

# **Analysis of Pico-Projection Technologies and Attempt at Design of Pico-Projection Optics**

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## ABSTRACT

A preliminary exploration of technologies used in pico-projection was carried out, and an attempt was made in the design of a lens system to produce a compact system capable of both capturing an image and projecting one. Technologies such as digital light projection (DLP), active-matrix liquid-crystal display (AMLCD), liquid-crystal on silicon (LCoS), and beam scanning were explored and their basic design aspects, performance metrics, and commercial uses listed. A projector lens system capable of image capture was also attempted, utilizing at first a camera lens, then a Cooke triplet, and finally a fisheye lens. This fisheye lens was then modified to accommodate for both projection optics as well as image capture optics, and finally a design was finalized with some error caused by lack of fields during optimization. However, because the system is locked in to its local minimum, the system cannot be easily relieved of this error.

**Keywords:** Projector, camera, hybrid, pico, mobile

## 1. INTRODUCTION

Since the first commercial use of projection in the 1600s in the form of the magic lantern to entertain crowds, projection technology has found a much more utilitarian purpose in modern society. Using candles and oil as illumination sources, magic lanterns (and by extension, projection) have been used to deliver slides since the 1800s, with Moses Holden using this type of projector to deliver his lectures between 1814 and 1815. <sup>[1]</sup>

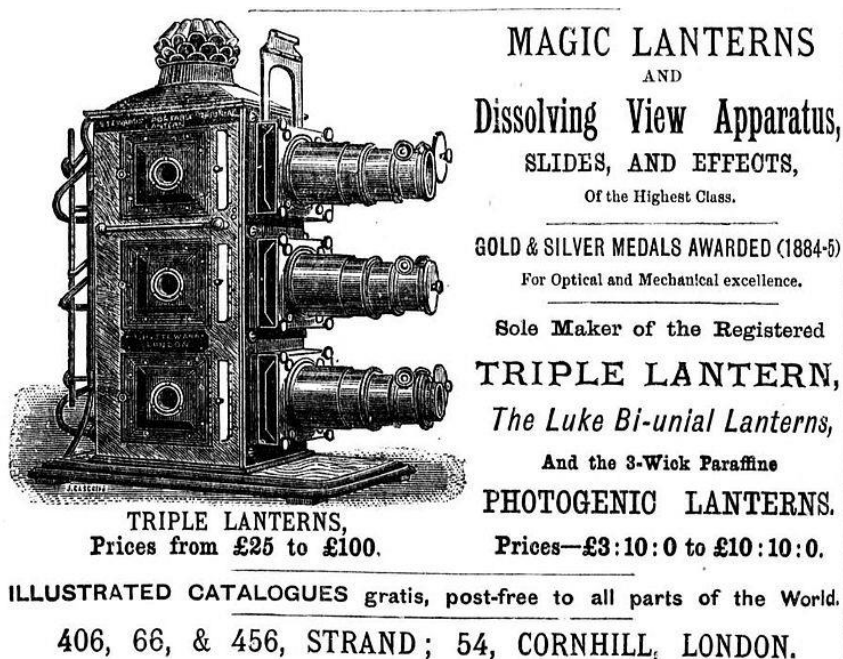


Figure 1. Magic Lantern, Late 19<sup>th</sup> Century

From the magic lantern, projection technology advanced toward the opaque projector (epidiascope). This next iteration of projection essentially used mirrors, prisms, and/or lenses to focus an image of an opaque object onto a screen. These

devices tended to require extremely bright light sources, historically fulfilled by the limelight. Two forms of these devices exist: those intended for opaque objects (episcope) and those intended for transparent objects (diascopic).<sup>[2]</sup> A predecessor of the overhead projector, this technology was popular until the mid-20<sup>th</sup> century, when it was largely replaced by the overhead projector.



Figure 2. Opaque Projector, Late 19<sup>th</sup> Century

Originally referred to as the “vertical lantern,” overhead projectors were made popular in the mid-20<sup>th</sup> century as a method to display transparent documents. Originally created by 3M after their creation of photocopying documents, an aggressive promotional campaign, involving the delivery of transparencies, the overhead projector became a staple of teaching well into the early 21<sup>st</sup> century.



Figure 3. Vertical Lantern, Late 19<sup>th</sup> Century

During the same time as the overhead projector, slide projectors were used for presentations and a form of entertainment and saw uses in industry.

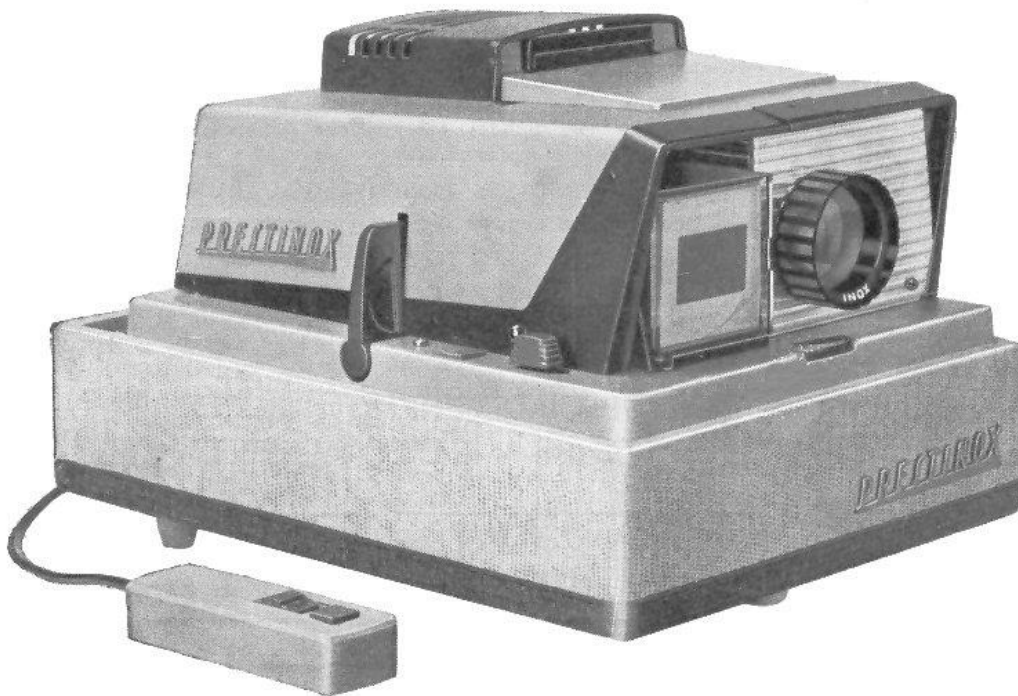


Figure 4. Slide Projector, Mid-20<sup>th</sup> Century

During the late 20<sup>th</sup> century, improvements to MEMS technology, cooling, optics, as well as computing replaced overhead and slide projectors with digital projection: a self-contained method of projection.



Figure 5. Digital Projector, 21<sup>st</sup> Century

Today, the advent of mobile devices capable of higher-level processing has forced the industry to consider digital projection of ever decreasing size. Early attempts at monetizing this new trend (dubbed “pico-projection”) brought force several issues, including the design of new projection optics as well as considering modified display technologies. Pico-projectors have been publically available since 2005. They are typically comprised of the battery, laser or LED sources, a combiner, and projection optics. They are capable of projecting onto various surfaces but have historically suffered from poor illumination in everyday circumstances. As such, they have been relatively unpopular in mainstream usage. Several attempts at producing a projector phone have been made, although none with success and less with decent image quality. An example of this technology can be found in the Samsung Galaxy Beam.



Figure 6. Samsung Galaxy Beam

These technologies will be discussed in this report, as well as an attempt to identify difficulties of designing new projection optics for pico-projection devices.

## 2. DIGITAL LIGHT PROCESSING (DLP)

In order to deviate from the logical iteration of projection as a simple scaled down version of traditional digital projectors illuminated without use of arc lamps, alternative technologies must be considered. To create projectors of minute scale, it is logical that technology be miniaturized in order to reduce size of packaging. The creation of Microelectromechanical System (MEMS) as well as its utilization in projection was explored by Texas Instruments,



and its employment in the form of DMDs has become the basis of what Texas Instruments (TI) refers to as Digital Light Processing (DLP).

## 2.1 Digital Micromirror Device (DMD)

Microelectromechanical Systems (MEMS), in its simplest term, is the ability to manufacture extremely small electronic devices. The concept of MEMS has preceded the ability to actually create MEMS, being mentioned as early as 1959 by Richard P. Feynman.<sup>[1]</sup> It is on the basis of this technology that the Digital Micromirror Device (DMD) was created: a cantilever mirror capable of operating at extremely high frequency. The existence of MEMS and its use in displays was not unknown before the invention of DMDs. Precursor display technologies to the DMD fall into three categories: elastomers, membranes, and cantilever devices produced by multiple companies as referenced below.<sup>[2]</sup>

Table 1. Display Technologies with Basis in MEMS

Type	Company
Elastomer	CBS Laboratories (1971)
	Xerox Gamma-Ruticon (1977)
Membrane	Perkin-Elmer (1968)
	RCA (1973)
	Texas Instruments (1981)
Cantilever Mirrors	Westinghouse Mirror Matrix Tube (1974)
	IBM (1977)
	Texas Instruments (1981)

The DMD itself is an array of pixels, with the most basic form being a 1:1 representation of the projected image; a 1920×1080 image would, in the most basic form, be projected by a 1920×1080 DMD. Various methods to reduce the required complexity of the system such as wobulation will be discussed later. The DMD pixel possesses a singular function: the quick and precise rotation of an aluminum mirror, around  $16\mu\text{m}^2$ , to rotate to a number of angles between  $\pm x$  degrees. For simplicity, the majority of this section will refer to the extreme angle of rotation as  $\pm 10$  degrees, as it was the first iteration of commercial DMD technology. The pixel itself consists of multiple layers in order to perform necessary functions. These layers are described as follows.

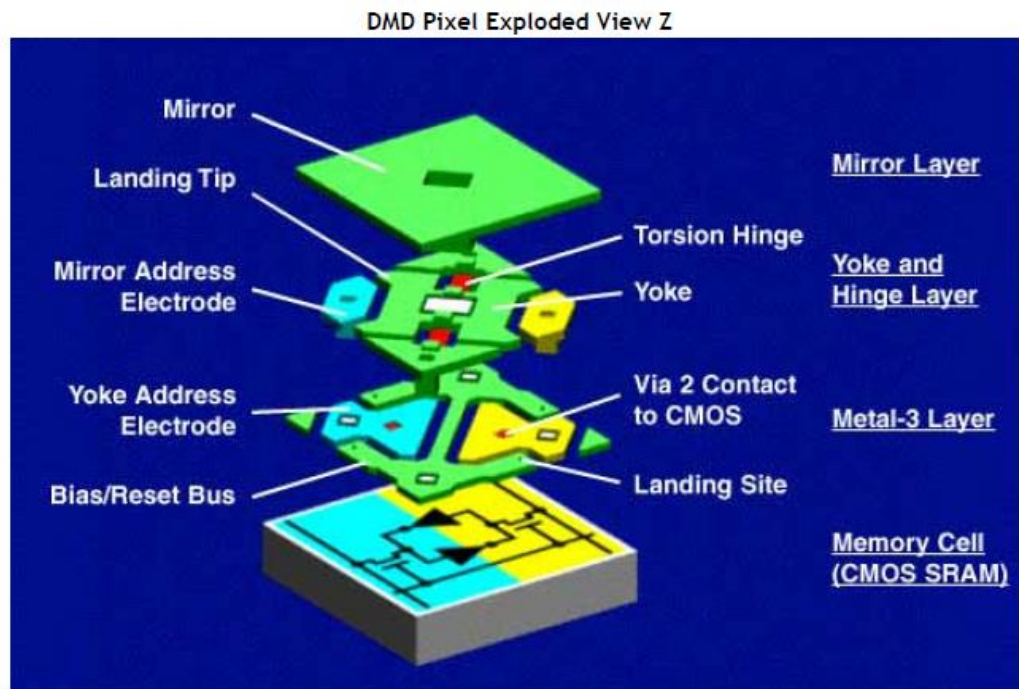


Figure 7. Exploded View: DMD Pixel (Source: TI)

As the DMD array is entirely digital in its construction the system depends on precise changes in voltage to rotate the individual pixels. The system is run with a 5V conventional CMOS device typically in an electrostatically bistable mode to minimize address voltage requirements. A bias voltage is applied to the yoke and mirror. A mirror that is flat means the bias of the system produces no net torque. So long as address voltage is zero the rotation of the system can be expressed in the form of energy as it has arrived at a stable equilibrium (local minimum), meaning that the restoring torque and the electrostatic torque are equivalent. This position could also refer to the local maximum (unstable equilibrium), but the mirror is static in either circumstance.

### Potential Energy of a Mirror as a Function of Angle and Bias (address voltage = 0)

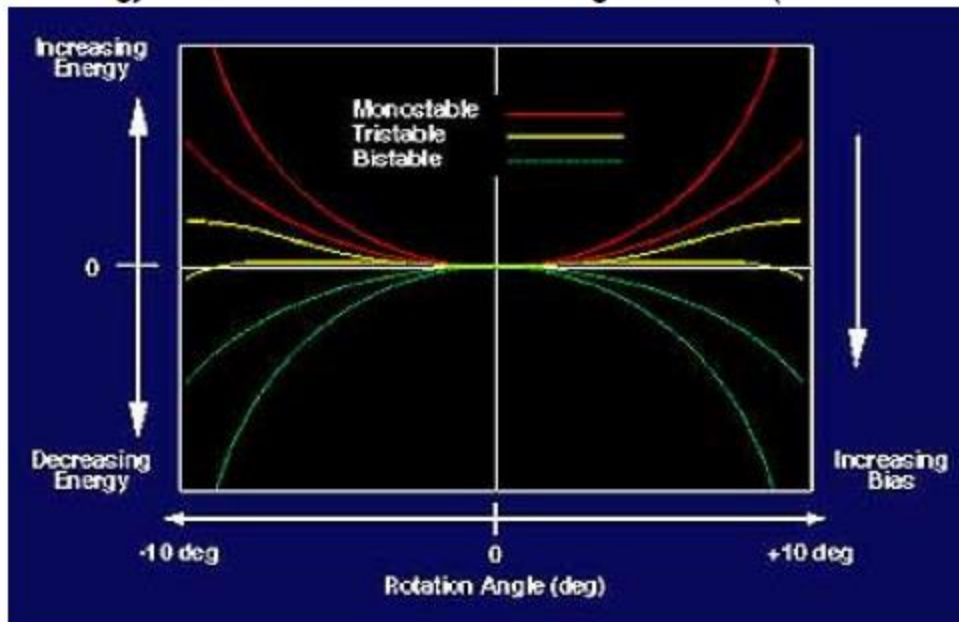


Figure 9. Potential Energy of Mirror as Function of Angle and Bias (Source:TI)

For zero bias voltage (upper red curve), the rotation of the mirror changes parabolically with angle. This implies that the stable equilibrium is at the zero angle, meaning that without a voltage the system will be in its flat state (monostable). As the bias voltage increases, potential energy begins to decrease for larger rotation as torque is produced by the bias voltage. At the point of the lower red curve, it can be seen that although no torque acts on the system with a low bias angle, the mirror begins to see torque caused by the bias voltage when the system is not in its flat state. As bias voltage increases, the system begins to form an equilibrium point at  $\pm 10$  degrees. There are now three stable points (tristable). As the bias voltage increases further, a maximum is formed at the rotation angle and it becomes easier for the system to be at any of the extreme degrees of rotation, forming a system with two stable equilibrium positions (bistable). The minimum required bias voltage to achieve the bistable condition is referred to as the bistable threshold voltage. <sup>[2]</sup>

Control of the DMD is not just limited to the bias voltage of the system, however. The system also requires control of each pixel in the DMD array. To control the pixels, each pixel is provided with an 8-bit word, each bit of which defines how long the mirror must reflect toward the desired direction (on). The first bit, or the least significant bit (LSB) defines the duration of  $1/256$ ,  $2/256$ ,  $4/256$  and so on until the most significant bit (MSB)  $256/256$  second. This control of the DMD allows control for 256 levels of brightness, representing a form of light modulation. This instruction is incorporated into the sequence of events to address the mirror to either side of the binary states. Address and reset of a pixel can be represented as follows.

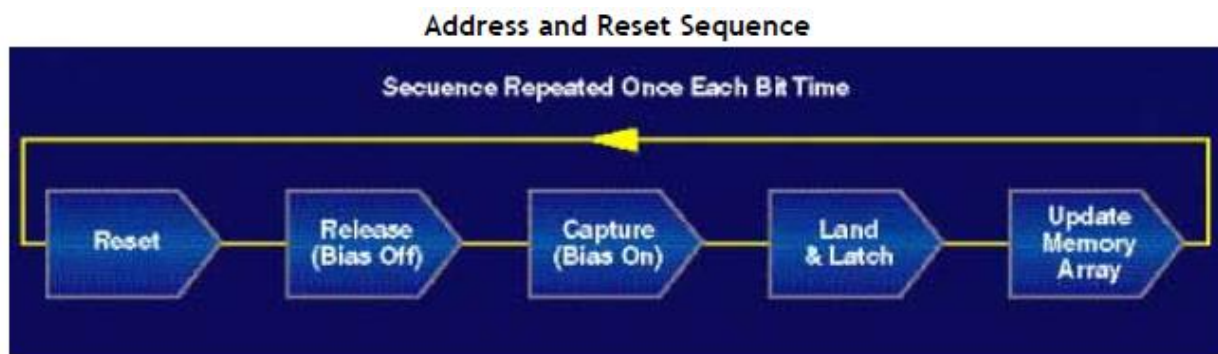


Figure 10. Address and Reset Sequence of a Pixel (Source: TI)

When the bias voltage is on, the mirror will change its stable state resulting in a tilt to  $\pm 10$  degrees. This energy is then stored in the torsion hinges, which allows the system to return to its flat state when the system cycles to its bias off state. The address sequence stages are summarized as follows.<sup>[2]</sup>

Table 2. Address and Reset Sequence Summary

Step	Purpose
Reset	Resets all mirrors in array
Release	Turns off bias to allow mirrors to begin to rotate to flat state
Capture	Turn bias on to enable mirrors to rotate to addressed states ( $\pm 10$ Degrees)
Land & Latch	Keep bias on to latch mirrors
Update Memory Array	Address SRAM array under the mirrors, one line at a time
Repeat	Repeat sequence beginning at reset step

The reset step, although seemingly unnecessary in light of simply reducing bias voltage, is necessary as the van der Waal forces between molecules requires more than the hinge restoring force to reliably reset the mirrors. A voltage pulse at resonant frequency of the mirror but well above the resonant frequency of the torsional hinges allow the energy holding the mirrors to be restored as potential energy which is converted to kinetic energy when the pulse is turned off. The torsional hinge can then return the structure to the flat state reliably.

