Progress in Projection and Large-Area Displays

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Invited Paper

A new class of compact high-definition electronic projection systems has emerged that are based on microdisplays. Very large scale integration process technology is adapted to fabricate the three classes of microdisplays: 1) transmissive liquid crystal on high-temperature polysilicon/quartz; 2) microelectromechanical devices on silicon; 3) and reflective liquid crystal on silicon. A variety of system architectures are discussed. Key ancillary technologies include small arc lamps, color separation and recombination optics, and rear-projection screens.

Keywords*—*Arc lamps, front projectors, microdisplay, projection, projection screens, rear-projection television.

I. INTRODUCTION

The emergence of microdisplay technology over the past decade has revolutionized the electronic projection display industry. A microdisplay essentially integrates the imaging capability and capacity of a desktop monitor onto a chip. Small (<1-in diagonal) integrated-circuit (IC) backplanes are combined with light modulating front planes to produce a microdisplay device. One to three of these microdisplays are combined with projection lamps and optical devices into projection systems with a broad range of performance and price capabilities.

The technical literature abounds with excellent references that provide an overview of products and technologies [1], [2]. Fig. 1 shows a two-dimensional portrayal of the classes of systems either in production or contemplated by developers. Further, the diagram is overlaid with several vertical lines showing the approximate projection output power (lumens) required, which is determined both by display size and required screen brightness. Projection display opportunities center around screen sizes in the 60-in (150-cm) diagonal size, where about 1000 lm of engine power is required with a image definition of at least 700 lines or extended graphics array (XGA) definition (1024 × 768 pixels). Niche markets already exist for larger sizes with developers targeting high-volume television (TV) and monitor markets with smaller sizes.

The classes of displays are also targeted at a wide variety of market opportunities. The existing markets are relatively low-volume high-priced niche markets whereas the target markets are mainstream high-volume value-priced consumer markets as shown in Fig. 2. Current worldwide markets range from 10 000 units per year for large venue and eCinema projectors up to 1 million units annually for portable and rear-projection TV opportunities. Factory prices for the current high volume markets are falling toward $1000 per system.

It is widely agreed by market analysts that the current projection display markets will grow rapidly over the next five years from its current base of more than 3 million units to more than 7 million units in 2006 [3]. The forecast for the emergence of new projection products such as personal-computer TV (PCTV) monitors and TVs is much more uncertain. It is not clear that system designers can achieve either the performance or price requirements for these high volume markets, where active-matrix liquid-crystal display (AMLCD) flat panels continue to erode the market position of the incumbent CRT products.

In summary, the product requirements for major market segments are shown in Table 1.

1) *Presentations Market:* The first three market segments can be generally grouped under the presentations market banner. The three major segments—large venue, conference rooms, and portables—continue to see constant and significant improvements in system performance and lower prices. Microdisplay projectors have largely driven the older CRT systems from the market and created the market for smaller portable systems.
2) *Big-Screen Rear-Projection TV:* While the market has been dominated by rear-projection cathode-ray tube (CRT) projection technology sets, it is ripe for change as microdisplay systems disrupt the market with high-definition and high-brightness images.
3) *PC Monitors and TVs:* The technology story in the monitor market has been the influx of AMLCD flat-panel monitors. While a number of rear-projection system developers are targeting 25–35-in

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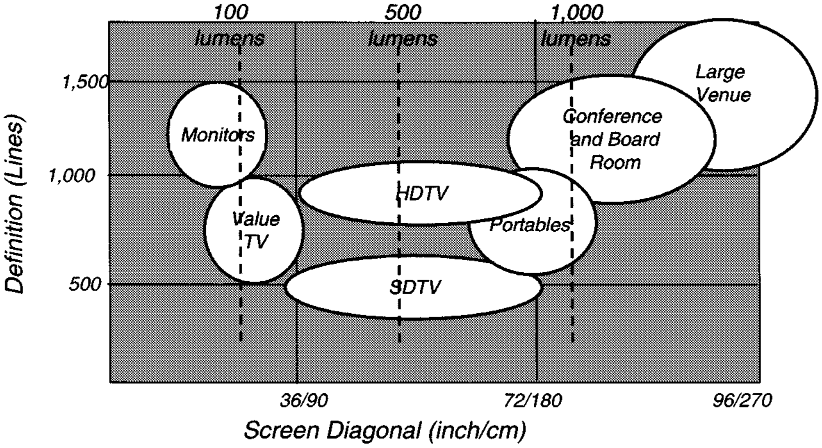


Fig. 1. Projection display classes.

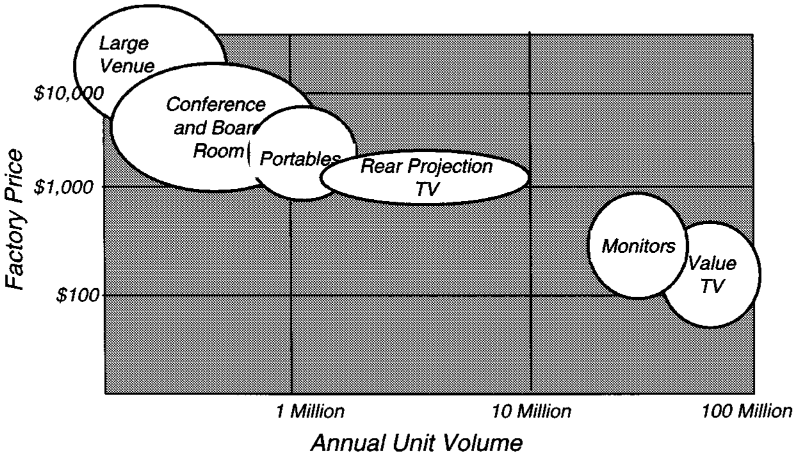


Fig. 2. Projection display markets.

Table 1
Requirements for Market Segments

Market	Large Venue	Conference Room	Portable	Big Screen TV	PCTV
Projection Mode	Front	Front	Front	Rear	Rear
Diagonal (inch)	>100	72	60	60	36
Definition	HDTV UXGA	SXGA	XGA	1360x720	1360x720
Lumens	>5,000	>1500	1000	>600	>200
Other	Transportable	Internet	Weight < 3Kg		
Factory Price	$40,000	$10,000	$2,000	$2,000	$800
Market Potential (Units)	<100,000	>100,000	>1,000,000	>4,000,000	>10,000,000

rear-projection PCTV models, it remains to be seen if such monitors can stack up competitively against the flat-panel alternatives.

