Projection Displays Issue

Information DISPLAY

SID

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Flexible Displays' Killer App?

Pico Projectors: Big Images, Small Packages

- The Pico Gold Rush
- The Future of Pico Projectors
- Projection System in a Handset
- Holographic Laser Projection Technology
- *Journal of the SID* December Preview

Information DISPLAY

DECEMBER 2008
VOL. 24, NO. 12

2 Editorial
Looking Ahead with Optimism?
Stephen P. Atwood

3 Industry News
Michael Morgenthal

4 Guest Editorial
Whither Pico Projectors?
Robert L. Melcher

6 President's Corner
Turning Technology into Products.
Paul Drzaic

12 The Pico-Projector Gold Rush
The development of pico-projector technology and the possible market opportunities for this exciting new technology is discussed.
Chris Chinnock

16 The Future of Pico Projectors
Coming advances in projector throughput and LED brightness create a rapidly broadening design space for pico projectors that will lead to applications yet unforeseen.
Mark A. Handschy and Bruce F. Spenner

22 Holographic Laser Projection Technology
A unique holographic laser projection technology that offers advantages over imaging and scanned-beam display technologies is described.
Edward Buckley

26 A Single-Mirror Laser-Based Scanning Display Engine
Myriad pico projectors are scheduled to become commercialized in 2009, and each one offers a different pathway to success. Here, one manufacturer details the technology and development decisions that have lead to its single-mirror laser-based scanning display engine.
David Lashmet, David Baty, and Matt Nichols

30 Rolling toward a Revolution?
Polymer Vision plans to launch the Readius, the first commercial application to feature a rollable flexible display, in early 2009. Will it be the "killer app" for rollable flexible displays?
Michael Morgenthal

34 *Journal of the SID* Preview
Selected papers appearing in the December 2008 issue of the Journal of the SID *are previewed.*
Aris Silzars

46 Display Week 2009 Hotel Reservation Information

48 Sustaining Members

48 Index to Advertisers

For Industry News, New Products, Current and Forthcoming Articles, see www.informationdisplay.org

COVER: *The current interest in pico projectors presents an interesting confluence between technology-driven product development and market-driven product requirements. Despite this favorable circumstance, the eventual commercial success of these products is still uncertain. The inset shows a photograph of Polymer Vision's Readius, the first commercial application to feature a rollable flexible display, to be released in early 2009. Will it be the "killer app" for rollable flexible displays? See page 30 for the details.*

CREDIT: Cover design by Acapella Studies, Inc.
Inset: Readius photos courtesy of Polymer Vision.

Next Month in *Information Display*

Display Metrology Issue

- 3-D Layout Perception in Stereo Displays
- Characterizing Autostereo 3-D Displays
- Metrics for Local-Dimming Artifacts in HDR Displays
- Minimizing the Effects of Veiling Glare
- HDTV: To Calibrate or Not to Calibrate?
- *JSID* Janaury Preview

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editorial

Looking Ahead with Optimism?

It is hard to believe that 2008 is almost over and we are beginning the 2009 calendar year and *Information Display*'s 2009 editorial-calendar cycle. I'm extremely pleased with the issue themes and technology topics we are working on as well as the team of Guest Editors we have recruited thus far. In 2009, we have two issues dedicated to the topics of portable and low-power displays. As you will see in the articles this month, there is renewed energy in the field of handheld and portable products, from pico projectors to OLEDs to MEMS-based devices. Minimizing power for cordless use and longer battery life continues to be a significant part of the picture as well.

We are also bringing back the topic of display manufacturing. Manufacturing is, of course, the obvious end game for almost all of the development work that we chronicle. In most cases, the money spent on development is investment in future revenue and profits that must be realized for the cycle to repeat. A technology that cannot be manufactured in high volume for a reasonable cost rarely gets past the research phase at most companies. Sometimes new developments require new manufacturing methods to be realized, and it is frequently at this last stage where the largest part of the investment gets consumed. In this current economic climate, which I must acknowledge is looking more and more like a global downturn, making those new investments, let alone keeping up with current research costs, is becoming harder than ever.

This month, our theme is Projection Displays and as we began planning with our Guest Editor, Bob Melcher, we realized that much of the effort is clearly focused in the portable or pico-projector area, where extreme miniaturization, high light efficiency, and ultra-low power consumption are critical design goals. This is reflected in two of our articles, one by Mark Handschy from Displaytech, who is developing a color-sequential single-panel liquid-crystal–on–silicon (LCOS) system with LED backlighting. The other is by David Lashmet from Microvision, who is pursuing a metal-on-silicon microelectromechanical system (MEMS) illuminated with lasers. Both approaches employ very recent developments in their fields and appear to be very promising. Worth noting, it was last year at this time that we published David Lashmet's Business of Displays column titled "Re-Focusing Microvision" where he gave us a very candid look into their internal process to re-engineer their company and overcome some organizational challenges, to focus themselves properly on this new effort. It's great to see what has evolved over the ensuing year and to recognize that their efforts are starting to bear fruit. The story does not always end this way.

Bob Melcher is a former colleague of mine and a well-respected member of our display community. Bob has extensive first-hand experience in developing imaging devices, including LCOS, and put a great deal of effort into building this issue for us. We are very grateful for his generous efforts. You can read the introductions for the rest of our December feature articles in Bob's guest editorial.

Another interesting article this month is the exciting announcement of the commercialization of the Readius portable ebook reader based on E-Ink technology. This, we believe, is the first truly foldable display being sold to consumers. (If you are not familiar with the product, it is shown in the inset on our cover.) The display portion folds back into the housing, providing a small shirt-pocket-sized enclosure that still allows a full page of text to be easily read when the display is unfolded. This marks a tremendous milestone on the path of flexible displays and one that will surely be

(continued on page 45)

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LG, Sharp, CPT Plead Guilty in LCD Price-Fixing Conspiracies, Agree to Pay Total of $585 Million in Fines

WASHINGTON — Three major display developers - **LG Display Co. Ltd.**, **Sharp Corp.** and **Chunghwa Picture Tubes Ltd. (CPT)** - have agreed to plead guilty and pay a total of $585 million in criminal fines for their roles in conspiracies to fix prices in the sale of liquid-crystal-display (LCD) panels, the **U.S. Department of Justice** announced November 12. Of the $585 million in fines, LG will pay $400 million (payable over five years), the second highest criminal fine ever imposed by the Department's Antitrust Division. Sharp will pay $120 million, and CPT, which was charged with conspiring with LG, will pay $65 million.

According to the Justice Department, the companies have agreed to cooperate with the Department's ongoing antitrust investigation. Companies directly affected by the LCD price-fixing conspiracies are some of the largest computer, television and cellular telephone manufacturers in the world, including **Apple**, **Dell** and **Motorola**.

> *"These price-fixing conspiracies affected millions of American consumers who use computers, cell phones and numerous other household electronics every day."*

"These price-fixing conspiracies affected millions of American consumers who use computers, cell phones and numerous other household electronics every day," said **Thomas O. Barnett**, Assistant Attorney General in charge of the Department's Antitrust Division. "LG Display, Sharp and Chunghwa have agreed to cooperate in the Department's ongoing investigation. In fact, they have already begun to cooperate. The Board of Directors for LG Display, Sharp and Chunghwa deserve credit for making a timely decision to accept responsibility and cooperate. Today's fines would have been significantly higher were it not for their cooperation."

According to **iSuppli**, LG was the world's second-largest supplier of large-sized LCD panels in the second quarter of 2008, with 20.3% of unit shipments; CPT was the world's fifth largest supplier of large-sized LCD panels in the second quarter of 2008 with a 5.9 % share of unit shipments; and Sharp Corp. tied for the sixth-largest supplier ranking during the same period, with a 3.9% share of unit shipments.

LG Display and Chunghwa are charged with carrying out the conspiracy by:

- Participating in meetings, conversations, and communications in Taiwan, Korea and the United States to discuss the prices of TFT-LCD panels;
- Agreeing during those meetings, conversations and communications to charge prices of TFT-LCD panels at certain pre-determined levels;
- Issuing price quotations in accordance with the agreements reached; and
- Exchanging information on sales of TFT-LCD panels, for the purpose of monitoring and enforcing adherence to the agreed-upon prices.

LG Display Co. Ltd., a South Korean corporation, and its wholly-owned subsidiary, LG Display America Inc., a California company, agreed to plead guilty to participating in a conspiracy from September 2001 to June 2006 to fix the price of TFT-LCD panels sold worldwide. During the conspiracy, LG Display Co. Ltd. was known as LG.Philips LCD Co. Ltd. (a joint venture between LG Electronics and Philips Electronics) and LG Display America Inc. was known as LG.Philips LCD America Inc.

LG did not issue a statement regarding the agreement.

CPT, a Taiwanese TFT-LCD panel manufacturer, has agreed to pay a $65 million fine for its participation with LG and other unnamed co-conspirators in a conspiracy from September 2001 to December 2006 to fix the price of TFT-LCD panels sold worldwide.

CPT issued a brief statement acknowledging the agreement, adding: "CPT also likes to highlight that this fine has been recognized on accounts, and therefore this fine will not cause material impact to the company's finance and sales."

Sharp is charged with participating in three separate conspiracies to fix the price of TFT-LCD panels sold to Dell, Motorola and Apple by:

- Participating in bilateral meetings, conversations, and communications in Japan and the United States to discuss the prices of TFT-LCD panels to be sold to Dell, Apple and Motorola;
- Agreeing during those bilateral meetings, conversations and communications to charge prices of TFT-LCD panels at certain pre-determined levels to Dell, Apple and Motorola;
- Issuing price quotations in accordance with the agreements reached; and
- Exchanging information on sales of TFT-LCD panels to be sold to Dell, Apple and Motorola, for the purpose of monitoring and enforcing adherence to the agreed-upon prices.

Sharp Corp., a Japanese consumer-electronics manufacturer, has agreed to pay a $120 million fine for its participation in separate conspiracies to fix the price of TFT-LCD panels sold to Dell Inc. from April 2001 to December 2006 for use in computer monitors and laptops; to Motorola Inc. from fall 2005 to the middle of 2006 for use in Razr mobile phones; and to Apple Computer Inc. from September 2005 to December 2006 for use in iPod portable music players.

"After carefully taking into consideration the applicable laws and regulations, the facts, and other factors, Sharp has decided that the best possible course of action would be to conclude the aforementioned agreement," the company said in a statement, adding that it has fully cooperated with the DOJ investigation since December 2006. "In consideration of this matter and the fact that similar investigations are being conducted in Japan and Europe, causing inconvenience and/or anxiety to our shareholders and other persons concerned, (the) Sharp Chairman & CEO and some other directors will voluntarily return 10% to 30% of their remuneration for three months starting December 2008. Sharp understands the gravity of this situation and will strengthen and thoroughly implement measures to prevent the recurrence of this kind of problem, and will earnestly work to regain the public's confidence."

— Staff Reports

Whither Pico Projectors?

by Robert L. Melcher

The current interest in pico projectors presents an interesting confluence between technology-driven product development and market-driven product requirements. Despite this favorable circumstance, the eventual commercial success of these products remains yet uncertain. The pico projector is the natural evolution of projector technology ranging from the large-venue projectors providing tens of thousands of lumens, through conference-room products providing a few thousand lumens, to portable products providing about one thousand lumens, to pocket projectors providing several tens to a few hundred lumens, and now to pico projectors for which ten or so lumens is a reasonable objective for a very small battery-operated portable device.

There appears to be little market doubt that the consumer and professional would embrace a portable display device which is the physical size of a cell phone, but produces a useable image the size of a laptop display on almost any surface. Of course, the price will have to be right and the power consumption low enough to have a useful battery life. Thus far, head-mounted displays, which claim these features, have failed to catch on in any significant way except for certain niche applications; probably because of ergonomic inconvenience and cost/benefit trade-offs. The latest attempts to serve this presumed market are pico projectors, which are the subject of the four papers in this issue of *Information Display*.

The technological developments addressing this market objective have been substantial in recent years. These include the development and use of both LED and laser light sources, the development of high-resolution highly integrated LCOS imaging devices with tiny pixels and hence low manufacturing cost, the development of small and fast MEMS light reflectors and scanners, new small low-cost optical elements to help create and control the image, novel forms of image generation, and, finally, the continued development of low-cost low-power video-processing capability.

The first paper in this issue is from Insight Media and describes the market opportunity for pico projectors with emphasis on cell phones and PDAs. Both stand-alone pico projectors as well as those embedded or integrated as part of the portable device are considered. The conclusion is that the market opportunity is huge, if and when products are offered which meet the technical and cost requirements while being ergonomically satisfying.

An example of new pico projectors, which have arrived in the market this year, is the Optoma EP-PK-101, which is based on a color-sequential Texas Instruments DLP pico micromirror device. Another is the MPpro 110 from 3M, based on a Himax LCOS microdisplay with integrated color filters. Both products use LED illumination and are about the size and weight of an iPhone. The 3M product utilizes novel multi-functional low-cost acrylic polymer optical prism elements with 3M multilayer optical film technology.

The following three papers are examples of some of the exciting new technological approaches currently under development, which have the goal of providing successful pico-projector products.

The paper from Displaytech covers a high-speed LCOS device suitable for color-sequential application and based on ferroelectric liquid-crystal materials. The design includes color-sequencing and frame-buffering circuitry on the microdisplay back plane, demonstrating the potential of LCOS to reduce system size, power, and cost.

(continued on page 42)

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Turning Technology into Products

Last week, I was having a casual conversation with a friend of mine who was gushing for about the hundredth time about how much she loves her Kindle ebook reader. The Kindle, which is officially named on the Amazon Web site as "Amazon's Wireless Reading Device," is a portable electronic device designed for reading not only books, but a variety of other content as well. It has a built-in connection to Sprint's 3G EVDO network, and the linkage to Amazon provides access to a lot of content.

To the casual observer, the most prominent difference between the Kindle and other portable electronic devices is that the Kindle uses an electrophoretic display developed by E Ink as its screen. What was surprising to me in our conversation, though, was her perspective of what made the Kindle such a cool device. Her comments were interesting to me in describing what it takes to launch a successful product based on new technology. Here's a hint: it's not just the display!

The Kindle and other electronic-book devices are of personal interest to me due to my association with E Ink. I joined E Ink in 1998, as their first Director of Technology, right as the company was getting started. Those first few years were great fun, and many of the capabilities now seen in E Ink products were demonstrated relatively quickly. In particular, in collaboration with IBM Research, we were able to demonstrate in 2001 that an a-Si backplane developed for use in AMLCD technology could be used to build a high-resolution active-matrix electrophoretic display (AMEPD). While the technology has been refined in many ways since that time, the basic performance demonstrated by the screen in the Kindle is similar to the displays over 7 years ago.

Since technical success was coming so quickly, there was an expectation that commercial success would not be far behind. I recall an early conversation, though, with the late David Mentley, who was a display industry analyst for Stanford Resources (later acquired by iSuppli Corp.). Dave and I were talking at some SID function and he told me that any new display technology takes at least 7 years from inception to market success. Not only was I unhappy hearing that prediction, but in fact was confident that the electrophoretic active-matrix product would be different. The electrophoretic screen showed a combination of sunlight readability, low power, and wide viewing angle that could not be matched by any other high-resolution display technology at that time. While I left, E Ink in 2002, it appeared that the only remaining hurdle was to convince a display company to launch a product. How long could that take?

Well, Dave was prophetic. While the electrophoretic screen showed some great benefits, there were also looming uncertainties. Manufacturing teams were nervous – the electrophoretic technology required a brand new assembly technology, required an expensive TFT backplane, and there was no history regarding the high-volume fabrication of electrophoretic products. Launching an AMEPD as a real product would be a significant investment in time and money, with some risk. On the marketing side, there was nervousness that a display that could not deliver color, nor show video, would be accepted by consumers. The screen showed some unusual visual transitions in changing from one image to another, which was also a cause of concern. Finally, it was not clear where the content for an electronic-book reader would come from.

