NEW DIRECTIONS

Information DISPLAY

SID

January 2001
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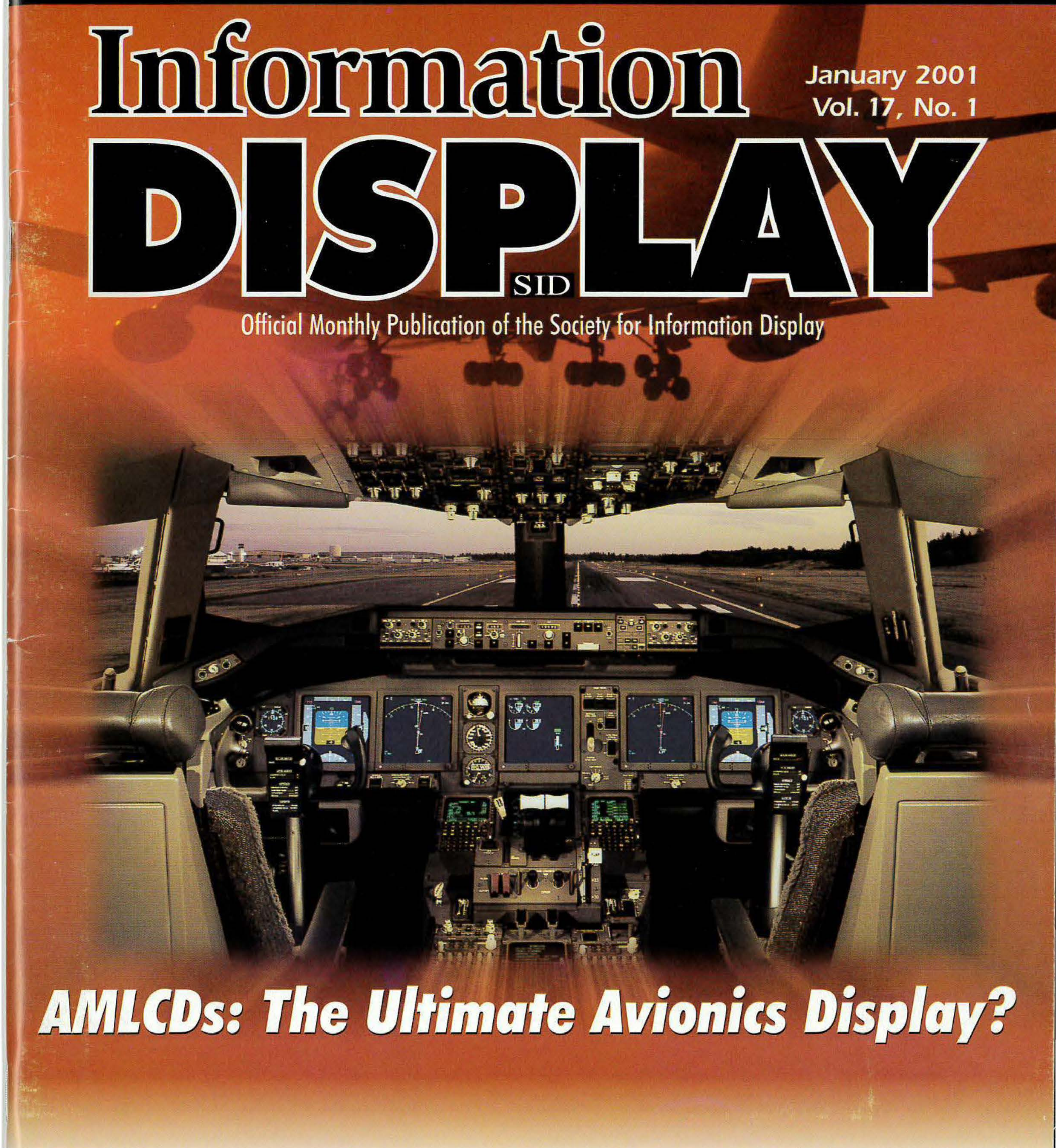
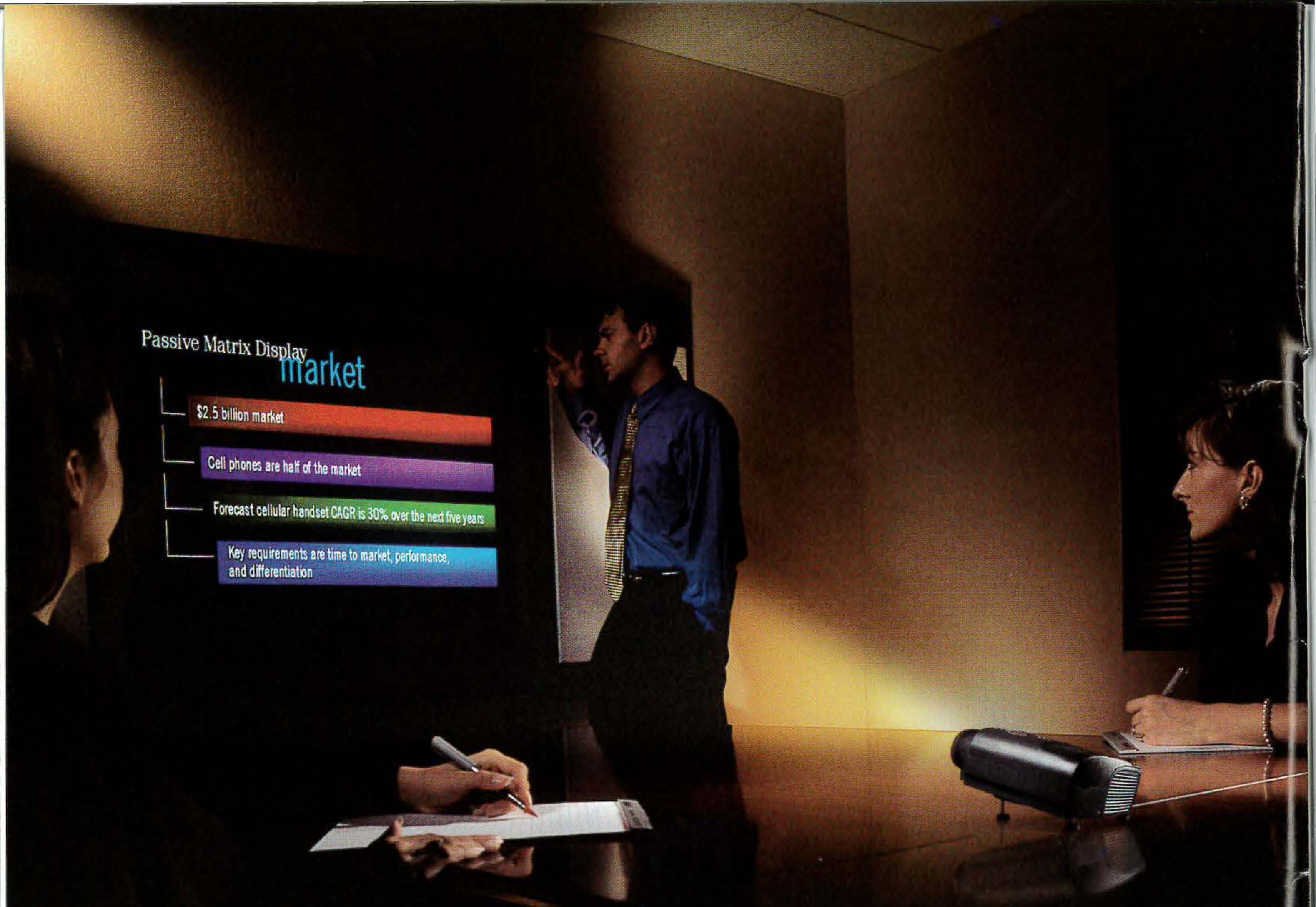
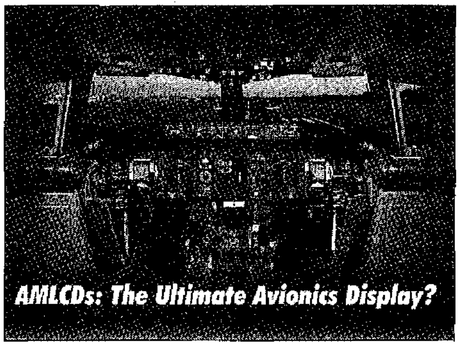


AMLCDs: The Ultimate Avionics Display?

- ***Designing Projection Engines***
- ***Tiled AMLCD Displays***
- ***The Ultimate Avionics Display***
- ***Plastic Displays at IDRC***


Passive Matrix Display market
$2.5 billion market
Cell phones are half of the market
Forecast cellular handset CAGR is 30% over the next five years
Key requirements are time to market, performance, and differentiation

COVER: This state-of-the-art "glass cockpit" is standard issue in Boeing's new 767-400ER. The displays and system integration are by Rockwell Collins. Leading AMLCDs for avionics applications are remarkably good displays, but is there nothing better on the horizon? In the article beginning on page 22, consultant Larry Tannas says there isn't.



The Boeing Company

For more on what's coming in *Information Display*, and for other news on information-display technology, check the SID Web site on the World Wide Web: **http://www.sid.org.**

Next Month in *Information Display*

Flat-Panel Issue
- Recent Trends in Electronic Projection
- LC Modes for LCoS Microdisplays
- Traditional LCDs for Electronic Paper
- ASID 2000 Report
- SMAU 2000 Report

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ID On-Line

Because *Information Display* is a monthly magazine, it has been difficult for us to include "breaking news" about the display industry. By the time a news story could appear in print, it would have been outdated. As a result, we've had to leave many of these stories out of our editorial mix. Much the same has been true of our "Industry News" and "New Products" columns. Although readers say they like these columns, the items in them have sometimes had a dated look, and the columns themselves have appeared irregularly in recent months. We have now solved these problems with *Information Display On-Line (IDOL).*

IDOL is a featured component of the Society for Information Display's rethought, redesigned, and news-driven Web site. Go to www.sid.org and you will find that *IDOL* occupies a large part of the home page, and continues onto linked pages. In addition, *Information Display*'s staff is compiling the international display industry Conference Calendar that appears on the Web site. The calendar is updated weekly, and we believe it to be the most comprehensive and up-to-date display-oriented conference calendar in existence. (But you can help us make it even better. If you know of a display-related conference we've missed, please notify Dian Mecca at dmecca@sid.org.).

What you will not find in *IDOL* is an archive of feature articles from *Information Display*. Not yet. We're working on it.

An Apology

In my October editorial – the one about INFOCOMM – I repeatedly attributed JVC's exciting D-ILA™ microdisplay technology to another Japanese company, and I even indicated that JVC Vice-President Bill Bleha worked for this other company. This inexplicable error is entirely my responsibility. I apologize to JVC, to Dr. Bleha, and to the readers of *Information Display*.

– KIW

We welcome your comments and suggestions. You can reach me by e-mail at kwerner@nutmegconsultants.com, by fax at 203/855-9769, or by phone at 203/853-7069. The contents of upcoming issues of *ID* are available on the *ID* page at the SID Web site (http:// www.sid.org).

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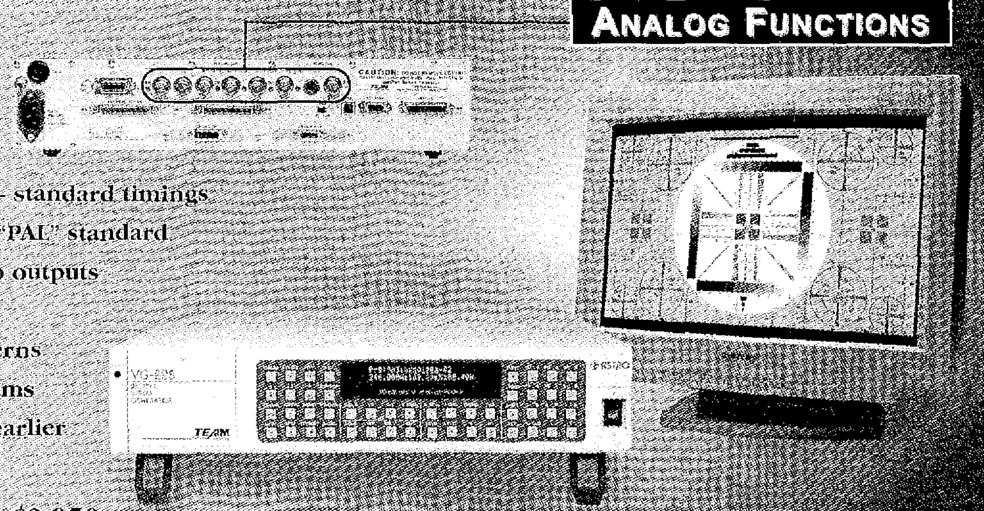

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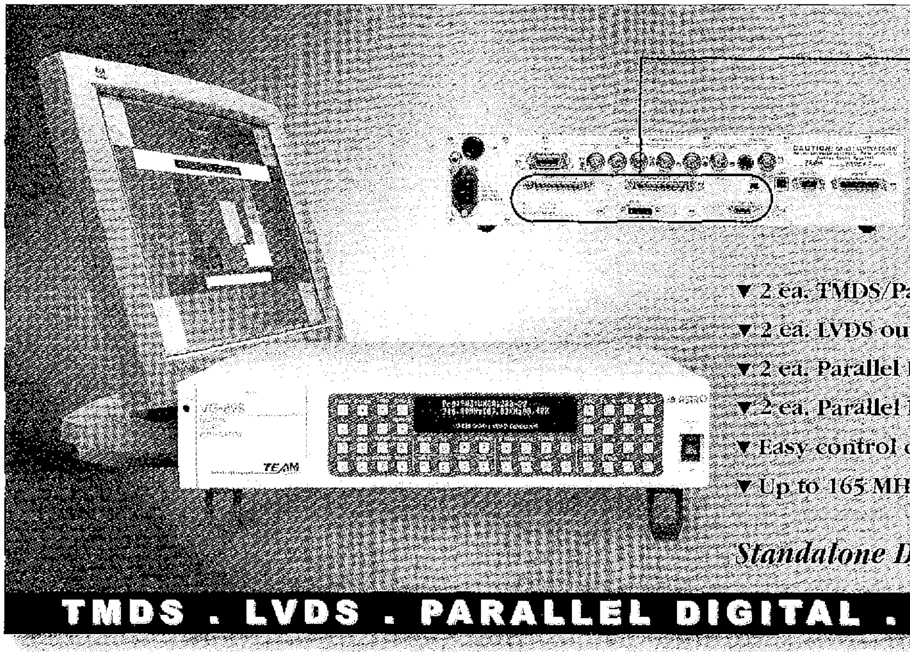

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Circle no. 2

a view from the hilltop

Getting It Right ...

by Aris Silzars

October 6, 2000. It is already past 11:00 p.m., and I am determined to respond to a few more e-mails before retiring for the evening. I must still pack my suitcase for an 8:00 a.m. flight that will take me by way of New York to Moscow for the FLOWERS 2000 Display Conference. Suddenly, in the middle of an e-mail that must reach my Russian colleagues before my arrival, the house plunges into darkness, followed by a deep explosion-like sound somewhere off in the distance. I momentarily ponder if this is an unexpected but effective demonstration that the speed of electric current in wires exceeds the speed of sound in air.