A. Projection Metrics

The obvious advantage of projection technology is large image size. The portable presentation system is a benchmark

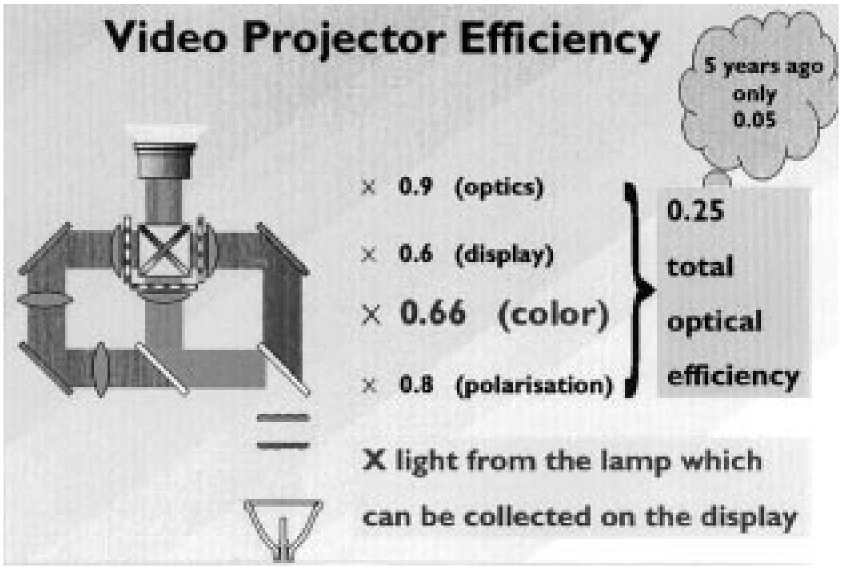


Fig. 3. Typical LCD projector power efficiency.

for competitive performance. A 2-kg box using ≈100 W of power can put a 60-in bright full-color video image on a wall or screen. Embedded in that statement are all of the key metrics for projectors.

1) Full-Color Video: For a display technology to be successful today, it must deliver full-color video rate images. The direct-view CRT remains the benchmark for video performance and projection technologies vary considerably with regard to matching up. Further, a common problem for all projection displays is that color saturation suffers with increased ambient lighting. The color performance of most technologies are acceptable in darkened theater like environments, but color levels and saturation tend to be marginal is office lighting conditions.

2) Brightness: Historically, CRT technology projection systems have also had marginal brightness, whether front projectors or rear-projection TV. The advent of high light throughput microdisplay based projectors ($>$1000 lm) has made brightness a nonissue for presentation applications and the next generation of microdisplay based rear-projection TVs will offer brightness levels far superior to current models. Historically, projection screens have directed the image into a preferred high brightness viewing cone (referred to as high gain screens) at the expense of wide-angle viewing. Again new high output projectors can achieve a high brightness with a large viewing volume.

3) Pixel Count: The bigger the image size, the higher the pixel count necessary to assure adequate image resolution, especially at closer viewing distances. Market feedback has clearly shown that users demand about 700 lines of pixels for screen sizes $>$50 in, making XGA (1024 × 768 pixels) a requirement for the presentations market and 720-line high-definition TV (HDTV) definition, a must for rear-projection TV. Even higher pixel counts are preferred and usually required for larger screen sizes. Again, the dual requirement for high brightness and high pixel counts give the microdisplay projectors a major advantage over the incumbent CRT projection systems.

4) Power: While even the portable projection systems are line powered, there is a big incentive to design and engineer a projector to be power efficient, i.e., to convert as much of the electrical power as possible into light and to deliver that light to the screen. Fig. 3 shows the subsystem efficiency levels typical of today's liquid-crystal dispaly (LCD) projection engines that result in an overall efficiency of 25%. Note that the system efficiency was only 5% five years ago. As we look at projection architecture and component efficiency below, remember that substantial progress has already been made, but there is still a lot of room for improvement. Power efficiency comes with the added advantage of a system that runs cooler, potentially eliminating the need for a noisy cooling fan.

B. System Architecture

The name of the game in projection then is to deliver a full-color video image with high pixel count to a screen while maximizing the efficiency of converting the electrical power to screen brightness. A small army of engineers have sustained an impressive record of continuous improvement, punctuated by significant breakthroughs, in achieving this goal. Their accomplishments are chronicled by both SPIE [4]–[10] and SID [11].

Ten years ago, there were two principal architectures and technologies used for electronic projection.

1) *Red-Green-Blue (RGB) CRT:* Used in both presentation front and big-screen rear-projection systems, three 7–9-in high-brightness monochrome CRT tubes (one each red, blue, and green) are arrayed horizontally with appropriate lenses and convergence to produce a full color video image. The system requires extremely bright CRT tubes that are driven for maximum brightness at the expense of product life and high-resolution spot size. The design is limited to 150–300 lm output [1].

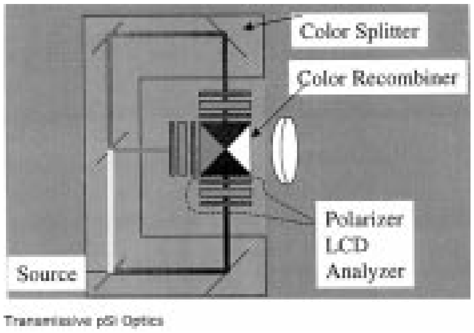


Fig. 4. Diagram of transmissive LCD light engine [14].

2) *Spatial Color Transmissive LCD Panel:* While the primitive products simply combined a laptop computer color LCD panel (≈10-in diagonal) with a conventional overhead projector, later models have employed smaller custom configured panels (≈6-in) in a more highly engineered light collection and projection system. While it is difficult to conceive of a more simple system, the spatial LCD projectors are big, heavy, and inefficient. Typical light output has improved from a few hundred to nearly 1000 lm.

During the past decade, a variety of projector architectures have been commercialized that embody microdisplay imagers. The technology and performance of microdisplays is discussed in detail below. The architectures, however, make use of a set of common modules.

1) *Arc-Lamp Light Sources*. All of the microdisplay systems use an arc lamp, reflector, and beam homogenizer to produce a highly collimated light beam to illuminate the microdisplay imagers.
2) *Color Generation and Recombination Optics:* The white light from the lamp is either split into RGB components for modulation by three microdisplays, then recombined, or is filtered by a color wheel and modulated time sequentially.
3) *Microdisplay Image Modulators:* These very large scale integration (VLSI) components modulate the incident colored light into the projected image. Initially, transmissive LCD microdisplays were used, but more recently, microelectromechanical system (MEMS) technology micromirror devices have become popular and a number of developers are promoting reflective LCD devices.
4) *Projection Optics:* Conventional projection lenses are used in most systems.
5) *Projection Screens:* While most of the commercial front projection products used for presentations used conventional reflective projection screens, rear-projection TV and monitor displays require a new class of screen capable of higher resolution and capable of delivering a broader viewing cone.