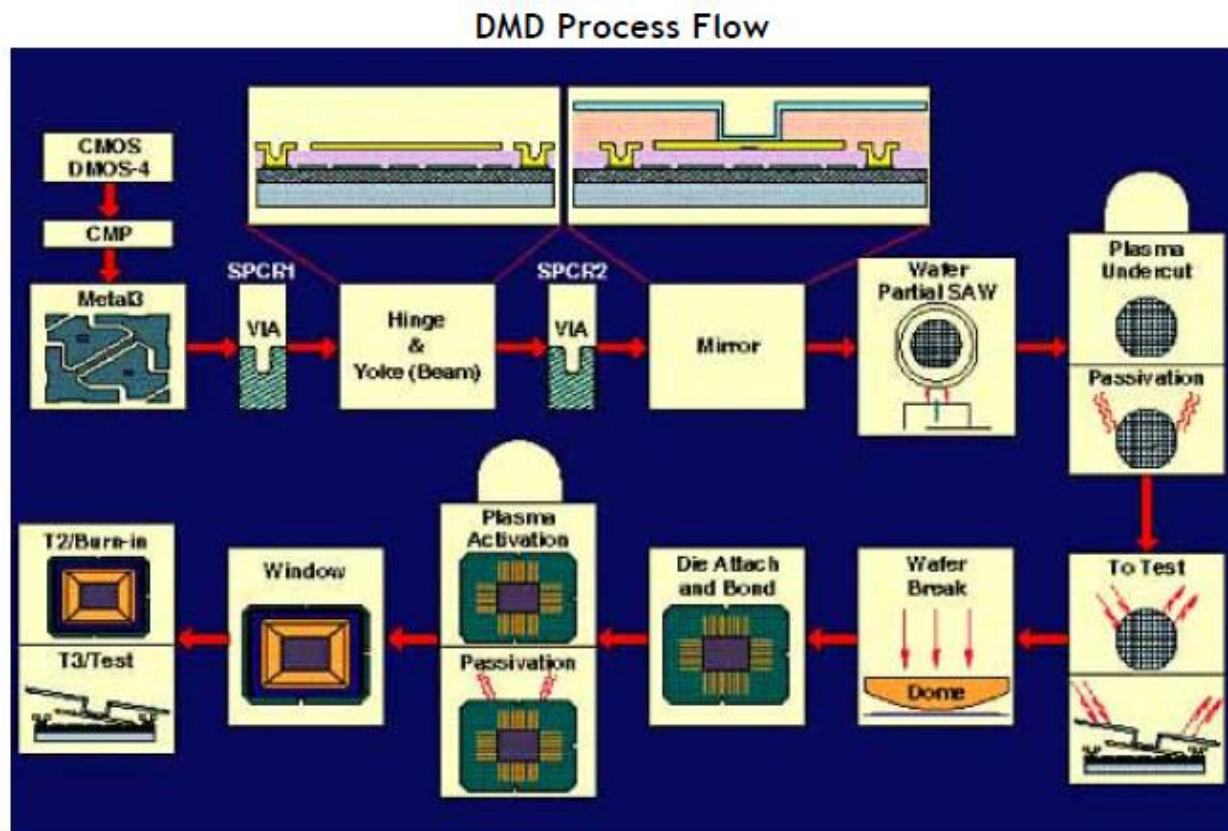


Figure 11. DMD Manufacturing Process (Source: TI)

As the DMD array is quite minute, it is manufactured using semiconductor processing techniques including sputter metal deposition, lithography, and plasma etching (to create an air gap allowing movement). Some fabrication steps differ from conventional CMOS wafer flow due to the mechanical and optical nature of the DMD. After the initial CMOS layer is created using  $0.8\mu\text{m}$  double-level metal CMOS technology, an oxide layer is deposited over Metal-2



and flattened using chemical mechanical polishing (CMP). Aluminum is then deposited to the Metal-3 layer and an organic sacrificial layer (Spacer-1) is patterned with perforated holes (similar to a pack of stamps). Support struts are also patterned after the yoke metal covers their sidewalls to support hinges and the mirror address electrodes. A metal layer (600Å) is sputter-deposited for the hinges covered with a layer of SiO<sub>2</sub> to act as an etch mask for the hinges later on. The yoke is then created using the same process as before with the same oxide mask. A plasma etch patterns the yoke and the hinge and defines the geometry of the system. This singular plasma etch has the benefit of having the hinge metal continuous everywhere under the yoke metallization layer. A second layer of organic spacer (Spacer-2) is patterned and to form support posts for the reflective surface itself and finally, an aluminum layer is used to create the mirror. To separate the layers of the DMD to allow movement, some of the organic layer is removed using the plasma etch which creates air gaps. An anti-stick layer is then added to the system and the pixel is tested for functionality. Finally, the flat array (with perforated holes) is placed on a dome head and the individual pixels are separated from each other and rearranged as desired. [2]

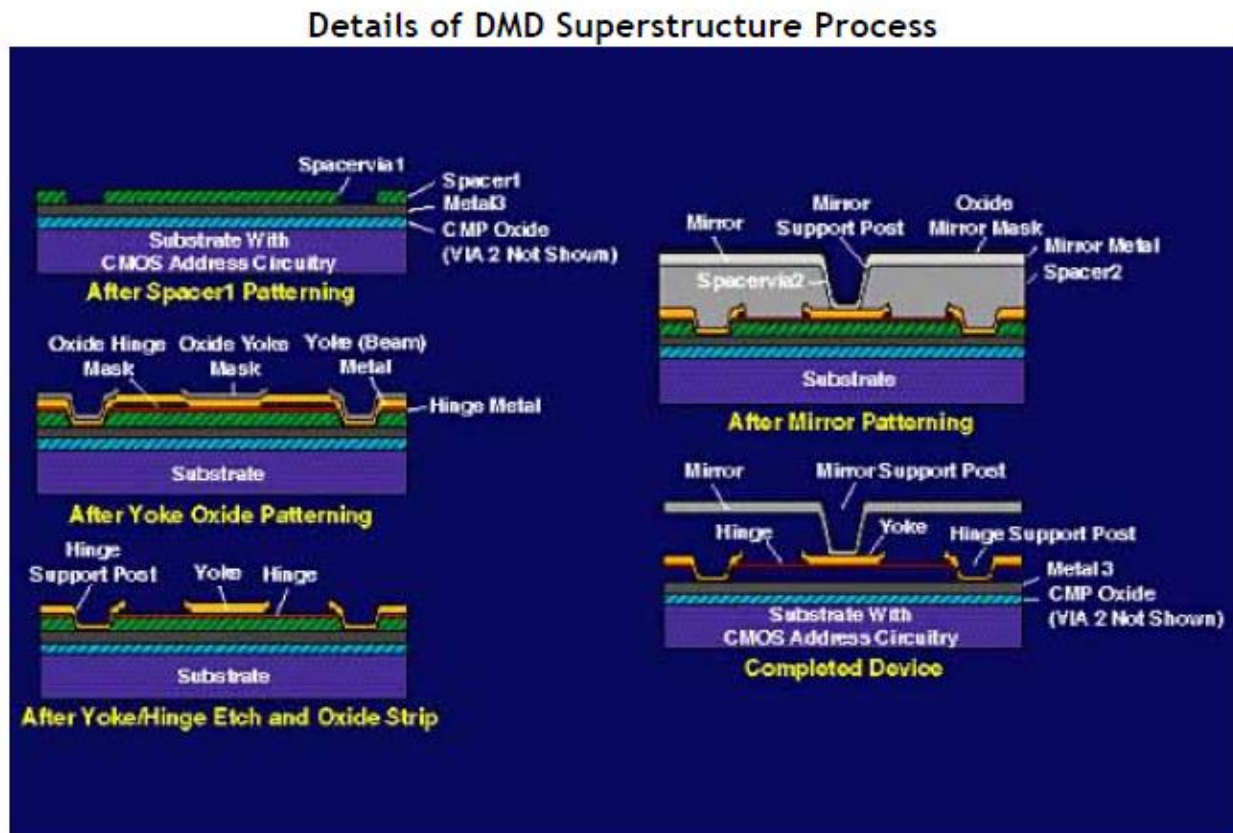


Figure 12. Details of Manufacturing Process (Source: TI)

When the pixels are assembled, a completed DMD is produced.



Figure 13. DLP Cinema DMD

## 2.2 Optical Switching Principle

As mentioned previously, control of a DMD pixel is reliant on an 8-bit word which dictates the amount of time the pixel remains “on.” This control forms the basis of the DMD optical switching principle.

### DMD Optical Switching Principle

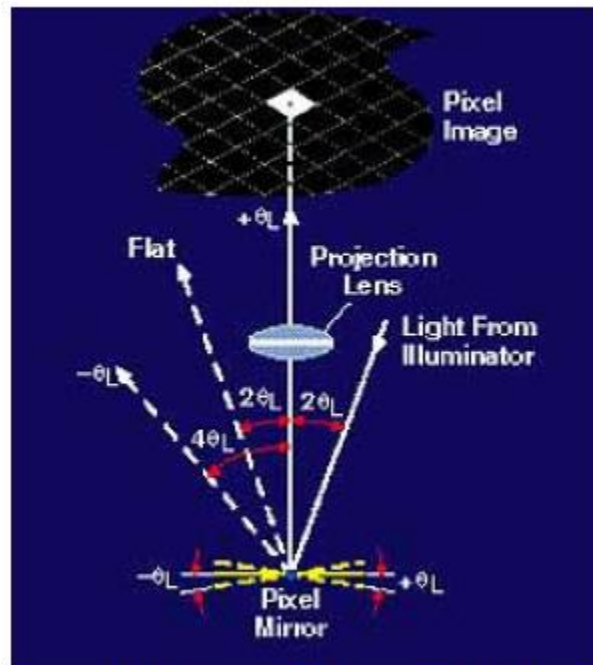


Figure 14. DMD Optical Switching Principle (Source: TI)

The method to which the system employs switching is quite straightforward. When the DMD pixel is in the flat state it behaves as a simple mirror orthogonal to the optical axis: light incident on the surface of the DMD pixel will reflect

at an angle equal but negative to angle of incidence. By placing the projection optics on the same axis as the flat state mirror and the illumination source off axis the vast majority of light will miss the pupil of the projection lens allowing nearly zero projection through the lens when the DMD pixel is in its flat state. From this point, the DMD pixel has two other states: the “on” state and the “off” state, defined by rotating the DMD pixel mirror so the reflection of the illumination source enters the projection optics versus being further removed from the pupil, respectively. Both of these states are, as previously described, well-defined as the yoke upon which the mirror is mounted physically rests on the landing spot of the mechanical stops. This design effectively forces two of the DMD pixel’s three stable states to reflect light away from the projection system, and as the “on” and “off” state are widely separated, fast projection optics (small back focal distance, BFD) can be utilized while still maintaining good photon efficiency and a high contrast ratio. This act is referred to in the industry as the “Optical Switching Principle” of DMDs.<sup>[2]</sup>

With the optical switching principle, it becomes relatively simple to force the projected image to contain different levels of brightness, usually referred to as the grey scale. By using binary bits to control the amount of time the system is “on,” it becomes possible to define shades of grey. Typically, the system utilizes 8-bits to achieve 256 levels of grey.<sup>[2]</sup> For simplicity’s sake, the figure below is an example of the time intervals using a 4-bit system, allowing for up to 16 different levels of grey.

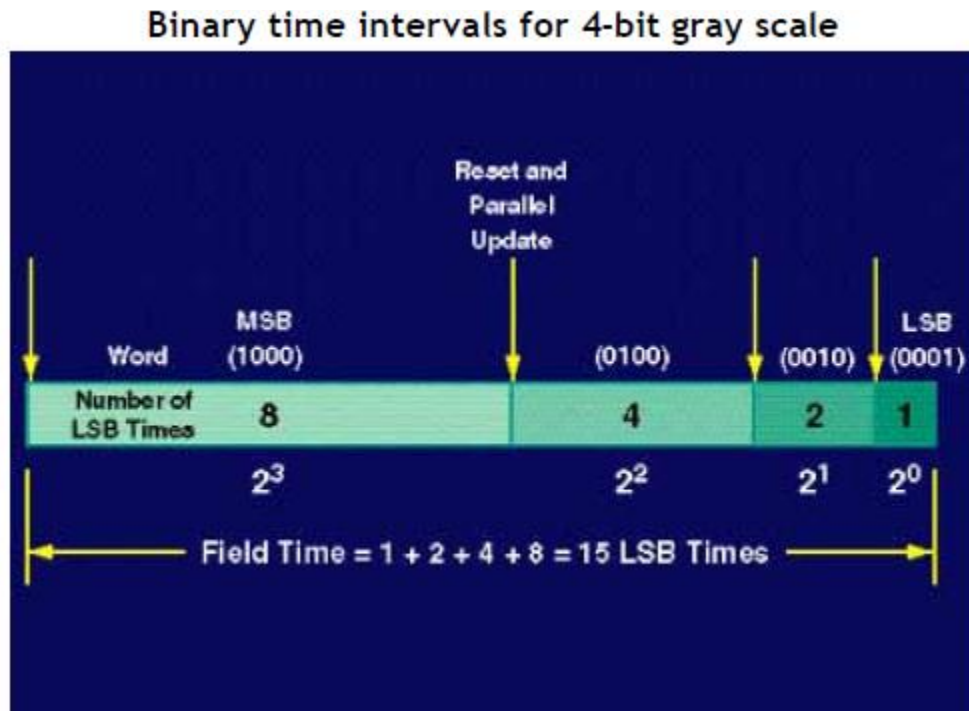


Figure 15. Example of 4-bit Control Scheme (Source: TI)

Each time a pixel receives the control signal, the MSB is interpreted first and placed into the memory a single bit at a time. Once the MSB has been interpreted and loaded into the memory, the DMD pixels are reset and the process repeats for the next bit. As the light reflected is modulated by each bit, the observer notices varying light levels as the typical 8-bit control word switches light levels at a lower time than the integration time of the eye, creating the illusion of varying colours of grey.

### Example of DMD Array of Digital Light Switches Projecting Gray Levels

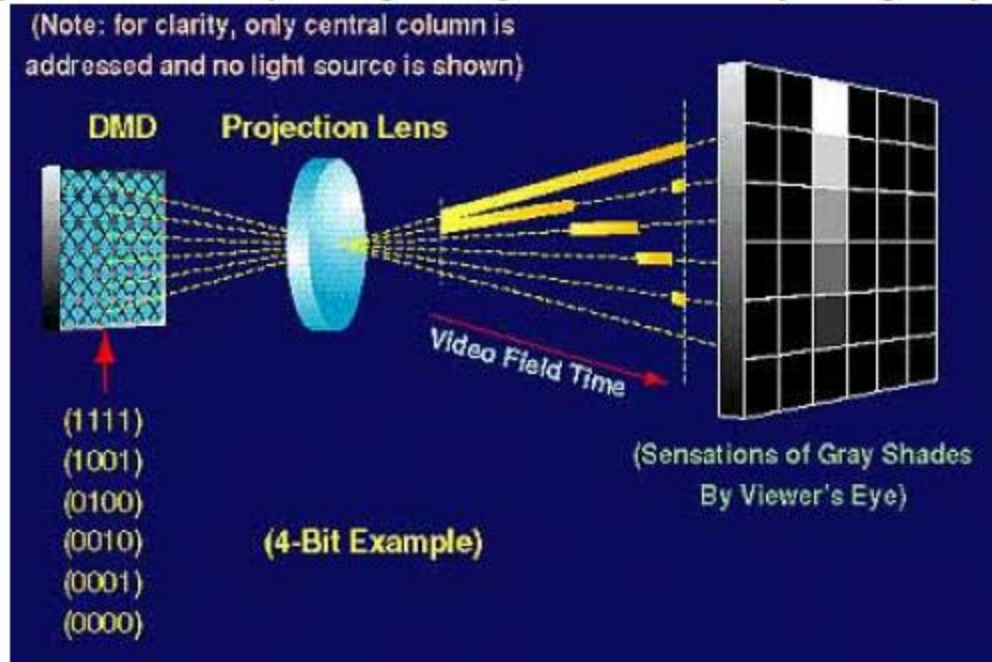


Figure 16. DMD Brightness Levels from Switching (Source: TI)

This control scheme only defines the software control for the DMD, however. In order to completely understand the DMD's capabilities to produce shades of grey, we must also consider the hardware capabilities of the DMD. In a typical DMD setup, time required by the hardware to reset is defined by two parameters: the mechanical switching time and the optical switching time. The mechanical switching time is the interval between when the reset signal is received and the mirrors have settled to a level where the SRAM can be updated. The optical switching time is the time required from when light first enters the projection system until the projection lenses are completely filled by light. In a typical system, the mechanical switching time is  $15\mu\text{s}$  and the optical switching time is  $2\mu\text{s}$  (roughly 10% of the LSB time). Considering the NTSC broadcasting standard requires each colour field to be  $16.3\text{ms}$  ( $59.94\text{ Hz}$ )<sup>[4]</sup> and the LSB represents  $1/256$  of the total time, the LSB is equal to roughly  $21\mu\text{s}$ . This low switch time allows the system to achieve the 256 levels of grey for a single-chip projector under heaviest load.

Unwanted light is typically directed to a light dump to ensure unwanted reflections do not return to the system.



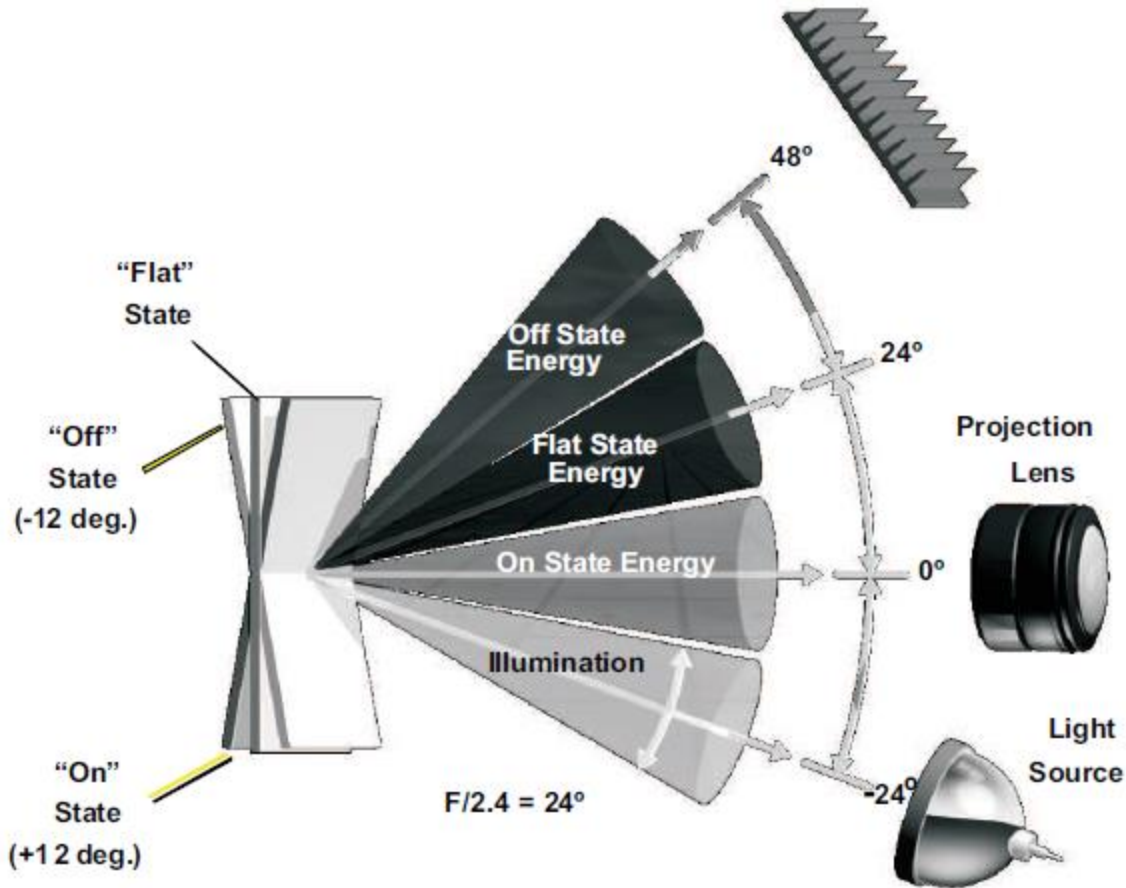


Figure 17. Example 12-Degree DMD Pixel (Source: TI)