(continued on page 42)

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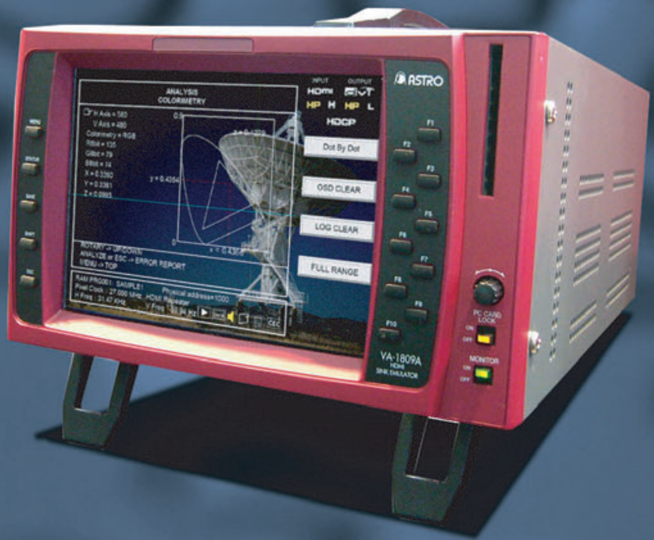

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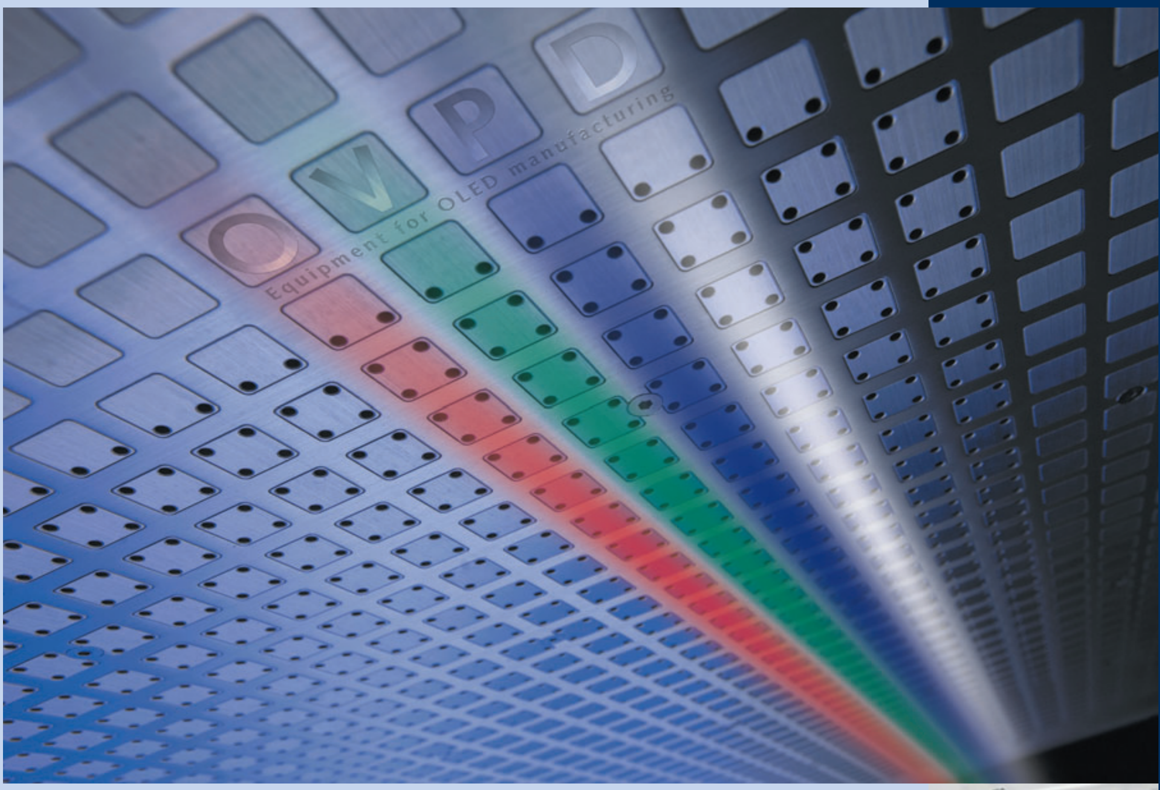

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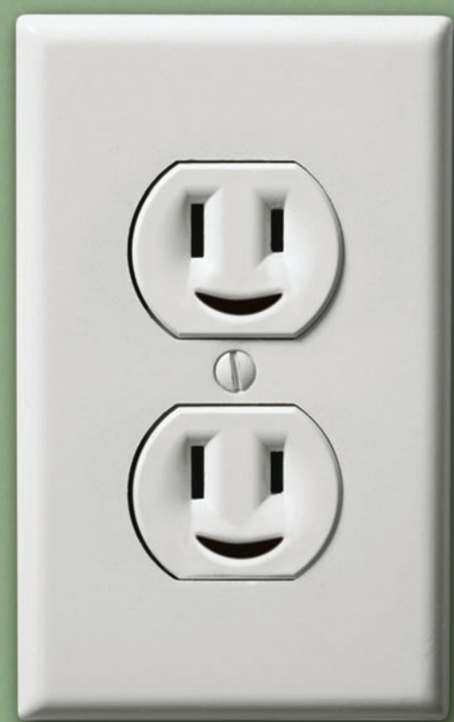

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The Pico-Projector Gold Rush

This article examines the development of pico-projector technology and the possible market opportunities for this exciting new technology.

by Chris Chinnock

INTEREST in low-lumen projectors has been building for the past few years and has been at a high level of activity for about the past year and a half. Sometimes called pico projectors, nano projectors, or pocket projectors, these products all feature light-emitting-diode (LED) or laser illumination and offer a lower light level compared to that of conventional lamp-based projectors. However, the primary attractiveness of these projectors is their small size and fairly low cost, plus the new-use models that developers envision for them. If all goes as planned in terms of product development and rollout, there is potential to sell millions of these projectors in the next few years – an amount that could outstrip today's entire established projection market.

However, success is far from guaranteed, as there remain a number of issues in this nascent market, among the most crucial of which is acceptance by end users.

Low-Lumen Projectors 2.0

Remember, the first pocket projectors arrived at the end of 2005, and during the next 2 years, two generations of products were introduced. The first-generation projectors offered no more than 25 lm, while the second-generation devices reached about 50 lm. They were modest-sized products selling for $700–900 and were marketed mainly to business users as a notebook accessory. They did not sell very well, however, prompting many to drop out of the market.

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What was the problem? Simply put, the value proposition was not very good. The price was simply too high for the light output level and image quality for the intended applications. In most business scenarios calling for these projectors, such as sharing information in small-meeting environments, the room lights will be on (at least dimly), which would probably require a minimum of 100 lum to create a usable image in the 20–30-in. range; the room would need to be much dimmer for a 50-lm projector to generate a viewable image of this size image or the image would have to be considerably smaller. This is feasible, of course, but the market did not find this attractive for an $800 projector.

In the so-called pico-projector class, which we define as under 50 lm, a new generation of products is now coming to market. Why will it be different this time around? There are a number of reasons, but it boils down to an improved value proposition. These projectors will be much smaller, more efficient, and much less expensive (more on this below), enabling them to be used as accessories to a variety of portable products, with embedded versions to follow. Plus, the roadmap for their price/performance evolution over the next few years shows that this value proposition will improve significantly.

The big unknown, however, remains the acceptance of the end user to these products, which in turn depends on both the end-user use model and the price/performance of the devices. We forecast users will find these products compelling, but no one will really know until there is enough sales history with these new products to get beyond the "cool gadget" phase.

As the other articles in this issue detail, there are lots of ways to create pico projectors, as detailed in Table 1.

Clearly, developers have many options to consider, with each approach offering advantages and disadvantages. We have analyzed these approaches in some detail and have characterized their strengths and weaknesses, but a detailed discussion is beyond the scope of this article. The bottom line is that for embedded applications, small size, low power, and low cost are critical, so we think the scanned mirror approaches and the small LCoS approach (see Fig. 1) offers the best solutions.

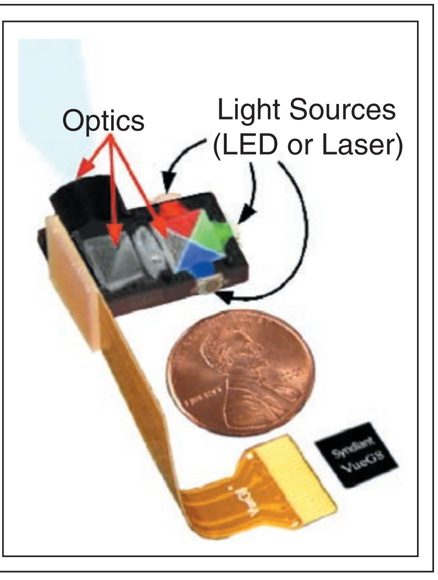

***Fig. 1:** Syndiant's pico projection core is tiny.*

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Table 1: Comparison of Microdisplay/Scanning-Device Suppliers

Supplier	Technology	Panel Diagonal (in.)	Resolution	Pixel Pitch (μm)	Driver
TI	DLP	0.17	HVGA	7.5	External
		0.24--0.32	VGA	7.5 or 10.1	External
		0.30--0.41	SVGA	7.5 or 10.1	External
		0.29--0.40	WVGA	7.5 or 10.1	External
Syndiant	Single-Panel FSC* LCoS	0.21	SVGA	5.1	External
		0.21	WVGA	5.1	External
		0.31	WVGA	8.0	External
		0.45	1280 x 800	7.6	External
Aurora	Single-Panel FSC* LCoS	0.17	VGA	5.4	MCM
		0.55	1280 x 720	9.5	External
Displaytech	Single-Panel FSC* LCoS	0.37	VGA	11.7	Internal
		0.45	WVGA	11.7	Internal
		0.46	SVGA	11.7	Internal
		0.20	QVGA	12.7	Internal
Himax	CFA** LCoS	0.47	VGA	14.9	External
Iljin	Transmissive FSC* LCD	0.24	QVGA	15.2	External
Microvision	Single-Mirror Scanner	1 mm x 1 mm	WVGA	N/A	External
Tendo (formerly TeraOp)	Two-Mirror Scanner	Dual-mirror	VGA	N/A	External

* Field-sequential color.
**Color-filter array.

For companion projectors, power efficiency, compact size, higher lumens, and moderate cost should be most critical. Here, the playing field is more difficult to handicap. In the short term, companion projectors with color-filter LCoS and HVGA DLP will enter the market first. But as LED and laser sources improve in the next few years, almost all of the solutions can potentially compete. Success will more likely be determined by finding the right mix of price, performance, size, power, and features that are tailored for specific-use models. Low power consumption will be particularly necessary because this will help differentiate these projection products from their bigger much-higher-lumen cousins using lamp-based technology.

In addition, having a strong brand to push the product will be critical – a companion projector that is offered by Dell or HP, for example, will have a better chance of success than a product sold by a third-tier Chinese electronics company. Conversely, even a good product that does not have enough marketing and brand support can fail in the market. Developers need to carefully evaluate failures to understand the root cause because it may not be price/performance.

Forecasting the Opportunity

Developing a forecast for a tiny or non-existent market is never easy. To undertake this task, Insight Media first started with a solid engineering analysis of the capabilities of each approach and the prospects for improvement of the imagers, LEDs, and lasers that will drive them. We then developed a cost-throughput model to estimate the light output, power efficiency, bill-of-material costs (BOMs), and other factors. This was used to generate an overall average selling price for embedded (integrated) pico-projector modules and stand-alone companion pico projectors. Table 2 shows the results of this analysis.

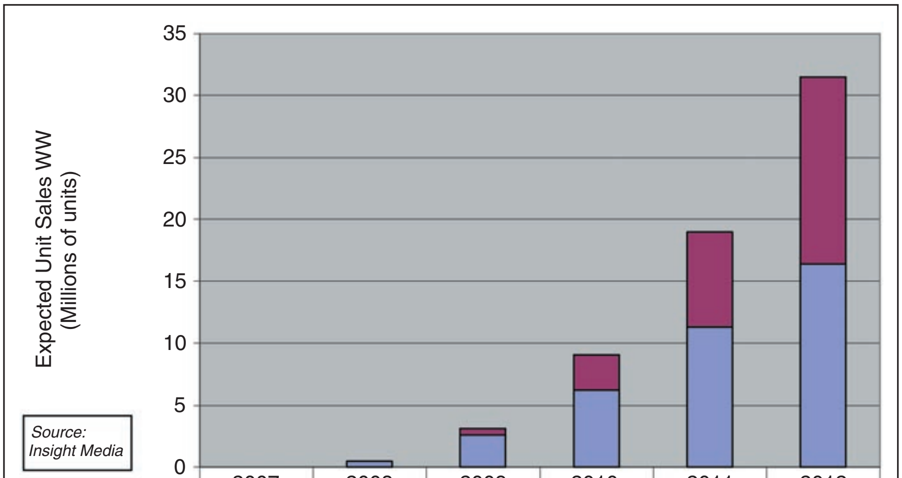
We next developed a worldwide estimate of the total available market (TAM) for these two classes of projector. This consisted of game consoles, laptops, ultramobile PCs/mobile Internet devices, cameras, handheld games, portable media players, and cellular phones/PDAs. For each of these categories, we created a forecast for their sales through 2012. This is the TAM.

To estimate sales into this TAM, we looked at several penetration examples including the "average" consumer-electronic product, cameras into cellular phones, MP3 players, *etc.* Each of these shows a different rate of growth, leveling off at different values. In our analysis, we tried to select the best curve for the market segment we were evaluating, making adjustments to the slope and saturation point based upon differences in the two products. This is clearly a qualitative assessment, but if the details of the assumptions are made clear, the reader can independently judge the validity of the assessment.

To build the forecast, we analyzed each of the above market segments for embedded and stand-alone (companion) products, adjusting the total as embedded products began to cannibalize companion product sales in the out years. In addition, we created three forecast scenarios: conservative, expected, and optimistic. In general, the conservative forecast delayed the ramp in penetration by about a

Table 2: Pico-Projector ASP Forecast

Expected	2007	2008	2009	2010	2011	2012
Companion		$375	$300	$225	$180	$150
Integrated			$300	$160	$115	$ 75



	2007	2008	2009	2010	2011	2012
Integrated	0.0	0.0	0.529	2.86	7.6	15.1
Companion	0.0	0.485	2.61	6.2	11.3	16.4

***Fig. 2:** Composite expected unit sales of pico projectors.*

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year, and the optimistic adopted a more aggressive penetration curve. This was done to show the potential range of outcomes.

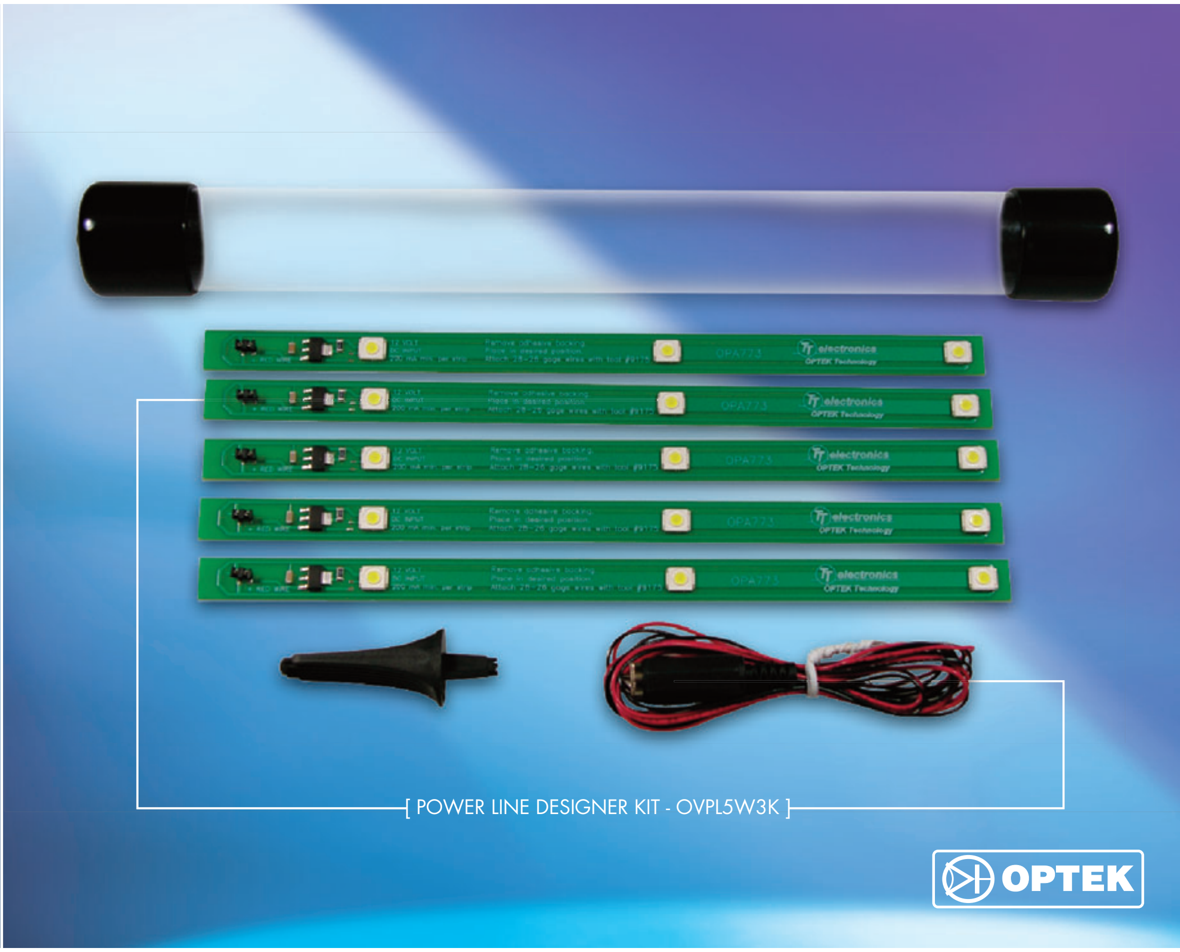
Figure 2 shows the unit sales forecast for integrated and companion pico projectors in the expected scenario. In the optimistic scenario, sales in 2012 could balloon to 41 million integrated projectors and 46 million companion projectors, whereas in the conservative scenario, sales of integrated projectors reach only 4 million units while companion projectors reach nearly 11 million units.

This broad range in possible outcomes is due to the newness of the category, the new target audience (consumers), and the big unknown – consumer acceptance of these products.

On the other hand, time is on the side of the pico-projector developers. In a few years, the price-performance of these products will improve considerably, creating a different value proposition for the end user. Therefore, part of the dilemma for developers is timing. Enter the market too early and you may launch a dud; enter too late and you have lost the leadership role to another company.

