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INTRODUCTION

Large-screen, high-brightness electronic projection displays serve four broad areas of application: (1) electronic presentations (e.g., business, education, advertising), (2) entertainment (e.g., home theater, sports bars, theme parks, electronic cinema), (3) status and information (e.g., military, utilities, transportation, public, sports) and (4) simulation (e.g., training, games). The electronic presentation market is being driven by the pervasiveness of software that has put sophisticated presentation techniques (including multimedia) into the hands of the average PC user.

A survey of high-brightness (>1000 lumens) electronic projection displays for comparing the already existing three types of projection display technologies namely, Oil film, CRT-LCD, and AM-LCD was conducted. Developed in the early 1940s at the Swiss Federal Institute of Technology and later at Gretag AG, oil film projectors (including the GE Talaria) have been the workhorse for applications that require projection displays of the highest brightness. But the oil film projector has a number of limitations including size, weight, power, setup time, stability, and maintenance. In response to these limitations, LCD-based technologies have challenged the oil film projector. These LCD-based projectors are of two general types: (1) CRT-addressed LCD light valves and (2) active-matrix (AM) LCD panels. LCD-

based projectors have not provided the perfect solution for the entire range of high-brightness applications. CRT-addressed LCD light valves have setup time and stability limitations. Most active-matrix LCDs used for high-brightness applications are transmissive and, because of this, heat generated by light absorption cannot be dissipated with a heatsink attached to the substrate. This limitation is mitigated by the use of large-area LCD panels with forced-air cooling. However, it may still be difficult to implement effective cooling at the highest brightness levels.

In response to these and other limitations, as well as to provide superior image quality under the most demanding environmental conditions, high-brightness projection display systems have been developed based on Digital Light Processing technology. DLP is based on a micro electro mechanical system (MEMS) device known as the Digital Micro mirror Device (DMD). The DMD, invented in 1987 at Texas Instruments, is a semiconductor-based array of fast, reflective digital light switches that precisely control a light source using a binary pulse modulation technique. It can be combined with image processing, memory, a light source, and optics to form a DLP system (*Figure2*) capable of projecting large, bright, seamless, high-contrast color images.

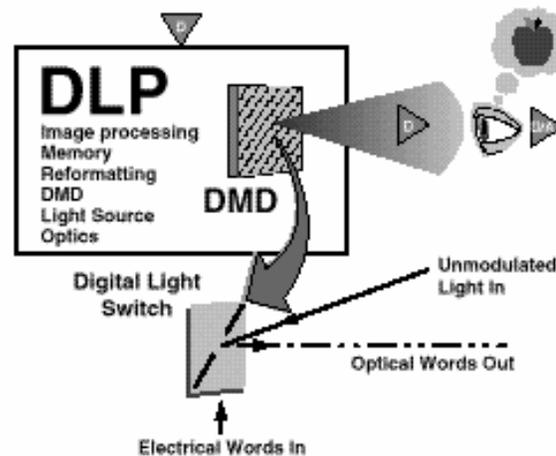


Figure 2. Digital Light Processing system

Figure 3 shows a DLP projector in an auditorium environment. This photo was taken at the Texas Instruments Digital Imaging Business Center in Dallas, Texas.

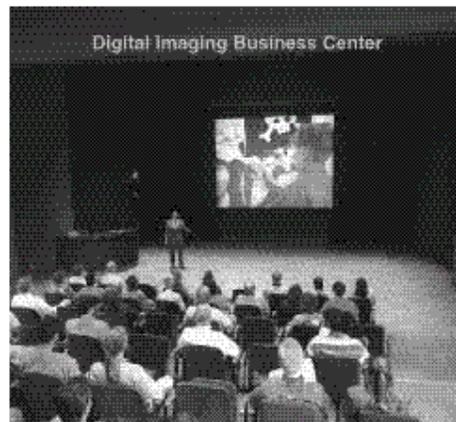


Figure 3. DLP projector in auditorium environment

DLP-based projection displays are well-suited to high-bright-ness and high-resolution applications: (a) the digital light switch is reflective and has a high fill factor, resulting in high optical efficiency at the pixel level and low pixelation effects in the projected image; (b) as the resolution and size of the DMD

increase, the overall system optical efficiency grows because of higher lamp-coupling efficiency; (c) because the DMD operates with conventional CMOS voltage levels (~5 volts), integrated row and column drivers are readily employed to minimize the complexity and cost impact of scaling to higher resolutions; (d) because the DMD is a reflective technology, the DMD chip can be effectively cooled through the chip substrate, thus facilitating the use of high-power projection lamps without thermal degradation of the DMD; and (e) finally, DLP-based systems are all-digital (digital video in, digital light out), so reproduction of the original video source material is accurate and the image quality is stable with time.

The general movement of the display industry is in the digital direction. Digital sources that are currently available include digital video disk (DVD), digital satellite system (DSS), and the Internet (World Wide Web). In the future, the recently approved Advanced Television Standard (ATV) and the digital distribution of movies (digital cinema) will be added to the list of digital sources. Interfacing these digital sources to currently available analog displays requires digital-to-analog conversion and, in some instances, analog encoding (e.g., s-video or composite), which result in degradation of the source image quality. DLP-based displays, on the other hand, preserve the digital integrity of the source image all the way to the eye. The result is the best possible video quality.

DMD LIGHT SWITCH

The mirror as a switch

The DMD light switch (*Figure 4*) is a member of a class of devices known as microelectromechanical systems. Other MEMS devices include pressure sensors, accelerometers, and microactuators. The DMD is monolithically fabricated by CMOS-like processes over a CMOS memory. Each light switch has an aluminum mirror, $16\ \mu\text{m}$ square that can reflect light in one of two directions depending on the state of the underlying memory cell.

