1

Introduction

1.1 The Case for Projection

Daily life increasingly relies on electronic displays. Indeed, the information age is unimaginable without them. An electronic display is a device or system that converts an electronic signal representing video, graphic, or text information to a viewable image of this information. A display can be virtual, direct view, or projection. With a virtual display, there is no real image in space and the image information is brought to a focus only on the retina. Such displays are limited to one observer only. Direct-view displays are most familiar to the average person. The most common direct-view displays are cathode-ray tubes (CRTs) in televisions (TVs) and computer monitors. Other direct-view technologies, such as plasma displays, organic light emitting diode displays (OLEDs), and liquid crystal displays (LCDs), are starting to challenge the dominant position of the CRT in display applications. Active matrix LCD (AMLCD) computer monitors outshipped CRTs for the first time in 2003. These displays are all capable of high resolution and satisfactory luminance. However, it is difficult and expensive to make a direct-view display large enough to accommodate several viewers simultaneously.

The human eye has an angular resolution of approximately 1 minute of arc. Assuming an image is displayed at a distance of 2 meters from the viewer, the size of the display must be as large as $\sim 70''$ to fully resolve the high-definition television (HDTV) content, which is shown in 1920×1080, $\sim 0.6\,\text{mm}$, full-color pixels (see Figure 1.1). It is certainly challenging, and expensive, to make a direct-view display of this size at present.

Projection displays utilize an optical imaging system to magnify a small picture created either by conventional direct-view technologies, such as CRTs, or by modulating the light from an illumination system with a device called a light valve or panel. A projection display can be operated either in front-projection mode, where the viewer and projector are on the same side of the screen, or in rear-projection (RP) mode, where the viewer and projector are

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Polarization Engineering for LCD Projection M. G. Robinson, J. Chen and G. D. Sharp

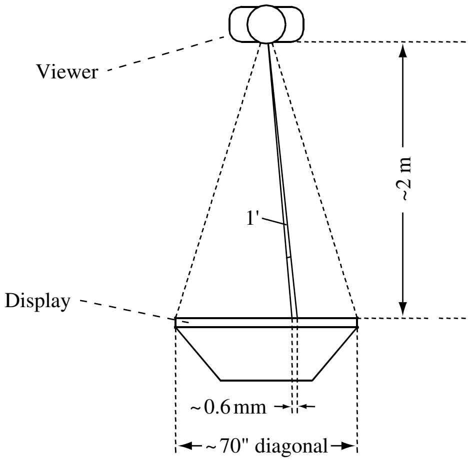


Figure 1.1 Viewing geometry for direct-view HDTV

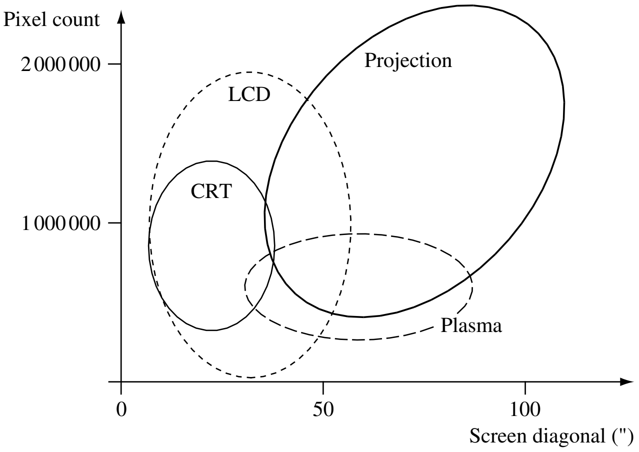


Figure 1.2 Display technologies as a function of screen size and resolution

on opposite sides of the screen. At the present time, projection systems offer the only economical solution to large, high-resolution displays. Figure 1.2 shows where projection displays figure in the display market with regard to resolution and screen size [Stupp E. H., 1999, p. 4].

1.2 History and Projection Technology Overview

1.2.1 Cinema Film

The history of projection systems begins with cinema movie projectors, which are the earliest and most familiar projection systems to the public. This type of projector is able to deliver a large, high-resolution image viewable by a large audience. The first machine patented in the United States, that showed animated pictures or movies, was a device called the "wheel of life" patented by William Lincoln in 1867 [http://inventors.about.com/library/inventors/blmotionpictures.htm]. However, the Frenchman Louis Lumiere and his brother Auguste are often credited with inventing the first motion picture camera and projector in 1895. They presented the first projected moving photographic pictures to a paying audience. The first commercially successful projector was invented by Thomas Edison in 1896. The advantage of the film projector is that it displays very high-resolution images, which no modern projection technologies have surpassed as yet. Other types of film projectors include slide projectors and overhead projectors commonly used in classrooms.

The system layout of a typical cinema projection system is shown in Figure 1.3. It consists of an illuminator (lamp), film rotation drums, a sync shutter, and a projection lens. The film frame rate is 24 frames/sec, but is illuminated through a sync shutter operated at double the frequency to avoid flicker. A 16 mm diagonal format is the typical film size used for motion pictures. Although the projection system is relatively simple and cheap, the film is not in digital format and must be physically copied for individual media content. It is therefore expensive to distribute the media and is clearly incompatible with the modern digital information age.

1.2.2 CRT-based Projection Systems

The most common projection systems are CRT based, as they dominate the middle and low-end rear-projection system market [Wolf M., 1937]. Three monochrome tubes, each optimized for luminance and beam width of a specific primary color, are imaged onto the screen. Since the path of the electron beam is relatively short, the beam spot size can be better controlled, minimizing any smearing effects. These features are required in projection systems to produce good resolution and chromaticity with high brightness. There are two configurations for CRT projectors, using either three lenses or a single lens as shown in