### 2.3 DLP Projection – Single-Chip

There are three primary methods for utilizing DMDs to achieve projection. These methods call for use of either one, two, or three DMDs with trade-offs in cost, light utilization efficiency, power dissipation, weight, brightness, lamp technology and volume. The most basic form of DLP projection employs a single DMD alongside a colour-wheel to allow the DMD to be illuminated alternatively with red, green, or blue light. Because wavelengths of light are effectively filtered from this system, a light source of significant luminous efficiency is preferred (ex. metal halide arc lamp). A condenser will image light to the surface of the colour wheel, which is then collected by optics and allowed to evenly illuminate the DMD board. The system then allows the reflected light to be projected to a surface from a projection lens. Because of its comparative simplicity to the two and three-chip systems, the single-chip system is self-converged, has lower cost, and has better portability. Early single-chip systems suffered from the rainbow effect (consequence of chromatic aberration). However, with the introduction of improved optics as well as the six-segment colour wheel utilizing both additive and subtractive colours, this issue has been largely dealt with in exchange for the system having to increase frame rate from 180Hz to 360Hz. <sup>[5]</sup>

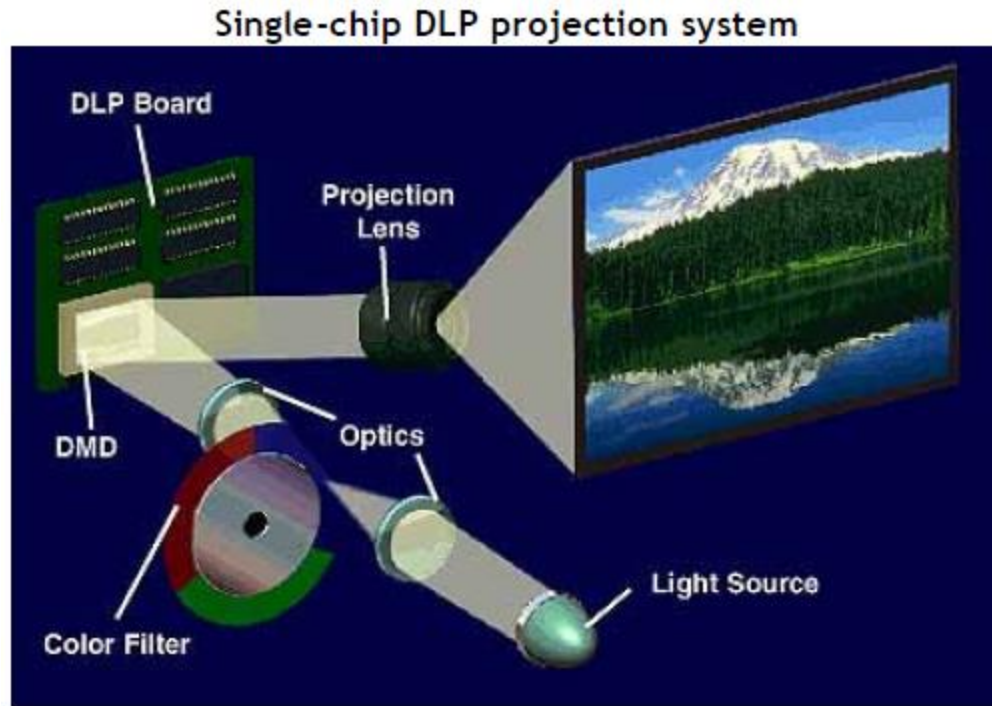


Figure 18. Single-Chip DLP Overview (Source: TI)

There are two primary methods for the single-chip projection architecture: telecentric and non-telecentric. While the typical telecentric system allows movement of the object without effect on the magnification of the system, the telecentric projection system places the exit pupil of the illuminations system (entrance pupil of the projection lens) at infinity from the device surface to essentially ensure the chief ray of every bundle is parallel upon incidence with the DMD. Because of the uniform angles of incidence, the resulting reflected fields will also produce uniform images. In a generic design, the illumination axis is separated from the projection axis by slightly greater than twice the DMD pixel maximum tilt angle. The projection axis is orthogonal to the DMD. This allows a prism and TIR to be used to place light on the DMD and reflect collimated light into the projection lens.<sup>[6]</sup>

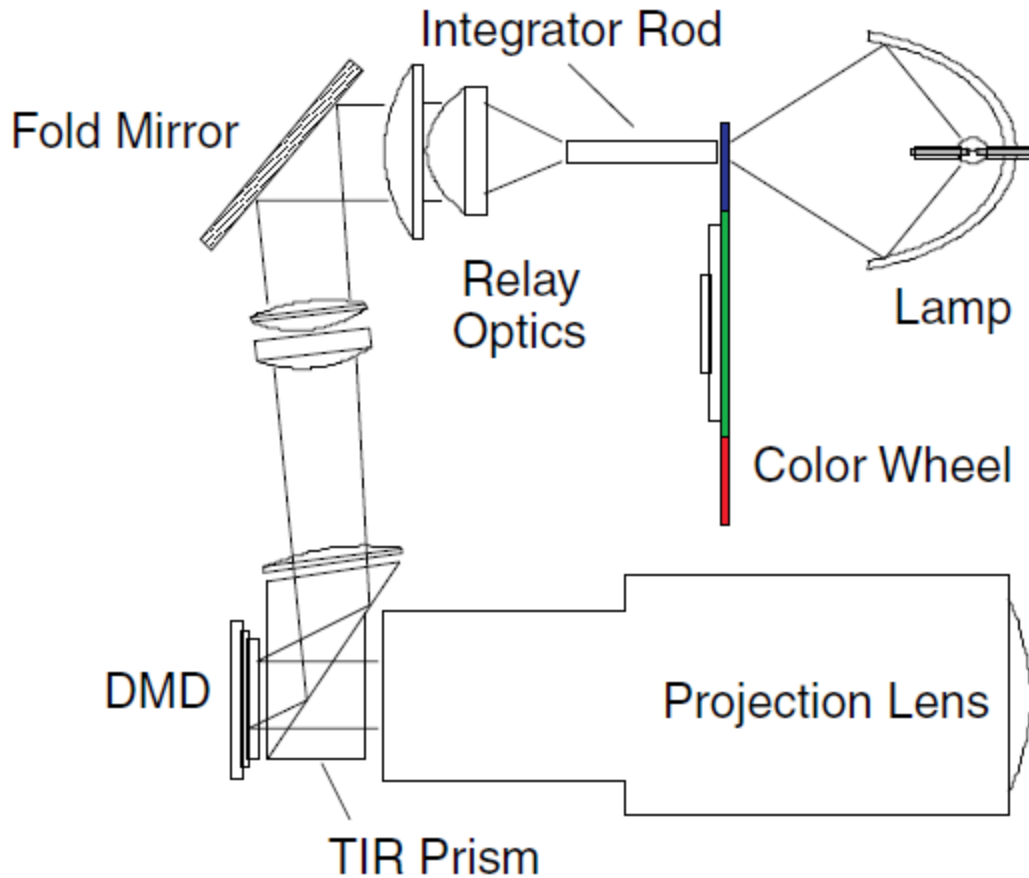


Figure 19. Generic Telecentric Optical System Components Using a TIR Prism (Source: TI)

Advantages of this design are as follows: <sup>[5]</sup>

- Uniform black levels due to uniform illumination on DMD
- Shorter OPL due to separation of illumination and projection in glass
- Shorter working distance for the projection lens for above reason
- Projection offset for keystone correction can be optimized for application to minimize field of projection lens
- Prism allows variable projection offset for flexibility in stacking applications (better brightness) and fixed-install
- Zero offset and minimal lens size can be achieved for rear-screen applications with prism design (rear screens cannot accept high angles of incidence caused by offset due to Fresnel-lens screen limitations)
- Telecentricity ensures magnification cannot change with focus
- Lower illumination angles results in less distortion of illuminating light at device, producing less overfill losses and higher efficiency
- System can be packaged such that projection-lens offset displacement will not add to package height
- Projection and illumination paths can be designed independently, allowing for multiple sources and lenses

Disadvantage of the design are as follows: <sup>[5]</sup>

- Absolute black level higher due to low illumination angle
- Prism based system is more costly, increases size of the system, and adds weight.
- High angles of incidence induces polarization effects and makes AR coating design difficult
- TIR air-gap coatings have high loss (2-3%)
- Prism can produce surface reflections that enter the projection pupil

- Lower contrast due to low illumination angle
- Due to telecentricity, elements must increase in size to compensate for field differences. This is especially problematic in adding an offset to correct keystone distortion

Non-telecentric designs for a single-chip DMD differs in that the exit pupil of the illumination device is a finite distance from the DMD. An illumination angle offset is manually added from the source. This increases contrast while providing more angular separation between the illumination path from the projection path. The duty of illuminating the DMD to allow for projection can no longer be easily fulfilled by a prism, so a field lens is added to reduce path length. The bundle, after reflection, converges on the pupil of the projection lens, producing non-uniformity while minimizing the size of the projection optics.

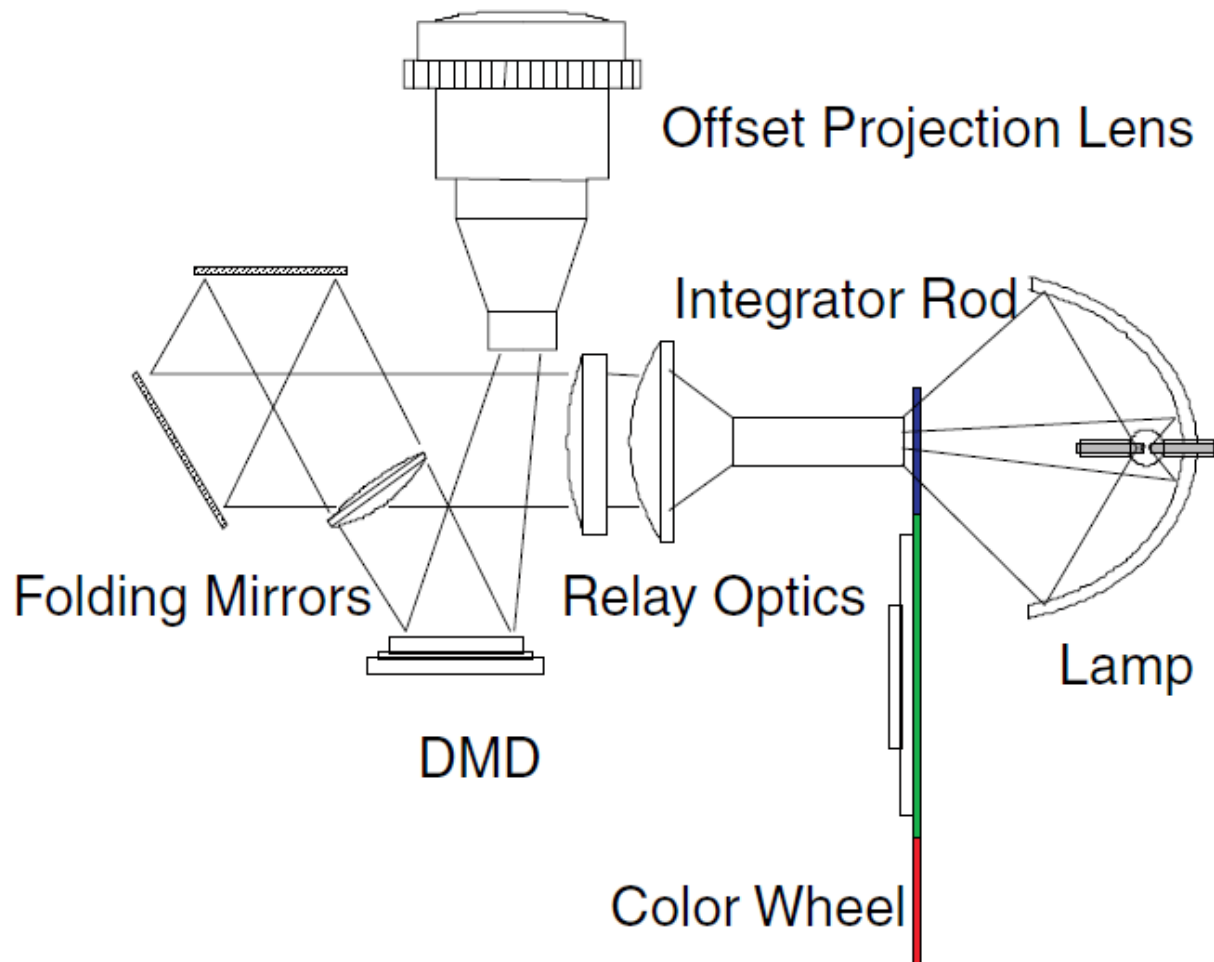


Figure 20. Generic Non-Telecentric Optical System Components Using a Field Lens (Source: TI)

Advantages of this design are as follows: <sup>[5]</sup>

- Uses fewer optical elements with fewer photon losses, increasing efficiency and decreasing cost
- Offset angle increases illuminations angles, increasing contrast
- Inherent keystone correction by placing the DMD device below the optical axis of the projection lens, allowing angular separation of illumination and projection optics
- Smaller elements in the rear of the projection lens due to finite pupil location

Disadvantage of the design are as follows: <sup>[5]</sup>

- Variation in black level
- Vertical offset requirements increase as f-number increases as the ray bundles get larger with smaller f-number
- Projection lens elements on the screen side tend to become larger and more numerous due to non-telecentric nature
- Increased distortion due to higher illumination angles, creating overfill losses
- Matching pupils at finite distance from device increases complexity of projection and relay lens design
- Not useful for rear-projection due to the offset angle
- Vignetting due to higher illumination angle requiring more clearance for aperture opening
- More off-state light trapped in device by window aperture, producing thermal effects and border artifacts
- Magnification changes with focus
- Requires large field size requirement for projection lens for high offset requirements
- Difficulty designing projection lens (number of elements, size, and shifting of elements difficult in non-telecentric applications)
- Difficult to manage stray light entering the system due to proximity of stop to rear aperture

## 2.4 DLP Projection – Two-Chip

The two-chip system is similar to the telecentric single-chip design. Dichroic prism splits illumination source and separates red from green and blue and replaces the RGB colour wheel with a one consisting of yellow and magenta. This design allows for greater light efficiency and is appropriate for longer-term use where the longevity of the illumination source is inverse to the proficiency of producing the colour red. [7]

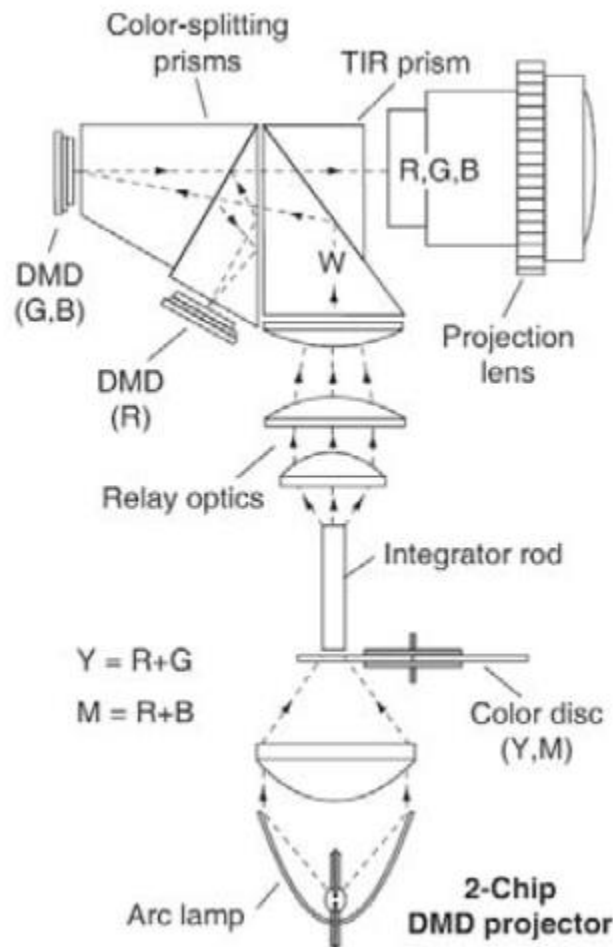


Figure 21. Two-Chip Configuration

## 2.5 DLP Projection – Three-Chip

This configuration of projection is similar to the previous two-chip configuration in that dichroic prisms are utilized, with the addition of a second dichroic prism to separate green and blue to their respective DMD chips. This setup is capable of up to 35 trillion colours due to the ability to introduce more light modulation on the projection screen.

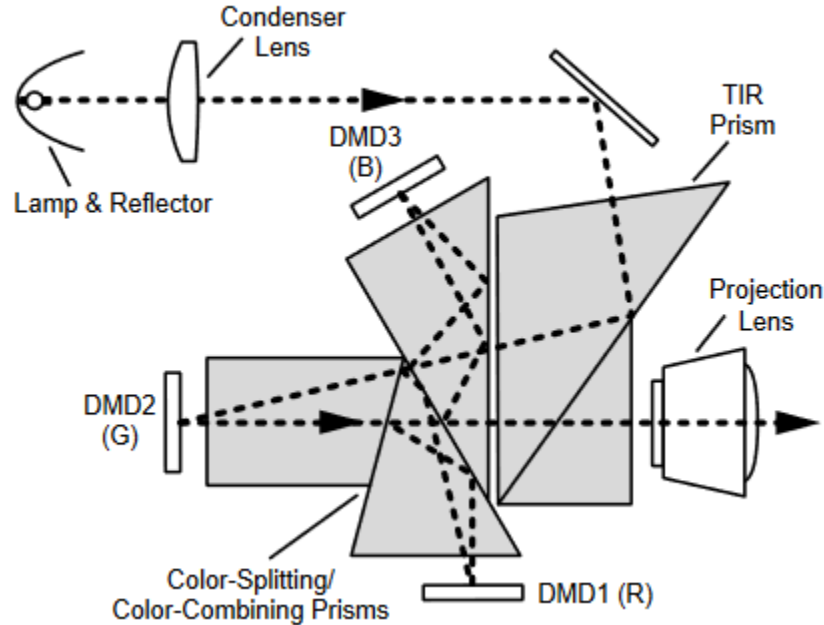


Figure 22. Three-Chip DLP Projection Scheme (Source: TI)

The dichroic prisms split the light by reflection and transmission into red, green, and blue components. The red and blue prisms are reflected once more through TIR in order to properly direct their respective colours onto the DMD components. Light reflected from the “on” state mirrors is redirected through the prisms and recombined, fails to achieve TIR and is thereby transmitted through the projection system. Three-chip systems possess the highest light efficiency, and are well suited to applications requiring bright displays. <sup>[8]</sup>

## 2.6 Display Performance

DLP system are available in a wide variety of resolutions including VGA (640×480), SVGA (800×600), SXGA (1280×1024), FHD (1920×1080), and 4KUHD (3840×2160).

