Design and fabrication of a prototype projection data monitor with high information content

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A prototype 28-in.-diagonal desktop data monitor capable of displaying 2048 × 2048-pixel images has been designed, built, and evaluated. The monitor uses optical projection technology. A reflective, crystalline silicon active-matrix light valve using liquid crystal electro-optics and a digital electronic interface architecture is described. This rear-projection monitor has four million resolvable pixels, uses three light valves to achieve color, has a low-gain surface diffuser screen, and functions as a fully interactive, color personal computer monitor with motion video capability. The monitor is 20 in. deep.

Introduction

The demand for displays to provide higher information content in a format suitable for the human visual system and in a size consistent with the modern office environment is increasing. The most common computer monitor pixel format, that is, the number of columns and rows used to display information, has evolved from VGA (640 × 480) to SVGA (800 × 600) to XGA (1024 × 768) in just a few years. We expect this trend to continue to SXGA (1280 × 1024), to UXGA (1600 × 1200 or 1600 × 1280), and beyond. Although data bandwidth and memory have historically constrained the increase in information content, we are now rapidly approaching constraints imposed by the cathode ray tube (CRT) display device itself. Among these constraints are shadow-mask pitch, space-charge effects, which limit electron-beam lateral spot size at high resolution, and physical size and weight of the display. For instance, a 20-in. viewable diagonal display with 1600 × 1200-pixel resolution requires a resolvable pixel pitch (distance between pixels) of 0.25 mm. This is close to the current state of the art for shadow masks and does not take account of the electron-

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beam spot size. In addition, a typical 20-in.-diagonal CRT monitor has a depth of about 20 in., making it as large a display as will fit comfortably on a typical office desk. On the basis of the perceived need for high-information-content large-screen desktop displays and the difficulties facing future CRT development, we initiated a program to evaluate and develop alternative technologies.

In this paper we describe the design and fabrication of a rear-projection prototype display which represents one of the highest-information-content interactive displays ever built. The prototype color display has four million resolvable (as opposed to only addressable) pixels and is based on a reflective light valve which utilizes liquid crystal electro-optics combined with a single-crystal silicon CMOS active matrix. The performance of this first prototype compares favorably in many ways to that of direct-view CRT monitors of comparable size and information content.

Display requirements and design objectives

The objectives of the program were 1) to evaluate and develop all aspects of the technology required to display high-information-content data, graphics, and images; 2) to provide the data in a form suitable for the desktop environment, especially considering the size, weight, and power of the display device; and 3) to develop the necessary electronic data-handling architecture required to move data from a computer and from a video source to the display in a suitable format. With these general objectives in mind, we adopted the following design targets: format, 2048 $\times$ 2048 pixels; resolution, 100 pixels/in. on the rear-projection screen of size 20 $\times$ 20 in. (28-in. diagonal); color depth of 4 bits per color, with additional enhancement through error diffusion; screen refresh at 74 Hz; total monitor power of less than 200 W, monitor size and weight commensurate with the desktop application (e.g., depth much less than the screen diagonal); screen brightness at least 100 cd/m^2; and contrast ratio of 50:1. In general, the objective was to develop and evaluate all elements of the display for very high-resolution desktop applications and to do so by building a prototype.

Display technology choices

Within the context of the above design requirements, we considered several technologies. As indicated, direct-view CRTs were rejected because of resolution, physical size, and weight limitations, and high cost for the design points considered. Plasma panels were rejected because we do not believe that they are capable of the very high resolution needed in this program. TFT/LCD flat-panel displays are capable of the resolution required on the desktop and are expected to reach the large screen sizes consistent with our starting objectives. However, we concluded that the evolution of TFT/LCDs to the large screens with high information content consistent with our design objectives will require a longer time than we envisioned. Other flat-panel technologies will require an even longer time to approach our design criteria. On the basis of these considerations, we concluded that some form of projection display was the most likely means to achieve the objectives. We considered three fundamentally different types of projection: emissive, transmissive, and reflective. Each technology was evaluated in reference to our initial objectives.

- *Emissive light valves*

The emissive projection approaches considered were CRT, field-emission, electroluminescence, and scanned laser. Although significant advances in rear-projection CRTs for wide-screen television have been made in recent years, we do not consider the rear-projection CRT to be suitable for high-resolution desktop applications because of physical size and weight as well as resolution versus brightness constraints. Field-emission and electroluminescent sources for projection displays were judged not to have the brightness required at high resolution. Although laser sources will almost certainly have a major impact on displays in the future, we judged that the laser cost structure will prevent widespread use of lasers for several years.

- *Transmissive light valves*

The transmissive projection display technologies considered are all based on active-matrix TFT/LCD approaches. By far the preponderance of all projection displays used for business data and graphics applications are of this type. We evaluated amorphous silicon, polycrystalline silicon (polysilicon), and single-crystal silicon active matrices and considered both twisted nematic and polymer-dispersed liquid crystal modes. The decision not to pursue any of these transmissive approaches was based on the conviction that high information content requires large numbers of pixels and that in order to contain the system cost and the system size, each pixel must therefore be very small. Previous work by Mitsubishi [1, 2] with transmissive light valves for rear-projection monitors demonstrated that attractive dimensions can be achieved (30-in. diagonal and 16-in. depth) compared to CRTs, but they experimented with pixel counts of less than 0.35 megapixel and with large pixel sizes. In any transmissive display, the optical efficiency as determined by the aperture ratio (defined as the ratio of the transparent part of each pixel to the total area occupied by the pixel) necessarily decreases as the pixel size is reduced. For example, a typical current projector product with VGA resolution and using polysilicon TFT/LCDs has individual pixels which are

42 μm on a side and an excellent aperture ratio of 67%. However, scaling a light valve with this pixel size from the VGA format to, say, a 2048 × 2048 format yields a 4.7-in.-diagonal array. This size leads to a considerably increased display device cost; it also greatly affects the size and cost of the optical components in the projection system and thereby effectively eliminates the desktop application. Reducing the pixel size inevitably reduces the aperture ratio and the optical efficiency of the device. Consequently, we concluded that the transmissive LCD technologies are not probable candidates for the very high-information-content data monitors.

- *Reflective light valves*

Many factors led to the conviction that only reflective technologies offer a viable approach to the design objectives. The most obvious advantage of reflective technologies is that the optical aperture ratio varies slowly with pixel size for the range of pixel sizes of interest (from about 5 to 30 μm on an edge). This is because the reflective element (mirror, diffraction grating, etc.) can be placed on top of any electronic or structural elements required for operation. Therefore, these elements do not affect the optical aperture, which is limited only by the ability to pattern small mirrors (or diffraction gratings) with photolithographic techniques to reasonably tight tolerances. We considered both micromechanical and liquid crystal reflective devices.

Micromechanical

An example of a reflective light-valve device that has already reached the market is the Texas Instruments digital mirror device (DMD) [3]. The DMD is essentially an array of individually addressable, mechanically tiltable mirrors on 17-μm centers. The individual mirrors "tilt" in either a +10° or a −10° orientation relative to the array normal, depending on how they are addressed. When the array of mirrors is illuminated with collimated light, the reflected light consists of a first part, which is reflected from the mirrors tilted in the +10° orientation, and a spatially separate second part, which is reflected from the mirrors tilted in the −10° orientation. The projection lens and the rest of the optical system are designed to accept, say, the first part of the reflected light and to reject the second part. Thus, when the array is properly addressed, the projected light of the first part forms an image on a projection screen. Since the DMD is essentially a binary device, it requires a high data rate and rapid mirror movement to achieve gray scale by frame-sequential addressing [3]. The activated mirror array (AMA) under development by Aura Systems [4] and Daewoo is a conceptually similar device based on piezoelectric or electrostrictive-mechanical, angular deflection of the individual mirrors in an array. The AMA is, however, fundamentally an analog device and is therefore capable of analog gray scale without the high data rates required by the DMD. A light valve based on an array of small micromechanical diffraction gratings (GLV) is under development by Silicon Light Machines [5]. This device is also binary and relies on a high-data-rate, rapid grating movement to achieve a digital gray scale. These three technologies (DMD, AMA, and GLV) are among the most sophisticated micromechanical devices ever fabricated. All three depend on silicon microstructure fabrication. To make use of more standard CMOS processing and to retain flexibility in the choice of pixel size and electronics, these approaches were rejected in favor of liquid-crystal-based Si light valves.