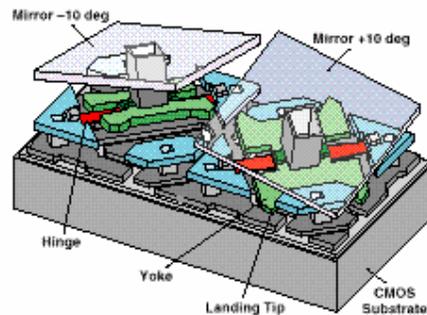


Figure 4. Two DMD pixels (mirrors are shown as transparent)

Rotation of the mirror is accomplished through electrostatic attraction produced by voltage differences developed between the mirror and the underlying memory cell. With the memory cell in the on (1) state, the mirror rotates to +10 degrees. With the memory cell in the off (0) state, the mirror rotates to -10 degrees. A closeup of DMD mirrors operating in a scanning electron microscope (SEM) is shown in *Figure 5*.

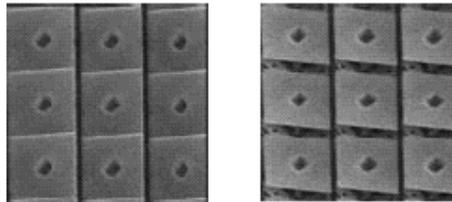


Figure 5. SEM video images of operating DMD

By combining the DMD with a suitable light source and projection optics (*Figure 6*), the mirror reflects incident light either into or out of the pupil of the projection lens by a simple beam-steering technique. Thus, the (1) state of the mirror appears bright and the (0) state of the mirror appears dark. Compared to diffraction-based light switches, the beam-steering action of the DMD light switch provides a superior tradeoff between contrast ratio and the overall brightness efficiency of the system.

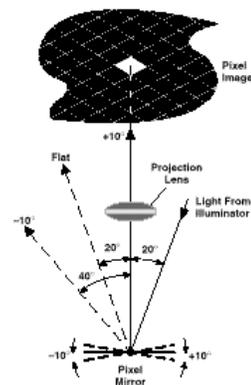
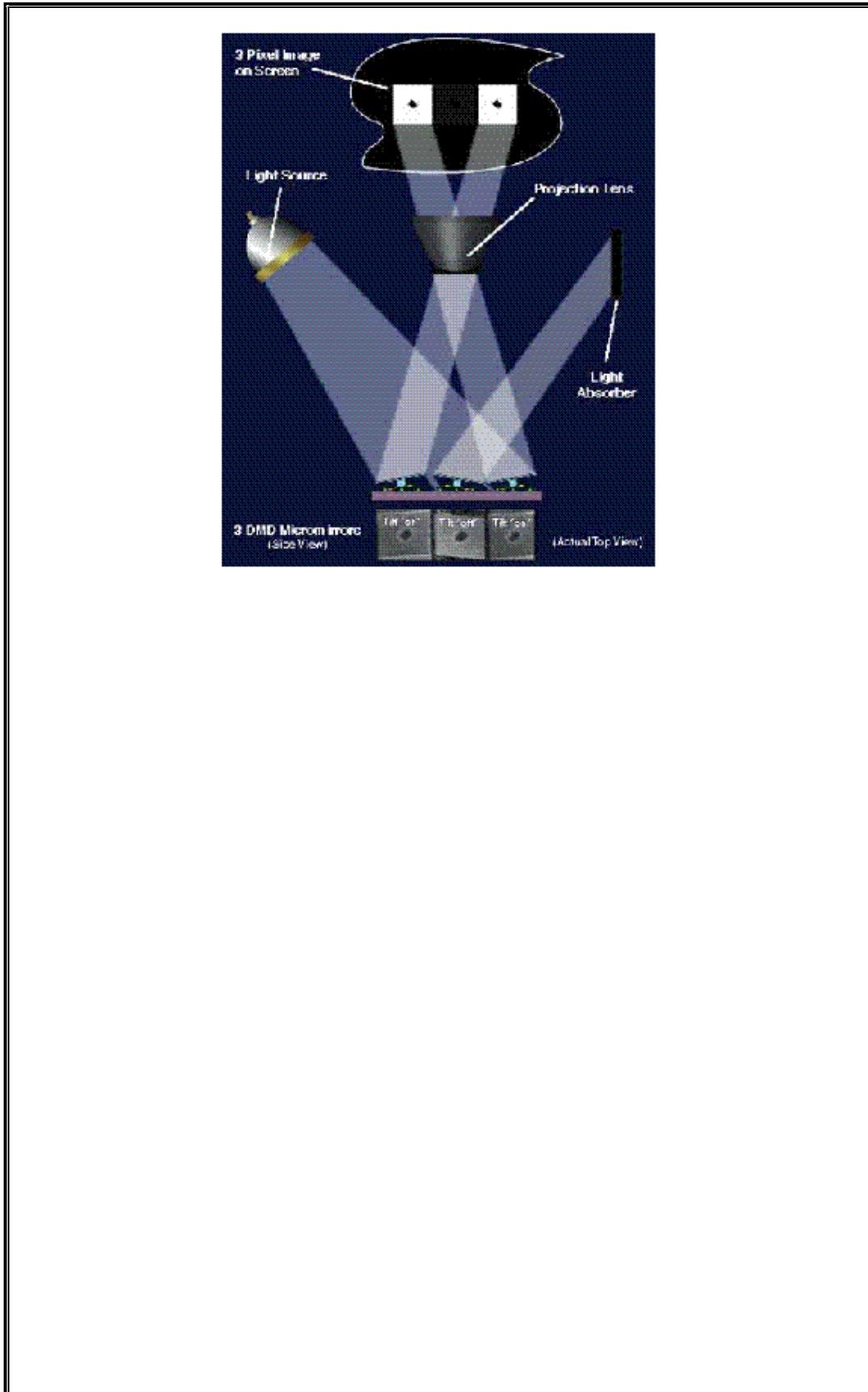


Figure 6. DMD optical switching principle

By electrically addressing the memory cell below each mirror with the binary bit plane signal, each mirror on the DMD array is electrostatically tilted to the on or off positions. The technique that determines how long each mirror tilts in either direction is called pulse width modulation (PWM). The mirrors are capable of switching on and off more than 1000 times a second. This rapid speed allows digital gray scale and color reproduction. At this point, DLP becomes a simple optical system. After passing through condensing optics and a color filter system, the light from the projection lamp is directed at the DMD. When the mirrors are in the on position, they reflect light through the projection lens and onto the screen to form a digital, square-pixel projected image (*figure shown in the next page*).