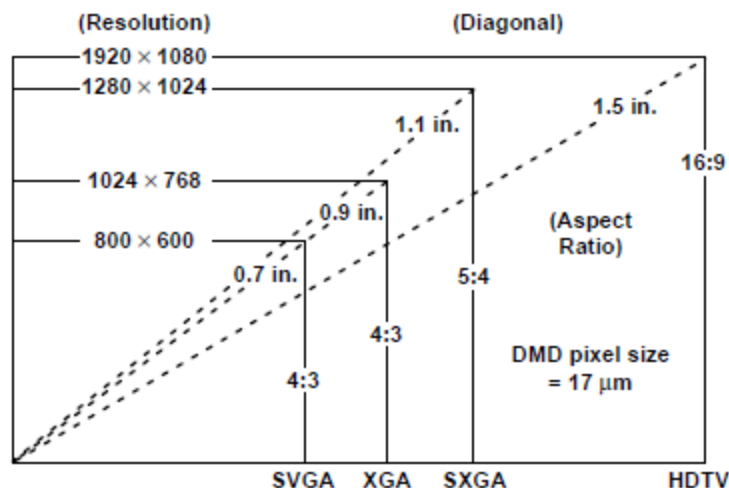


Figure 23. DMD Resolution vs. Chip Diagonal (Source: TI)

All DMD chips use a common pixel design consisting of a 16 $\mu$ m mirror arrayed in a 17 $\mu$ m pitch. As resolution needs increase, the pitch remains constant but the DMD itself increases in diagonal size. This allows high optical efficiency and contrast ratio at all resolutions while keeping pixel timing common to all designs.<sup>[8]</sup>

The brightness of DLP projection systems tend to increase with resolution as optical efficiency increases, limited by the ability to cool the chip to 65°C. This is due to the hinge temperature of the DMD being limited to this value. Illumination source logically also determines the brightness of the system. Theoretically, with available technology, the brightness on screen can reach 10,000 lumens with the hinge temperature being cooled to below 65°C.<sup>[8]</sup>

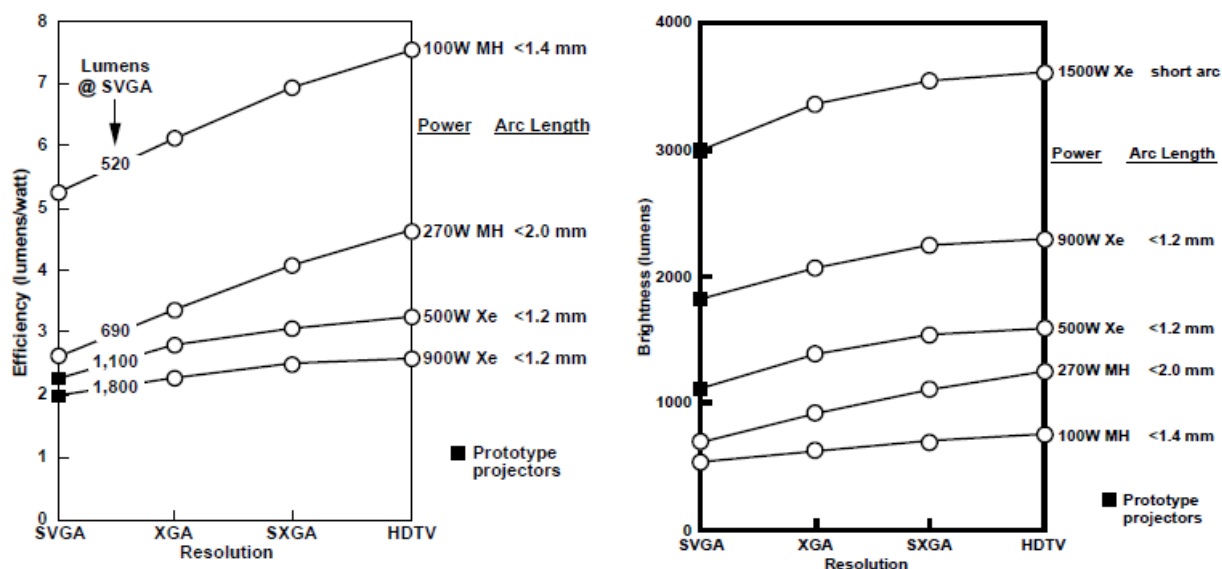


Figure 24. Modelled Optical Efficiency and Brightness vs. Resolution for DLP Three-Chip Projectors (Source: TI)

Inherent contrast ratio of the DLP system is determined by measuring the ratio of light flux with all pixels on vs. off limited by diffraction around the mirror edges, the underlying substrate, and from the mirror's structural dependencies (metallized hole in middle of mirror acting as mount). System contrast ratio is determined by measuring the bright and dark portions of a 4×4 checkerboard. The current typical contrast ratio is 1000:1 due to improvements to tilt angle.<sup>[7]</sup> Further improvements are expected as architectural design improves on DMD pixels.<sup>[8]</sup>

Table 3. Contrast Ratio for Standard and Improved System (f/3.0), 1995

	Original Design	More Recent Design
Full on/Full off	255:1	370:1
Checkerboard (4×4)	142:1	177:1

## 2.7 Commercial Applications

Apart from use in pico-projection due to its size efficiency and brightness, DLP projection also finds use in additive manufacturing (3D printing) as a power source to cure resin. DLP projection had been used in rear-projection TVs competing with LCD, LCoS, and plasma technologies in the late 2000s as a cheaper alternative to achieve larger screen size, but as competitive technologies reduced in price, found a larger market as a cinema projection system, occupying up to 80% of the market.<sup>[9]</sup>

In the realm of pico-projection, DLP projectors tend to be illuminated by LED sources, reducing brightness but also decreasing size and weight while increasing battery life. Another advantage of DLP technology is the consistent size of the DMD regardless of purpose of use, allowing control for DMD pixels to be uniform throughout size requirements.



Figure 25. DLP Pico-Projection Development Kit

## 3. ACTIVE-MATRIX LIQUID-CRYSTAL DISPLAY (AMLCD)

While its use in pico-projection was undesirable due to its inefficient nature and size, the introduction of miniaturizing technologies such as High-Temperature Polysilicon (HTPS) has contributed to its growing use in pico-projection applications. The most mature technology to be discussed in this report, LCDs were first considered for optical applications as early as the 1920s, when their ability to operate as a light valve were first demonstrated. As



technology demanded higher pixel count and density, LCDs transformed from passive-matrix controls to active-matrix controls in order to decrease response time. Due to the mature nature of LCDs, it has spawned several derivative technologies, one of which will be analyzed later on in this report.

### 3.1 Liquid-Crystals (LCs)

LCs exist in an intermediate state of matter, wherein they are not an ordered crystalline solid state, nor are they an isotropic liquid. Many organic materials pass through this intermediate phase (mesophase) when heated from their crystalline to isotropic liquid phase. LC materials can be split into two categories dictated by the variable required to control their material phase: lyotropic materials and thermotropic materials. Lyotropic materials change depending on the concentration of a surfactant (material that reduces surface tension) in a solvent, whereas thermotropic materials change depending on temperature. Commercial display technologies typically employ the latter type, where molecules are composed of rod-like molecules, fulfilling the requirements that LC molecules must be anisotropic in shape. Three phases defined the thermotropic LC: nematic, smectic, and cholesteric (chiral).

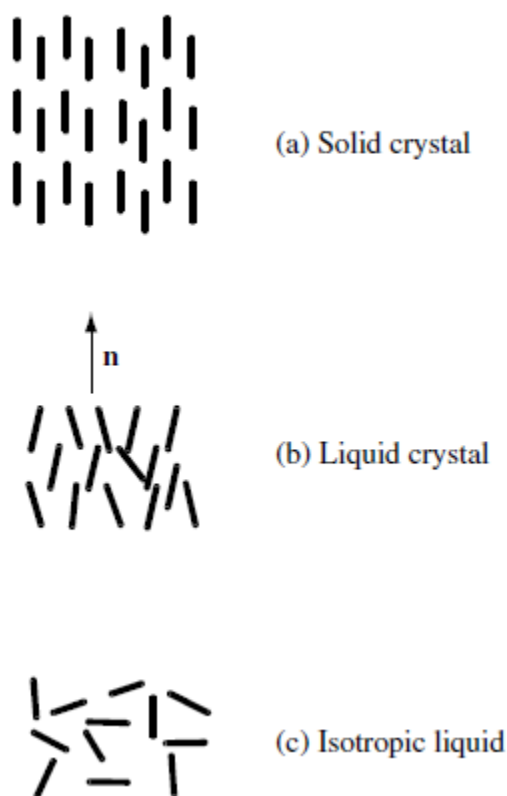


Figure 26. Molecular Order of Different Phases (Source: Polarization Engineering for LCD Projection)

Thermotropic LCs responding to an electric field forms the basis of optical switching. LCs come in three different molecular arrangements. The nematic LC has, generally, axial order, wherein crystals possess a preferred direction from which the somewhat uniform nature is strongly optically birefringent. The cholesteric mesophase (chiral mesophase) is related to the nematic phase with the exception that the molecules are optically active. In this phase crystals will acquire a twist about the axis normal to the alignment layer either left-handed or right-handed (depending on molecular conformation). This spiral arrangement results in selective reflection of circularly polarized light and rotatory power, allowing for strong optical rotation. LCs used in display typically have a chiral dopant added to create a mode capable of fast switching. Finally, smectic LCs have stratified structures. In the smectic A phase, molecules are upright in each layer with centres irregularly spaced similar to liquids. The smectic C phase is similar to the A phase, except tilted with respect to the layer normal. A smectic B phase exists, similar to smectic A with exception that molecules are arrayed into a network of hexagons within the layer.

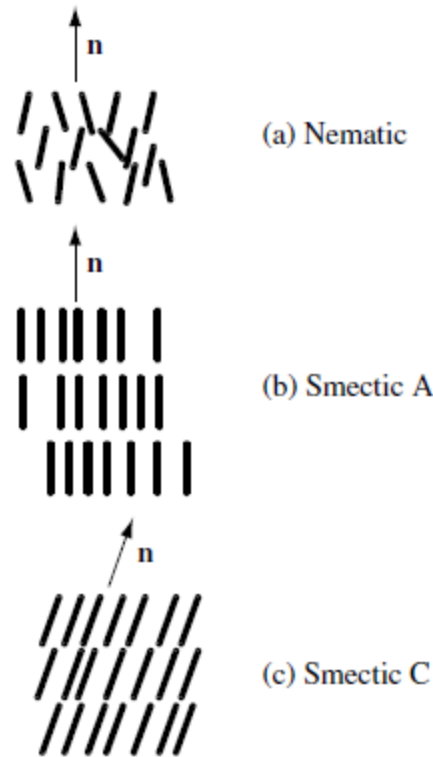


Figure 27. Molecular Arrangements of LCs (Source: Polarization Engineering for LCD Projection)

Ultimately, with high enough temperature, all LCs will reach the isotropic phases, wherein they are identical molecularly to an isotropic liquid.

### 3.2 Liquid Crystal Display (LCD)

Beginning in the 1970s, development of multiplexing, matrix addressing technologies made it possible to drive large-pixel displays. The creation of twisted nematic and super twisted nematic LC cell configurations gave birth to LCDs. Thin film transistors (TFTs) allowed transistors to be manufactured in a substrate of glass capable of producing nearly transparent transistors and further advanced the LCD industry in the 1980s.

As LCs are a phase that react to external stimuli which changes the molecular arrangement allowing for manipulation of photons, LCs cannot produce photons (non-emissive), acting only to modulate or switch an external light source. When controlled the birefringent nature of LCs act as an optical switch based on electro-optical effects of LCs. The simplest form of the LC cell is a layer of LCs sandwiched between two electrodes. The orientation of the LC director (the axis to which LCs align themselves), in commercial use, is affected by an electric field that orients the director parallel to the electric field if the dielectric anisotropic constant is positive and perpendicular if it is negative. Because the electric field influences the director profile, it also dictates the anisotropic properties of the LC film. By varying the electric field applied to an LC layer (spatially) the polarization of transmitted light can be controlled and is thereby capable of transmitting an image.

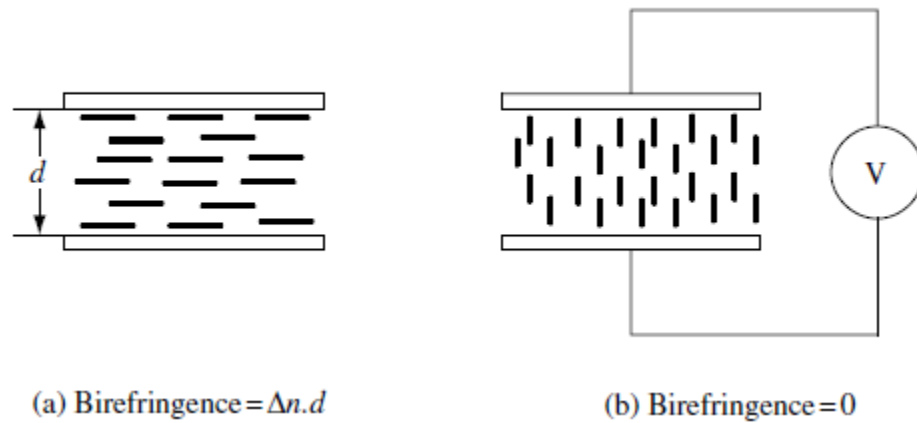


Figure 28. Electro-Optical Effect (Source: Polarization Engineering for LCD Projection)

The most common form of LCD used in display today is the 90° twisted-nematic (TN) cell, invented in 1971 and made miniature using HTPS. The operating principle of this cell is simple. Two linear polarizers are placed before and after the transmission axis of the LC cell with a 90° difference, and the LC director is anchored perpendicular from the top to the bottom. In the inactivated case, the LC director undergoes a 90° twist. Light that enters the cell is first linearly polarized then follows the director, undergoing rotation while propagating through the cell. Light then reaches the second polarizer (sometimes referred to as the analyzing polarizer) oriented parallel to its transmission axis, allowing the light to leave the cell. Because of this, the default state of the TN cell is equivalent to the “on” state of a DMD. When an electric field is applied to the LC layer, the director distribution in the middle of the cell (least anchored, more freedom to rotate) will rotate parallel to the electric field. As the intensity of the electric field increases, the twisted structure of the LC layer begins to vanish. Rotation of linearly polarized light can no longer occur and light is no longer allowed to exit the system.

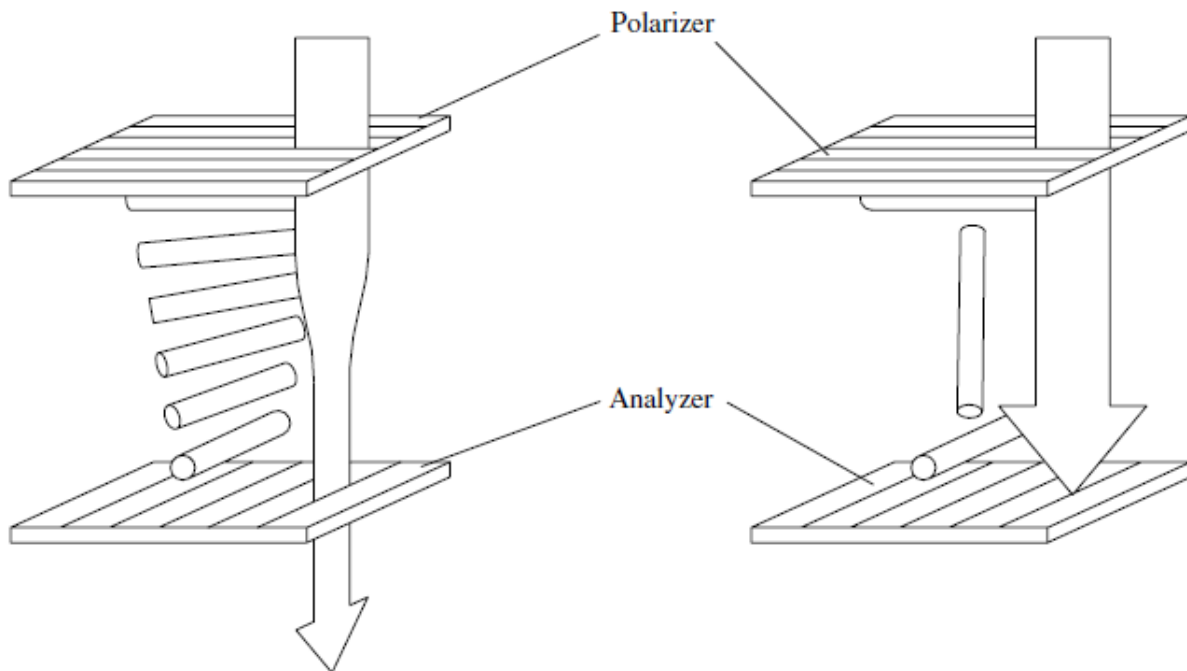


Figure 29. 90° TN Mode, Inactive and Active, Respectively (Source: Polarization Engineering for LCD Projection)

The ability of the TN cell to operate depends on the Mauguin condition,  

$$\Delta n d \gg \lambda/2$$

Where  $n$  represents refractive index,  $\lambda$  represents wavelength, and  $d$  represents thickness of the cell. As this condition cannot be completely satisfied, actual displays employing TN cells tend to have reduced brightness and contrast, as well as colouration caused by interference of the modes. Typically, TN cells operate at:

$$\Delta nd = 0.866\lambda$$

Which is referred to as the first minimum condition representing a compromise between FOV, colouration, and brightness.

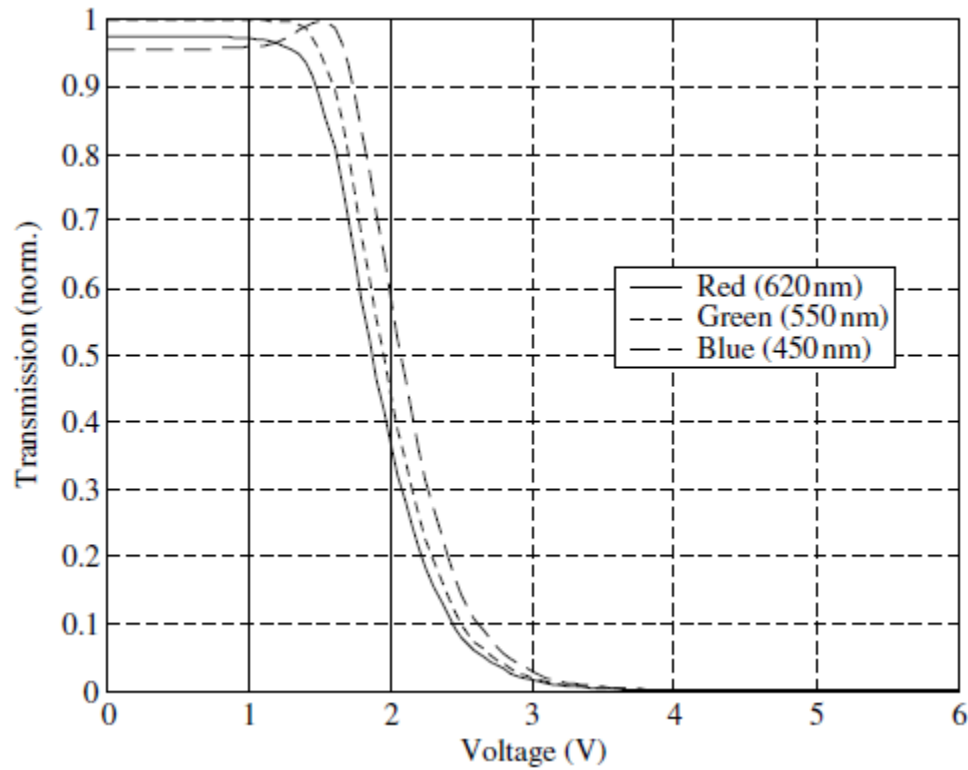


Figure 30. Transmission vs. Voltage of the First Minimum, White TN Mode at 550nm (Source: Polarization Engineering for LCD Projection)

In the first minimum case, light enters the cell at a linear polarization and steadily evolves to a circular polarization state at the midpoint, returning to an orthogonal linear polarization at the end of the cell. The manner in which an ideal TN cell operates can be simulated with an extremely thick cell, which would allow a constant linear change in polarization to achieve orthogonality.