Liquid crystal

Reflective liquid crystal light-valve arrays have been demonstrated using various phenomena such as polarization conversion, scattering, and diffraction by the liquid crystal material. Since scattering and diffractive phenomena utilize unpolarized light, they appear to be more optically efficient than devices that rely on polarized light. However, detailed optical design and analysis would be required to confirm this. Prototype projection displays based on polymer-dispersed liquid crystal (PDLC) modes driven by an active matrix have been demonstrated by Raychem/Hitachi [6] and others[1]. In general, these displays show high brightness, but with modest contrast ratio, which limits their application. The PDLC material is transparent in the bright state and approximately a Lambertian scatterer in the dark state. Thus, the contrast and brightness are related. The system contrast increases as the numerical aperture (NA) of the optical system decreases, because of the reduction in the amount of scattered light collected by the projection lens in the dark state. Conversely, the brightness increases as the NA is increased by allowing the optical system to collect more light from the lamp to illuminate the light valve. Optimizing this design tradeoff is critical to successful application of PDLCs to projection displays. The optimization may involve "shaping" the scattering state of the PDLC so as to de-emphasize forward scattering in the dark state.

Diffraction-mode LC projection displays based on twisted nematic liquid crystals have been described [7]. In these, the alignment layer of an individual pixel is patterned in stripes such that alternate liquid crystal stripes are twisted in opposite directions. In the low-voltage state, the optical birefringence of the liquid crystal causes the striped pixel to act as a diffraction grating. In the high-voltage state, the liquid crystal molecules are oriented perpendicular to the substrate and hence do not diffract the incident light. When combined with a Schlieren optical

[1] Mitsubishi product LVP-G1A.

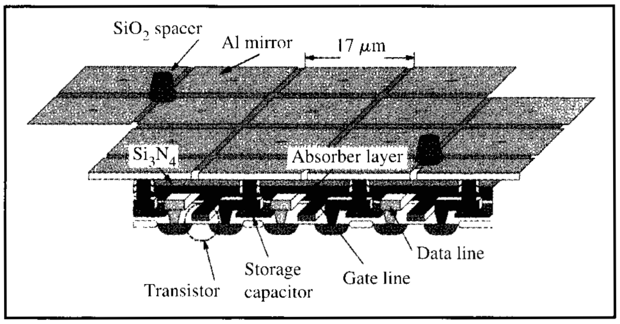


Figure 1

Schematic diagram of a spatial light-modulator array showing the cross section of the light valve used in the prototype monitor. To complete the light valve, a top glass plate with a transparent conductive layer is placed on top of the posts and glued to the silicon substrate along the edges. Finally, the gap between the mirrors and glass is filled with liquid crystal material.

system, this diffractive effect provides a liquid crystal light valve that makes use of both polarization directions of the illumination system and consequently appears to have a throughput advantage of 2× over other liquid crystal modes, which are based on polarized illumination. However, this theoretical advantage disappears because of the *étendue* difference between polarization and Schlieren types of systems and recent improvements in polarization recycling in liquid-crystal-based projectors.[2]

The remaining major class of liquid crystal modes to be considered for reflective light valves are based on nematic liquid crystals and require the use of polarized light. These include twisted, homogeneously aligned (aligned parallel to the surface) modes and homeotropically aligned (aligned perpendicular to the surface) modes. Selection of which mode to use involves consideration of whether normally white or normally black operation is desired, the operating voltage of the active-matrix circuit process applied, the polarization-conversion efficiency of the mode, whether the cell design is suitable for all colors rather than having separate red, green, and blue cells, the availability of suitable liquid crystal materials, and the ease and reliability of the liquid crystal alignment process. As described below, we chose to use a 45° twisted nematic liquid crystal in a normally black mode for the prototype display.

Light valves for the prototype display

• *Active-matrix array*

One advantage of a reflective light valve is the possibility of using crystalline silicon for the active-matrix array and associated circuitry. This greatly speeds up the development process, since the array can be designed as a modification of an existing silicon process. We chose to start with a medium-voltage version of the IBM CMOS process with 1.5-μm ground rules. Modifications to the process included introducing a second layer of polysilicon to form the storage capacitor with the first polysilicon gate-line layer, a light-blocking metal layer to prevent incident illumination from affecting the active-matrix circuitry, and two steps of chemical-mechanical polishing to ensure that the top mirror layer is planar and hence highly specularly reflecting. The final structure, shown schematically in **Figure 1**, has the additional feature that the vertical data lines do not couple strongly to the pixel electrodes. The metal absorber layer, held at a fixed potential, eliminates unwanted data-line-to-pixel parasitic coupling. Even under intense illumination, no measurable light leakage has been detected through or around the light-blocking layer (even multiply reflected light cannot pass this layer because the gap between the light-blocking layer and the pixel mirrors was designed to be a waveguide beyond cutoff for visible radiation). The mirrors themselves are made of thin layers of deposited aluminum. SiO_2 spacer posts are fabricated on the top of the mirror array in order to fix the liquid crystal cell gap at a predetermined value. Colgan and Uda describe the process and structure in detail [8]. We note that since this paper was first submitted for publication, both Pioneer [9] and National Semiconductor [10] have reported the fabrication of reflective, liquid-crystal-on-crystalline-silicon light valves and their use in projection displays.

• *Silicon array architecture*

The design objective of a 2048 × 2048-pixel array imposes significant constraints on the overall architecture of the light valve, the liquid crystal cell design, and the package concept. Thus, the individual pixels were chosen to be on a 17-μm-square grid, which was almost as small as allowed by the process ground rules. This enabled the design of an adequate pixel storage capacitance, C_S, of approximately 100 fF. The pixel storage capacitor is about equally divided between the capacitance of the two polysilicon layers and the capacitance between the light-blocking layer and the individual pixel mirrors. Consistent with the liquid crystal voltage requirement for maximum optical efficiency, the active matrix was designed to provide a pixel voltage of up to 3.5 V RMS. Row drivers were integrated into the array, and each row was driven from both ends to avoid possible excessive time skew across the array. We chose not to integrate the column drivers because of time constraints and because of the availability of "standard" driver chips suitable to the task. Many of the same system bandwidth issues are addressed using this approach as would be the case if drivers were integrated. For this particular monitor design point, one would

[2] A. E. Rosenbluth, unpublished result.

choose to integrate drivers in a product-level design. Separating the array and data-driver performance issues at this early stage of development seemed prudent. To reduce the number of data-driver contacts to the chip from 2048 to 1024, circuits were designed into the chip to demultiplex the input data stream to drive pairs of columns. When the array is driven both from the top and the bottom, the resultant "pitch" of the connections to the demultiplexer becomes $2 \times 2 \times 17 = 68$ μm. This is still less than the standard tape-automated bonding (TAB) contact pitch of about 100 μm. Thus, fan-out to the required TAB pitch was necessary. Consequently, although the active-matrix array was only 35×35 mm in size, the chip dimensions with fan-out and TAB are 64×64 mm. At this size, only one chip per 5-in. wafer was possible. See Sanford et al. for a complete description of the silicon array architecture and design [11].