Three mirrors efficiently reflect light to project a digital image. Incoming light hits the three mirror pixels. The two outer mirrors that are turned on reflect the light through the projection lens and onto the screen. These two "on" mirrors produce square, white pixel images. The central mirror is tilted to the "off" position. This mirror reflects light away from the projection lens to a light absorber so no light reaches the screen at that particular pixel, producing a square, dark pixel image. In the same way, the remaining 508,797 mirror pixels reflect light to the screen or away from it. By using a color filter system and by varying the amount of time each of the 508,800 DMD mirror pixels is on, a full-color, digital picture is projected onto the screen.



GRAYSCALE AND COLOR OPERATION

Grayscale is achieved by binary pulse width modulation of the incident light. Color is achieved by using color filters, either stationary or rotating, in combination with one, two, or three DMD chips. The DMD light switch is able to turn light on and off rapidly by the beam-steering action of the mirror. As the mirror rotates, it either reflects light into or out of the pupil of the projection lens, to create a burst of digital light pulses that the eye interprets as an analog image. The optical switching time for the DMD light switch is $\sim 2 \mu\text{s}$. The mechanical switching time, including the time for the mirror to settle and latch, is $\sim 15 \mu\text{s}$ [36]. The technique for producing the sensation of grayscale to the observer's eye is called binary pulse width modulation. The DMD accepts electrical words representing gray levels of brightness at its input and outputs optical words, which are interpreted by the eye of the observer as analog brightness levels.

The details of the binary pulse width modulation (PWM) technique are illustrated in *Figure 7*. For simplicity, the PWM technique is illustrated for a 4-bit word (2⁴ or 16 gray levels).

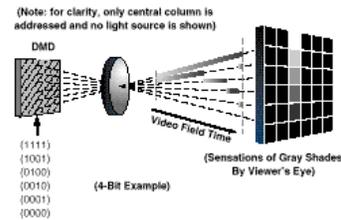


Figure 7. DMD binary pulsewidth modulation (4-bit example)

Each bit in the word represents time duration for light to be on or off (1 or 0). The time durations have relative values of 2⁰, 2¹, 2², 2³, or 1, 2, 4, 8. The shortest interval (1) is called the least significant bit (LSB). The longest interval (8) is called the most significant bit (MSB). The video field time is divided into four time durations of 1/15, 2/15, 4/15, and 8/15 of the video field time. The possible gray levels produced by all combinations of bits in the 4-bit word are 2⁴ or 16 equally spaced gray levels (0, 1/15, 2/15 . . . 15/15). Current DLP systems are either 24-bit color (8 bits or 256 gray levels per primary color) or 30-bit color (10 bits or 1024 gray levels per primary color).

In the simple example shown in *Figure 7*, spatial and temporal artifacts can be produced because of imperfect integration of the pulsed light by the viewer's eye. These artifacts can be reduced to negligible levels by a "bit-splitting" technique. In this technique, the longer duration bits are subdivided into shorter durations, and these split bits are distributed through-out the video field time. DLP displays combine pulse width modulation and bit-splitting to produce a "true-analog" sensation, but with greater accuracy and stability than can be achieved by analog projection systems.

DMD CELL ARCHITECTURE AND FABRICATION

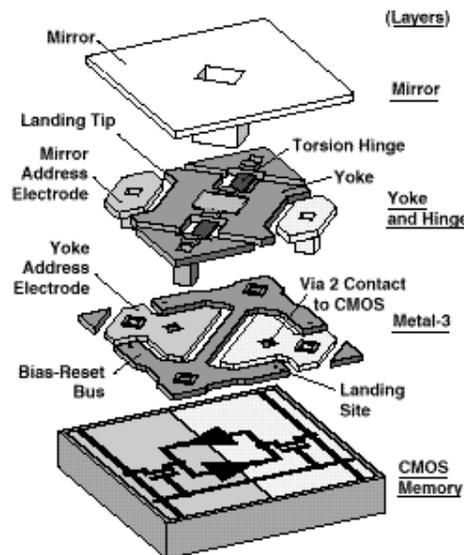


Figure 8. DMD pixel exploded view

The DMD pixel is a monolithically integrated MEMS super-structure cell fabricated over a CMOS SRAM cell (*Figure 8*). An organic sacrificial layer is removed by plasma etching to produce air gaps between the metal layers of the superstructure. The air gaps free the structure to rotate about two compliant torsion hinges. The mirror is rigidly connected to an underlying yoke. The yoke, in turn, is connected by two thin, mechanically compliant torsion hinges to support posts that are attached to the underlying substrate.

The address electrodes for the mirror and yoke are connected to the complementary sides of the underlying

SRAM cell. The yoke and mirror are connected to a bias bus fabricated at the metal-3 layer. The bias bus interconnects the yoke and mirrors of each pixel to a bond pad at the chip perimeter. An off-chip driver supplies the bias waveform necessary for proper digital operation. The DMD mirrors are 16 μm square and made of aluminum for maximum reflectivity. They are arrayed on 17 μm centers to form a matrix having a high fill factor (~90%). The high fill factor produces high efficiency for light use at the pixel level and a seamless (pixelation-free) projected image.

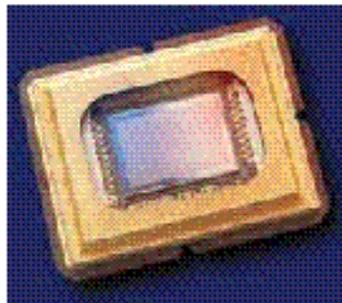
Electrostatic fields are developed between the mirror and its address electrode and the yoke and its address electrode, creating an efficient electrostatic torque. This torque works against the restoring torque of the hinges to produce mirror and yoke rotation in the positive or negative direction. The mirror and yoke rotate until the yoke comes to rest (or lands) against mechanical stops that are at the same potential as the yoke. Because geometry determines the rotation angle, as opposed to a balance of electrostatic torques employed in earlier analog devices, the rotation angle is precisely determined.

