together it was possible, for the first time, to produce stable, homogeneous liquid crystal solutions which could operate over a broad temperature range including ordinary room temperature.[8] Later, cyanobiphenyl materials with improved properties and even broader temperature ranges were developed[9]; these compounds form the basis of most of the liquid crystal materials used today in commercial products.

During the mid 1960s work on liquid crystal displays was also being performed by A. Kapustin and L. S. Larinova in the Soviet Union[10] and by George Elliott and J. G. Gibson at Marconi Electric in England.[11] Later, a group which included Joseph Wysocki, James Adams and Werner Haas at Xerox also carried out extensive liquid crystal display research.[12]

By 1969, it became clear to the RCA group and others, that the development of large screen, LCD television sets would require "many years of research," although we did not think it would take 16 years. Thus, an effort was mounted to develop simpler display devices which could be commercialized quickly. One of these was the "Point-of-Purchase" display, a moving advertisement display which was used in retail stores. These segmented displays (produced by RCA and Ashley-Butler in the early 1970s) were made in sizes up to 12 × 12 inches. The system used a rotating copper drum which was patterned in such a way as to send electrical signals to the appropriate segments of the display at the proper time in order to create the desired motion. Although this application proved to provide a very limited market, many of the techniques developed for production of these large size LCDs were later used for the manufacture of smaller displays.

Among the most important early applications were the wrist watch and portable calculator, made possible by the low power consumption of LCDs and the integrated circuit industry, then in its infancy. Some of the "products of the future" which I wrote about in papers published in the 1969–1971 period[13,14,15] were numeric indicators for instruments, digital clocks, digital wrist watches, optically tuned color filters using the so-called "Guest-Host" effect, electronically controlled "window-shades," and "displays for auto dashboards, aircraft cockpits, scoreboards, highway signs and computers." Today, we see LCDs in virtually all of these applications.

Another major breakthrough occurred in late 1969 when James L. Fergason, working at a newly formed firm, International Liquid Crystal Company (ILIXCO) in Kent, Ohio, discovered the twisted-nematic field effect LCD which ultimately proved to be the most successful for the watch, calculator and later, other applications including TV. Because Mr. Fergason's patent application was not made public until several years later,[16] Drs. Wolfgang Helfrich and Martin Schadt of F. Hoffmann La-Roche in Basel, Switzerland, published a paper on the same effect in 1971.[17] Mr. Fergason was recently awarded the highest honor of the Society for Information Displays for his initial discovery.

Between 1970 and 1972 activity in the LCD field increased enormously and many companies in the U.S.A., Europe and Japan began to exploit the development of the sixties. The coincident development of large-scale integrated circuits for driving and timekeeping functions resulted in the development of the LCD wrist watch and calculator.

The early 1970s also saw a number of new American companies formed to exploit LCD technology. Among these were ILIXCO in Kent, Ohio, Optel Corporation and Princeton Materials Science in Princeton, New Jersey, Microma in Cupertino, California, Micro Display Systems in Montgomeryville, Pennsylvania. All of these firms set out to manufacture LCDs and the digital watches which used them.

In those early days, it was American engineers and scientists that developed the first processes for the fabrication of LCDs and digital watches. It was an exciting but sometimes frustrating time because the technology was in its infancy and engineers were forced to work with equipment that was adopted from other industries. Although the equipment used was crude by today's standards, the same fundamental techniques are now being used to manufacture the several hundred million LCDs made each year throughout the world.

During these early years, many Japanese firms followed and copied the developments coming out of the United States. However, they quickly began striking out on their own by developing improved fabrication and packaging techniques which resulted in greater reliability and lower manufacturing cost. They envisioned that a large marked for electronic products made with low power, highly legible LCDs would be forthcoming and they dedicated themselves to pursuing that goal.

The first LCD digital watches used the "dynamic scattering effect."[5] However, by late 1974 this display practically vanished because of its relatively high voltage requirement (at least for the CMOS devices made at that time) and viewing angle restrictions created by the need for a specular (mirror) reflecting back electrode. It was soon replaced by the twisted-nematic, field-effect (TN-FE) display[16,17] and the LCD watch began to gain momentum in 1976. Compact, attractive LCD calculators and watches made in Japan soon became household items.