So much for my nearly completed e-mail, and so much for the several others I had planned to answer. Using a flashlight and a propane camping lantern, I finish my packing, set the alarm for an hour earlier than I had planned, and retire for the night. Perhaps the blown power transformer will be repaired sometime during the night and I will still be able to get my important correspondence completed in my last-chance time slot between 5:00 and 6:00 a.m.

At 3:15 a.m., the smoke alarms let out a piercing screech; the lights flash a couple of times and then stay on. I utter a few choice words as I stumble around the house in my deep-sleep-interrupted state and turn everything off, especially the computer, which is now most unhappy that its power was interrupted in the middle of an important thought.

October 7, 2000. While waiting for my connecting flight in New York, I encounter the following futuristic description in an *EE Times* article by Bob Weber about biometrics technology:

> When she walks in the house, she notices the TV is on and wants to know if the kids have been watching the tube all afternoon or have been actively working on their homework. After touching the remote sensor with her finger, the digital broadband set-top box displays the times the TV has been on and the channels that have been surfed. With another cue, the set-top box goes out and retrieves any e-mail messages that have come in, and reminds her that her husband will be arriving that night on flight 336 and that the electric bill needs to be paid. When she approves the payment, the system asks for her fingerprint again so that it can cross-check the authorization, and the money is then transferred from her checking account to the utility company.

Sounds great, doesn't it? It's another version of the electronic home – the long-standing technologists' dream that has recently been receiving renewed attention through the highly publicized efforts of several major computer and software companies.

For those of us in the display community, the "electronic home" should be a great opportunity – a display on every refrigerator door, displays for environmental and ambiance control, displays for interactive art works and wall decorations, displays for ordering products and reminding us when existing inventory is about to be depleted. Everything is displayed, controlled, and customized to match the wishes and habits of the inhabitants.

continued on page 33

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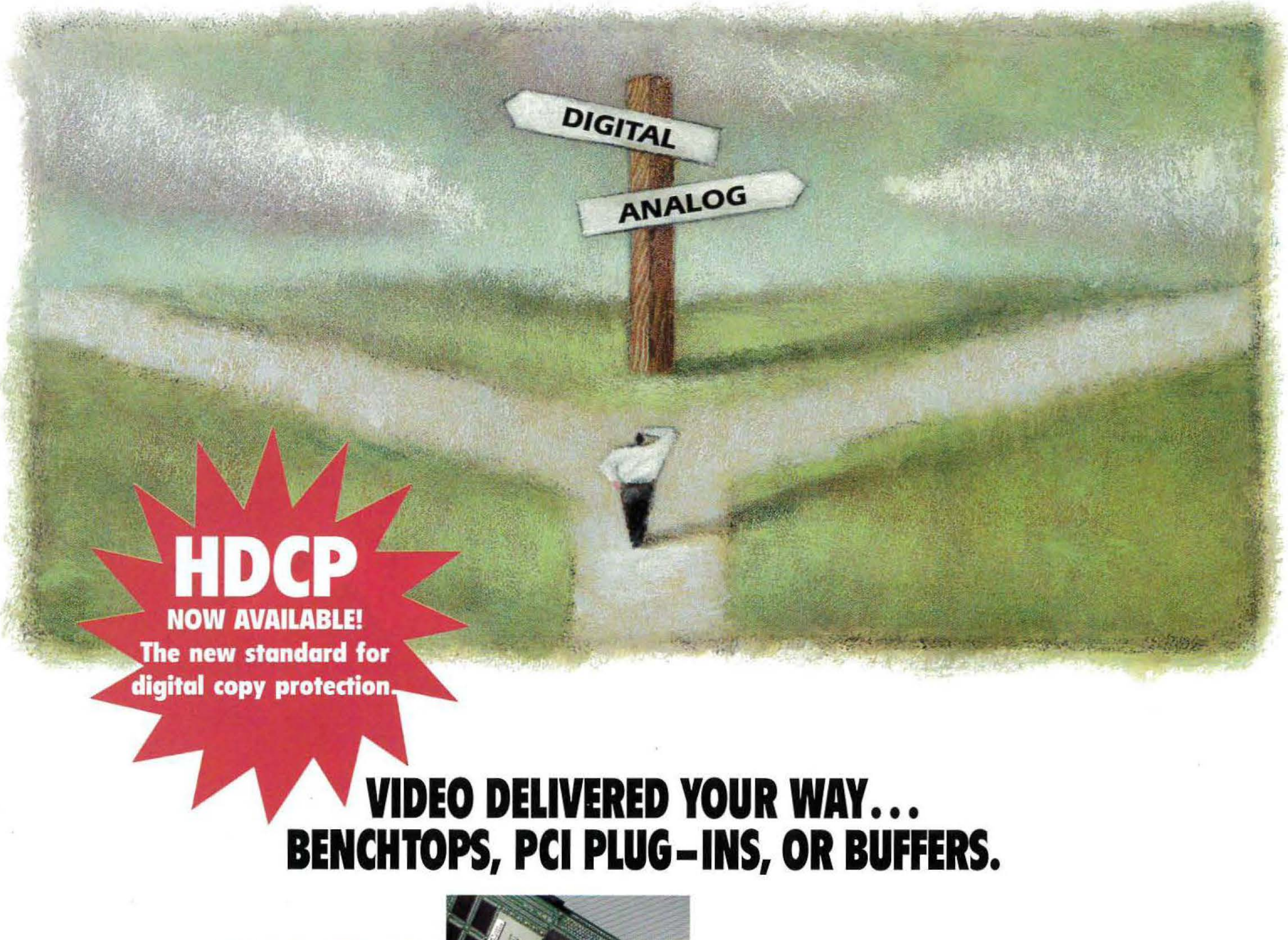

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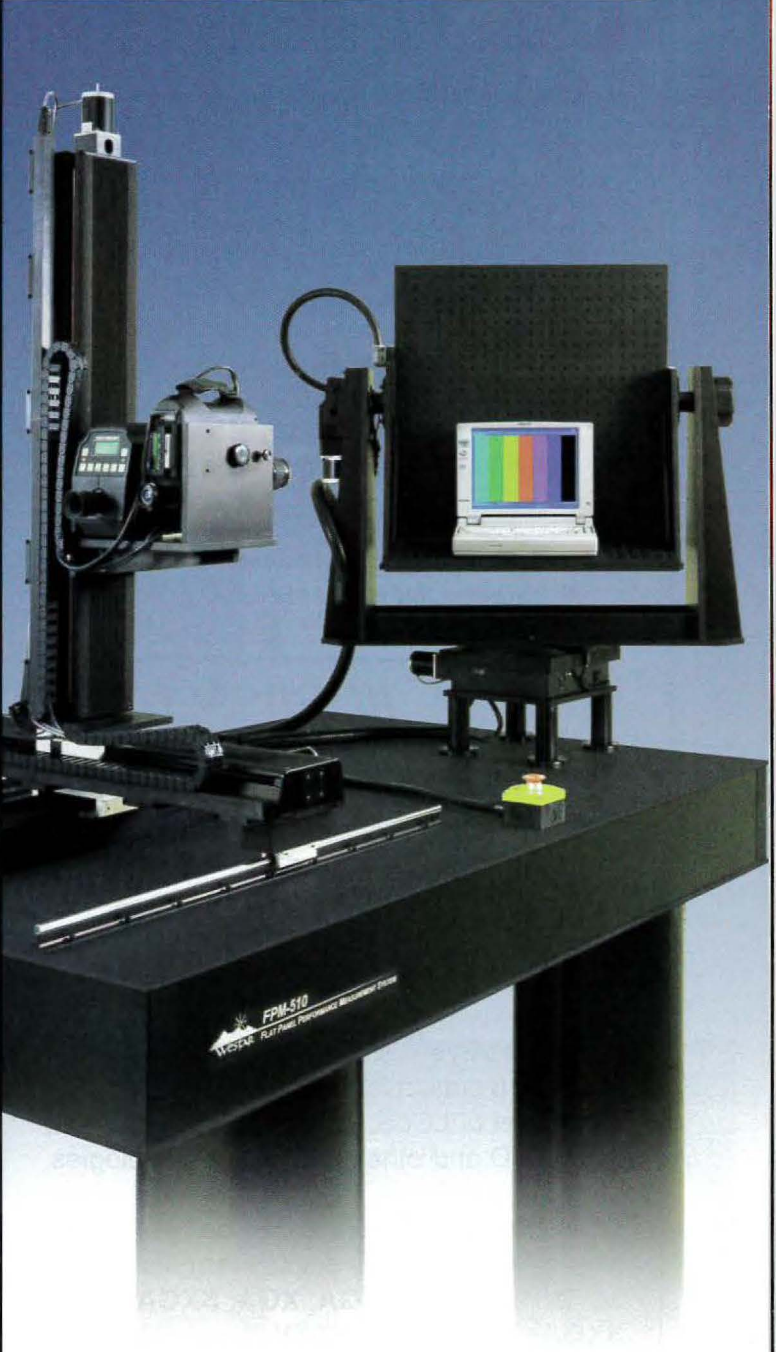

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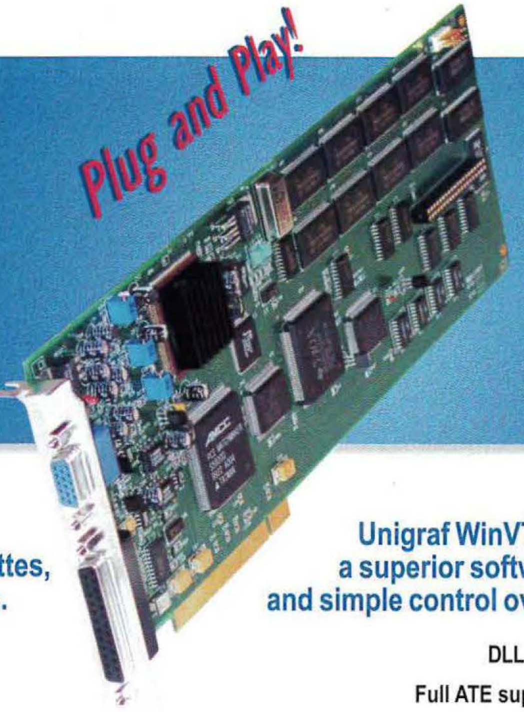

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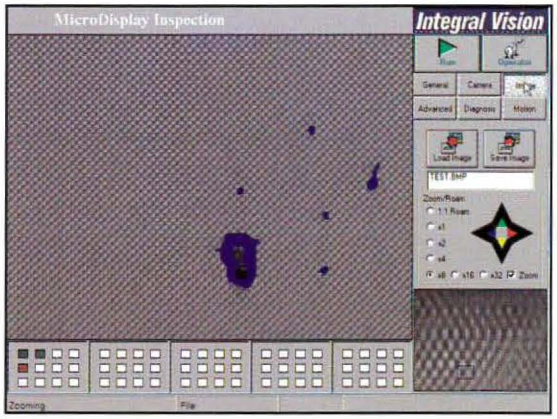

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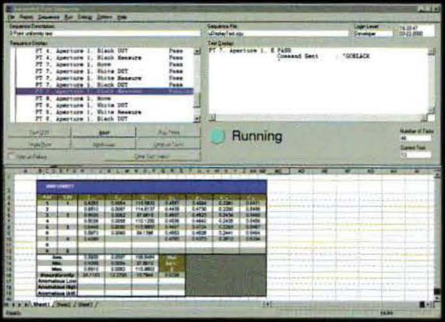

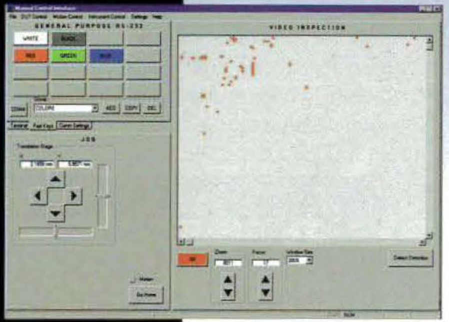

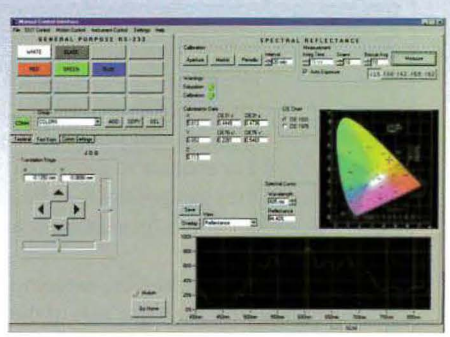

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Circle no. 8

Optical-System Designs for LCoS Front Projectors

LCoS front projectors could change the display landscape, but only if optical systems can be made that offer high throughput, high contrast, compact dimensions, and low cost.

by Matthew Bone

IN RECENT YEARS, the viability of liquid-crystal–on–silicon (LCoS) technologies has been successfully demonstrated and introduced to the marketplace. The basic structure of an LCoS device is that of a more or less traditional liquid-crystal "sandwich" positioned on top of a CMOS silicon chip (Fig. 1). But the lower pixel electrodes are metallic mirrors instead of transparent indium tin oxide (ITO), and the pixel-switching transistors are not the thin-film transistors (TFTs) of traditional liquid-crystal displays (LCDs), but single-crystal CMOS transistors fabricated in the chip. This structure controls the reflection of light that enters the device from the front (or top in Fig. 1), in contrast to the more common LCD structures that control the transmission of light from a source positioned behind the display.