It must be noted that other architectures and technologies are under development, including e-Beam addressed modulators [12] and scanned laser projectors [13].

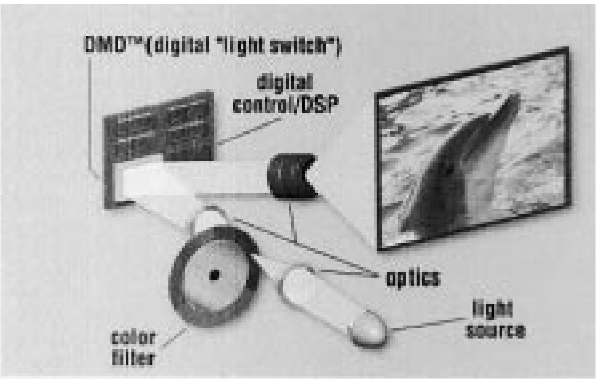


Fig. 5. Diagram of single imager MEMS light engine [15].

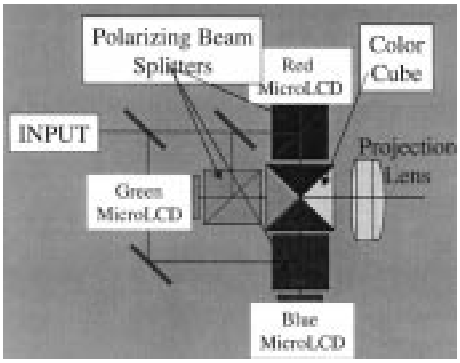


Fig. 6. Diagram of reflective LCD light engine three PBS.

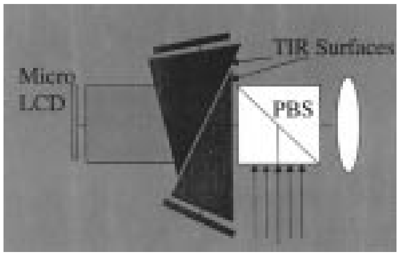


Fig. 7. Diagram of reflective LCD light engine trichroic prism.

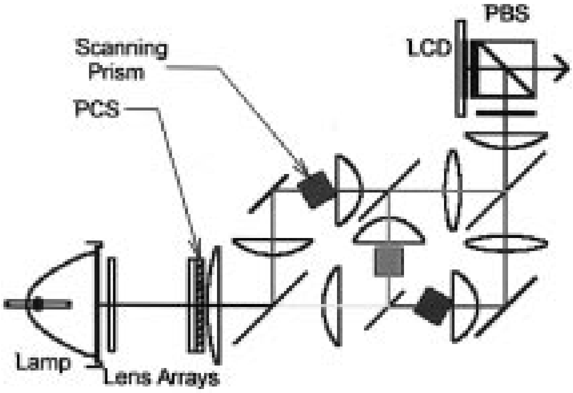


Fig. 8. Reflective LCD color scrolling system.

1) Commercialized Microdisplay Projector Architectures: The major differences in performance and cost for microdisplay projectors derive from differences in the light engine architecture and optical performance of the microdisplay light modulators themselves. Looking first at the engine architectures, Figs. 4–7 present diagrams of the most popular transmissive LCD and MEMS and two representative layouts of a reflective LCD design. There

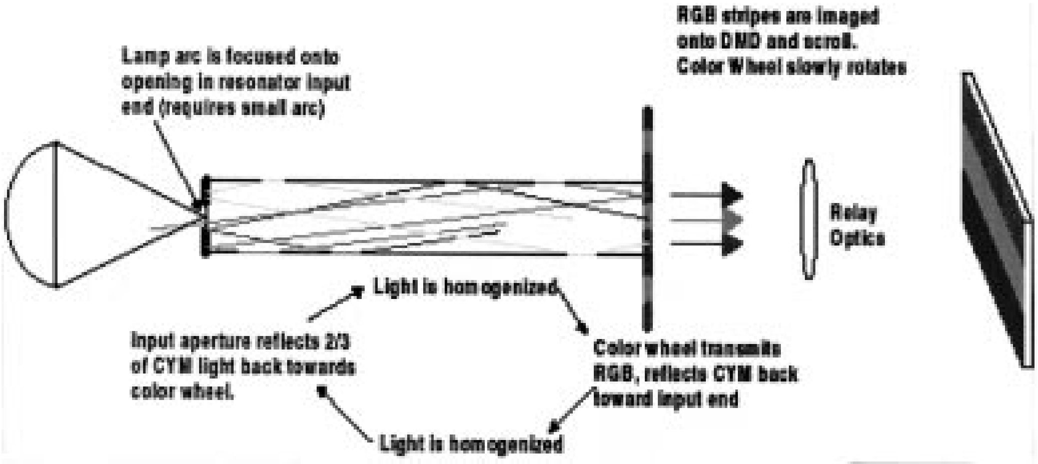


Fig. 9. Scrolling MEMS architecture.

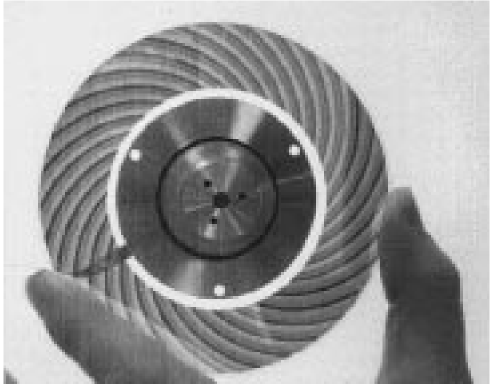


Fig. 10. Scrolling color wheel for MEMS projector.

are at least three other reflective architectures vying for commercial acceptance [14].

2) New Architectures—Color Scrolling: Developers of both LCD and MEM projection systems are promoting a new architecture referred to as color scrolling. The approach enables the use of a single microdisplay imager without paying the throughput penalties associated with either a spatial color filter or color field sequential system. Diagrams of LCD [16] and MEMS [17] architecture are shown in Figs. 8 and 9 as well as a picture of the scrolling color wheel employed with the MEMS approach in Fig. 10.

3) Comparison of Architectures: Each of the alternative architectures has a maximum throughput efficiency associated with loses resulting from color separation, modulation, and recombination, which is called the color throughput limit. Comparing the popular projection architectures (see Tables 2 and 3), the three-imager transmissive LCD design common to the most popular front projectors has the highest limit on color efficiency. Both the spatial and field sequential color architectures lose nearly two-thirds of the collected light from the lamp. The emerging color-scrolling systems, especially those using the single imager MEMS devices hold great promise to match the 100% limit of the three-microdisplay system.