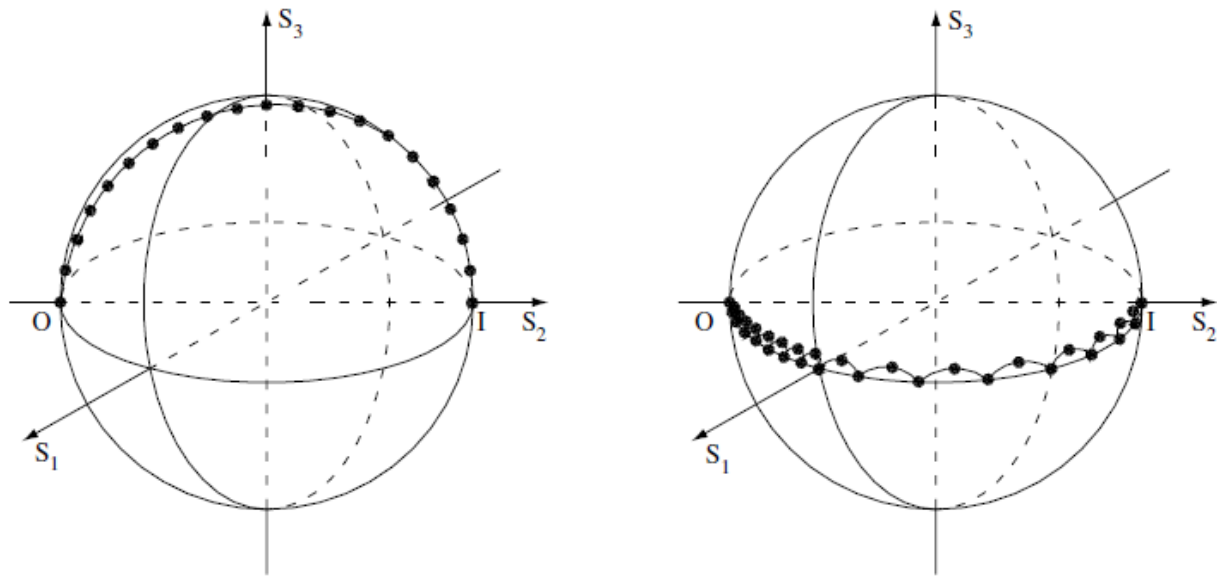


Figure 31. Evolution of Polarization State,  $\Delta n d = 0.866\lambda$  and  $18\lambda$  on Poincaré Sphere (Source: Polarization Engineering for LCD Projection)

Alternatives to the  $90^\circ$  TN cell exist in the field of LCD projection. Using a negative dielectric, a TN cell can be made to be in the “off” state by default, allowing for transmission only when a voltage is applied to create an electric field. This is called the  $90^\circ$  VA TN mode.

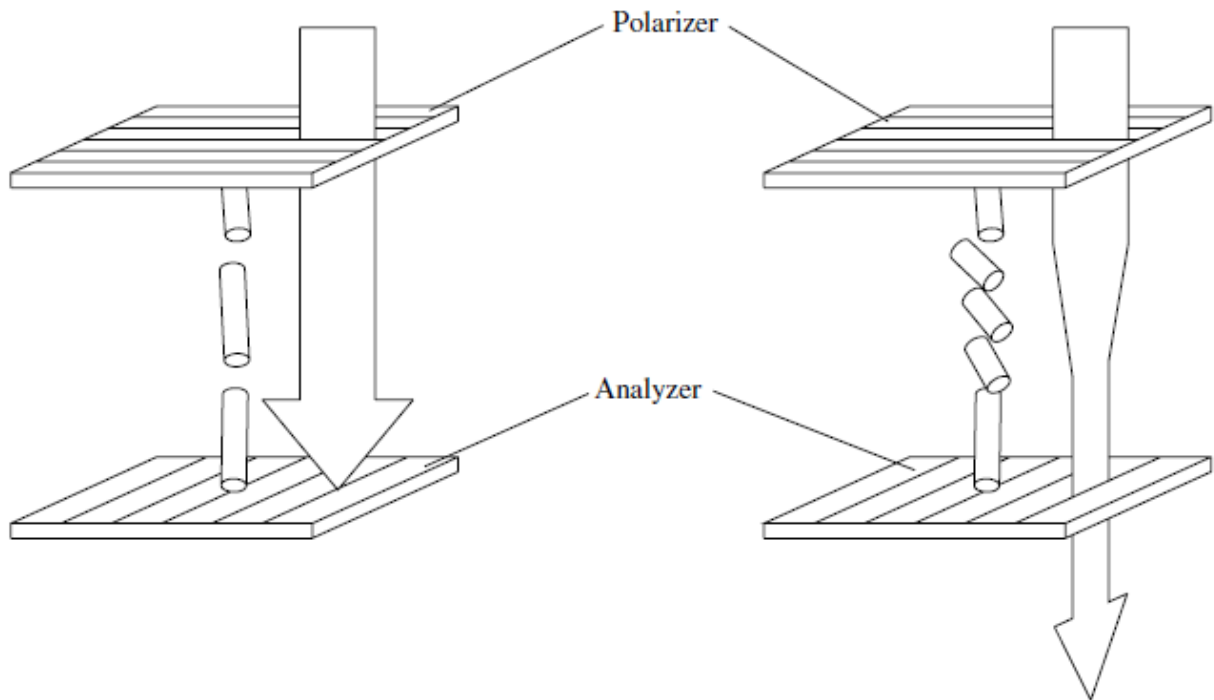


Figure 32.  $90^\circ$  VA TN Mode, Inactive and Active, Respectively (Source: Polarization Engineering for LCD Projection)

$90^\circ$  VA TN modes have comparatively more symmetric and wider FOV, higher incidence contrast, and larger cell gap tolerance to conventional  $90^\circ$  TN. In practice, lack of contribution near the boundaries requires a thicker cell ( $\Delta n d$ ) to

achieve full bright state. This system also has the benefit of being able to be used for both transmissive and reflective projection.<sup>[10]</sup>

### 3.3 LCD Projection

In terms of projection, LCDs are the epitome of analogue meeting electronic controls. All commercial HTPS AMLCD systems operate in the three-panel mode, wherein a light source is placed behind a microlens array to achieve lighting uniformity. The light is then passed through dichroic beam splitters to separate the source into its red, green, and blue portions and passed through three LCD panels. The RGB components are then recombined through a cross dichroic prism (X-cube) and passed through the projection optic. Pathing of light is achieved through a 45° inclined blue light reflection filter, a 45° inclined green light reflection filter, two 45° inclined red image reflection mirror, a 45° inclined blue light mirror, a cross dichroic prism, and three LCD panels. Considerably high luminance on the illumination source should be considered due to the nature of TN mode polarization dynamics. Typically a metal halide lamp is used to reduce cost and increase resolving power.<sup>[11]</sup> Modern systems attempt to recapture light rejected by polarizers in an attempt to increase efficiency.

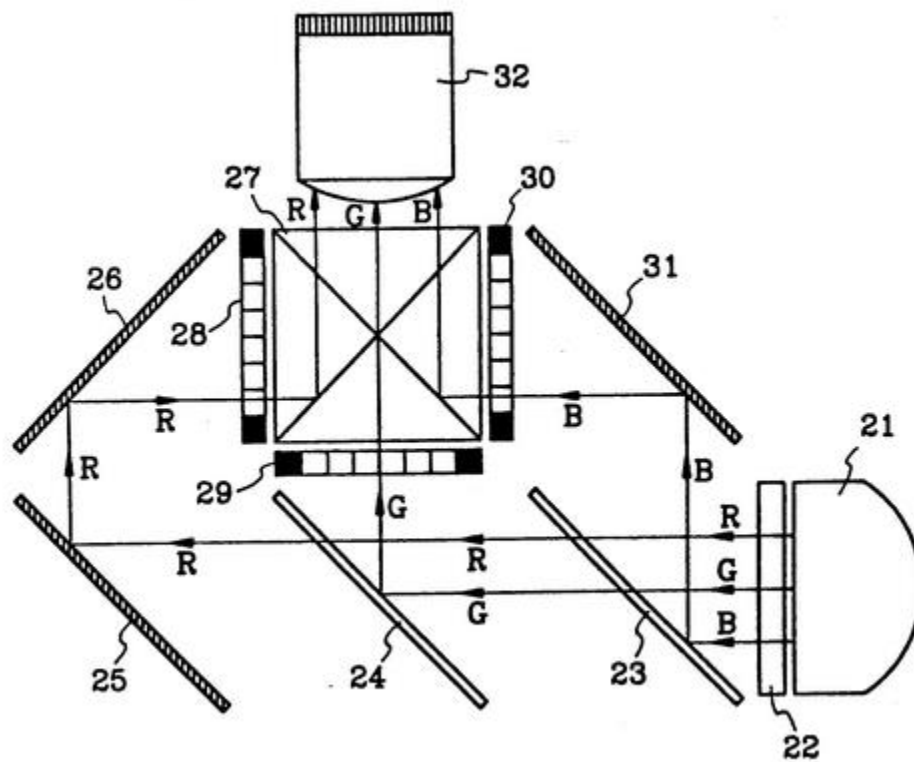


Figure 33. Basic Three-Panel LCD Setup (US Patent: US5196926A)

In the realm of pico-projection, small HTPS AMLCD panels are used and illuminated by laser diodes (LDs) or light-emitting diodes (LEDs).

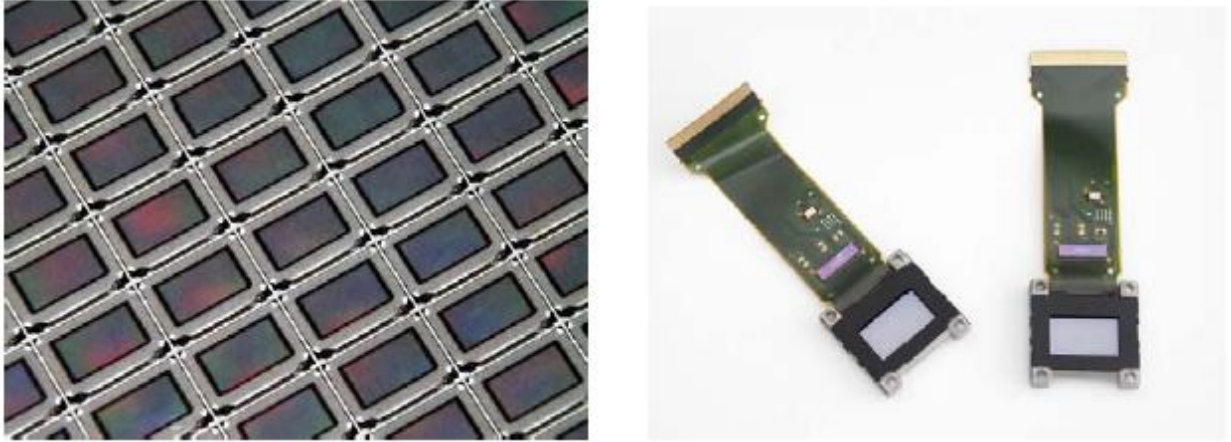


Figure 34. HTPS LCD Wafer (Left) and Two LCD Chips (Right)

### 3.4 Display Performance

HTPS AMLCD panels are available in a variety of resolutions and sizes, including VGA (640×480), SVGA (800×600), WVGA (848×480), XGA (1024×768), WXGA (1280×800), SWGA+ (1400×1050), UXGA (1600×1200), FHD (1920×1080), and WUXGA (1920×1200). Chips vary from 0.5" to 40" in diagonal size.

The advantages of HTPS AMLCD projection include: <sup>[7]</sup>

- Sharper image than equivalent resolution DLP systems
- High lumen output compared to single panel DLP systems
- Manufacturability (very mature technology)

The disadvantages of such projection include: <sup>[7]</sup>

- Screen door effect black matrix TFT elements create visible pixilation due to poor fill factor
- Low contrast, typically lower than 1000:1 currently, due to poor viewing angle
- LC susceptible to UV and deep blue light photochemical damage

### 3.5 Commercial Applications

LCD projection tends to be the most common form of projection used for day-to-day tasks due to their relative simplicity and inexpensive nature. Original developed by EPSON, three-panel LCD projection accounts for up to 51% of the market share among traditional buyers (>500 lumens). <sup>[12]</sup>



Figure 35. EPSON 3LCD Pico-Projector

## 4. LIQUID CRYSTAL ON SILICON (LCOS)

A technology with roots in LCDs, liquid crystal on silicon (LCoS) relies on similar LC technology in a reflective manner. Advances in LCoS technology, originally intended for larger displays to compete with AMLCD and DMD technology, have discovered a niche market in pico-projection, electronic viewfinders, and head-mounted displays (HMDs). Google glass utilized LCoS projection before its cancellation in 2015.

### 4.1 Liquid Crystal on Silicon (LCoS) Functionality

Originally demonstrated in the 1970s, LCoS systems are essentially LC cells with a mirror on one side. LCoS systems in commercial applications were manufactured in two different configurations: the system could be driven in an analogue or digital manner. Analogue systems apply voltages row-by-row to dictate brightness levels in an attempt to avoid digital flicker and is beneficial for short illumination pulses. Certain disadvantages affect this method of control; Systems utilizing analogue control must compensate for drift and balance of voltages. Digital methods of drive use constant voltage between the pixel mirror and a transparent conductor employing pulse width modulation (PWM) to brightness levels using a bit system not unlike the control method for DMDs. The advantage of digital control is the repeatability of signals and its stability, but digital flicker is a concern.<sup>[13]</sup>

The most widely available LCoS mode available today is a ferroelectric LC using a smectic LC material that has a time constant (response time) of microseconds and is operated by a digital binary pulse.



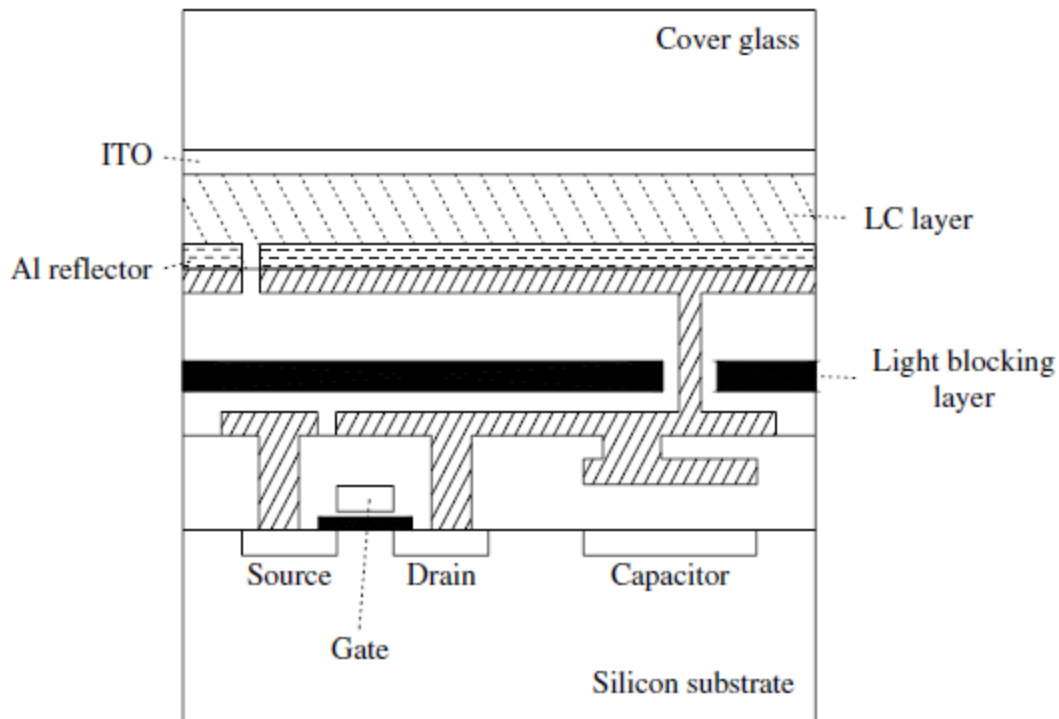


Figure 36. Cross-Section of LCoS (Source: Polarization Engineering for LCD Projection)

#### 4.2 LCoS in Projection

There are three categories of LCoS projection displays: single-panel displays, two-panel displays, and three-panel displays.

Single-panel displays are inexpensive systems that place stringent criteria on the method of illumination to avoid colour breakup. In this system, either a colour wheel or LEDs capable of red, green, and blue illuminates the system. The light emitted is then passed through a collimator and a lenslet array to collimate and uniformly distribute the light. A magnification lens then magnifies the homogenized light onto a mirror into a polarizing beam splitter (PBS), allowing the horizontally polarized light through while reflecting the vertically polarized light onto the LCoS panel. This is then reflected back into the PBS and allowed to pass through the projection optic.<sup>[14]</sup>

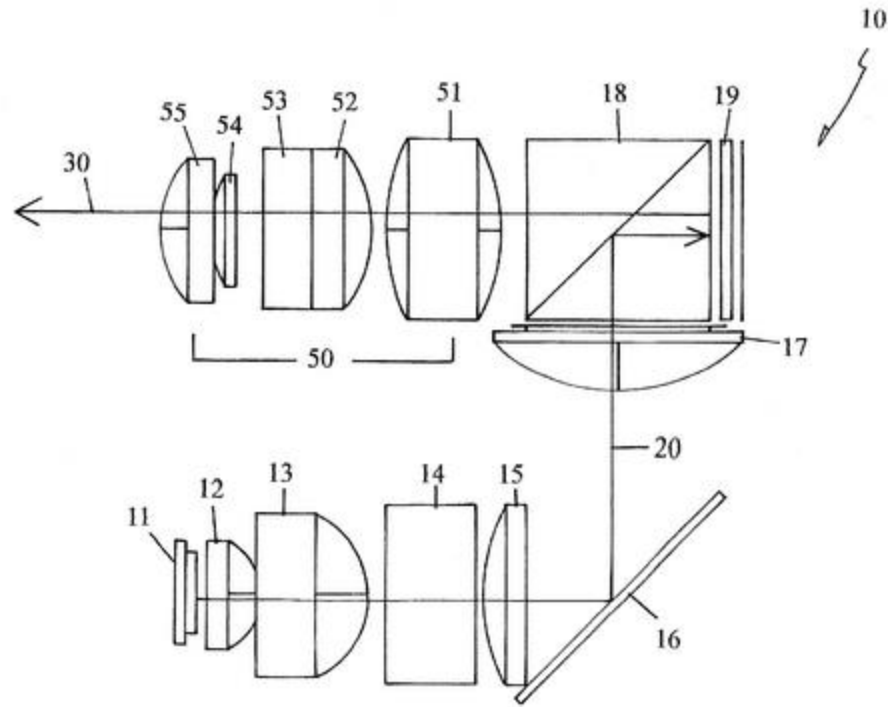


Figure 37. Single Panel LCoS Projector (US Patent: US20110261274A1)

Two-panel systems fall under similar design ideas, separating red from green and blue components. These systems have not been successfully marketed.

Three-panel systems has each panel separating the red, green, and blue light. Initially developed by IBM in 1998, it used Philips colour prisms in an attempt to separate and recombine light through a PBS. However, this system was found to be difficult to maintain the state of polarization from this dichroic prism, and contrast was poor. An off-axis system was developed in which incident and reflective beams do not counter-propagate. Sheet polarizers are used instead of a PBS to separately polarize the beam and analyze the reflected beam. However, panel convergence is difficult to achieve.<sup>[15]</sup>

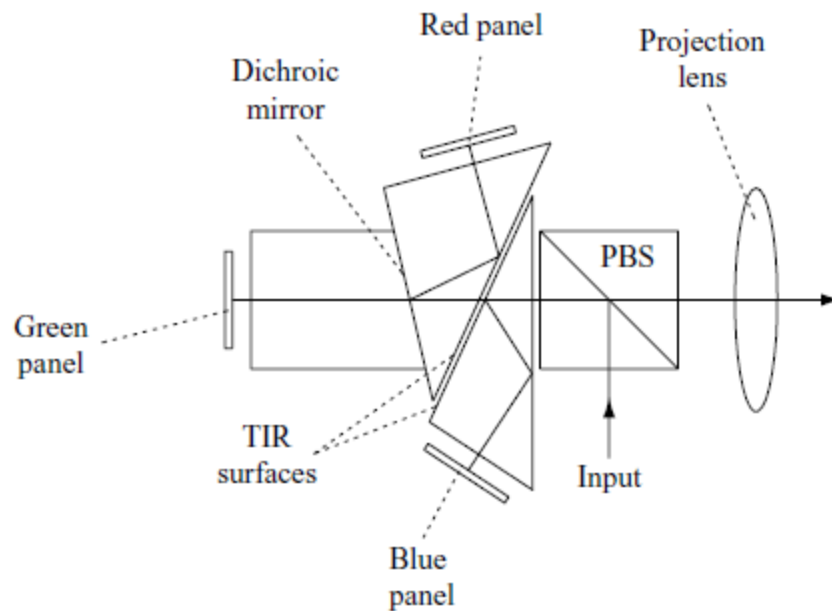


Figure 38. Early LCoS System (Source: Polarization Engineering for LCD Projection)

Modern three-panel projection technologies fall into two categories: three PBSs with an X-cube ( $3\times$ PBS/X-Cube) and retarder stacks with MacNeille PBSs, which combine polarizing and analyzing with splitting and combining of colour.