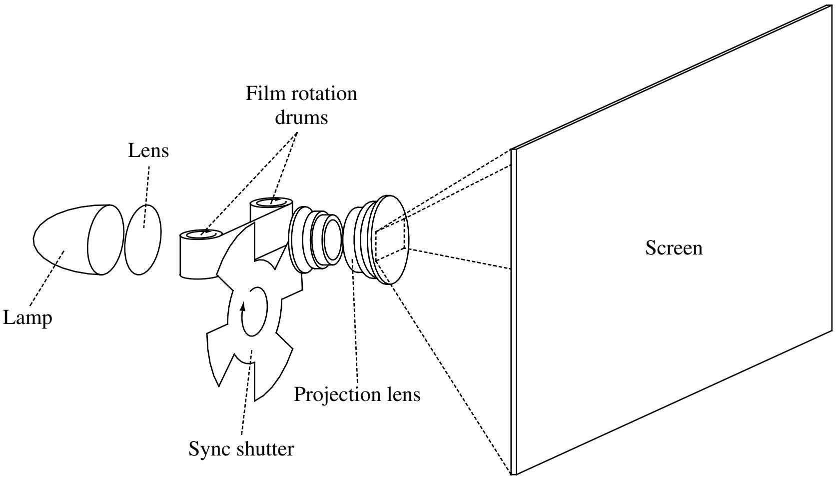


Figure 1.3 System layout of a typical cinema projection system

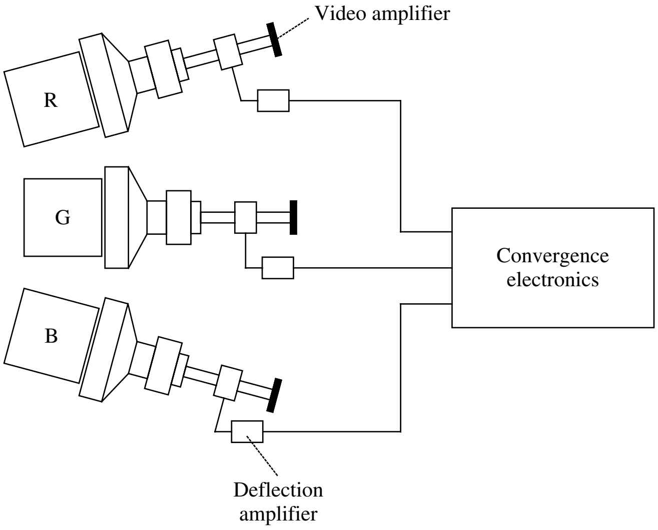


Figure 1.4 Three-lens CRT light engine. The red and blue lenses are tilted to partially correct geometrical errors

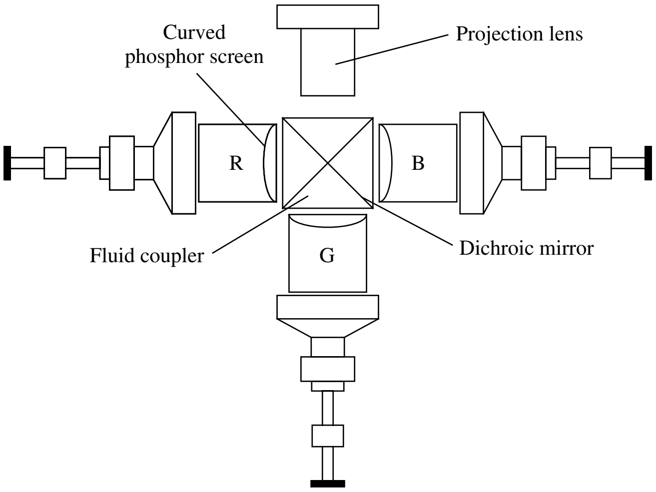


Figure 1.5 Single lens CRT light engine

Figure 1.4 and Figure 1.5 respectively. The optical coupling between the tube and projection lens is enhanced by the cooling fluid placed between the tube face front and the first optical surface of the lens. Furthermore, the tube faceplate is usually curved to improve the light collection by the lens [Stupp E. H., 1999, p. 202; Malang A. W., 1989].

Convergence of CRT projection systems is a major challenge. For good image quality, it is desirable to converge the images from three tubes to within about a half pixel. Since red and blue channels are in an off-axis arrangement in the three-lens CRT projection system, the off-axis tubes will generate a trapezoidal image (keystone distortion) [Hockenbrock R., 1982]. The angular dependence of the Fresnel reflection coefficients can cause color non-uniformity, which can be reduced by tilting the red and blue lenses. Suitable deflection circuits must also be implemented to correct for these errors.

Even though single lens CRT projectors are free from convergence errors arising from trapezoidal distortion, there are many other sources degrading convergence of CRT projectors due to optical, electrical, and magnetic issues. [George J. G., 1995]. Issues specific to single lens systems include the long back focal length (bfl) due to the dichroic combiner, and the relatively high $f_{/\#}$ required to avoid color non-uniformity stemming from the angular sensitive dichroic filter. High $f_{/\#}$ systems are typically low in brightness.

CRT projection cabinets are usually bulky. There is a trade-off between the cabinet size and image quality. A shorter focal length lens decreases the optical throw distance and allows a thin cabinet. However, it increases offset angles between tubes, which results in poor image quality due to increased electron beam deflection.

1.2.3 Schlieren Optics-based Projector

Among the earliest optical configurations employed in electronic projection systems was the schlieren optics-based projector. It was originally developed for the study of defects in lenses using dark-field optics [Fischer, F., 1940; Glenn W. E., 1958; Glenn W. E., 1979; Johannes H., 1979]. Diffracted beams can be either stopped or projected onto a screen depending on whether dark-field or bright-field optics are used. The higher contrast dark-field system is shown in Figure 1.6.

The projection panels in this system are diffractive light valves specifically based on phase gratings, which produce angular separation between the modulated and unmodulated beams. Systems can operate in either reflective or transmissive mode. The phase profile for the light valve is shown in Figure 1.7. The phase profile is flat in its non-diffracting state while imparting a spatially varying phase profile in its diffracting state. The maximum diffraction efficiency of a typical square phase profile can be achieved with (π, 0) phase modulation.