4) Etendue and Light Throughput Limitations: As previously noted, the light throughput efficiency of a projector is a critical performance parameter. A simple engineering approach to budgeting the throughput of an architecture and design is further complicated by a geometric light utilization parameter called etendue. The etendue is determined by the size and degree of collimation of the light source, the size of the microdisplay, and the f number of the projection lens [1]. A simplified equation and diagram is shown in Fig. 11 and Table 4 [18]. For maximum etendue efficiency, small arc lamps, large-area microdisplays, and small f number lens are advantageous.

C. Key Projection System Modules

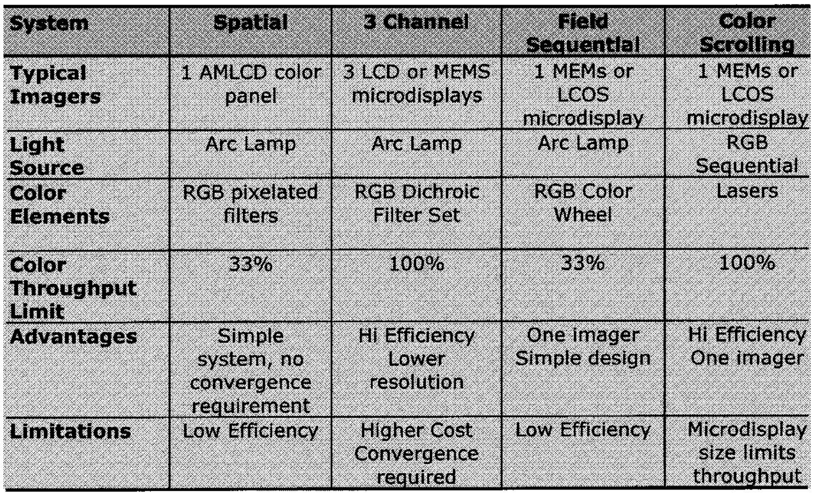
The key building blocks of a microdisplay based projection system include:

2) microdisplay light modulators and associated electronics;
3) small arc lamp and light collection and homogenizer optics, including polarization recycling optics for LCD displays;
4) color-management filters, color wheels, beam splitters, and recombiners, including polarization optics for LCD microdisplays;
5) projection lens;
6) screen.

The technology employed in each of these areas has evolved during the past ten years and has helped support the dramatic improvements in system performance and the downsizing and cost reductions that have enabled market growth.

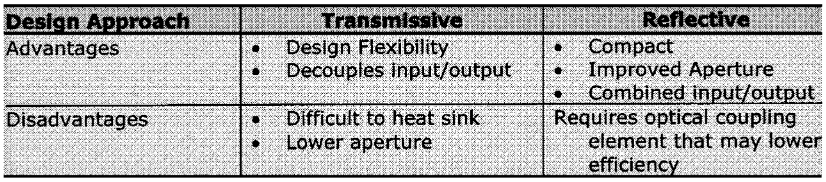
1) Microdisplay Imaging Module: The brains of modern projection systems are the microdisplays and associated application-specific integrated circuits (ASICs) that make up the imaging module. The microdisplay device itself consists of a VLSI backplane that provides the electronic control for each pixel and a light modulating front plane, either a liquid crystal or MEMS modulator. Depending on the microdisplay technology, the interface ASIC can be either simple, resembling a flat-panel interface IC, or complex, incorporating media-processing capability and multiple frame buffer memory. In addition to the imaging module, the projector

Table 2
Comparison of Projection Architectures



System	Spatial	3 Channel	Field Sequential	Color Scrolling
Typical Imagers	1 AMLCD color panel	3 LCD or MEMS microdisplays	1 MEMs or LCOS microdisplay	1 MEMs or LCOS microdisplay
Light Source	Arc Lamp	Arc Lamp	Arc Lamp	RGB Sequential
Color Elements	RGB pixelated filters	RGB Dichroic Filter Set	RGB Color Wheel	Lasers
Color Throughput Limit	33%	100%	33%	100%
Advantages	Simple system, no convergence requirement	Hi Efficiency Lower resolution	One imager Simple design	Hi Efficiency One imager
Limitations	Low Efficiency	Higher Cost Convergence required	Low Efficiency	Microdisplay size limits throughput

Table 3
Transmissive and Reflective Imagers



Design Approach	Transmissive	Reflective
Advantages	• Design Flexibility • Decouples input/output	• Compact • Improved Aperture • Combined input/output
Disadvantages	• Difficult to heat sink • Lower aperture	Requires optical coupling element that may lower efficiency

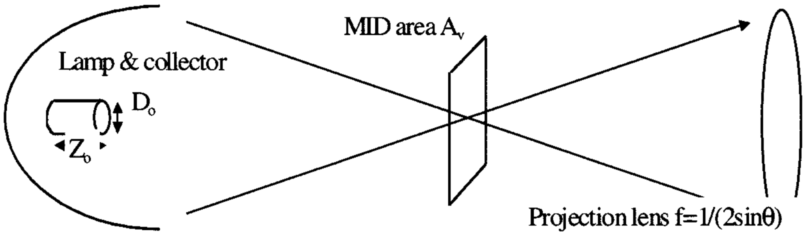
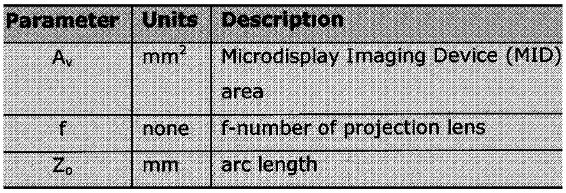


Fig. 11. Etendue relationship.

Table 4
Entendue Effieciency = $f\{A_v/f^2, Z_o\}$



Parameter	Units	Description
A_v	mm^2	Microdisplay Imaging Device (MID) area
f	none	f-number of projection lens
Z_o	mm	arc length

