FLAT-PANEL ISSUE

Information DISPLAY

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SID
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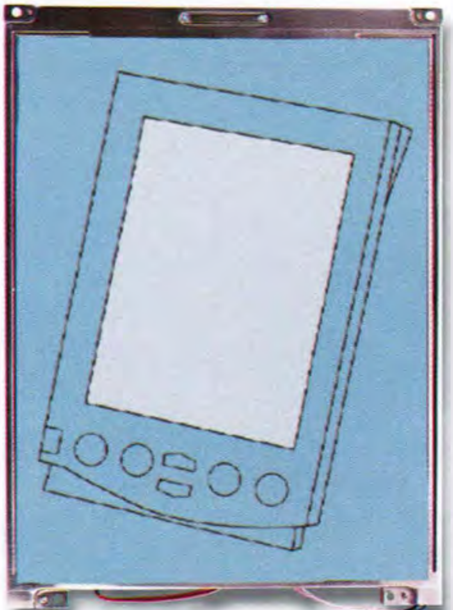

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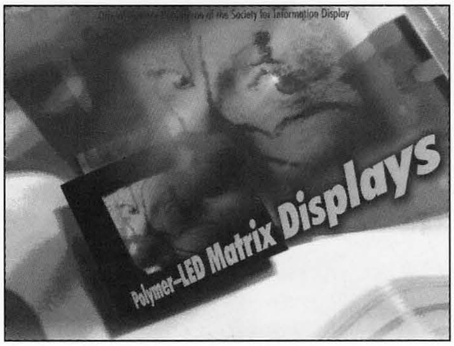
Circle no. 1

BPA INTERNATIONAL

COVER: *Passive-matrix polymer LEDs can be made in almost any size, but the power losses go way up and the average luminance comes down. So larger PLEDs will have active matrices, perhaps with multi-transistor pixel controllers.*



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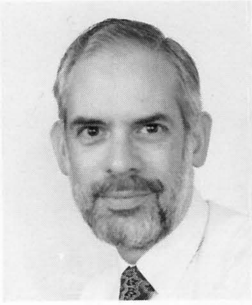
A Millennial Editorial



This is my "new millennium" editorial. Yes, I know it's February and all the other editorialists did their millennial editorials in January or December. But it doesn't matter because all of us are late – years late. The 21st century began in 1996. Let me explain.

We can certainly define the beginning of a new century (and a new millennium) by the tick of a clock and the turning of a new page on the calendar. By that measure, the new century indeed begins with the first second of January 1, 2000 (actually 2001, but we're not being picky). But in terms of the important things – cultural paradigms, attitudes, geopolitics, national character, lifestyles, global economics – what changes on January 1st? Not much.

Certainly, not much changed with the turn of the 19th century. The Belle Epoque continued in Europe and the United States. Attitudes and class structures continued virtually unchanged. While there was a fascination with technology and industry, the social expectations were of stability and steady progress that would somehow not change the dominant order. But the 19th century did end, not in 1900 (or 1901) but in 1914 – and then everything changed. Social orders, political systems, personal expectations and attitudes, art, literature, psychology, class structures – and lives, millions of lives – all were shattered, and painfully replaced or rebuilt in the succeeding years and decades. In many ways, that rebuilding was what the 20th century has been about.

Now, I am of European ancestry and I realize that this is a somewhat Eurocentric view. From an Asian perspective, it may be that the 20th century began with the conclusion of the Russo-Japanese War in 1905 – the first victory of an Asian power over a European power in modern times. The ascendance of Asia has certainly been another of the 20th century's grand themes.

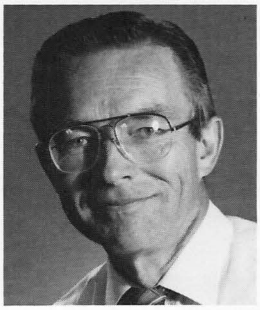
I was lazily discussing these ideas with Mark, my tolerant and philosophically minded barber, the other day, and I wondered aloud what cataclysmic event might end the 20th century and begin the 21st, and how many years into the 21st century it would be before that event occurred. Mark stopped clipping and looked at me as if unable to believe the stupidity of the person sitting in his chair. "It's already happened," he said. "It's the Internet."

Yes. Of course it is. Democratized, universal, global, nearly instant communication. It has already changed our world view, the way we communicate, the way we do business, the way we make friends, the way we can find opportunities, the way we can freely explore ideas regardless of the attitudes of autocrats, and the way we can find information despite the passion politicians and bureaucrats continue to have for secrecy. And the changes are just beginning. Despite the vast amount of dot-com foolishness and trivial e-commerce, this incredible technology will continue to be the vehicle for sweeping social, intellectual, artistic, commercial, and technological change. Working through those continuing and expanding changes is likely to be one of the major topics of the first half of the 21st century.

So it doesn't matter that this editorial is appearing in February of 2000 because the new millennium began in 1996. Maybe 1997.

— KIW

the display continuum



Weather Vanes ...

by Aris Silzars

In the center of Issaquah, Washington, not more than two blocks off Main Street, there is a full-fledged operating salmon hatchery. The founders of Issaquah, apparently not being a very creative lot, named this street "Front Street." Today on Front Street you will find restaurants featuring a cross section of quasi-ethnic cuisine, a camera repair shop, a musty-smelling used-office-furniture store, and a large commercial dairy with pictures of cows painted on the side facing Front Street - which also happens to be the side where the large shiny tanker trucks pull up to pump out their loads of fresh milk.

A few steps further there is a small bridge crossing an offshoot of the creek used by the salmon to get to the hatchery. Next is the Village Theater with its Stage Right Cafe, an art gallery, a dentist's office, several modest variety stores, a dilapidated used-everything store, and a TV repair shop with 50s-vintage sets in the window. There are the obligatory four gas stations at the intersection with Gilman Blvd. If you can visualize all this and add some fir- and maple-tree covered mountains for a background, you will have a reasonably good idea of what you would encounter on a stroll down Front Street. And in keeping with the reputation of the Pacific Northwest, you may also wish to include a few clouds and a raindrop or two.

The only disruption to this bucolic sleepy-little-town scene is the daylong traffic jam reflective of the all-too-rapid growth that the Pacific Northwest has experienced over the last few years. The "serious" shopping areas, however, are a few blocks away at the quaint boutiques of Gilman Village and the upscale strip malls that have taken over the adjacent area that not too long ago was a dirt-strip airport.

Each October the town of Issaquah celebrates fall with an event appropriately called "Salmon Days." The main activity is a two-day arts and crafts fair that lines Front Street and the cross street leading to the hatchery with hundreds of booths offering the gamut of oil and watercolor paintings, photographs, musical instruments, objects to decorate one's person or one's home, and various other wood and metal crafts. Interspersed among these are the food booths that offer everything from kettle-roasted popcorn to elephant ears, various wraps, skewers, and dishes of yet more substantial fare. Other than the proximity of the salmon hatchery, which provides a crowd-pleasing opportunity to watch the spawning salmon bashing themselves repeatedly into the concrete dam that blocks their way until they finally happen to find the fish ladders leading to the hatchery's holding ponds, this is much like any other outdoor crafts fair.

No matter where you live on this planet, or which country you visit, such fairs seem to be much the same. The food vendors always appear to be the busiest. At the Issaquah Salmon Days, the barbecued salmon steaks are a particular favorite - for obvious reasons, I suppose. The rest of the arts and crafts vendors seem to be mostly providing free entertainment for the wandering crowds. People love to look and compare, but few buy. I often wonder why the vendors come. The business model for such a venture looks mighty shaky. With the cost of the tent and set-up, the rental of the booth space, the cost of inventory, and the cost of putting in at least two days away from home, the sales rate for

continued on page 36

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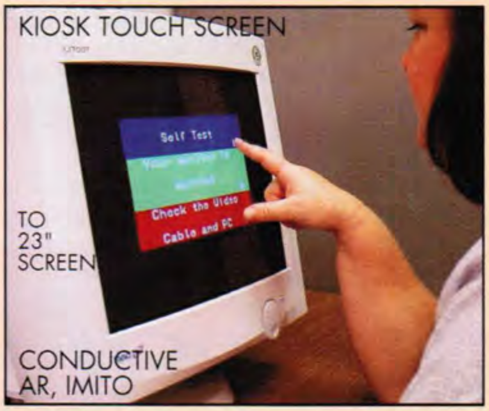

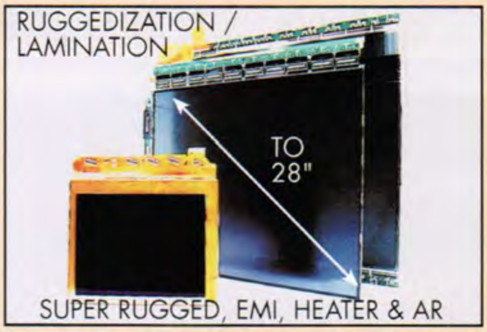

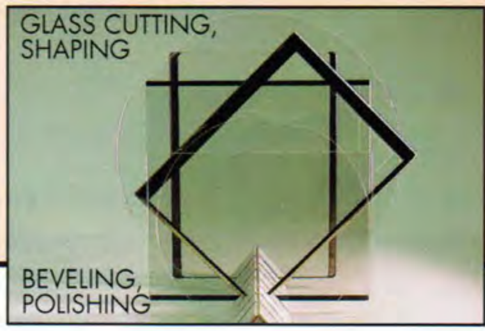

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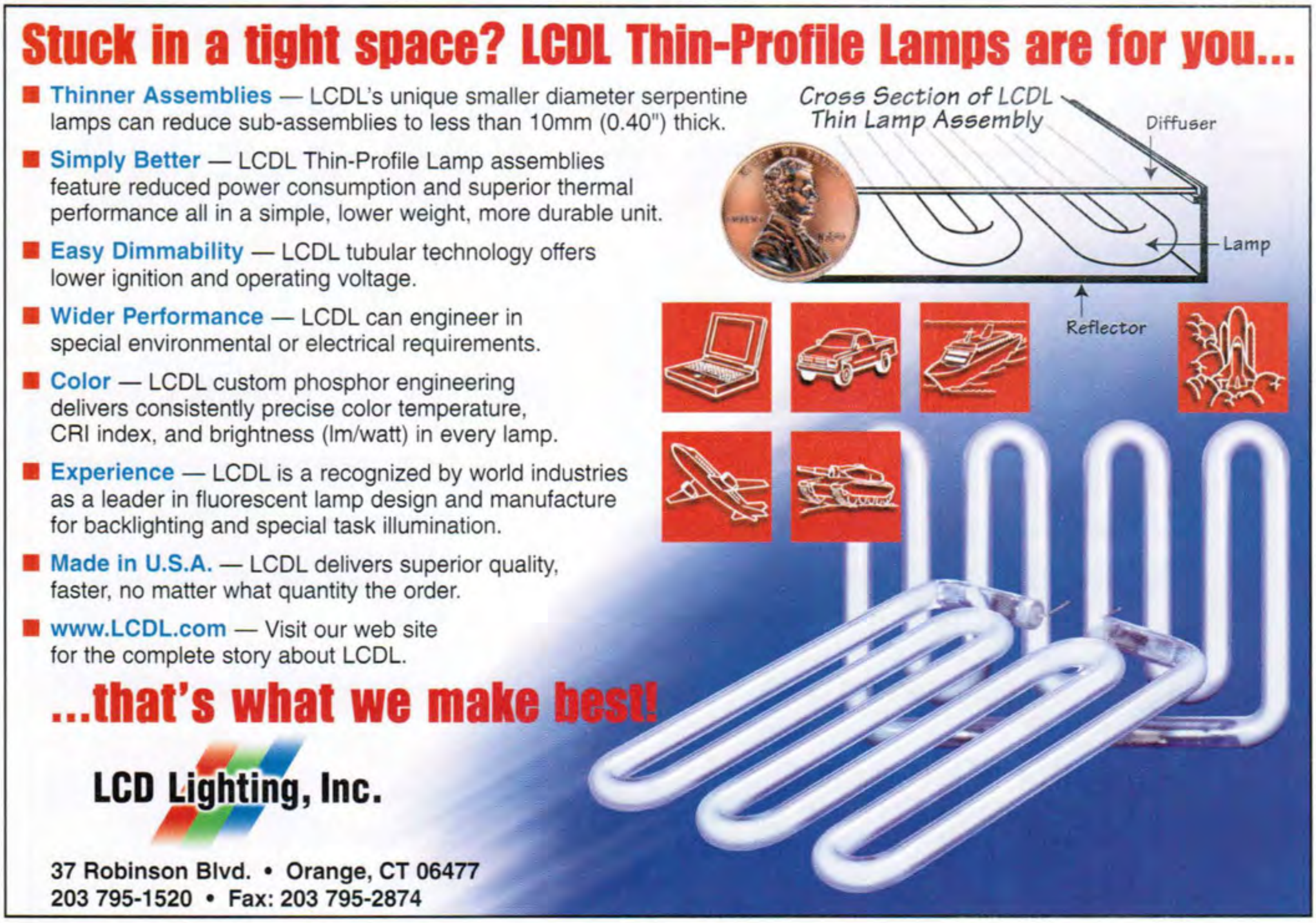