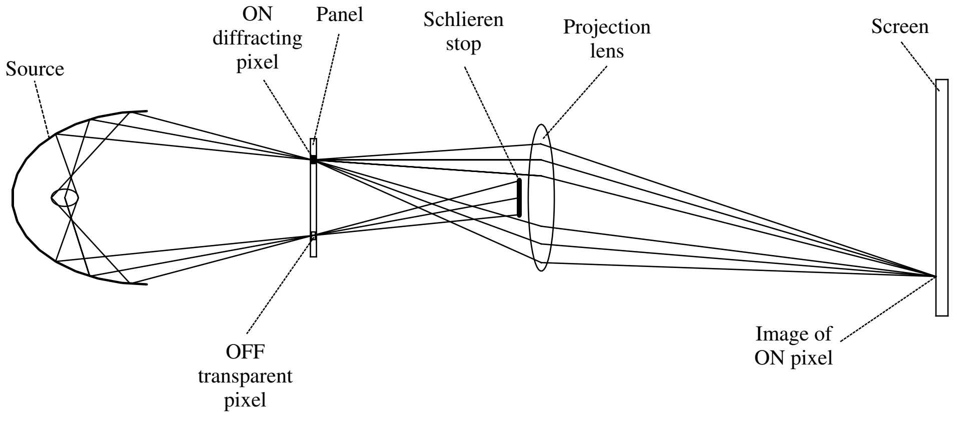


Figure 1.6 The principle of a schlieren projection system based on dark-field optics

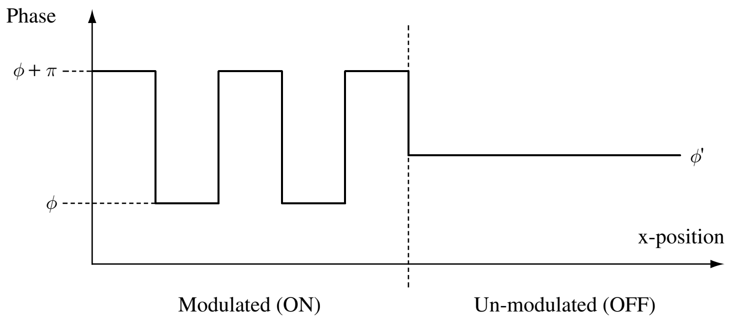


Figure 1.7 Phase profile of a diffraction grating light valve used in schlieren projection systems

Two high-output systems have been made using dark-field schlieren optics: the Ediophor® [Johannes H., 1979; William S. A., 1997] and the Talaria® [Glenn W. E., 1958] systems. Both are based on electron beam-written diffractive gratings in oil films. The Eidophor® is operated in reflective mode, while the Talaria® is operated in transmission. Eidophor® projectors use three separate modulators for the three primary colors. They are among the highest luminance projectors ever made (~9500 lumens). Talaria® is no longer in production and can be operated with one, two, or three light valves.

A Schlieren projection system based on LC diffractive light valves was proposed by Bos *et al.* [Bos P. J., 1995]. It consists of a periodic structure with alternating left- and right-handed twisted nematic (TN) LC strips (Figure 1.8). Such a structure is realized by patterning LC alignment. When the retardance (Δnd) of the LC cell satisfies the first minimum condition (see Chapter 5), the output beams from adjacent strips have the desired π phase difference. Furthermore, an advantage of this light valve is polarization insensitivity, as no polarizer is required. The gray scale can be well controlled by the applied voltage. Other diffraction structures based on LC light valves have been subsequently proposed [Yang K. H., 1998; Wang B., 2002], many of which can be operated in reflective mode.

In principle, dark-field schlieren systems can deliver high-contrast images. However, the demanding requirement of defect-free optical components results in expensive optical systems that are difficult to manufacture. Disclination lines at the boundary between two adjacent strips in LC diffractive light valves also degrade system contrast and reduce light throughput.

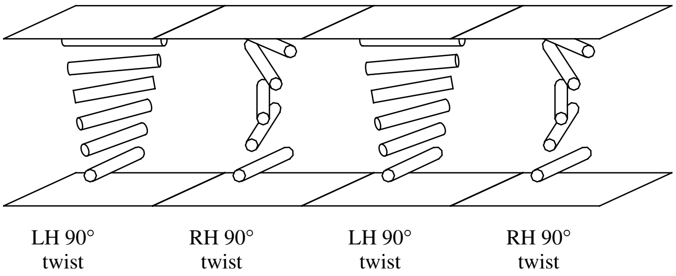


Figure 1.8 LC diffractive light valve based on periodic alternative right/left-handed TN stripes

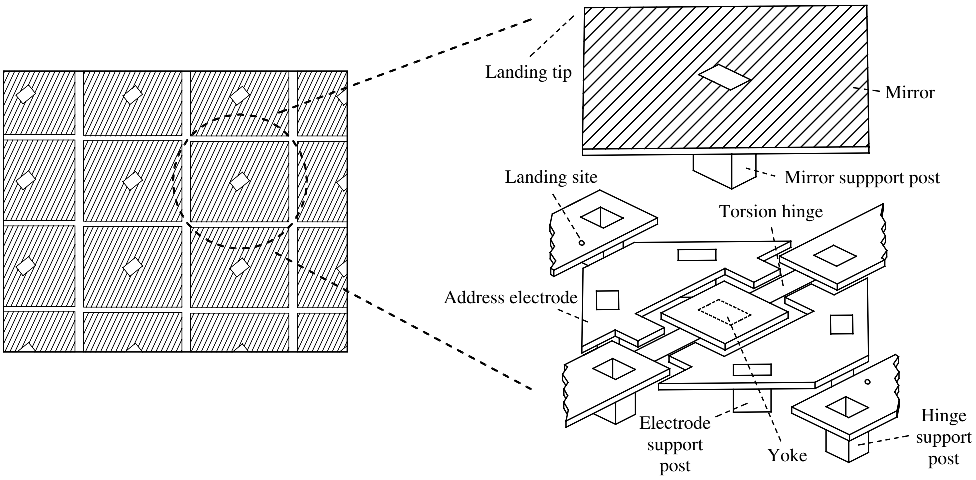
1.2.4 Microdisplay-based Projection Systems

Microdisplay-based projection is quickly overtaking CRT-based projection in the large-screen projection TV market. In the near future, microdisplay projection will displace CRT projection due to its superb image resolution, and brightness. There are three major microdisplay technologies, based on digital micromirror devices (DMDs), high-temperature polysilicon (HTPS), and liquid crystal on silicon (LCOS) technologies. Each technology has unique properties that influence the quality of the image.