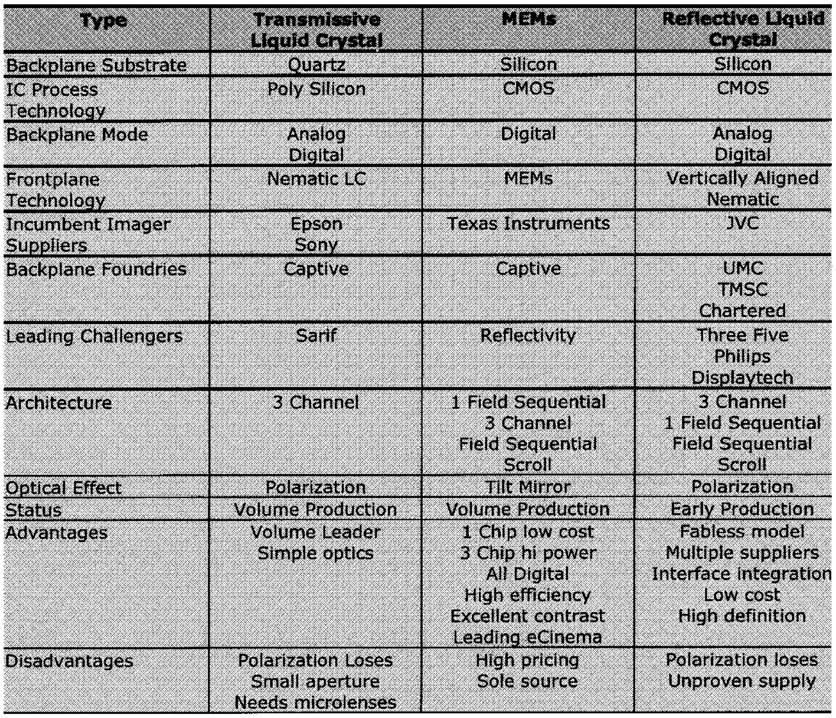
electronics system also includes an image processor IC that assures that the projection system can be interconnected to both computer and entertainment video systems.

Table 5 compares the three major microdisplay technologies.

1) *Liquid Crystal/Polysilicon on Quartz:* The first microdisplays were developed by Epson and Sony as an extension of their charge-coupled device technology and were first used as viewfinders in cameras. Projection microdisplays were commercialized during the mid 1990s and became the foundation of the presentation projector market. The devices are manufactured in a dedicated fab which is very similar to a complementary metal–oxide–semiconductor (CMOS) fab except that the line processes the transparent quartz wafers. High temperature processing is used to fabricate the polysilicon circuitry. The devices are now used in the transmissive mode as opposed to the other technologies which must be used in reflective mode, enabling somewhat simpler optical architectures and designs. However, the opaque circuit elements reduce the free aperture of the pixel, reducing light through put when compared to reflective devices. Conventional twisted-nematic liquid-crystal technology is used in the front plane modulator.

2) *MEMS/CMOS:* After years of research, Texas Instruments introduced the digital micromirror device (DMD) about five years ago. Since its introduction, it has come to dominate two sectors of the presentation market. Single-chip DMD systems have enabled a new

Table 5
Comparison of Microdisplay Technologies



Type	Transmissive Liquid Crystal	MEMs	Reflective Liquid Crystal
Backplane Substrate	Quartz	Silicon	Silicon
IC Process Technology	Poly Silicon	CMOS	CMOS
Backplane Mode	Analog Digital	Digital	Analog Digital
Frontplane Technology	Nematic LC	MEMs	Vertically Aligned Nematic
Incumbent Imager Suppliers	Epson Sony	Texas Instruments	JVC
Backplane Foundries	Captive	Captive	UMC TMSC Chartered
Leading Challengers	Sarif	Reflectivity	Three Five Philips Displaytech
Architecture	3 Channel	1 Field Sequential 3 Channel Field Sequential Scroll	3 Channel 1 Field Sequential Field Sequential Scroll
Optical Effect	Polarization	Tilt Mirror	Polarization
Status	Volume Production	Volume Production	Early Production
Advantages	Volume Leader Simple optics	1 Chip low cost 3 Chip hi power All Digital High efficiency Excellent contrast Leading eCinema	Fabless model Multiple suppliers Interface integration Low cost High definition
Disadvantages	Polarization Loses Small aperture Needs microlenses	High pricing Sole source	Polarization loses Unproven supply

class of ultraportable low-cost projectors. Three-chip DMD systems have come to dominate the large venue market segment. The DMD device has an extremely fast switching speed (<10 μsec) and gray scale is achieved using a time domain dithering system. The optical performance of the DMD has become the benchmark for high brightness and contrast. The device has a high aperture and very low throughput losses.

3) *Liquid Crystal on Silicon (LCOS):* LCOS projection microdisplays have recently had some success in the market. The allure of the technology is its potential to achieve high pixel counts and reflective throughput efficiency using high-volume low-cost CMOS foundries. JVC is currently leading the market with its high-performance vertically aligned liquid-crystal modulator technology. Other developers use twisted-nematic and ferroelectric device technology.

The cross section of a typical LCOS microdisplay is shown in Fig. 12. The complexity of the pixel circuitry ranges from a single transistor and capacitor to more than five transistors, depending on whether the pixel uses analog or digital gray scale. The pixel circuitry is interconnected to row and column buses, which, in turn, are controlled by much more sophisticated row and column driver circuitry on the periphery of the backplane chip. Light blocking and planarization layers are fabricated on top of the control and pixel circuitry with a highly reflective and planar pixelated mirror on the chip's surface interconnected by vias to the underlying CMOS circuitry. Using conventional liquid crystal technology, a light modulator is built on the surface of the CMOS.

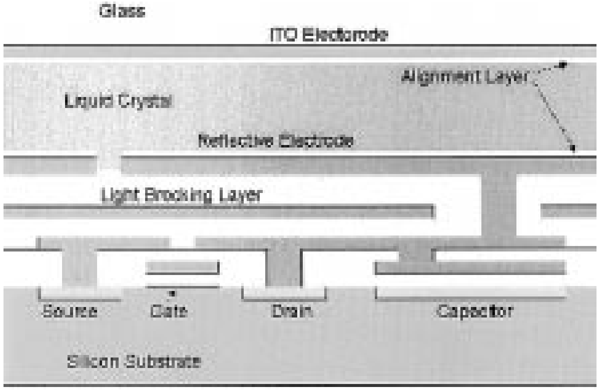


Fig. 12. Cross section of LCOS microdisplay [19].

It has proven to be more difficult than expected to achieve high yields and low costs for the microdisplay devices. Backplane yield problems such as defective pixels have been significantly reduced, but the challenge of marrying the backplane and frontplane technologies continue to challenge manufacturers. The MEMS technology has been particularly challenging in production, resulting in shortages and high costs for DMD parts and the withdrawal of several developers from the market. Cost are particularly high for testing and packaging the finished microdisplay product. Fig. 13 shows a comparison of the estimated production costs for the three leading technologies [18]. While costs for both of the liquid-crystal microdisplay technologies are estimated to be $\approx$\$70, those for the DMD are estimated to be twice as much. Most of the costs for the DMD are related to packaging and test. The hermetic package specified for the DMD is a major cost element.