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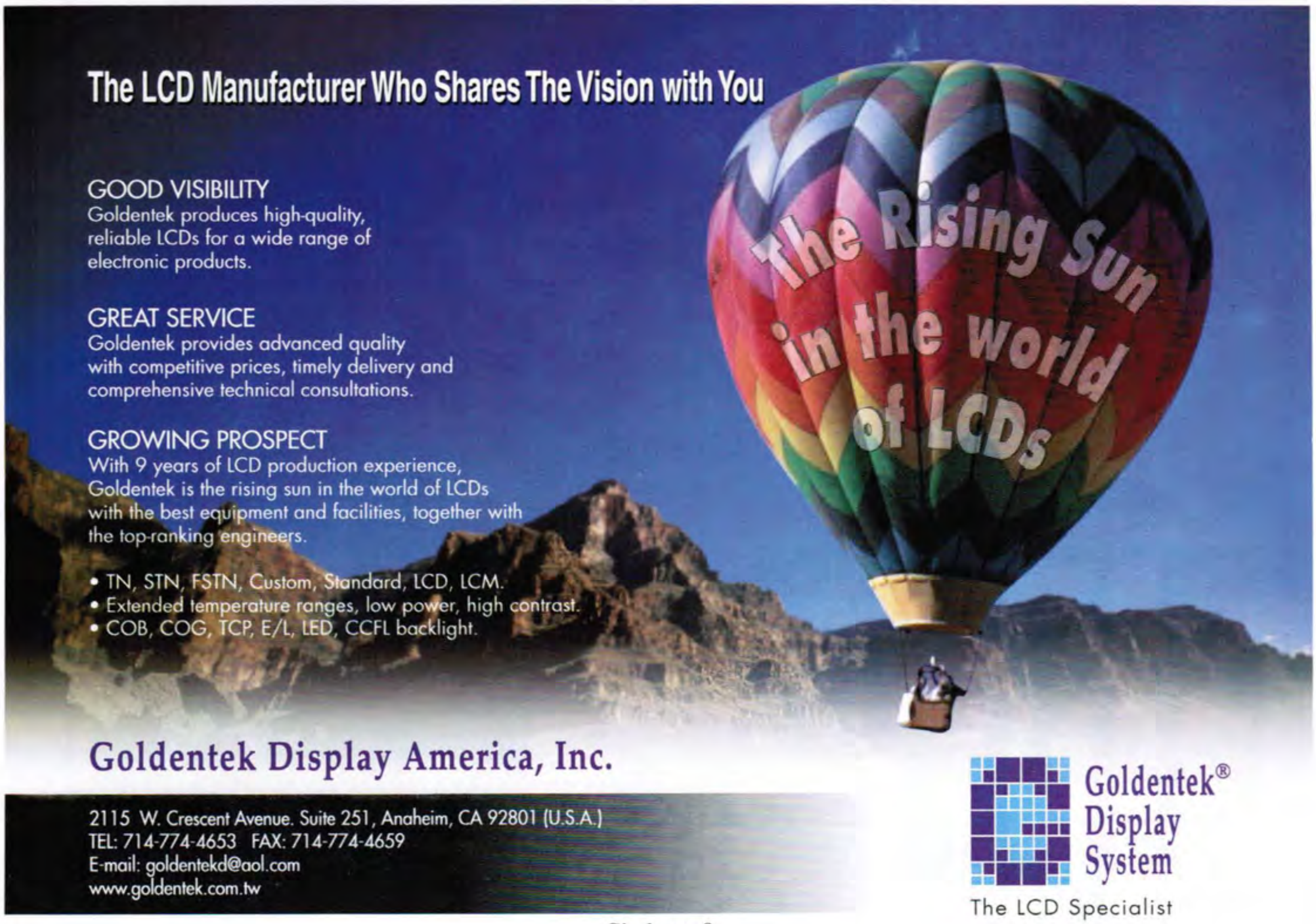

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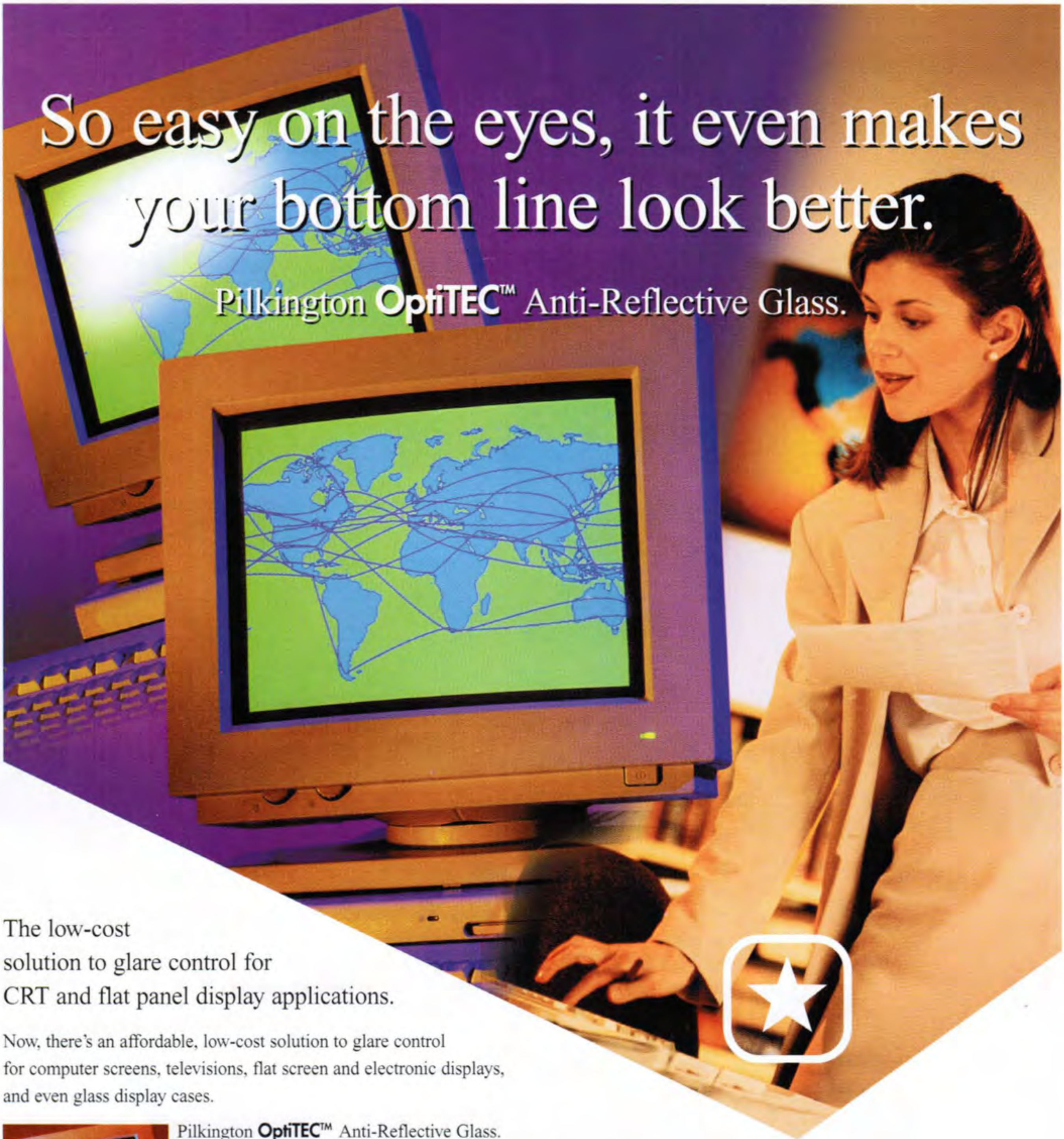

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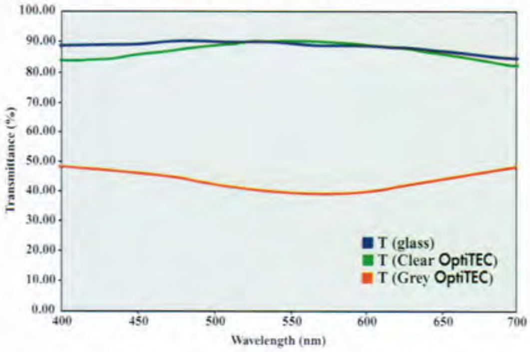
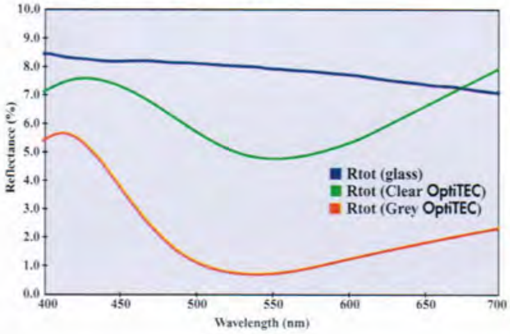
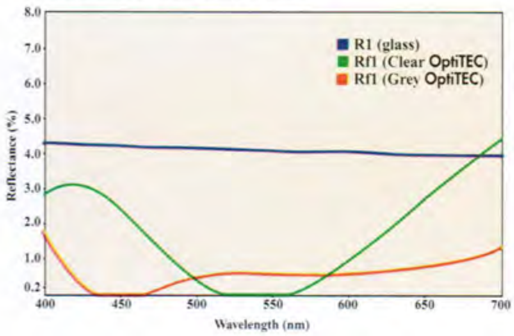
Transmission of OptiTEC Glass Compared to Clear Glass (3.2mm)



Total Reflectance of OptiTEC Glass Compared to Clear Glass (3.2mm)



Front Surface Reflectance of OptiTEC Glass Compared to Clear Glass (3.2mm)



Pilkington OptiTEC Anti-Reflective Glass Performance Data

Product	Total Reflectance	Total Transmittance	Sheet Resistance
	(%)	(%)	(ohms/square)
Clear OptiTEC	<5.3	89.5 +/– 1.0	<250
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Polymer-LED Matrix Displays

Light from plastic is setting the display world aglow, but as these PLED displays get larger, designers will have to use active matrices with multi-transistor pixel controllers.

by Mark T. Johnson and Aad Sempel

IN 1990, THE DISPLAY WORLD was surprised when a group at Cambridge University demonstrated the first light-emitting plastic device – the polymer light-emitting diode (poly-LED or PLED) had been born. The device consisted of a glass substrate and a thin sputtered layer of transparent ITO metal (the anode) with a thin layer of special plastic spun on top. It was finished by depositing a top metal layer (the cathode). When a current is passed through such a device from anode to cathode, the special polymer produces light (Fig. 1). At present, the polymers used are polyparaphenylenevinylene (PPV) compounds, which are conjugated polymers with semiconducting properties.

Several research groups, including an industrial group from Philips, soon recognized the potential of this technology to produce ultra-thin, flat, low-power, and lightweight displays with CRT-like performance that could challenge the liquid-crystal display (LCD) – the flat-display industry's benchmark. We are now several years further along, and Philips has its own pilot factory to produce poly-LED displays in Heerlen, in the south of The Netherlands. The factory is supported by a considerable team from Philips Research. The poly-LEDs have improved dramatically. All colors are now available (Fig. 2), efficiencies are extremely high, and lifetimes have improved by factors of 10 every year – and are currently in excess of 10,000 hours for some colors. In particular, the improvements in encapsulation layers (which now seal the device so thoroughly that water and oxygen molecule penetration is no longer a problem) and the use of current drivers for the matrix pixels have contributed to the longer lifetimes. In organic LEDs (OLEDs), which are related devices, Pioneer already has small matrix products for car radios on the market.

All this activity leads to expectations for even better display products: brighter, more colorful, and with higher resolution. In particular, we are looking forward to displays that are *bigger* than the 2-3-in. displays upon which the industry is now concentrating. But this expectation of larger size will be difficult

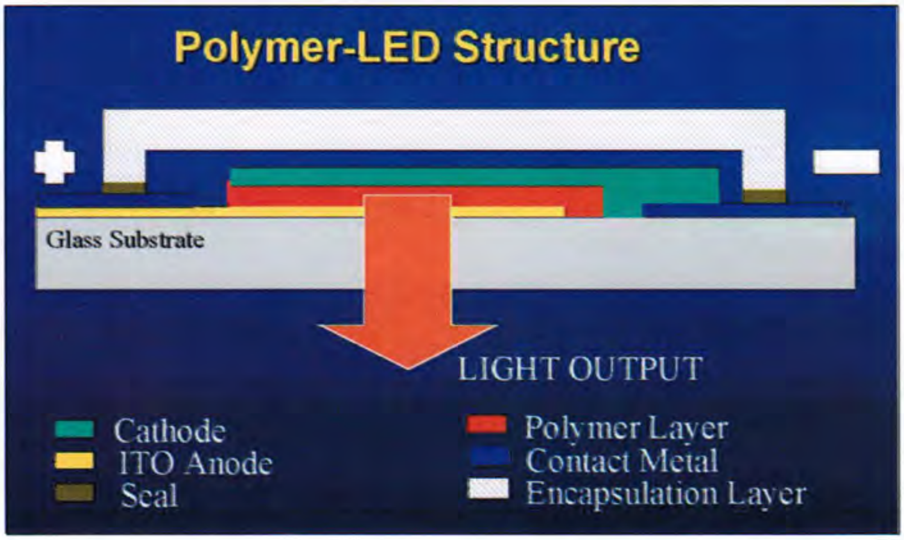

Fig. 1: *A polymer LED consists of a glass substrate, a thin sputtered layer of transparent ITO metal as the anode, and a thin layer of special plastic spun on top. It is finished by depositing a top metal layer as the cathode. When a current is passed through such a device from anode to cathode, the special polymer produces light.*

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Fig. 2: Poly-LEDs have improved dramatically. All colors are now available, efficiencies are extremely high, and lifetimes – currently in excess of 10,000 hours for some colors – have improved by factors of 10 each year.

to realize with the manufacturing technologies being developed today for both poly-LED and OLED devices. The problem in realizing *bigger* displays lies in the fact that the technologies being implemented use passive-matrix technology.

Passive-Matrix Poly-LED Displays

A passive-matrix poly-LED display consists of a matrix of transparent ITO columns upon which a thin layer of light-emitting polymer is spun. The display is completed with a structured metal cathode, which forms the rows [Fig. 3(a)]. The crossover of row and column forms the LED.