Now, some 12 years later, manufacturing techniques and equipment are readily available and highly reliable, low cost liquid crystal displays are being made by the hundreds of millions, primarily in Japan and the Far East. These displays are, for the most part, driven by a low level of multiplexing (30 to 50% duty cycle) or directly driven with each segment receiving full voltage.

The LCD technology became successful because of its "passive" (non-light emitting) nature which provided the combined characteristics of low power and viewability in bright light, factors that made miniaturization and portability a reality.

III. RECENT DEVELOPMENTS & PRODUCTS

Today, we see more sophisticated LCDs appearing in industrial and consumer products. These second generation LCDs, driven by a high level multiplexing scheme, or using a "Supertwisted" technique provide a higher level of information content and appear in the applications envisioned nearly 20 years earlier: automobile dashboards (Figure 1), hand-held color TV sets (Figure 2) aircraft cockpits (the Boeing 757 and 767 have LCDs), instruments, and electronic test equipment (Figure 3). Meanwhile, displays for general computer use are still a few years away; the cost of the displays are still too high compared with the traditional cathode ray tube. What was not envisioned in those early years was the truly portable computer which became a reality because of the advent of personal computers in the late 1970s and early 1980s. Today, portable (Figure 4) computers and word processors with high information content LCDs are being sold by the millions. Many of these products can be operated with a set of small batteries; others use a backlighting scheme to enhance viewability in dimly lit environments (Figure 5). A list of the existing applications for liquid crystal displays is presented in Table I.

Clearly, LCDs have come of age. But, developments in this technology have continued and now we are beginning to see what I would call the third generation of LCDs. These are based on the use of thin-film electronic devices (such as thin-film transistors or TFTs) to drive a large number of picture elements (pixels) without the loss of contrast or angle of view. Coupled with the use of color filters, these full-color displays now appear in large numbers of hand-held color TV sets and soon will be used in table top TV sets, portable computers, automobile dashboards, instruments and many other applications.

Although the concept of a thin-film transistor (TFT) may sound like a newly discovered approach to attack the display addressing problem, it actually predates the discovery of the point contact and junction transistor. Patent applications for TFTs were actually made by J. E. Lilienfield in 1925 and 1926.[18] There was no widespread application for the device when it was invented. Due to the undeveloped fabrication facilities and a lack of fundamental materials science principles, the TFT did not become practical until the late 1960s when T. Peter Brody and his associates mounted a major development effort.[18] At the time of the early TFT development work, the liquid crystal display had no visibility as a product and was still a laboratory curiosity.