It turns out that extracting the outgoing modulated light from the same side of the display that receives the incoming unmodulated light is challenging – at least if the task is to be done in a way that is simultaneously efficient and inexpensive. So, a key to implementing three-panel LCoS projection systems is the optical-system design. For front-projector applications, the optical system must support high resolution, high lumen throughput, high contrast, and low cost. At the same time, the optical-system design must be consistent with a low-noise, low-cost, lightweight, and compact mechanical design.

Most LCD projectors on the market today use transmissive LCDs having polysilicon TFTs for their pixel switches. And many of these polysilicon products use the same basic three-path optical architecture, which is a mature design that delivers competitive brightness, contrast, package design, and cost (Fig. 2). Optical designs for LCoS projectors must essentially match the performance of this standard transmissive design.

Future growth markets for projection technology include monitors and consumer TV and HDTV, which require contrast ratios of greater than 300:1. If LCoS technology is to penetrate these markets, the contrast requirement must be satisfied with low-cost high-performance optical architectures.

Several design approaches have been used for three-panel projection engines. Most of them are "on-axis" designs, as are most optical systems in general. Let's look at these

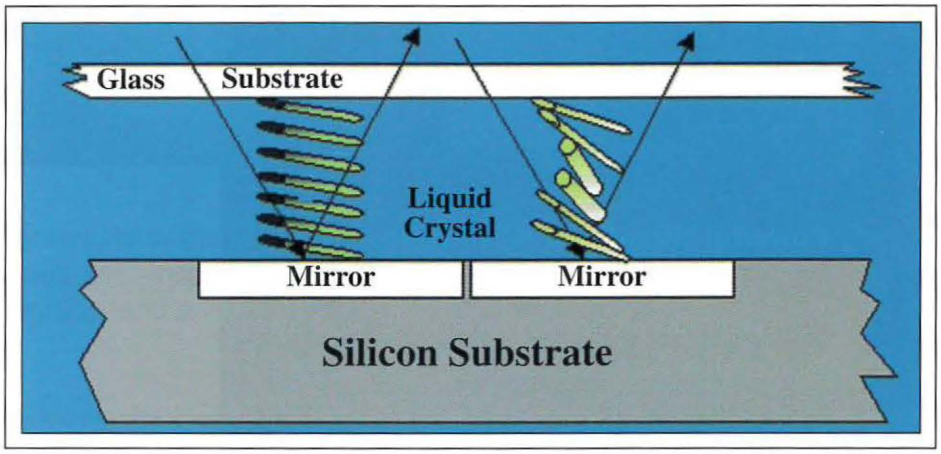

Fig. 1: The basic structure of an LCoS device is that of a more or less traditional liquid-crystal "sandwich" positioned on top of a CMOS silicon chip.

Matthew Bone *is Senior Director, Optical Systems, at Aurora Systems, Inc., 60 Daggett Dr., San Jose, CA 95134; telephone 408/432-7917, fax 408/452-5568, e-mail: mbone@aurora-sys.com. This article was adapted from the author's presentation at Microdisplay 2000 (Boulder, Colorado, August 7–9, 2000).*

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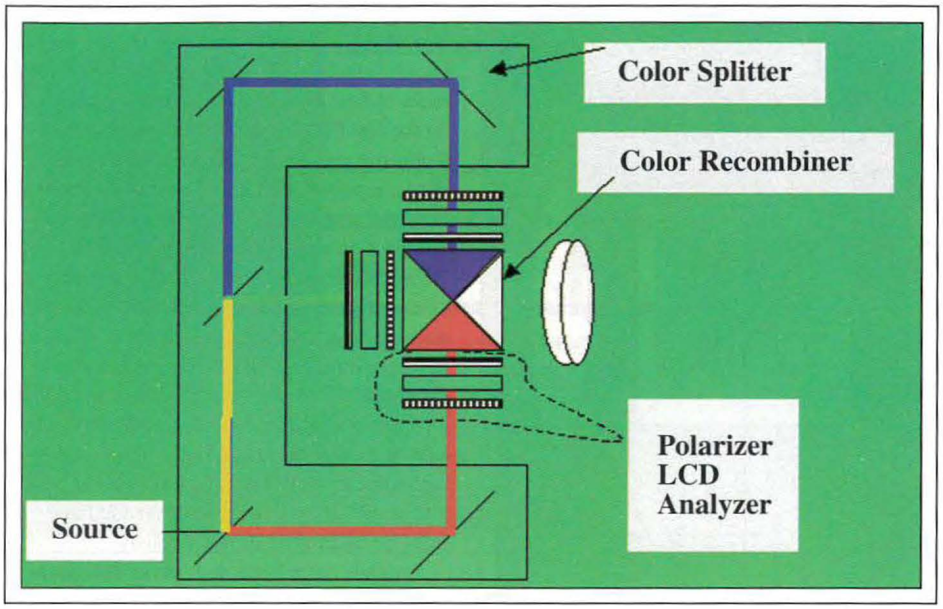


Fig. 2: *This basic three-path optical architecture is a mature design that delivers competitive brightness, contrast, package design, and cost.*

projection systems, and then do the same for a unique off-axis system we have designed at Aurora Systems, Inc.

Optical Designs

In a transmissive LCD optical system, the polarizing and analyzing functions are isolated from the color optics. Consequently, the limiting contrast of each color – exclusive of the LCD – is determined by the film polarizers only. Film polarizers of this type can support extremely high contrast ratios of more than 1000:1 at the *f*/numbers required to achieve high lumen throughput. In combination with a transmissive LCD, a contrast exceeding 300:1 is easily achieved. In addition, the separation of the color splitting and recombination optics allows system colorimetry to be controlled very precisely.

Things may not be so simple for reflective projectors, but a number of reflective architectures have been reported over the years. In one very compact on-axis layout, light from a source is polarized by a polarizing beam splitter (PBS) and reflected towards a color cube and LCoS display (Fig. 3). The color cube separates the polarized beam into the primary colors.

In this architecture, the limiting contrast for the optical system is dominated by the thin-film design of both prisms and stress birefringence in the glass. System contrasts of greater than 100:1 could not be achieved easily at competitive *f*/numbers.

Modifying this general architecture by incorporating a Philips Prism reduces the angular sensitivity of the P and S splitting in the dichroics, which provides a better opportunity to preserve the integrity of the polarized light transmitted through the system (Fig. 4). But the use of total internal reflection (TIR) in this layout introduces additional reflections which are likely to introduce changes in polarization state and subsequent degradation in contrast. Opportunities to improve the contrast of the Philips Prism architecture have been reviewed in the literature, and theoretical limiting contrasts of more than 1000:1 have been reported. But we don't know of any products that use this type of design.

The problems associated with having the color separation and recombination embedded within the polarizing/analyzing path can be reduced by using an architecture similar to that developed by Robert Melcher and his colleagues (Fig. 5). In this layout, a PBS is used for each color, and the color splitting and recombination optics operate in the same mode as that of a transmissive system. Using a PBS for each color minimizes the contrast losses from depolarization by tilted color-splitter coatings, but it also adds cost and complexity. Nonetheless, products based on this architecture have been commercialized.

Recently, Sharp and Birge reported that wavelength-selective retarder stacks can be used to manipulate the polarization and color management in optical systems [*SID Intl.*

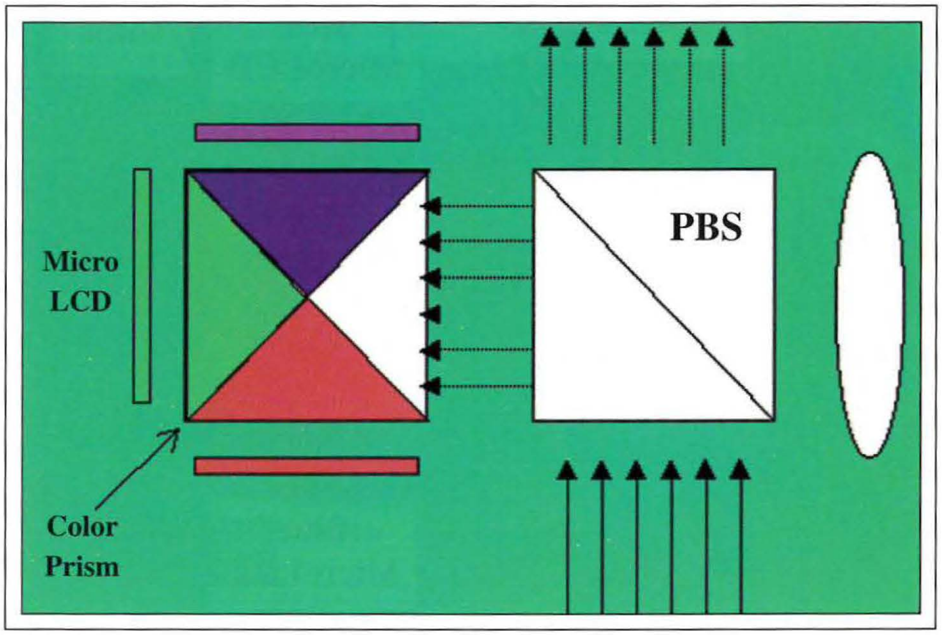


Fig. 3: *In one very compact on-axis LCoS design, light from a source is polarized by a polarizing beam splitter (PBS) and reflected towards a color cube and the microdisplay.*

Symp. Digest Tech. Papers, 1072 (1999)]. The ability to control polarization and wavelength selectively has enabled the development of new optical-design configurations. At the last SID International Symposium, Robinson and Korah, together with Sharp and Birge, reported a new design that takes advantage of these retarder stacks to create a very compact on-axis optical design (Fig. 6).

In all designs that use a PBS, the projection of the polarization vector onto the LCD is not uniform as a function of field angle. This can severely limit contrast as the *f*/number is decreased. Consequently, contrast and brightness are coupled in an undesirable way. On-axis reflective designs have the potential to minimize product package size, but the color and polarization optics are embedded and must be optimized simultaneously.

Another complication of these designs is that lower-cost glasses such as BK7 and SF2 have relatively high stress coefficients that

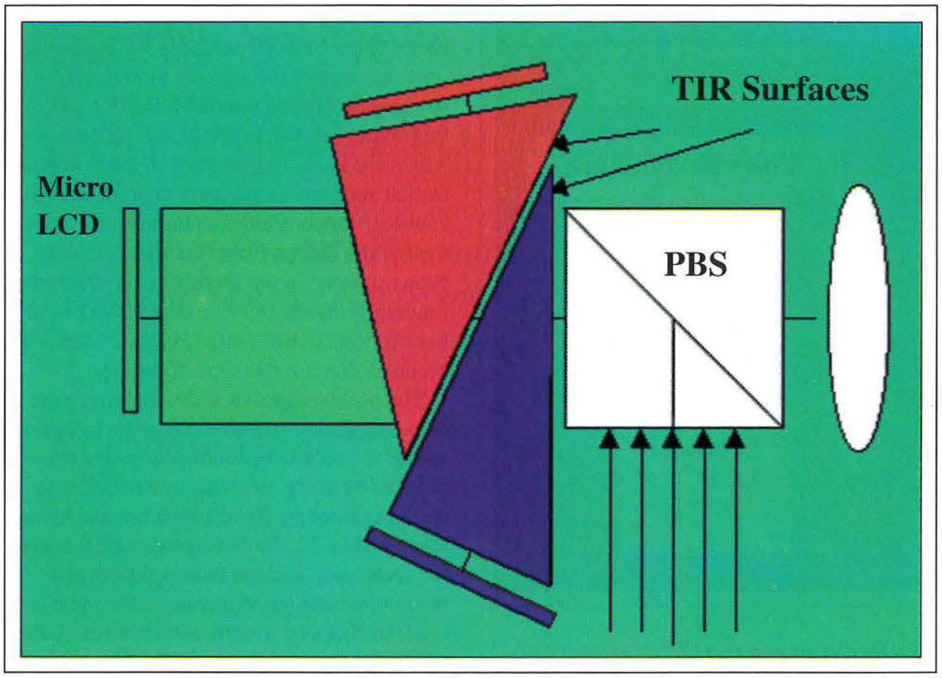


Fig. 4: *The Philips Prism architecture includes a broadband PBS, low-stress glass, and a complex thin-film design.*

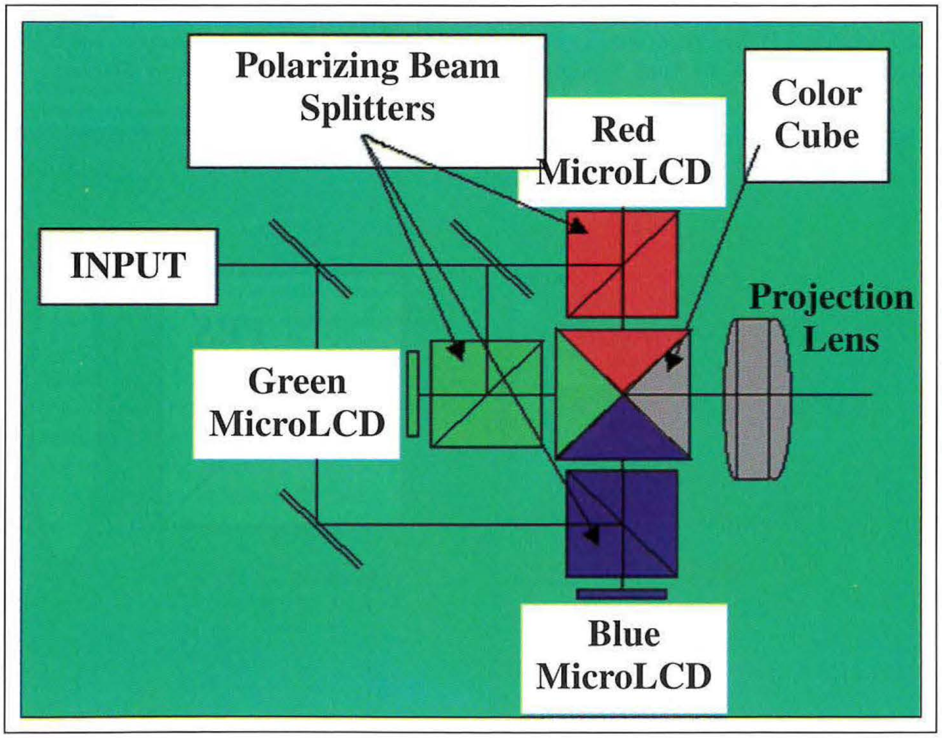


Fig. 5: *The three-PBS design for reflective LCDs uses a PBS for each color, and the color splitting and recombination optics operate in the same mode as that of a transmissive system.*