In a passive-matrix poly-LED display, the picture is built up in much the same manner as in a television tube: Each line of the picture is written sequentially and flashes very brightly for a very short time. This is achieved by holding all diodes in reverse bias other than the line being addressed, which is set to a lower voltage [Fig. 3(b)]. Due to the diode characteristic, it is possible to multiplex a poly-LED display as much as is desired without diminishing the image quality. By scanning the lines sufficiently quickly (to make up about 60 pictures per second), the eye will integrate all the light flashes into a nice picture, as occurs when we watch a traditional CRT-based TV (Fig. 4).

The problem with this method of building up a picture is that in order to obtain normal picture brightness, the light pulses have to be extremely bright because they are only present for a short time. In a 100-line display, for example, the light pulses will have to flash with a peak luminance that is 100 times the average luminance one actually perceives. As illustrated in Fig. 3(b), this means that high currents and voltages are needed for the light pulses, which in turn causes a great deal of power to be dissipated in the wires of the display. Since this power is not used to produce light, the display efficiency falls dramatically. This power dissipation will ultimately limit the extension of passive-matrix poly-LED technology to larger displays.

Power Dissipation

In a poly-LED display, there are three sources of power dissipation.

1. ***Light production***:
   $P_{light} = I_{LED} \times V_{LED}$
   This is a product of current and voltage in the LED, and it is reduced when the LED efficiency is increased.

2. ***Capacitive losses***:
   $P_{cap} = C \times V_{swing} \times V_{supply} \times freq.$
   This is the power required to charge up all the diode capacitances in the display, and can be reduced by limiting the volt

Table 1: Power Dissipation in Poly-LED Displays with Increasing Size and Resolution

Resolution column/row	Diagonal (in.)	P_{light} (mW)	P_{Cap} (mW)	P_{res} (mW)	P_{total} (mW)	Efficacy (lm/W)
80 × 60	1.2	15	10	1	26	5.3
160 × 120	2.4	80	110	10	200	2.8
320 × 240	5	400	1300	300	2000	1.1
640 × 840	10	2000	1800	8000	28000	0.3

Note. In each case the pixels are 300 × 300 μm, the luminance is 100 cd/m², and the luminous efficiency is 15 cd/A (typical for green-emitting poly-LEDs).

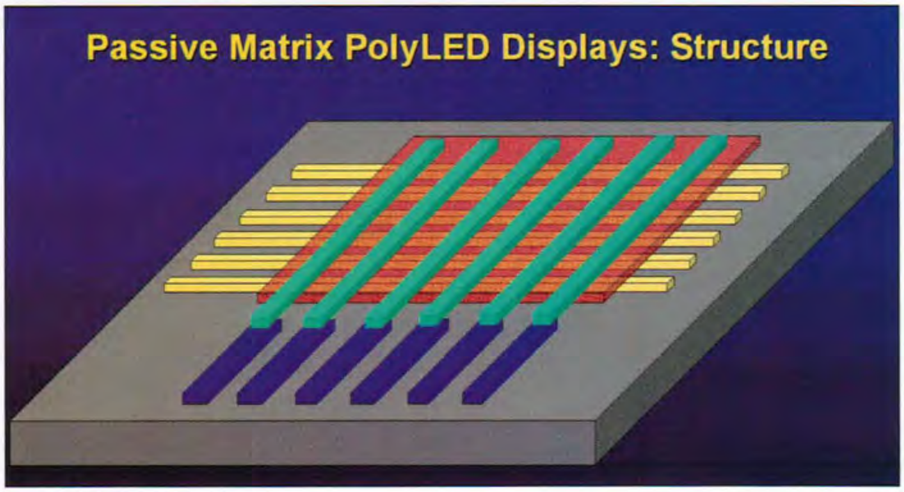

Fig. 3: A passive-matrix poly-LED display consists of a matrix of transparent ITO columns upon which a thin layer of light-emitting polymer is spun. The display is completed with a structured metal cathode, which forms the rows.

age swings and lowering the frequency - which can be done, for example, by reducing the frame frequency or multiplex rate.

3. *Resistive losses*:
   $P_{res} = I^2 \times R$
   This is the Joule heating in the rows and columns of the display, and can be reduced by decreasing the resistances of the metal lines.

Simulations show that when increasing the display area by a factor of four (*i.e.*, the diagonal is doubled), the power typically increases by a factor of 10, but we only obtain four times as much light. Although a 2-in.-diagonal passive-matrix poly-LED display for telephones may be more power efficient than a backlit LCD, an equivalent display with a 10-in. diagonal will be extremely inefficient (see Table 1).

Solving the Power Problem

There are various approaches to reducing the power dissipation in poly-LED matrix displays (see Table 2).

Increasing LED efficiency. By increasing the poly-LED efficiency, the currents required to produce a given light intensity and the driving voltages are reduced. These current and voltage reductions produce lower resistive and capacitive power dissipation, respectively. A doubling of the LED efficiency to 30 cd/A would roughly halve the power losses in both a 5- and a 10-in. display.

Lowering resistances of row and column metals. By decreasing the resistances of the lines in the display (by using thicker metals or back-up-metal technologies), the resistive power dissipation can be reduced. Decreasing resistances by a factor of 10 would reduce the power dissipation in a 10-in. display by 25%, but it would have little impact on a 5-in. display because the resistive losses are already small.

Adding more driver ICs. Splitting the display columns in two and driving the display from the top and bottom with extra column drivers is an extremely efficient method of reducing power dissipation. What we end up with is two sub-displays, each of which has only half of the multiplex rate of the initial display. Driving voltages are therefore reduced and the capacitance of the column is

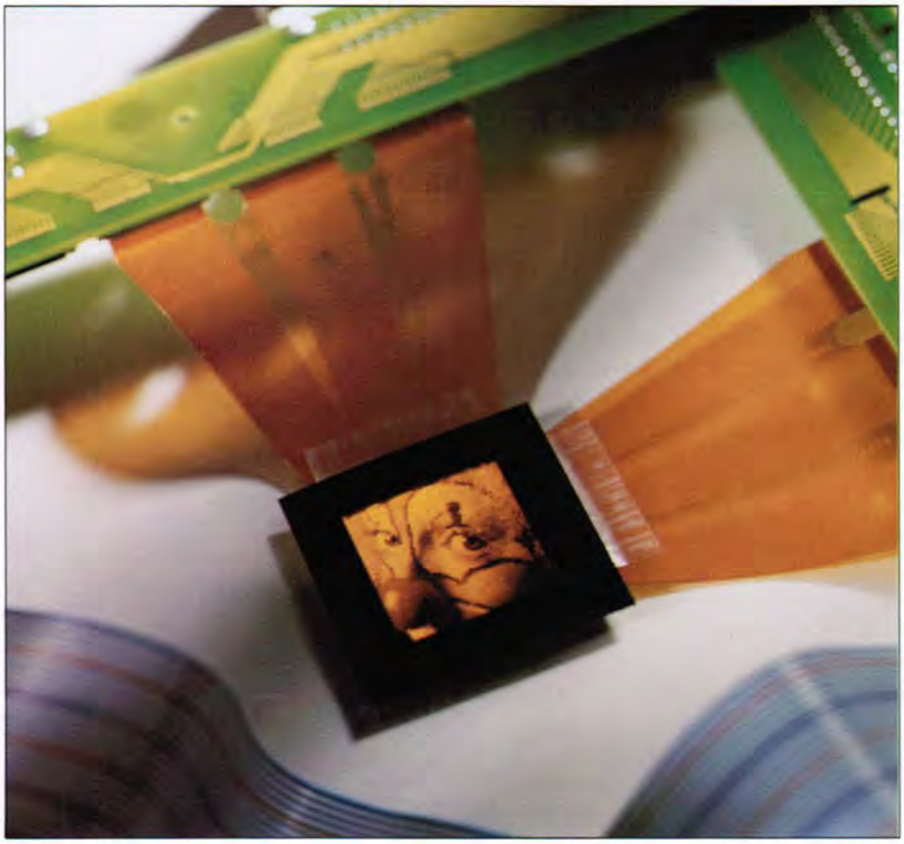

Fig. 4: The average luminance seen at each pixel site in a passive-matrix PLED results from a brief, bright "spike" of light combined with zero output for most of the frame period. The image in the photo, which has 256 gray levels, was built up in this way.

Table 2: Power Dissipation in Poly-LED Matrix Displays with Various Power-Saving Approaches

Display diagonal (in.)	Initial power dissipation	Double-efficiency Poly-LED	Lower-resistance lines	More driver ICs	Combined approach	Active-matrix poly-LED
5 in. 320 × 240	2 W	1.1 W	1.8 W	0.9 W	0.4 W	even lower power
10 in. 640 × 480	28 W	13 W	21 W	11 W	3.6 W	even lower power

Note. Initial power dissipation is taken from Table 1.

halved, as is the frequency. All of this leads to a large reduction in the capacitive dissipation. In addition, the column resistance is smaller, which lowers resistive losses. All this adds up to a 60% power savings in both the 10- and 5-in. displays.

Combining higher LED efficiency, lower resistance, and more driver ICs. The three independent approaches to lower power dissipation discussed above could be combined in a passive-matrix poly-LED panel. This will reduce the power dissipation of the 10-in. panel by nearly a factor of 10 (to 3.6 W) and that of the 5-in. panel by a factor of 5 (to 0.4 W).

Active-Matrix Poly-LED Displays

While several methods, including those mentioned above, may be adopted to reduce the power losses in passive-matrix poly-LED displays, there will come a point at which the step to a bigger display becomes impractical. At that point, it will be necessary to move away from the line-at-a-time pulsed light emission of the passive matrix to a technique in which all of the display emits light continuously, as is the case in an LCD. The logical step will be to shift from a passive-matrix to an active-matrix technology.

In active-matrix poly-LED displays, some extra electronic circuits are added to the glass substrate (Fig. 5). The active-matrix poly-LED consists of a CMOS polysilicon TFT array fabricated on a glass substrate using technologies similar to that used in the manufacture of AMLCDs. The poly-LED display is built up on this substrate using the usual spinning and evaporation steps.

As in AMLCDs, the polysilicon active matrix defines the pixels with structured ITO, whereby extremely high resolutions and good pixel brightness are possible. In addition, the pixel circuitry must perform two functions. It must provide a controlled current source to drive the poly-LED and also provide some storage to enable the pixel to continue providing current after the addressing period. Because the pixel emits continuously, peak drive currents are reduced, as are the associated voltage drops along the rows and columns. This means that large active-matrix polymer-LED (AMPLED) displays can be made with much lower power losses than the normal passive-matrix PLED displays. The route to large and extremely large AMPLED displays is now open.

The basic circuit that performs the functions just described is the two-transistor circuit introduced by Kodak (Fig. 5). This circuit uses individual transistor characteristics to convert a signal voltage to a current, and also to draw current during the addressing period. The pixel design produces a display that suffers from artifacts resulting from information-dependant horizontal crosstalk and non-uniform transistor characteristics.

A three-transistor pixel design enables the signal voltage to be applied to the gate of the driving transistor while it simultaneously blocks the current path of the poly-LED. This pixel circuit - introduced by Philips at the International Display Workshops in Sendai, Japan, in 1999 - reduces horizontal crosstalk. The consortium based around Sarnoff, Kodak, and Planar has proposed pixel circuits consisting of four or more TFTs, which should lead to even more uniform active-matrix displays.

At recent display conferences and electronics shows, there has been a run of AMPLED and active-matrix OLED demonstrators. Seiko-Epson, together with Cambridge Display Technology, is already demonstrating active-matrix displays with very high resolution, and is pushing towards a full-color AMPLED display. At the recent Japanese Electronics Show (October 1999), Sanyo demonstrated a full-color active-matrix telephone display based upon OLED technology. Although these first displays are rather small, they have enabled us to establish the principles of active-matrix driving that will be required in large PLED displays.■

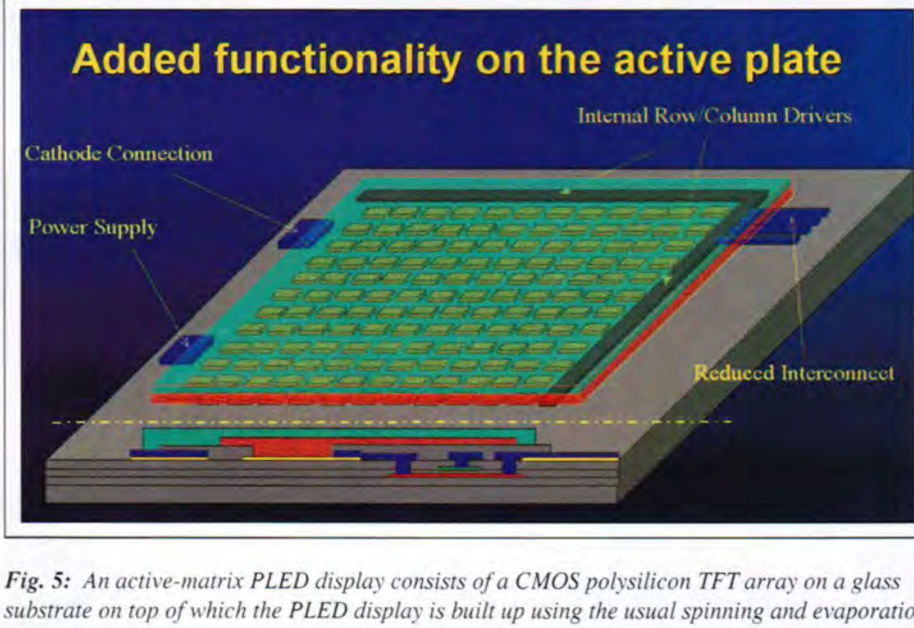

Fig. 5: An active-matrix PLED display consists of a CMOS polysilicon TFT array on a glass substrate on top of which the PLED display is built up using the usual spinning and evaporation steps. There is also the potential for adding functionality to the active plate, as is being done today with polysilicon LCDs.