But one thing is clear. The potential for this product category is huge, which is why there is such a high level of interest. Is it fair to characterize it as a gold rush? Will the value propositions be sufficiently different this time around to generate real sales volumes? We will see soon enough. ■

TROUBLESOME DARK SPOTS?



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The Future of Pico Projectors

Coming advances in projector throughput and LED brightness create a rapidly broadening design space for pico projectors that will lead to applications yet unforeseen.

by Mark A. Handschy and Bruce F. Spenner

COMPUTERS OF THE 1960s (Fig. 1) were large, slow, and power hungry. However, the introduction of the integrated circuit (IC) changed all that. Displays, though, have not seen similar progress: Today's low-power displays have small, low-resolution images, such as cell-phone displays, while high-information-content displays such as LCD TVs are large and power hungry. But, as we are just beginning to see, the combination of new high-brightness LEDs with IC-based microdisplay imagers (Fig. 2) in pico projectors may launch displays on a trajectory matching that followed by IC-based computers.

Although others have characterized pico projectors as "low-lumen" devices, we assert they will soon be able to generate large (> 60 in.), bright images from an engine no larger than a standard incandescent light bulb. In the 60s, no one would have guessed that everyone would have a personal computer or that automobiles would be operated by hundreds of computers – 10 years from now imagine what small, bright, inexpensive pico projectors will bring.

Critical Pico-Projector Performance Parameters

Initial applications of pico projectors will likely be driven by small form-factor mobile electronics products such as PDAs and cell phones (Fig. 3). By decoupling image size from device size, pico projectors enable large, crisp images to be projected and shared with nearby friends and colleagues.

Market analysts divide mobile electronics pico-projector applications into three segments: palm (projector powered by wall plug), companion (projector powered by its own battery), and embedded (projector powered by platform battery).

The embedded segment with its large potential market draws the most attention because pico projectors that could be embedded into mobile-phone handsets would have an available market of 1 billion units annually. Achieving even small penetration into this market will require a pico projector with unusually high performance for its cost. In addition to producing enough light from an

Fig. 1: *Burroughs B5500 computer ca. 1964 (image courtesy of the Charles Babbage Institute, University of Minnesota, Minneapolis).*

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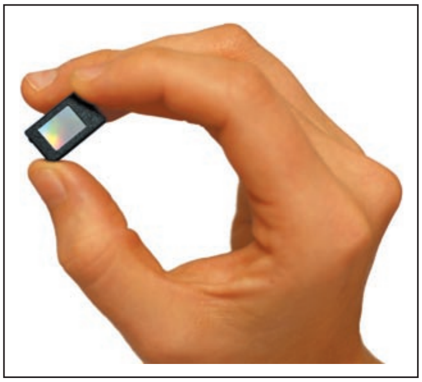


Fig. 2: Displaytech's 800 × 600 SVGA FLCOS microdisplay. Its on-board 2.6-MB memory for double-buffering digital video exceeds the memory capacity of the entire computer shown in Fig. 1.

Ratatouille is available on iTunes.

Fig. 3: Mobile electronics are now capable of showing the same TV and movie content as large screens, but display sizes preclude the usual shared viewing experience (image courtesy of Apple).

engine whose cost is a small fraction of the total handset cost, a successful pico projector will also have to be very small and consume very little power.

We believe single-panel color-sequential engines are the only feasible route to pico projectors that satisfy these requirements. The apparent simplicity of scanned laser projectors is appealing, but reducing their image speckle to acceptable levels may be more challenging than first thought. Projection engines based on three-panel color-splitting architectures offer high optical efficiency, but their cost, size, and complexity weigh against their use in pico projectors. Light absorption by their color filters reduces the optical efficiency of color-filter-array (CFA) microdisplays compared to field-sequential-color (FSC) displays. The large 2.5× efficiency difference detailed in Table 1 will result in power consumption in CFA pico projectors that is too high for embedded applications.

The optical throughput advantages of the FSC architecture can be retained, though, only if the standard-to-sequential video conversion can be accomplished without consuming significant power. Figure 4 compares a hypothetical color-sequential system with the usual external ASIC and frame buffer memory to a system like Displaytech's FLCOS imager where the sequential conversion is performed by the microdisplay backplane. Color-rate multipliers and digital gray-scale schemes mean high data bandwidths between the ASIC, the frame buffer memory, and the imager. In turn, high-bandwidth interconnect always consumes power. For a VGA system, we estimate the external electronics system plus imager consumes 600 mW, while less than 100 mW is consumed by the imager with internal conversion. This difference is very significant given the 1-W power budget expected for an embedded pico projector. The extra 0.5 W consumed by external drive electronics is power that cannot be delivered to the LEDs, reducing light output in a way that cannot be overcome even with a MEMS-based microdisplay (*i.e.*, Texas Instruments DLP) using unpolarized light. The high-I/O-count ICs used in the external-electronics system also substantially increase the pico projector's size and assembly cost.

Pico-Projector Design-Space Evolution

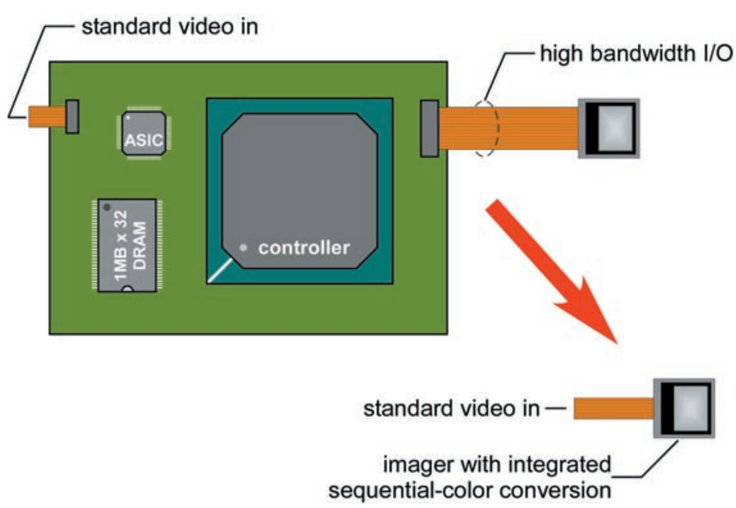
Sequential-color pico projectors based on current technology could achieve light outputs varying from 8 lm for a 1-W engine to nearly 90 lm for a 45-W engine, creating a large design space for meeting different application needs. Advances in solid-state light sources, microdisplay imager performance, and projection-engine optics will greatly broaden this space over the next few years.

Light-source lumens are the first major element of pico-projector performance. Current LED products (Table 2) with emitting areas small enough that all their light can be used by a 0.5-in.-diagonal imager provide color-sequential illumination from 60 to over 800 lm, depending on LED die size and drive level.[1] Today, efficacies range from 56 lm/W for the lowest light output to 19 lm/W at the higher drive level needed for the highest light output. Achievable LED output can be expected to increase in the future according to the well-known Haitz's law,[2,3] which predicts LED light output per package to double every 18–24 months. To cast a similar law in a form relevant to pico projectors, we base our following predictions on the assumption that LED efficacy (lm/W) increases by a factor of 1.5× every 3 years at constant drive current density (A/mm^2).

Microdisplay optical throughput forms the second major element of pico-projector performance. The second column of Table 3 breaks down the 62% optical throughput typical of Displaytech's current SVGA imager;

Table 1. Comparison of CFA and FSC microdisplay optical efficiencies.

	CFA	FSC	Units
LED efficacy (white)	67	41	lm/W
Pixel fill factor	0.70	0.92	
Filter photopic throughput	0.325	1.000	
Relative efficiency	15	38	lm/W



	FLCOS	MEMS	UNITS
Total system power	1.0	1.0	W
Electronics power	0.1	0.6	W
LED power	0.9	0.4	W
LED white efficacy	56	56	lm/W
Illuminator flux	50	22	lm
Polarization throughput factors			
Pre-polarizer	0.40	–	
PBS round trip	0.85	–	
PCS	1.60	–	
Total polarization throughput	0.54	1.0	
Flux after polarization losses	27	22	lm
Throughput net of polarization	0.30	0.30	
Projector output	8.2	6.6	lm
Overall efficacy	8.2	6.6	lm/W

Fig. 4: *System complement and light-efficiency comparison of sequential-color microdisplays with integrated (FLCOS) and external (MEMS) electronics.*

the next two columns enumerate improvement coming over the next 6 years. Broad-band anti-reflection (BBAR) coating of the imager window and increased FLC switching angle, along with incremental improvement in pixel fill factor, should increase the throughput to 74% within about 3 years. The next step, replacing the aluminum pixel mirrors by higher-reflectivity materials, along with continued incremental improvements, takes imager throughput to 86% (+6 years).

Projection-engine optical throughput forms the final element determining pico-projector light output. Table 4 breaks down engine throughput factors, with an exemplary engine today putting 15% of the light emitted by the LEDs onto the screen. Changing from a MacNeille-type polarizing beamsplitter (PBS) to one with higher round-trip throughput [such as 3M's Mulitilayer Optical Film (MOF)] and capturing the imager improvements of Table 3 are the principal improvements we speculate will occur in the next 3 years to push projector throughput to 24%. The use of future polar-

Table 2. Current LED product performance.

Maker	Lumileds		Luminus
Type	Rebel		PT54
Drive (A)	0.35	0.70	13.50
Die size (mm^{2})	1.0	1.0	5.4
CW green (lm)	79	130	1400
CW red (lm)	61	100	700
CW blue (lm)	23	38	275
G/R/B duty	49/27/24	49/27/24	39/33/28
FSC white (lm)	60.5	100	854
FSC power (W)	1.1	2.4	45
White efficacy (lm/W)	56	41	19

Table 3. FLCOS imager optical throughput evolution.

	NOW	+3 Years	+6 Years
Mirror reflectivity	0.86	0.86	0.95
Fill factor	0.92	0.94	0.97
Gap effects	0.97	0.98	0.99
FLC tilt	0.90	0.97	0.97
Air/glass reflection	0.92	0.98	0.98
ITO reflection	0.98	0.98	0.99
TOTAL	**0.62**	**0.74**	**0.86**
Pixel pitch (µm)	11.75	11.75	11.75
Interpixel gap (µm)	0.50	0.35	0.20
FLC switch angle (°)	36	40	40

Table 4. Pico-projector optical throughput evolution.

	NOW	+3 Years	+6 Years
Polarization			
Pre-polarizer	0.43	0.43	0.80
PBS	0.84	0.92	0.92
PCS	1.44	1.53	1.00
Total polarization	0.52	0.61	0.74
Reflection			
Illuminator optics	0.80	0.85	0.90
Color combination	0.80	0.85	0.85
FLCOS imager	0.62	0.74	0.86
Projection lens	0.90	0.90	0.90
Total reflection	0.36	0.48	0.59
Other			
Imager overfill	0.83	0.86	0.91
Temporal "fill factor"	0.96	0.96	0.97
TOTAL	0.15	0.24	0.38

ized light sources, such as lasers or polarized LEDs,[4] eliminates the need for a polarization conversion system (PCS) and, along with continuing imager and illumination-optics improvements in the 6-year time frame, finally drives engine throughput to 38%.

The performance parameters outlined in the above tables draw the boundaries of the pico-projector design space; within the space, different pico-projector configurations can support varying product requirements. For example, Table 5 shows how the light output achievable with the 1-W power allowance typical of an embedded application grows from today's 8.4 lm to 20 lm and then 48 lm. Figure 5 similarly shows the consequences of expected improvements for 3.3- and 45-W projectors, relevant to the companion and wall-plug segments, respectively (the 45-W projector is assumed to have a somewhat lower optical throughput than the others since its LEDs are too large for PCS).

Finally, Fig. 6 extrapolates the evolution of a 20-lm projector. Increased LED efficacy allows reduced LED size and power; smaller LEDs in turn allow the imager to shrink, reducing system size and cost.

Conclusions

Pico projectors are positioned to provide consumers with an all-in-one mobile-electronics experience – movies downloaded to the phone can be played back to friends. However, as we hope the above analysis shows, pico projectors need not be confined to low-lumen applications. Their small size, low noise level, and long lamp life will encourage their use as data projectors in conference rooms as future years bring increased lumen outputs.

With light output eventually approaching 1000 lm, as predicted in Fig. 6, one could imagine a wireless television that simply screwed into a standard light socket, as depicted in Fig. 7. Given their high light efficiency, their integration of all needed driver electronics into the single microdisplay backplane chip, and a projection screen being their only need for a full-diagonal material component, pico projectors may become the least expensive way to display an image in the 8–40-in.-diagonal range.

Table 5. Light-output evolution for 1-W example pico projector.

	NOW	+3 Years	+6 Years
LED efficacy (lm/W)	56	84	126
LED power (W)	1	1	1
LED output (lm)	56	84	126
Projector throughput	0.15	0.24	0.38
Output (lm)	8.4	20	48

The future improvement of pico-projector performance can be predicted fairly certainly. The consequences of the improvements, though, cannot be seen any more clearly today than the personal computer was seen in the 1960s as the successor to mainframe computers.

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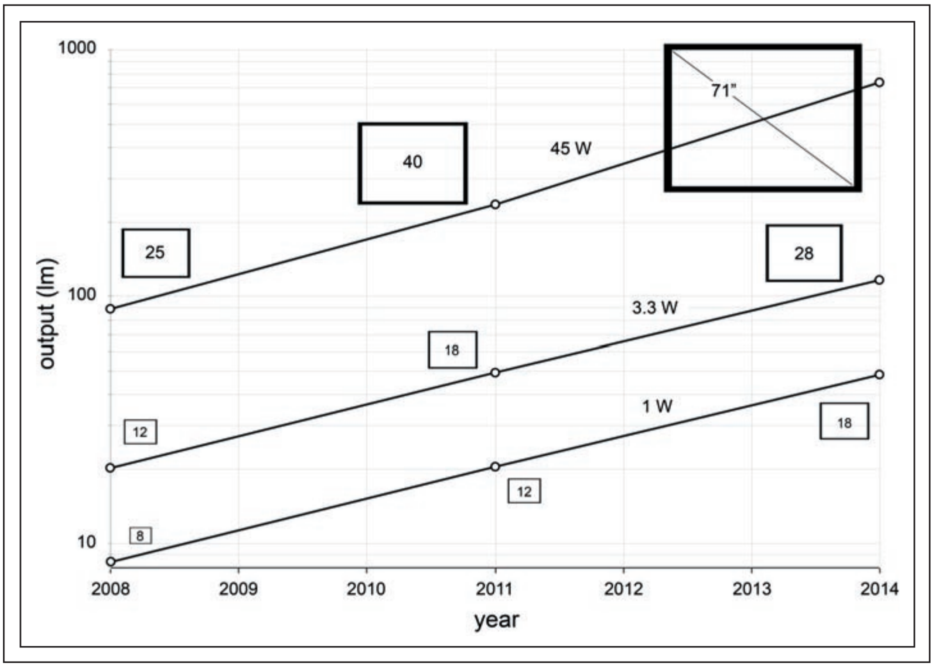

Fig. 5: Pico-projector light-output roadmap. The 1-W line starts with a 56-lm/W illuminator efficacy; the 3.3-W line begins at a 41-lm/W efficacy, while the 45-W line begins at 19 lm/W. In following years, illuminator efficacy improves by a factor of 1.5 every 3 years. Projector optical throughput advances one generation of Table 4 every 3 years. Rectangles show the corresponding achievable image diagonal in inches for a 150-cd/m² image brightness.

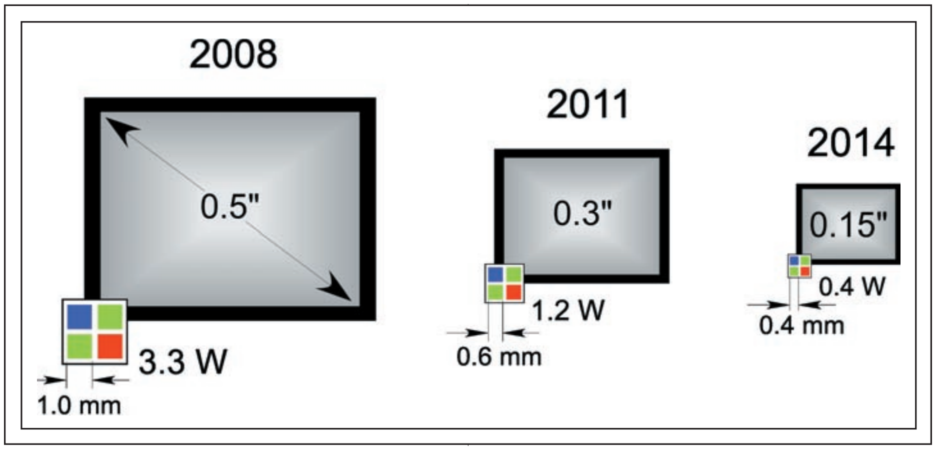

Fig. 6: *Performance roadmap for 20-lm pico projector. Increasing LED brightness and projector throughput allows smaller, lower-power LEDs to suffice; reduced LED area in turn permits smaller imagers at constant projector f/#.*

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Fig. 7: *Artist's conception of lamp-socket pico TV.*

Holographic Laser Projection Technology

Conventional lamp-based imaging projection technology is unable to simultaneously satisfy the demands from consumer-electronics manufacturers for projectors that are small, low in cost, consume little power, and offer a robust implementation, all while providing high-quality images. A number of LED- or laser-based microprojector technologies are now being developed to address these issues. Here, one manufacturer details its approach – a unique holographic laser projection technology that offers advantages over imaging and scanned-beam display technologies.

by Edward Buckley

THE CONVENTIONAL imaging projector is a near-ubiquitous device in today's offices and is also commonly found in cinemas and homes. Despite the capabilities of such projection systems, technical limitations in terms of miniaturization and power efficiency currently prevent the widespread adoption of projection subsystems into consumer-electronics (CE) and automotive applications.