• *Liquid crystal mode*
The choice of which reflective liquid crystal electro-optic modes to use was made on the basis of the following criteria: 1) voltage required to switch the liquid crystal cell; 2) achievable contrast ratio; 3) conversion efficiency, or optical throughput; 4) normally black operation, since for the small LC cells considered, LC disclinations which appear in the high-voltage state would seriously degrade contrast in normally white modes (in normally black operation, disclinations appear as dark lines in the bright state and consequently affect only brightness, but not contrast, to first order); 5) cell-gap tolerance and ability to achieve gray scale; and 6) availability of materials and alignment processes that are reliable and manufacturable. Extensive LC modeling was carried out by Yang and Lu [12] to choose the optimal LC mode. Various twisted nematic modes, vertically aligned modes, electrically controlled birefringent modes, polymer-dispersed liquid crystal modes, and ferroelectric modes were considered for this application. On the basis of the above criteria, we chose the 45° twisted nematic liquid crystal (TN LC) mode. The main process differences between the reflective light-valve cell and conventional transmissive TN LC cells are the cell-gap tolerance and the small cell size. The 45° reflective TN light valve has rather tight cell-gap tolerance (about $\pm 7\%$ uniformity) and small size (about 1- to 2-in. diagonal). Internal stresses in the silicon chips cause them to be distorted by as much as 1 μm, well outside the required cell-gap tolerance. We developed a process to "flatten" the silicon array chip between two pieces of glass and glue the assembly together so that the LC cell gap is uniform to within the required tolerance. The temperature dependence of the liquid crystal birefringence, together with the dispersion in the birefringence, leads to a temperature sensitivity of 0.25% per degree shift in optimum operating cell gap and/or wavelength.

• *Package*
The packaging of the light-valve device must serve several functions, including 1) electrical interconnection of more than 1000 leads; 2) management and dissipation of the heat, if any, absorbed by the light valve from incident radiation, from the electrical circuitry, from waste heat from the arc lamp, or from any other part of the system; and 3) provision to align and hold alignment of the three (R, G, B) light valves relative to the optical system and to each other. We chose TAB with anisotropic conducting films (ACF) to make the electrical contacts to the silicon array chip [13]. The main sources of heat absorption by the silicon array from the incident light arise from the imperfect reflectivity of the aluminum mirrors, the gaps between the pixel mirrors that lead to the light-blocking layer, and partial absorption in the ITO and polyimide alignment layers. As observed by Narayan et al., the heat absorption from the arc lamp is of the order of a watt and is readily dissipated with conventional cooling methods.[3] The light valves are aligned in the prototype by mounting the LC cell assembly in an aluminum holder, which is rigidly attached to the printed-circuit card to which the driver flex circuits are soldered. This LV assembly is aligned with the two other LVs and with the optical system by mechanical manipulators, an arrangement which readily achieves and maintains subpixel alignment.

Optical system and mechanical design

• *System specifications*
In designing an optical projection system employing reflection light valves, several particular considerations arise. Systems employing CRT-addressed light valves, as in the Hughes/JVC system [13], can take advantage of CRT scan corrections to relieve the distortion and color-convergence specification of the projection lens. With fixed-pixel light valves, the system must provide a highly accurate mapping of the red, green, and blue images from the light valves onto the screen. Another feature is that since the light valves are polarization devices, care must be taken to avoid unwanted polarization effects due, for example, to birefringence within key optical components. Since the optical package was required to fit into a desktop monitor, the configuration had to be kept compact, and the distance from projection lens to screen had to be less than one meter. We also had the objective of converging red, green, and blue images to approximately 1/3 pixel. The aim was to produce a system with pixel resolution at the screen. This is aided by the fact that convergence in the projection display is static and is limited only by the perfection of mechanical alignment

[3] C. Narayan, R. Horton, and E. Colgan, unpublished work.

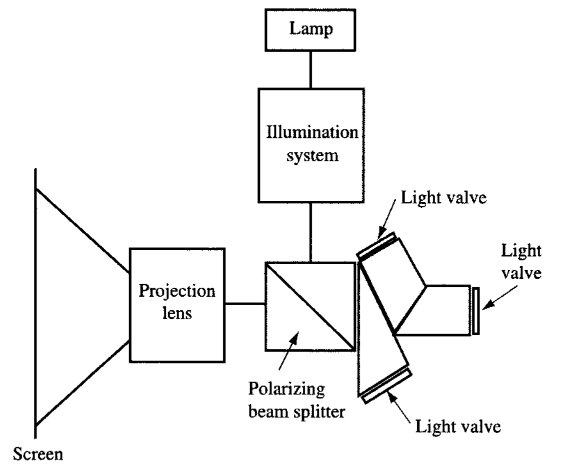


Figure 2

Major optical system components and their arrangement in the prototype display monitor.

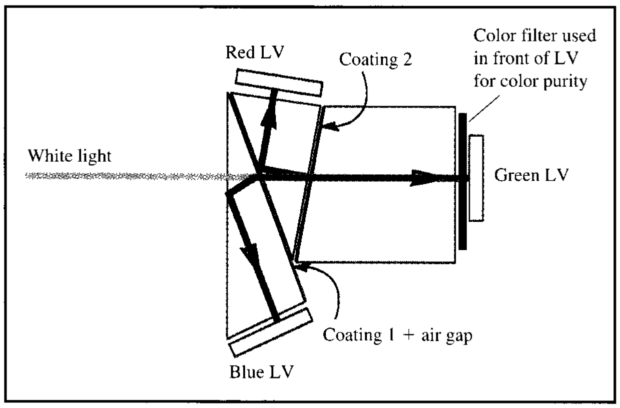


Figure 3

Color prism block used to separate the light into red, green, and blue components.

of the three light valves and by the degree of color correction of the imaging system. The resulting white spot size is close to the individual pixel level. By contrast, in a CRT color convergence is both a static and a dynamic process involving a high level of attention to stray magnetic field effects and to scanning current waveform corrections. The electron beam of a CRT commonly covers several color triads of the CRT shadow mask, producing, by comparison, a large spot on the screen.

- *Optical layout for color splitting and recombination*

Figure 2 shows the layout of the major functional units of the optical system. Aspects of the design are discussed in detail in a companion paper in this issue by Doany et al. [14]. Light from the lamp is brought by an illumination system into a polarizing beam-splitter prism (PBS) designed to operate across the visible spectrum, having a numerical aperture in air of 0.1. The PBS reflects light of one polarization (S) and transmits light of the opposite polarization (P) very efficiently. The design of such a high-performance PBS prism is key to obtaining good performance using polarization-based reflective light valves [15]. The reflected S-polarized beam enters a block of prisms of the type commonly found in three-charge-coupled-device (CCD) video cameras [16]. The individual prism elements have dichroic coatings, so that the incident beam is separated into red, green, and blue bands, and each band is directed onto a reflective light valve which has a transmissive color filter attached to its face. When a voltage is applied to the light valve, conversion of polarization from S to P occurs, and the reflected beams consisting of a mixture of S- and P-polarization re-traverse the prism block in the opposite direction and are recombined at the PBS prism. The P-polarized component is transmitted by the PBS prism and is focused upon the screen by the projection lens, while the S component is reflected back into the illumination system and is lost. The color prism block presents a design challenge in achieving a suitable set of color-dividing coatings and antireflection coatings for the air interfaces, and in achieving low birefringence within the glass medium. The glass used for the PBS prism was Schott SSKN5; for the image-combining prisms it was Schott SK5. The ray paths through the color-dividing and -combining prisms may be understood with reference to **Figure 3**. Issues relating to light-valve optical properties and their implications for optical system design have been described by Rosenbluth et al. [15].

- *Projection lens features*

The numerical aperture (0.1) of the PBS prism was chosen to give good S, P discrimination over a wide range of wavelengths, since this design uses only one PBS prism. This NA of 0.1 provides the basis for projection lens design. In order to introduce light onto the light valves with minimal variations in angle across their surface, a telecentric illumination system was chosen; that is, the principal rays were kept as parallel as possible through the system. Because the back focal length was large relative to the lens-to-screen distance required, a telecentric, retrofocus design was required. This lens has excellent properties, including low distortion, good color convergence, and a high modulation transfer function (MTF).