The fabrication of the DMD superstructure begins with a completed CMOS memory circuit. A thick oxide is deposited over metal-2 of the CMOS and then planarized using a chemical mechanical polish (CMP) technique. The CMP step provides a completely flat substrate for DMD superstructure fabrication, ensuring that the projector's brightness uniformity and contrast ratio are not degraded.

Through the use of six photomask layers, the superstructure is formed with layers of aluminum for the address electrode (metal-3), hinge, yoke and mirror layers and hardened photo-resist for the sacrificial layers (spacer-1 and spacer-2) that form the two air gaps. The aluminum is sputter-deposited and plasma-etched using plasma-deposited SiO₂ as the etch mask. Later in the packaging flow, the sacrificial layers are plasma-ashed to form the air gaps.

The packaging flow begins with the wafers partially sawed along the chip scribe lines to a depth that will allow the chips to be easily broken apart later. The partially sawed and cleaned wafers then proceed to a plasma etcher that is used to selectively strip the organic sacrificial layers from under the DMD mirror, yoke, and hinges. Following this process, a thin lubrication layer is deposited to prevent the landing tips of the yoke from adhering to the landing pads during operation. Before separating the chips from one another, each chip is tested for full electrical and optical functionality by a high-speed automated wafer tester. Finally, the chips are separated from the wafer, plasma-cleaned, relubricated, and hermetically sealed in a package.

Figure 9 shows a packaged DMD chip.



An 848 x 600 Digital Micro mirror Device. The central, reflective portion of the device consists of 508,800 tiny, tilt able mirrors. A glass window seals and protects the mirrors.

ELECTRONIC OPERATION

The DMD pixel is inherently digital because of the way it is electronically driven. It is operated in an electro statically bistable mode by the application of a bias voltage to the mirror to minimize the address voltage requirements. Thus, large rotation angles can be achieved with a conventional 5-volt CMOS address circuit.

The pulse width modulation scheme for the DMD requires that the video field time be divided into binary time intervals or bit times. During each bit time, while the mirrors of the array are modulating light, the underlying memory array is refreshed or updated for the next bit time. Once the memory array has been updated, all the mirrors in the array are released simultaneously and allowed to move to their new address states.

This simultaneous update of all mirrors, when coupled with the PWM bit-splitting algorithm produces an inherently low-flicker display. Flicker is the visual artifact that can be produced in CRTs as a result of brightness decay with time of the phosphor. Because CRTs are refreshed in an interlaced scan-line format, there is both a line-to-line temporal phase shift in brightness as well as an overall decay in brightness. DLP-based displays have inherently low flicker because all pixels are updated at the same time (there is no line-to-line temporal phase shift) and because the

PWM bit-splitting algorithm produces short-duration light pulses that are uniformly distributed throughout the video field time (no temporal decay in brightness).

Proper operation of the DMD is achieved by using the bias and address sequence shown in *Figure 11* and detailed in *Table 1*.

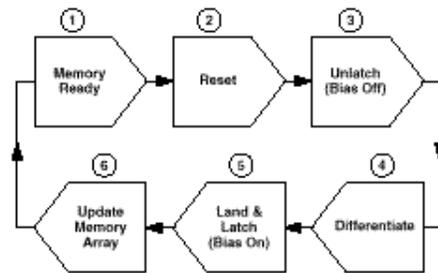


Figure 11. DMD address and reset sequence

Table 1. DMD address and reset sequence

1. Memory ready—All memory cells under the DMD have been loaded with the new address states for the mirrors.
2. Reset—All mirrors are reset in parallel (voltage pulse applied to bias bus).
3. Unlatch—The bias is turned off to unlatch mirrors and allow them to release and begin to rotate to flat state.
4. Differentiate—Retarding fields are applied to the yoke and mirrors in order to rotationally separate the mirrors that remain in the same state from those that are to cross over to a new state.

5. Land and latch—The bias is turned on to capture the rotationally separated mirrors and enable them to rotate to the addressed states, then settle and latch.
6. Update memory array (one line at a time)—The bias remains turned on to keep the mirrors latched so as to prevent them from responding to changes in the memory, while the memory is written with new video data.
7. Repeat sequence beginning at step 1.

The bias voltage has three functions. First, it produces a bistable condition to minimize the address voltage requirement, as previously mentioned. In this manner, large rotation angles can be achieved with conventional 5-volt CMOS. Second, it electromechanically latches the mirrors so that they cannot respond to changes in the address voltage until the mirrors are reset. The third function of the bias is to reset the pixels so that they can reliably break free of surface adhesive forces and begin to rotate to their new address states.

Although the metal surfaces of the superstructure are coated with a passivation layer or lubrication layer, the remaining Van der Waal or surface forces between molecules require more than the hinge-restoring force to reliably reset the mirrors. A reset voltage pulse applied to the mirror and yoke causes the spring tips of the yoke (*Figure 12*) to flex.

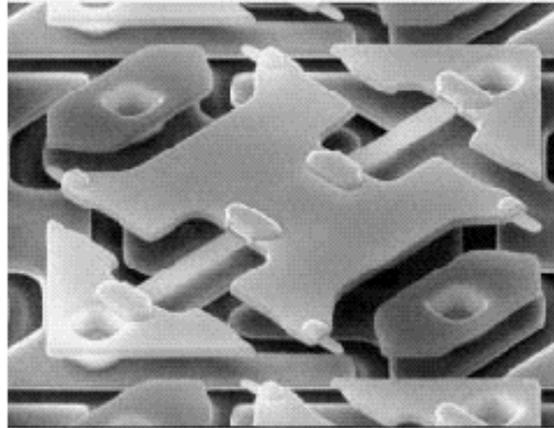


Figure 12. SEM photomicrograph of yoke and spring tips (mirror removed)

As the spring tips unflex, they produce a reaction force that causes the yoke landing tips to accelerate away from the landing pads, producing a reliable release from the surface.