The need for small, power-efficient projectors in the CE space is aptly demonstrated by the advent of mobile TV. It is clear that the high-resolution content available is incompatible with a typical cell-phone display of 2.5-in. diagonal and, as consumers and manufacturers alike have long since realized, such a display format is inconvenient for sharing content with multiple viewers. These restrictions could be solved by employing a battery-powered projection accessory or embedded projection device to display the content.

Applications such as reconfigurable instrument clusters and head-up displays (HUDs) in the automotive sector are also creating demand for miniature projection systems. Whilst there are clear benefits in using projectors for both applications, similar barriers to integration also apply because – as in the CE space – conventional projection systems are generally unsuitable for integration. For example, in addition to the high brightness and contrast ratios required for HUD applications[1] and extremely tight space constraints for rear-projection instrument cluster displays,[2] the entire projection subsystem must be robust, fault tolerant, and optically efficient while maintaining wide operating and storage temperature ranges.

As a result, a number of LED- or laser-based microprojector technologies are now being developed to address these issues and to overcome the fact that conventional lamp-based imaging projection technology is unable to simultaneously satisfy the key requirements of small physical size, low cost, low power consumption, and a robust implementation. In addition, it is clear from discussions with automotive and CE customers that there are several additional, and perhaps more restrictive, requirements that also must be fulfilled for the commercialization and acceptance of such miniature projection displays:

- High resolution
- High brightness
- Low speckle
- Eye safe
- Large depth of focus and wide projection angle.

Light Blue Optics (LBO) has been developing a unique holographic laser projection technology since 2004 that, unlike imaging and scanned-beam display technologies, has the unique ability to simultaneously fulfill the key OEM requirements outlined above.

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Holographic Laser Projection

LBO's technology represents a revolutionary approach to the projection and display of information. Unlike other commercially available projection technologies, this projection engine exploits the physical process of two-dimensional diffraction to form video images.

A typical imaging projection system works by displaying a desired image F_{xy} on a microdisplay, which is usually sequentially illuminated by red, green, and blue light to form color. In this case, the microdisplay simply acts to selectively block (or amplitude modulate) the incident light; after passing through magnification optics, the projected image F_{xy} appears. Conversely, holographic laser projection forms the image F_{xy} by illuminating a diffraction (or hologram) pattern h_{uv} by laser light with a wavelength of λ. If the hologram pattern is represented by a display element with pixel size Δ, then the image F_{xy} formed in the focal plane of the lens is related to the pixellated hologram pattern h_{uv} by the discrete Fourier transform $\mathcal{F}[\cdot]$ and is written as

$$F_{xy} = \mathcal{F}[h_{uv}] \qquad (1)$$

as shown in Fig. 1.

The key task in a holographic projection system is to compute the hologram h_{uv}; a

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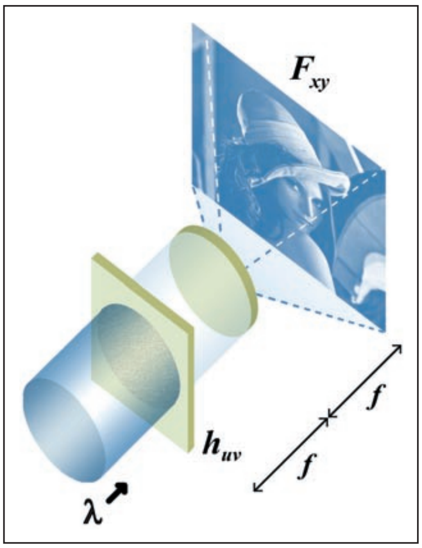


Fig. 1: *The relationship between hologram h_{uv} and image F_{xy} present at the back focal plane of a lens of focal length f, when illuminated by coherent monochromatic light of wavelength λ.*

reasonable first guess might be to calculate the inverse Fourier transform of the image F_{xy} to obtain the desired result. However, the result of this calculation would be fully complex, and there is no liquid-crystal (LC) material in existence that can independently and continuously modulate both amplitude A_{uv} and phase φ_{uv} where $h_{uv} = A_{uv}\exp j\varphi_{uv}$. Even if such a material became available, the result contains amplitude components that would absorb incident light and reduce system efficiency. A much better approach is to restrict the hologram h_{uv} to a set of phase-only values φ_{uv} such that $h_{uv} = \exp j\varphi_{uv}$. As a result, when the hologram patterns are displayed on a phase-modulating microdisplay and subsequently illuminated, no light is blocked.

LBO's system uses a custom-manufactured ferroelectric-liquid-crystal–on–silicon (LCoS) microdisplay from Displaytech, Inc., to display the hologram patterns, which requires that the hologram phase φ_{uv} is quantized to a set of binary values. This procedure inevitably introduces quantization noise into the resultant image F_{xy}, which must be mitigated in order to maintain high image quality. Thus, the microdisplay is used to display N independent holograms per video frame within a temporal bandwidth of the eye of 40 msec, each of which produces a subframe F_{xy} exhibiting statistically independent quantization noise.[3] If the intensity of the i_{th} displayed image is $I = |F_{xy}|^2$, then the time-averaged percept over N sub-frames is

$$V_{xy} = \frac{1}{N}\sum_{i=1}^{N} \left|F_{xy}^{(i)}\right|^2 \qquad (2)$$

which is noise-free, as illustrated in Fig. 2.

Uniquely, the key to this holographic laser-projection technology lies not in the optical design but in the algorithms used to calculate the phase hologram h_{uv} from the desired image F_{xy}. LBO has developed and patented proprietary algorithms for the purposes of calculating N sets of holograms per video frame, both efficiently and in real time, as first demonstrated in 2004.[4] Crucially, such algorithms can be efficiently implemented in a custom silicon chip.

A practical realization of a holographic laser projector is rather simple and is shown in the schematic of Fig. 3. A desired image is converted into sets of holograms by LBO's proprietary algorithms and displayed on a phase-modulating microdisplay that is time-sequentially illuminated by red, green, and blue laser light, respectively. The subsequent diffraction pattern passes through a lens pair L_1 and L_2, which is chosen to provide an ultra-wide projection angle in excess of 100°. As a result of the phase-modulating microdisplay, the incident light is steered into the desired image pixels – without blocking – and, due to Fourier optics, the image remains in focus at all distances from the lens L_2.

Advantages of Holographic Laser Projection

Low Speckle Contrast: One of the huge advantages of LBO's technology is the ability

Hologram	Subframe	Frame
$h_{uv} = \exp j\varphi_{uv}$	$\left|F_{xy}\right|^2 = \left|\mathcal{F}[h_{uv}]\right|^2$	$V_{xy} = \frac{1}{N}\sum_{i=1}^{N}\left|F_{xy}^{(i)}\right|^2$

Fig. 2: *The relationship between hologram h_{uv}, sub-frame F_{xy}, and frame V_{xy} in LBO's holographic projection technology.*

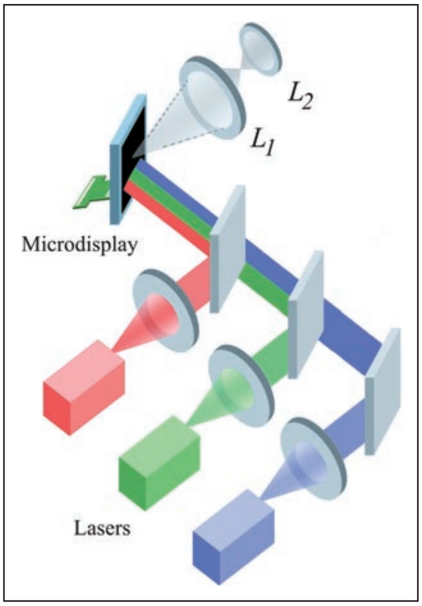


Fig. 3: A schematic diagram of LBO's projection technology.

to substantially reduce laser speckle, a phenomenon that makes the image "sparkle" due to scattering of coherent light from an optically rough projection surface and subsequent interference at the retina. The ability to reduce speckle is important because, not only do users find the artifact very unpleasant, it also severely impacts the perceived image quality and effective resolution.

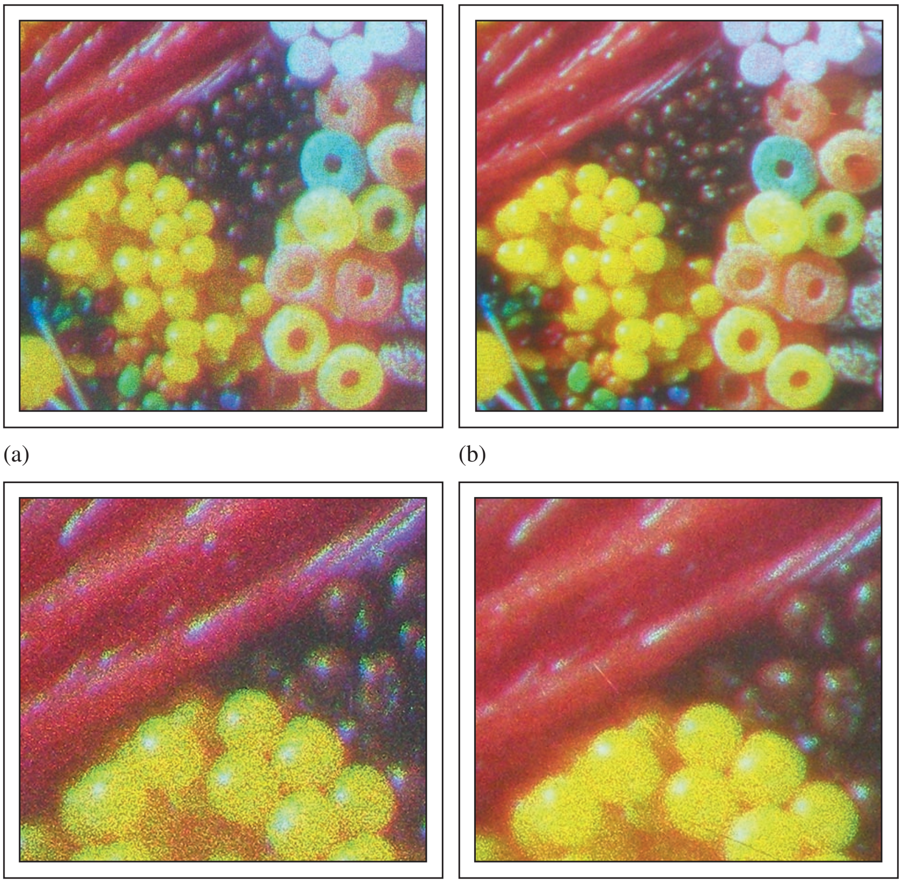
Although there have been several demonstrations of speckle reduction in the literature,[5-10] thus far only LBO has demonstrated the possibility for speckle reduction within the projection optics of a miniature laser projector.

As has been shown previously,[3] several methods can be combined in the LBO projector in order to reduce speckle. The first results from the method of image generation and display used in the LBO system. Since *N* phase-independent sub-frames per video frame are shown within the eye's integration period, then the eye acts to add *N* independent speckle patterns on an intensity basis, and the contrast of the low-frequency components of the speckle in the field V_{xy} falls as $N^{1/2}$. Evidently, some speckle reduction is inherent in LBO's multiple holograms per video frame approach to image display.

Additional methods can be combined to further reduce the speckle contrast because *N* cannot be increased indefinitely. Several methods[11-13] have been demonstrated to remove speckle, but each require that the operation is performed multiple times per laser dwell period. This is straightforward in LBO's system because the laser modulation frequency is low and all pixels are formed simultaneously. In addition, the intermediate image plane formed between L_1 and L_2 in Fig. 3 makes it simple to embed a speckle-reduction mechanism in the projector optics. The high laser modulation frequency and lack of an image plane make time-varying speckle reduction techniques difficult to implement in a scanned-beam system, as experts in the field have noted.[14] These restrictions dictate that speckle in a scanned-beam projector can only be acceptably suppressed by using potentially costly custom diffusing screens, thereby limiting the utility of such systems in CE applications.

A demonstration of the efficacy of LBO's combined speckle reduction techniques is shown in Fig. 4; note that laser speckle is substantially reduced in the projected image, without significant loss of focal depth or resolution.

High Brightness and Efficiency: It has previously been shown[15] that, due to the phase-modulating approach to image formation, a holographic display can project significantly brighter images than imaging and scanned-beam systems when displaying video and photo content. In addition, because the image pixels are formed using an expanded beam which has an extremely wide projection angle, it is possible to make a holographic laser projection system much brighter than a scanned-beam display for the equivalent laser safety classification.



(a) (b)

(c) (d)

Fig. 4: A sample image from LBO's projector (a) without speckle removal and (b) using a combination of speckle reduction techniques. The close-ups (c) and (d) clearly show substantial speckle reduction.

The same combination of laser and phase-modulating hologram provides a highly power-efficient method of projection since, unlike imaging displays, no light is blocked in the system. Furthermore, the phase-modulating nature of the microdisplay means that it is not necessary to continuously illuminate the micro-display; the lasers are modulated in accordance with the frame brightness, thereby only utilizing the power required to illuminate "on" pixels in the same way as a scanned-beam system.

Although LBO's projection technology carries the overhead of hologram computation, the overall system efficiency is expected to be comparable to that of scanned-beam systems. This is principally due to the low frequency at which the lasers are modulated in LBO's system; since gray scale is formed by the hologram and because the phase-modulating microdisplay directs a fixed proportion of light onto the image, it is only necessary to modulate the laser sources with respect to average video-frame brightness. This necessitates a laser modulation frequency on the order of 1 kHz, allowing efficient digital modulation schemes to be used for each color.

This is significantly more efficient than the method typically employed by scanned-beam projectors, where the pixel-by-pixel method of image formation requires the lasers to be switched at high currents and frequencies of tens of MHz using complex and power-hungry circuitry. Furthermore, limitations in green-laser switching speed also necessitate that the laser is inefficiently analog modulated above and below threshold to render gray scale.

High Resolution, High Image Quality, and Wide Color Gamut: In imaging systems, it is difficult to achieve high resolutions while maintaining an acceptable form factor because field breakdown, diffractive effects, and étendue-matching considerations set the minimum pixel size of the microdisplay.[16] The resolution of scanned-beam systems, on the other hand, is principally limited by the achievable laser modulation frequency.

In LBO's system, the resolution of the image is decoupled from that of the microdisplay and is controlled largely by the hologram computation algorithm; this allows the resolution to be fully variable up to a maximum of WVGA using just a 7 mm × 7 mm active-area microdisplay. Furthermore, the holographic system does not have a 1:1 correspondence between microdisplay pixels and projected image pixels as imaging systems do; in fact, each pixel on the microdisplay contributes to every pixel in the image, making the system tolerant to microdisplay defects.

It is generally accepted that microdisplay-based technologies, whether LCoS or DLP-based, have the capability to offer higher image qualities than scanned-beam systems.[17] Scanned-beam systems tend to suffer from poor image quality due to the unacceptably high speckle contrast ratios,[18,19] scanning artifacts,[20] and image distortion, making the use of such a technology unfeasible in applications where high image quality is required.

It is well known that laser sources can provide images with extremely wide color gamuts, due to their narrow spectral bandwidth; the Helmoltz-Kohlrausch effect can also increase perceived brightness due to the psychophysical effects of highly saturated primaries. RGB LED systems exhibit an acceptable color space for CE applications, although systems that use white LEDs have significantly reduced gamuts due to the strong absorption of the microdisplay color filters at red wavelengths.

Conclusion

LBO's holographic laser projection technology represents a revolutionary approach to the projection and display of information, exploiting the physical process of two-dimensional diffraction to form video images. Such an approach simultaneously provides many compelling benefits compared to competing LED- and laser-based miniature projection systems, and the ability of this technology to satisfy the stringent requirements outlined by CE and automotive customers will allow LBO to bring this truly disruptive display technology to market in 2009.

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A Single-Mirror Laser-Based Scanning Display Engine

Myriad pico projectors are scheduled to become commercialized in 2009, and each one offers a different pathway to success. Here, Microvision details the technology and development decisions that have lead to its PicoP single-mirror laser-based scanning display engine.

by David Lashmet, David Baty, and Matt Nichols

THE RACE TO MARKET for pico projectors has never been more heated. Companies active in this sector have all taken somewhat different methods to developing these tiny projectors that will be mobile and lightweight while delivering a big-screen viewing experience from mobile devices. Following an aggressive 24-month design program, kicked off in 2006, Microvision is on the verge of commercializing its ultra-miniature laser-based display engine, which will first be integrated into a battery-operated handheld pico projector roughly the size of an iPhone and will follow as an embedded pico projector in mobile phones and other portable devices.

This article details Microvision's fundamental technology, reasons for its design approach, historical development, advantages, and future direction for the PicoP display engine.

