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Optical design of ultrashort throw liquid crystal on silicon projection system

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Abstract. An ultrashort throw liquid crystal on silicon (LCoS) projector for home cinema, virtual reality, and automobile heads-up display has been designed and fabricated. To achieve the best performance and highest-quality image, this study aimed to design wide-angle projection optics and optimize the illumination for LCoS. Based on the telecentric lens projection system and optimized Koehler illumination, the optical parameters were calculated. The projector's optical system consisted of a conic aspheric mirror and image optics using either symmetric double Gauss or a large-angle eyepiece to achieve a full projection angle larger than 155 deg. By applying Koehler illumination, image resolution was enhanced and the modulation transfer function of the image in high spatial frequency was increased to form a high-quality illuminated image. The partial coherence analysis verified that the design was capable of 2.5 lps/mm within a 2 m × 1.5 m projected image. The throw ratio was less than 0.25 in HD format. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.56.5.051408](https://doi.org/10.1117/1.OE.56.5.051408)]

Keywords: liquid crystal on silicon; Koehler illumination; telecentric; ultrashort throw projector.

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1 Introduction

The requirement for a high-quality display as a viewing accessory is in high demand for smart phones, HUDs, computers, home games, and home cinema systems. Of all the types of displays, projectors are used in large venues, such as the classroom and theater. Although direct-view liquid crystal display (LCD) is popular, it cannot fully replace the projector because it is unable to support adjustments in viewing angle and image size. LCD also creates problems with respect to environmental pollution during fabrication.

1.1 Projection System

In the past, the rear TV projection system involved projecting the image behind the screen, whereas the forward projection-projecting LCoS or PLD panel projected an image in front of the screen. In these cases, the throw ratio of projection ranged from 1.4 to 1.6. In recent years, the throw ratio has been reduced to less than 0.5.¹ Sanyo and Ricoh² produced a reflective-type projection system, and Sony was able to decrease the throw ratio even further to less than 0.2475 for the VPLSW235.³ However, the lens contains multiple aspheric surfaces that increase the complexity and cause poor contrast for the real image. Thales⁴ reported several reflective designs that used the optical deviated and tilted method. However, these products have not gone on market.

1.2 Definition of Short Throw Ratio and HD Format

Figure 1 shows the throw ratio D/W , where D is the distance between the lens and the screen, and W is the width of the screen. For a short throw ratio projector, the throw ratio is defined as D'/W , where D' is the distance between the

bottom side of the screen and the mirror of the projector. The small D'/W means that the projector can generate an image at a short distance in a wide-angle screen.

The HD format is shown in Table 1, and DCI 4K format: 4096×2160 is applied. The projection lens is required to reimage each pixel in the LCoS to the projected screen. If the viewers sit in front of the image screen (2-m wide and 1-m high) at a distance of 0.5 m, they will see the full performance of a 4K-format movie. The projector must project the emitted LCoS to the image screen properly, and the small pixel size displayed on the screen is $500 \mu\text{m}$. Thus, the cut-off frequency of the modulation transfer function (MTF) on the image is 2 lps/mm (line-pairs/mm). The projector lens projects each pixel in the LCoS to the screen. However, any object size less than one pixel is irrelevant and is not considered in this case. In the three-panel LCoS system, the size of the LCoS element is $4 \mu\text{m}$, and the minimum size for the 4K2K-projected screen is $500 \mu\text{m}$. The magnification system for each LCoS element is 125. The finite conjugate has been set up while the distance of the image and the distance of the object have been approximated.

A typical projection system with illumination and optics is shown in Fig. 2. The light source is collimated through a diffuser to illuminate the LCD panel, and the projection lens is then used to project the object from the emitted LCD panel to the screen.

Due to the complexity in optical metrology that occurs when making an aspherical surface, the projected image has poor contrast when current projectors are used. Therefore, this study aimed to design a wide-angle projector with a short throw ratio that produces a high-contrast image.

1.3 Three-Panel LCoS Projector

A three-panel LCoS projector has been developed in this study. Figure 3 shows the projector that includes the relay