Solid-State Lasers for Projection Displays

High-performance solid-state lasers can be used to make excellent projection displays that are compact and - eventually - inexpensive.

by Eric B. Takeuchi, Robert Bergstedt, and David E. Hargis

THE IDEAL DISPLAY has a bright and uniform image, is responsive enough to show full-motion images, and has stable color so that different shades can be produced reliably, yet is still compact, lightweight, and efficient. Most display technologies fall short in one or more of these categories, but a new form of laser can produce a pure light that may become part of displays that meet all these requirements.

Major television manufacturers - including RCA, Zenith, Hitachi, and NHK - have been developing laser displays since the late 1960s. One of the major barriers to creating viable products has been the lack of red, green, and blue lasers that can be mass-produced at low cost.

Argon-ion gas lasers were used for the blue and green wavelengths, while krypton-ion gas lasers or argon-ion-laser-pumped liquid-dye lasers were used for the red wavelength. These lasers typically have a low electrical-to-optical conversion efficiency of ~0.1%, which leads to significant heating inside the laser. In order to remove the excessive heat from the system, water cooling is required along with the associated - and cumbersome - closed-loop chillers. The low efficiency and low optical gain of gas lasers also require cavity lengths approaching 1 m, giving rise to very large overall package sizes. Finally, the cost of these lasers to date has been high, with no clear path for significant cost reduction, even in high-volume production. As a consequence, the lack of suitable visible lasers has severely limited the acceptance of laser displays in the broad marketplace.

Visible solid-state lasers have also been used for laser displays. One type of solid-state laser uses a broadband lamp to pump the solid-state gain medium. Using conventional intracavity frequency-doubling techniques, continuous-wave (cw) Nd:YAG lasers operating at 532 nm have been developed with higher conversion efficiencies than gas or liquid lasers. However, because of the optical inefficiencies associated with broadband pump sources, water cooling still remains necessary. In addition, solid-state lasers with

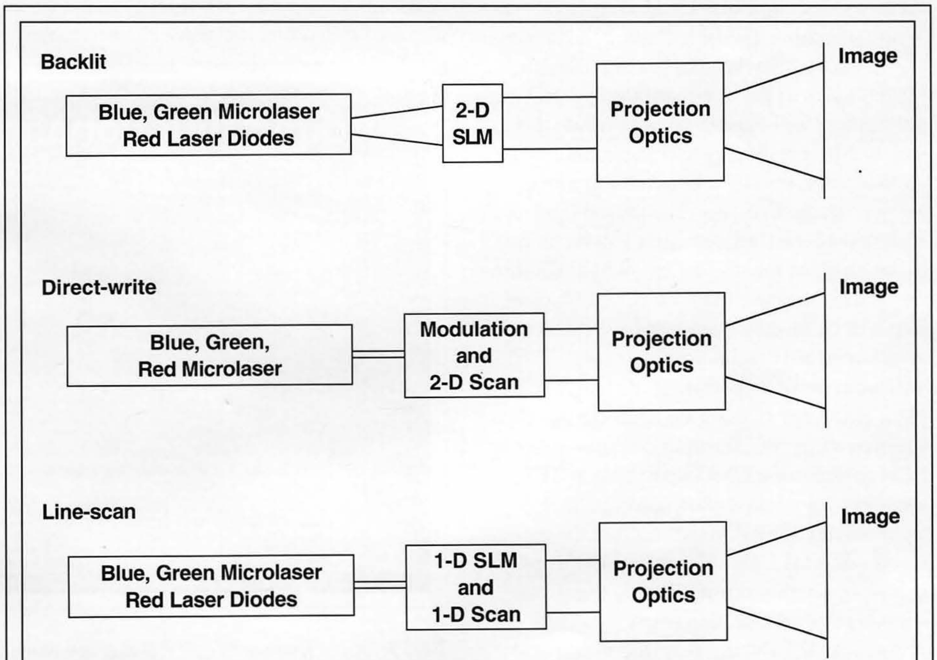

Fig. 1: *Three different approaches are under development for laser-display architectures.*

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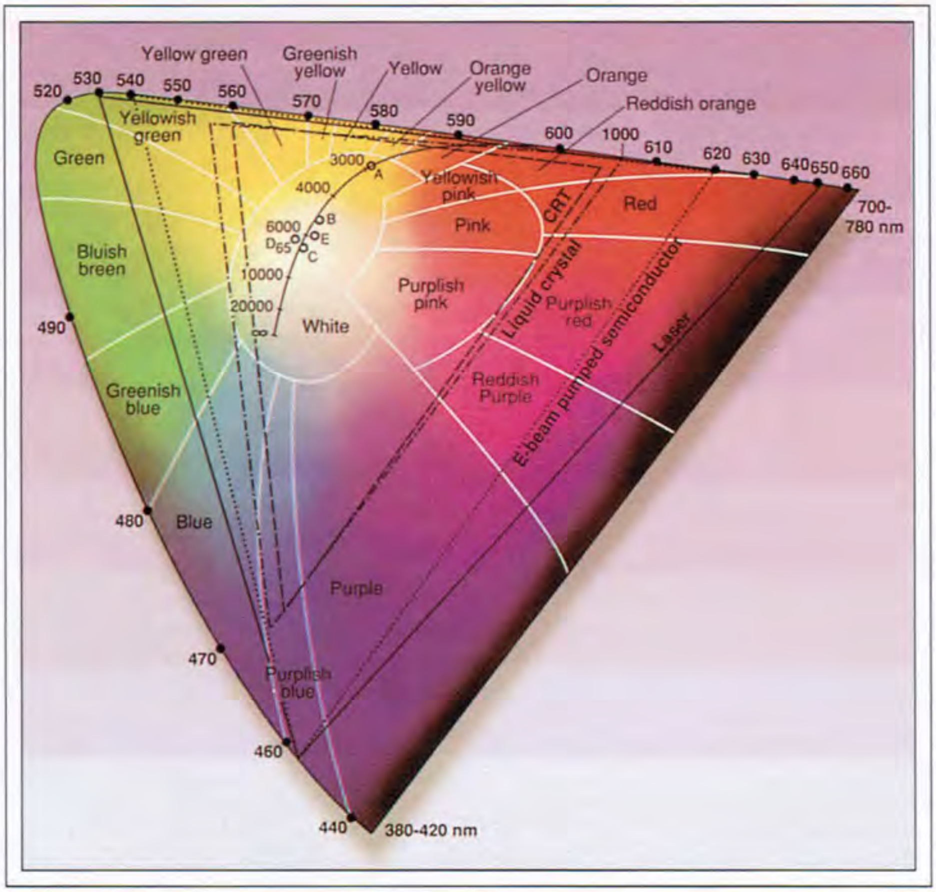

Fig. 2: Comparing the color gamuts of different display technologies demonstrates the advantages of color microlasers.

emission in the blue and red have been difficult to achieve.

To overcome this difficulty, Q-switched or mode-locked solid-state lasers have been used that allow for efficient extracavity nonlinear processes because of the high peak power of the pulses. Unfortunately, the pulsed laser light limits the type of display architecture that can be used, and gives rise to eye-safety considerations. In addition, because of the complexity and number of optical components required to realize pulsed solid-state lasers, these systems have much higher manufacturing costs than their cw counterparts.

In an attempt to solve many of the problems associated with lamp-pumped lasers in display systems, diode-laser-pumped solid-state lasers have been developed in both pulsed and cw configurations. Diode-pumped cw systems operating in the green are now commercially available. Although high electrical-to-optical efficiencies have been achieved at high optical output power levels, most of the current designs and manufacturing techniques are not amenable to the low-cost high-volume production that is required for commercial displays. Despite a great deal of ongoing research focused on watt-class diode-pumped solid-state lasers operating at blue and red wavelengths, only one product is commercially available.

A new approach is creating excitement in the laser field: direct-emitting visible semiconductor-diode lasers. High-efficiency high-power multi-mode broad-stripe AlGaInP red-diode lasers are commercially available, with the potential to meet the display cost targets in high volumes. Diode lasers at shorter wavelengths are just now becoming available. Semiconductor-diode lasers based upon InGaN active layers are now commercially available with 5-mW output at ~410 nm. However, most of this effort is currently focused on optical-storage applications at short wavelengths. This family of devices has been demonstrated with very limited power levels at wavelengths in the blue and green – ~450–550 nm – that would be usable for display applications.

Diode lasers called master-oscillator power amplifiers (MOPAs) have been demonstrated with near-diffraction-limited beam quality. Unfortunately, these lasers do not appear to be amenable to long lifetime or low-cost production, thus eliminating them as immediate candidates for displays.

Over the past several years, we have been developing miniature red-, green-, and blue-diode laser-pumped solid-state lasers, termed microlasers. Our microlasers use low-cost long-lifetime conventional near-IR AlGaAs semiconductor lasers as pump sources for rare-earth ion-doped crystals. Intracavity nonlinear processing is used to create visible wavelengths. The proper selection of the laser crystal, nonlinear crystal, and thin-film coatings can produce a variety of visible wavelengths. These lasers typically have very high electrical-to-optical efficiencies in the 1–5% range, eliminating the need for water cooling. Air-cooled microlasers have been made small enough so that compact, portable laser displays are now possible. In addition, the microlasers can probably be produced at relatively low cost in high volumes.

Laser-Display Overview

We have been pursuing three basic approaches to microlaser-based displays (Fig. 1). The first approach is termed "backlit," which uses the microlasers as a light source for illuminating conventional two-dimensional spatial light modulators (SLMs) such as liquid-crystal displays (LCDs) or digital micromirror devices (DMDs). With this approach, the lasers simply replace the metal-halide or xenon arc lamps used as illumination sources in conventional LCD or DMD projectors. The second approach is a direct-write laser display system wherein the microlaser beams are rapidly scanned/modulated to form the two-dimensional image and directly form the pixels on the screen.

A third approach we have developed is a hybrid of the backlit and direct-write configurations employing an array of microlaser beamlets, the number of which corresponds to the number of pixels in a single dimension in the display. The array is then modulated and scanned in the orthogonal dimension to create

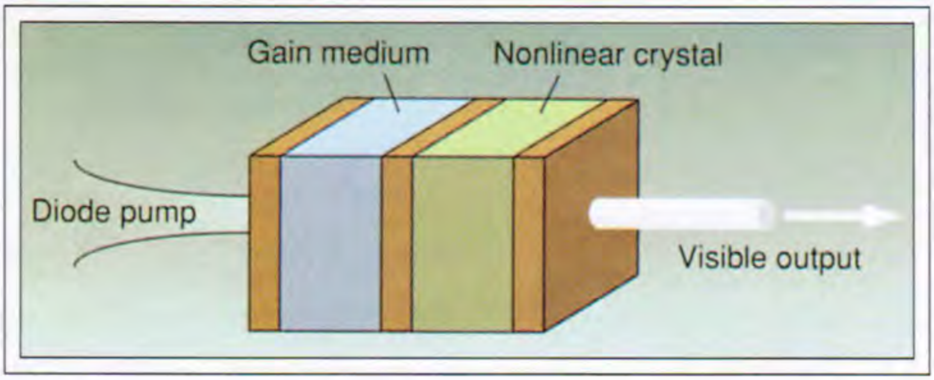

Fig. 3: *This schematic diagram of a diode-laser-pumped visible microlaser shows how two crystals are used to produce visible light.*

the entire image. This reduces the total number of pixel elements required in the SLM in the backlit geometry while reducing the total bandwidth requirement of the single-beam direct-write approach.

Microlaser properties result in important advantages for displays: long lifetime (low maintenance), ruggedness, high luminance, large color gamut, color accuracy, image uniformity, high resolution, and large depth of focus. These advantages make them attractive for display applications such as military/commercial cockpit displays, helmet-mounted displays (HMDs) and head-up displays (HUDs), simulators, command-and-control centers, video walls, high-end CAD/graphics design workstation monitors, and longer-term applications such as electronic cinema.

Both high-luminance CRT-based and arc-lamp-based displays have limited lifetimes between a few hundred and a few thousand hours. This leads to reliability issues and significant maintenance costs in high-use applications. The expected lifetimes of the microlasers are approximately 10,000–20,000 hours, limited only by the lifetime of the diode-laser pump sources, which is increasing dramatically with improvements in the technology. Microlaser lifetimes will significantly reduce the display maintenance costs associated with arc-lamp replacement and CRT maintenance.

Arc lamps emit over a broad spectrum, making them inefficient in producing the narrow bands of red, green, and blue light that are required for a full-color display. Although some effort has been directed toward tailoring the spectra of arc lamps, the fundamental inefficiencies of broadband emission still remain. The broadband spectral content of conventional arc lamps results in colors that are not saturated and a small color gamut. If color filters are used to isolate the desired wavelengths, a significant fraction of the light is absorbed (or reflected) and optical efficiency is further impaired. The UV and IR filters necessary to reject undesirable radiation also reduce the visible light available. The spectral content also shifts over time; the color temperature shifts as the arc lamp degrades, causing a change in the apparent colors of the images.

For some military display applications – such as those used in tactical aircraft – the flight dynamics associated with the airborne platform produce spatio-temporal gradients in the position of the arc itself. This increases differences in brightness in the display, and this non-uniformity can have a significant impact on the effectiveness of the display.