• *Illumination system*

For the illumination system, a 100-W lamp with an arc length of 1.4 mm was chosen [17]. We estimated that it should be possible to achieve 100 lumens on the screen from this lamp at the NA of 0.1. The small arc size is of considerable advantage for addressing light valves of relatively small size, of order several cm in width. Light from the parabolic reflector was focused onto the entry surface of a rectangular-cross-section light tunnel. The light tunnel behaves in a manner similar to that of a kaleidoscope. Light from the arc lamp is reflected from the walls of the tunnel so that the lamp, if viewed looking into the exit face of the tunnel, appears together with its multiple reflections. Further lenses focus the light into the PBS, and the exit face of the tunnel is focused onto the light valves. The effect of the light tunnel is to reshape and homogenize the light from the lamp into a uniform rectangular cross section.

• *Screen*

The screen employed was a flat diffuser screen from DaLite Corporation which had a gain of 1.3. Several screen types were evaluated, and the thin diffusive screen was found to be superior in preserving resolution at the required 100 dots/in. in comparison to structured screens. The displayed image is 20 in. by 20 in. Experiments with test plates showed that sag distortion is less than 0.25%. Individual pixels could be resolved everywhere across the screen. However, there is no visible pixellation in the final image. Resolution tests showed that there was very little loss in resolution due to the screen. Screen speckle could be observed at a level that interfered with the legibility of one-on-one-off pixel lines. Although it did not degrade normal computer images, speckle is clearly a feature of rear-projection screens that must be taken into account when designing a system for high-resolution close-up viewing, as discussed by George et al. [18] and Goldenberg et al. [19]. Screen speckle is an optical coherence effect that is commonly present to a greater or lesser extent in rear-projection systems. It is seen as a fine structure similar to that associated with a fine-grained screen, except that the visible structure appears to move as the viewer's head moves. Speckle can be reduced by increasing the scattering in the projection screen and hence causing a reduction in the optical coherence. However, this can lead to a reduction in screen resolution. Various approaches are being explored by different groups to minimize screen speckle without loss of other desirable screen attributes.

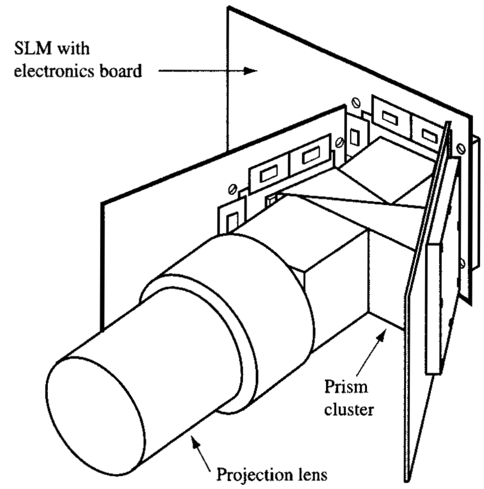


Figure 4

Mechanical arrangement of the light valves, color prism block, and projection lens. The light valves are attached to printed-circuit boards which provide electronic support functions.

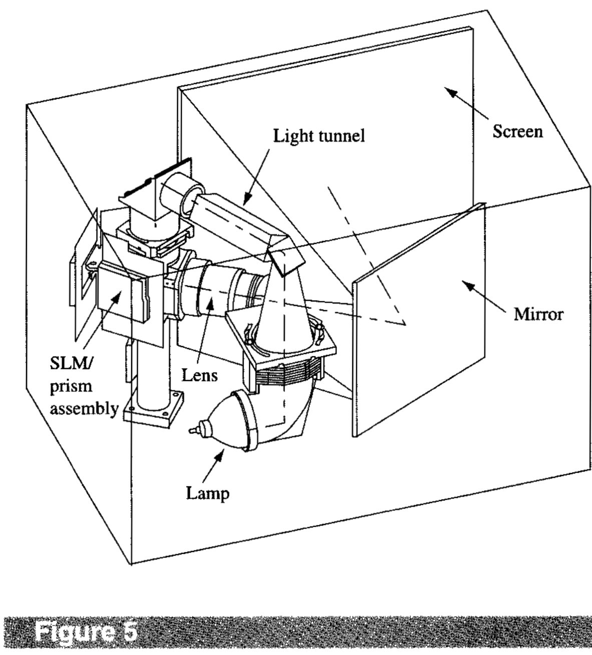


Figure 5

Schematic diagram of the optical layout as implemented within the monitor.

• *Mechanical layout*

The light valves were attached to printed-circuit boards, and the boards were mounted to commercial small x, y, z translation stages which were also provided with rotation for alignment of the three light valves. The boards were aligned with the color prism cluster as shown in **Figure 4**. **Figure 5** shows a schematic of the optical layout as implemented within the monitor. It can be seen that the illumination section has several folds to accommodate the long length imposed by use of the light-tunnel homogenizer. The images from the three light valves could be readily brought into focus and mechanically converged on the screen. The red, green, and blue images could be brought into coincidence to within a fraction of a pixel at the center of the screen. Pixel displacement at the corners of the screen was due to the small remaining residual color-correction error in the lens.

The monitor has proven to be sufficiently robust to withstand transportation by normal land and air freight services. All electronic boards and power supplies were contained within the monitor, resulting in a monitor depth of 20.4 in. The design of the internal configuration of the monitor provided a cooling airflow path to reduce heating of the optics and light valves by heat generated by the lamp and electronics. Heat generated within the light valves from the incident light flux was negligible. Large thermal gradients within the optical system have to be avoided to prevent loss of contrast from stress-induced birefringence in the glass components. Typically, the light valves reached a temperature of 30 to 35°C in operation.

Display subsystem electronics

The prototype projection monitor had two generations of support electronics which differed primarily in the level of interactivity provided to the user. Initially, a personal computer (PC) could be used to load an appropriately formatted image into the display frame buffer housed inside the monitor. This image was refreshed 74 times a second, although lower frequencies and other light-valve operating parameters could be programmed through a parallel-port connection to the PC. The image data path from the computer bus to the frame buffer was a custom high-performance serial link (200 MB/s raw data rate), although the data-limiting step was fetching the data from the hard disk. Initially, when the emphasis was on making the monitor operational and characterizing performance, this solution was adequate. The requirement to have a fully interactive monitor running real applications surfaced quickly, however, and the resulting second-generation system is described below.

- *System overview*

Bandwidth

Consider first the bandwidth of the monitor. The data rate is highest at the interface between the frame buffer and the light valves, where the display refresh function is performed. Although the physics of image formation in this monitor is different from that found in a CRT, one consideration remains constant for both: The image must be continuously refreshed (or rewritten). The refresh rate is dictated by flicker considerations, and flicker perception increases with screen size and screen luminance. The highest refresh rate, 74 Hz, consistent with the addressing speed of the light valves was chosen. For a system having 6 bits per primary color, the gross refresh bandwidth would be (2048 × 2048 pixels/frame × 18 bits/pixel × 74 frames/s), i.e., about 700 MB/s. Instantaneous burst rates are even higher when the discontinuous nature of the data delivery is considered. The actual bandwidth in the display adapter is lower, since direct color (no lookup table) was used at 16 bits/pixel. This bandwidth is managed by parallelism in the prototype monitor. First, the image is broken into red, green, and blue signals for the three light valves. Second, each light valve has six data drivers addressing the pixel array, and data are supplied to them simultaneously (54 data paths in parallel). Finally, each driver accepts three pixels per load clock. This parallelism reduces the data clock rate to an easily managed value, although the data path is wide. The details are discussed below.

System elements

One immediate consequence of the parallelism just mentioned is that the refresh frame buffer must be of custom design. In addition, since the data path is very wide, the only practical location for the frame buffer is near the light valves, inside the monitor. A high-level diagram of the display subsystem is shown in **Figure 6.** The desired system performance was to run any Windows** application and have a 60-Hz update rate and a display refresh rate of 74 Hz. A current-generation Intel-based PC running Windows NT** and having a 32-bit PCI bus is the host machine. It contains a modified display adapter which outputs digital pixel data. The digital data are taken from the output of the display adapter frame buffer and run from differential line drivers through flat-ribbon cables to receivers inside the monitor. This interface gives reliable performance even with long cables.