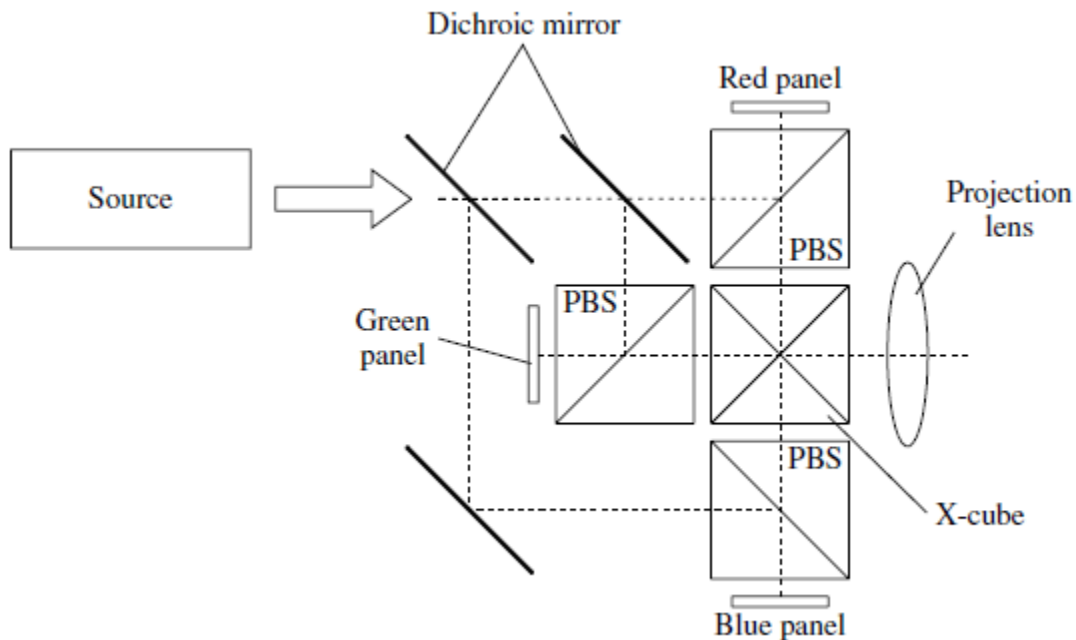


Figure 39.  $3\times$ PBS/X-Cube LCoS Projector (Source: Polarization Engineering for LCD Projection)

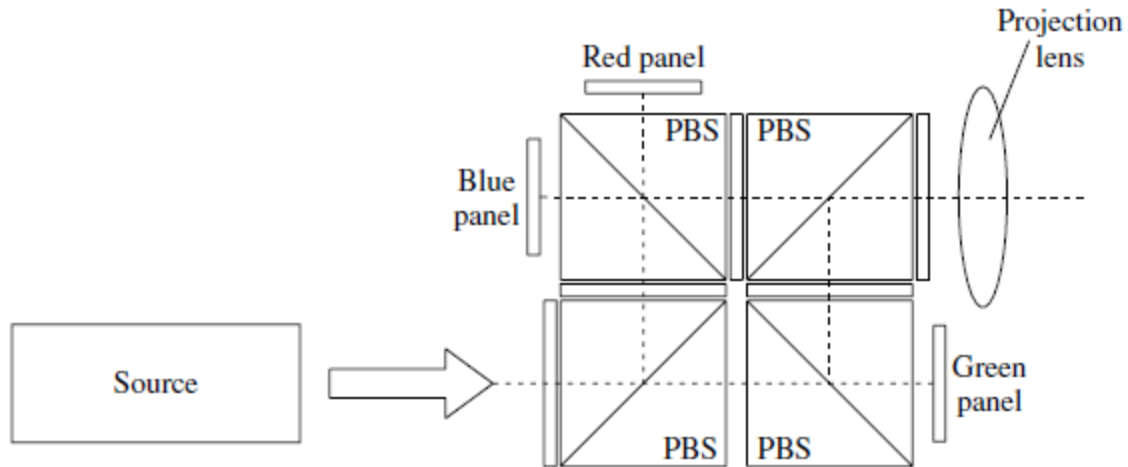


Figure 40. Retarder Stacks with MacNeille PBS LCoS Projector (Source: Polarization Engineering for LCD Projection)

### 4.3 Display Performance

Modern LCoS micro-displays possess pixel pitch of  $4\mu\text{m}$  with decreasing size under active development. Similar to LCDs, they are available in a wide variety of resolutions up to 4K with a pixel pitch of  $6.8\mu\text{m}$ - $8.5\mu\text{m}$ , with demonstrator models capable of up to 8K at a pixel pitch of  $4.8\mu\text{m}$ . Space between pixel mirrors is at  $0.2\mu\text{m}$  with a fill factor of around 93%. Diagonal size range from 0.17 to 1.3 inches with larger devices used for projection at  $>20,000$  lumens. Peak contrast ratio of 100,000:1 have been produced. Effective heat sinking allows for luminous densities of  $>2000$  lumens/ $\text{cm}^2$  to be achieved with 70-80% light efficiency. Response times can drop as low as 1ms. [13]



Figure 41. Various LCoS Micro-Displays

Advantages of LCoS projection include: [15]

- Compatibility with standard IC technology
- Cost effectiveness for high resolution, relatively simple to scale up compared to HTPS and DLP

- No screen door effect due to high resolution and fill factor
- Smooth picture
- High contrast, averages 2000:1
- High response speed

Disadvantages of LCoS projection include: <sup>[15]</sup>

- Lifetime due to breakdown from UV and deep blue sources
- Colour break-up similar to single-panel DLP systems
- Complexity due to control of polarization states

#### 4.4 Commercial Application

Due to their small size and power consumption, LCoS technology is used extensively in smaller technologies, including HMDs and pico-projection. <sup>[13]</sup> They were also used extensively in the now defunct Google Glass.

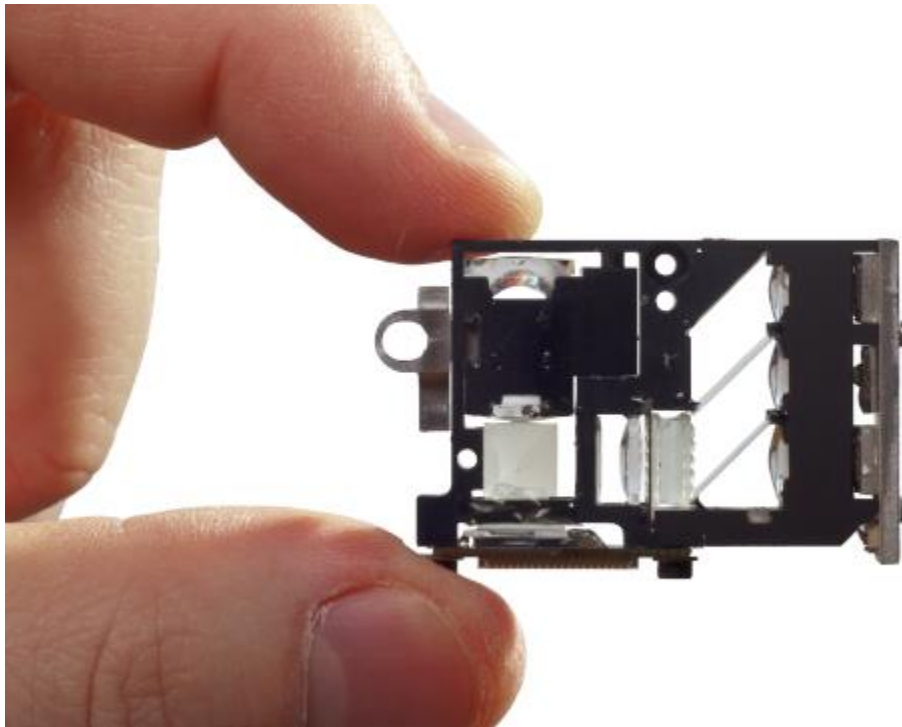


Figure 42. ImagineOptix LCoS Projection Module (Source: ImagineOptix)

## 5. BEAM SCANNING

A technology with roots in MEMS, beam scanning is much smaller compared to the other technologies described in this report. Unlike other technologies mentioned, beam scanning was conceived for the sole purpose of pico-projection. It also does not require use of a projection lens. An untried technology, beam scanning aims to aggressively tackle the pico-projection market.

### 5.1 Beam Scanning

The method to which beam scanning functions combines cathode-ray tube (CRT) technology with current DMD technology in its method to deliver an image. A red, green, and blue light sources, typically laser diodes (LDs), outputs light that is collected by a lens and combined by dichroic elements into a single beam. This beam is then directed, using a beam-splitter or fold mirror optics onto a MEMS controlled biaxial scanning mirror. This mirror then redirects the beam to the screen in a raster pattern. By modulating the three lasers with the position of the scanned beam, an

image is created. This projection engine, called the integrated photonics module (IPM), is 7mm in height and 5cm<sup>3</sup> in volume.<sup>[16]</sup>

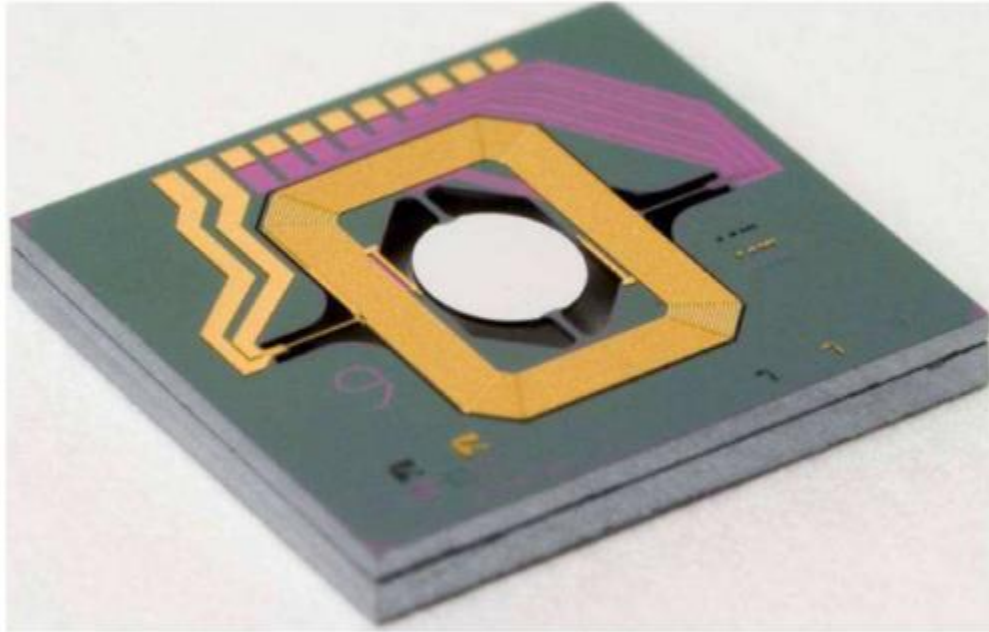


Figure 43. Biaxial MEMS Scanner (Source: Microvision Inc.)

The MEMS mirror itself is 1mm in diameter in its current WVGA (800×480) resolution with an active scanning cone of 43.2° by 24.3° using moving coil activation from two drive lines. Because the scanning mirror must create an image one pixel at a time, proper colour creation is dependent on the driving voltage on the LDs. As the colours are not created sequentially, there is no colour break-up. Efficiency is improved in that only the necessary energy is allocated to each LD, and contrast is high due to the sources being physically off during need for black rather than modulating light.

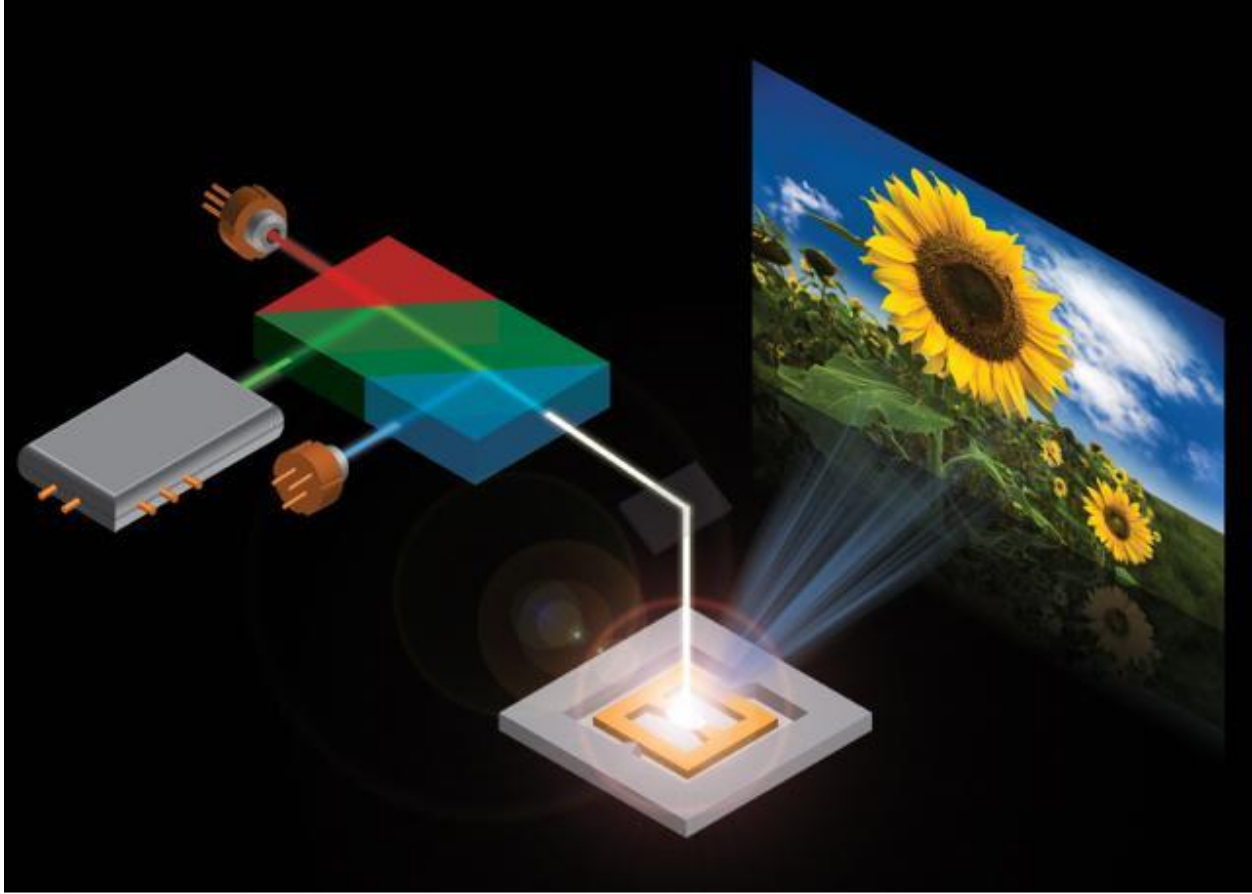


Figure 44. Beam Scanning Projection (Source: MicroVision Inc.)

The system operates at 18 kHz for WVGA and is controlled through a MEMS drive ASIC and a video ASIC. Because pixel positioning can be manipulated through software, the system is capable of accounting for keystone, parallelogram, and pincushion distortion. This ability to control pixel location as well as LD light levels form the backbone of this projection technology. The colour gamut of this system is limited only by sources available.

Due to its lack of projection optics, this beam scanning possesses infinite focus limited by light levels. By design, the collection lenses of the system possesses low numerical aperture, and expands the beam as distance from the scanning mirror increases, allowing pixels to scale with distance.<sup>[16]</sup>

## 5.2 Commercial Applications

Currently in its demonstrator phase, beam scanning technology aims to tackle pico-projection in mobile devices. No current marketed technology employ this method of projection.

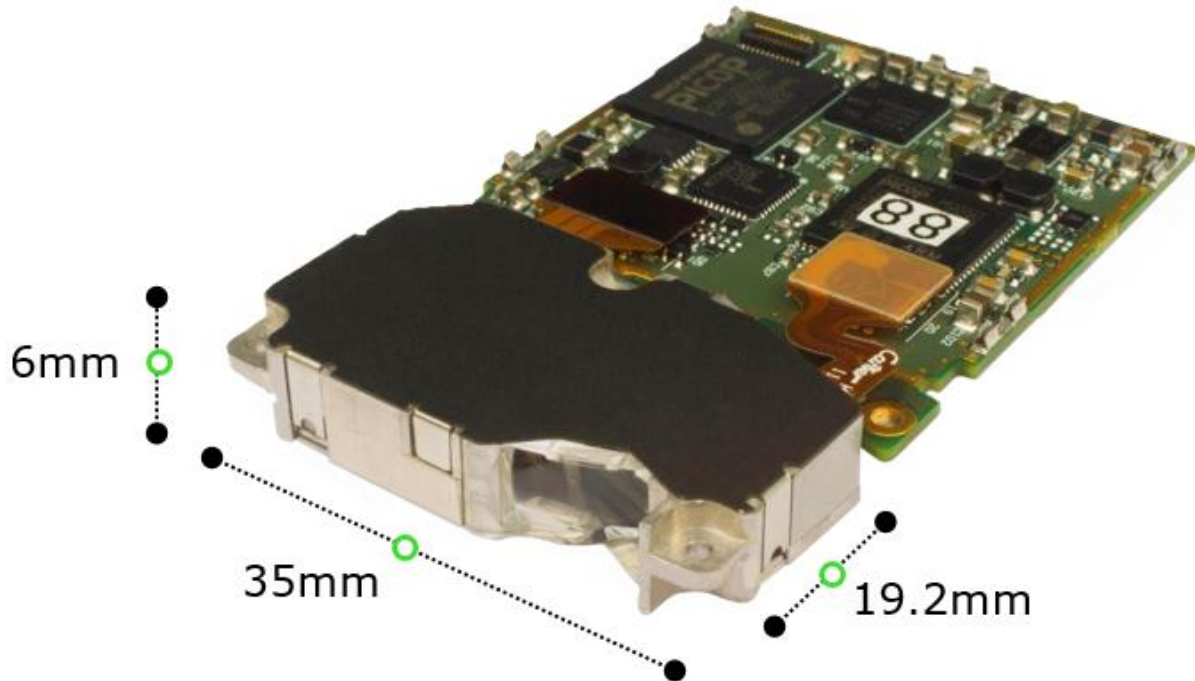


Figure 45. MicroVision PicoP Module (Source. Microvision Inc.)

## 6. DESIGN OF PICO-PROJECTION OPTICS

Due to many of these devices being developed for the mobile market (beam scanning especially), the issue the writer wished to tackle in this section is the creation of a camera/projection lens capable of the combination of a projector with a conventional image capture device. That is, the combination of a camera and a projector. The system must adhere to similar requirements as modern cameras while still offering decent screen size at short throw distances.