Laser-based displays designed with the proper primary wavelengths produce a very large color gamut with a fixed color temperature. We have developed polarized microlasers with outputs at wavelengths of 457, 532, and 656 nm. These wavelengths yield an exceedingly large color gamut, creating a display technology that encompasses nearly the entire color range of the human visual system (Fig. 2). The color becomes deeper or more saturated in the areas close to the edges of the diagram. Thus, as shown, a microlaser-based display can provide greater color saturation in all three primaries than is produced by conventional technologies. Due to the inherent monochromatic nature of laser light, color filters are not required, so no light is lost. In addition, the primary wavelengths do not shift with time, so as long as the relative RGB amplitudes from each laser are maintained the color temperature remains fixed.

Arc lamps emit unpolarized light in many directions, which makes it difficult to couple the light efficiently onto small SLMs – such as DMDs and LCDs – that have finite angular acceptance. As the power of an arc lamp increases, the arc length also increases, making the coupling task ever more difficult. As SLMs become smaller with higher resolution, it becomes more difficult to attain good contrast and good illumination efficiency with arc lamps.

Table 1: Summary of RGB Microlaser Characteristics

	Blue	Green	Red
Wavelength	457 nm	532 nm	656 nm
Maximum cw output Power to date	1.5 W	5.4 W	1.6 W
Typical output power	0.50 W	3.0 W	1.0 W
Laser head size	1 × 1 × 4.5 in.		
Noise (10 Hz to 1 MHz)	<3% peak	<3% peak	50% peak @ 100s of kHz
Beam radius	0.08 mm	0.150 mm	0.31 mm
Beam divergence (half angle)	4.4 mrad	6.3 mrad	3.0 mrad
Beam product	0.35 mm-mrad	0.94 mm-mrad	0.93 mm-mrad
Electrical power consumption (including cooling)	30–100 W		

Laser sources, on the other hand, can be remotely coupled to a miniature high-resolution SLM through an optical fiber, an approach that has been investigated for cockpit display applications such as tactical HMDs and HUDs. One important advantage of this arrangement is that the light sources can be at a distance from the display, something that cannot be achieved efficiently with arc-lamp sources. As a result, the complete system has reduced power consumption, size, complexity, and (ultimately) cost. In addition, because of the high spatial coherence of lasers, a very large depth of focus is achieved with excellent image uniformity. The output linear polarization of microlasers also eliminates the requirement for the complicated optical schemes to split and recombine light from an arc lamp for illumination of polarization-sensitive SLMs.

Fig. 4: A prototype air-cooled laser-illuminated portable LCD projector is fully self-contained and has dimensions of 15 × 15.5 × 8.5 in.

Colorimetry and Laser Requirements

The laser requirements for any specific display application are strongly dependent on the type of architecture employed. A study performed on the human eye's spectral response relative to multicolor display systems concluded that the wavelengths for optimum luminous efficiency for the three primaries of a display are 610 nm (red), 530 nm (green), and 450 nm (blue) (Fig. 3). This combination maximizes the visual response per watt of input light power. Fortuitously, we have developed efficient microlaser sources that are very close to two of these wavelengths - 457 nm in the blue and 532 nm in the green - but work remains to be done on the development suitable red lasers.

Table 2: Performance Specification of the Laser-Illuminated LCD Projector

AMLCD panel	1.3-in. diagonal
Pixel resolution	1280 × 1024
Source lifetime	>10,000 hours
Projection distance	Not limited with different projection lenses.
Image size	2-10-ft. diagonal demonstrated (larger range with different projection lenses)
Luminous output	>500 ANSI lm
Uniformity	±1.5% across image field
Image distortion	keystone corrected
Contrast ratio	>100:1
Dimensions	15 × 15.5 × 8.5 in.
Audible noise	<45 dBA

We have performed some work with red microlasers emitting at 625-635 nm, but most of the development work in the red has focused on microlasers emitting at 656 nm and red-emitting AlGaInP diode lasers at ~650 nm. One problem with these lasers is that they require more power. Both require significantly more power than the green and blue microlasers to produce a D_{65} white. The ideal red wavelength - which optimizes color gamut and required optical power - is at approximately 625-635 nm. Recently, high-power red semiconductor diode lasers in the 635-645-nm range have become available. Although the color gamut is reduced slightly, the eye is much more responsive at this wavelength, and the power level required for achieving a brightness equivalent to a 656-nm source is reduced by a factor of about 4.

As an example, a 1000-lm D_{65} white image requires optical power of 0.9 W at 457 nm, 1.2 W at 532 nm, and 4.2 W at 656 nm. If a laser emitting at 630 nm is used, the red power requirement drops to 1.4 W. Note that these power levels are required on the screen; the actual power levels required from the lasers are a function of the optical efficiency of the projector.

Microlasers: Concept and Characteristics

The red, green, and blue microlasers under development employ well-developed near-IR diode-laser technology as a pump source for rare-earth ion-doped solid-state microlasers. This facilitates the conversion of broadband non-diffraction-limited near-IR diode emission into coherent narrowband near-diffraction-limited visible light. We are actively pursuing several novel approaches for obtaining RGB microlaser emission. To date, we have demonstrated visible microlaser operation at 670, 660, 656, 635, 628, 594, 532, 473, 457, 454, and 451 nm.

The technique employed to generate visible light from a microlaser is based upon intracavity frequency doubling of the near-IR laser emission of a diode-pumped Nd^{3+}-ion-doped crystal (Fig. 4). The microlaser consists of two crystals: an Nd^{3+}-ion-doped gain medium and a nonlinear medium. Dielectric coatings are used to define the linear Fabry-Perot cavity, and are often deposited directly upon the surfaces of the crystals. The diode-laser output is tuned to the ~800-nm absorption transition of Nd^{3+}, causing fundamental laser action to occur at approximately 1313, 1064, and

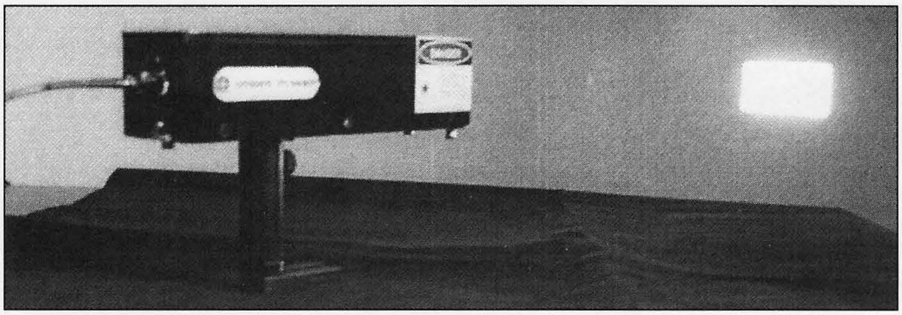

Fig. 5: This white-light laser source is fiber-coupled with a beamshaping integrated package and suitable for a wide range of display applications.

914 nm. Intracavity frequency doubling of this fundamental radiation is achieved with an appropriate nonlinear crystal, which generates visible light at approximately 656, 532, and 457 nm.

It should be noted that from the inception of our development effort, the red-, green-, and blue-microlaser sources have been geared toward designs that are ultimately amenable to low-cost mass production. As such, every aspect of the microlasers has been tailored for the maximum possible benefit relative to a compact display system. The RGB microlasers have been designed into extremely compact packaging. AlGaAs diode-laser arrays with a nominal output power of 10 W are used. The diode array, microlaser crystals, and integral thermoelectric coolers are contained in a complete laser-head package size of 1 × 1 × 4.5 in. This package is mounted onto an air-cooled heat sink. The size of the heat sink is a function of the maximum ambient temperature and the required operating temperature of the diode laser. Typically, for display applications multiple microlaser packages are mounted onto a common heat sink.

The beams from multiple microlasers can easily be combined to achieve any desired brightness, which provides an additional advantage over lamps. The nominal electrical drive power required by a microlaser package - including cooling - varies between 30 and 100 W, depending upon the ambient temperature.

To date, 1.5 W from a blue microlaser operating at 457 nm has been demonstrated. To the authors' knowledge, this power level is the highest average power for an all-solid-state cw blue laser ever reported. Additionally, 5.4 W from green (532 nm) and 1.6 W from red (656 nm) microlaser sources have been demonstrated.

The mode size, beam divergence, and amplitude noise have been measured for the RGB microlasers (see Table 1). The blue and green microlasers are very close to meeting all of the specifications for both backlit and direct-write displays. However, because of the high power requirement at 656 nm, the red microlaser falls short of the required power levels. Microlasers at this wavelength will require further development work and power scaling to enable before they can be used in high-luminance display systems. High-power red-diode lasers have now been developed, and they could be used as an alternative to red microlasers in backlit display configurations.

The differences in the peak output power and the power levels typically achieved can be attributed to the performances of key system components. Slight variations in crystal quality, surface finish, and thin-film-coating characteristics can lead to variations in output power from device to device. We are currently working on the manufacturing technologies required to eliminate these variations. We believe that the ultimate lifetime of the microlasers will be limited by the near-IR diode-laser pump sources - AlGaAs diode-laser devices that have measured lifetimes of ~10,000–20,000 hours. The fundamental degradation mechanism has been shown to be due to the Al site in the lattice. Recent breakthroughs in Al-free diode lasers show promise for lifetimes approaching many tens of thousands of hours.

Prototype LCD Projector

Together with Proxima Corporation, we have developed and fabricated a microlaser-based LCD-projector prototype (Fig. 4). The design goal for the joint development project was to develop a projector configuration that resembled existing lamp-based desktop projectors in size, weight, and electrical power consumption, while providing the long lifetime, high resolution, image uniformity, large color gamut, and color accuracy that can be had with lasers. The backlit LCD configuration was selected because appropriate green and blue microlasers, along with high-power red-diode lasers, were ready for commercialization. Several SLM technologies were evaluated, including transmissive polysilicon LCDs and DMDs. However, only reflective active-matrix LCD (AMLCD) devices could provide high throughput efficiency and full video frame rates at pixel dimensions of 1280 × 1024.

The projector prototype contained a single green-microlaser module, three blue modules, and an array of red-diode lasers to produce the requisite power for the 500-lm projector: 1.35 W at 457 nm, 1.53 W at 532 nm, and 4.65 W at 650 nm, with a total optical-system throughput efficiency of approximately 33%. Additionally, the air-cooled projector prototype was fully self-contained, including all power supplies, modulation electronics, and standard RGB computer interface, so that the projector could be used with a Windows-based PC, VCR, or videodisc player. The projector was capable of producing acceptable full-color images at a maximum luminous output of ~700 lm. With precise D_{65} color balancing, the output was closer to 500 lm (see Table 2). The image also displayed a relatively large depth of focus as compared to lamp-based LCD projectors. This first prototype used inefficient off-the-shelf power supplies and electronics, and therefore was much larger and heavier than if customized components had been used.

Cockpit Display Module

The long lifetime (reliability), ruggedness, and high luminance of microlasers make them attractive for high-performance display applications such as those for military and commercial aircraft. Supported by the U.S. Air Force Research Labs, we have begun development of a laser illumination module employing our green microlaser with red-semiconductor-diode lasers as a high-luminance source for illuminating a subtractive-color AMLCD assembly to be used for target/

symbol display in tactical HMD applications. In general, this type of configuration can provide a common light engine to be used for illuminating any of a number of displays in the cockpit. The output after the beam-shaping optics at the end of the fiber was approximately 24,000,000 cd/m^2. Further optimization of the optical coupling and diffusion angle should yield increased luminance.

A full-color RGB laser light engine can provide a white-light laser source suitable for illuminating full-color instrumentation displays within the cockpit, as well as enabling commercial applications such as projection displays and laser light shows (Fig. 5). At the output end of the optical fiber, appropriate beam-shaping and speckle-elimination optics are integrated to provide a uniform speckle-free light source for backlighting a variety of display platforms. Further engineering development of these types of systems could lead to full-color laser illuminator systems of substantially reduced volume.