Within the computer, the system runs in a 2K × 2K mode using direct color at 16 bits/pixel. The display adapter is of conventional design and has a color lookup table (palette) and a digital-to-analog converter (DAC) following the frame buffer. The palette DAC, however, is not used for monitor operation. One consequence of this is that the hardware cursor function located in the palette DAC cannot be used. Instead, the Windows software cursor function is used. One can use the palette DAC output to drive a CRT for testing.

The interface between the computer and the monitor is digital and transfers 8 pixels/clock, 16 bits/pixel at a 60-Hz rate. Thus, the average bandwidth at this point is approximately 500 MB/s. Inside the monitor, the data stream is processed in hardware from 16 bits/pixel (5 red, 6 green, 5 blue) to 12 bits (4 bits for each color). This is

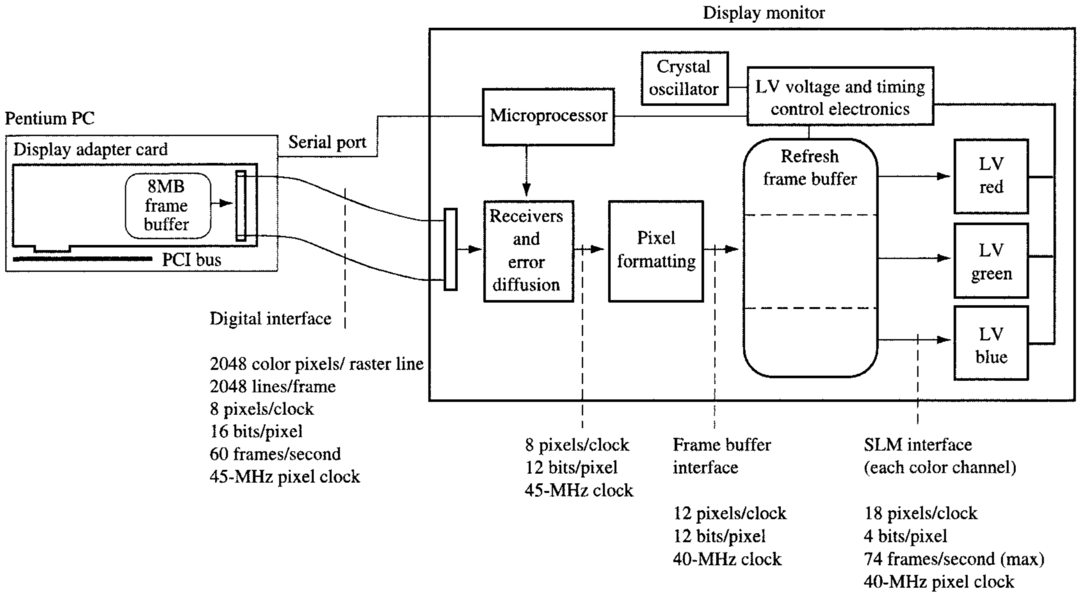


Figure 6

Overall diagram of the main elements of the display subsystem for the prototype monitor. The display monitor box houses the refresh frame buffer as well as other processing functions.

done using an error-diffusion technique which minimizes any contouring in continuous-tone images and maintains proper color. Converting the 16-bit data stream to 12 bits accommodates the 4-bit light-valve data drivers which were used. A consequence of the error-diffusion step is reducing the bandwidth after this stage by a factor of 12/16. Next the data are reformatted to match the addressing needs of the refresh frame buffer discussed below. The data path is changed from 8 pixels/clock to 12 pixels/clock and is fed to three separate frame-buffer cards, one each for red, green, and blue data. Finally, the data are read from the frame buffer into the three light valves.

A microprocessor inside the monitor provides numerous monitoring and control functions. One of these provides RS-232 command decoding from the serial port on the computer. This allows the user to set operational features such as the gamma and color balance of the monitor, the polarity inversion scheme for the LC light valve, and the display refresh rate.

- *Light-valve architecture and interface*

The light valve was designed to have integrated row scanners but external data drivers. Data-line demultiplexers were integrated, however, to reduce the I/O count. The resulting architecture is shown in **Figure 7**. Each data driver has 4-bit voltage precision and 198 outputs. The voltage swing on the outputs is 0 to 7 V. Sixteen reference voltage levels are supplied to the driver, and the input data are used to select one of these levels and pass it to the output. In operation, two sets of 16 voltages are multiplexed onto the driver's reference voltage pins to provide the alternating polarity excitation required by the liquid crystal cell. Three pixels of data (12 bits) are loaded into the driver at each pixel clock. Thus, 66 clocks are needed to load data for all 198 outputs.

Three drivers supply data to the array top and three supply data to the array bottom. Each driver is supplied data independently, resulting in a light-valve interface that is 18 pixels wide per clock transition. This architecture allowed a relatively quick and conservative implementation of the array, but at the cost of additional complexity in the display subsystem. For example, to write a full line on the display, the data drivers must be loaded twice within one line time (approximately 6.4 μs) with data that are not in raster order. Since data enter the monitor in raster order, the refresh frame buffer requires an organization that allows quick address translation. The address translation occurs on the input side and is the reason for the change from 8-pixel-wide data at the computer output to 12-pixel-wide data at the frame buffer input. Data are organized to supply driver pairs, say the leftmost top and bottom driver. To have data available for one data-pair load for

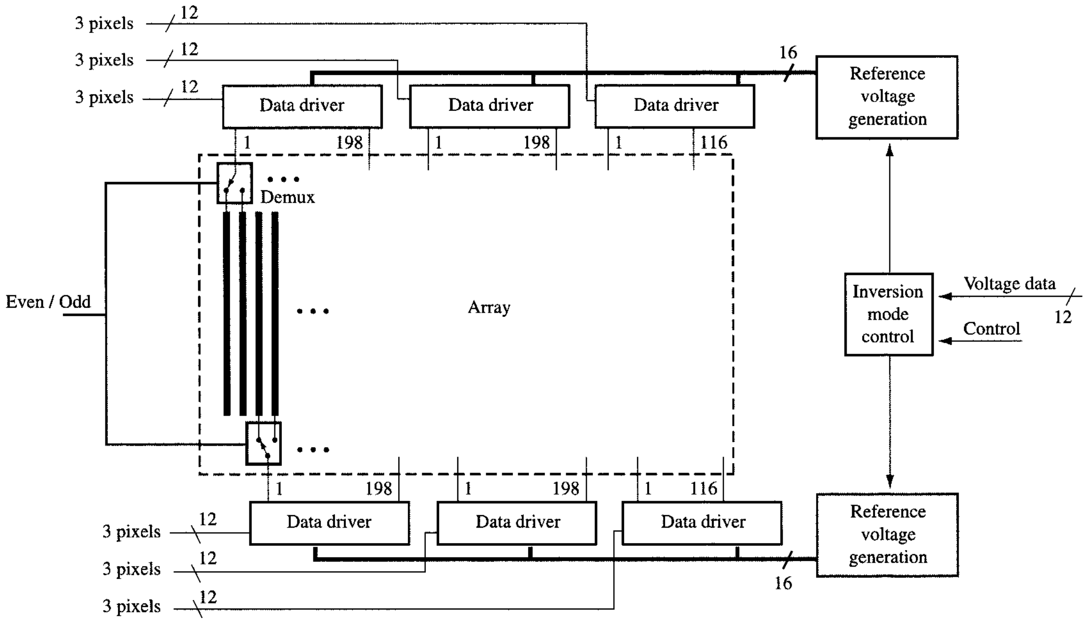


Figure 7

Diagram showing the flow of data into the external data drivers, through the demultiplexers (Demux) and onto the data lines of the array.

both the odd- and even-line multiplex phases requires 12 pixels of data—the top driver receives pixels 1, 5, 9 in the odd-line phase and pixels 2, 6, 10 in the even-line phase, while the bottom driver receives pixels 3, 7, 11 and pixels 4, 8, 12, respectively. Thus, with one memory write, pixel data are written into memory in the correct sequence for memory readout in sequential order. This memory arrangement and the timing of the data driver and demultiplexers are shown in **Figure 8**. Note that the two demultiplexer cycles are clustered in time, so that a significant portion of the line time may be allotted for the gate pulse, in the center of the array, to fall below the threshold of the pixel transistor after the gate driver has turned off. This is called gate-line skew; in our case, its value is approximately 1.7 μs due to the resistance and capacitance of the polysilicon gate lines.