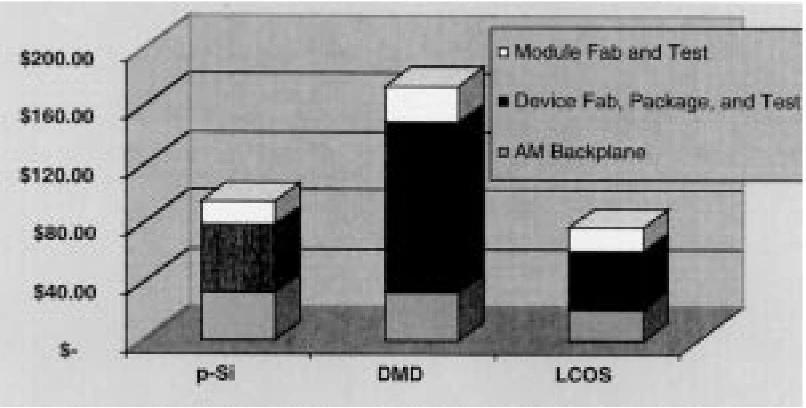


Fig. 13. Comparison of microdisplay costs.

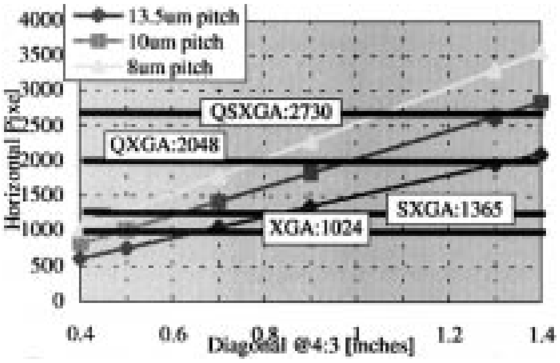


Fig. 14. Pixel dimension, imager size, and definition [20].

Microdisplay costs are related to chip size, but as shown above, most of the cost are related to device and module fab, packaging, and test. However, as the chip diagonal approaches 20 mm, backplane fab and yield play a more important role. Foundry design rules and limitations as well as chip yield considerations limit practical microdisplay sizes to $<$ 22 mm. Therefore, designers must move toward smaller pixel dimensions in order to achieve high pixel counts within the chip size limit. Fig. 14 shows the relationship between pixel dimension and chip size for several high pixel count targets. Developers of LCOS technology currently are leading the industry to these high-definition configurations. It is more difficult for MEMS and liquid-crystal polysilicon to achieve pixel dimensions $<$12 μm.

2) Lamps: At the heart of the projection system is the lamp, typically, a high-efficiency and high-power arc lamp. The most popular lamps are short-arc high-pressure mercury and metal halide lamps in the range of 100–500 W. For large venue projectors requiring $>$ 3000 lm, Xenon lamps are employed with power ranges $>$ 1000 watts. Table 6 compares the characteristics and performance of current technology lamps.

The high-pressure mercury lamp with its highly efficient short arc and long life has come to dominate the small conference room and portable projector segments and is proving popular in early rear-projection big-screen TVs due to its 10 000-h life. However, as power levels are increased, the mercury lamp benefits begin to fade as arc gap increases and lifetimes decrease to a few thousand hours.

There are many suppliers developing the metal halide technology and it is the most popular lamp for microdisplay projectors outputting 1000–3000 lm. Xenon lamps are used in the most powerful large venue projectors. Most of the popular lamps are supplied with an integrated reflector, as shown in Fig. 15.

As noted above, the arc gap is a key determinate of the projector system etendue; the smaller the gap, the greater the efficiency of delivering the light to the projector lens. Fig. 16 illustrates the relationship for a 125-W lamp [22]. However, another key aspect of the lamp is the collection efficiency of the lamp reflector and the beam homogenizer.

The small arc and efficient reflector focus the light into a beam homogenizer. Fig. 17 shows a rod integrator that operates with the principle of total internal reflection. LCD projectors can also employ a lens array optical device that performs a polarization recycling function as well as homogenizing the beam prior to the color optics and microdisplay modulators. The polarization conversion optics serves to increase overall efficiency by a factor of 1.7 and has helped maintain liquid-crystal systems competitive in throughput with polarization-independent MEMS.

3) Optics: About the only optical element common to all projector architectures and designs is the projection lens. Both fixed-focus and zoom lenses are widely available for even high-definition electronic projectors and are not on the critical path to system improvement and cost down.

Otherwise, there are diverse approaches to color separation, modulation, and recombination for each of the microdisplay technologies. The color optics for several designs are shown in Figs. 18 and 19 and consist of dichroic filters and mirrors and prisms as well as color wheels and beam splitters.

The majority of the DMD systems employ either the color wheel for field-sequential color (portable and TV applications) or dichroic devices for color separation and a beam splitter for recombination in a three-device RGB color system.

The transmissive liquid-crystal polysilicon devices are similar to, but even simpler than, the RGB DMD architecture since they do not require the more complex recombination of reflected beams.

Table 6
Comparison of Production Lamps [21]

Lamp Technology	Units	High Pressure Mercury	Metal Halide	Xenon
Typical Power	watt	125	250	125
Output	lumen	7,750	15,000	1570
Efficacy	lm/w	62	60	12.6
Color Temp.	°K	5600	8500	5600
Lifetime	hours	>5,000	3000	1000
Arc gap	mm	≈1	≈2	1
Advantages		Small arc Lifetime	Color Higher power	Highest power Small arc
Weaknesses		Color Limited lumens	Lifetime Larger arc	Lifetime Poor efficiency
1997 High Volume	$	200.00	200.00	520.00
2000 Very High Volume	$	50.00	50.00	100.00

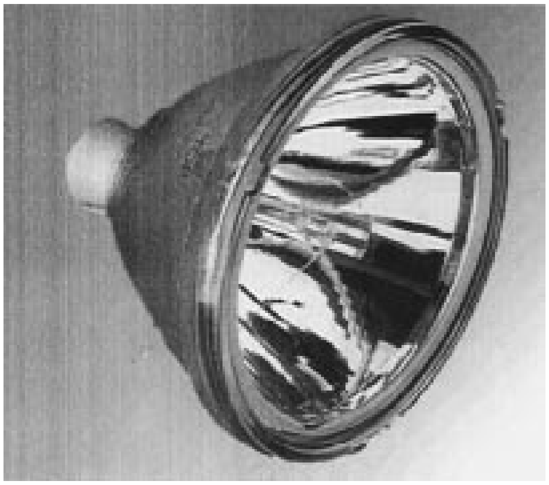


Fig. 15. Typical arc lamp and reflector.