Display-Engine Platform

Microvision's PicoP™ display-engine platform provides a distinct display approach in the emerging pico-projector category. The foundation of the display engine is based on modulating light temporally and scanning spatially using a single tiny oscillating MEMS silicon mirror to produce an image. The tiny scanning mirror itself is less than approximately 1 mm^2 in area – about the size of the head of a pin. The MEMS scanning mirror is integrated with red, blue, and green lasers, video and MEMS drive electronics, and an optical combiner that enables the total display engine (which measures 42 mm × 20 × 7 mm and weighs 20 grams) (see Fig. 1). In an accessory device, this design could use as little as 3 W with a further expected reduction to 1.5 W or lower for implementation into embedded mobile-phone projectors.

The RGB lasers are modulated on an 8-bit-per-color-channel basis to address each of the individual picture elements, or pixels, that comprise a digital image or frame of video. Thus, if one of the three colors is not needed due to the image content, this laser is down-modulated, which minimizes power consump-

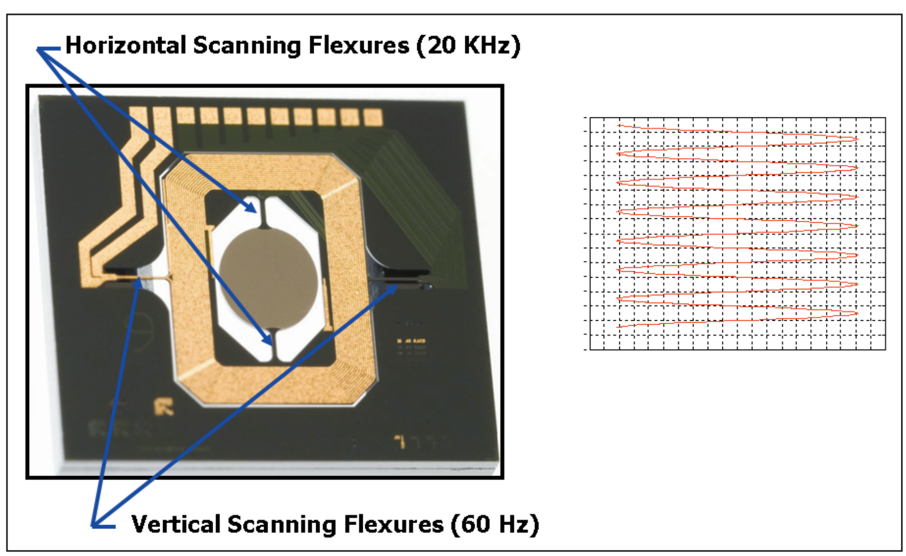

Fig. 1: A single MEMS mirror oscillates biaxially to raster-scan a two-dimensional image – much like old TVs but with photons instead of electrons.

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tion. All three colors are combined by optics into a single light path. The single scanning mirror then scans the combined beam of light in a raster-like fashion, one pixel at a time, at 60 frames per second (fps)to project large, high-resolution video images (Fig. 2).[1] The current PicoP display engine projects a WVGA (848 × 480) resolution image in a 16:9 format at a brightness of 10 lum, with a diagonal image size of about 1 m at a projection distance of 1.1 m.

Laser Advantages

In addition to the advantages of low power and enabling the small size of the display engine, laser light sources require no projection lens or expansion optics. This is because they generate a collimated beam of light, which is raster scanned by the single biaxial MEMS mirror. Furthermore, this allows Microvision's projector to be focus-free because each pixel is essentially a fast dwell-time dot from a laser pointer – and collectively, this re-creates the digital image across any brightly reflective surface at any viewing angle. In other words, a scanned-laser display eliminates the need for the movable optical lens associated with LED-based projectors that use physical arrays of pixels. Plus, it dispenses with the expansion lens needed for laser-lit physical arrays, whether LCOS or DLP. Lenses introduce losses, distortion, vignetting, and chromatic aberration. But the real issue is package size. Every cubic millimeter in a projector assembly is valued, especially in converged devices such as handsets, and size significantly affects adoption. In addition, reducing the size and complexity of the optical train reduces component and design costs.

Lasers also provide other advantages besides being focus-free, including a broader color gamut (greater than 100% of NTSC) and very high contrast ratios (>10,000:1), which leads to better gray scale. Lasers produce monochromatic red, green, and blue that, in the PicoP display-engine design, is directly transmitted through the system without having to pass through any filters or light-valve mechanism that can alter the emitted spectrum. For portable projection from handsets, this makes text and video images easier to see in a wide variety of lighting conditions.

Design Considerations: The Road to Commercialization

One or Two Mirrors? There are actually quite a few approaches to scanning light with MEMS mirrors; Microvision, Motorola, and Konica-Minolta have all shown commercial prototypes. The key differentiator between these is in the number of scanning mirrors: two mirrors; one for each axis of oscillation or one mirror that goes both back and forth and up and down bi-axially. In a two-mirror system, the second mirror has to catch the spread beam of the first mirror, which can cause image alignment or geometry issues, along with possible optical degradations. If either mirror is out of skew, the effects on the final image can be dramatic. In the case of a single-mirror system, only a single reflection of the modulated laser image is required and the registration between horizontal and vertical scanning is always ensured. Thus, we focused our efforts on a practical design with one MEMS mirror, not two.

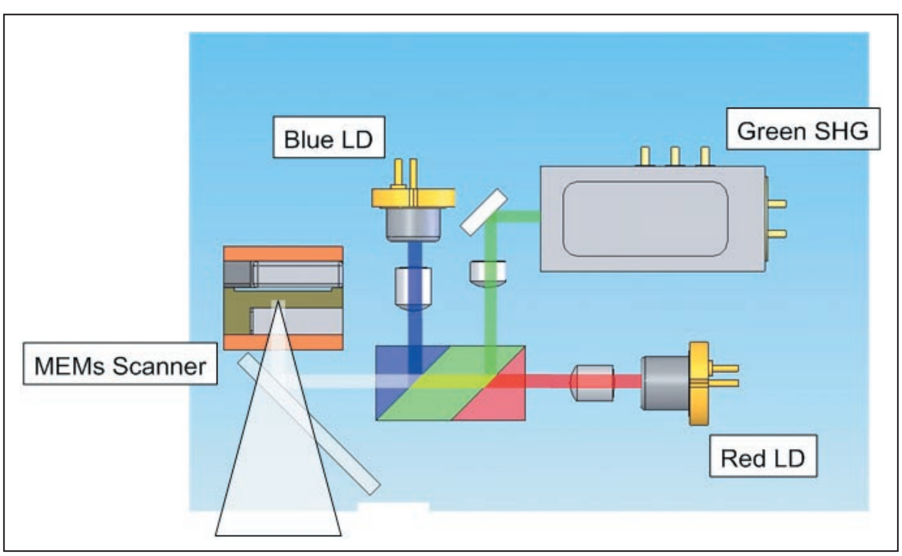

Fig. 2: A model PicoP-enabled projector system using a MEMS scanning mirror and three lasers requires no focus lens.

Lasers in Scanned-Beam Pico Projectors

Building an ultra-miniature mobile laser projector, naturally enough, starts with small laser diodes. In terms of supporting an RGB laser system, red diodes are readily available, as they are found in consumer CD players. Blue laser diodes were first developed by Shugi Nakamura at Nichia in 1997 – today, these are used in Blue-ray DVD players. Blue laser diodes are also suitable for mobile projectors. True green laser diodes, however, are not yet available. But commercial plans for laser TVs as well as miniature projectors have encouraged both start-ups and companies such as Corning and OSRAM to develop frequency-doubled infrared laser diodes that yield green at a 530-nm wavelength.[2] Although each of these companies has a different approach to making green laser diodes, all have been successful, and they all are currently designing their production capabilities to support the high-volume requirements of the mobile marketplace beginning in 2009 and growing rapidly thereafter.

Form Factor: From Refrigerator Size to Cell-Phone Size in 14 Years

In order to deliver an optimized single-mirror scanned-laser display solution, numerous fundamental design considerations and quality goals have had to be addressed. Microvision's highest priorities have been on solidifying image quality, reducing power, and designing the engine for high-volume manufacturability.

Meeting all of these challenges has been the collective effort of 14 years of development, including 2 years focused exclusively on the PicoP display-engine product and miniaturizing the core scanning mirror technology. The point of entry for this project was the scanning mirror used in the Nomad™ wearable head-up display. That product was a technical success, but a consumer-market failure because it was only powered by a red laser. Moving to RGB meant a rich color palette and a broad gray scale, with contrast ratios greater than 1000:1.

Nomad itself went through two iterations. The most notable was a change in mirror design from an electrostatic drive – requiring hermetic sealing and a 500-V transformer – to an electromagnetic drive that worked at 1 atm with a simple dust cover. Next, a military contract yielded the Spectrum 500 eyewear, which provided RGB (with chemical lasers) in a milk crate (> 10 liter) form factor. That is vastly smaller than Microvision's circa 1998 electronics suite, which included a rack of servers and could easily mimic a very warm refrigerator.

Thanks to Moore's Law and advances in solid-state laser technology, Microvision's first bench-top pico-projector prototype was realized prior to and demonstrated in 2006 at SID's Display Week. This demonstrator showcased the capabilities of an RGB single-mirror scanned-laser display, with greatly reduced electronics. Essentially, the electronics were the size of a pizza box, while the integrated photonics module (IPM) was well under 10 cc, suggesting today's smaller 5.6-cc IPM. This same benchtop demonstrator delivered bright 800 × 600 resolution at 60 Hz and 10 lum using wall power. But the core Nomad MEMS mirror only projected at a 22° horizontal angle (+/-11°), whereas the research-grade next-generation mirror offered twice the horizontal throw angle of 44° (+/-22°).

Given tremendous customer interest in a wider field of view, the second-generation MEMS mirror became Microvision's core focus, so this design was optimized for reliability, as its electronic controls were reduced to FPGAs. Thus, at Display Week 2007, Microvision demonstrated a benchtop PicoP display-engine projection system based on this wide-angle MEMS scanner, delivering "letter-box" WVGA (852 × 480) resolution in a 16:9 aspect ratio. The wide-angle MEMS mirror produced a full-color digital image with a viewable area four times larger than the 2006 prototype. The electronics were shrinking and speckle, a frequently cited somewhat objectionable optical artifact seen in most laser-based projection systems, was demonstrated to be largely undetectable to most observers of this demonstration, greatly mitigating this concern.

Further improvements in drive electronics and color control produced the battery-operated self-contained prototype in January 2008 for the Consumer Electronics Show in Las Vegas. Code-named the SHOW™ prototype, this handheld device illustrated the concept of cell-phone projectors, given its compact integrated photonics module its wide field of view, bright colors, and high contrast ratio (>1000:1). The SHOW prototype supported content from a host of companion devices, including an iPod, a Nokia N95 cellular telephone, and a notebook computer.

By September 2008, the FPGAs in the electronics platform for Microvision's handheld pico projector were being converted to ASIC chips. This process produced the current third-generation (SCP-3) prototypes, which first were shown in public at the SID Mobile Displays Conference in September 2008. Compared to the SCP-1 SHOW prototypes, the SCP-3s exhibit much better small-font readability, with legible 10-point font text, along with a 200% color gamut compared to broadcast television, or roughly 100% more than NTSC. Technically speaking, the SCP-3s also normalized the color balance between the projectors for large-scale manufacturability. This established a reliable D65 white point for Microvosion's pico projectors and increased side-by-side contrast ratio on a checkerboard pattern to greater than 2000:1.

By commercial launch in 2009, the major drive electronics will be converted to ASIC chips, a process that significantly reduces the image noise introduced by prototype lasers. In parallel with this conversion of FPGAs to ASICs, a global team of supply-chain partners has been assembled to support requirements for initial and high-volume manufacturing of the integrated photonics module, as well as final product assembly. While many of the partners remain confidential, lead design assembly is being driven by Asia Optical, one of the largest assemblers of digital cameras in the world.

Debut, Debits, and a Brighter Future

Microvision is preparing for commercial product launch of an accessory pico projector in 2009. To support embedded designs, PicoP display-engine evaluation kits will also be made available. This 10-lum WVGA projector will be 5.6 cc in volume and only 7 mm in height, so it is optimized for incorporation into cellular handsets.

Microvision's pixel-by-pixel image creation method optimizes the power efficiency of its laser light sources. Currently, red and blue laser diodes offer double-digit electrical-to-optical efficiency, rivaling LED light sources, while producing a polarized, collimated beam. Frequency-doubled IR lasers – producing green laser light – are less efficient today, but pathways exist to improve these at least beyond incandescent lights. True green laser diodes have not yet been invented. But given the potential size of this market, we expect efforts by material scientists to solve this dilemma.

Also on the future roadmap is a higher resolution image, to 720p and beyond. Using Microvision's core technology, a higher resolution also means a broader angle of projection, and even further reduction in an already acceptable level of speckle. Other image-quality strategies are in advanced development: on the laser side, in the optical train, and with proprietary screening material. These continued improvements to image quality are likely to make pico projectors key supplements to mobile devices, ultimately becoming ubiquitous in smart phones, then in all phones. Eliminating the projection lenses and using lasers seems the most efficient way to accomplish this. Add focus-free capabilities, and it is easy to recognize the value of a single MEMS scanning mirror to end users.

Notes

PicoP, Nomad, and SHOW are trademarks of Microvision, Inc.

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Rolling toward a Revolution?

Polymer Vision plans to launch the Readius, the first commercial application to feature a rollable flexible display, to be released in early 2009. Will it be the "killer app" for rollable flexible displays?

by Michael Morgenthal

"We're trying to break the rules." That is how Michael McCreary, Vice President of Research and Advanced Development at E Ink Corp., describes the Polymer Vision Readius, which will be the first rollable flexible-display device to enter the marketplace when it launches in 2009. Polymer Vision has partnered with E Ink in the development of the Readius, which will initially serve as an e-reader device, but one that clearly will be unlike any that has preceded it.

Certainly, attendees at Display Week 2008 can testify to the ground-breaking nature of the Readius. Polymer Vision showcased various prototypes of its rollable flexible display there, and it quickly became one of the most talked about demonstrations at Display Week. Audible gasps were heard as the electrophoretic screen unspooled from its case, reaching a diagonal width of nearly 5 in. The image on the screen refreshed several times, and then the screen disappeared back into its packaging.

But wowing display enthusiasts with prototypes is one matter; ramping up for commercial production on a product that "is trying to break the rules" and then winning over consumers represents a entirely different set of challenges.

Officials from Polymer Vision and E Ink allowed *ID* a look at how the Readius has evolved, what their hopes are for the product, and what they think it represents in terms of flexible-display development.

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The Readius

Polymer Vision believes that the Readius will distinguish itself from all other current e-reader products in the marketplace, such as the Amazon Kindle, because none of those are truly portable in the modern sense. Edzer Huitema, CTO of Polymer Vision, compares those devices moreso to tablet or notebook PCs because they are too big to fit into a consumer's pocket.

"Our aim for this product is to be the first ones to make a real mobile product for e-reading," Huitema said. "(The Readius) has mobile-phone size and weight – not smartphone weight but typical mobile-phone weight (115 g) and still has a large display (5 in.)."

The device is 115 mm long and 21 mm thick at all times, but expands from 57 mm wide when the screen is closed to 160 mm when it is open (Fig. 1). The active-matrix backplane, developed and manufactured by Polymer Vision, has a performance level comparable to that of a-Si backplanes, Huitema stated (the on/off ratio is a little higher than that for a-Si backplanes, but the drive voltages are similar). The resolution is QVGA (320 × 240), which is lower than most e-readers currently on the market. This decision was made as a compromise between technological capability and market demands.

"We didn't want to make the display too complex from a manufacturing perspective, while also trying to make a display that is acceptable from a market perspective," Huitema disclosed. "At Display Week, we showed a display that is 900 × 550 with a 254-ppi resolution. Our technology now is so far developed that we can do that (build it in our R&D line). For production, we said we would first make a QVGA 5-in. display. Technology-wise, we can go larger – it's more a limitation of our equipment set."

E Ink used its Vizplex™ electrophoretic imaging film to develop the frontplane. The entire display weighs just 5.6 g and is only about 100 µm thick, about 10 times thinner than glass displays of similar size and about five times thinner than current plastic displays.

Developing such a thin display was critical for several reasons. The first of which is display performance. When pieces of plastic are rolled up, they tend to spring apart, and it is hard to keep them aligned, which is critical for in the performance of any display. As the display rolls up, tremendous strain is placed on the outer and inner layers, McCreary explained, but there is a "neutral plane" in the middle where strain is minimal, but increases with the thickness of the stack. This can result in separation of layers, cracking, or crinkling, any of which could drastically reduce the display's performance.

"Normally, we have a protective sheet that goes on top of the displays that is several hundred microns thick, and the electronic-ink sheet that is laminated to the transistor backplanes is also several hundred microns," McCreary detailed. "We developed new types of materials that could collapse a 100-µm-thick display down to 60–70 µm. Everything is integrated under one sheet, and the actual plastic substrates we use are about the

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(a) (b) (c)

Fig. 1: (a) When the display is closed, the Readius measures 115 mm long, 21 mm thick, and 57 mm wide. (b) The display is only about 100 μm thick, about 10 times thinner than glass displays of similar size and about 5 times thinner than current plastic displays. This allows it to bend easily as well as to roll and unroll frequently without any degradation to image quality. (c) When fully extended, the display measures about 5 in. on the diagonal and extends the device to a width of 160 mm.

thickness of a piece of Saran Wrap – they are that floppy and really really thin."