The TFT is the ideal device for separating the addressing of a matrix

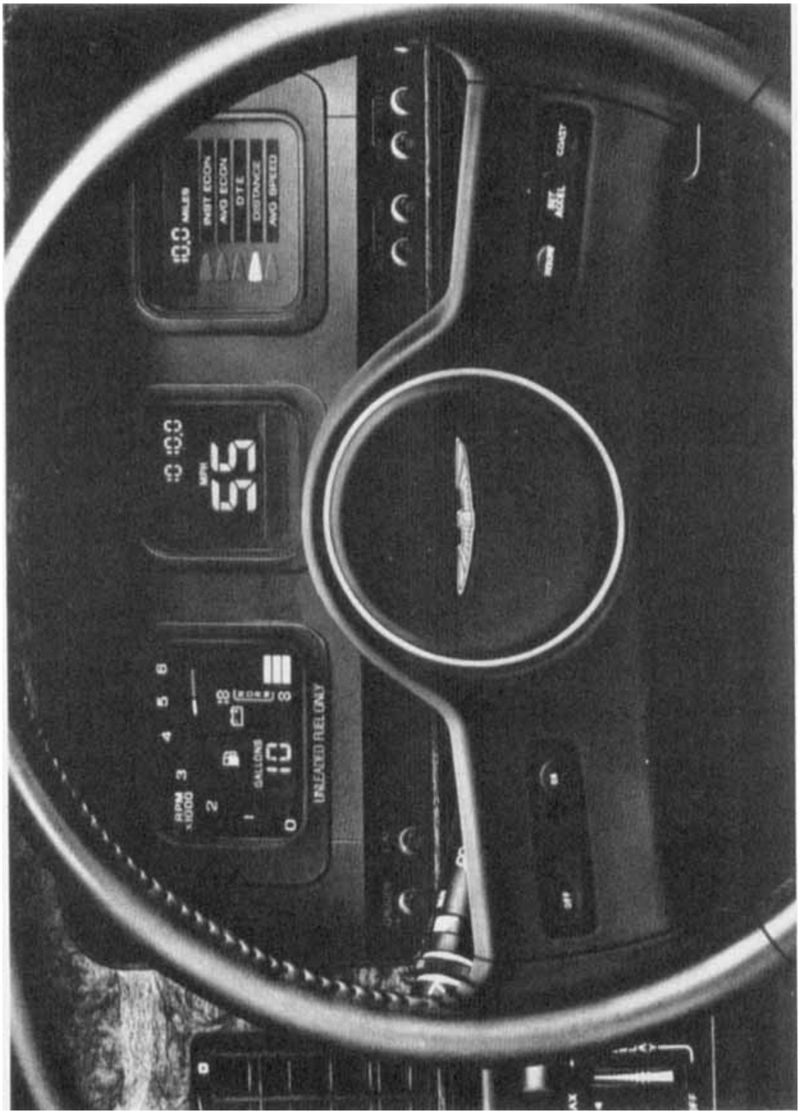

FIGURE 1 Primary LCD auto dashboard instrument cluster. **See Color Plate I.**

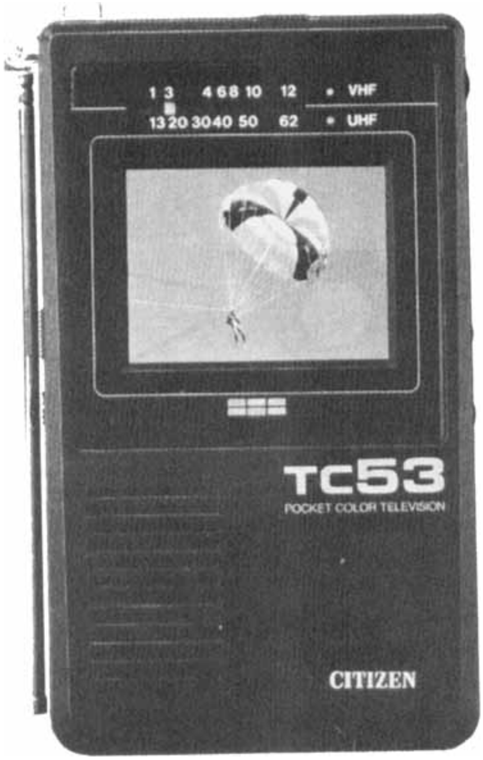

FIGURE 2 Hand-held TV with full-color LCD.
See Color Plate II.

of (addressable) dots from the task of sending contrast producing energy to those dots. But, in order to do this, the system becomes very complex due to: (1) the large number of devices which must be built; (2) the density of the devices; (3) the multilayer structure necessitated by the use of at least 3 terminals per device; and (4) the large area which the display must cover. Thus, the fundamental problem of addressing nearly a thousand rows and columns still remains to be conquered in an economical fashion, although progress is being made rapidly. Emulation of a cathode ray tube (CRT) in everything except physical volume has been achieved in small displays for hand-held color TV.[19,20] By the mid-1990s, David Sarnoff's dream of the large screen, color TV-on-a-wall will likely be realized through the use of liquid crystal displays.

In addition to the use of "active" devices in conjunction with 90° twisted-nematic liquid crystals, a more recent development has been