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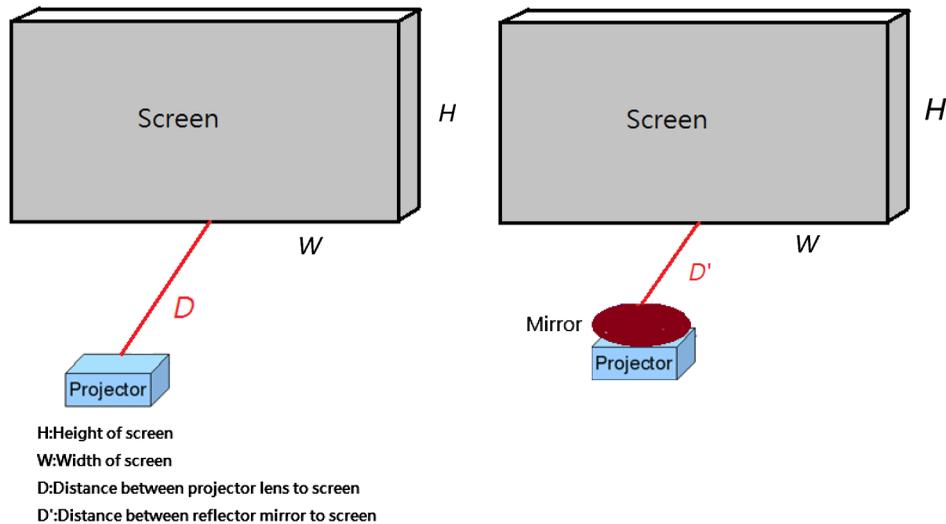


Fig. 1 The definition of throw ratio (D/W) or (D'/W) for projectors.

Table 1 Format for ultrahigh-definition television.

| Format | Resolution | Display aspect ratio | Pixels |
|---------------------------------|-------------|----------------------|------------|
| Ultrahigh-definition television | 3840 × 2160 | 1.78:1 (16:9) | 8,294,400 |
| Ultrawide television | 5120 × 2160 | 2.37:1 (21:9) | 11,059,200 |
| WHXGA | 5120 × 3200 | 1.60:1 (16:10) | 16,384,000 |
| DCI 4K (native resolution) | 4096 × 2160 | 1.90:1 (19:10) | 8,847,360 |
| DCI 4K (CinemaScope cropped) | 4096 × 1716 | 2.39:1 | 7,028,736 |
| DCI 4K (flat cropped) | 3996 × 2160 | 1.85:1 | 8,631,360 |

lens, reflective mirror, and the emitted LCoS panels. The emitted RGB panels, which carry modulated LCoS video information, pass through dichroic filters and polarized beam splitters into a lens system to form an image on the screen.

2 Theory

An LCoS projector has two main components. One component is projection optics. The other is an LCoS panel as

a light source. The design of a projection system is based on two theoretical approaches. One approach involves applying image theory to projection optics, and the other enhances image quality using optimization of illumination.⁵

2.1 Image Formation and Illumination of the LCoS Projector

The high-performance short throw ratio LCoS projector yields wide-angle projection and high-contrast images. A movie shown on an LCoS is projected onto a wall or screen with a large field of view by a projection lens consisting of three emitted LCoS panels in the screen. This can produce a small throw ratio of less than 0.4. The collimated light source passes through integrated dichroic cubes to illuminate the LCoS RGB panels, and pixels in the LCoS panels coded with an image stream form frames of the movie.

2.2 Telecentric System

Because this type of emitted LCoS has a long optical path to the pupil; the ratio of the pupil's size to the optical path is larger than 3. Therefore, the lens must have a long back focal length. Furthermore, the projection requires a fixed size for the LCoS as an object while the best position is obtained during focusing.

It is necessary to apply a telecentric system to LCoS projection. Because the LCoS as an emitted object is integrated with prisms, this requires a long optical path to deliver the

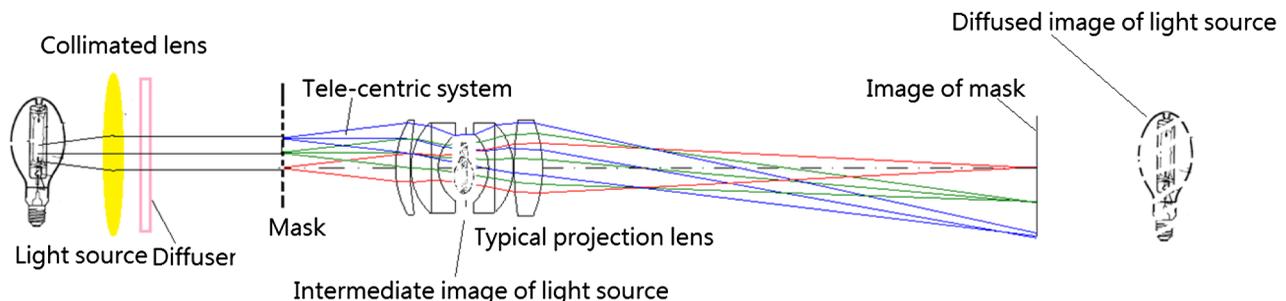


Fig. 2 Projection system with illumination and optics.