While McCreary would not elaborate on how this was accomplished other than to say that E Ink modified the polymers and process flow it normally employs, he did state that working with such thin layers of plastic was obviously a tremendous challenge, as was getting all the multiple layers required for the display in a protective sheet – including UV absorbers to eliminate glare and humidity barriers – that could then be coated with the ink for the display.

"We did tests where we rolled (the display) 25,000 times, and afterwards, we would not accept degradation in image quality," Huitema added. "There were tests at high temperature, low temperature, rolled-up storage — all kinds of tests on the mechanical side. In the end, it really comes down to having good adhesion between the layers as well. All layers really need to stick very well to each other and that is the only way you can get a rollable system that you can roll multiple times."

The thickness was also critical in order to keep the Readius at a comfortable size – the device could not be too thick when the display was rolled up.

"In general, the rule of thumb (with plastic displays) is that you can roll (the display) to a radius that is 50 times its thickness," Huitema explained. "In 2003, we set a spec for ourselves in that we wanted to be able to roll the display 10,000 times at a radius of 7.5 mm. At that time, we were not close to that. But we knew that if you go below those specs, it would be very hard to make any product because either the device becomes too thick or it has a serious reliability problem because you cannot roll it enough."

Polymer Vision has been pleasantly surprised by recent improvements in shelf lifetime, Huitema added. Lifetime has been an issue throughout the plastic electronics field, but lifetime for the Readius currently exceeds 5 years.

Manufacturing: From R&D to Pilot Production

In 2004, Polymer Vision started a "pre-pilot" line in the Netherlands to develop rollable displays for research and development. There, the company made 50–100 displays per week in, week out, and then subjected them to all manner of torture tests in order to eliminate defects, which come from what Huitema colorfully describes as a "big burrito" of sources. Gradually, the company eliminated the defect sources until it reached a point where only particle-related defects remained.

"We replaced a number of processing steps used in the a-Si world – which are performed at high temperature – by spin-coating or spray-coating steps, all of which are done at room temperature," he said. "This is really important because our plastic substrates are so thin that firstly you do not want to melt them and, secondly, you do not want to deform them.

"If you go to high temperature, the plastic will deform. We need to align five masks on top of each other, as in all typical displays, within 1 μm per sheet; thus a total of 5 μm. So we really need to have only very small deformations in the plastic during the processing steps. That is key for all other technologies on plastic, to get that right."

In February 2007, the company partnered with British manufacturing concern Innos to launch its pilot line at a factory in Southampton, U.K. A carbon copy of the R&D line from Holland was installed in the U.K. and within two months the first displays were being produced there.

Huitema would not discuss yields other than to say that they plan to scale up to mass-production levels in the coming years.

Flexible Displays' Killer App?

Huitema is buoyed by the success of e-reader devices such as the Kindle (Amazon does not release sales figures for the device, but speculation online and in the media has centered around 500,000 devices shipped in 2008), but he is quick to add that he does not see the Readius as direct competition for the Kindle and other current e-readers.

"We will probably attract a different set of customers," he explained. "The reason I say that is that we are a portable solution for e-reading. The Kindle is a rigid-based e-reader tightly connected to a proprietary library, while we are more like an open platform that targets mobility. So it will attract a different set of consumers, and in that way make the market bigger. I don't think there will be a lot of consumers where we are competing."

Polymer Vision already has a section of its Web site called Content World, where both free and paid content such as eBooks and RSS feeds will be available.

"You can choose your content from whatever source you wish, be it via Content World, another Web site, or from your own PC," the Web site states. In addition, the Readius will come complete with a 3.5G cellular-phone platform, although there is no specific speaker or earpiece on the device – a headset will be necessary to use the phone.

Pricing for both the device itself and its content has yet to be made public; in fact, Polymer Vision has been quiet about which retail and service-provider partners will carry the Readius. However, in 2007, the company did announce a deal with Italian mobile provider Telecom Italia to distribute the device in Italy.

Huitema stressed that the e-reading platform will be the main application for the Readius "for a while," but other uses are definitely being explored, including full-color and video. At Display Week 2008, Polymer Vision showed a full-color prototype of the Readius that generated a tremendous amount of buzz.

"We have solved the problem of aligning a flexible color filter with a flexible display. It is a difficult problem to solve because they both expand and shrink during the processing, and aligning them at the end on top of each other is almost impossible," he explained. "We are now in the process of tuning color performance, whiteness, and the color-filter process, but we are already quite far along in making the complete stack to a level that we can put it into production. I would say in general it will be ready within 2 years."

So, this is how the Readius differentiates itself from current e-readers. But will it succeed and live up to its billing – that of a killer app for flexible displays?

"For rollable displays, we see this as a killer app, and the reason is very simple," Huitema proclaimed. "At this moment, data-centric devices are becoming more and more dominant in the mobile space. Smart phones are gaining increasing market share in the mobile space and they are more and more data-centric. Data revenues are rapidly increasing, and voice revenues are shrinking a little bit per user. So data is becoming important."

He added that while typical smart phones have about 30% of their area covered by a display and the iPhone's display occupies almost the entire device, the Readius will allow users to go beyond 100% of the device's size for the display.

"That is without adding any weight," he added. "People don't want to have a larger device, but want to have a larger display because we have high-speed networks."

David Barnes, Vice President of Strategic Analysis for a market-research firm, likened the Readius' potential impact to that of the iPhone.

"I hesitate to forecast (the potential of the Readius) because in my mind, it is a category creator (not a category changer)," Barnes said. "You look at something like the iPhone. We had touch technology around for more than a decade, and no one was really that excited about it until Apple managed to package it with the right kind of hardware and software, and suddenly everyone wants it."

"Even though people say they may read a book or read e-mail on a cell phone, frankly the only way to have a big screen in a small pocketable device is to have it be able to be folded up or rolled up – I can't think of another good way of doing it, where the screen is bigger than the actual device you are sticking in your pocket," McCreary concluded. "It's ground-breaking. It's a major technical and capability milestone in the growth of non-glass displays. I do think it's the first concept, not the last. It's just the beginning." ■

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Edited by Aris Silzars

Inorganic EL devices with high-performance blue phosphor and application to 34-in. flat-panel televisions

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Abstract — A high-performance inorganic electroluminescence (EL) device has been successfully developed by using an EL structure with a thick dielectric layer (TDEL) and sputtered $BaAl_2S_4$:Eu blue phosphor. The luminance and efficacy were higher than 2300 cd/m^2 and 2.5 lm/W at L_{60}, 120 Hz, respectively. Furthermore, the luminance at L_{60}, 1.2 kHz was more than 23,000 cd/m^2. The phosphor layer has a single phase and a highly oriented crystalline structure. The phosphor also shows high stability in air. A 34-in. high-definition television (HDTV) has been developed by combining a TDEL structure and color-conversion materials. The panels with an optimized color filter demonstrated a peak luminance of 350 cd/m^2, a color gamut of more than 100% NTSC, and a wide viewing angle similar to that of plasma-display panels. The high reproducibility of the 34-in. panels using our pilot line has been confirmed.

Figure 1 shows the schematic structure of a TDEL device. The TDEL device has a thick dielectric layer, which replaces the thin dielectric layer of TFEL devices. The thick dielectric layer is prepared by combining the screen-printing method and firing process without using any vacuum processes. The thick dielectric layer consists of materials with high dielectric constants.

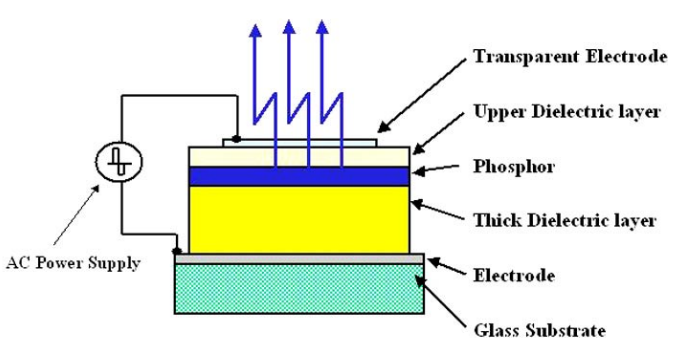


FIGURE 1 — Schematic drawing of the TDEL structure.

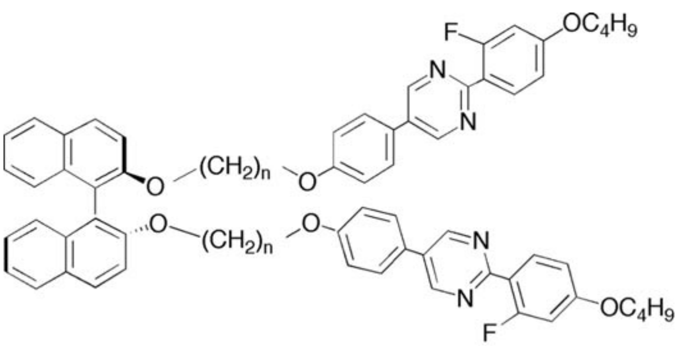
Molecular design for stabilizing a blue phase III and electro-optical switching in the blue phase

Atsushi Yoshizawa

Hirosaki University

Abstract — The molecular design of a liquid crystal to stabilize a blue phase III (BPIII) is reviewed, and the electro-optical switching with a response time on the order of 10^{-2} sec for BPIII exhibited by a novel chiral liquid crystal is reported. Binaphthyl derivatives and T-shaped compounds are presented, and the structure–property correlations of the chiral compounds are discussed. Two origins of the twisting power of the compounds, *i.e.,* their inherent molecular chirality and the chirality-induced twist conformation, play an important role in the appearance of the BPIII. Furthermore, BPIII was also induced in some binary mixtures of a host nematic liquid-crystal possessing molecular biaxiality and a conventional chiral compound. The electro-optical switching in the BPIII is attributed to an electric-field-induced phase transition between the BPIII and nematic (N) phases. BPIII is on the microscopically twisted nematic order, but is macroscopically isotropic. Therefore, the present technology can offer a pronounced black state in the BPIII without surface treatment and a homogeneous bright state in the induced N phase.

The appearance of blue phases results from the competition between the chiral twisting force and the desire for molecules to fill space uniformly. Although many types of liquid crystals have been prepared, molecular design for stabilizing blue phases has never been obtained. Theoretical work suggests that biaxaility plays an important role in the blue phases. However, the biaxiality in most chiral nematic liquid crystals is slight, and as a result the double-twist structure cannot exist in a wide temperature range.



1-n

FIGURE 1 — Molecular structure of the binaphthyl derivative **1 – n**.

Effects of display properties on perceived color-gamut volume and preference

Masato Sakurai (SID Member)
Rodney L. Heckaman
Stacey E. Casella
Mark D. Fairchild (SID Member)
Takehiro Nakatsue (SID Member)
Yoshihide Shimpuku (SID Member)

Sony Corp.

Abstract — The effect of varying the color gamut of an extended-gamut LCD on color appearance and preference was measured psychometrically in two experiments at each of two separate laboratories over a representative set of 10 images each. The first experiment measured the effect of color gamut on appearance, and the effect on the appearance attribute colorfulness was shown to be relatively strong compared with other attributes as the volume of display color gamut is varied. Overall, colorfulness monotonically increased at constant sensitivity as the gamut area in *xy* chromaticities increased while tending to become less and less sensitive to increasing the gamut volumes in CIELAB and CIECAM02. In the second experiment, the overall preference indicated an optimal color gamut for the display gamut volume even though the results were shown to be highly scene-dependent.

Four versions of each scene were rendered to each of four sets of simulated display primaries with gamut volume factors of 1.0, 0.8, 0.6, and 0.4 times the full-color gamut of the display in CIELAB *a*b** at Group-A and 1.0, 0.89, 0.77, and 0.63 at Group-B, respectively. All the versions were constrained to maintain both the display's white point and hue within the ability of CIELAB to maintain perceptual hue. Therefore, the lightness in each version of any given scene was rendered equally.

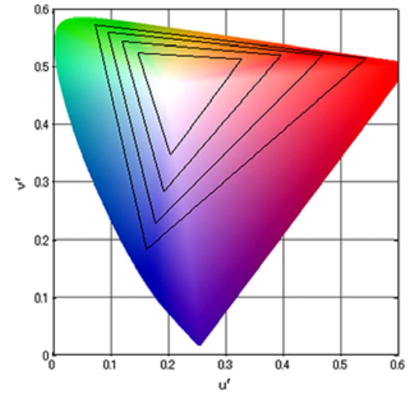


FIGURE 2 — Color gamut for the simulated primaries plotted on a *u′v′* chromaticity diagram. The outside triangle indicates the full gamut of the display in this experiment.

High-performance MgO thin films for PDPs with a high-rate sputtering-deposition process

Masaharu Terauchi, Jun Hashimoto, Hikaru Nishitani, Yusuke Fukui, Michiko Okafuji, Hitoshi Yamashita, Hiroshi Hayata, Takafumi Okuma, Hitoshi Yamanishi, Mikihiko Nishitani, Masatoshi Kitagawa

Panasonic AVC Networks Co.

Abstract — A high-rate sputtering-deposition process for MgO thin films for PDP fabrication was recently developed. The deposition rate of the MgO thin film was about 300 nm/min which shows the possibility of production-line application. The MgO film deposited in this work has a higher density than that of other deposition processes such as electron-beam deposition and shows good discharge characteristics including firing voltage and discharge formation. These were achieved by controlling the stoichiometry and/or the impurity doping during the sputtering process.

To improve the uniformity of the film thickness, a groove in the target was made. Figure 3 shows a photograph of the target with a grooved circle. It was shown that the groove in the target was made to be incandescent and the other part of the target was not incandescent in sputtering. By making the groove, the incandescent part of the target can be controlled. So, the uniformity of the film thickness was improved within ±10% in the 10-cm square.

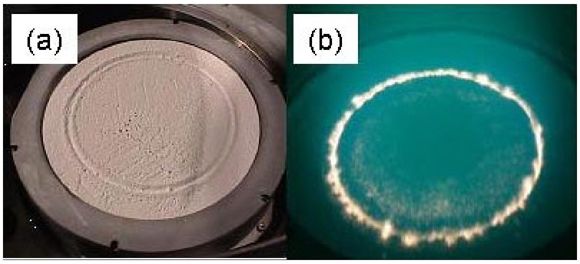


FIGURE 3 — Photograph of the target with the circled groove: (a) Before discharging, (b) discharging.

Use of self-erase discharges for high-speed and low-voltage addressing of PDPs

Masakazu Shimura
Tsuyoshi Yamaguchi
Tomokazu Shiga (SID Member)
Shigeo Mikoshiba (SID Fellow)

University of Electro-Communications

Abstract — A technique called "self-erase-discharge addressing" has been incorporated with a address-while-display driving scheme, contiguous subfield, and erase addressing to obtain high-speed and low-voltage addressing of PDPs. The technique uses a relatively high X-sustain pulse voltage V_{Xsus}, which produces a weak self-erase discharge at its trailing edge. An application of a data pulse V_{data} synchronous to a weak self-erase discharge results in full erase discharge and eliminates all the wall charges. The technique assures a wider operating-voltage margin since it provides identical amounts of priming charges as well as wall charges to all the horizontal scan lines just prior to addressing. The priming charges are generated by the weak self-erase discharges, resulting in low V_{data} of 30 V and a high addressing speed of 0.66 μsec for a Ne + 10% Xe PDP. V_{Xsus} = 245 V, and the voltage margins of V_{data} and V_{Xsus} were 35 and 16 V, respectively. For a 30% Xe PDP, V_{data} and V_{Xsus} were 30 and 335 V, respectively, with an addressing speed of 1.0 μsec. In order to obtain high dark-room contrast, it is essential to use ramp reset pulses, with which erase addressing cannot be achieved. By adopting the write addressing only to the first subfield and the self-erase-discharge addressing to the subsequent subfields, a peak and background luminance in green of 3100 and 0.22 cd/m^2, respectively, were obtained with a dark-room contrast of 14,000:1. The number of subfields was 28, and the light emission duty was 83%. The number of ramp reset pulse drivers could be reduced to 12 by adopting the common reset pulse technique.

Figure 4 shows a timing chart of the proposed driving scheme. There are a reset period and 32 subfields having a constant width of 512 μsec within a TV field time of 16.7 msec. Each subfield consists of an address period and a sustain period. The address period of one of the scan electrodes is provided within the display period of other scan electrodes, and hence the name address-while-display scheme. The number of sustain pulses in the respective subfields can be varied from 2 to 126. This allows for smooth gray scales even at low luminance levels.

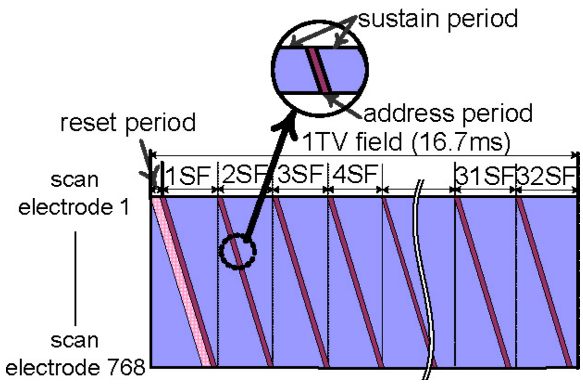


FIGURE 4 — Timing chart of self-erase-discharge addressing scheme.