Table 4. Combination Camera/Projection System Requirements

Type	Requirement
Illumination Source	LED or Laser
Luminous Flux, Source	15 – 200 Lumens
Throw Distance	2 – 7 ft.
Screen Size	20 – 40 in. at 1m (~ 60°)
Resolution	1920x1080 or 1920x1200
LCD Panel Size	5 – 7 mm
Type	Requirement
F/#	2 - 3
Sensor Size	Preferably, Same as LCD Panel
FOV	60°

### 6.1 Design Considerations

It is typically much simpler to employ two separate systems for image capture and projection, and as such, very little has been done to tackle this issue of interest. However, some factors can be considered when approaching this issue.

- It is not atypical that the field-of-view (FOV) of a camera lens to be near 30 to 40 degrees. However, for the purpose of employing the camera lens as a method of projection this typical FOV is not acceptable to the issue at hand. The camera lens must possess a FOV of greater than 45 degrees for a throw ratio (screen size



to distance ratio) of 0.5, and typical projectors have throw ratios much greater than this value. For the purposes of this project, the FOV will be set to 60 degrees. This allows a throw ratio of approximately 0.7.

- The back focal distance (BFD) in typical mobile device camera lenses is minimal. This, combined with the low F/# of the system means that it is extremely difficult to create a system that could allow a relay lens to accommodate for projection optics. This means that the initial camera system must possess a BFD of significant length.
- The system must be sized on the order of millimetres as it must be mobile.
- The system must have its stop accessible within the design of the system so as to become an intermediate image location. This would serve the purpose of allowing the system to fill the entire FOV when projecting.

## 6.2 Initial Approach

When initially planning the system, it was determined that for simplicity sake that the system possess as few moving sections as possible. As such, it was determined that the projection system would be a simple x-cube arranged so that LEDs of differing wavelengths would be allowed to illuminate three separate LCD panels in an attempt to project the image on the LCD to the screen in question. One of the LED-LCD combinations would then be removed (physically) when attempting to capture an image and a CCD be placed in the LCD's spot instead. The system would function utilizing a plane parallel plate in this case, with the x-cube then removed so that the image could be captured using more than one wavelength to provide a polychromatic image. An LCoS design was considered, and would have behaved similarly to LCD. However, documentation for LCD projectors was more readily available.

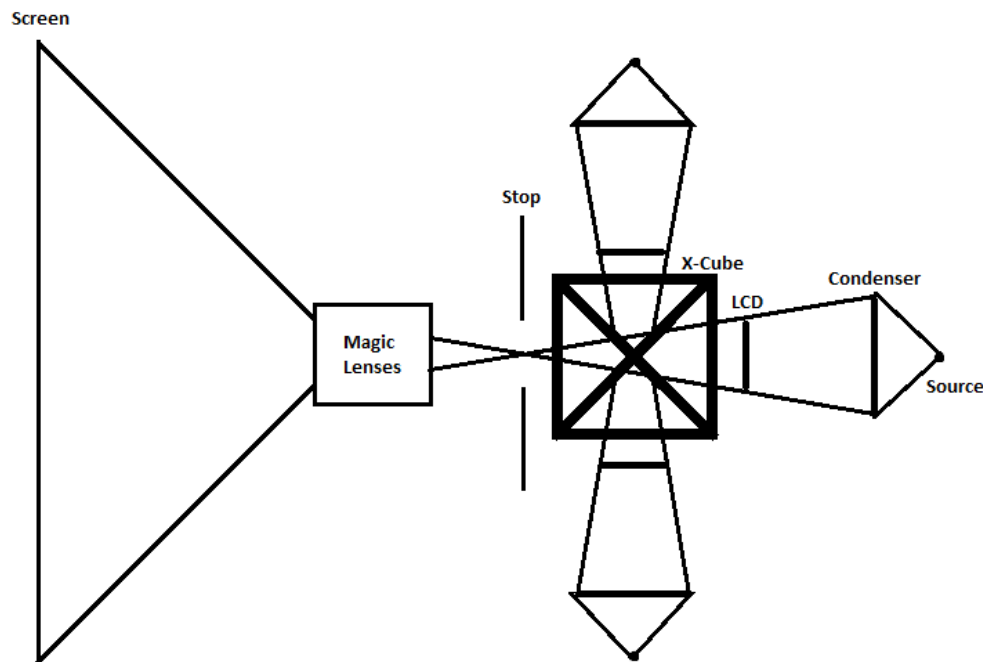


Figure 46. Projection Approach

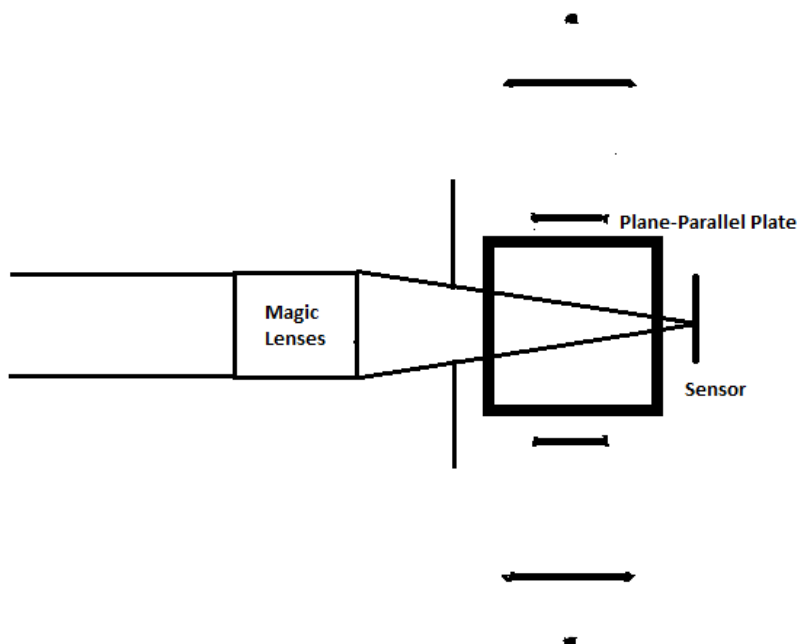


Figure 47. Image Capture Approach

For the first attempt at a solution, a patent was found online that was produced for the sake of a phone camera system. An attempt was made to increase the BFD of the system while moving the stop from the first surface to a more central location. This did not work as the original design had an extremely low F/#, making relaying impossible due to TIR.

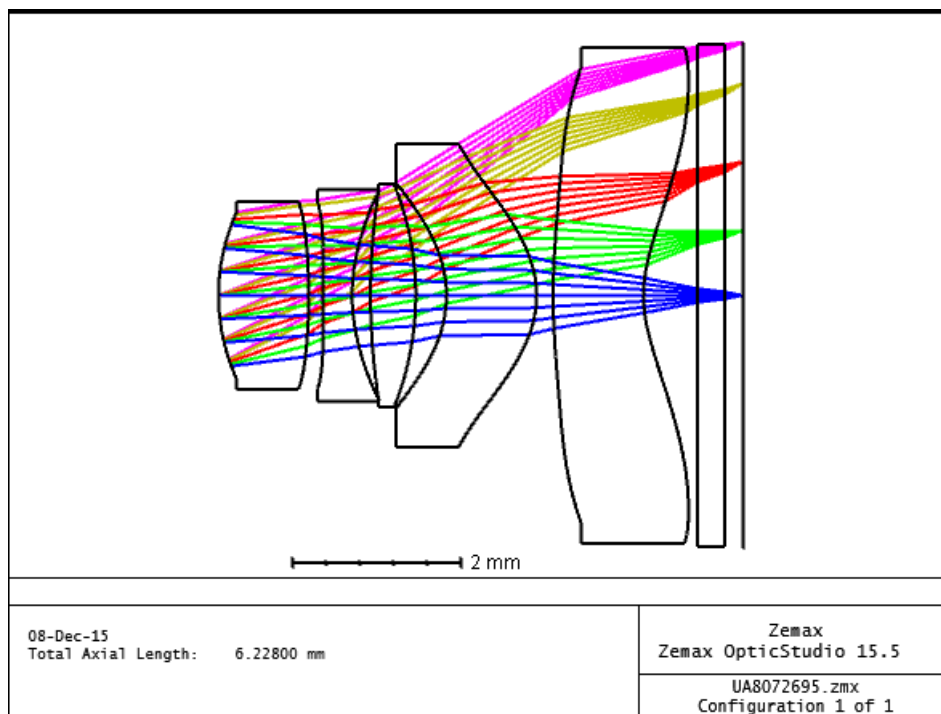


Figure 48. Mobile Phone Lens (US Patent: US8072695)

The second attempt at a solution was done in the form of a classic Cooke triplet, of which the design and derivatives have been used in many phone systems. Although initially offering larger BFD, which is ideal for the purpose intended,

the Cooke triplet depends entirely on symmetry to minimize aberrations, from which a forced increase in FOV had increased considerably. As such, this second avenue was discarded after some consideration.

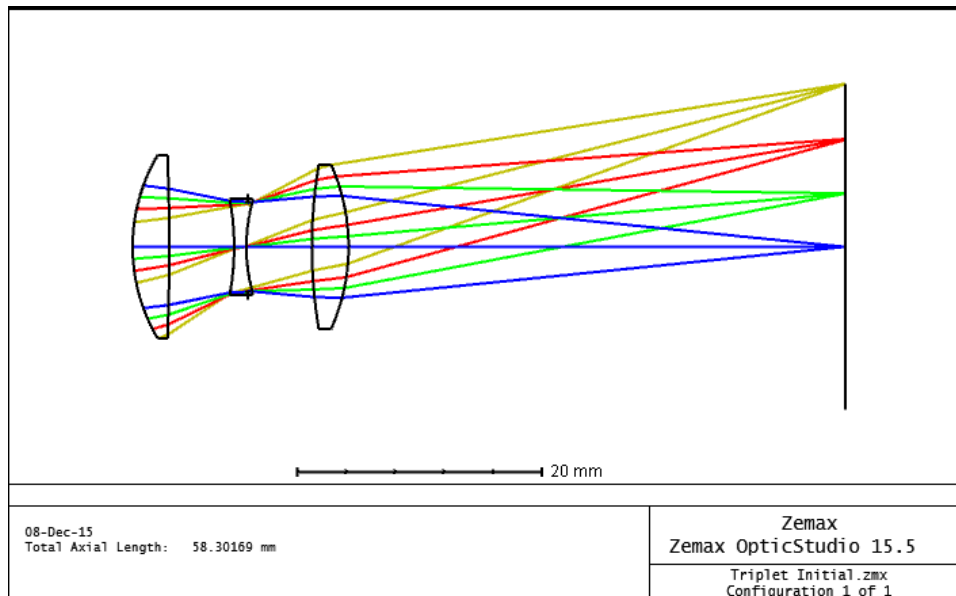


Figure 49. Cooke Triplet

The final approach tackled the issue in the most brute force fashion. Using a fisheye lens, which naturally has high FOV, several elements were added to increase the BFD of the system, reduce the effect of distortion and field curvature (FC), and accommodate for chromatic aberration. This lens was scaled and allowed to change in size to accommodate for the field in question. It was this lens that was employed in the subsequent process.

### 6.3 Design

Using the fisheye lens from the previous section, several optimization loops were conducted to lower the total amount of overall aberration while still maintaining the workable BFD of the fisheye lens. In this case, weight of optimization loops was placed mostly within attempting to reduce the FC and distortion, which placed most of this responsibility within the field flattener placed toward the latter half of the system. Once this was realized, it was necessary to force the flattener to have more degrees of freedom in the aspheric powers.

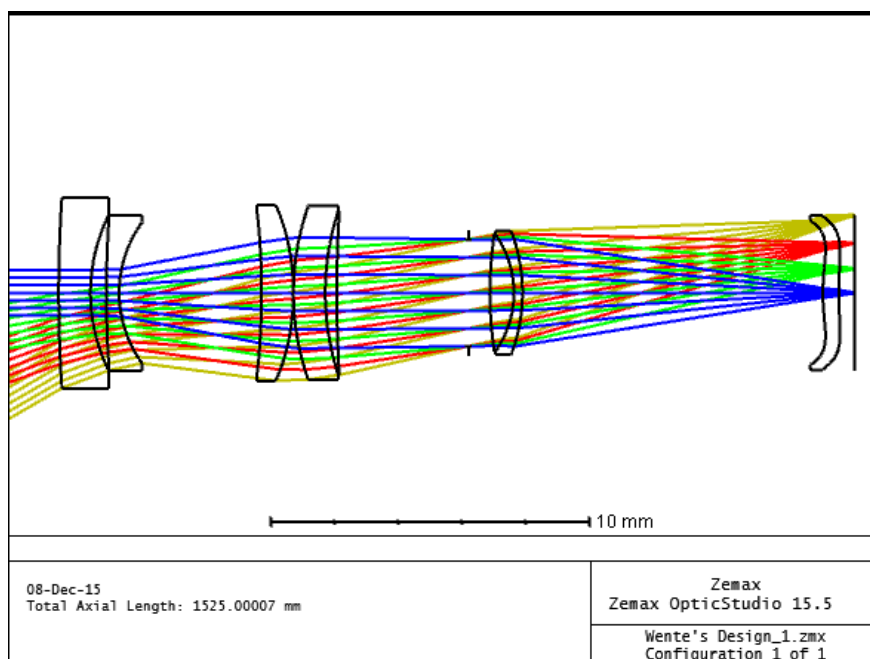


Figure 50. Starting Point for Fisheye Solution

A plane-parallel plate, roughly the size of the x-cube and composed of the same material on-axis was inserted into the system before the field flattener. This is so the chief ray is high enough to accommodate for the aberrations in question while the marginal ray is low enough to not affect other aberrations in a significant manner. Essentially, the field flattener will have to be in front of each LCD during projection. With this step complete, it was possible to begin construction on the projection system.

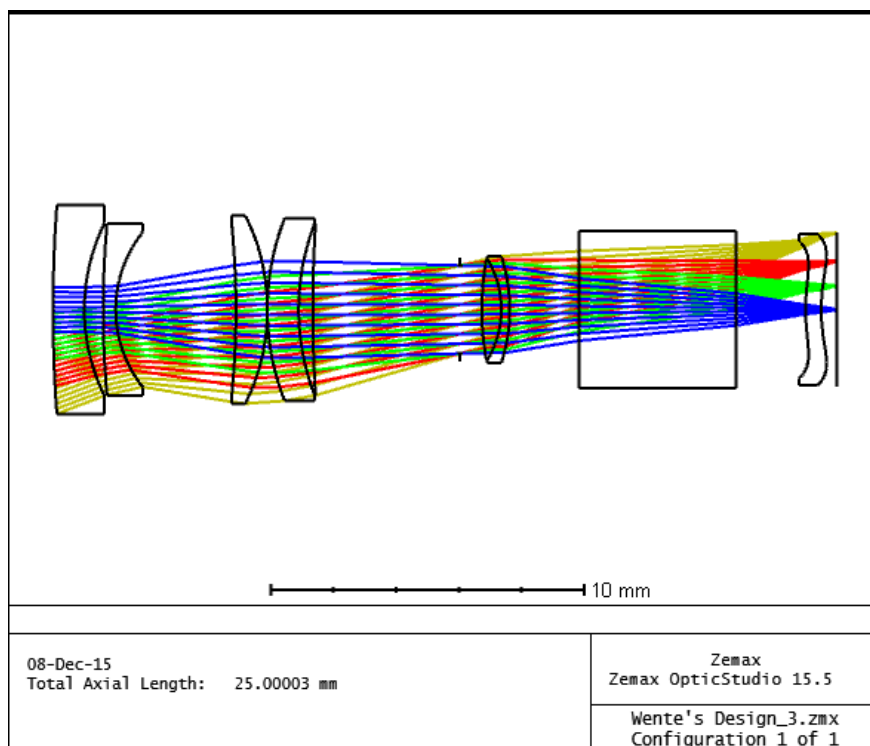


Figure 51. Fisheye System, Accommodating for X-Cube with PPP

In order to force the projection of the system, it is necessary to both design the LED source and a combining lens that was capable of using the system stop as the point of focus. This lens should also completely encompass the LCD panel (which has taken the place of the CCD during image capture) on its way to the point of focus, making it the new system stop, from which the entire FOV of the camera lens could be filled.

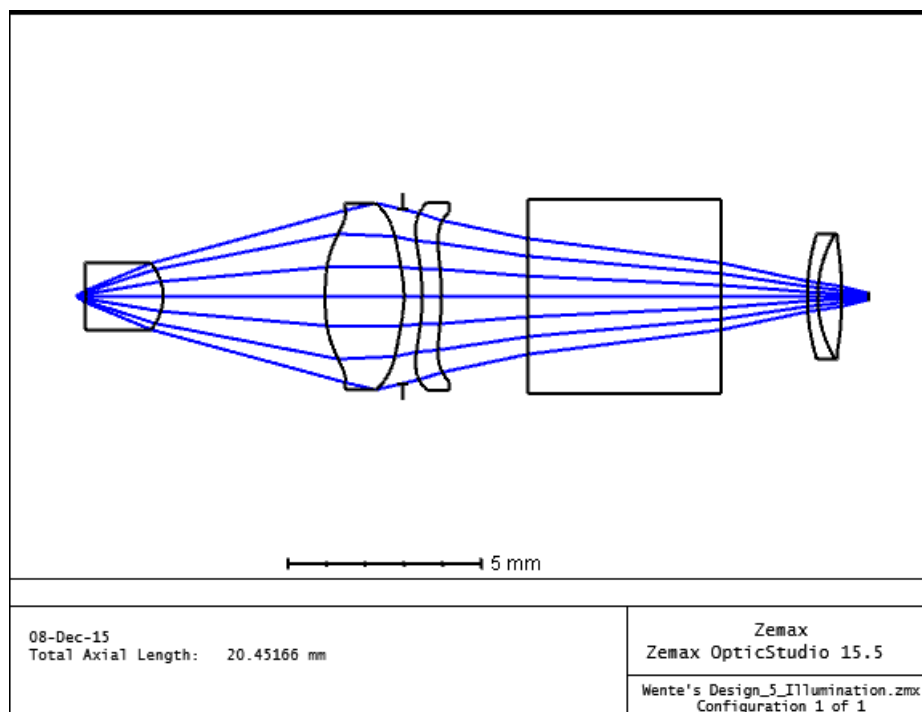


Figure 52. Illumination Source and Projection System

This allows the system to achieve maximum throw ratio given the system used for image capture.

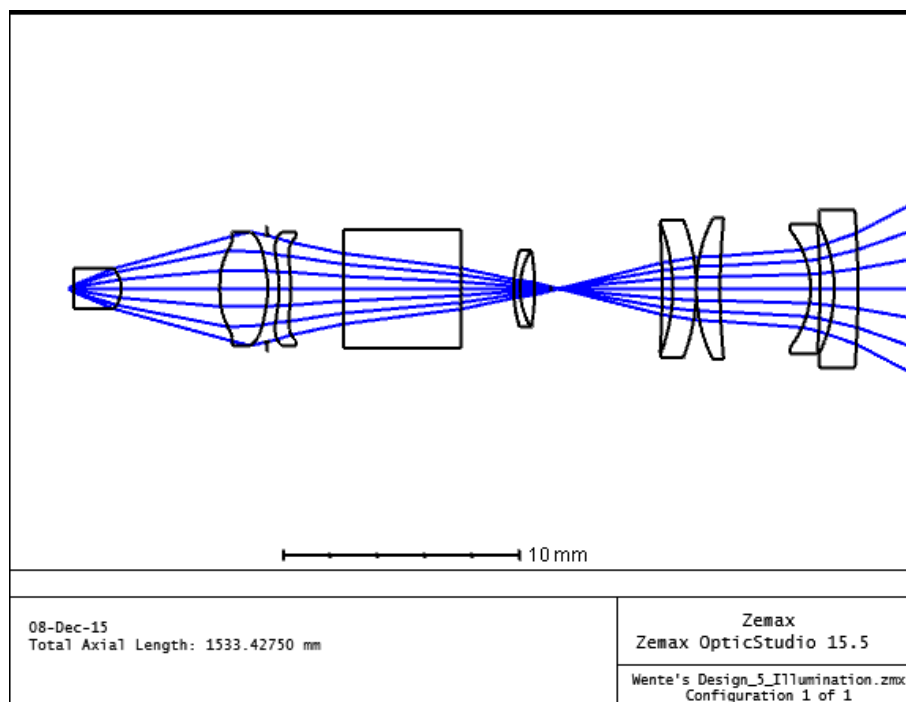


Figure 53. Projection System

## 6.4 Performance

Upon initial glance, it would appear that the system performs quite well given its requirement of versatility. However, upon closer inspection, some performance metrics have not met ideal requirements.