DLP SYSTEM DESCRIPTION AND OPERATION

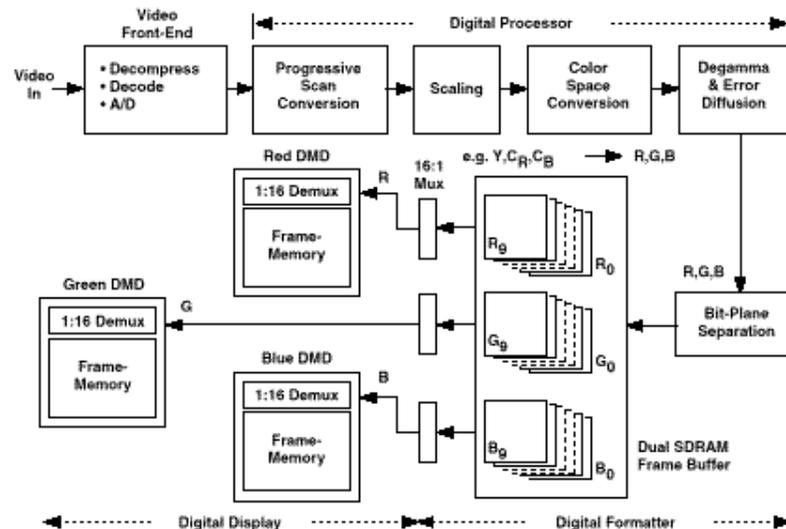


Figure 13. Generic DLP system diagram

Figure 13 illustrates a generic three-chip DLP system broken down into its functional components (video front-end, digital processor, digital formatter, and digital display). The generic video front-end accepts a variety of video sources (digital, digital compressed, digital graphics, analog composite, analog s-video, and analog graphics). The video front-end performs the functions of decompression, decoding, and analog-to-digital conversion, depending on the nature of the video source.

The first operation in the digital processor is progressive-scan conversion. This conversion is required if the original source material is interlaced. An interlaced format provides even lines of video during one video field time and odd

lines during the next field time. Progressive-scan conversion is the process of creating (by an interpolation algorithm) new scan lines between the odd or even lines of each video field.

Interlacing has been historically used in CRT-based systems to reduce the video bandwidth requirements without producing objectionable flicker effects created by the temporal decay in phosphor brightness. For progressively scanned CRTs, interlacing is unnecessary because additional bandwidth is allocated so that every line of the CRT is refreshed during each field time. Progressive scanning that incorporates motion-adaptive algorithms helps to reduce interlace scanning artifacts such as interline flicker, raster line visibility, and field flicker. These are particularly noticeable in larger display formats.

The next operation in the digital processor is digital resampling (or scaling). This operation resizes the video data to fit the DMD's pixel array, expands letterbox video sources, and maintains a correct aspect ratio for the square pixel DMD format. After the scaling operation, the video data is input to the color space conversion block. If the video is not already in a red, green, blue (R, G, B) format, it is converted from luminance and color difference encoding (e.g., Y, CR, CB) into R, G, B. Next, a degamma (inverse gamma) function is performed. CRT systems have non-linear signal-to-light characteristics. In order to compensate for this error, an error correction, called Gamma correction is done on images. But as the DLP system has linear signal-to-light characteristics, this correction is to be removed,

which is done in the degamma section. The degamma operation can produce low-light-level contouring effects, but these are minimized by using an error diffusion technique.

Finally the R, G, B signal is input to the digital formatter. First, the scan-line format data is converted into an R, G, B bit-plane format. The bit planes are stored in a dual-synchronous DRAM (SDRAM) frame buffer for fast access of the bit-plane data. The bit-plane data is then output to the DMDs in a PWM bit-splitting sequence. The DMD chip has multiple data inputs that allow it to match the frequency capability of the on-chip CMOS with the required video data rates. The bit-plane data coming out of the frame buffer is multiplexed 16:1 and fed to the multiple data inputs of each DMD. The bit-plane data is then demultiplexed 1:16 and fed to the frame-memory underlying the DMD pixel array.

PROJECTION OPTICS

DLP optical systems have been designed in a variety of configurations distinguished by the number of DMD chips (one, two, or three) in the system. The one-chip and two-chip systems rely on a rotating color disk to time-multiplex the colors. The one-chip configuration is used for lower brightness applications and is the most compact. Two-chip systems yield higher brightness performance but are primarily intended to compensate for the color deficiencies resulting from spectrally imbalanced lamps (e.g., the red deficiency in many metal halide lamps). For the highest brightness applications, three-chip systems are required.

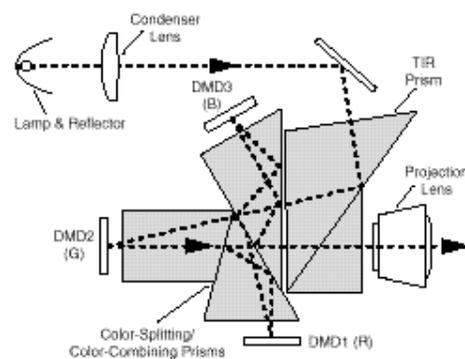


Figure 14. DLP three-chip optical system

A DLP optical system with three chips is shown in *Figure 14*. Because the DMD is a simple array of reflective light switches, no polarizers are required. Light from a metal halide or xenon lamp is collected by a condenser lens. For proper operation of the DMD light switch, this light must be directed at 20 degrees

relative to the normal of the DMD chip (*Figure 6*). To accomplish this in a method that eliminates mechanical interference between the illuminating and projecting optics, a total internal reflection (TIR) prism is interposed between the projection lens and the DMD color-splitting/-combining prisms.

The color-splitting/-combining prisms use dichroic interference filters deposited on their surfaces to split the light by reflection and transmission into red, green, and blue components. The red and blue prisms require an additional reflection from a TIR surface of the prism in order to direct the light at the correct angle to the red and blue DMDs. Light reflected from the on-state mirrors of the three DMDs is directed back through the prisms and the color components are recombined. The combined light then passes through the TIR prism and into the projection lens because its angle has been reduced below the critical angle for total internal reflection in the prism air gap.