The light-valve support electronics reside on a printed-circuit board to which the light valve is directly attached (see **Figure 9**). These electronics provide for all of the voltages, voltage sequencing, and timing required by the light valve. They include a computer interface allowing the user to set all voltages necessary for operation, to set the gamma of the display, to choose different types of LC polarity inversion, and to select different refresh frequencies. The refresh rate is programmable and has a maximum value of 74 Hz. Storage for default values is also provided.

Performance

All elements of the described rear-projection display functioned, and experience was gained in using it as a large PC monitor. **Figure 10** shows a photograph of the monitor displaying optical test patterns. **Figure 11** shows front-of-screen (FOS) images, one a closeup of the screen. Performance can be described in several ways, the most common being a set of quantitative display parameters, which are given below. Also, comparisons with known displays are useful, as are subjective comments about image quality. Each of these approaches is employed.

Table 1 summarizes the parameters measured on the prototype display. System throughput was significantly lower in blue light than in red or green. Table 1 luminance values reflect a significant attenuation in the green-channel brightness that was required for good color balance. (The luminance values included in Table 1 were made after about two years of operation. Initially the peak luminance was measured to be 115 cd/m^2). As can be seen from the table, sag distortion was at a very low level. Color pixel overlap over most of the screen was good; however, pixel overlap at the corners was of the order of 1 pixel separation

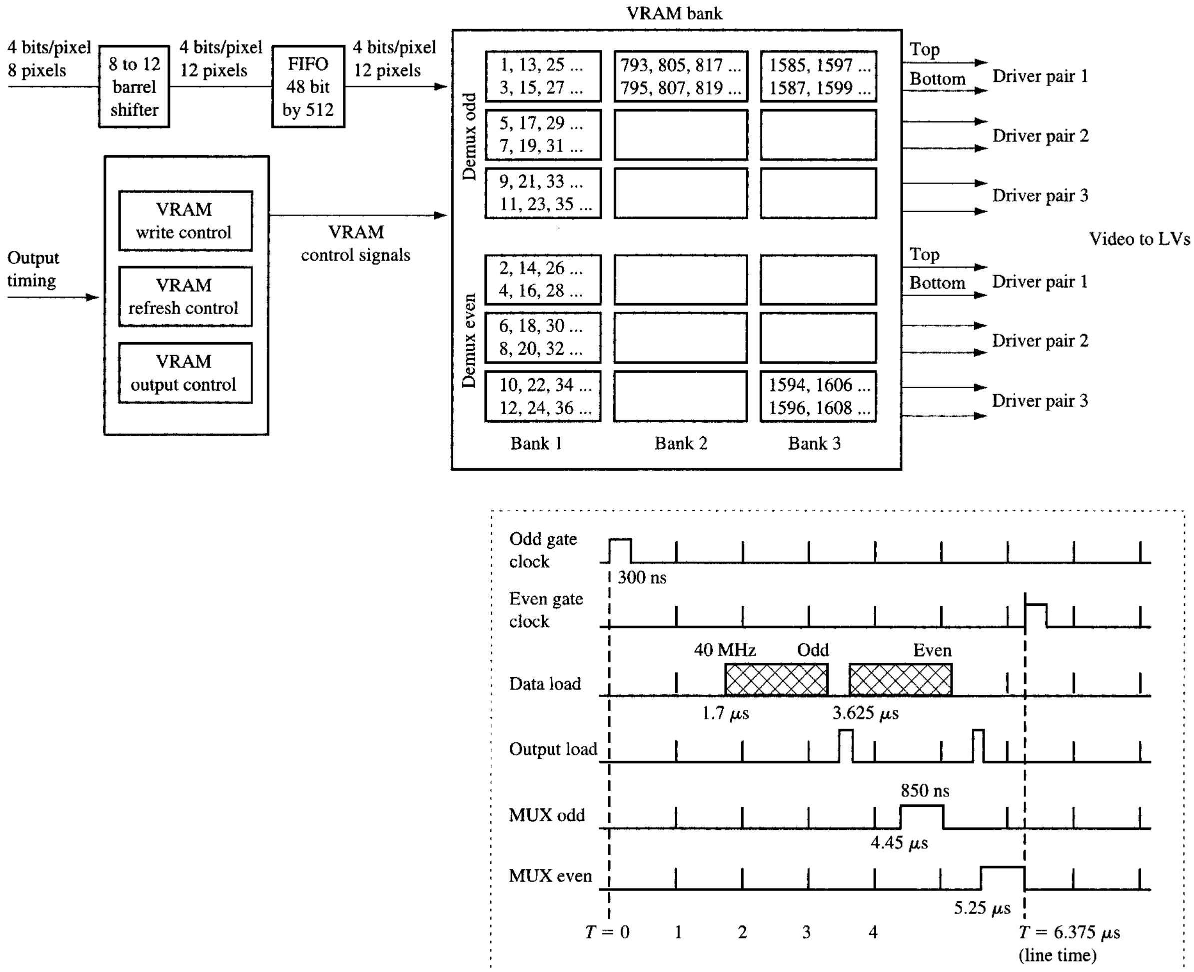


Figure 8

Architecture of the display refresh buffer with the data driver and demultiplexer timings for one color channel. The same architecture is used for all three color channels. The video data are digital throughout the system except for the final step of writing charge onto each pixel electrode.

instead of 1/3. Aligning the three light valves proved to be relatively straightforward.

The subjective appearance of the images is much better than the numbers in Table 1 might suggest. The combination of high pixel count at high spatial resolution, good contrast at very high spatial frequencies, and proper color balance might be invoked to explain this. As might be expected with a diffusive screen, contrast declines as the ambient illumination increases. Contrast can be recovered in this polarized light system, however, by using a polarizing filter on the front of the screen.

For comparison, the same images were displayed on the prototype projection display and on a Sony DDM 2802C CRT data monitor. This CRT had a screen size of 20×20 in. and addressability of 2048×2048, similar to the projection display. Differences in luminance, resolution, and size were apparent. The CRT monitor had a rated luminance of 80 cd/m^2, but was frequently used at a much lower value (of the order of 20 cd/m^2) for optimum resolution, whereas the prototype projection display could be set at differing levels of luminance with negligible effect on resolution. The prototype described here has a luminance of the order of 100 cd/m^2, but could have been designed for much higher luminance if desired.

The projection display had a striking pixel-level resolution. A contrast ratio of more than 3:1 was

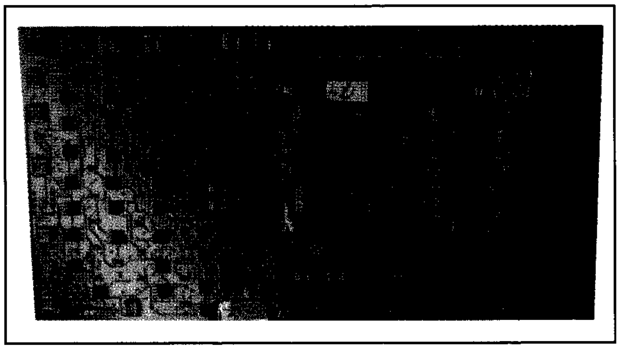


Figure 9

Photograph showing a light valve with external data drivers attached to its electronic support board.