Characteristics of ACPDP test panels with aluminum fence electrode formed via anodic bonding with soda-lime glass

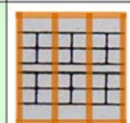
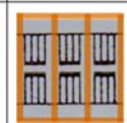
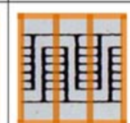
Seog-Young Lee (SID Student Member)
Mi-Yeon Lee
Won-Yeol Choi
Dong-Heon Lee
Yong-Seog Kim (SID Member)

Hongik University

Abstract — In an attempt to reduce materials and processing costs of ACPDPs, aluminum fence electrodes were prepared on soda-lime glass substrates by chemically etching aluminum foil bonded directly onto the substrate via an anodic-bonding process. Several different fence-electrode patterns were designed and coated either with a glass dielectric layer or with an anodic aluminum oxide layer. Firing voltages, operation margin, luminance, and luminous efficiency of such test panels were evaluated. The results indicated that the performance of test panels with aluminum fence electrodes is comparable with conventional test panels with ITO/Ag electrodes, demonstrating the possibility of a dramatic reduction in the costs of ACPDPs.

Table 1 shows various types of aluminum fence electrodes prepared in this study. Type A is the typical fence electrode with shorting bars formed at the center of the cells. The fence width was 20 μm and the sustaining gap was 70 μm. Type B and C were designed to increase the electrode area near the sustaining gap and, therefore, intensify the glow discharge as in the in-bus structure. In those designs, the width of the fence at the sustaining gap was increased to 40 μm and the cell opening ratio of the cells was decreased by 11% for type B and 7% for type C, respectively. Type D was designed to maximize the area of the facing electrodes such that the firing voltage can be reduced further.

TABLE 1 — Geometry and cell-opening ratio of fence-type electrodes used in this study.

Type	A-type	B-type	C-type	D-type
Cell geometry				
Cell opening ratio	85.3%	74%	77.4%	75.2%

Ink-jet-printable phosphorescent organic light-emitting-diode devices

Takuya Sonoyama
Masaki Ito
Shunichi Seki
Satoru Miyashita
Sean Xia (SID Member)
Jason Brooks (SID Member)
Kwang-Ohk Cheon
Raymond C. Kwong (SID Member)
Michael Inbasekaran
Julie J. Brown (SID Member)

Seiko-Epson Corp.

Abstract — A novel method for the fabrication of ink-jet-printed organic light-emitting-diode devices is discussed. Unlike previously reported solution-processed OLED devices, the emissive layer of OLED devices reported here does not contain polymeric materials. The emission of the ink-jet-printed P^2OLED (IJ-P^2OLED) device is demonstrated for the first time. It shows good color and uniform emission although it uses small-molecule solution. Ink-jet-printed green P^2OLED devices possess a high luminous efficiency of 22 cd/A at 2000 cd/m^2 and is based on phosphorescent emission. The latest solution-processed phosphorescent OLED performance by spin-coating is disclosed. The red P^2OLED exhibits a projected LT50 of >53,000 hours with a luminous efficiency of 9 cd/A at 500 cd/m^2. The green P^2OLED shows a projected LT50 of >52,000 hours with a luminous efficiency of 35 cd/A at 1000 cd/m^2. Also discussed is a newly developed sky-blue P^2OLED with a projected LT50 of >3000 hours and a luminous efficiency of 18 cd/A at 500 cd/m^2.

Figure 9 shows the normalized EL spectra of the red, green, and the newly developed sky-blue P^2OLEDs measured at 10 mA/cm^2 and the 1931 Commission International de l'Eclairage (CIE) coordinates. The red P^2OLED has a peak wavelength at 623 nm with coordinates of (0.66, 0.33). The green P^2OLED has a peak wavelength at 521 nm with coordinates of (0.33, 0.63). The sky-blue P^2OLED has a peak wavelength at 474 nm with coordinates of (0.19, 0.40). No cavity was used in this experiment to affect the emission.

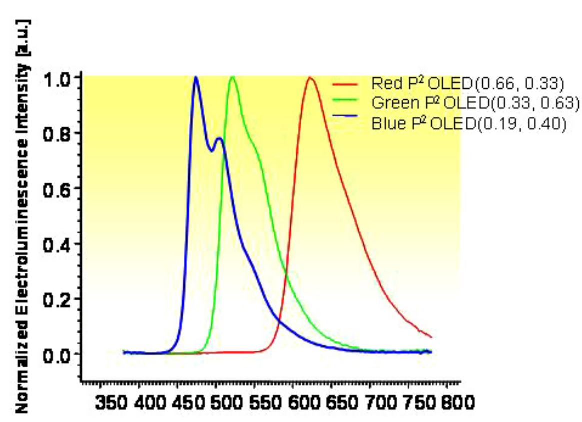


FIGURE 9 —Normalized electroluminescence spectra of red, green, and blue P^2OLEDs with CIE coordinates of (0.66, 0.33), (0.33, 0.66), and (0.19, 0.40), respectively, measured at 10 mA/cm^2.

Contrast gain and power savings using local-dimming backlights

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Remco Muijs (SID Member)
William van Beek

Philips Research Laboratories

Abstract — The contrast and power consumption of today's liquid-crystal displays (LCDs) can be improved substantially by introducing (local) dimming backlights. In fact, infinite dynamic contrast and power savings of well over 50% have been claimed for such displays. Because these claims are generally made for very specific backlight designs and image content, the contrast gain and power savings are quantified as a function of the number of backlight segments for a large variety of image content.

The number of segments (# segments) was the main independent variable. Two-dimensional quadratic Lorentz optical profiles of which the width was chosen in such a manner that the maximum luminance nonuniformity of a full white screen amounts to 1% were used. A static panel contrast of 1000, which is typical for today's LC panels, was scanned. The backlight drive values were established from the incoming video content using the Max(R,G,B) algorithm.

FIGURE 1 — Illustration of local dimming. The backlight (rear image) is at full brightness at the position of the cat's eyes and is dimmed at the darker parts of the image. The panel (front image) is simultaneously compensated for the backlight modulation such that the scene is properly depicted.

Full-color photo-addressable electronic paper using cholesteric liquid crystals and organic photoconductors

Haruo Harada (SID Member)
Makoto Gomyo
Yasunori Okano
Tai j yu Gan
Chisato Urano
Yasuhiro Yamaguchi
Tomozumi Uesaka
Hiroshi Arisawa

Fuji Xerox Co., Ltd.

Abstract — Full-color photo-addressable electronic paper using cholesteric liquid crystals and organic photoconductors was developed. The electronic paper is comprised of two stacked photo-addressable elements displaying blue/green and red images, respectively. Each photo-addressable element was independently controlled by two different color-addressing lights. Furthermore, blue and green images were selectively switched by one organic photoconductor using the threshold characteristics of cholesteric liquid crystals. A highly reflective polymer-dispersed cholesteric liquid-crystal (PDCLC) layer was obtained by a new formation process based on the sol-gel transition behavior of a gelatin matrix and an agar overcoat layer. The PDCLC layer had a close-packed honeycomb-like monolayer structure with a flat surface. The A6-sized prototype had paper-like features and showed full-color bistable images instantly written with a viewer-type writing apparatus.

Figure 7 shows the formation process of the PDCLC display layers. Monodispersed ChLCs-in-water emulsion was obtained by a membrane emulsification technique. A membrane with a 4.4-μm pore size was used, and the average diameter of the obtained droplets was about 15 μm. The concentrated emulsion was mixed with an aqueous solution of acid-processed bovine bone gelatin to obtain a mixed emulsion containing 10.5 vol.% ChLC and 4.5 vol.% gelatin. The mixed ChLC-in-gelatin aqueous emulsion was applied to the substrate at a wet thickness of about 75 μm and was over-coated with a 1-wt.% aqueous solution of agar having a wet thickness of about 30 μm. Since this process was carried out at high tem-perature (60°C), both layers were in a low viscosity sol state.

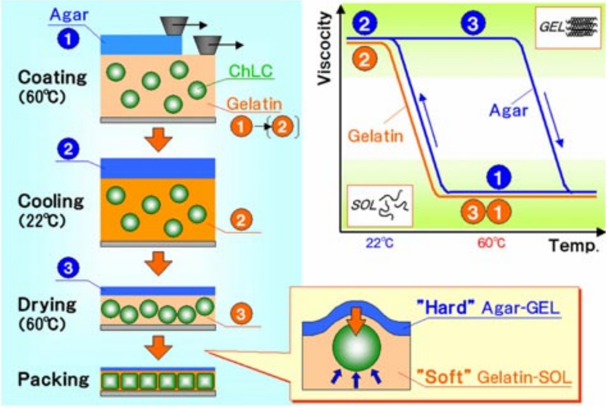

FIGURE 7 — Formation process of the PDCLC display layer. The close-packed honeycomb-like monolayer PDCLC is formed by using the differences in the sol-gel behavior between gelatin and agar.

A 5-in. flexible ferroelectric liquid-crystal display driven by organic thin-film transistors

Yoshihide Fujisaki
Hiroto Sato
Tatsuya Takei
Toshihiro Yamamoto
Hideo Fujikake (SID Member)
Shizuo Tokito
Taiichiro Kurita (SID Member)

NHK Science & Technical Research Laboratory

Abstract — An organic thin-film-transistor (OTFT) driven color flexible ferroelectric-liquid-crystal (FLC) display with 160 × 120 pixels and a resolution of 50 ppi has been developed. The flexible FLC was fabricated on a pentacene-OTFT array using printing and lamination techniques. To drive the display at a fast driving speed, an OTFT was developed with a short channel length having a large current output. The fabricated OTFT array with a channel length of 5 µm exhibits a carrier mobility of 0.3 cm^2/V-sec and an ON/OFF ratio of over 10^7 at a low drain voltage of –6 V. A field-sequential-color system with a flexible backlight unit was also developed and used to drive the display. Color moving images were successively shown on the 5-in. display using an active-matrix driving technique of the OTFT.

The structure of the flexible FLC display is shown in Fig. 1. A composite film, consisting of the FLC and polymer fibers, is sandwiched between rubbed polyimide alignment layers on plastic film. Lattice-patterned polymer walls that adhere to the surface of the substrates are formed in the composite film. This structure provides high mechanical stability of the device in a bent state. The FLC molecules are mono-stabilized by the strong anchoring effect from the polymer fibers that lie in the rubbing direction of the polyimide alignment layers.

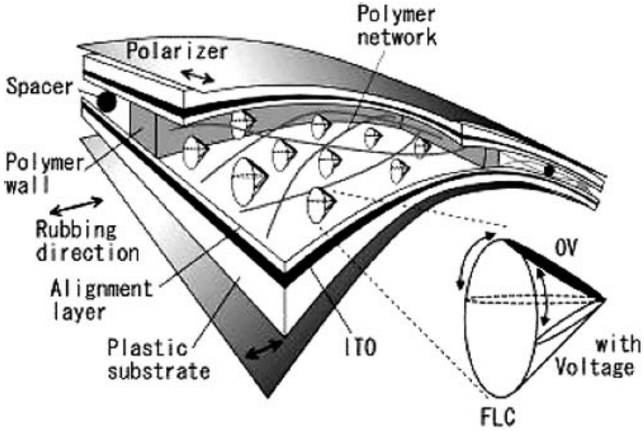

FIGURE 1 — Structure of a flexible FLC display panel.

Improved discharge time lag of address pulse in an ACPDP with auxiliary electrodes

Cheol Jang
Kyung Cheol Choi (SID Member)

Korea Advanced Institute of Science and Technology

Abstract — New driving waveforms are proposed for an ACPDP with an auxiliary electrode. Auxiliary pulses and a stepped scan pulse during the address period distinguish the proposed waveforms from conventional waveforms. The address discharge time lag in an ACPDP with auxiliary electrodes was improved by application of auxiliary pulses and a stepped scan pulse during the address period. The interaction between the auxiliary pulse and the stepped scan pulse generates priming particles directly prior to the address discharge, and these priming particles influence the address discharge. As a result, the firing voltage of the address pulse is lowered, and the minimum address voltage is lower than that of conventional driving waveforms. Experimental results confirm that the address discharge time lag of the proposed waveforms is 32% lower than that of conventional driving waveforms.

As shown in Fig. 1, the FEEL PDP has an auxiliary electrode between the sustain electrodes. When auxiliary pulses were applied to the auxiliary electrodes during the sustain period, the luminous efficacy was increased. The auxiliary pulses were applied between the sustain pulses, which were applied, in turn, to a common electrode and a scan electrode.

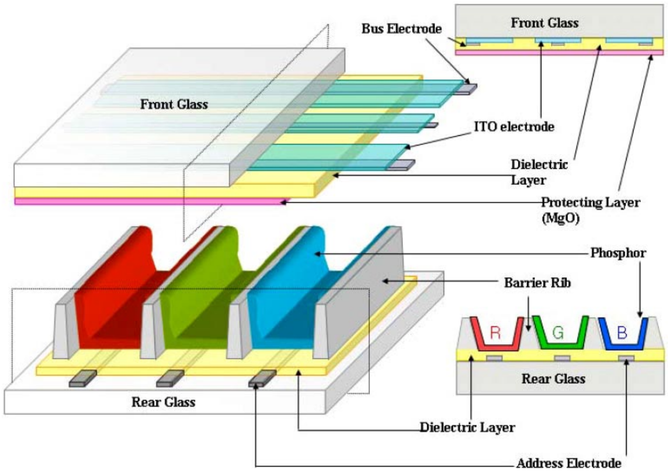

FIGURE 1 — Schematic diagram of an ACPDP with a coplanar gap of 200 µm and an auxiliary electrode.

Fault-tolerant display image-data-manipulation unit for system-on-panel

Hyun-Goo Lee
Jae-Hee You

Hongik University

Abstract — Bit-partitioned and conventional shifts, as well as type transformations of multimedia data, are frequently used for display image-processing systems. A data manipulation unit with fault-recovery capability based on redundancies is proposed for system-on-panel with low-processing technology yield. Utilizing data manipulations that are similar to normal shift operation, a proposed data-manipulation unit is designed with a few additional paths added to the existing barrel shifter. The design methodologies are verified with FPGA and the performance is evaluated in terms of the advantages.

The proposed DMU, as SOP technology evolves, can be integrated on the display panel. Also, since it is based on two 32-bit barrel shifters, it can be utilized in multimedia processors with more than two arithmetic units. Since the DMU is mainly composed of regular interconnections with higher yield compared to the devices, fault tolerance with redundancies and scaling can be easily realized.

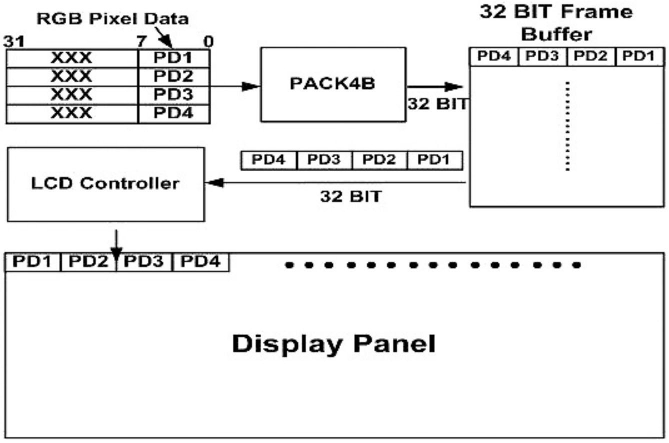

FIGURE 3 — The proposed DMU architecture.