Table 1: System Performance

Specification	Performance
Luminous flux	>1100 lm ANSI
Lamp type and power	150 W UHP (>7.0 lm/W)
Sequential contrast	>300:1
ANSI contrast	>150:1
Colors (x/y)	
Red	0.64/0.35
Green	0.32/0.65
Blue	0.14/0.04
White	0.29/0.30 (6500K)
Color uniformity (du′v′)	<0.015
Native resolution	XGA 1024 × 768 or SXGA 1368 × 1024
Optical-engine size	233, 278, 116 mm
Device size	0.97-in. (19-µm pixel pitch)
Zoom lens	1.3:1 zoom
Image offset	100%
Distortion	<0.25%
MTF (33 lp/mm)	>50%

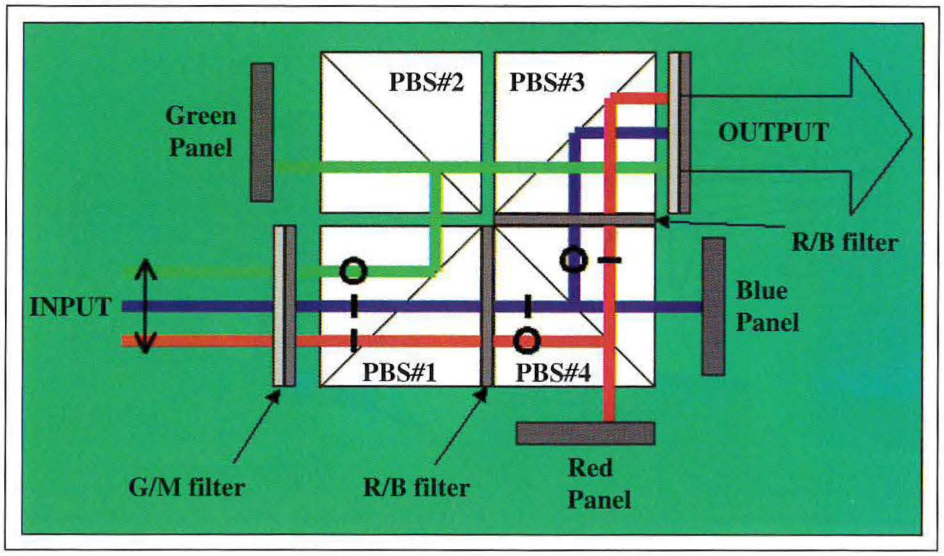


Fig. 6: *This new four-prism architecture takes advantage of the retarder stacks to create a very compact on-axis optical design.*

can result in severe problems with black-state uniformity. The stresses induced by coatings, mechanical mounting, and thermal gradients can result in retardation of more than 30 nm in a 30-mm prism of BK7 glass. If the axis of retardation is aligned at 45° to the polarization vector, a limiting contrast of less than 50:1 can be expected. The most common manifestation of this problem is bright corners with very low contrast, which is unacceptable for most commercial products.

The lowest stress coefficients are found in materials such as SF57 (Schott) and PBH71 (Ohara). New high-transmission versions of these glasses could significantly reduce stress-induced birefringence.

Off-Axis Design

At Aurora Systems, we have developed an approach to reflective-projector design that addresses the need for high contrast and cost-effectiveness. To achieve high contrast, we separated the color-splitting and recombination optics. We did this by using an off-axis architecture – one in which the central light ray enters at least some of the optical elements at an angle to the element's optical axis. A new design based on this architecture has been completed. It has extremely low distortion and operates at *f*/2.65 (Fig. 7).

In this layout, the source is separated into the primary colors and then polarized prior to impinging upon the microdisplay. The reflected beam is analyzed by a separate polarizer that is optically isolated from the illuminating beam (this is possible because of the off-axis design). With this approach, low-cost film polarizers can be used and very high contrasts can be achieved.

Off-axis optical designs have been used infrequently because they have the reputation for requiring expensive aspherical optical elements. And off-axis designs do present challenges to the lens designer that must be addressed. One previously reported design used a truncated optical element to couple the off-axis beam into the projection lens. This design had marginal distortion and was limited to *f*/3.5.

In the new design, the off-axis beam is coupled into the main projection lens through a decentered and tilted doublet. This design has been fabricated using only spherical optics, and it can be manufactured using high-volume low-cost manufacturing techniques. The optical performance of the lens exceeds the requirements (Fig. 8). The design presented here uses an LCoS microdisplay with a pixel pitch of 19 μm. The modulation transfer function (MTF) at this limiting spatial frequency [26 line pairs per millimeter (lp/mm)] is over 60%. A zoom-lens design has also been completed for use in front-projection applications.

Where Are We Now?

Table 1 summarizes the typical performance of a front-projection system using the off-axis design we've described. Prototype systems readily produce a luminous flux of more than 1000 lm. In an LCoS device with a diagonal of 0.97 in., system efficiencies of more than 7.0 lm/W have been demonstrated at *f*/2.65.

The limiting contrast of the optical system is greater than 1100:1, and system contrasts of more than 400:1 have been demonstrated using a 45° TN LCoS device. Recently, new designs have produced system contrasts greater than 500:1.

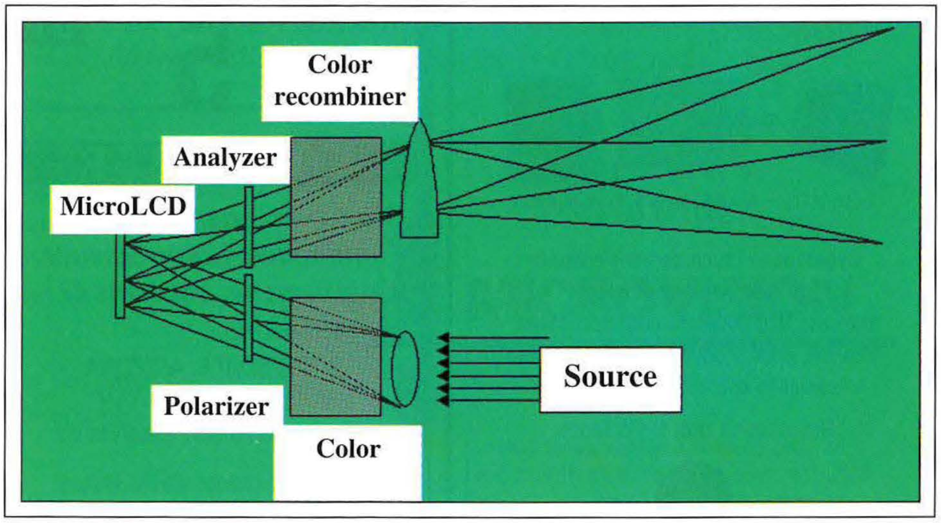


Fig. 7: *In this new off-axis optical design the color splitting and recombination optics are isolated from the polarizer/analyzer functions and each LCD has an independent polarizer/analyzer pair. It has extremely low distortion and operates at f/2.65.*

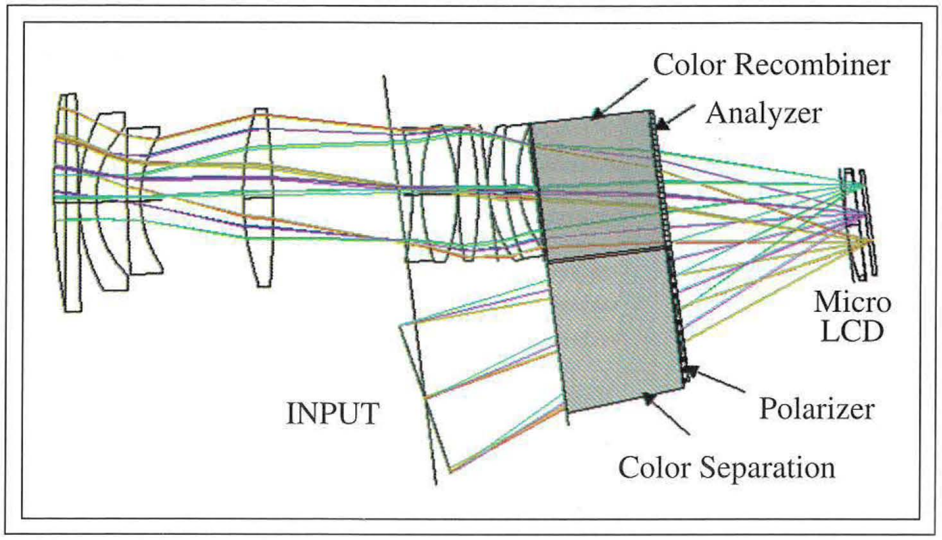
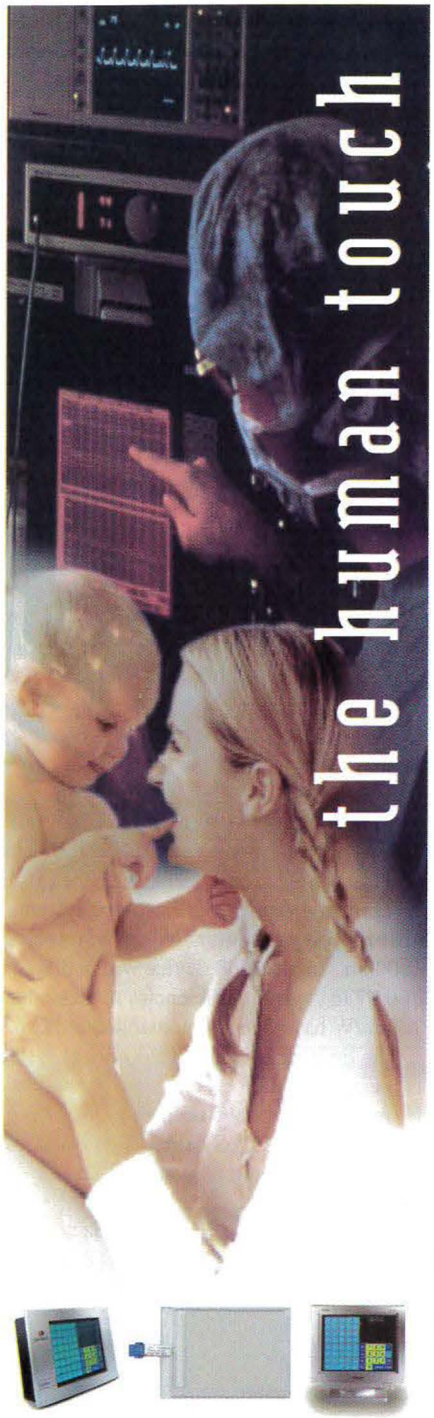


Fig. 8: *In this new design, an off-axis beam is coupled into the main projection lens through a decentered and tilted doublet. This design has been fabricated using only spherical optics, and it can be manufactured using high-volume low-cost manufacturing techniques. The optical performance of the lens exceeds the requirements.*

The design is scalable to higher resolutions (XGA, UXGA, and HDT) and smaller chip sizes, and it uses mature optical-component technologies that can be readily purchased in volume. Incremental performance improvements can be expected as coating, lamp, and illumination technology improves. ■

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Are Tiled AMLCDs Ready to Leapfrog Large FPD Trends?

Seamless display tiling has failed in the past, but Rainbow Displays has shown impressive prototypes and is ready to ramp up.

by Ray Greene, Peter Krusius, Don Seraphim, Dean Skinner, and Boris Yost

ACTIVE-MATRIX liquid-crystal displays (AMLCDs) have become the dominant flat-panel-display (FPD) technology, and appear to be ready to overtake the cathode-ray tube (CRT) within a couple of years. Practical color LCDs using passive-matrix addressing were first introduced in personal portable-display applications, particularly televisions and computers.

The first generation of AMLCD products were introduced in the early 1990s in portable computers. The AMLCD overcame the electrical coupling problems that had plagued earlier FPDs by controlling pixels with thin-film transistors (TFTs). Because first-generation AMLCDs were designed for VGA format (640 × 480 pixels), about 307,000 TFTs were needed for monochrome displays and about one million TFTs for color displays. The number of row-to-column interconnect crossovers in such panels equals the TFT count. As a result, AMLCD-panel manufac-

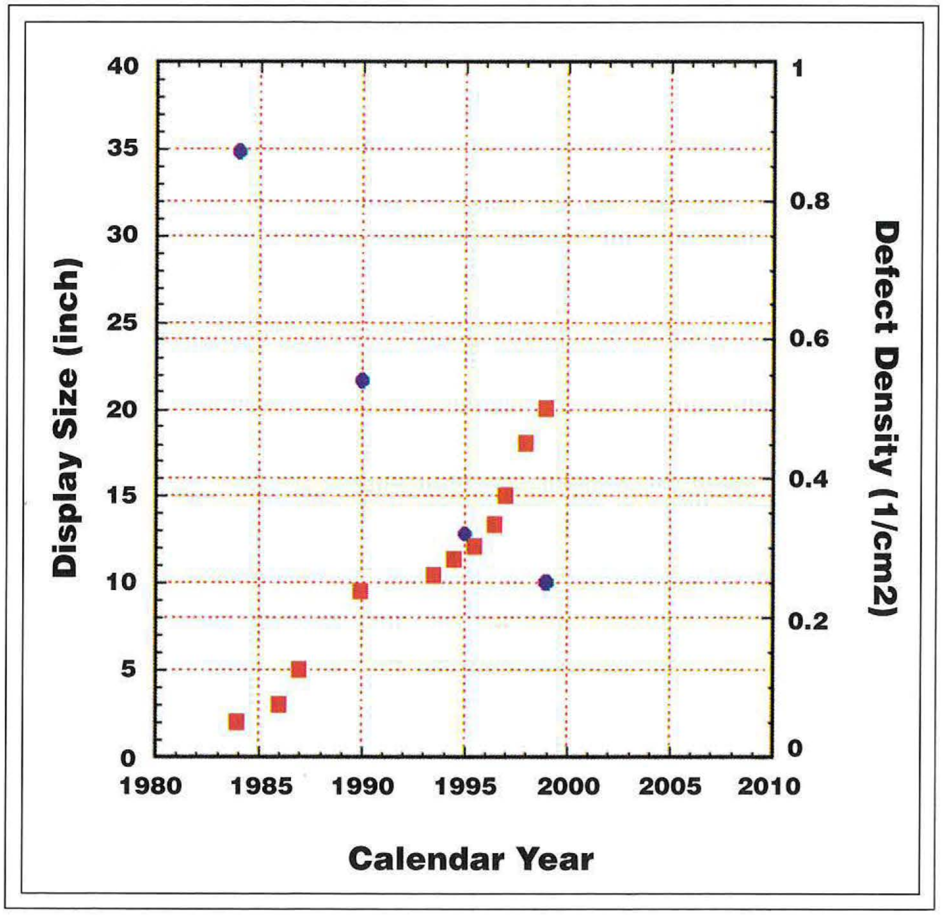

Fig. 1: *The size of practical monolithic AMLCDs (red) can increase only to the extent permitted by reductions in defect density (blue). (Data from Morozumi, HAPD, Japan, 1999.)*

Ray Greene, Peter Krusius, Don Seraphim, Dean Skinner, *and* ***Boris Yost*** *form the core of the technical team at Rainbow Displays Inc., Glendale Technology Park, 1041 Perimeter Rd. East, Endicott, NY 13760, that has developed the company's seamless tiled AMLCD technology. Contact information for Peter Krusius: telephone 607/754-5670, ext. 28, fax 607/754-7218, e-mail: krusius@rainbowdisplays.com, URL: www.rainbowdisplays.com.*

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Rainbow Displays, Inc.