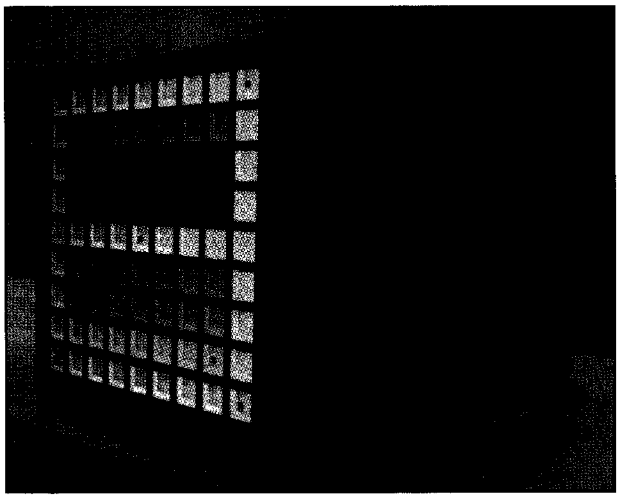


Figure 10

Photograph of the prototype projection display monitor. All elements needed for monitor operation are contained within the monitor covers. The screen image in this case was formed by optical plates which were used to characterize the optical behavior of the system. The monitor dimensions are height, 23 in., width, 31 in., and depth, 20.4 in.

measured for adjoining on/off-pixel columns. The DDM CRT had a linewidth specification of 0.046 to 0.052 in. at the 5% level (the shadow-mask pitch is 0.31 mm = 0.012 in. Thus, the CRT resolution was considerably less than that of the projector, whose resolvable pixel size is 0.01 in. The DDM CRT monitor exhibited better color performance, better luminance uniformity, and better large-area contrast in a dark room. The projection display prototype, however, had better small-feature contrast.

The projection display was constructed as a laboratory prototype and was fully integrated into a case whose height, width, and depth are 23 in., 31 in., and 20.5 in., respectively. This is to be compared with the Sony DDM CRT monitor at 29 in., 27 in., and 30.6 in., respectively. The depth advantage for the projection display is significant in those applications for which footprint is a factor. No attempt was made to design the prototype projector for low weight; a robust optical assembly was used with typical optical-bench-type fixturing. However, the final weight of the unit was about 150 lbs, which

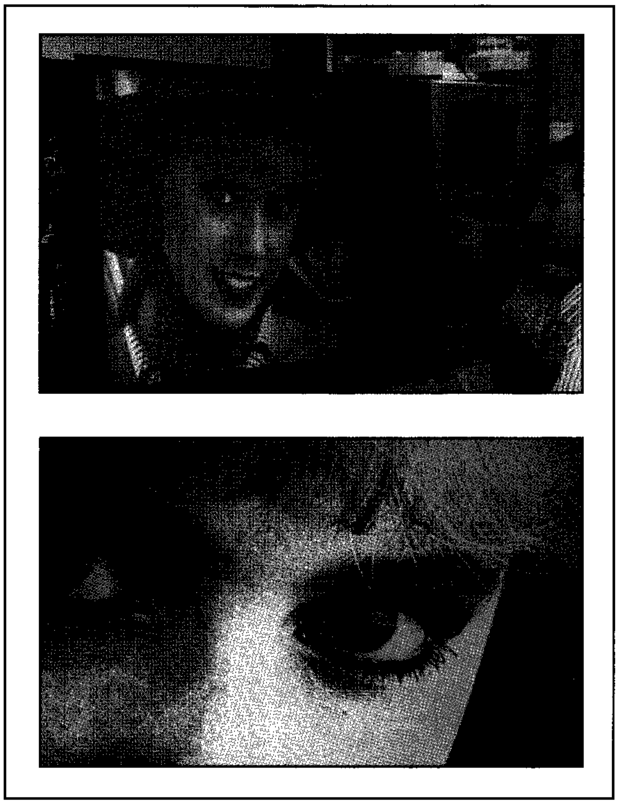


Figure 11

Photographs showing the front-of-screen performance of the prototype monitor. The image is a Kodak Photo CD image (3K × 2K pixels) which has been electronically cropped to 2048 × 2048 pixels. The vertical magenta bars on the left third of the screen shown in the upper photo derive from data-line shorts to the absorber layer on the green light valve; to prevent driver loading, these lines have data voltages set equal to the absorber (and ITO) voltage so that these green data lines are off. The lower photo shows a closeup view of the same image. Though the reproduced images may not show it, the front-of-screen image was balanced to show good facial tones.

Table 1 Four-megapixel projection monitor parameters.

Parameter	*Value*	*Units*
Columns × rows	2048 × 2048	number
Pixel size	17 × 17	μm^2
Aperture ratio	82	%
Array diagonal	1.94	in.
Screen diagonal	28.3	in.
Monitor size	23H × 31W × 20.4D	in.
Spatial resolution	100 (on screen)	pixels/in.
Luminance	73 (center)	cd/m^2
	57 (ANSI)	
Uniformity	+28%, −60% (ANSI-13 point)	
Contrast ratio	40:1 (all on/all off)	number
	27:1 (ANSI)	
	3.8:1 at 2 lp/mm (green)	
Colors	65,536	number
CIE coordinates	R: $x = 0.57$, $y = 0.29$	
	G: $x = 0.30$, $y = 0.62$	
	B: $x = 0.14$, $y = 0.08$	
	White: $x = 0.30$, $y = 0.34$	
Frame rate	74 (progressive scan)	Hz
Lamp power	100	W
Screen (DaLite)	Low gain, surface diffusion	
Color convergence	1 (at corners)	pixel
Sag distortion	<0.25%	%
LC mode	Twisted nematic, 45°	

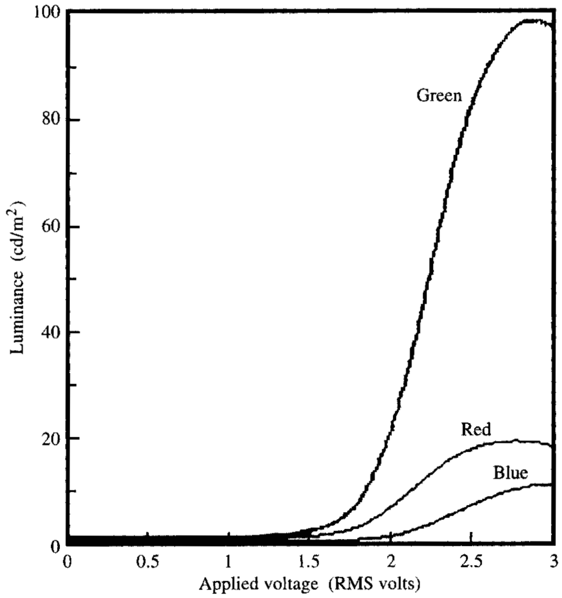


Figure 12

Measurement of the luminance–voltage characteristics for the three color channels. The data were measured normal to the screen near the center of the display. The relative intensities were adjusted with optical filters to achieve nominal color balance. Final balance is achieved electronically.

compares favorably with the Sony DDM 2808C weight of 227 lbs. The DDM CRT consumes 450 W of power, whereas power consumption of the projection prototype is about 300 W. Although the arc lamp is rated at only 100 W, the electronic system, including the frame buffer, consumes between 150 and 175 W.

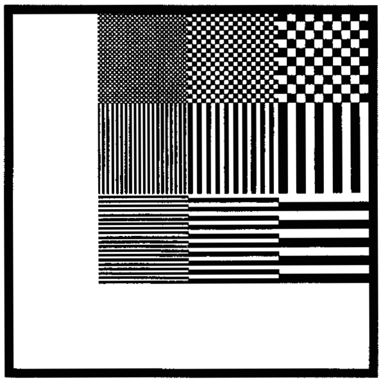
Cost comparisons between the CRT and the projection prototype are difficult to make at this time. The DDM CRT is sold in relatively low quantities and is correspondingly priced. The production cost of the present projection technology is only poorly understood at this time.

Light-valve characteristics

The FOS luminance-voltage characteristics of the three color channels are shown in **Figure 12**. The intensities are adjusted with optical filters to achieve partial color balance. The green channel response in Figure 12 is measured with this optical attenuation in place. Electronic control is used for final color balance. A total attenuation of 40% is needed to balance green against blue. The green channel is set for a gamma of 2.2; for proper white balance, the red and blue channels are slightly different. Note that the shapes of the three curves are each different, requiring that the reference voltages for the data drivers of each color channel be set independently. The transient response for the slowest cell (red) was 20 ms for either transition direction.