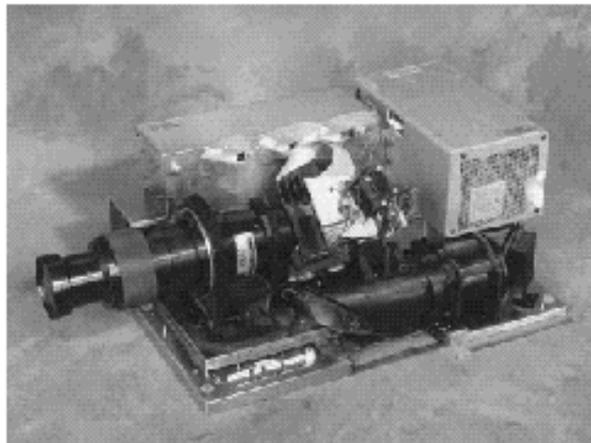


Figure 15. DLP three-chip prototype projection engine

A DLP three-chip prototype projection engine is shown in *Figure 15*. It projects 1100 lumens with a 500-watt xenon lamp. The size of the engine is $19.5 \times 12.8 \times 10$ in. and it weighs 38 pounds. One of the DMD package assemblies with thermoelectric cooler and fan is visible.

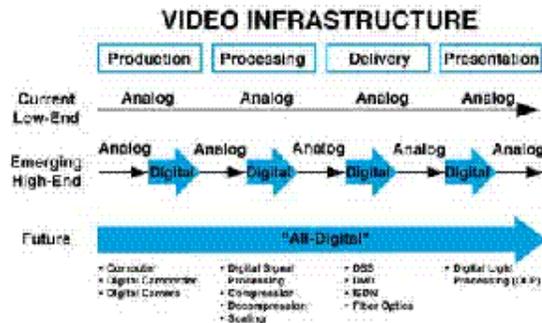
TECHNOLOGICAL ADVANTAGES

1. The Digital Advantage

The audio world started the trend toward digital technology well over a decade ago. Recently, an abundance of new digital video technology has been introduced to the entertainment and communications markets. The digital satellite system (DSS) quickly became the fastest selling consumer electronics product of all time, selling record numbers of units in its first year of introduction. Sony, JVC, and Panasonic have all recently introduced digital camcorders.

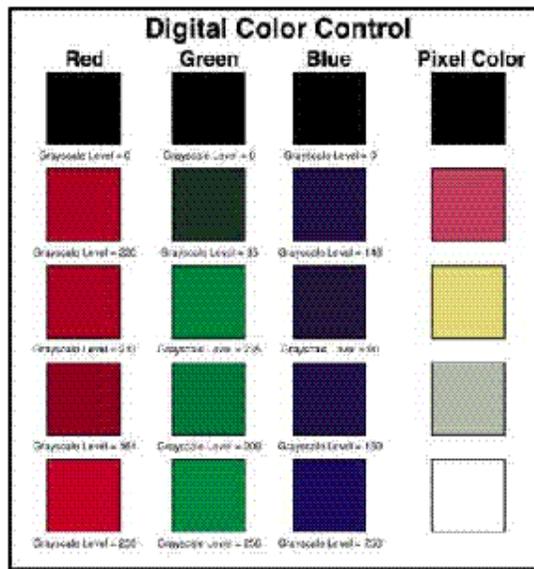
Epson, Kodak, and Apple are a few of the companies that now have digital cameras on the market. The digital versatile disc (DVD), a widely anticipated new storage medium, will feature full-length films with better than laser disc video quality by placing up to 17 gigabytes of information on a single disc. Today we have the ability to capture, edit, broadcast, and receive digital information, only to have it converted to an analog signal just before it is displayed. DLP has the ability to complete the final link to a digital video infrastructure as well as to provide a platform on which to develop a digital visual communications environment. Each time a signal is converted from digital to analog (D/A) or analog to digital (A/D), signal noise enters the data path. Fewer conversions translates to lower noise and leads to

lower cost as the number of A/D and D/A converters decreases. DLP offers a scalable projection solution for displaying a digital signal, thus completing an all-digital infrastructure (*figure shown below*).



The video infrastructure. DLP offers the final link to a complete digital video infrastructure.

Another digital advantage is DLP's accurate reproduction of gray scale and color levels. And because each video or graphics frame is generated by a digital, 8- to 10-bits-per-color gray scale, the exact digital picture can be recreated time and time again. For example, an 8-bits-per-color gray scale gives 256 different shades of each of the primary colors, which allows for 256^3 , or 16.7 million, different color combinations that can be digitally created (*Figure shown below*).



DLP can generate digital gray scale and color levels. Assuming 8 bits per color, 16.7 million digitally created color combinations are possible. Above are several combinations of different gray scale levels for each of the primary colors and the resultant digitally created pixel colors.

2. The Reflective Advantage

Because the DMD is a reflective device, it has a light efficiency of greater than 60%, making DLP systems more efficient than LCD projection displays. This efficiency is the product of reflectivity, fill factor, diffraction efficiency, and actual mirror "on" time.

LCDs are polarization-dependent, so one of the polarized light components is not used. This means that 50% of

the lamp light never even gets to the LCD because it is filtered out by a polarizer. Other light is blocked by the transistors, gate, and source lines in the LCD cell. In addition to these light losses, the liquid crystal material itself absorbs a portion of the light. The result is that only a small amount of the incident light is transmitted through the LCD panel and onto the screen. Recently, LCDs have experienced advances in apertures and light transmission, but their performance is still limited because of their dependence on polarized light.

3. Seamless Picture Advantage

The square mirrors on DMDs are $16 \mu\text{m}^2$, separated by $1 \mu\text{m}$ gaps, giving a fill factor of up to 90%. In other words, 90% of the pixel/mirror area can actively reflect light to create a projected image. Pixel size and gap uniformity are maintained over the entire array and are independent of resolution. LCDs have, at best, a 70% fill factor. The higher DMD fill factor gives a higher perceived resolution, and this, combined with the progressive scanning, creates a projected image that is much more natural and lifelike than conventional projection displays (*Figure 18*), (*Figure 19a*), (*Figure 19b*).