1.2.4.1 Digital Micromirror Device (DMD)

The DMD was developed by Texas Instruments Inc. (TI) [Hornbeck L. J., 1983; Sampsell J. B., 1994; Hornbeck L. J. 1996] and is based on micro-electromechanical systems (MEMS) technology. Its fabrication is compatible with integrated circuit (IC) manufacturing. It consists of an array of aluminum mirrors (one per pixel), which are suspended above individual electrically addressed SRAM (Static Random Access Memory) cells by two thin metal torsion hinges attached to posts. A small tilting yoke, address electrodes, torsion hinges, and landing electrodes are created by successive photolithographic mask steps. A square mirror is fabricated that is integral to the post formed by each via. The sacrificial layers are then removed simultaneously. Figure 1.9(a) shows a photomicrograph of a DMD mirror array and its detailed structure is illustrated in Figure 1.9(b).

The working principle of the DMD is shown in Figure 1.10. Electrostatic forces are created between the mirrors and address electrodes connected to the SRAM nodes, at which positive and negative voltages (representing 1 and 0) are applied. These forces twist the mirrors one way or the other about an axis through the torsion hinges until the yoke hits a



(a) Top view

(b) Pixel detail

Figure 1.9 (a) Top view of a portion of a DMD mirror array, (b) a schematic drawing of the construction of a DMD mirror element

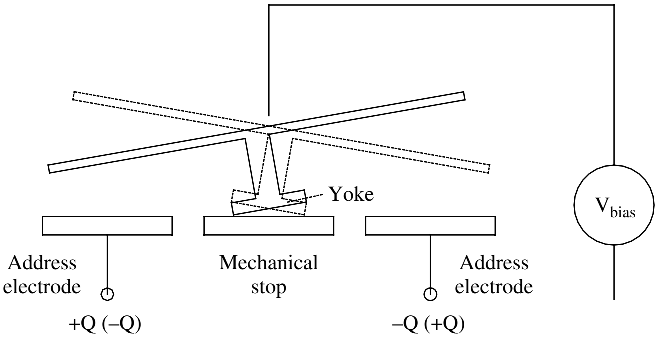


Figure 1.10 Principle of DMD operation

mechanical stop. The mirror rotation angle is typically ~10°, which determines the system $f_{/\#}$ and ultimately system brightness. TI recently developed DMD chips that operate with a tilt angle of ~12°.

The idea of a metal mirror suspended by deformable metal hinges was initially proposed by Van Raalte in 1970 [Van Raalte J. R., 1970]. However, the original device was operated in an analog mode, where the deflection was controlled by the voltage levels on the address electrodes. In practice, it is very difficult to use analog driving schemes to produce a uniform gray scale for an entire mirror array. The DMD developed by TI is bistable and its associated circuitry is entirely digital.

The layout of a projection system based on a DMD, also called digital light processing (DLP), is shown in Figure 1.11. A total internal reflection prism is used. When the DMD

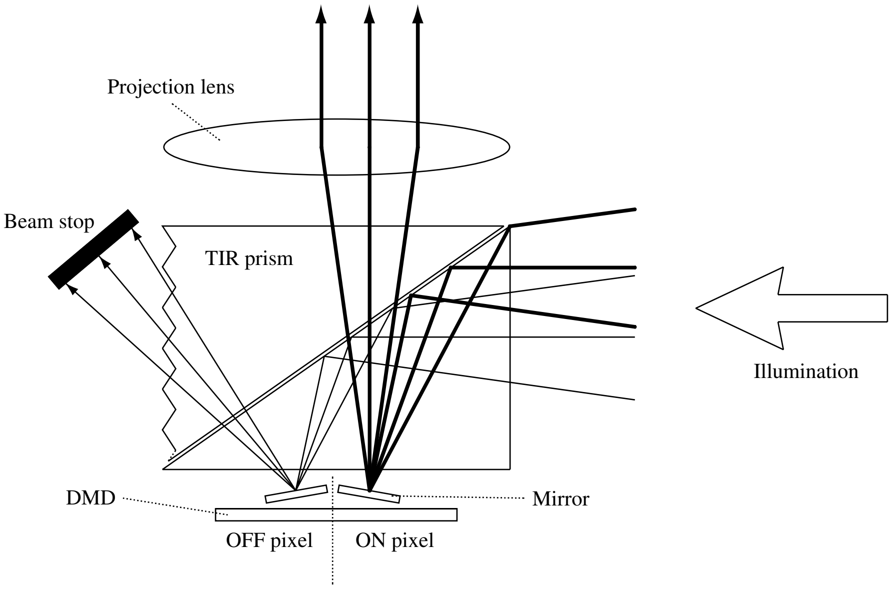


Figure 1.11 DLP projection system based on a DMD

is in the $+\theta$ state, light incident onto the mirror will be reflected into the projection lens, producing a bright state. Conversely, when the DMD is in the $-\theta$ state, the light is reflected away and is internally absorbed. The projection system is operated in a binary mode. In very expensive DLP projectors, there are three separate DMD chips, one each for each primary color. However, in DLP projectors under \$10 000, there is only one chip where full color is created by sequential R, G, and B illumination by a color wheel. Typical color wheels consist of red, green, and blue segments, although white segments can be introduced to boost brightness.

The gray scale in DLP projection systems is generated by time multiplexing enabled by the fast (~15μs) switching between the mirror ON and OFF positions. For example, a single panel system operated at a 60 Hz field rate (shown in Figure 1.12) has a color field duration of 5.56 ms. For 256 gray levels, the shortest address interval required is about 22μs, which is comparable to the DMD's switching speed. Signal correction is needed to avoid errors in the low gray-scale levels due to the finite switching speed. In a real DMD, the driving scheme uses so-called bit plane weighting, which dramatically improves manufacturability [Sampsell J. B. 1994; Tew C. 1994].

There are several unique advantages of DLP projection systems. They include:

- Small package size, a feature most important in the mobile presentation market. Since DLP light engines consist of a single chip rather than three LCD panels, DLP projectors tend to be compact. All of the current 3 lb (1.4 kg) mini-projectors on the market are DLP based.
- High contrast ratio. TI has developed a new generation of DMD, which increases the mirror tilt angle from 10° to 12° and features an absorbing coating to the substrate under the mirrors. These improvements significantly improve the DLP system contrast. Over 1000:1 system contrast is quite common for DLP systems.
- High aperture ratio. DMD operates by deflecting suspended mirrors allowing the driving circuits to reside underneath. The gap between adjacent mirrors is usually less than 1μm. Aperture ratios can therefore often exceed 90%. Visible pixel boundaries leading to the so-called 'screen door effect' are barely seen in DLP systems.