In analyzing the OPD, it was obvious that the given the form of the OPD, most of the aberrations are due to FC and distortion. However, the magnitude of the highest OPD is less than 0.2 waves, which, for a system of this size and purpose is acceptable. This however, does not paint a complete picture, as will be demonstrated later on.

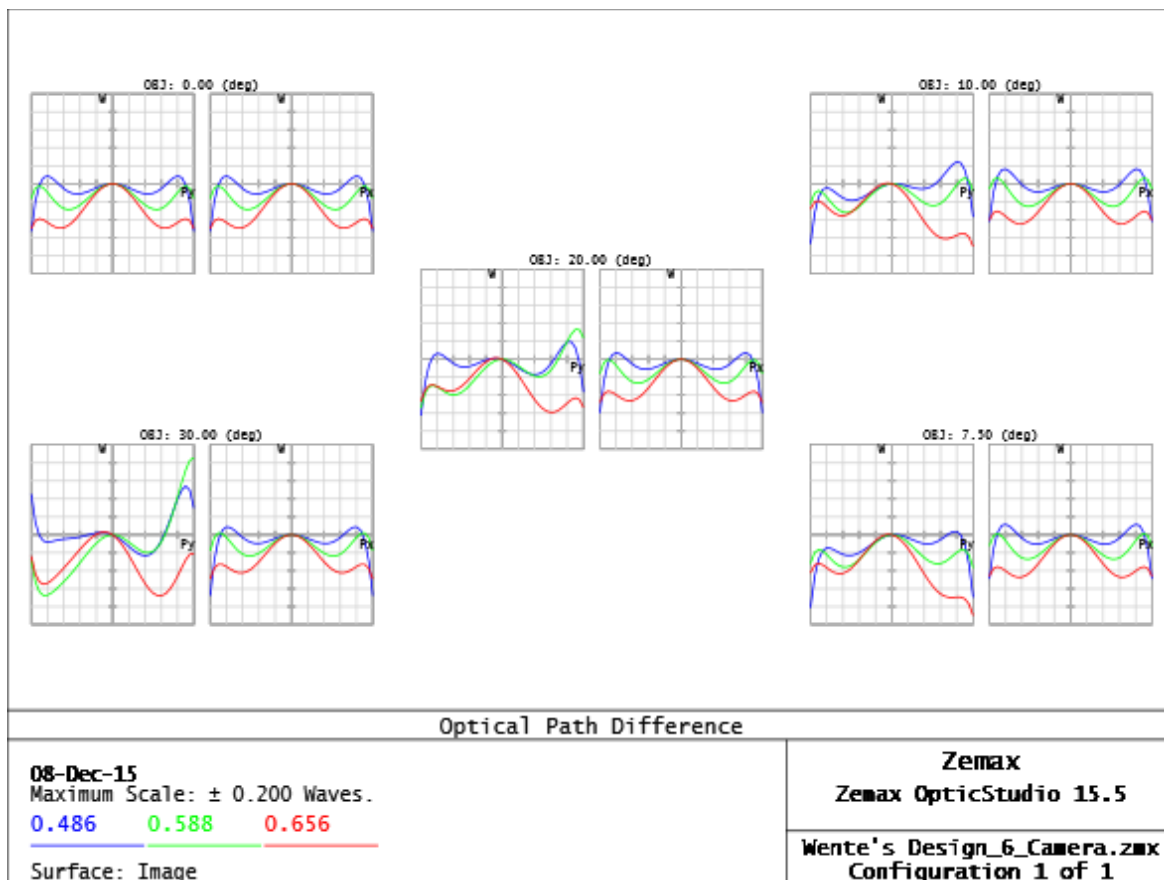


Figure 54. OPD of System

Relative illumination does not drop below 70% at the furthest field. This is acceptable although ideally this would ideally be above 80%. This drop in illumination is due to a sudden increase in FC as the field deviate from the axis.

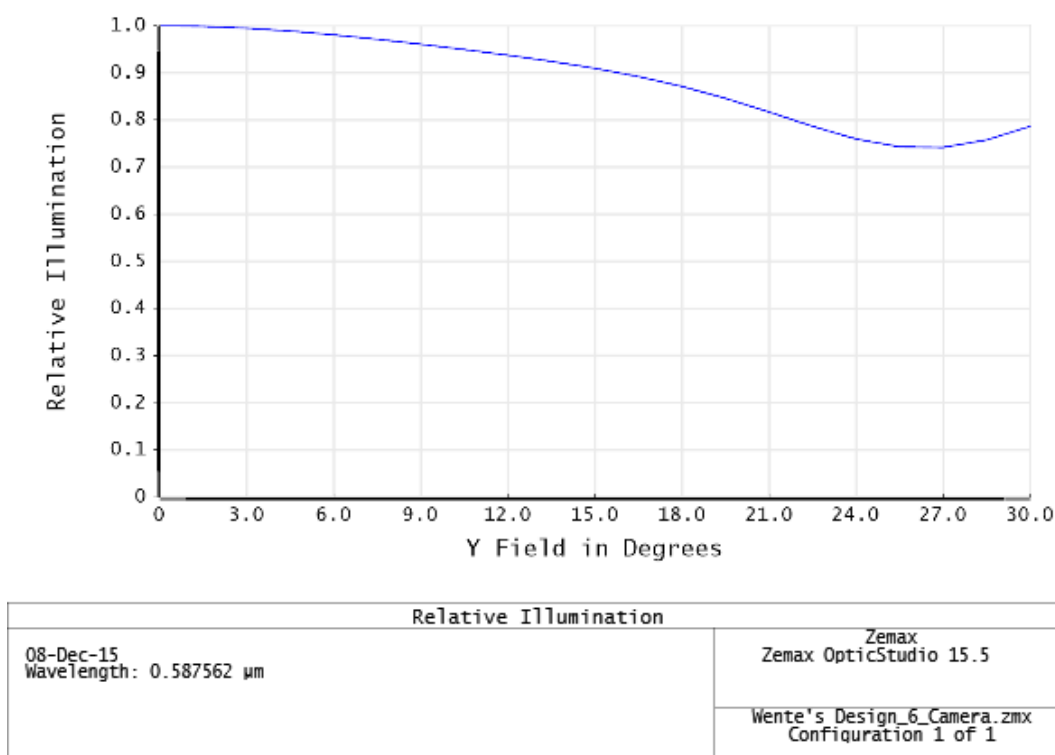


Figure 55. Relative Illumination

It is apparent that the MTF vs. Frequency is quite close to the diffraction limit.

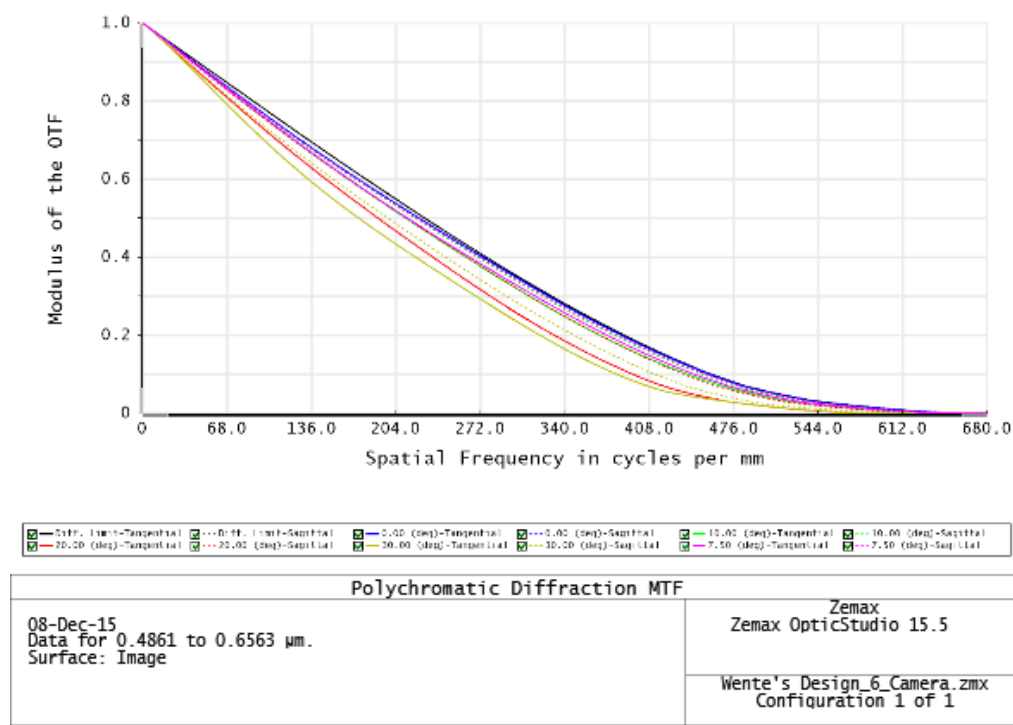


Figure 56. MTF vs. Frequency



However, it is necessary to observe the MTF vs. Frequency from 0 lp/mm to 50lp/mm. This is due to the industrial standard dictating this as the standard for image acquisition. The performance of MTF vs. Frequency at this range is still close to the diffraction limit, and as such, this performance metric is acceptable.

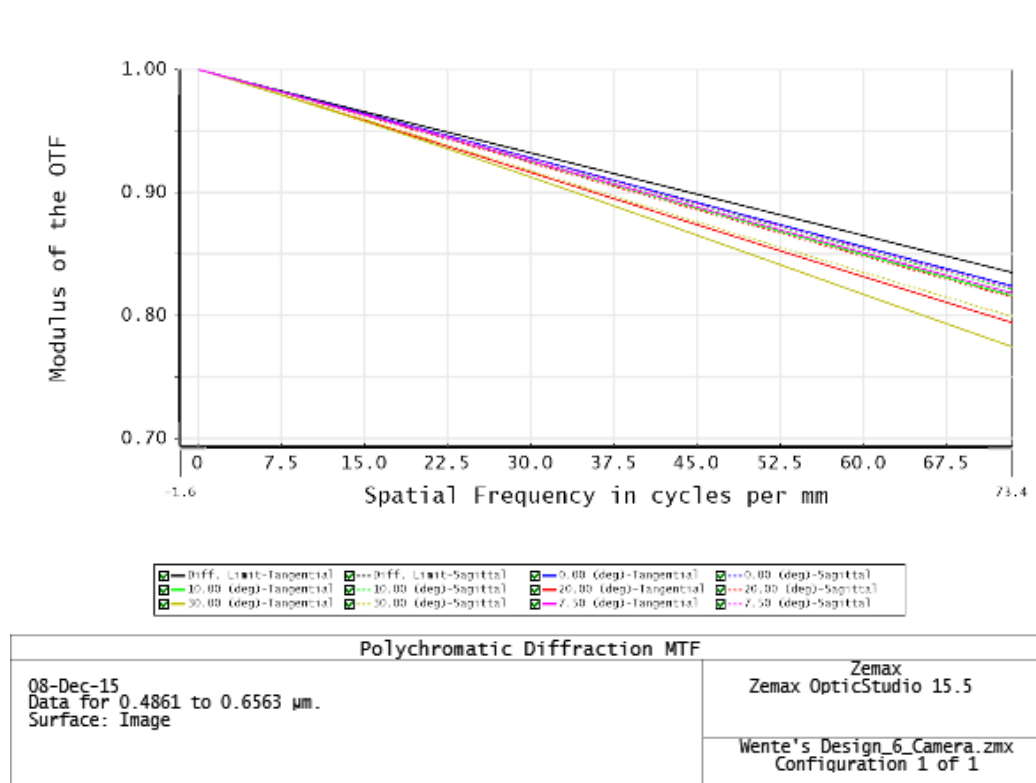


Figure 57. MTF vs. Frequency, 0lp/mm to 50lp/mm

MTF vs. Field clearly indicates something is amiss with the field past 20 degrees off-axis. This is due to the FC off field.

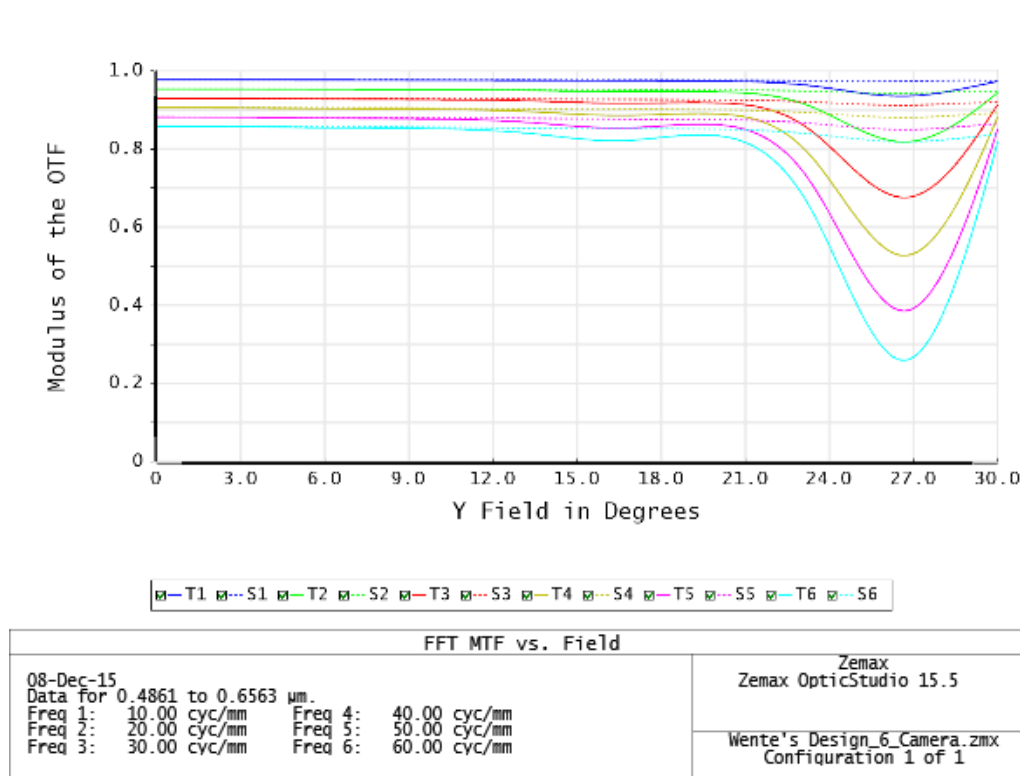


Figure 58. MTF vs. Field

Examination of the FC of the system indicates that FC increases significantly past 20 degrees. This is definitely due to the fact that optimization and design of the system was designed with four fields, from 0 to 30 degrees with 10 degree increments. This was obviously not enough, as this plot indicates that, indeed, FC at the fields used were perfect, but in-between the fields, this was not the case. More fields should have been used during design, and redesign was difficult as most of the system had been locked into the local minimum. The system would have to be redesigned from the stage before the PPP was inserted into the system. This is possible, but time does not allow for this redesign, as each optimization loop uses around 30 minutes.

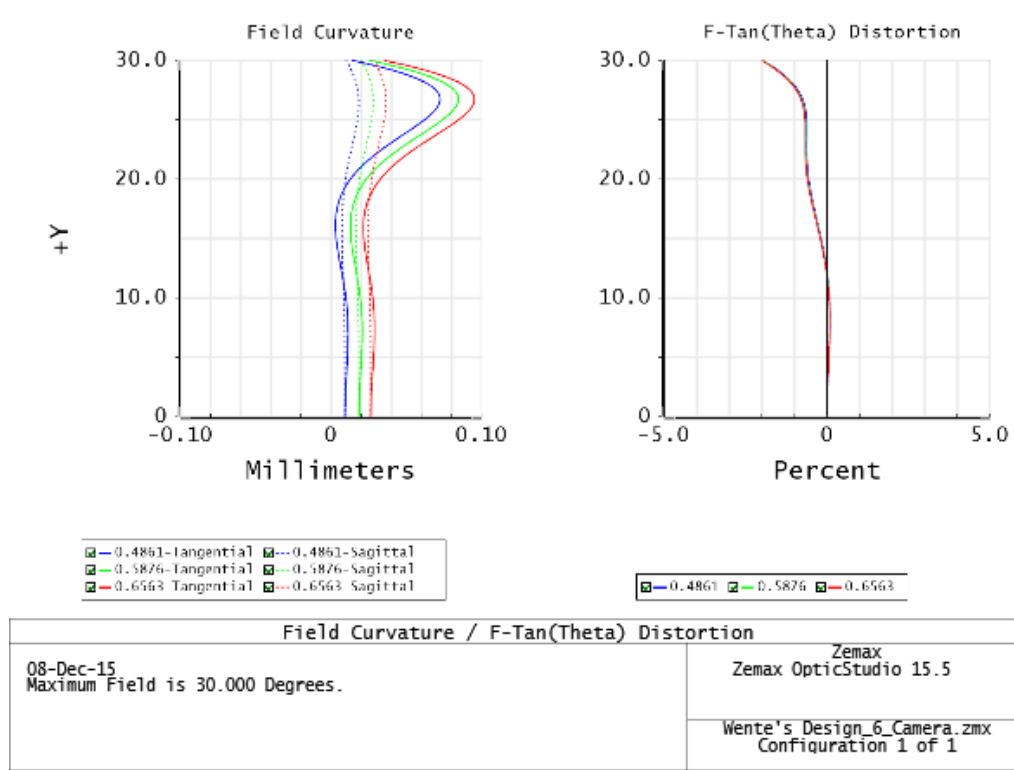


Figure 59. Field Curvature and Distortion

## 6.5 Fulfillment of Objectives

Overall, the objectives set forth in this project have been achieved, although they were quite loose intentionally. The system functions and makes a pipeline to producing a system possible. The system did remain under tens of millimetres, and as such, the feasibility of this project is confirmed.

Table 5. Fulfillment of Objectives

Type	Requirement	Fulfillment
Illumination Source	LED or Laser	Yes
Luminous Flux, Source	15 – 200 Lumens	Yes
Throw Distance	2 – 7 ft.	Yes (1.5m)
Screen Size	20 – 40 in. at 1m (~ 60°)	Yes (800mm)
Resolution	1920x1080 or 1920x1200	Yes
LCD Panel Size	5 – 7 mm	Yes
F/#	2 - 3	Yes
Sensor Size	Preferably, Same as LCD Panel	Yes
FOV	60°	Yes

Should future steps be taken to produce a similar system, the FC should be fixed by adding more fields, and the system be converted to employ plastic surfaces and aspheres.

## 7. CONCLUSION

The projection technologies of DLP, AMLCD, LCoS, and beam scanning were explored, and a rudimentary attempt at designing a pico-projection lens was carried out. The feasibility of the intended design has been shown, and although a perfect system was not designed, it is possible given enough time. The major flaw was the creation of the system

without enough fields and as such, future attempts should try to employ more fields during optimization. Further steps can be taken to increase the number of aspheric surfaces and convert all surfaces to plastic.

While commercial pico-projection has largely disappeared from mobile electronic and has only a marginal market in use as a conventional mobile projector for media, the popularity of pico-projection continues in the fields of HMDs in the application of augmented reality. Prime examples of this is the development of Google glass and Microsoft Hololens, although both cases employ waveguides instead of in-air projection. Should the weaknesses of pico-projection be addressed through iterations of improved technology, a resurgence in its popularity is completely possible.

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