Fig. 2: *Rainbow Display's 37.5-in. WVGA SDTV display is composed of one row of three tiled AMLCDs, with vertical seams. (The image on the display is from the 1999 ICIA INFOCOMM Shoot-Out CD.)*

turing became yield-limited and first-generation AMLCDs were only 9–11 in. in size.

The filling of AMLCD assemblies with LC material, also a strongly size-dependent step, was the second major yield detractor. The introduction of larger AMLCDs required the development of tools, processes, and substrates with lower defect densities – and defect densities have declined impressively (Fig. 1). Today, defect densities are low enough to make the manufacture of moderately large AMLCDs practical.

The largest AMLCDs in volume manufacturing today have diagonals of about 21 in., but display sizes large enough for typical video, TV, and HDTV applications are nowhere in sight. But unless the current AMLCD-manufacturing paradigm can be broken, the introduction of wide-screen (25–50 in.) AMLCDs in high volumes will remain an elusive dream. This realization provides the entry point for the tiled AMLCDs we are pursuing at Rainbow Displays, Inc. (Fig. 2).

Approaches to Tiling

There are two fundamentally different ways to assemble tiled displays. In the first, the seams between the display tiles are deliberately made visible, and displayed images are

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Fig. 3: *This simulated image suggests the appearance of a tiled display with visible seams in a 1 × 3 array.*

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Fig. 4: *This simulated image suggests the appearance of a tiled display without visible seams in a 1 × 3 tile array. In a truly seamless display, seams are not visible in any image data viewed under the intended conditions.*

Table 1. Specifications of Seamless Tiled Color Video AMLCDs from Rainbow Displays

Display characteristic	2 × 2 SVGA	1 × 3 SDTV	Units
Tile technology	TN-AMLCD	TN-AMLCD	
Tile array	2 × 2	1 × 3	
Tile addressing	Two-sided matrix	One-sided matrix	
Display aspect ratio	4 × 3	16 × 9	
Display pixel format	800 × 600	852 × 480	
Pixel pitch	0.980	0.974	mm
Pixel area dimensions (diagonal)	784 × 588 (980)	830 × 468 (952)	mm
Pixel scan	Progressive Quad	Progressive One Edge	
Frame rate	60	60	Hz
Pixel response		<25	msec
Aperture ratio (apparent)	50	75	%
Color space	24	24	bit
Color saturation		68	% NTSC
Brightness	200	500	cd/m^2
Contrast (dark)	100:1	200:1	
Viewing angles (H/V)	160/160	160/140	degrees (°)
Housing depth	130	150	mm
Display power		<350	W
Display weight		22	kg

extended continuously over the tiles and seams (Fig. 3). This approach is used by Clarity and Pioneer, among others, in their stackable video-wall display products.

In the second tiling approach, an attempt is made to hide the seams and, if possible, make them completely "invisible" or "seamless" under specified viewing conditions (Fig. 4). This is very difficult to achieve for all but the largest pixels – more than 20 mm. Attempts by Magnascreen, a defunct Pittsburgh-based company, and Sharp of Japan were not successful. Rainbow Displays has recently overcome the barriers that blocked these efforts, and has developed seamless tiling technology for AMLCDs with pixel pitches less than 1 mm.

A truly seamless direct-view display must hide all structures at the edge of the display tiles in the inactive areas of edge pixels. In addition, the visual appearance of the edge pixels must match that of pixels located in the interior of the tiles.

Nonuniformities in tiled displays arise either from optical or electrical factors. Nonuniformities such as checkerboard appearance, dark seams, and bright seams cannot be -allowed. These overall goals lead to the following requirements for seamless tiled displays designed for a specified range of viewing distances and a specified distribution of viewing angles:

- Continuous pixel pitch across the seems.
- Tile alignment with a lateral precision better than visual acuity.
- Uniform tile luminance across the seams.
- Uniform tile chromaticity across the seams.

Seamlessness is judged by the viewer's ability to detect any seam-related artifacts or patterns, a capability dependent on visual acuity and sensitivity to contrast, brightness, and chromaticity. These requirements are very demanding and can only be met for displays in which the tile edges can be fabricated with a precision much better than pixel size. The AMLCD is such a display.

Designing a Tiled AMLCD

Conventional monolithic AMLCDs are usually accessed from two edges by attaching row and column driver chips to the TFT's

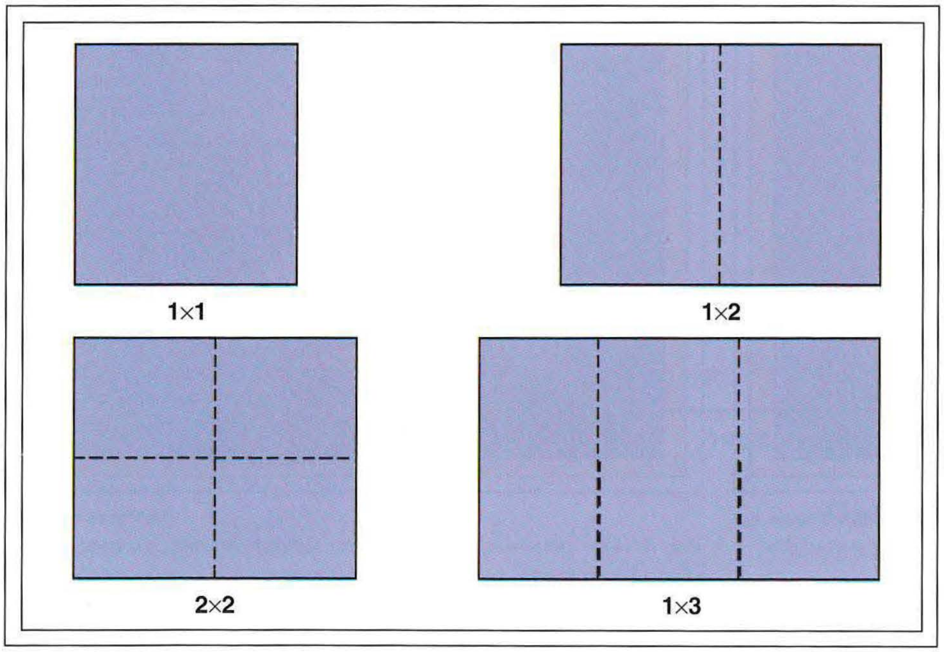


Fig. 5: *In these examples of possible tile-array formats, the tiles are accessed from one or more edges.*

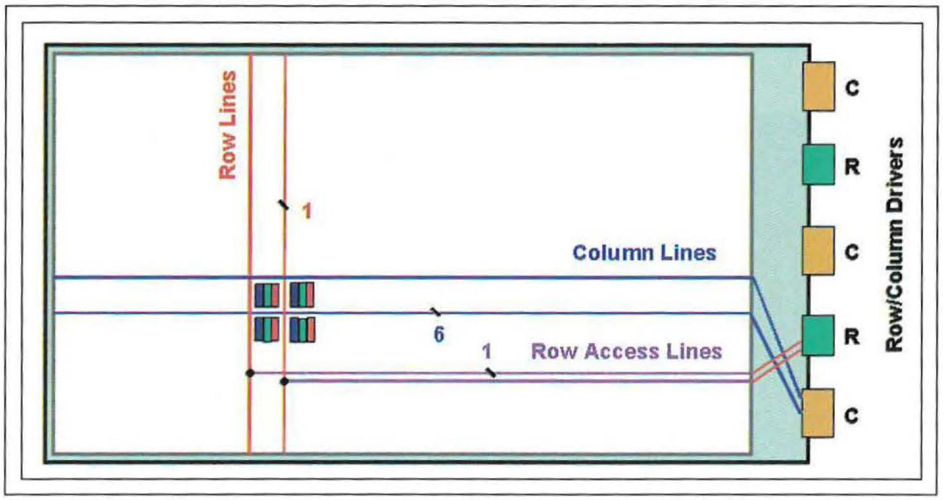


Fig. 6: *Pixels in Rainbow Display's 21-in. AMLCD tile are arranged in double columns with six column lines running in between. Matrix addressing is used, and access is through just one edge of the tile. Row access lines run parallel with column lines. R and C refer to the row and column driver TABs.*

glass substrate using tape-automated-bonding (TAB). In this access technique, tiling can only be done if at least two edges of each tile remain accessible, which limits tile arrays to 1 × 1, 1 × 2, or 2 × 2 formats.

In a more radical departure from common practice, Rainbow Displays has shown that tiles can also be accessed from a single edge, which makes 1 × *n* and 2 × *n* tile arrays possible (Fig. 5).

This single-sided wiring, combined with matrix addressing, requires row and column lines to cross outside the pixel array in the fan-out region close to the TABs (Fig. 6). These crossovers facilitate the reordering of row and column lines so that conventional row and column driver chips can be used. The number of crossovers in the fan-out region is still small compared to the row-to-column crossovers within the pixel array.

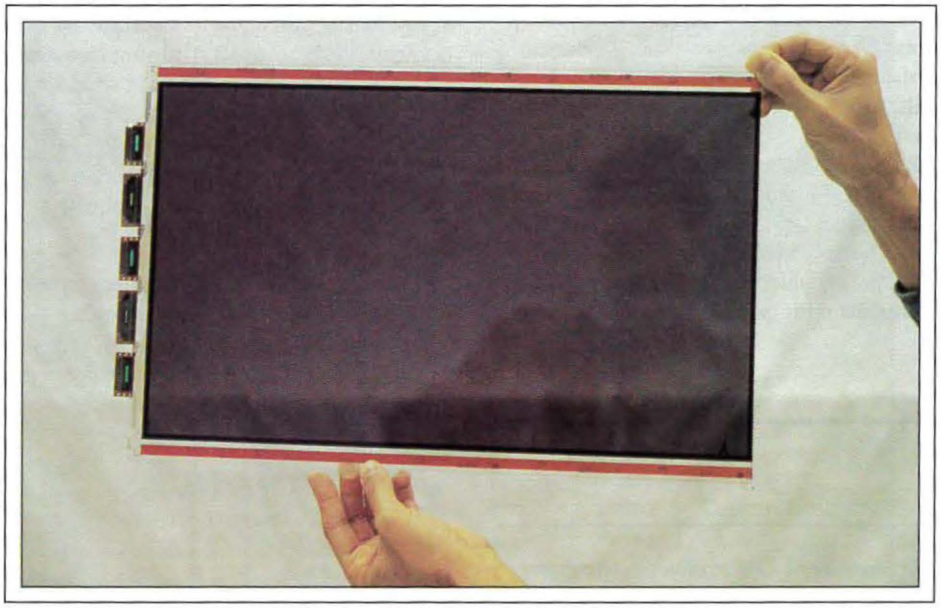
Except for the narrow seal and the precisely fabricated tile edge, both of which must fit into the inactive areas of the edge pixels, standard AMLCD manufacturing can be used for the tiles. This is true for both the TFT and color-filter (CF) glass substrates. Rainbow Displays has developed intellectual property that allows the narrow inner seal to be fabricated and the inner tile edges to be finished to the desired precision. Outer seal widths can remain at conventional values. Current tools facilitate seal widths of less than one-fifth of a 1-mm pixel pitch. Display tiles can also be filled on conventional AMLCD-manufacturing lines (Fig. 7).

The completed AMLCD tiles can best be assembled in their precise positions by laminating them between continuous glass cover and back plates with a compliant optical adhesive. Tiles are aligned using precise optical registration. Polarizer films can also extend continuously over the entire tile array. This produces a robust AMLCD assembly with mechanical characteristics similar to those of laminated windshields in automobiles.

Light rays passing through a tiled AMLCD assembly cannot be allowed to enter into the seam regions in a truly seamless display. Rainbow solves this problem by collimating light rays from the backlight to a predetermined angular distribution before they enter the AMLCD assembly. Additional aperture masks can be placed on the glass cover or back plates, if desired. A suitable optical screen mounted on the cover plate reshapes the angular distribution of the light rays emanating from the display.

In this light-management technique, the apparent aperture ratio can be made much larger than the physical one. It also allows tiled displays to be designed to a wide variety of visual specifications. Viewing angles for a tiled AMLCD operating in the twisted-nematic liquid-crystal (TN-LC) mode, for example, can be set much wider than those of a conventional AMLCD using the same mode.

Minor optical and electrical nonuniformities may remain, even after all of the above measures have been taken in the design, fabrication, assembly, and operation of the tiled



Rainbow Displays, Inc.

Fig. 7: *This 21-in. AMLCD tile for the 37.5-in. display has been fabricated on a standard AMLCD manufacturing line at Philips Components in Kobe, Japan. Kerf regions along the long edges of the tile have not yet been removed.*

display. Rainbow Displays applies proprietary signal-processing algorithms to incoming video data in real time to correct for residual nonuniformities, as well as to color balance the tiles. These algorithms are implemented on the display's control card.