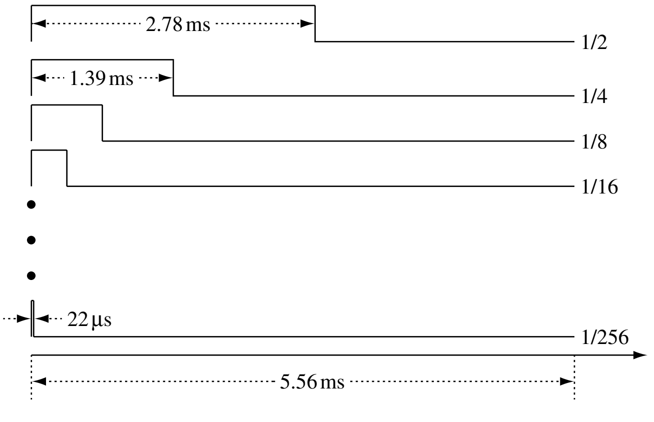


Figure 1.12 Simple time-multiplexing scheme to generate gray scale with a binary DMD

- Good reliability. Tests indicate that current DMD performance is not degraded after thousands of hours of operation under harsh environmental conditions [Gouglass M. R., 1995; 1996].
- Polarization independence. No loss is associated with polarizing the source.

Each technology has its own weaknesses, and DLP systems are no exception. These include:

- Manufacturing complexity. The CMOS electronics in the underlying silicon substrate consists of a six-transistor SRAM circuit per pixel, and additional auxiliary addressing electronics. This drives the price of high-resolution DMD chips.
- Color break-up—rainbow effect. DLP systems based on a single panel DMD require a spinning color wheel to achieve full color, resulting in a visible artifact known as color break-up, or the "rainbow effect." At any given instant in time, the image on the screen is red, green, or blue, and the technology relies upon the relatively slow response of the human visual system for the perception of full color. Unfortunately, a proportion of people in the population are sensitive to color break-up, resulting in eyestrain or even headaches. TI and DLP vendors have made progress to address this issue, such as increasing field rates from 180 Hz (1×) to 360 Hz (2×). Today, many DLP projectors being built for the home theater market incorporate a six-segment color wheel, which has two sequences of red, green, and blue, and spins at 120 Hz. Since R, G, and B are refreshed twice in every rotation, the industry refers to this as a 4× rotation speed. This further doubling of the refresh rate has again reduced the number of people who can detect color artifacts, but nevertheless it remains a problem for a number of viewers even today.
- Temporal artifacts. Even in static images the binary nature of the DMD creates the sensation of temporal modulation. In fast-moving video images that cause the eye to move rapidly, object edges can become temporally unstable and appear fuzzy. Improvements to the addressing algorithms have reduced this effect, but it can still be perceived under certain viewing conditions. Low gray-scale contouring also results from the binary addressing.
- Poor color saturation. In most single panel DLP projectors, color wheels often contain a clear (white) segment to boost brightness. Though the image appears brighter, this reduces color saturation.

1.2.4.2 High-temperature Polycrystalline Silicon (HTPS)

The structure of a polycrystalline silicon LC panel is very similar to that of an amorphous silicon active matrix LCD (AMLCD) commonly used for laptops and monitor screens. The electron/hole mobility of polycrystalline silicon is, however, much higher than that of amorphous silicon, allowing the size of a thin-film transistor (TFT) to be made much smaller. It is also possible to make on-panel driver ICs. Due to the good aperture ratio (>60% is possible), high-brightness polysilicon LC projection systems are feasible. The Sony Grand WEGA RPTV based on HTPS is currently the highest volume selling microdisplay RPTV [Shirochi Y., 2003].

There are two methods of fabricating polycrystalline silicon. The more common method used for projection light valves is HTPS [Yamamoto Y., 1995]. Low-temperature (<600°C) polycrystalline silicon (LTPS) on glass is possible through either furnace or laser annealing.

However, the leakage currents are higher in LTPS than in HTPS. HTPS is fabricated with processes requiring temperatures in excess of 1000°C [Morozumi S., 1984]. Therefore, fused silica substrates must be used. HTPS panels offer extremely high performance in terms of degree of miniaturization, high definition, response speed, and reliability.

Almost all HTPS active matrix light valves are transmissive and are based on the 90° TN mode (see Chapters 5 and 9 for further details). The cross-section of such a device is shown in Figure 1.13. The device has a self-aligned gate to minimize parasitic capacitance, which causes DC offset of the pixel voltage relative to the signal voltage, resulting in image sticking. The active matrix structures, such as the row and column metal lines, TFT, and storage capacitor, must be covered by an opaque material (the black matrix) to avoid undesirable optical effects (ITO = Indium Tin Oxide). For instance, direct light exposure of the TFT will cause current leakage. The black mask also hides the low-contrast regions created by the disclination lines from edge fringe fields. Since the total area of the hidden structures behind the black matrix is nearly independent of pixel pitch, the aperture ratio is dramatically reduced as the display resolution increases (see Chapter 9).

All commercially available HTPS projection systems are operated in three-panel mode, due to the slow LC response time of the transmissive TN mode. Architecturally, like the DLP system, they have become standardized. The incident white light is split into three primary colors by dichroic filters. Each primary color passes through an HTPS panel sandwiched between two sheet polarizers. The output light is spatially modulated by the voltage applied to the pixels (see Chapter 5). A dichroic X-cube is used to combine the three colors immediately before the projection lens (Figure 1.14). Details of the system operation are covered in Chapter 9.