Microlasers have attributes that make them ideally suited for a wide range of display applications. Whether it is by direct illumination of reflective LCD panels or remotely coupled applications using fiber optics, these light sources promise advantages in light output, efficiency, weight, lifetime, and cost over other technologies. As further improvements are made in the efficiency and wavelength of these tiny light sources, microlasers may find their way into a wide range of displays for military, commercial, and consumer products.■

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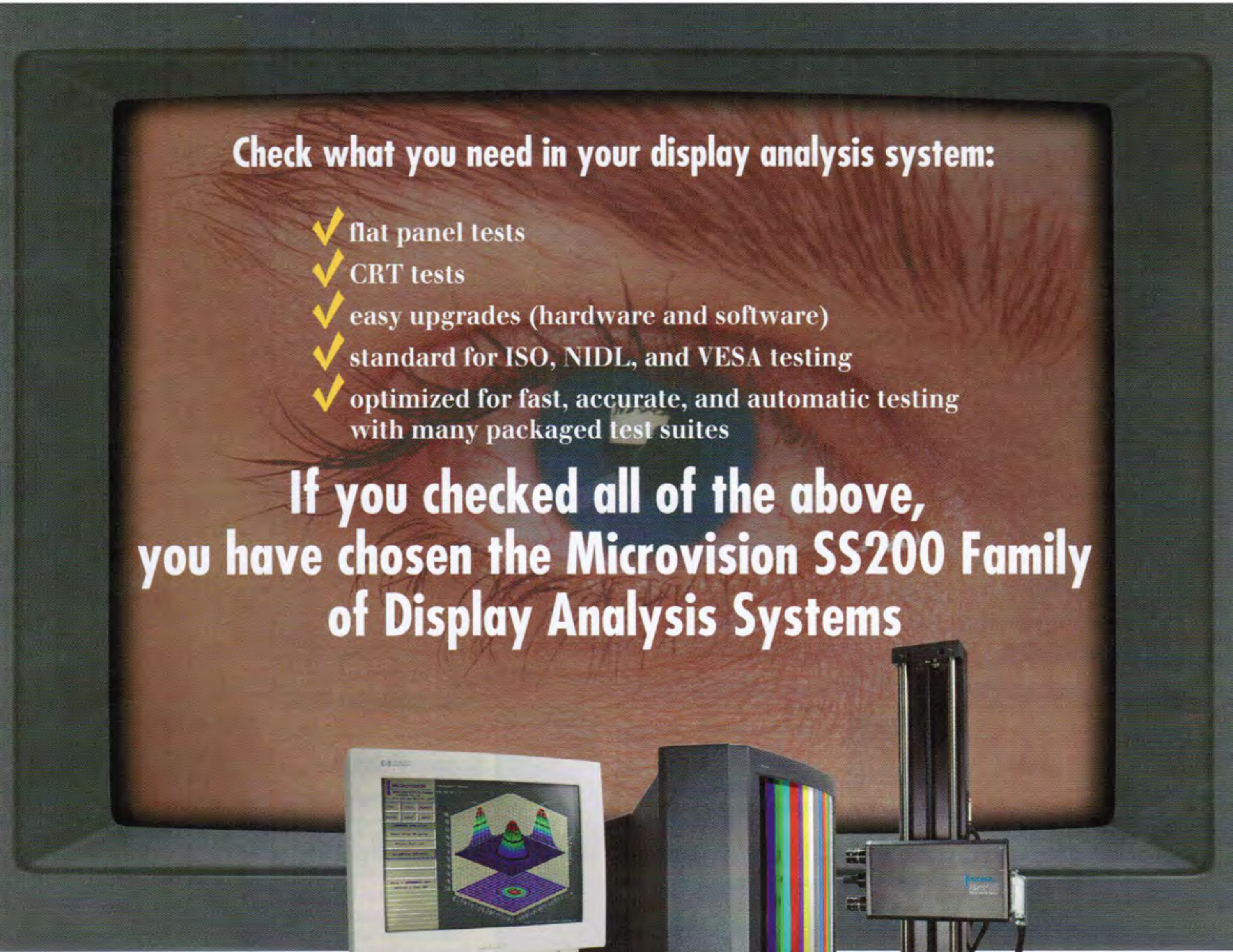

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Reflective Color Liquid-Crystal Displays

A wide range of portable electronic products will benefit from the low power consumption and light weight of high-resolution reflective color LCDs – but brightness, color saturation, and contrast ratio still need to improve.

by Yoichi Taira

THE MOST COMMON liquid-crystal displays (LCDs) are reflective. Examples can be seen in watches and calculators, which demonstrate the ability of liquid crystals to display crisp images with very low power consumption. Are reflective displays used in more sophisticated LCDs as well? In general, the answer to this is no. Today, the most common flat-panel LCDs in higher-resolution applications are backlit, not reflective. The main drawback of reflective displays is that their performance is not high enough for these more sophisticated applications.

Various types of reflective display technologies are available. Let's look at these technologies so we can improve our understanding of the goals that designers and product planners have for reflective displays, as well as improve our understanding of the current status and remaining shortcomings of these technologies. Finally, what can we expect of reflective displays in the future?

Why Reflectives?

The key performance factors of reflective displays are (1) power consumption, (2) reflectivity, and (3) contrast ratio. Direct-view reflective displays are considered to be among the most important candidates for future-generation displays. Although current backlit LCDs can display crisp and flicker-free images without much driving power, there is still room for improvement in their power consumption and user friendliness. More than half the power of these LCDs is consumed in the display illumination. In a 12.1-in.-diagonal LCD, for example, 3 W are used for the backlight and 2 W are used for driving the LC panel. This high backlight power is required because less than 10% of the backlight illumination goes through the LC pixels. We could expect the total display power to be reduced by 60% by using a non-backlit system, which would allow high-information-content displays to be used in a wider variety of applications.

In addition to low power consumption, another important advantage of reflective displays is their paper-like appearance. Unlike the luminance of a self-emitting display - which is fixed regardless of the environment or illumination conditions - the luminance of a reflective display is always determined by the environment. This often results in better eye adaptation and a faster reading speed, with less eye strain. The key features of a paper-like display are a reasonably high resolution [such as 300 dpi for a two-level (black-and-white) display], a reflectivity close to that of a sheet of paper, and a contrast ratio (CR) better than 10:1. If the display has gray-level capability, the pixel density can be less, *i.e.*, 150 dpi.

Reflective displays could be useful in both portable and desktop applications, but it is not

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Fig. 1: *A double-layer guest-host (DGH) LCD can have a contrast ratio as high as 15:1 and a reflectivity of as much as 60%. This early DGH prototype had not yet realized such high performance levels.*

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easy to realize a color reflective display with satisfactory performance. This is because the theoretical maximum transmission of an ordinary color LC pixel using an ideal color filter is only one-sixth; the polarizer absorbs half of the light and the color filters absorb two-thirds of what remains. To realize higher reflectivity, it would be better not to use a polarizer or color filters, but there are trade-offs with other factors such as contrast ratio and drivability.

In order to meet the key performance factors, we have to consider techniques for realizing (a) an optical switch or transducer having two level states - on and off - or gray-level capability, (b) enhanced usage of the illuminating light, (c) presentation of color, and (d) low power consumption.

Reflective Pixels

There are three basic ways of enabling the transducer function: controlling (1) the polarization state, (2) the absorption, or (3) the reflection and/or scattering. However, the situation is a little more complicated than it would appear from this simple statement because a given transducer often changes two parameters at the same time. The amount of the change is often dependent on the wavelength and the direction of the light ray. Complicating the situation still further, the transducer function must be driven electrically with a reasonable set of driving conditions. There are many possible ways of realizing such functions (see Table 1).

Liquid-crystal technology is the most common choice. It is capable of controlling the polarization state, the absorption, *and* reflection/scattering, but the most successful scheme for the transducer to date has been to control the reflectivity by changing the polarization.

All of the candidate reflective techniques are improving and have some advantages over the other techniques. If a technology with far superior performance is developed, the choice will evolve naturally. The most common reflective method today - which uses a polarizer and color filters - has been determined mainly by its process compatibility with existing display-fabrication facilities. One can simply use existing TFT and color-filter fabrication facilities to make a side-by-side subpixel structure. The use of a good subpixel reflection-enhancement method, described in the following section, is the key to good performance with this approach.

Table 1: Technology Candidates Useful for Reflective Pixels

Transducer system	Main principle	Wavelength dependence	Remark
TN	Polarization change	Achromatic	Normally black (NB) or Normally white (NW)
ECB mode	Polarization change	Dependent	Limited color or gray level
Birefringent mode	Polarization change	Achromatic	OCB, VA, FLC
Guest host	Absorption	Dye dependent	TN effect also exists.
PSCT (planar-focalconic)	Reflection	Dependent	Bistable, reflecting only one circular polarization
PSCT (focalconic-homeotropic)	Scattering	Achromatic	Higher voltage
PDLC	Scattering	Achromatic	
Holographic PDLC	Reflection	Strongly dependent	Volume hologram
Electrophoresis (EP)	Absorption	Monochrome	Black or scattering white
Reverse-mode EP	Absorption	Particle dependent	Clear or absorbing
Magnetophoresis	Absorption	b/w	Mechanical writing head
Micromechanical devices	Absorption/ interference/ scattering	Structure dependent	Many varieties

In these polarizer/color-filter displays, the reflective twisted-nematic (TN) mode is used to reduce the effective birefringence. This is done because the optical retardation of the LC layer is too large with typical LC-cell thicknesses (typically on the order of 5 μm) when a homogeneous alignment is used.[1] The TN material can be used in either a low-twist or high-twist configuration.[2] It is important that the TN - or any other polarization-changing technique - provide a good CR.

If a good polarizer-less transducer candidate could be developed, then a display could be made that is twice as bright as similar ones made with conventional technology. Current candidates include guest-host LC,[3,4] PDLC, and electrophoresis. Although fabrication and driving connection are more difficult, techniques using stacked structures have even more potential to achieve higher brightness because the color-filter losses of two-thirds can be eliminated. Cholesteric, guest-host LC, or holographic PDLC can be used as the transducer for a stacked structure. Encapsulated guest-host LC has been shown to be useful.[5]

The multilayered structure is also effective for achieving a high-contrast high-reflectivity monochrome pixel. An orthogonally aligned double-layer guest-host (DGH) LCD has been shown to have a 15:1 CR and 60% reflectivity,[6] while a single-layer guest-host LC produces a CR of only 5:1 (Fig. 1).

Enhancing Luminance

Since a liquid-crystal pixel using two polarizers is simple and provides high contrast, it is commonly used in watches, calculators, cellular phones, and other portable devices. However, because the reflector is placed under the lower glass plate, parallax becomes a problem in a high-density display. A single-polarizer system is desirable for such displays because it does away with the absorption in the second polarizer.

There should be a diffuser in a reflective display to allow the illuminating light to reach the viewer's eyes. The diffuser can be either a diffusing reflector or a forward scatterer. When a diffusing reflector is placed next to a material with a refractive index higher than that of air, we need to remember not to make the diffusing power too large.

The incident light ray is reflected through total internal reflection (TIR) when the reflected angle exceeds the critical angle,

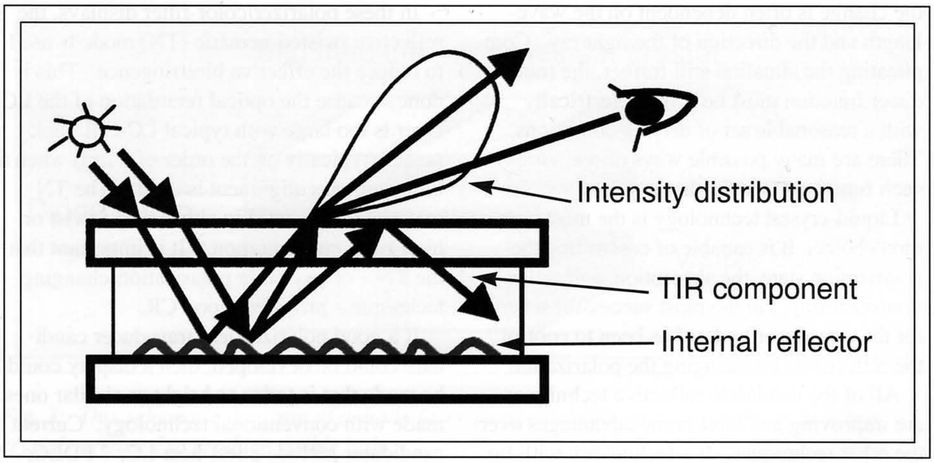

Fig. 2: If the internal reflector in a reflective display reflects light at too great an angle, the light does not re-emerge from the display because it undergoes total internal reflection.

which is 42° for a material with an index of 1.5 (Fig. 2). The maximum slope of the reflector is designed to be about 10°, and a similar condition holds for a front diffuser. When the diffusing power is reduced, the reflected light power per unit solid angle increases accordingly, although the optimum viewing direction is limited. We often use the term "reflector gain" to mean an increase in the luminance obtained by using a controlled reflector or diffuser.

Since there is always a specular-reflection component from the top surface or an internal interfacial surface, better viewing performance can be obtained by using an asymmetric diffuser. Such a diffuser can be made by using an off-axis hologram, asymmetric diffusing-reflector structures, or asymmetric forward-scattering prism structures.

An off-axis hologram is a volume hologram, and its reflection is dependent on wavelength. Therefore, it is possible to make a color display if three-color reflectors are formed like color filters. The advantage is that there is less transmission loss than with filters.

Presenting Colors

The most common technique for displaying a color image is to use color filters. The high color-filter losses are sometimes reduced in reflective displays by giving the filters a higher transmission by widely overlapping of the wavelength-transmission regions. This makes the display colors more pastel-like.

The tri-layer stacked guest-host LCD can display full-color images if each layer absorbs one of the three color components (red, green, and blue) sequentially. This can be achieved by choosing appropriate dyes. Three-layer holographic PDLC displays can produce full-color images when each layer reflects one of the three color components. Reflective displays with an absorbing system use subtractive color presentation with cyan, magenta, and yellow primaries, while the stacked holographic PDLC and side-by-side reflective subpixel systems use RGB additive color presentation.

Driving the Pixels

TN-based LCDs are usually driven by using thin-film transistors (TFTs), a technique that produces better temperature stability and faster response. STN-based LCDs are driven by using a simple passive matrix. A polymer-stabilized cholesteric liquid crystal (PSCT) has hysteresis and memory. Therefore, a simple passive matrix can drive PSCT. Because the voltage is high and a special pulse sequence is necessary to write an on or off state to each pixel, demonstration displays fabricated by Kent Displays require several TV frames to refresh the total frame image. Although the time requirement is a problem, this scheme is appealing because TFT plates are not necessary, and simple matrices can be used for the three-layer stacked cell. The power consumption of PSCT can be very low because this is a memory type of pixel, in which a stationary image is displayed indefinitely without power. (A longer refresh time in non-memory displays also reduces power consumption.)

In tri-layer LCDs that require TFTs, one can use three independent TFT-array plates to drive the pixels.[7] Since it is costly to use three TFT plates, we may need to make further simplifications, such as using only one TFT plate and connecting the pixel electrode vertically from the bottom. The three-layer holographic PDLC also has to be driven by TFTs, as does the three-layer guest-host LCD. The driving voltage has to be compatible with that of the TFT.

Applications and the Future

Watches and calculators use monochrome reflective TN-LCDs with a fixed-pattern driving method. At one time, PDAs and small portable computers used an STN-based matrix-driven reflective monochrome display. An STN-based color reflective display was used in a color PDA in 1996. In 1998, color PDAs and a color portable game machine using a TN-based color reflective display were released.