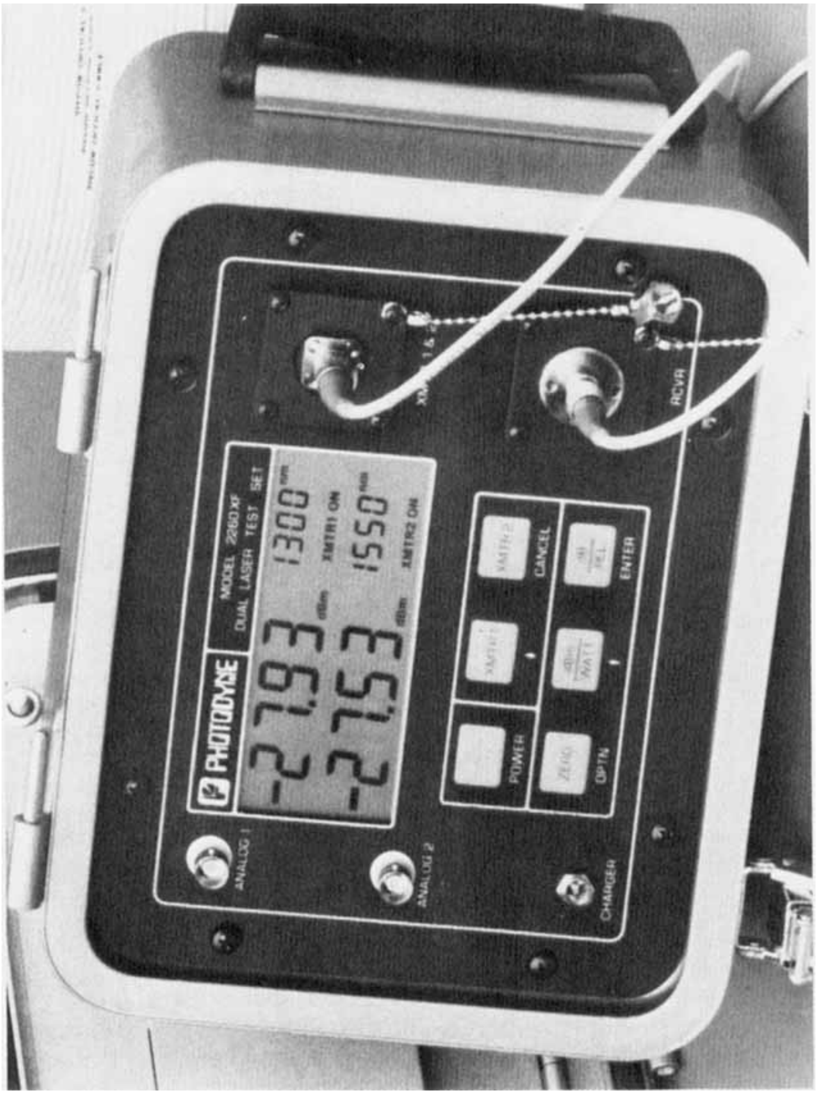

FIGURE 3 Multi-digit LCD in test instrument. **See Color Plate III.**

FIGURE 4 Supertwisted LCD in portable computer.
See Color Plate IV.

FIGURE 5 Supertwisted LCD in transportable computer with backlighting.
See Color Plate V.

TABLE I

Current applications for liquid crystal displays

Analytical Instruments	Jewelry, Assorted
Auto Dashboards	Marine Engine Indicators
Auto Radios & Clocks	Marine Speedometers
Battlefield Computers	Marine Depth Finders
Blood Pressure Indicators	Overhead Projector Plates
Calculators	Pens
Cameras	pH Meters
Cash Registers	Photocopy Machines
Clock Radios	Point-of-Purchase Displays
Digital Pyrometers	Point-of-Sale Terminals
Digital Multimeters	Portable Radios
Digital Thermometers	Portable Computers
Electric Shavers	Portable Word Processors
Electronic Billboards	Portable Oscilloscopes
Exercise Equipment	Telephones
Gasoline Pump Indicators	Toys & Games
Hand-Held TV	TV Channel Indicators
Hand-Held Terminals	Typewriters, Editing
Hand-Held Data Collection	Vacuum Cleaners
Heart Monitoring Devices	VCR Channel Indicators
Highway Signs	Windometers
Household Appliances	Wrist Watches

the "Supertwisted-Nematic" (STN) liquid crystal display. There is some controversy over the origin of this type of display effect. In one respect, the "supertwisting" is a modification of the Cholesteric-Nematic phase change effect described by workers at RCA and Xerox in the late 1960s; the new technique uses a smaller helical pitch, better alignment techniques and polarizers; dyes may also be used. But STN displays were not seriously investigated for practical application until work was conducted at the Royal Signals and Radar Establishment in 1982; the work was published in 1984.[21] Then, Scheffer, *et al.* at Brown Boveri & Company put all the pieces together after a three year effort and in 1985 showed the first large area, high information content displays; Scheffer coined the term "Supertwisted Birefringent Effect (SBE)" to describe the new effect.[22] In 1986, Hitachi described a modification of Sheffer's technique which used a smaller twist angle. Known as the "Highly Twisted LCD," Hitachi and others began to manufacture these displays in high volume.