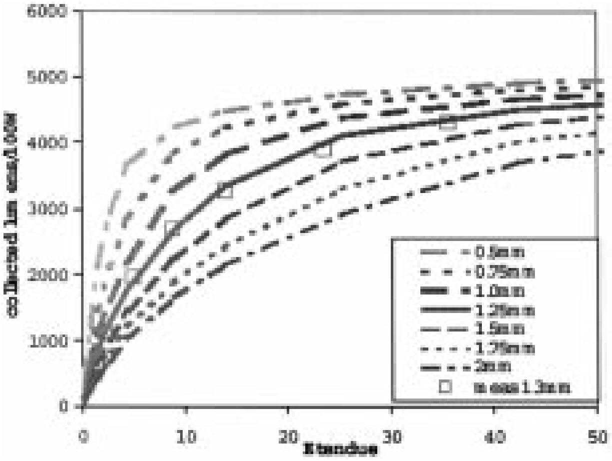


Fig. 16. Collected light and etendue.

Architectures and designs for LCOS projectors are the most varied and complex in that they must cope with not only color issues, but also polarization. In addition to the architectures described above, there are several four-prism designs that are currently being brought into production, one of which is shown in Fig. 18 [23], [24]. Note the complexity of the designs and the large number of optical interfaces.

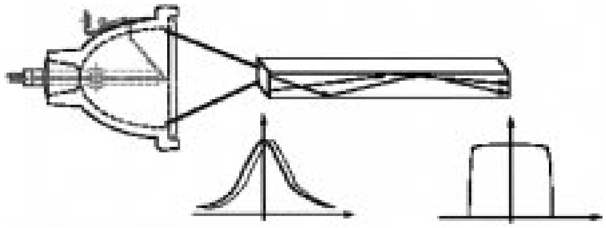


Fig. 17. Typical rod integrator.

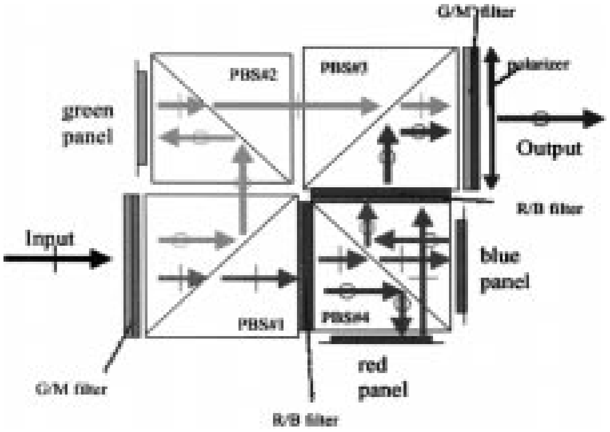


Fig. 18. Four-polarizing-beam splitter LCOS design.

The performance, availability, and cost of the color separation and recombining optics is a substantial cost of a projector system. The optical elements not only impact light throughput, but are major controlling elements of display contrast and color saturation. The continuous improvement and cost reductions for these devices has been very significant.

Another optics technology that has enabled the liquid-crystal polysilicon technology to remain competitive are microlens arrays (MLAs). As noted above, one problem with the transmissive imager approach is that the free aperture of each pixel is limited by the opaque backplane circuitry. By employing MLA, the incident lamp light is focused into the clear aperture, dramatically reducing losses. Fig. 20 illustrates the impact of MLA technology in keeping liquid-crystal polysilicon competitive.

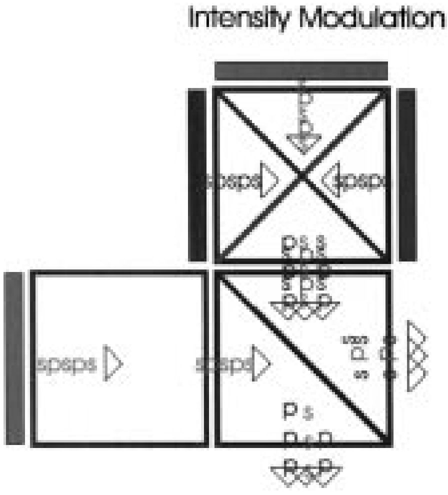


Fig. 19. Three-beam splitter LCOS architecture.

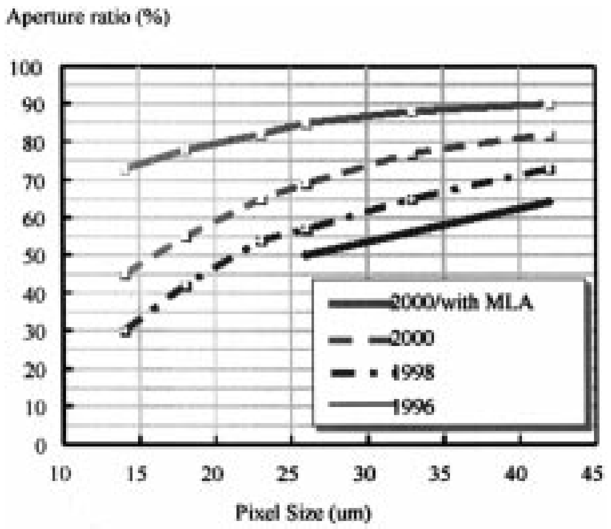


Fig. 20. Improvements is liquid-crystal polysilicon aperture.

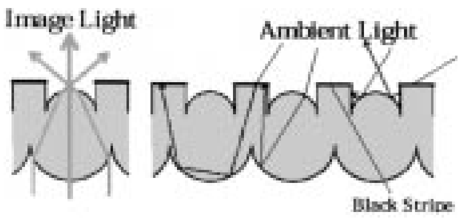


Fig. 21. Black-stripe screen.

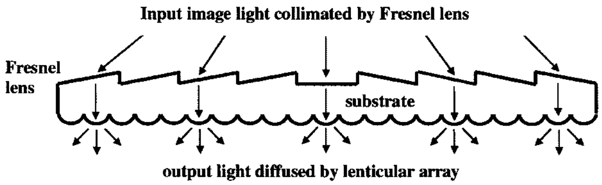


Fig. 22. Combined Fresnel and lenticular lens.

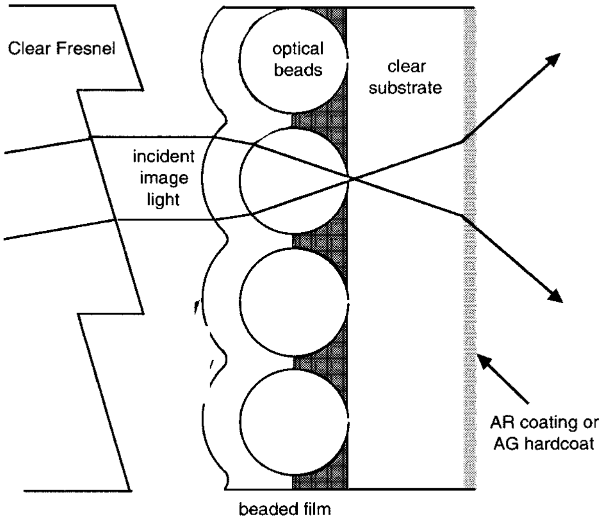


Fig. 23. Beaded screen.