In the future, main application areas will presumably be PDAs – including watch or cellular phones – and paper-like displays. For the latter application, the key requirement is to achieve satisfactory performance. When reasonably high-performance reflective displays become available, it will be possible to use displays in ways that are totally different from the ways in which we use them now.

High-quality TN-based reflective color displays are already being used in various products. These reflective displays exhibit good performance and can be used in many environments. However, their actual readability is not equal to that of printed paper. So there is considerable room for improvement, and substantial improvement will require revolutionary new ideas.

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The Secret of Success

Different display markets require different sales and support structures.

by Dale H. Maunu

EVEN IF ONE SUCCEEDS in building a better mousetrap, the world still may not beat a path to ones doorstep. In most cases, the secret to success is finding an efficient and effective way to get the product to the user's doorstep. And the solution that works for one market may not be the best for another.

Color thin-film-transistor (TFT) flat-panel displays (FPDs) are desirable alternatives to cathode-ray tubes (CRTs) in various applications for a number of reasons. They are lighter, easier to handle, more maneuverable, and consume significantly less power for equivalent picture quality. Some markets require enormous numbers of TFT modules - generating large amounts of revenue - but there are other markets with smaller-volume demand that still offer attractive profits. Success depends on striking a balance between the support needs of the high- and low-volume applications.

How PC and Non-PC Markets Differ

When people think of TFT displays, they often think of PC-based applications, such as notebook computers or desktop LCD monitors. There is also a large market for TFT displays that are not part of a computer; this market has widely differing market characteristics and places widely differing demands on TFT FPD manufacturers.

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PC original-equipment manufacturers (OEMs) typically order more than 20,000 TFT FPD modules per month from a given supplier. PC makers usually order modules from two to five sources so that they are able to fill their enormous shipment volumes and so that a shortage in shipments from one supplier doesn't end up stopping the PC maker's production line. Display suppliers must adapt to wildly fluctuating market prices for their TFT FPD modules, based on the push and pull of supply and demand. PC display modules also have short life spans - typically 6-9 months - as changing styles and tastes modify user demands, and as technological improvements and new standards become adopted throughout the industry (Fig. 1).

The non-PC market has a much more diversified customer base, divided into different market segments. OEM customers with industrial, medical, and instrumentation applications typically require displays with more customized designs than those typical of more standardized PC products. These OEM customers typically order 10-2500 displays per month, usually from one supplier but sometimes from two if volumes warrant. Display pricing for these segments tends to be much more stable than for PCs, but display manufacturers must keep their pricing competitive or they run the risk of losing future design wins.

Industrial, medical, and instrumentation displays typically require extremely long product life cycles - anywhere from 3 to 5 years, and sometimes more than 10 years. One reason for this difference is that product certification and approval often requires an extensive and exhaustive approval process, which results in time and dollar costs that the OEMs must amortize over the useful life of the product. This is especially true for medical equipment, which often must go through the long and expensive process of obtaining approval from government agencies such as the Food and Drug Administration (Fig. 2).

The non-PC consumer market segment - typified by flat-screen TV and other consumer display applications, as well as those for automotive after-market products - presents a very different picture. OEMs weigh the display's front-of-screen performance against its price as one of the key differentiators in choosing a supplier for the panels.

Consumer products are, by nature, extremely cost-sensitive, which severely limits profit margins per display. Only an efficient manufacturing process can hope to succeed in such a market. Fortunately, like PCs, consumer display applications offer large revenues from display volumes of more than 10,000 units per month. Consumer display products tend to lag behind products in other market segments in terms of technical innovation, which is one way they can achieve their aggressive cost goals. Consumer-display-product life cycles are typically short, which is a result of fads and technological evolution, so frequent design changes with rapid turnaround times are essential.

PC Sales and Support Channels

PC and non-PC markets also require different kinds of sales channels to support their business models. Display manufacturers typically employ three models of sales channels for the

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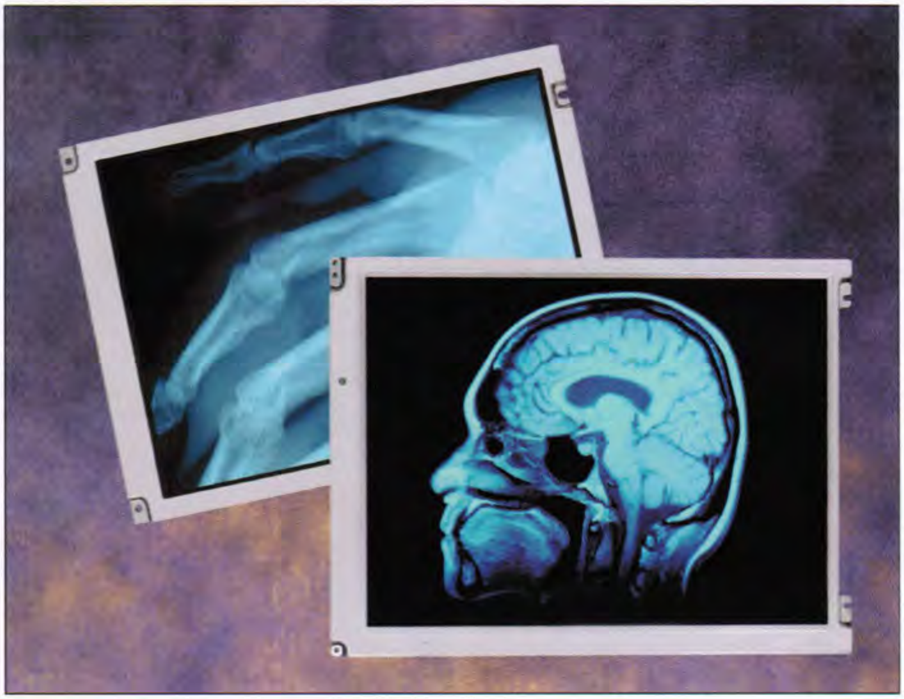
Fig. 1: CRT-monitor replacement is a fast-growing segment of the PC market for TFT flat-panel displays. The Silicon Graphics 1600SW flat-panel monitor is shown.

PC market: direct OEM, indirect OEM, and subcontractor.

In the direct-OEM sales-channel model, a PC OEM secures the display-module allocation directly from the display manufacturer, which is often based overseas. The OEM handles all of the accounting and administrative details of ordering, receiving, and storing the display modules in-house because the size of the OEM's operations makes it feasible and cost-effective to process these tasks internally. The PC OEM is also responsible for production forecasts and associated risks. This greatly reduces the administrative burden on the display provider, so the OEM is able to negotiate a discounted price for the display modules. The display manufacturer ships the display modules from its overseas facility directly to the OEM, and the OEM processes the products through customs and maintains its own inventory.

If the shipment volumes to the OEM are sufficiently large, the display manufacturer may even set up and maintain a warehouse near the customer site for receiving and processing display-module shipments. The modules are then delivered nearby to the OEM on an "as needed" basis, supporting either demand-pull or just-in-time (JIT) inventory systems. This approach gives the OEM the convenience of having a large display inventory available, but without the hassle of maintaining on-site module inventory.

In the indirect-OEM sales-channel model, a PC company secures the allocation from the display manufacturer. A subcontractor then buys the product allocation for the PC OEM, usually offshore. The subcontractor then



Mitsubishi Electronics America, Inc.

Fig. 2: The medical market uses TFT FPDs for viewing images obtained from such modalities as ultrasound, CAT scans, and x-rays.

takes care of bringing completed notebook PCs or flat-panel monitors (FPMs) into the country where the OEM operates and processing them through customs. The subcontractor takes care of inventory, accounting, administration, and distribution of the product for the PC OEMs that do not maintain their own in-house staff to do these activities. The subcontractor also performs any necessary quality inspections on the modules before manufacturing and sends the finished products to the PC OEM customer. As a result, the PC companies using this model will often pay a higher per-unit rate for the display modules than do the direct OEMs.

In the subcontractor sales-channel model, the subcontractor secures the display-product allocation for a worldwide PC supplier. The subcontractor then takes care of receiving, inventory, accounting, administration, customization, and distribution of the product to the PC company's configuration centers worldwide.

One important element of the support channel for the PC market is the repair of defective modules. Historically, when display modules were returned for service, they were sent from the PC OEM directly to the display manufacturer's repair facility, which is often located at an offshore facility far away from the customer. This procedure created an undesirable situation for customers because shipping defective modules offshore and receiving repaired modules back took many weeks, and required them to keep very large inventories of displays just to assure that they would meet their shipment targets.

Repair was wasteful for manufacturers, too. Since PCs have short product life cycles, this meant that by the time some modules returned from repair, they were obsolete. Mitsubishi Electric Corp. has solved these problems by contracting with a third-party repair service that provides worldwide warranty for repairing displays to the to end of their lives. Modules that require repair can be serviced locally in Europe, Asia, or North America. A worldwide third-party repair service benefits OEM customers because the quick turnaround for repairs allows them to substantially reduce the amount of inventory they have to keep on hand. It also reduces the amount of scrap that display manufacturers have to recycle.

Non-PC Sales and Support Channels

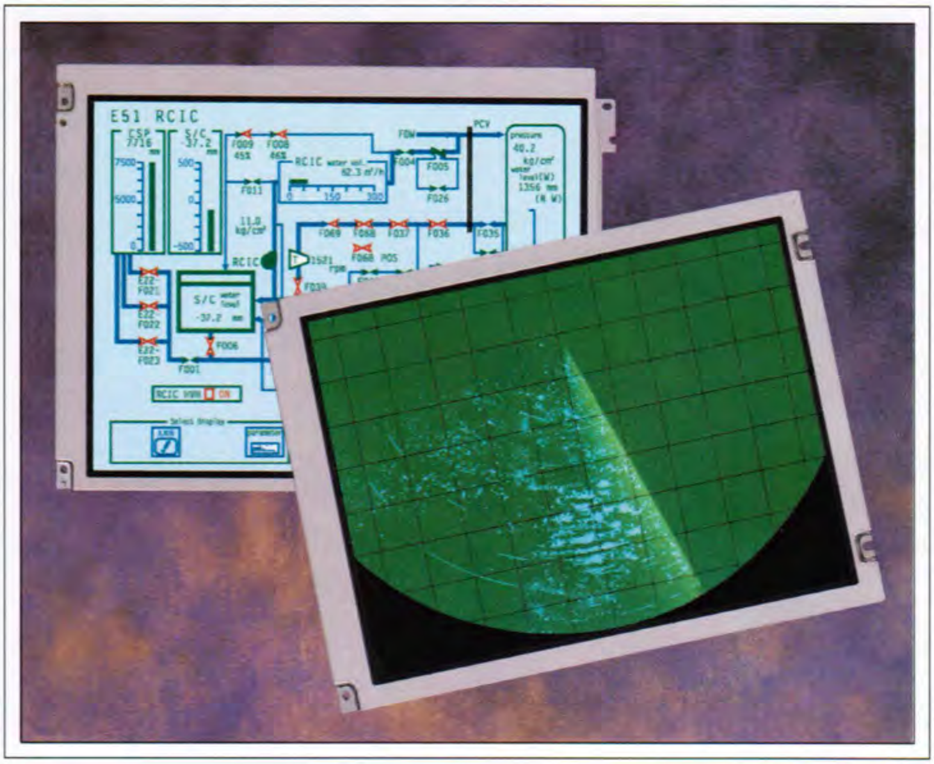
Display manufacturers usually address the non-PC market by using the direct OEM and value-added distributor (VAD) sales-channel models. The direct-OEM model is similar to the direct-OEM model for PCs. The U.S.-based direct OEM secures the display-module allocation directly from the manufacturer, and the direct OEM handles all the administrative details of ordering, receiving, taking the display modules through customs, and keeping inventory in-house.

The direct OEM requires only the module from the display manufacturer and provides its own technical expertise for customizing that technology for its own highly specialized end products (Fig. 3). Large medical, industrial, and instrumentation direct OEMs, like the large PC OEMs, supply the support staff necessary to cost-effectively handle these activities. Because non-PC direct OEMs order products in sufficiently high volumes and place a minimal support burden on the display manufacturer, they can negotiate a lower per-unit price on modules. Non-PC direct OEMs require competitive pricing and long-term product support, as well as the availability of warranty repair service in areas convenient to their business worldwide so that they don't have to send their displays offshore for repairs.

The VAD model is becoming an extremely important resource for display manufacturers that have limited resources for supporting those medical, industrial, and instrumentation OEM customers which have highly customized requirements for their end products. VADs provide product-acquisition services similar to those supplied by subcontractors that support the PC market, but they also provide specialized in-house application-engineering expertise directly to the OEM.

Medical, industrial, and instrumentation OEMs that have their displays supplied by VADs generally have core competencies in largely unrelated technologies. These customers want a complete solution, with the VAD supplying everything from the display controller, inverter, and cables to kitting the display for production. They also need the VAD to supply the expertise to help design these elements into the customer's final product.

VADs are very similar to large OEM customers in the volume of display units they require and in the demands they place upon



Mitsubishi Electronics America, Inc.

Fig. 3: Instrumentation and industrial applications for TFT FPDs include imaging, control-room, and process-control applications.

display manufacturers. Like OEMs, they require competitive pricing and long-term product support, as well as the convenience of worldwide warranty repair service for their display modules.

Serving Diverse Non-PC Customers

Two potential non-PC customers could easily incorporate the same kind of TFT display technology in their end products, and still meet different performance goals. Two potential customers could use a VAD to take advantage of available configuration options, but for very different applications.