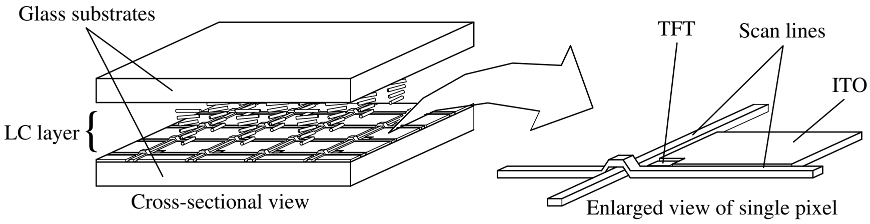


Figure 1.13 Cross-section of an HTPS light valve

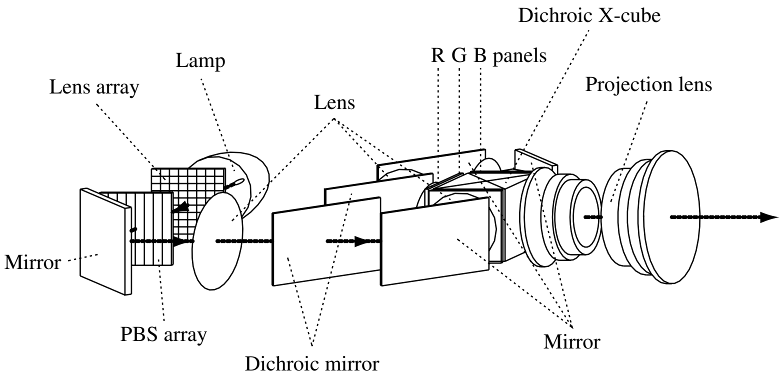


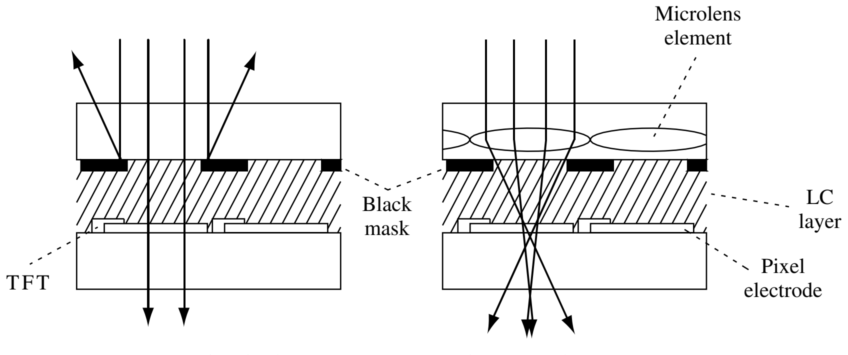
Figure 1.14 HTPS projection system

The advantages of HTPS projectors include:

- Better color saturation. Since HTPS projectors use three separate RGB panels, colors tends to be rich and vibrant.
- Sharper image. LCDs deliver a somewhat sharper image than equivalent resolution DLP systems, whose tilted pixels can appear blurred at the corners. The difference is more noticeable when viewing high-resolution text than with video content.
- High ANSI lumen output. Three-panel HTPS systems deliver significantly higher output than single panel DLP projectors with the same wattage lamp [Itoh Y., 1997].
- Manufacturability. HTPS is the most mature microdisplay technology. Epson alone has manufactured more than 18 millions HTPS panels to date.

The disadvantages of HTPS projectors include:

- Screen door effect. The black matrix TFT element shielding structures necessary in HTPS panels creates visible pixelation. It looks as if the image is being viewed through a screen door. Several measures have been taken to alleviate this effect. The first one is through increased pixel count. A WXGA projector has over 1 million pixels while a VGA one has only 3 00 000 pixels. Second, the inter-pixel gaps, independent of resolution, are continually being reduced in width through technological advances. A third development is the use of microlens arrays (MLAs) (Figure 1.15), developed primarily to boost efficiency [http://www.espon.com]. Fortuitously, the concentration of light through the pixel aperture acts to de-emphasize the sharp pixel edges.
- Relatively low contrast. System contrast >1000:1 with HTPS projectors is difficult, as a result of the field of view (FOV) of the TN LCD mode. Retarder-based compensation is one very effective way to improve the FOV of LCs as described in detail in Chapter 9.
- Potential lifetime issues. LC alignment layers used in HTPS light valves are organic polyimides (PIs). PI is susceptible to UV and deep blue light photochemical damage, which reduces operation lifetimes. UV filters with a long-wavelength cut-off are helpful,



(a) Conventional substrates (b) MLA substrates

Figure 1.15 Increased throughput by using MLAs in HTPS projection systems but tend to reduce the blue content of the final color imagery. The industry trend is toward UV filters with 50% transmission points between 430 and 435 nm.

1.2.4.3 Liquid Crystal on Silicon (LCOS)

In the previous sections, we have described two projection systems based on different microdisplay technologies: DLP and HTPS LCD. A new emerging technology is LCOS, which potentially has the advantages of both LCD and DLP and could surpass both technologies in final image quality.

The HTPS LCD is a transmissive technology using LC modulators, while the DLP panel is inherently a reflective display. LCOS is therefore a hybrid technology, using LC modulators on a passive mirror. Pixel brightness depends upon the polarization state from a double pass of the LC layer, which is controlled by an electric field. The field is induced by a voltage applied between the pixel mirror and a transparent conductor (see Chapters 7, 10, and 11). A cross-section of an LCOS light valve is shown in Figure 1.16. Traditional LCOS back planes provide analog addressing, but more recently full digital LCOS panels have been developed. The latter have unique advantages, such as stable and uniform gray levels, low fabrication costs, and high reliability [Shimizu S., 2004].

In three-panel LCOS projection systems, each panel separately modulates red, green, and blue light. The first three-panel projection system based on LCOS was developed by IBM [IBM, 1998] and used a Philips color prism to separate and recombine colored beams (Figure 1.17). While improvements were made to the performance of the Philips color prism [Greenberg M. R., 2000], it is difficult to maintain the state of polarization adequately in a dichroic prism, resulting in poor system contrast. As an alternative, off-axis systems were developed [Bone M. F., 1998; 2000], in which the incident and reflective beams do not counter-propagate (Figure 1.18). Sheet polarizers can be used instead of polarizing beam splitters (PBSs) to pre-polarize the incident beam and separately analyze the reflected