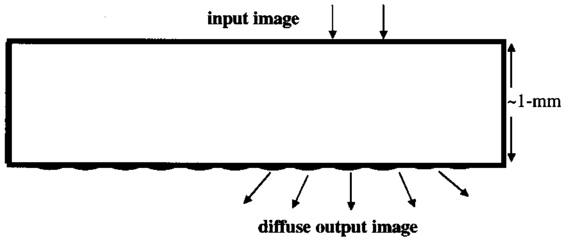


Fig. 24. Holographic screen.

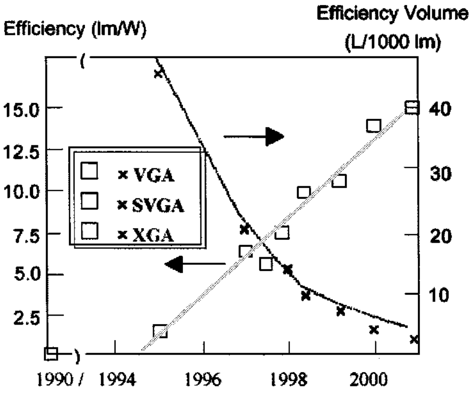


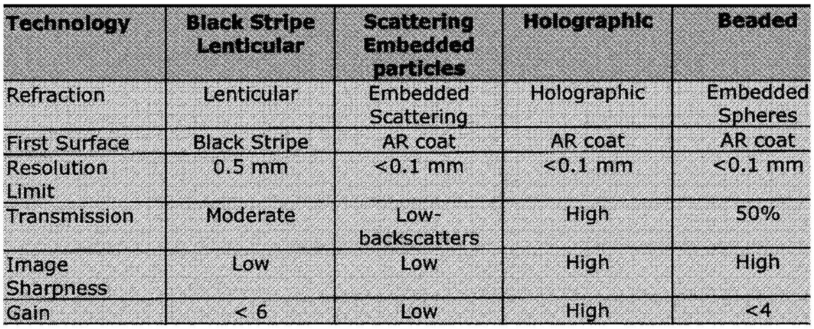
Fig. 25. Projector efficiency over the past decade.

4) Screens: The face of the projection system is the screen. In the high-volume segments of the presentation market, simple reflective screens are used or, frequently, images are projected directly on walls. In most conference rooms and certainly in large venues, sophisticated reflective screens are used that optimize the image brightness in a preferred viewing area. However, the leverage of screen technology is highest in the big-screen rear-projection market segment, where the optical characteristics of the screen are critical to achieve acceptable performance.

The optical leverage of a screen has several key characteristics.

1) *Ambient Glare and Reflection Reduction:* To permit acceptable performance is a brightly lighted interior

Table 7
Screen Technologies



Technology	Black Stripe Lenticular	Scattering Embedded particles	Holographic	Beaded
Refraction	Lenticular	Embedded Scattering	Holographic	Embedded Spheres
First Surface	Black Stripe	AR coat	AR coat	AR coat
Resolution Limit	0.5 mm	<0.1 mm	<0.1 mm	<0.1 mm
Transmission	Moderate	Low-backscatters	High	50%
Image Sharpness	Low	Low	High	High
Gain	< 6	Low	High	<4

room, the screen must reduce the degradation caused by reflections and glare.

2) *Viewing Angle Control:* Preferred screens optimize brightness and contrast in a preferred viewing area usually, at the expense of wide-angle performance. The figure of merit used to describe the ratio of the image brightness normal to the screen to a Lambertian screen standard is screen gain.
3) *Brightness Uniformity:* Many screens integrate a Fresnel lens to compensate for the oblique angle of the projected light incident on the screen and to improve brightness uniformity across the screen.

The challenge for screen technology is to provide the most leverage to address such goals without degrading the quality and sharpness of the image projected on the back of the screen. Typical shortfalls of existing screens include significant losses of projected image brightness and reduction of image sharpness usually due to light scattering.

The most popular screen type used in today's rear-projection big-screen TVs is the black-stripe screen shown in Fig. 21. The screen is oriented with the stripes vertically such that the lens between the stripes controls a wide horizontal field of view. Ambient light is absorbed by the strips either on incidence or after reflection from the rear lens. Rear incident-projected light is focused through the front aperture. The black-stripe screen is usually used with a rear Fresnel lens and a light diffusion film. The typical gain level for a commercial screens is six. The optical effect of the Fresnel lens and a lenticular screen are shown in Fig. 22.

Recently, several companies have commercialized screens that combine glass spheres and with an opaque plastic. Fig. 23 shows such a screen in combination with a Fresnel lens and with the addition of a first surface antireflective coating. Beaded screens can be used to advantage with high-definition images because they do not degrade image sharpness as much as typical lenticular screens. However, the gain for beaded screens is two to three, well below the level of four to six for lenticular.

Holographic diffuser films also offer unique leverage in rear-projection screens to control viewing angles. Such screens can be used in conjunction with lenticular arrays. Fig. 24 shows a diagram of such a screen.

While the black-stripe lenticular screen remains the workhorse for standard-definition big-screen TVs, the newer technology screens are required for the high definition products of tomorrow. Table 7 compares the performance of the available technologies.

II. FUTURE SYSTEMS

The past decade has seen impressive progress in increasing projector efficiency and in downsizing while steadily increasing image pixel counts, as shown in Fig. 25 [25]. Current projectors are approaching 25% efficiency and deliver nearly 15 lm/W. The weight and volume of the projectors has been reduced to a few kilograms and a few liters.

Prices have also decreased as production volumes have expanded. Microdisplay-based front projectors now dominate presentation markets and the technology is poised to take over the big-screen TV market during the next decade.

Look for further improvements to come on several fronts.

1) *High Pixel-Count Microdisplays:* Two to five megapixel microdisplays have been shown and may be brought to production by LCOS developers.
2) *Long-Life Solid-State Lamps:* Radio-frequency-driven lamps are one approach to improving lamp life.
3) *Laser-Light Sources:* Laser technology is driven forward by several complimentary market pulls. While current scanned laser-projection systems are not cost competitive, the next decade shows promise.
4) *New Architectures:*. The color-scrolling designs will achieve commercial success in the near term. Innovation and breakthroughs in color separation and recombination continue.

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