Rainbow Displays has demonstrated this seamless tiling technology in two different direct-view FPD formats. The first is a manufacturing prototype of a video AMLCD with a 2 × 2 tile array, SVGA (800 × 600) format, and a 38.5-in. diagonal. The second is a product prototype of a tiled video AMLCD with a 1 × 3 tile array, SDTV (852 × 480) format, and a 37.5-in. diagonal. The SDTV unit has been developed jointly with Philips Flat Display Systems, with which Rainbow has a joint-development agreement.

Invisible seams in orthogonal directions are present in the 2 × 2 tile display, while the 1 × 3 display carries only two parallel invisible seams (the characteristics of these displays are summarized in Table 1). The SDTV display was showcased at CEATAC in October 2000 in Tokyo, Japan.

Rainbow Display's AMLCD tiling technology is scalable to smaller pixel sizes and larger display formats. The maximum tile size is limited by AMLCD manufacturing lines and their yields, while the maximum tiled display size can grow with the availability of the common glass plates and polarizer films. The minimum pixel pitch is determined by the ability to manufacture reliable narrow seals, precision tile edges, and the TFT aperture ratio.

Rainbow Displays is currently developing its first HDTV product with a 42-in.-diagonal 16 × 9 aspect ratio, and 1280 × 720 pixel format. The development is being done jointly with Philips, which holds a minority equity investment position in Rainbow Displays. ■

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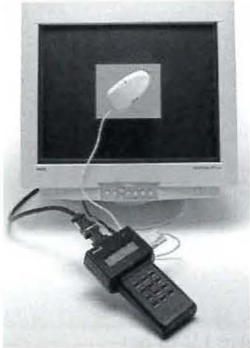

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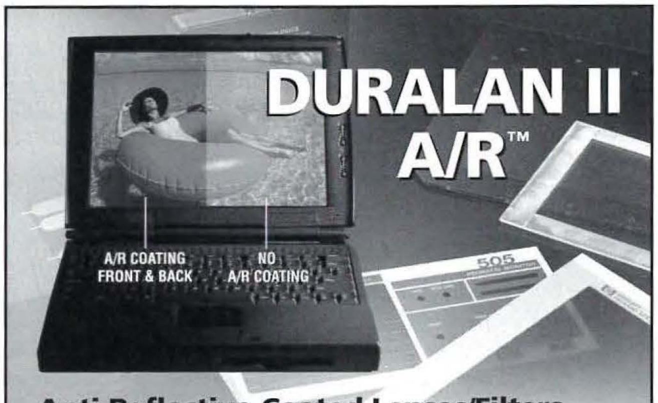

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Opinion: The AMLCD Is the Ultimate Avionics Display

The requirements for avionics displays are higher than ever, and of all the available technologies only properly ruggedized AMLCDs can meet today's criteria.

by Lawrence E. Tannas, Jr.

AVIATION is about to celebrate its 100th anniversary. During the last century, we have experienced the Age of the Mechanics of Flight, which included developments such as aerodynamics, radial engines, supersonic flight, and jet engines. We are now in a new age that could be called the Digital Electronics Age.

Digital electronics is having significant impact, but is almost unrecognizable because of its slow development relative to the industry at large. The new digital avionics is the best hope for improving safety by a factor of 10, the goal established by the U.S. National Transportation Safety Board (NTSB) for the 21st century. But the central technology of this age must be the electronic cockpit display, which couples the pilot to all of the avionics and the airplane itself (Fig. 1).

Digital Electronic Age

The aviation industry is very conservative. Changes do not occur as revolutions but as evolutions – and typically do so well after the revolution has occurred elsewhere. Also, because the aviation industry is not a major user of electronics it has a minor impact on the course of events in the electronics industry. Aviation generally follows on the coattails of developments in the industrial world at large. An exception is the quest for air superiority for national defense, where developments in the interest of advanced performance are not justifiable on purely economic or safety grounds.

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The digital electronic evolution includes the use of microprocessors instead of analog computers and sequences, electronic fly-by-wire controls instead of cable linkages, glass cockpit displays instead of analog gauges, hand-held calculators instead of E-6B circular slide rules, and GPS navigation instead of earth-bound VHF radio signals. Yet, perhaps only 10% of the 200,000 or so airplanes in worldwide service today are equipped with integrated digital avionics. Fewer aircraft are outfitted with the complete electronics suite of GPS, TCAS, *etc.*, with integrated electronic computers, buses, and displays, and with redundancy to meet the MTBF requirement and single-point and generic-failure criteria unique to aviation. Because the cost of the new digital avionics is high, the non-turbine sector of general aviation has not changed yet, and the turbine sector has been slow to bear the cost of conversion.

The Digital Cockpit

The new components and systems enable information to be gathered, reorganized, and presented to the pilot to enhance his or her situational awareness. Digital avionics includes sets of components and systems such as

- Microprocessors, memory chips, electronic buses, ASICs, *etc.*
- Flat-panel displays.
- Solid-state sensors.
- Global-positioning satellite systems.
- Collision-avoidance systems.
- Ground-proximity warning systems.
- Lightning and wind-shear detectors.
- Satellite communications.
- Radar.
- Sensors, cameras, *etc.*

The enablers are integrated to give the pilot new display groupings:

- Electronic Flight Instrument System (EFIS) for all the primary flight data, such as attitude, speed, altitude, and heading.
- Navigation Situation Display (NSD), showing flight path, waypoints, weather, terrain, traffic, lightning strikes, *etc.*, all on a horizontal map rotating with heading up.
- Engine instruments, showing the status of all engines.
- System status, showing the status of all systems, including pages of detailed information with diagrams for each system.
- Flight Management System (FMS) for computing flight profiles and flight planning.
- Electronics library, showing handbooks, checklists, maps, *etc.*
- Backup displays for primary flight control.

Each of these groupings is now typically shown on a single display, where EFIS, NSD, and the electronics library (when used) are repeated for the copilot; engine instruments and system status are centrally located and interchangeable; FMS is doubly or triply redundant and on the pedestal; and backup displays are on a single, centrally located display.

The first four groupings are all interchangeable for redundancy, and several formats can be combined into single formats. There is enough redundancy so that one display can be non-functional and the pilot can still safely depart with the passengers.

In consideration of the pilots' learned skills and expectations, new training needs, fleet commonality, and safety, the arrangements of displayed information and formats are always only one small step from the previous cockpit panel.

The Display Is Critical

The display is key to the new digital electronic cockpit. Analog displays always lacked many features we now demand in the new glass cockpit. New displays must have the following characteristics (Table 1):

- Good resolution, contrast, uniformity, and brightness.
- Multimode operation.
- Sunlight readability.
- Dimmability.
- Color.
- Freedom from parallax.
- High ratio of display area to panel space.
- Cross-cockpit visibility.
- Video speed with gray scale.

An aviation display must be readable at any time within a fraction of a second, regardless of lighting or other environmental or flight conditions. This requirement is unique to aviation and essential for pilot instrument-scan patterns and flying technique. The pilot is not expected to move his or her head to read a primary flight instrument. For the new digital avionics, gyros cannot tumble or drift, images cannot wash out in bright light during the day

The Boeing Company

Fig. 1: This state-of-the-art "glass cockpit" is standard issue in Boeing's new 767-400ER. Display layout and format are common in the Boeing 777. The displays and system integration for the 767-400ER are by Rockwell Collins.

Table 1: Performance Ratings of Critical Display Parameters by Technology

Performance	AMLCD	Taut CRT	Domed CRT	LED	EL	PDP	FED	OLED
Constrast in sunlight	2	2	3	3	4	5	5	5
Color in sunlight	1	3	3	5	5	5	5	5
Resolution/dimming	1	4	4	3	5	5	5	5
Uniformity/off-axis	2	2	2	2	2	2	2	2
Uniformity/normal	1	2	2	2	2	2	2	2
Video/gray shades	2	1	1	1	2	1	1	1

The rating criteria are as follows:

1. Exceeds performance of the human visual system in the cockpit viewing geometry.
2. Fully meets performance requirements for cockpit open to direct-sunlight exposure.
3. Fully meets performance requirements for shielded cockpits, which are not exposed to direct sunlight.
4. Limited performance due to poor readability.
5. Unacceptable performance for aircraft applications or undemonstrated.

or flood the cockpit with light at night, and black-hole effects or white-shirt glare conditions cannot be tolerated.

The AMLCD is the only cockpit display that can do all the things we want done in the cockpit. It can do so only because of the things we learned to do during the developmental history of the glass cockpits, such as the use of a black matrix and the application of precision antireflection coatings.

Recent Developments

Two relatively recent AMLCD developments have crowned the technology's superiority for avionics displays. The first is logarithmic dimmability over the full mesopic and photopic visual range. No other display technology offers this ability without the sacrifice of another performance parameter, such as resolution in the case of CRTs. The wide dimming range of AMLCDs is made possible by the separation of the luminance source and the image-generating mechanism. The backlight and image are completely independent, and the AMLCD can be made as bright or as dim as the backlight allows. Dimming ranges up to 4000:1 are available.

The second recent development is the ability to make the display immune to ambient illumination without loss of contrast or color separation. This was the greatest challenge for avionics-display engineers; the industry has struggled to overcome it since the introduction of CRTs into the cockpit.

The first breakthrough in making monochrome CRTs sunlight-readable was the use of P43 rare-earth phosphors with an emission spike in the green and high-density narrowband filtering designed to pass the green emission and absorb all other wavelengths of light. This was later extended to red and blue emissions. Domed- and taut-shadow-mask CRTs best maintain color purity and luminance with high beam current, and they are used extensively in avionics.

LCDs differ from all other technologies in that reflected light contributes to the image. Light incident on the display is either absorbed by the polarizers or transmitted through the open image-generating pixels and reflected back out from the backlight assembly toward the viewer. The ambient light passes through the color filters of each open pixel twice, so there is little or no color desaturation.

Wash-out comes from first-surface reflections or reflections from internal artifacts that cannot be eliminated but which have been minimized in high-quality AMLCDs. The image reflections from external illumination in color AMLCDs are small because of the small aperture and color filters. If the image reflection exceeds the first-surface and artifact reflections, the display can never completely wash out and the colors will remain saturated.

All other display technologies have a spatially uniform broadband reflection regardless of the image, which causes them to wash out at some point. Wash-out in CRTs, for instance, is characterized by a simultaneous loss of contrast and color gamut. At high ambient illumination, the AMLCD is characterized by a low but constant contrast and wide color gamut. So luminance contrast may be diminished while color contrast is not diminished, resulting in a continuously functional display.

Options for Custom AMLCDs

The availability of aviation-grade AMLCDs has been limited and the price has been high. The 1998 closing of OIS – the primary source of custom aviation AMLCDs in the U.S. – may go down as one of the greatest tragedies of the American display industry. One option available in today's market is to resize and customize a commercial-off-the-shelf (COTS) AMLCD to get a lower-cost square display or simply customize a rectangular COTS AMLCD without resizing. Both of these options are viable and cost-effective. But they are not the form, fit, and functional replacement of previous designs. The industry is using custom avionics displays available from several sources. Because the volume is low, they are priced more than an order of magnitude higher than COTS displays.

The image of a micro AMLCD can be rear-projected from inside the electronic instrument. The image can be made bright and nearly sunlight-readable. The size of the image is now unlimited because it is controlled by the projection optics, but the screen acts as a broadband reflector just as CRT phosphors do.

A color-sequential display utilizing a white imaging CRT with a liquid-crystal color shutter is of limited use in aviation. High readability under ambient light is achieved by means of the high-density color filtering of the LCD shutter. This CRT/LCD shutter combination does not reflect the image as a direct-view AMLCD does, and it eventually washes out like other CRTs.

Summary

The direct-view AMLCD has solved the last two problems in cockpit displays: sunlight readability with uncompromised color and unlimited dimmability with uncompromised resolution. This has been key to the evolution of digital electronic avionics and enhanced situational awareness. No other display technology has the potential to exceed – or even to match – the performance of AMLCDs in the cockpit. ■

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Circle no. 15

conference report

Kent and eMagin Show Innovative Prototypes at IDRC

Substrates and electronics for flexible displays, and technologies for electronic paper, were featured in special invited symposia.

by Ken Werner

The Society for Information Display's 20th International Display Research Conference (IDRC), held September 25–28 at The Breakers Hotel in Palm Beach, Florida, concentrated many of its most interesting papers in symposia of invited papers held at the beginning of each day's program. And, despite the lack of formal exhibits, IDRC included author interviews and poster sessions that frequently provided interesting demonstrations of display prototypes.

One of the invited symposia, Technologies for Electronic Paper, provided the most detailed presentation I've seen of E Ink Corp.'s innovative microencapsulated electrophoretic material, which is bistable, and a presentation of a new approach to ultra-low-power bistable LCDs from ZBD Displays. Y. Nakajima [Association of Super-Advanced Electronics Technologies (ASET), Tokyo, Japan] compared the strengths and weaknesses of different LCD technologies for full-color reflective displays. Most surprising (to me, at least) was a paper from J. H. Morrissy (Three Five Systems, Tempe, Arizona) that effectively made a case for fairly conventional LCDs being the technology of choice for low-power reflective displays.

In "Ultra-Low-Power Bistable LCDs," G. P. Bryan-Brown (ZBD Displays Ltd., Malvern, U.K.) discussed a variety of technological approaches to liquid-crystal (LC) bistability. In general, the approaches provide surfaces to which the LC molecules can attach in one of two ways, and the resulting states are usually splayed. One represents the OFF state and the other the ON state, and each is stable. Two splayed states permit "flexoelectric" selection, discovered in 1991.

Bryan-Brown zeroed in on gratings as the preferred way of establishing the different states, and wound up selecting a homeotropic monograting that leads to zenithal bistability (ZB) – the technology on which he based his company, which is a DERA spin-off. In a ZB display (ZBD), the LC domains are vertical in

Ken Werner

The PEDOT-based polymer-display prototype from Agfa-Gevaert and the University of Stuttgart was impressive for its high contrast ratio.

***Ken Werner** is the editor of* Information Display Magazine.

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one state and splayed from the normal in the other.

Bryan-Brown concluded that ZBDs offer power savings from 10 to 100 times greater than that of STN- or TFT-LCDs, offer the possibility of plastic LCDs without TFTs, and will permit an unlimited number of lines of displayed information. "Bistability," he said, "will be essential for high-resolution full-page electronic books."