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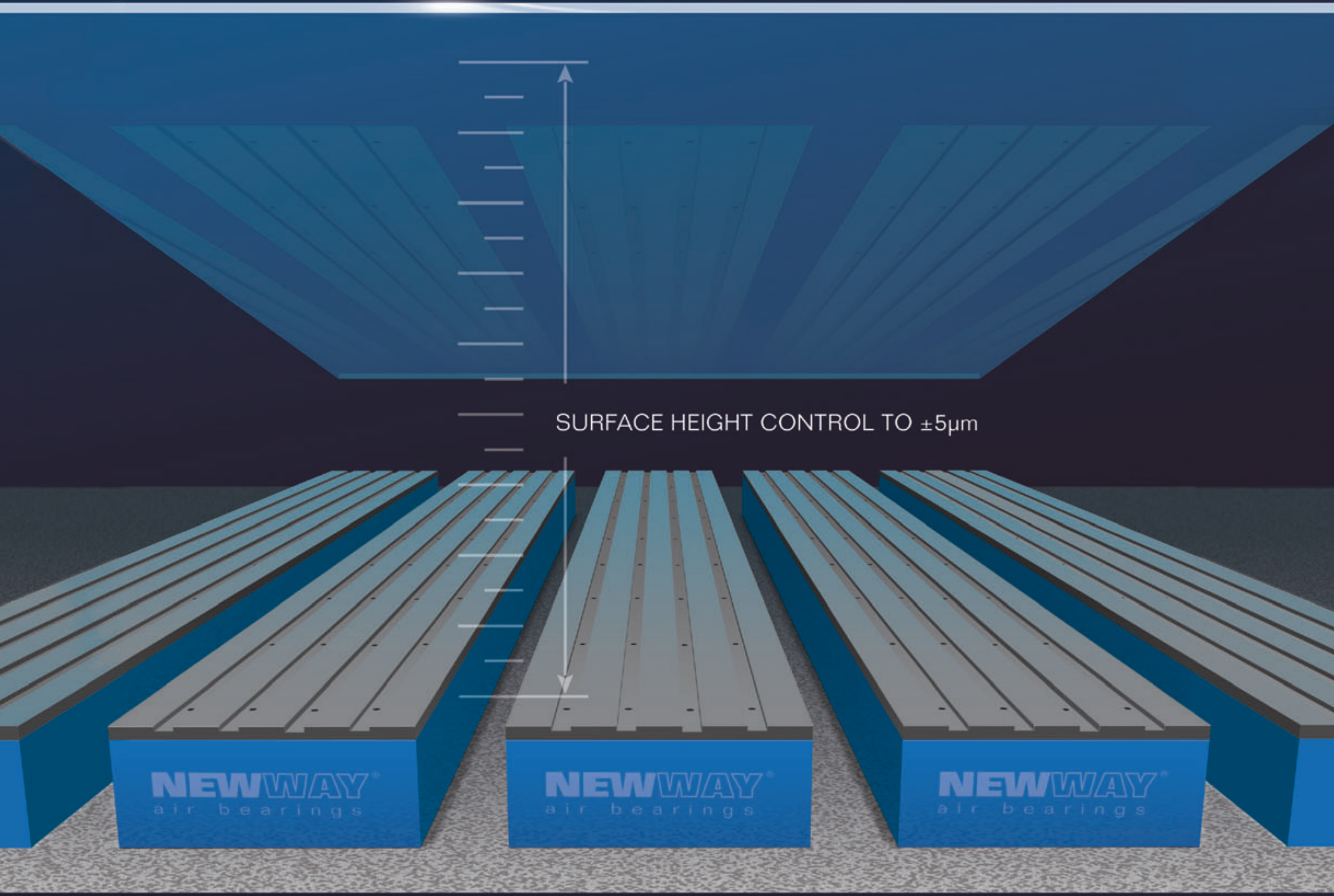

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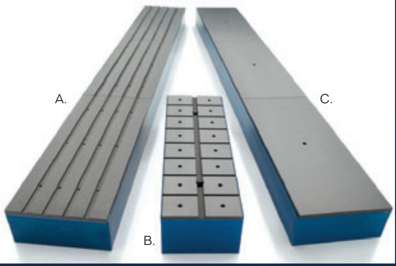

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guest editorial

continued from page 4

The authors analyze and compare the efficiency of color-filter array versus color-sequential pico-projector systems. They also compare the efficacy, lm/W, for the color-sequential systems utilizing both LCOS and MEMS-based microdisplay technology and provide a roadmap for future LED and microdisplay developments.

Light Blue Optics takes a very different approach to developing a pico projector in the third paper of this issue. They generate images by computing sets of statistically independent holograms corresponding to the desired image, which are then displayed at several times the video frame rate on a high-speed LCOS microdisplay. The microdisplay, used as a two-dimensional phase-only diffraction grating, is illuminated by pulsed R, G, B lasers. The system achieves high efficiency because the diffracted light is steered into the desired pixels, without absorption, to form the desired image. By using a number of techniques, including driving the microdisplay at several times the video frame rate, speckle caused by the coherence of the laser illumination is reduced.

In the final paper, Microvision takes yet another fundamentally different approach to pico-projector technology. Instead of using a high-resolution imaging device, *i.e.*, LCOS, DLP, *etc.*, they use a unique single-element MEMS mirror to scan nanosecond R, G, B laser light in two dimensions and thereby construct an image. Because of the high collimation of the lasers, the depth of field of the image is very large, resulting in simplification of the optical design and application flexibility. Like the CRT, image-format flexibility is another feature of a scanned-beam display system.

The market opportunity coupled with the novel and varied technological approaches make the pico-projector field one of the most dynamic areas of current display development. This issue of *Information Display* provides a sampling of the status of the development work in this field. Additional significant work is ongoing in laboratories around the world. The technology and the market should converge in the next year or two. Either pico projectors will form the basis of a significant new display market or they will possibly recede back to low-volume niche applications. The first products of this exciting endeavor should appear soon; their market acceptance will be a harbinger of the future.

Robert L. Melcher *is with Melcher International, LLC; telephone 650/391-9907, e-mail: rlmelcher@gmail.com.*

president's corner

continued from page 6

History shows that these fears and issues were overcome. Sony took the early plunge in launching the Sony Reader with some success, and now the Kindle is now generating buzz for both Amazon and for E Ink. It is tempting to think that finally, after all these years, the nagging technical problems that delayed a high-volume product have finally been solved. While I'm sure that there were many hurdles to solve, I am not convinced that technology was the issue here.

Let me come back to my conversation with my friend. After listening to her tell me how great the Kindle is, I asked her to tell me what she liked about it. She quickly rattled off a number of properties that were important to her: "It's easy to carry around – it fits in my purse"; "I can buy the books I want whenever I want to"; "I can read newspapers on it"; "I can fit lots of books on it at once."

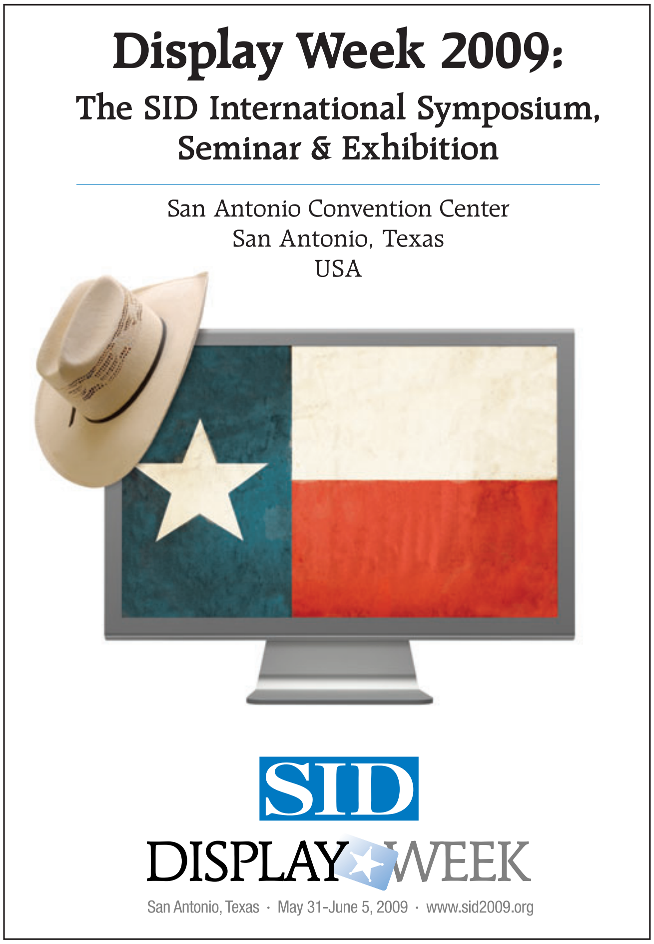
After she paused, I asked, "Well, what about the screen?" "Oh yes, I like the screen. It is easy on my eyes, not like my laptop."

So there you have it. The obvious value proposition (at least to the display-oriented person) is the cool display. To my friend, though, the most important aspects of the device were the portability and easy access to content. The screen was important, but wasn't what got her excited. This distinction may point out why the Kindle seems to be getting traction when electronic-book readers, using all sorts of technologies, have had a more difficult time. Amazon got it right!

I am tempted to draw similar distinctions between this case and the rapid rise in touch-screen technology fueled by Apple's iPhone. Touch-screen technology has been around for many years, but it took an Apple to identify what the killer application for touch would be. Now, SID conferences and publications are buzzing with discussions around touch technologies at a level unheard of just a couple years ago. It seems that all the technology was waiting for was a great idea on how to use it.

So, the lesson that bears repeating is that people generally buy products, not just displays. The Kindle product is a winner, and the display is just a piece of the pie, along with the wireless network and the large content library. Who would have thought?

Paul Drzaic
President
Society for Information Display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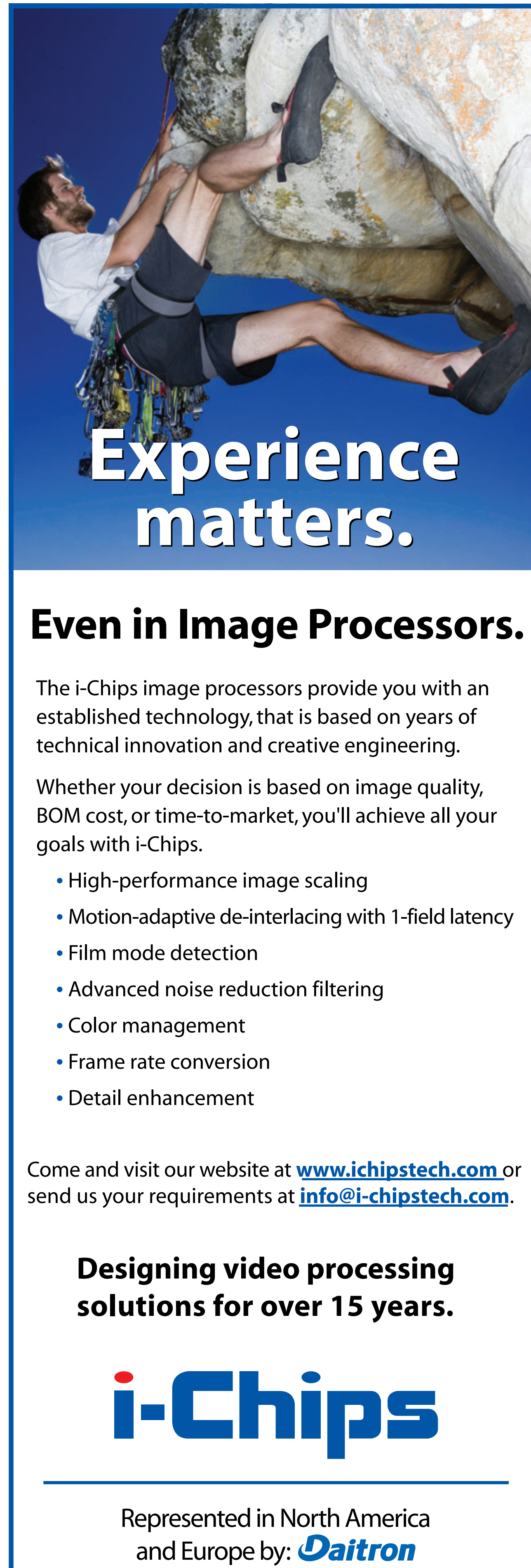
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editorial

continued from page 2

followed by other products and similar innovations. We suspect the manufacturing infrastructure for this type of product is still immature, but even a small amount of commercial success will surely spark rapid investment – this, as I mentioned earlier, is another reason we want to take a good look at display-manufacturing technology over the next year.

Last year at this time I also expressed my amazement of display technology itself, and how it seems to touch everyone's lives and envelope countless scientific disciplines. The displays we build serve as windows back into the world from where they came and help everyone to see things in ways they may not have imagined before. I sometimes use the term "magical" because I really believe that despite our critical investigation of the physical world, and our highly evolved understanding of materials and processes, there is a level of elegance in the final form that cannot be fully explained. For many of us, the magic may be lacking these days, with the economic downturn causing defensive reactions throughout the corporate world, such as reduced spending on research, consolidation of existing operations, and limits on funding for capital programs. The side effects will certainly be felt throughout the display community and affect all of us, but I believe this period will be short-lived.

Here at *Information Display*, we remain undeterred. If the past years have taught us anything, it is that the industry we love produces technology that people virtually cannot live without anymore. Rarely can you find anyone who does not own a television, and cell phones have penetrated almost every society in the world. People view their cell phones (with camera and video features) and their organizers as critical parts of their existence. It's easy to envision pico projectors and e-readers in a similar way, with the evolution of these devices into ones that create an integrated seamless personal-information space. The time is near when everyone will upgrade to some type of personal device that includes a virtual display and interactive information that is much more immersive than what is available today. Projection technology is surely an enabler of this evolution so it's hard to imagine any economic or political situation that can slow this down very much. Where consumers wait with needs unmet, there waits technology ready to fulfill. Our job is to bring that potential to life, and thus far our track record seems pretty good. I'm looking forward to the coming year and I hope you are also.

On a sad note, we were surprised to hear of the death of Chuck Pearson, well known to many of us for his tireless work in human resources for the display and semiconductor industries. Chuck volunteered countless hours to various SID activities and I always enjoyed his insights and counsel at our frequent meetings. He helped many people launch their careers and gave freely of his time to anyone who sought his help. It was an honor to be his friend and work with him on the SID Board. On behalf of the team at *Information Display*, we thank you, Chuck, for all you did to brighten our days. We will miss you.

Stephen P. Atwood

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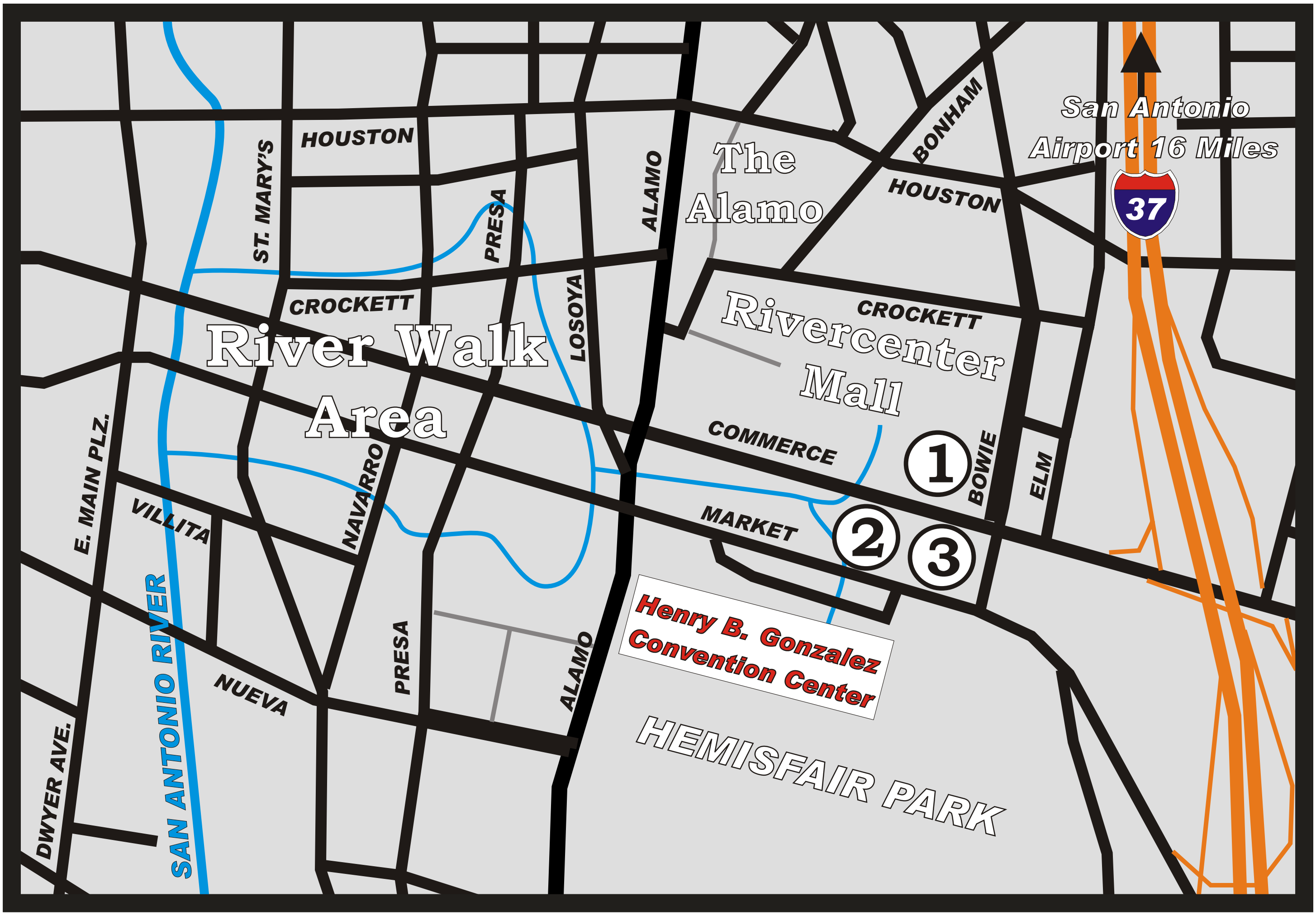

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index to advertisers

3M **9,29,C4**
Aixtron **8**
Astro Systems **7**
Benchmark **43**
Display of the Year Awards **44**
Display Week 2009 .... **33**
Eyesaver International **14**
i-Chips **43**
JDSU **21**
Lumetrix **20**
Merck Chemicals **11**
Microvision **10,C3**
New Wave Air Bearings **41**
OPTEK **15**
Optronics Laboratories **45**
Phlox **C2**
Radiant Imaging **5**

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314 ☐ Plasma Display Panels
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316 ☐ Display Components, Hardware, Subassemblies
317 ☐ Display Manufacturing Equipment, Materials, Services
318 ☐ Printing / Reproduction / Facsimile Equipment
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320 ☐ Communications Systems / Equipment
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