The SBE principle was implemented in an experimental display with an active viewing area of 4.8 by 9.6 inches in a format of 27 lines of 89 characters per line. The display was about ½ inch thick (which included the thickness of the integrated circuit drivers in back of the screen) and had full graphics capability, accommodating 145,800 pixels in a 540 × 270 dot matrix format. Information switching time was about 300 milliseconds at room temperature. The device used a double-matrix design, driving each matrix half at a multiplexing rate of 135:1 and bringing the number of connections to a total of 1,350 ([540 × 2] + 270). These were addressed by 30 driver ICs, each of which handles 45 connections. The display's power consumption is comparable to that of a multiplexed twisted-nematic LCD.

STN displays make use of existing materials, fabrication processes and drive electronics to achieve increased viewing angle and contrast ratio. The STN display is said to achieve a contrast ratio of about 10:1 when viewed at normal incidence. From an angle of 45 degrees, the contrast ratio is still a respectable 4:1. Today, STN displays have largely replaced multiplexed types for portable computer application but because the display lacks gray scale or full color capability, it is not yet suitable for TV applications. Also, the device is slow; it switches information at only four frames per second, a factor of seven less than it would need for broadcast TV.

The 270° SBE operates in a yellow mode or a blue mode. The yellow mode display operates with a bright yellow background with blue-black pixels when they are selected. When one of the polarizers is rotated by 90°, the display is changed to the blue mode. The blue mode display has a colorless appearance in the selected state and a purplish-blue color in the non-selected state. The contrast ratio of a 100 line multiplexed display in the yellow mode has been said to be measured at over 50:1 while the blue mode has a 15:1 contrast ratio. Switching times for the 270° SBE displays are in the neighborhood of 200 milliseconds which is fast enough to do text handling but not fast enough for video or high speed scrolling. The 180° SBE display operated in the yellow mode shows purple text on a green background. In the complementary mode, the display is a rather unpleasant yellow-green on purplish-pink. Contrast ratio is less than those obtainable with a 270° twist but more than a standard TN-FE display.

Another process, which is rapidly gaining popularity among LCD makers, uses a twist angle of around 240° in conjunction with special polarizer angles, and left-handed chiral compounds.[23] The advantage is greater contrast and viewing angle while maintaining a neutral color; hence, the devices are called Black-and-White STN displays. These display types are expected to displace the yellow and blue mode SBE types during the next 2 years.

The application of Ferroelectric-Smectic liquid crystals to very fast optical shutter devices and displays is another recent development.[24]

The devices are already being used in photocopy equipment and displays based on the technology are expected to appear very soon. The whole field of Ferroelectric-Smectic displays is now receiving a great deal of attention in laboratories throughout the world.[25] The technology is based on the bistability of some smectic phase liquid crystal materials. Surface stabilized ferroelectric liquid crystal (SSFLC) displays offer the potential for fast switching speed, high contrast, low voltage and low power. These displays are similar in appearance to the phase change displays mentioned above except that a chiral ("handed") smectic C phase is involved. In the structure of this type of liquid crystal, the long, rod-like molecules are arranged in "tilted" stacks. Each stack is rotated slightly with respect to its adjacent stack resulting in a helical structure. One complete helical turn or "pitch" length is in the range of 1 to 100 microns or 200 to 20,000 molecular layers.

Dozens of research labs around the world are now working on SSFLC displays, but much work remains to be done before a commercial product can be made. The three areas which need the most applied effort are cell spacing control, surface molecular alignment and materials. Very thinly spaced cells are required for the SSFLC displays. Thicknesses on the order of 2 to 3 microns are required to unwind the helical structures and to suppress the formation of a so-called "splay" state which can interfere with switching. Cell spacing control will probably benefit from the work being done on SBE displays as they require similar controls and thicknesses. Another possibility is the use of a technique called AC stabilization. A liquid crystal with a negative dielectric anisotropy is used and a high frequency signal is used to suppress the formation of the splay states.

Surface alignment of the ferroelectric display is probably the most important and least understood. The ideal structure would have the smectic planes aligned perpendicularly to the glass surfaces with the liquid crystal molecules aligned parallel to the surfaces with weak anchoring and no spontaneous tendency for any particular orientation. The glass must possess a slippery surface which is very difficult to implement. Much work has been reported on the use of organic aligning materials (such as Nylon) and the indications are that these materials will be compatible with existing LCD processes.