Fig.18

Photograph used to demonstrate the DLP advantage. This digitized photograph of a parrot was used to demonstrate the seamless, filmlike DLP picture advantage detailed in Figures 19a and b. A leading video graphics adapter (VGA) LCD projector was used to project the image of the parrot shown in *Figure 18*. In *Figure 19a*, the pixelated, screen-door effect common to LCD projectors can easily be seen.

The same image of the parrot was projected using a DLP projector and is displayed in *Figure 19b*. Because of the high fill factor of DLP, the screen-door effect is gone. What is seen is a digitally projected image made up of square pixels of information. With DLP, the human eye sees more visual information and perceives higher resolution, although, as demonstrated, the actual resolution shown in both projected images is the same. As the photographs illustrate, DLP offers compellingly superior picture quality.

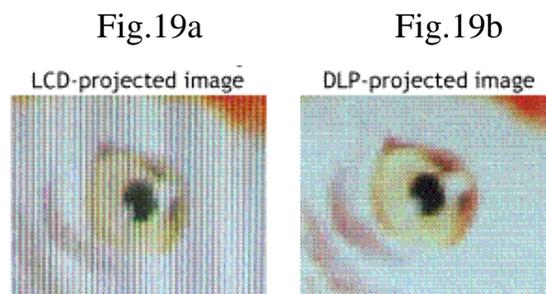


Figure 19. Actual close-up photographs of both (a) an LCD-projected image and (b) a DLP-projected image. A three-panel polysilicon VGA resolution LCD projector (a) and a one-chip VGA resolution DLP projector (b) both project the photograph of

the parrot shown in Figure 18. Both the LCD and DLP photos were taken under the same conditions, with each projector being optimized for focus, brightness, and color. Note the high level of pixelation in the LCD image in contrast to the seamless DLP image. DLP offers superior picture quality because the DMD mirror pixels are separated by only 1 μ thus eliminating pixelation.

BENEFITS

1. Clarity- As it is already explained, the DLP system provides high clarity images due to its improved digital technology.

2. Better Resolution-As the mirrors are very closely packed to give high fill factor of 90%. This high fill factor gives a higher perceived resolution which results in much more natural and lifelike projected image.

3. Maximum brightness-At high luminous flux densities (lumens/cm²), optical absorption creates heating effects. Excessive temperature can cause degradation of performance for both LCDs and DMDs. In the case of LCDs, excessive heating causes degradation of the polarizers. Furthermore, without adequate cooling of the LCD panel, the temperature of the LCD material can rise above its clearing temperature T_c . This renders the LCD material useless for polarization rotation and the display fails. For transmissive AM-LCD panels, a heatsink cannot be attached to the substrate, so forced air cooling must be relied upon. Larger transmissive panels mitigate this problem. Currently, AM-LCD projectors having 3000-lumen outputs use 5.8×5.8 in. panels.

Excessive temperatures can also affect the long-term reliability of the DMD by accelerating hinge deformation (metal

creep) that can occur under high-duty-factor operation of the mirror. Special hinge alloys have been developed to minimize this deformation and guarantee reliable operation. High duty factors occur when the mirror is operated in one direction for a much greater part of the time, on average, than in the other direction. For example, 95/5 duty factor operation means that a mirror is 95% of the time at one rotation angle (e.g., -10 degrees) and 5% of the time at the other rotation angle (e.g., +10 degrees). This situation would correspond to DMD operation with a video source having a temporal average brightness of 5% (or 95%) of the peak brightness. Although these extreme temporal averages are unlikely to occur for extended periods of time, 95/5 duty factor is chosen as a worst case reliability test condition for hinge deformation. With current hinge metal alloys, long-term, reliable DMD operation at the 95/5 duty factor is assured, provided the operating temperature of the hinge is limited to $<65^{\circ}\text{C}$.

For high-brightness applications, the mirrors can absorb enough energy to raise the hinge temperature above 65°C unless active cooling is applied to the package. Because the DMD is reflective and built on a single-crystal silicon (X-silicon) backplane, the absorbed heat can be efficiently extracted by connecting a thermoelectric cooler (TEC) to the backside of the DMD package. In *Figure 15*, one of the DMD package assemblies with the thermoelectric cooler is visible. The DMD package contains a "thermal via" to provide a low-thermal-impedance path between the DMD chip and the TEC. A thermal model predicts that for a three-chip SXGA projector producing 10,000

screen lumens, the hinge temperature can be held to $<65^{\circ}\text{C}$ (with TEC cooling and an internal ambient air temperature of 55°C).

4. Brightness Uniformity-Brightness uniformity is also an important part of image quality. Uniformity represents the percentage of brightness carried throughout a projected image. A higher uniformity percentage indicates that the projector delivers brightness more evenly from center to the corners of the projected image, eliminating hot spots and distortion. DLP system has got a brightness uniformity of more than 85%.

5. Low flicker effect-Flicker is the visual artifact that can be produced in CRTs as a result of brightness decay with time. Usually in scatter scanning technique, the lines in the video frames are scanned sequentially. So at a particular instant of a time different points on the screen will have different brightness levels. This will give rise to flicker. But in DLP, all the mirror pixels are updated in parallel at the same time. This minimizes the flicker.

6. Life like color -as already seen the digital technology will give lifelike color and makes it possible to display 16.7 million different color combinations on the screen at a time.

7. Contrast ratio-contrast ratio is the difference between the lightest and the darkest portions of an image. The larger the contrast ratio, the greater the ability of a projector to show subtle color details and tolerate a room's ambient light. The inherent

contrast ratio of the DMD is determined by measuring the ratio of the light flux with all pixels turned on versus the flux with all pixels turned off. The system contrast ratio is determined by measuring the light flux ratio between bright and dark portions of a 4×4 checkerboard image according to ANSI specifications. The checkerboard measurement takes into account light scatter and reflections in the lens, which can degrade the inherent contrast ratio of the DMD.