Resolution measurements

FOS resolution measurements were made using a 14-bit quantitative-image-acquisition system based on a low-noise, cooled Photometrics PM512 CCD imager connected to a PC. Typical integration times were in the 100–1000-ms range. For acquisition and processing, Microsoft-Windows-based PMIS Image Processing software was used. The software allows intensity profiles along any vertical or horizontal position to be extracted. The CCD camera is equipped with a lens adapter coupling to standard Nikon 35-mm lenses. The magnification was adjusted to provide approximately 5 CCD pixels for each display pixel. A test pattern having lines and spaces of various line widths was used for measurements. The test pattern is shown in **Figure 13**, along with a table of the contrast-ratio results. The test pattern has nine clusters of horizontal, vertical, and checkerboard patterns, as well as a large, bright L-shaped region. Features within the patterns have resolutions of 4-, 2-, and 1-pixel linewidths. The high-resolution checkerboard pattern, for example,



Measured contrast ratio – green channel		
Line width (Pixels)	*Horizontal*	*Vertical*
4	9.8	8.3
2	7.3	5.9
1	3.8	3.5

Figure 13

Test pattern used in the contrast ratio measurements of the light valves. Beneath the test pattern is a table of the contrast data for the green channel. This test pattern is the one shown in the photograph in Figure 10.

has one-pixel-on and one-pixel-off patterns in the horizontal and vertical directions. The measurements were made on a low-gain, 1.3× DaLite Corporation surface-diffuser screen.

The results for the green channel show a ratio of 3.8 in the intensities for single-pixel-on/off lines (corresponding to 2 lp/mm). In other terms, this is equivalent to a Michelson modulation [given by (max. intensity − min. intensity)/(max. intensity + min. intensity)] of 58%. For comparison, the performance of an ILA projector was reported by Bleha [13] as having a value of 12% at 1780 T-V lines. The intensity profiles corresponding to the green horizontal data are shown in **Figure 14**. Note that the contrast ratio data in Figure 13 show a consistently lower contrast for vertical lines. The microscopic behavior of the liquid crystal cell provides the explanation. A photograph of light-valve operation at pixel-scale resolution is shown in **Figure 15**. Several features of device construction and operation are worth noting. First, the four larger dark spots at the corners of four pixels are the SiO_2 spacer posts shown schematically in Figure 1. Next, while the array image is approximately uniform from row to row, it is not the case from column to column. Figure 15 shows a nonuniform response with a period of two pixels. The nonuniformities at the right edge of every other pixel are disclinations in the liquid crystal. These are caused by lateral electric fields between pixels, caused by addressing the display using column-pair inversion. This means that two columns (say columns 1 and 2) have the same voltage polarity at any point in time, and the lateral field between adjacent pixels is either zero (same data on each pixel) or small. The next two columns, however (columns 3 and 4), each have the opposite polarity, and the boundaries between columns of opposite polarities

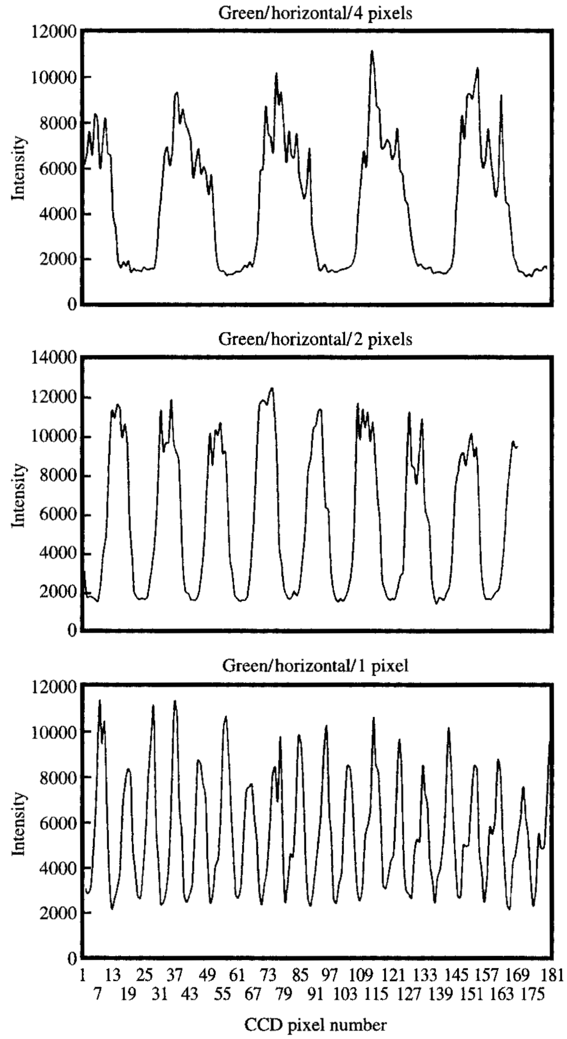


Figure 14

Green image intensity profile data corresponding to the contrast ratio data shown in Figure 13. The contrast ratio was computed by spatially averaging the intensities of each pixel in the scan and then taking the average of all of the averaged ON intensities and dividing by the average of all of the averaged OFF intensities in the scan.

have high lateral electric fields which induce disclinations. The details of this effect are under study, but the consequence is a loss of luminance in the on-pixels and shows up as a loss of contrast ratio in the vertical data given in Figure 13. Of the several modes of polarity inversion made possible by the electronics, the column-pair inversion mode described above was chosen as the default mode. Single-column inversion has more pronounced disclination effects, and frame-only inversion made some nonuniformities in the cell more apparent, as well as some flicker from the region near the LC fill hole.

The monitor has been used to demonstrate motion video in two ways. Software-compressed video is readily implemented in modern operating systems, and we were able to run video clips at updated rates (limited by the system, not the display) of approximately 15 frames/s. Second, we have implemented the electronics to allow simultaneous viewing of the computer data and motion video in an arbitrarily sized window. The video can be any standard analog or digital source. The description of this implementation is beyond the scope of this paper. For best operation with video, the monitor should be run at a refresh rate of 60 Hz. However, even with the monitor refreshed at 74 Hz, the motion video rendition is very good and requires special test sequences to show the effects of the mismatch between the 60-Hz update rate and the 74-Hz refresh rate. Except for testing, therefore, the monitor is run at its maximum refresh rate of 74 Hz.

Conclusions

The rear-projection monitor described above has demonstrated that very high-information-content data monitors can be built with reflective liquid crystal light valves, compact reflective optical design, and a unique electronic architecture. We believe that significant enhancements to the system contrast, optical throughput, mechanical layout, and electronic performance are achievable. Fundamental issues of screen speckle and system cost remain to be resolved.

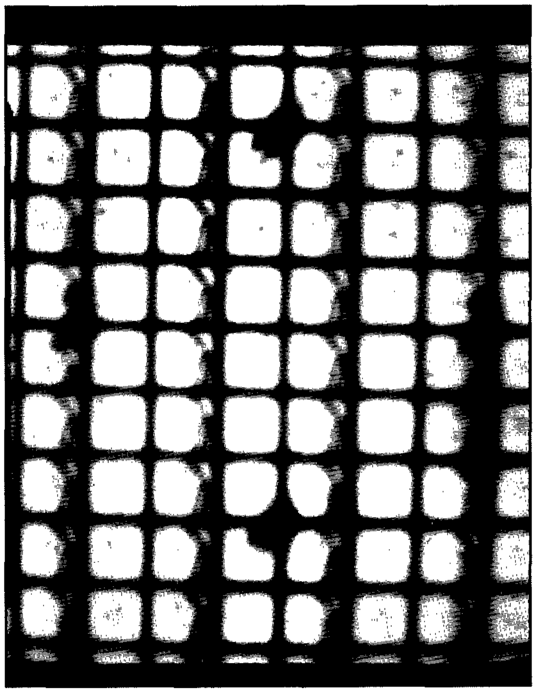


Figure 15

Photograph of light-valve operation at pixel-scale resolution. The light valve is imaged onto a CCD camera mounted in a polarizing microscope. The camera output feeds a monochrome CRT monitor, and this is a photograph of the CRT screen.

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