In the Q&A session following the talk, Allan Kmetz asked, "Isn't refresh an issue in many of these displays?" Bryan-Brown answered, "Most of these bistable technologies can update 1000 lines in less than a second. There will be divergence by application. If full-color video rate is desired, very long battery life will probably have to be given up."

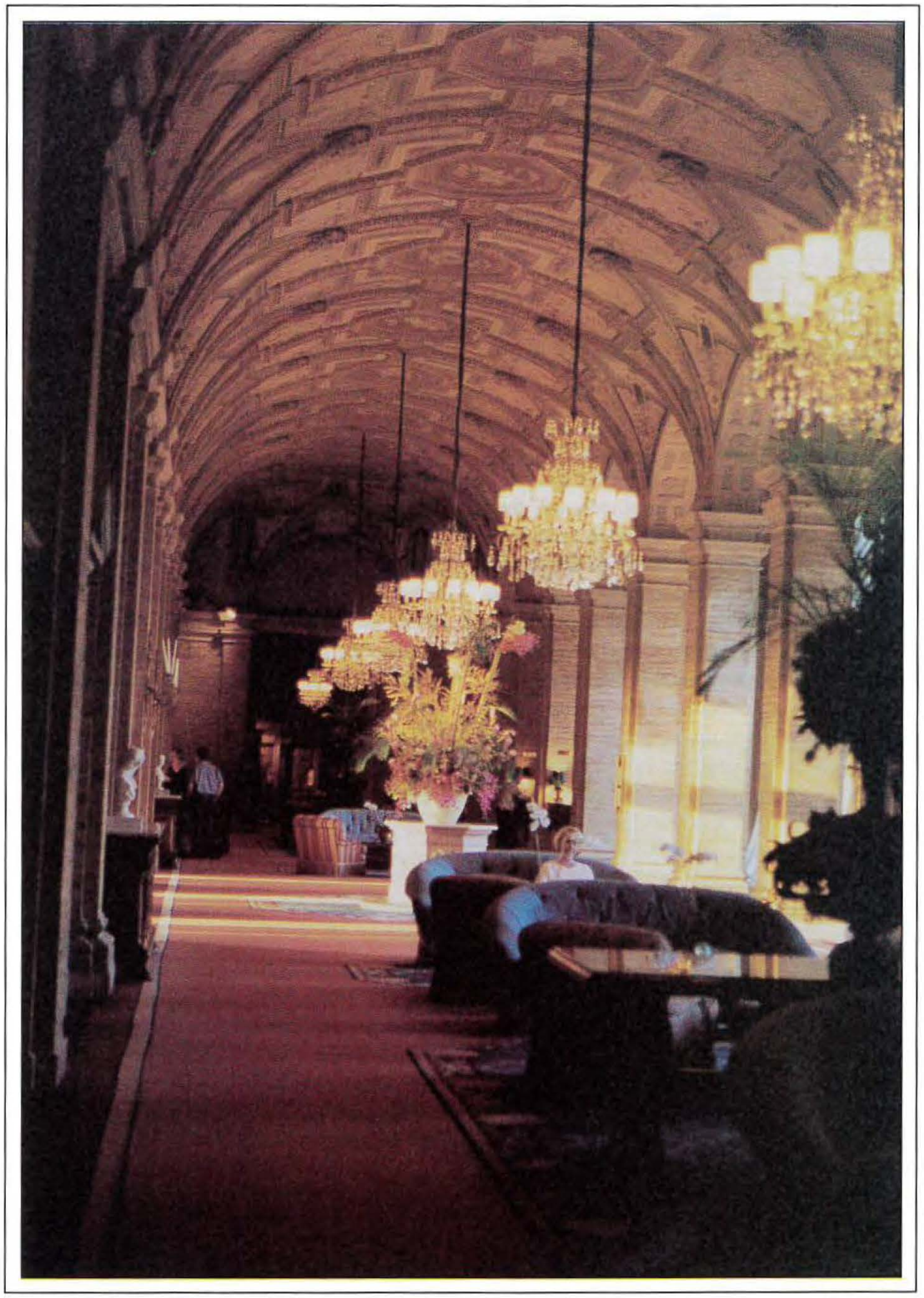
In "Microencapsulated Electrophoretic Materials for Electronic Paper Displays," Karl Amundson and Paul Drzaic of E Ink Corp. (Cambridge, Massachusetts) gave a detailed presentation of the status of their bistable technology, which has been under development for some time.

Electrophoretic (EP) displays utilize the mobility of charged particles through a suspending medium when an electric field is applied as the display medium. E Ink uses white particles in a blue-dyed medium. When the white particles are attracted to the "front" of the display, a white-on-blue image is produced. EP display research began in the 1970s. One difficult failure mode that presented itself was the transverse migration of the particles. E Ink's solution to that problem has been to encapsulate the solution in small microcapsules. With white particles and blue dye, the technology produces an appealing reflective display with full viewing angle, long-term image stability, low power consumption, large-area manufacturability, and compatibility with flexible surfaces.

Amundson showed a retail sign – which is a commercial product – with 35% reflectivity. It was effective even in the fairly dim lighting of the conference room. The switching time for the display, which had large pixels, was 150 msec. Amundson said that E Ink has achieved 50% reflectivity with some of their newer inks.

The company has made some high-resolution displays with more than 100 lpi, and has demonstrated that fractions of microcapsules can be addressed. The switching characteristics of these display – dc addressed, 15-V switch voltage, 2–8 V-sec of impulse, *etc.* – is compatible with organic TFTs, which offer potential breakthroughs in cost, although serious issues of performance, fabrication, and stability remain. E Ink Corp. and Lucent Technologies have a joint-development agreement to work on these issues, with the goal of creating a low-cost backplane.

With two of the session's papers devoted to novel bistable technologies, it was something of a surprise to hear J. H. Morrissy (Three Five Systems, Tempe, Arizona) argue in "Will Traditional TN/FSTN-LCDs Dominate in Low-



Ken Werner

The Breakers Hotel in Palm Beach, Florida (this is the lobby) was the location of the 20th International Display Research Conference.

Ken Werner

The author interviews at IDRC are well-attended, and provide opportunities for discussing and viewing technology demonstrations and prototypes.

Power Reflective-Display Applications?" that modifying traditional LCDs will provide the most cost-effective technology for "electronic paper" applications. But Morrissy made a convincing case for the proposition that "bistable LCDs will not find it easy to displace conventional LCDs in high-volume applications."

Starting with a coherent survey of the characteristics of various mass-market LCD technologies, he asked how are these technologies going to change to accommodate low power consumption. Optically, the displays would be used in reflective mode with a high-efficiency reflector and optional front light guide and LED lighting for illumination in low ambients. A reflector with gain would increase brightness over a limited range of angles in appropriate applications.

Electronically, the use of multi-line scanning (MLS) reduces FSTN power consumption by up to a factor of 32 by lowering the scan rate and driver voltages. For really low power in reflective color LCDs, we need to eliminate one polarizer, Morrissy said, and an internal mirror will prevent ghost images.

The current state of the art in reflective displays includes a contrast ratio of between 10:1 and 14:1 and a reflectivity of 34%. The current state-of-the-art power level, which has recently experienced sharp reductions, is 1 mW/cm^2.

In "Approach to the Full-Color Reflective LCDs," Yoshiharu Nakajima of ASET in Tokyo, Japan, also targeted reflective LCD technology as the most promising approach to low-power displays, but he chose to look at a broader range of technologies than did Morrissy. Nakajima presented stacked-layer structures, holographic polymer-dispersed LCDs, and directive-reflector devices as being the most promising, and discussed them in the context of work being done at ASET.

The power consumption of reflective displays is a tenth to a hundredth that of backlit LCDs of similar diagonal. The main issue is attaining enough brightness. The typical reflective LCD (RLCD) absorbs half of the input luminous flux in the polarizers and two-thirds of what remains in the color filters. Maximum reflectivity is thus one-sixth or 16%. Compared with the 55% reflectivity of newsprint, there is lots of room for improvement.

The approaches to improving reflectivity fall into two categories, those with a color filter and those with full color in one pixel. The stacked-trilayer guest-host LCD is in the second category. It features a fast response and a reflectivity greater than 60%, and it does not have a polarizer. A double-layered XGA monochrome prototype with 320 dpi has been made at ASET, which is currently working on a trilayered structure.

Microdisplays

In the Invited Symposium on Microdisplays, a recurring theme was the strong influence on display performance of fringe fields (FF) between pixels – caused by the very small pixel size in LCoS displays. One result is that optical throughput can be degraded substantially, said Minhua Lu and K. H. Yank (IBM T. J. Watson Research Center, Yorktown Heights, New York).

Hiap L. Ong (Kopin Corp., Westborough, Massachusetts) observed that FF effects might appear to be similar to image sticking or flicker effects. Another problem with reflective TN-LCDs, Ong said, is the V_{com} shift from an unbalanced dc voltage between the transmissive ITO electrode and the reflective Al electrode, a point also made by Lu and Yank.

In some geometries, the FF might completely reorient most of the LC in the reverse-tilt direction. In the process of switching off, the LC would take a much longer time than usual to relax back to its original state.

Boundary stick is a unique bistable FF effect that appears only in small-pixel geometries and resembles image sticking. Under the same LC and display geometries, boundary stick occurred in all the investigated displays with 12- and 15-μm pixels, but not in displays with 24-μm pixels.

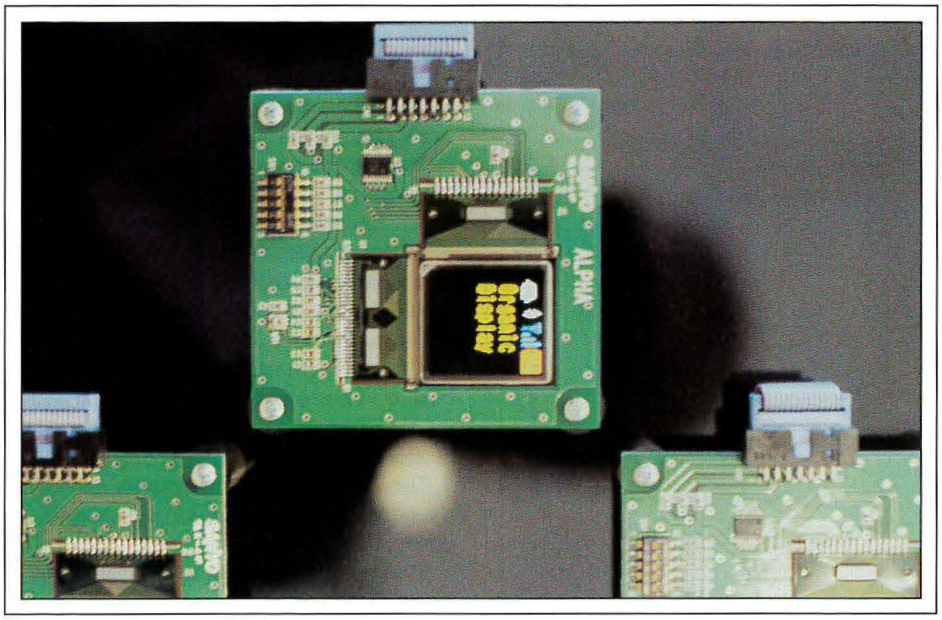
Ong concluded that FF effects are substantial and important, and that electro-optic effects in nematic microdisplays are more interesting and complex than those in direct-view LCDs.

Jiushi Xue and Mark A. Handschy (Displaytech, Inc., Longmont, Colorado) described the special characteristics of ferroelectric liquid-crystal (FLC) microdisplays, among which are minimal FF effects because of their thin cell gap and smectic-layer structures. In these displays, image sticking only occurs with unbalanced dc drive. In that case, going from a checkerboard pattern to a dark state produces a reduced-contrast version of the checkerboard image instead of the pure black one.

Displaytech has developed a technique they call "kicking" for the removal of image sticking without requiring overall dc balance in an FLC device.

Flexible Displays

In the Invited Symposium on Substrates and Electronics for Flexible Displays, presenta-



Ken Werner

Kodak and Sanyo's passive "area color" OLED cellular-phone display prototype was shown at the IDRC author interviews.

tions covered low-temperature-silicon technology, polysilicon-TFT technologies, organic TFTs for flexible-substrate displays, and flexible displays with fully integrated electronics.

S. Wagner and H. Gleskova (Princeton University, Princeton, New Jersey) indicated that amorphous silicon on polyimide (Princeton University), polysilicon on polyester (Lawrence Livermore National Laboratory), and pentacene on polyester (Pennsylvania State University) are among the interesting materials systems being investigated for TFTs on plastic substrates. "Bringing silicon to plastic substrates is not a matter of great discoveries, but of continuous optimization," Wagner said.

After looking at the many materials and compatibility issues, they concluded that direct deposition of silicon on plastic is a realistic prospect, but the matching of silicon-TFT materials to plastic substrates needs much methodical work.

In answer to a question from Roger Stewart, Wagner said, "The only fundamental problem I see in reducing the temperature of processes is bringing CMOS down to under 100°C from the current 250°C." Stewart: "Is LTPS harder than amorphous silicon in this regard?" Wagner: "No."

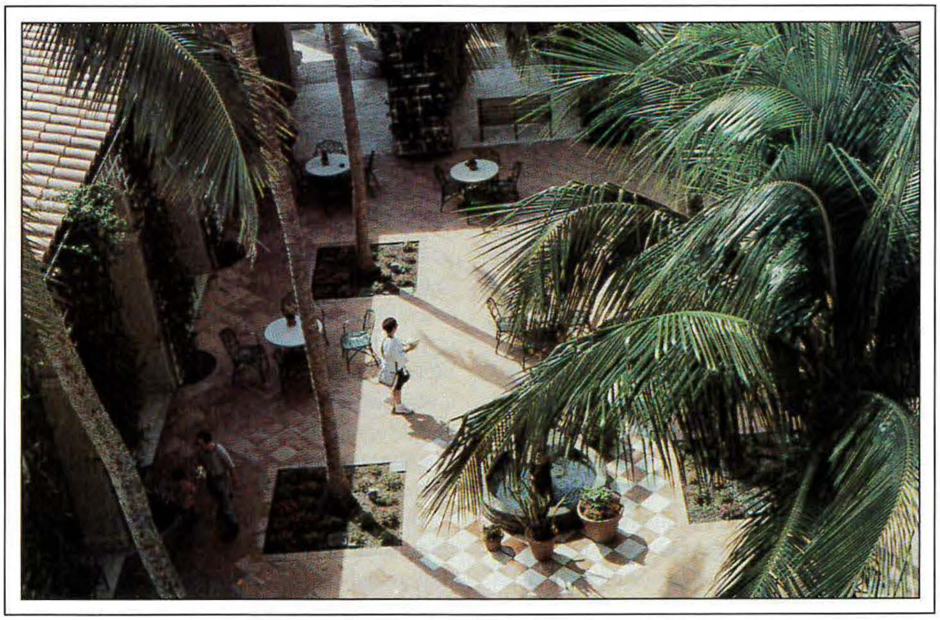
In "Poly-Si TFT Technology for Flexible Lightweight Flat- Panel Displays," T.-J. King (University of California, Berkeley) looked at the ways the next generation of active-matrix displays will make increased demands on TFT designs.