The full on/off contrast ratio determines the dark level for scenes having a low average luminance level (e.g., outdoor night scenes) as well as the video black level. The checker-board contrast ratio is a measure of the contrast for objects in scenes containing a full range of luminance levels.

The inherent contrast ratio of the DMD is limited by light diffraction from the mirror edges, from the underlying substrate, and from the mirror via (the metallized hole in the middle of the mirror that acts as the mirror support post, as shown in *Figure 4*). Recent architectural improvements to the DMD pixels have led to improved contrast ratios.

8. Portability-Because of its very low size and weight, DLP projector system is highly portable. A projector giving an output of 2000 lumens weigh only 6.6 pounds and that giving 1000 lumens, which is called as the micro projector weighs only 2 pounds.

9. Accuracy and Stability-Current high-brightness projection displays for use in the audio/visual rental and staging business and for private and corporate use have a number of limitations. These include warm-up or stabilization time; setup time for convergence, color balance, and gamma; and, finally, the stability of the image quality once the system is operating. Maintaining stability over a wide range of environmental conditions encountered in outdoor applications is particularly difficult.

For video wall applications or other applications requiring multiple side-by-side projectors, the setup time to make the entire displays look identical is often unacceptable. Even when great care has been taken in this procedure, lack of stability makes periodic adjustments necessary.

DLP-based projection systems offer the potential of short setup time and stable, adjustment-free images. Initial stabilization time is minimal. The working is also very fast. This is because of the fact that the optical switching time of the mirror is only 2 μ s and the mechanical switching time including the time for the mirror to settle and latch is only 15 μ s. Convergence is fixed by internal alignment of the three DMDs and is stable with time and in-dependent of throw distance. Color balance, uniformity, and gamma are digitally controlled by Pulse Width Modulation and are not affected by temperature. Brightness roll off is stable (fixed by a light integrator) and can be made small to accommodate video wall applications.

DMD Reliability

Steady improvements in DMD reliability have been made. Some of these are listed below:

- An improved hinge material that reduces metal creep that can occur under high-duty-factor and high-temperature operating conditions. The hinge material is manufactured using 'thin-film' technology to get less stiff material.
- Improved packaging techniques that preserve the "lubricity" of the landing surface over a wide range of environmental conditions.
- A new architecture that incorporates spring tips at the landing tip of the yoke. These springs store energy upon landing and push the mirror away from the surface upon release. The result is greater operating margins as the yoke releases (resets) from the underlying surface. The picture of this spring structure is shown below.

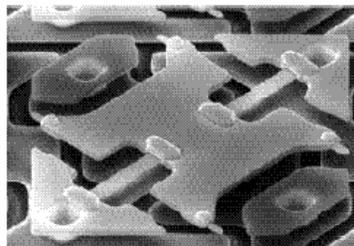


Figure 4: The addition of the 'spring tip' has further improved the reliability of the Digital Micromirror Device

- A particle reduction program that has dramatically reduced particle contamination within the DMD package.

The DMD has passed a series of tests to simulate actual DMD environmental operating conditions, including thermal shock, temperature cycling, moisture resistance, mechanical shock, vibration, and acceleration testing and has passed all of these tests. In addition to these, other tests have been conducted to determine the long-term result of repeated cycling of mirrors between the on and off states. Mirror cycling tests look for hinge fatigue (broken hinges) and failure of the mirrors to release because of increased adhesion (reset failure). To date, in accelerated tests, a lifetime of more than 765 billion cycles has been demonstrated (equivalent lifetime >76,000 hours ie, approximately 20 years of reliable operation) for a 10-bit/primary color, three-chip projector configuration).

DLP BRAND PRODUCTS

Texas Instruments is teamed with numerous projection display manufacturers spanning

- Business (conference room),
- Consumer (home theater), and
- Professional (high-brightness)

markets. DLP brand products and prototypes serving all three market segments have been demonstrated at numerous trade shows including Cedia, Comdex, CES, Infocomm, EID, IFA, JES, Photokina, Photonics West, SID, and Satis.

Currently, Digital Projection Ltd., Electrohome, and Sony are developing high-brightness DLP brand products with SVGA resolution and brightness levels ranging from 1100 lumens to 3000 lumens.

CONCLUSION

DLP brand projection displays are well-suited to high-brightness and high-resolution applications. The digital light switch is reflective and has a high fill factor that results in high optical efficiency at the pixel level and low pixelation effects in the projected image. The DMD family of chips uses a common pixel design and a monolithic CMOS-like process. These factors, taken together, mean that scaling to higher resolutions is straightforward, without loss of pixel optical efficiency.

At higher resolutions, the DLP brand projector becomes even more efficient in its use of light because of higher lamp-coupling efficiency. Because the DMD is a reflective technology, the DMD chip can be effectively cooled through the chip substrate, thus facilitating the use of high-power projection lamps without thermal degradation of the DMD. DLP brand systems are all-digital (digital video in, digital light out) that give accurate, stable reproduction of the original source material.

This single digital light display system is obviously going to be the technology of future revolutionizing the field of video display technology providing high clarity, high-resolution, high-brightness seamless images.

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ABSTRACT

Electronic projection display technologies for high brightness applications, from the initial Gretag Eidophor, an oil based projection, to solid state technology based LCD systems, are all analog devices having many disadvantages. All the products of this information age, digital cameras, digital concoders, digital satellite system, DVDs, play source material of unprecented image quality and so does the Internet-the seemingly endless forum of digitized information. The whole exercise of preserving digital video and graphic data would be pointless if it has to be converted to analog before viewing.

Texas Instruments' Digital Light Processing technology-the only available digital display technology is a revolutionary alternative. At the heart of the DLP display is the Digital Micromirror device (DMD), a semiconductor based array of fast, reflective digital light switches. Digital electronics and optics converge at DMD. Based on this DMD, DLP can form the final link to digital visual communication. In the same way the compact disc revolutionized the audio industry, DLP will revolutionize video projection.

This seminar describes the design, operation, performance and advantages of DLP based projection system for high brightness, high resolution application.