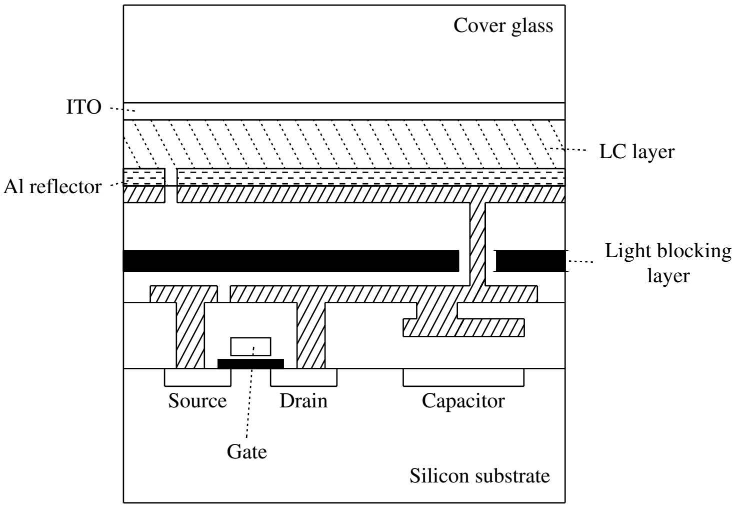


Figure 1.16 Cross-section of LCOS light valve

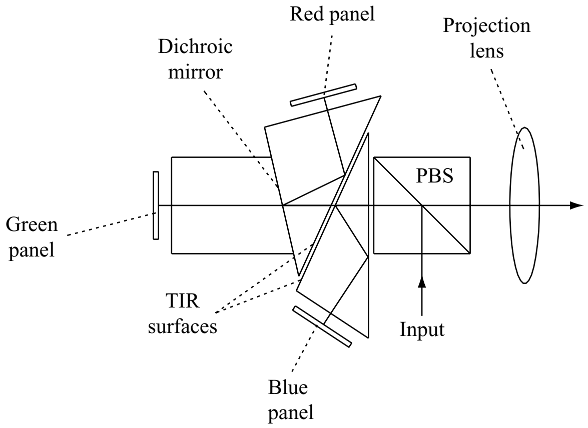


Figure 1.17 LCOS projection system based on the Philips color prism

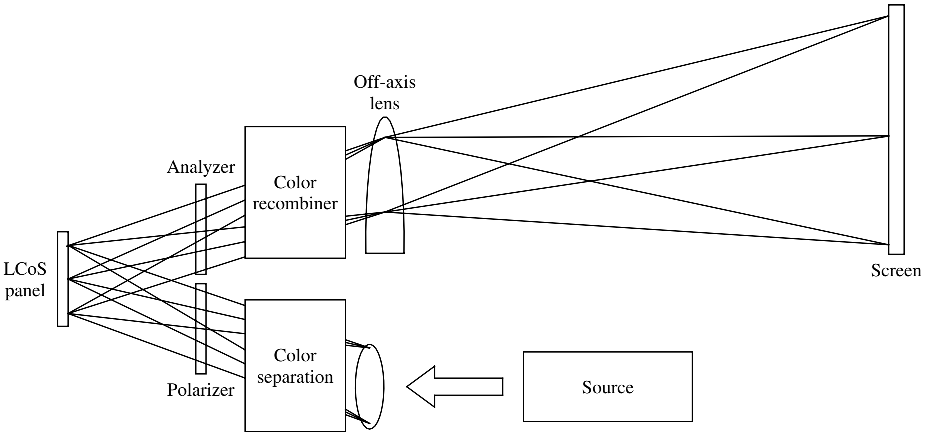


Figure 1.18 Off-axis LCOS projection system

light. With off-axis designs, however, the panel convergence and projection lens design are difficult.

After many years of development, the surviving color management architectures fall into two categories. The first is based on three PBSs with a combining X-cube (3 × PBS/X-cube), which is an extension of the HTPS LCD projection system. The PBSs can be of the conventional MacNeille type [Melcher R. L., 1998], the 3M reflective type, [Bruzzone C. L., 2003; 2004], or the wire grid type [Gardner E., 2003; Pentico C., 2003; Kurtz A. K., 2004] (Figure 1.19). The second group of LCOS projectors use retarder stacks with MacNeille PBSs, which combine the polarizing/analyzing functions with the splitting/recombining of color [Robinson M., 2000; Sharp G., 2002]. This technology is capable of very compact color management systems. The ColorQuad™ is one of many LCOS projection architectures based on this approach (Figure 1.20).

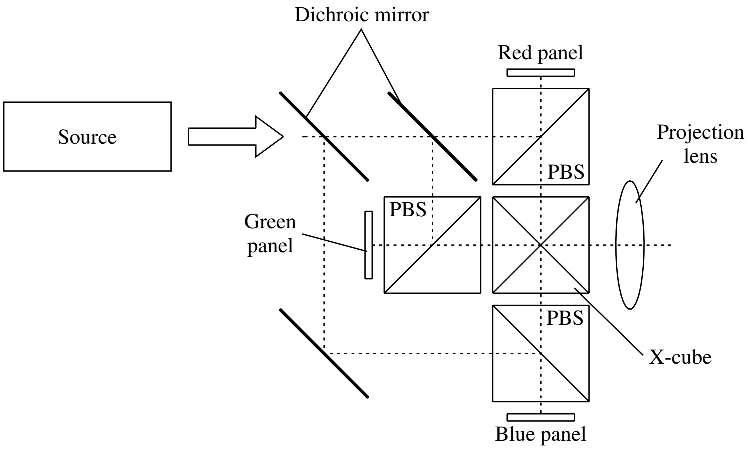


Figure 1.19 The 3× PBS/X-cube LCOS projection system

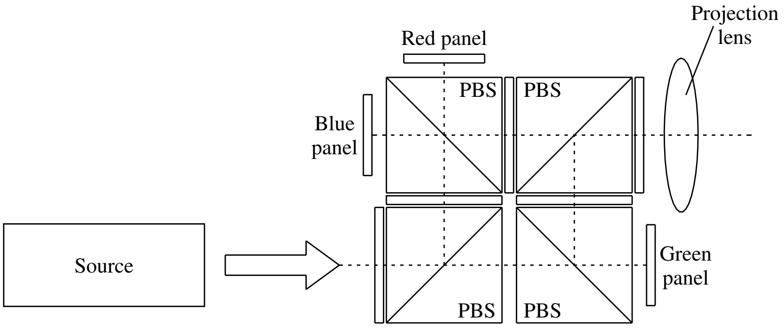


Figure 1.20 LCOS projection system based on the ColorQuad™

The merits of LCOS projection systems include:

- IC compatibility. The LCOS electronic substrate (back plane) is compatible with the standard silicon technology, allowing additional driving circuitry to be integrated into the back-plane design.
- Cost effectiveness for high resolution. LCOS is much more amenable to higher resolutions than HTPS and DLP. Due to standard silicon processes, it is relatively easy to scale up device resolution without suffering loss in manufacturing yield. LCOS can achieve HD resolution (1920 × 1080) in a 0.7″ panel and 1280 × 720 in a 0.5″ panel, which no other technology to date has accomplished.
- No screen door effect. This is due to high resolution and high fill factor (i.e., minimal space between pixels). Pixelation from an LCOS projection system is barely visible.
- Smooth picture. The pixel edges in LCOS tend to be smoother compared to the sharp edges of the micromirrors with DLP. Video images produced with this inter-pixel smoothing are more natural looking.