Due to the intense research efforts on SSFLC displays, the material availability has been improving very rapidly. When work first began on ferroelectric displays, a material with a stable smectic C phase at room temperature was not available, but now mixtures with wider temperature ranges are made by several manufacturers. Other properties such as spontaneous polarization, viscosity, dielectric anisotropy, birefringence, molecular tilt angle and pitch must also be optimized.

A group of engineers at the Electron Device Engineering Laboratory of Toshiba Corporation, Yokohama, Japan, has developed a ferroelectric multi-color LCD with RGB color filters.[26] This development was based on optimization of LC material, new alignment techniques and methods for cell thickness control. We can expect to see commercial products enter the market within the next 2 years.

The development of flexible substrate LCDs has been the subject of much interest over the last few years. The use of a plastic substrate instead of glass has the potential for high volume production because the displays could be made in large sheets on the equipment now being used for handling polymer film. One technique which shows great promise to achieve this goal is that developed by Fergason[27] and called NCAP for "Nematic Curvilinear Aligned Phase." The technology is now being developed by Taliq, a unit of Raychem Corporation, for application to commercial products. The display uses no polarizers and is made with plastic film substrates instead of glass.

The NCAP display is made with nematic liquid crystal material which is microencapsulated in a transparent polymer. The tiny microcapsules are then sandwiched between two plastic layers coated with a transparent conductive film. In the OFF state, the walls of the capsules cause the alignment of the liquid crystal to be random so that incoming light is scattered in all directions. The result is an opaque (white) appearance; colors are possible with dyes or color back lighting.

When an electric field is applied to the layer by supplying voltage (about 50 volts) to the transparent electrodes inside the plastic sandwich, the liquid crystal molecules align with the field. The force of the field overcomes the surface tension of the polymer capsule. The liquid crystal material then appears transparent and reveals whatever image is behind it. If a black background is behind the sandwich, then white characters can be formed with a black background.

The NCAP technology offers the capability to make flexible, large size displays which would be light in weight, consume low power, and have fast response time. The technology is not yet capable of matrix addressing but this could change in the future.

IV. PRODUCTS OF THE 1990s & BEYOND

Now that liquid crystal displays have become widely used in a whole variety of commercial products, what can we expect to see in the future? With the more than $100 million per year being spent on LCD research throughout the world, it is clear that the products of the next 20 years will be even more impressive than those of the past 20. Of course, color TV will be one of the most important applications and we expect to see sets with diagonal screen sizes of 5 to 6 inches on the market in 1988 and 1989. The first wall-mountable units will likely appear in 1990 with screen sizes of 10 to 14 inches. By the mid-1990s, color TVs with 20 inch diagonal LCD screens will appear on walls and tables in homes and offices; the 40 inch diagonal screen should be a reality by the year 2000.

The other major application for LCDs will be portable personal computers. Within the next five years, we expect to see the truly "book-size" computer become a reality. With an active matrix LCD screen of 6 to 8 inches (diagonal), this computer will have the power of many of today's desk-top units but will be about the size of a book (8 × 10 inches). This book-computer will become widely used by students, clerical workers, executives, salesmen, housewives and others. By the turn of the century, it will be as ubiquitous as the hand-held calculator is today.

Replacement of the cathode ray tube in the desk-top computer will likely begin in earnest early in the 21st century. In full-color, these computer screens will be wall-mounted or, in any case, will be extremely compact, freeing desk space for many of the other new, compact office automation products which will be available at that time.

Flexible LCDs will appear in primary auto dashboard instruments. The displays will be curved to the contour of the dashboard and be multi-colored. Other LCDs will be used for navigation, a full-color computer monitor, clock, etc.

Another major application for LCDs could be the electronic window-shade, a concept which has been around for more than 20 years. Once incorporated into large panes of glass, these electronically controlled windows could become commonplace on the buildings and skyscrapers of the 21st century. The NCAP technology discussed above appears to have the potential to fit this application.

In addition to these new applications, we expect to see LCDs continue to be used in all of the applications listed in Table I. However, the displays will have much greater information content, be available in color and, in some cases, be flexible and have very large screens. As I said 17 years ago,[15] the number and type of applications appear to be limited only by the imagination.

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