A TFT cell needs ±5 V, so the source-drain must take 10 V, and V_{GS} needs to be 20–25 V to charge C_{pixel} within one line time. This and other considerations mean TFT drive currents must be about 1 μA. Today, even a low amorphous-silicon mobility of less than 1 cm^2/V-sec permits the required drive current of 1 μA. Polysilicon has a mobility of greater than 30, allows smaller-pixel TFTs for higher aperture ratio (AR), and enables the integration of driver circuitry.

Trends for future displays include low power (reflective LCDs), lower-cost large-area displays (OLEDs), lighter weight and increased ruggedness (plastic substrates), more-compact displays, and roll-up displays (which implies monolithic integration of driver circuitry).

Each of these trends has implications for TFT design: reflective displays require a higher breakdown voltage, OLEDs require two transistors and an electron mobility greater than 10, plastic substrates enforce a process temperature of less than 200°C, and so forth. The requirements for integrated drivers are particularly demanding: high-frequency operation, large drive currents (in the mA range), mobilities higher than 20, low V_t, low power consumption, *etc.*

The most attractive electronics technology for plastic displays, said King, is polycrystalline silicon. It has already shown adequate characteristics, including fabrication by a 100°C process on polyethyleneterephthalate (PET) at Lawrence Livermore National Labo-



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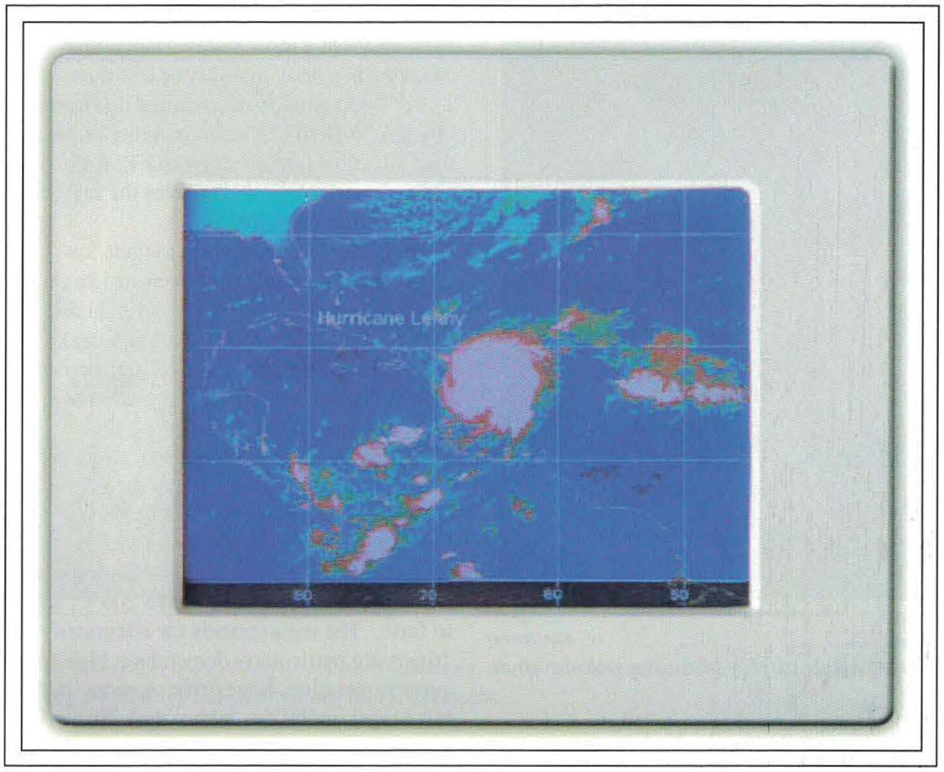
The Spanish Courtyard at The Breakers Hotel.



Ken Werner

Kent Displays showed its full-color stacked cholesteric LCD display prototype.

ratory (Berkeley, California) a couple of years ago, and can support integrated scan and data drivers. The ultimate goal is large-scale integration (LSI) on plastic.

Tom N. Jackson (Pennsylvania State University, University Park, Pennsylvania), in "Organic Thin-Film Transistors for Flexible-Substrate Displays," observed that the target specifications for organic TFTs (OTFTs) are in the range of current amorphous TFTs, and that's achievable.

Pentacene has shown mobilities in the range of 2. But structures are currently built on silicon substrates – which is not too useful – so realistic TFT structures are needed for actual devices. It will be necessary to define pentacene structures photolithographically so that the pentacene is not exposed to an organic solvent.

There are advantages in making complementary TFT circuits with amorphous silicon for the n-channel and pentacene for the p-channel. The authors have made these at small LSI levels of a few thousand gates.

Combining OTFT and OLED is a natural combination for an all-organic integrated pixel. Doing so removes one contact from the OLED and permits a high density of injected carriers. The goal is not video rate but small portable displays.

In "Flexible Displays with Fully Integrated Electronics," Roger Stewart (Alien Technology, Morgan Hill, California) discussed the current status of Alien's innovative technology of inserting electronics packaged in tiny NanoBlocks™ in the backplanes of flat-panel displays. The company's goal, he said, is to go head to head with other technologies for low-end display manufacturing. Fluidic self-assembly, the company's signature technology, and web processing uses very little labor; Stewart estimated that up to 3 million displays a year can be manufactured at the company's new Morgan Hill plant with only 250 people. The process is stable now, and the company is getting ready for manufacturing.

The first flexible-display product with fully integrated electronics will be a simple low-cost module embedded in Smartcards. It will be a monochrome bi-level reflective display. The display electronics is innovative, consisting of a single interface NanoBlock IC – called the "Enterprise," consistent with the company's alien theme – that services six smaller NanoBlock ICs called "Zircon shuttlecraft" to drive the display. There are no select or data lines; each NanoBlock extracts instruction and code from a bus that sequentially hits each block. There is software control of all major display functions, and there is direct connection to any ISO 7816 Smartcard with a four-lead interface and handshake logic.

The Enterprise chip is fairly complex, containing a small power supply. The Zircon chip features a function lead. The block can land in a hole in any of four orientations, and the block senses this and configures its connections accordingly.

The individual Zircon blocks are only 350 μm per side, and Alien plans to drive that down to 90 μm.

The system assigns a relatively large number of transistors to each pixel. Allan Kmetz questioned the cost of this approach. Stewart answered that intelligence is cheap but leads are expensive. Alien is currently limited by the cost of leads and must limit their number.

A Polymer Display

In "A TN Display Using Only Polymer-Based Materials for Substrates and All Coatings," a team of authors including J.-P. Tahon (Agfa-Gevaert, Mortsel, Belgium) and Ernst Lüder (Labor für Bildschirmtechnik, Stuttgart, Germany) described the building of a TN passive display using only polymer-based materials.

Despite the interest in plastic displays, there are only a few manufacturers, including Sharp, and only moderate success so far in the market for such displays for telecommunications and consumer-electronics hand-held products. The roadmap includes the development of larger, full-color, and full-polymer TN displays.

The authors find poly-3,4-ethylenedioxythiophene (PEDOT), an intrinsically conductive and transparent polymer, to be an attractive material for polymer displays. The authors have made a TN test display on polyethersulfone (PES) with PEDOT as conducting and alignment layers. The driving voltage is 3 V, and a PEDOT-on-PES test cell exhibited a contrast ratio (CR) of 98:1 (which compares to 128:1 for ITO on PES).

The system exhibits good performance and the display is flexible. Low-temperature patterning without vacuum is feasible. A lively Q&A session following the talk focused on very specific questions regarding possible patterning solvents, material stability, and similar issues. The test display demonstrated impressive contrast when shown at the author interviews.

OLEDs

In "Degradation Mechanism of OLEDs Based on ALQ_3," Zoran D. Popovic and his colleagues (Xerox Research Centre of Canada, Ontario, Canada) presented a paper on small-molecule OLEDs that could serve as a model for the experimental approach in device physics. They concluded that intrinsic degradation in ALQ_3-based OLEDs is primarily caused by the degradation of AlQ_3 molecules in the vicinity of the HTM/AlQ_3 interface as a result of the injection of holes and the formation of unstable cationic AlQ_3 species, a mechanism that explains a wide range of seemingly unrelated observations.

In "Electrophosphorescent Organic Light-Emitting Diodes," Mark E. Thompson spoke for a large team of co-authors from the University of Southern California Chemistry Department, the Princeton University Electrical Engineering Department, and Universal Display Corp.

Their goal is to try to beat the traditional inherent 25% limit on internal efficiency – the conversion of excitons to photons – observed in traditional fluorescence-based singlet-exciton OLED systems. They are moving toward 100% internal efficiency utilizing triplet excitons, phosphorescence, and confinement-optimizing recombination processes.

Most OLEDs focus on getting radiation out of the singlet excitons created by hole-electronic combination, but only 25% of excitons are singlets. Thompson's team has looked for materials in which triplet emission is allowed and reasonably efficient. In fact, there are such materials, even though radiation from triplets is normally forbidden.

Thompson indicated ways of making a variety of materials with different ligands that produce a wide variety of colors. ("We're chemists," he said, "so we like to make compounds.") The team has developed "a pretty good green and a red that is spot on for NTSC red with good efficiency!" Iridium compounds are all on the red-green axis of the CIE diagram, but the team has now developed a platinum compound that produces a blue.

In "Passive-Matrix OLED Displays: Operational and Storage Stability," Steve Van Slyke and his colleagues at Eastman Kodak Co. (Rochester, New York) and Sanyo Electric Co., Ltd. (Gifu, Japan) started by reviewing the multilayered structure of the OLEDs, which Van Slyke described as a low-voltage high-field device. It is possible to get a good selection of reds, greens, and blues by the appropriate selection of hosts and dopants.

Passive OLEDs are high-current high-bright-pulse short-duty-cycle devices. Active-matrix OLEDs are low-current low-peak-brightness high-duty-cycle devices, but the two varieties have similar average luminances. A device that produces high luminance at high duty cycle will have a short lifetime.

Patterning cathodes in passive OLEDs turns out to be a crucial process. The initial approach used in Japan was to perform cathode isolation using a conventional shadow mask. It works well but the mask gets too fragile for large sizes. Pioneer now uses an integral shadow mask, with which photolithography is performed prior to organic deposition. The process scales to large sizes. Kodak and Sanyo have used this technique to make 120 × 60-pixel area-color passive-matrix displays with 85% fill factor and a 23 × 25-mm active area.

A passive display is pushed up the I–V curve as one moves to a higher row count, so there is an effort to make the curve steeper, which would allow designers to go to a higher row count and higher current at modest voltages. Current passive displays have modest maximum row counts of about 60 lines. Displays survive well at a storage temperature of 85°C, but 105°C storage causes a rise in drive voltage. These displays are currently adequate for cellular phones, Van Slyke said, but more must be done for full color.

Active-matrix OLEDs (AMOLEDs), in which each pixel has at least one TFT and stays on for the entire frame – if it is supposed to be on – have now been made. A 5.5-in. QVGA AMOLED was shown at SID 2000 and a 2.4-in. QVGA AMOLED at JES 1999 and SID 2000. The 2.4-in. is harder to make because of its higher pixel density, Van Slyke said. They are now getting a pretty good green and red on the CIE diagram, but blue needs improving. Also, the efficiency of the red is low, so a disproportionate amount of power is currently going into the red channel.

The remaining OLED challenges are temporal stability (particularly differential aging), thermal stability, efficiency, drive voltage of passive displays at high row current, cathode adhesion, manufacturing yield, and color patterning. (The shadow mask is okay now, but something else is necessary for the next generation.)

Poster Session and Author Interviews

There were 56 poster papers presented at IDRC 2000, and many discussions and demonstrations in the evening author interviews. Here are a very few samples.

In the author interview for the paper "Optically Written Displays Based on Up-Conversion of Near-Infrared Light," a team from the University of Central Florida demonstrated a clever approach to color displays in which the light from a scanning near-infrared laser is up-converted to red, green, and blue by a fluoride-crystal host co-doped with Tm^{3+} ions for blue, Ho^{3+} or Er^{3+} ions for green, and Er^{3+} ions for red. The prototype only produced red, green, and blue dots but demonstrated the point. Fred Kahn of Kahn International did some shirt-cuff calculations and concluded that the luminous efficiency of the system was not impressive. We were told that the system was highly non-optimized, however.

In one of the author interviews, eMagin Corp. (East Fishkill, New York) unveiled the world's first full-color active-matrix OLED-on-silicon microdisplay. The demonstration attracted one of the largest crowds at the evening's interviews. The microdisplay uses a quad pixel arrangement, has over 1.3 million 12-μm subpixels, and uses a white-light OLED technology with color filters built directly on top of the display. The demonstrated technology will be applied to an SVGA+ display that will be the company's first microdisplay designed for consumer applications, said eMagin Executive V.P. Susan Jones. Samples should be available to system manufacturers early next year.

In a poster paper, Kent Displays (Kent, Ohio) described and demonstrated a full-color reflective cholesteric liquid-crystal display. Cholesteric displays are inherently monochromatic, so multicolor displays have been made in the past by stacking two or three cholesteric layers, each tuned for a different color. The current display adds gray scale to each of the three 0.5-mm layers and broadens and smoothes the reflectivity *vs.* wavelength response by fracturing the planar texture into many small domains. The approach produced

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16 **01**

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