- High contrast. System contrasts over 2000:1 have been demonstrated with vertical-aligned LCOS panels. This contrast is comparable to the contrast of DLP systems, and better than that of HTPS systems.
- High response speed. Compared to transmissive LCD panels, the response time of LCOS panels is much shorter. Since LCOS is operated in reflective mode, the cell gap is about half that of transmissive panels, which results in a 4 × faster response time. ON/OFF periods of less than 1 ms have been achieved using submicron cell gaps. With a suitable choice of a fast LCOS mode, sequential single and two-panel LCOS projection systems are feasible (see Chapters 5, 11) [Janssen P. 1993; Shimizu J. A., 2001].

Demerits include:

- Lifetime. Long-term reliability of LCOS systems, as with HTPS, is still a concern. However, the situation is much better if inorganic SiO_x LC alignment is used. D-ILA LCOS panels have recently been quoted as having a 300 000 hour lifetime under typical operating conditions [Bleha W. P., 2003; Schimizu S., 2004].
- Color break-up. In sequential color LCOS systems a rainbow effect is observed as in single panel DLP systems.
- Complexity. An LCOS optical system is more complex than either DLP or HTPS systems. Accurate control of the state of polarization is key to making LCOS products commercially competitive, which will be the main focus of this book.

1.2.5 Other Projection Technologies

In addition to the projection systems mentioned in previous sections, there are several other technologies under development. We will list them here without going into detail. For those seeking further information about specific technologies the following references should be consulted:

- Polymer-dispersed LC (PDLC) devices. Without applied voltage, PDLC devices scatter light but appear transparent when a high voltage is applied. Systems can deliver high brightness because they are operated under unpolarized light. However, it is difficult to deliver high contrast [Fergason J. L., 1992].
- Surface-stabilized ferroelectric LCs (SSFLCs) [Clark N. A., 1980]. This technology is based on a chiral smectic C* phase. Due to its ferroelectricity, it exhibits two states depending upon the polarity of applied voltage. The response is very fast, though switching is bistable in nature. Therefore, gray scale is generated by time multiplexing as for DLP systems. Due to issues with brightness loss from DC balancing requirements, SSFLCs are rarely used in projection systems. Currently, FLCs are primarily used in digital camera viewfinders and in head-mounted displays.
- Actuated mirror array (AMA) [Um G., 1992; 1995]. This technology was developed by Aurora Systems and Daewoo and is conceptually similar to the DMD. It is based on piezoelectric or electrostrictive-mechanical angular deflection of individual mirrors within

an array. The mirror tilt angle can be continuously adjusted. However, the maximum mirror tilt angle is much smaller than that of the DMD, and systems can only work with large $f_{/\#}$s. Systems tend to have low brightness.

- Micromechanical diffractive grating light valves. Developed by Silicon Light Machines [Apte R. B., 1993], there are based on the diffraction of light by a physical grating formed on the surface of the device. Each pixel of this reflective device consists of two or more parallel reflective ribbons. Alternate ribbons can be pulled down electrostatically by approximately a quarter wavelength to create a diffractive grating, which can be used in schlieren projection systems.
- Light amplifiers. A low-intensity input optical image from a CRT is amplified for high-intensity projection on a screen [Beard T., 1973; Ledebuhr A. G., 1986]. It consists of a photoconductor layer, a light-blocking layer, a dielectric mirror, and a nematic LC cell. A bias voltage is applied to the outside electrodes. In regions where the optical writing signal is absent, the photoconductor layer has high impedance and the state of the LC is not altered. Where a writing signal is present, the impedance of the photoconductor decreases and a switching voltage appears across the LC layer. The image from the CRT is therefore reproduced as a spatial modulation pattern in the LC, which can be projected with high-intensity illumination.

1.3 Scope of the Book

This book consists of 11 chapters. Following this introductory chapter, the basics of LC projection systems are addressed in Chapter 2. The concepts of color, brightness, balanced white point, visual artifacts, and the requirements of contrast and uniformity are described in this chapter. LC projectors are based on polarized light. Controlling the state of polarization is therefore the key to making a good LC projection system. Required mathematical representations of polarized light, state of polarization calculations, and modeling techniques are presented in Chapter 3. In Chapter 4, the key projection system components, such as PBSs, retardation elements, various types of transmissive and reflective polarizers, dichroic filters, and anti-reflection (AR) coatings, are illustrated. The basic LC property and its electro-optical (EO) effect are presented in Chapter 5. Here, LC modes used in LC projectors are summarized. Retarder stacks have been widely used in LCOS color management systems and more recently in HTPS systems (RPTV) for color uniformity improvement. Chapter 6 is designated to describing their basic properties and design. Chapter 7 presents methods to optimize system contrast in LCOS projection systems and illustrates general compensation schemes to enhance head-on and off-axis contrast. Color management is a key part of projector system design, and options in color management are summarized in Chapter 8. The three-panel transmissive system is presented in Chapter 9, with emphasis initially on throughput. One weakness of HTPS projectors is system contrast. The principle of operation and methodologies for system contrast improvement complete the chapter. Three-panel LCOS architectures are not standardized as yet. Mainstream three-panel configurations and their performance comparison are covered in Chapter 10. Finally, sequential LCOS systems are gaining popularity due to the cost pressure from DLP and HTPS. Two-panel and one-panel LCOS systems are presented in Chapter 11.

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