For example, Company A manufactures point-of-sale (POS) equipment. The end customer, a supermarket, requires that the display be bright enough to be used in the high-ambient-light environment that is conducive to shopping. The display also needs to be reliable so that the check-out stands are always available. The POS market is highly price competitive because supermarkets will generally select a single POS system for the entire chain. A solution presents itself in the form of a standard, off-the-shelf high-luminance display bundled with the appropriate inverter and cables from the VAD.

Company B, on the other hand, manufactures industrial automation equipment. Its end customer is a manufacturer that requires its assembly line to run 24 hours a day, 7 days a week, with an environment typified by wide swings in temperature, humidity, luminance, and airborne particles. In this application, it is desirable to utilize touch-screen technology so that the automation equipment can be completely sealed off from the environment. The VAD presents a solution in the form of the same high-luminance long-lifetime display, but this time modified by a third party to incorporate a protective panel and touch screen. The VAD is able to coordinate these services, provide the associated inverters and cables, and deliver the package in kit form to facilitate manufacturing. This allows the manufacturer of industrial automation equipment to focus on its core competency while leveraging display expertise from the VAD.

Striking a Balance

Clearly, the gigantic volumes and revenues of the PC market will dominate the supply strategies of large TFT FPD makers for many years into the future. But a display supplier risks being buffeted by the price volatility and profit erosion that can result from being committed to just the PC business. A balanced approach of supporting the lower-volume more highly customized needs of medical, industrial, and instrumentation applications can help buffer the TFT FPD supplier from such changes. Success in addressing the needs of non-PC applications can increase overall profitability. This will encourage display manufacturers to invest in technologies that might produce the better mousetraps that can benefit existing non-PC and PC applications - as well as new market opportunities - in the future. ■

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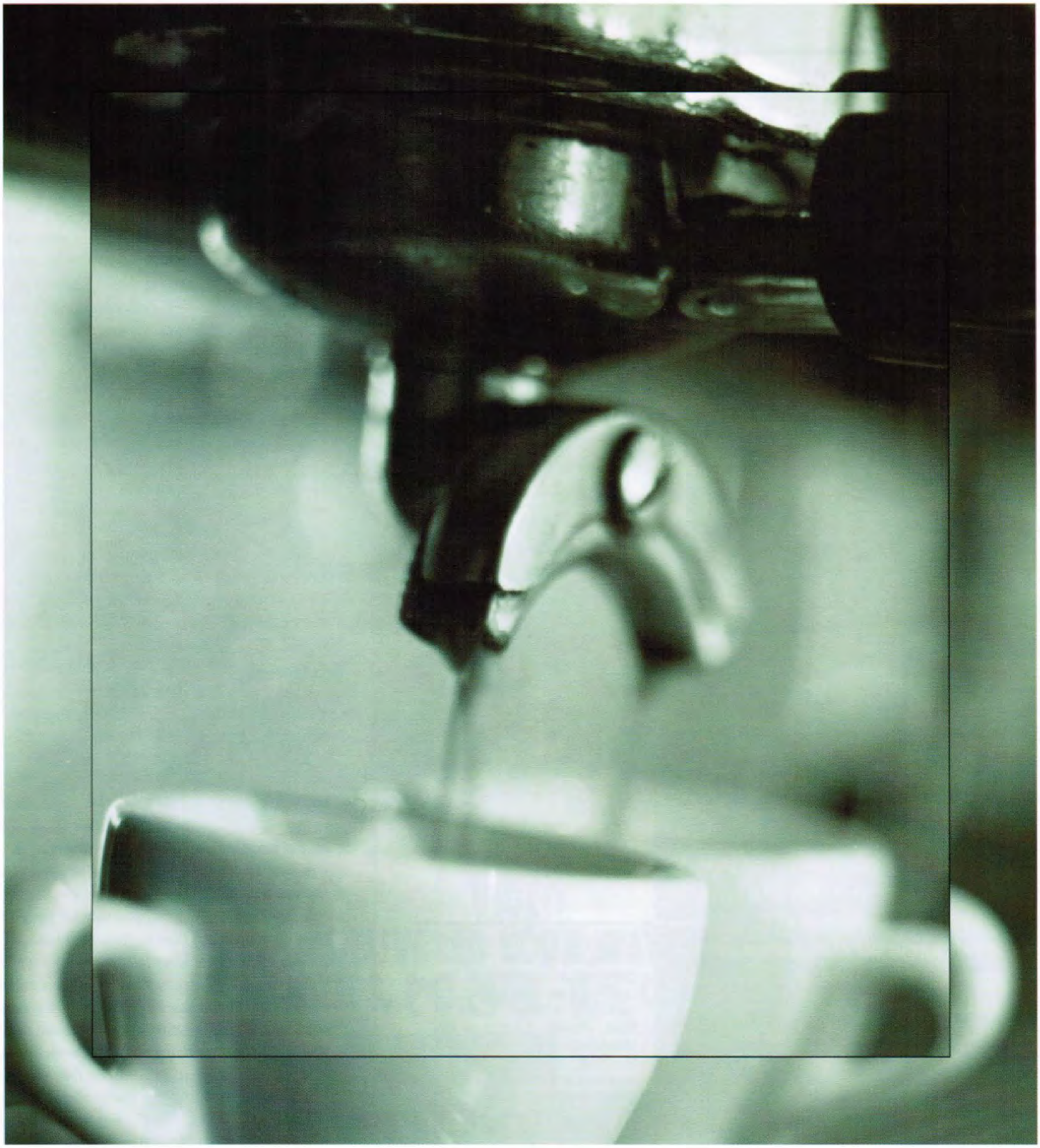

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most of the vendors doesn't seem to make for even a minimum-income operation. A few seem to do it to make contacts for hoped-for future sales.

Yet, there is an occasional exception. On that warm and rain-free October Sunday afternoon, as we strolled among the crowds on Front Street, I started noticing a person here or there carrying a weather vane. No, not the kind you mount on the peak of a roof. These were on six-foot black metal poles intended to be stuck into the ground. Most had an animal cutout (a rooster, cow, or dog) on top of the crossbar with the N-W-S-E letters, and immediately below there was an assembly that looked like anemometer cups. A few of them also had a person's name painted on a flat protrusion on the pole.

The more we strolled, the more weather vanes I noted. This was becoming very puzzling. They were certainly not very handy to carry around. The materials from which they were made did not look to be of particularly great quality. So why were people buying them? Was I maybe wrong about the craft items not selling well? No, hardly anyone was carrying a painting, photograph, or other evidence of a purchase. The weather vanes were definitely in the majority.

With my curiosity building, it was time to go take a look at this vendor's booth. I knew it wouldn't be hard to find. I would just go the opposite direction from the weather-vane carriers. When I came upon it, I couldn't believe what I saw. There was a line of at least 50 people, each patiently waiting to get his or her very own weather vane. Why? Of all the hundreds of items at this fair, why a weather vane? Every other vendor (except for the vendors of the barbecued salmon, elephant ears, and kettle popcorn) had to wait patiently for that occasional buyer. Yet, here were a couple of plain-looking fellows, with a well-stocked truck nearby, selling weather vanes as fast as they could assemble them. They must have known this would happen because they had come well prepared to meet the demand.

A partial explanation could be that the price was attractive. The basic matte-black weather vane was priced at $19.95. For an additional $7.00 one could add the non-functional anemometer cups, and for another $7.00, the personalized sign. This came to a typical total of $33.95 plus the Washington sales tax of 8.5% - not very expensive, but also not pocket change. But why stand in line for an item that doesn't provide much in the way of functional usefulness or, in my opinion at least, decorative value. What was the appeal? Perhaps I should have asked. Would these customers have told me? Was the price of $33.95 perceived as a great value for this type of object? Was the opportunity to choose the cutout figure from a dozen or so examples the appeal? I noticed that this same booth was also selling a black "Victorian" lamp post with a personalized name rider for $30.00. But, I didn't see one person buying that item. There was definitely some special and magical attraction to the weather vanes.

Here was a great lesson in product marketing. In an environment where the typical vendor is happy with a few sales that may barely cover expenses, these crafters had struck "gold." How did they know? What distinguished them from the rest? Or did they just stumble upon this by accident?

This led me to think about some of the marketing challenges that I regularly encounter in working with client companies and potential investors. Quantifying new market opportunities for evolving display technologies can sometimes be about as challenging as predicting that weather vanes will outsell every other product by an order of magnitude.

As a result of this Salmon Days experience, I have come to the conclusion that at times I must be trying to sell weather vanes before anyone has realized just how terribly important weather vanes are going to be. Corporations and institutional investors want lots of reassurances (typically known as due diligence) that their investment will not be too risky. However, if the only current examples are the "craft booths" that have hardly any sales, it is impossible to provide the quantitative data that will show that there exists a "weather vane" of an opportunity. ***It takes vision and perhaps some trial marketing to verify that such an opportunity is there and ready for exploitation***. Otherwise, by looking only at the existing markets, it is not possible to find the data to show how a new product based on a new technology will create an entirely new growth market.

Before there were desktop computers, what could we say about the market size for desktop CRT or LCD monitors? Before there was an Internet, could we quantify the opportunities for Internet shopping businesses? The early pioneers have the most difficult challenges in this regard. Until the new territory has been explored, there is no way to know how big or lucrative it may be. However, once the initial successes happen, everyone wants to jump in. And "everyone" is usually a few too many. I suppose at next year's Salmon Days there will be at least six vendors selling weather vanes. By then, the demand may no longer be there.

How can we desire the successes from "boldly going where no man has gone before" while at the same time hoping to "quantitatively assess the detailed outcome of our journey into the new and untested?" How can we see "weather vanes" when everyone else is looking for minor variations on existing "trinket themes"? In words no more sophisticated than these, I have at times been asked why I can't just go out and find "low-hanging fruit." As I understand it, this is intended to mean that there must be some immediate, and as yet untapped, opportunities just waiting to be "picked." In many years of working for and with companies and investor groups, I have yet to find one of these fruit-laden low-hanging branches. Have you ever found one? If you did, you were darn lucky. Looking for such niche opportunities, I have decided at least for myself, is a difficult and futile way to go through life.

Market success comes from thoroughly knowing potential customers and their needs. The only way to know those needs is to spend intelligent time in face-to-face interactions with as many of them as possible and, on occasion, doing some real-time inventing while in the middle of such a meeting. It is necessary to be able to interpret the customers' needs better than the customers can articulate them. Only then, by presenting a new technology or a new product concept in a way that clearly shows what needs it meets - whether obviously logical or sublimely mysterious - can a new product introduction be successful.

We in the display industry are fortunate. There are, and will continue to be, so many opportunities that we will have a difficult time choosing the best ones. Nevertheless, that doesn't mean that we are impervious to making bad choices. I am sure that each of you can name a couple of recently announced display technologies, or products using displays, that seem to have lost touch with the reality of what users might want even under the most optimistic of circumstances.

The process of marketing new technologies, and products based on them, perhaps has some parallels to quantum mechanics. We can determine some features but others are too fuzzy to see. An attempt to measure can disrupt the phenomenon being measured. The deeper we probe into new territory, the more uncertain becomes the measurement. Yet with understanding of the fundamental influences, and with skill at interpreting them, we can predict the opportunities on a grand scale. The process is not mysterious. But just as quantum mechanics combines the behaviors of particles with waves, the merging of technological possibilities with seemingly unpredictable emotion-driven human behavior is comfortable territory for only a few.

Should you wish to share your opinions of what you consider to be the most outrageous recent new-product announcements, or other topics of interest, you may do so by contacting me via e-mail at silzars@attglobal.net, by phone at 425/557-8850, by fax at 425/557-8983, or by way of the downtown Issaquah post office to my home office at 22513 S.E. 47th Place, Issaquah, WA 98029.■

Please send new product releases or news items to Information Display, c/o Palisades Institute for Research Services, Inc., 411 Lafayette Street, 2nd Floor, New York, NY 10003.

erratum

In the "Display of the Year Awards" article appearing in the December issue of *Information Display Magazine,* the correct awards committee listing should have read:

Mr. Alfred Poor, *Chair*
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Perkasie, Pennsylvania, U.S.A.

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Science University of Tokyo in Yamaguchi
Onoda, Yamaguchi, Japan

Ms. Cheryl Ajluni
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President, Northlight Displays
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Professor Chuji Suzuki
International Center for Materials Research
Nara, Japan

Mr. Chizuka Tani
NEC Corp.
Kanagawa, Japan

Mr. Kenneth I. Werner
Editor, *Information Display Magazine*
Norwalk, Connecticut, U.S.A.

letters

OIS Technology Alive

The demise of OIS Optical Imaging Systems last year was a major setback for its customers, shareholders, employees, the U.S. Government, and the U.S. flat-panel-display industry in general.

OIS technology, however, continues to make waves. Since the shutdown 11 more U.S. patents and three more European patents have been issued to OIS as of September 1999, with possibly more in the pipeline. Some of these patents cover processes and designs for high-aperture TFT-LCDs that are now becoming mainstream technology and wide-viewing-angle technology for LCDs based on retardation approaches.

Others are on TFT arrays for large direct-conversion x-ray sensors that were the first to receive FDA approval, and on novel configurations for thin-film diode LCDs.

Another exciting technology, demonstrated in protypes by OIS and presented in a paper at the Asia Display '98 conference, is color-filter integration on the TFT array.

NEC announced in August 1999, the development of an ultrahigh-resolution 9.4-in. 1200 × 1600-pixel TFT-LCD, in which color-filter integration on the TFT array is indispensable.

The OIS case is a typical example of the short-term horizon of U.S. investors. It has largely shielded them from the losses suffered by the AMLCD manufacturing industry from 1995 to 1998. On the other hand, it has led to missed opportunities to participate in an industry that is expected to grow from $10 billion to $70 billion in annual revenues over the next 10 years.

— Willem den Boer
Planar Systems
formerly Director of Advanced Technology,
OIS Optical Imaging Systems

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