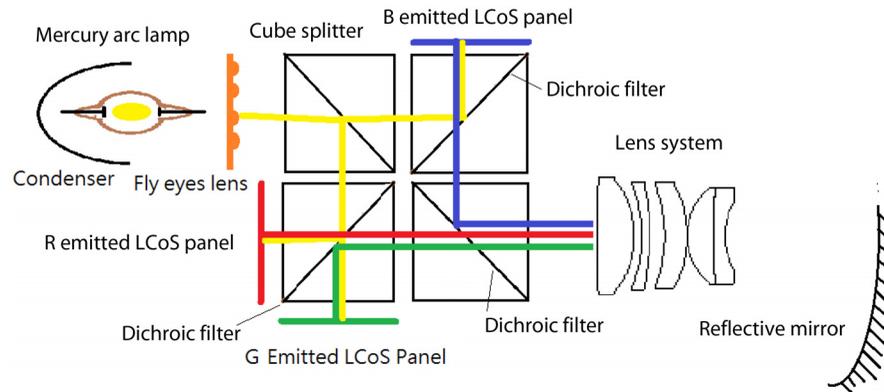


Fig. 3 Three-panel LCoS projection diagram.

emitted light source. Thus, a telecentric lens with proper aperture size must be designed to have a long back focal length.

Nevertheless, the telecentric system in the object side can separate the parallel axial rays and oblique axial rays from different optical paths. This easily forms coherence and partial coherence while the collimated light passes through to increase the contrast of the image plane.

The telecentric system can also project a nondistorted image or objects along the axis. Thus, this projection system can optimize the performance of the system. Using a telecentric system, the optical trace paths can be simplified analytically.

2.3 Koehler Illumination

Most projector designers only consider projection optics to be conjugate image systems that bring the panel to the screen. They neglect the effect of illumination such as the illumination of the projector. The partial coherence effect is an important factor that affects the performance of the projector. As previously discussed,⁴ two kinds of illumination are used in projection systems as shown in Fig. 4. One is Abbe illumination, and the other is Koehler illumination. For Abbe illumination, the object is focused by the light. However, for Koehler illumination, the object is illuminated by the collimated light. In general, optical lithography and projectors are projection systems, and most of the illumination for lithography is adapted using Koehler illumination because the critical dimension can be optimized to the minimum pitch of mask. This applies a partial coherence effect

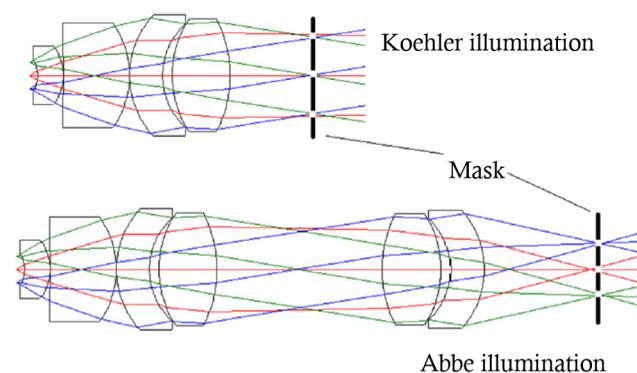


Fig. 4 Koehler illumination and Abbe illumination.

that can provide the best relative numerical aperture (RNA) to enhance the critical dimension by taking advantage of the ratio of the aperture of the lens and the aperture of Koehler illumination.

We introduce the Koehler structure light source to the short throw ratio projection because both are projection systems. The advantage of applying Koehler illumination to this system is that the emitted LCoS object obtained by telecentric optics generates a partial coherence effect in the system. Thus, the resolution of the image can be enhanced through projection optics.

In this study, a new design has been generated with two advantageous features. First, using the optical design of the telecentric lens with a conic reflector, the emitted LCoS panel is reimaged in a large field of view. Second, an enhanced image quality is obtained by applying partial coherence effect through Koehler illumination. As a result, the emitted LCoS generates parallel axis rays as the coherence and partial coherence illumination of the LCoS. As a light source, these are formed as a partial coherence image that integrates coherent and incoherent images. This optimizes the image and illumination, and the image quality becomes significantly enhanced.

2.4 Model of Components Build Up

In Fig. 3, the three LCoS panels are combined with all optical paths as one object, which forms a pseudo-Lambertian emission distribution as the telecentric source based on Koehler's type. The original light sources, such as the tunnel integrator illuminators or fly-eye arrays, are delivered by a condenser with a Koehler structure, providing the collimate light. This causes the light to hit the LCoS panel and bounce back in a specific direction. Thus, the LCoS panel emits the light and the rays are spread as an emitted object to form the parallel axial rays and oblique axial rays shown in Fig. 5.

2.5 Optical Design

The optical system is a crucial part of the projector system. Although forward-projecting refractive lenses are quite popular, the throw ratios they yield are almost above 1. However, the short throw projector is specially designed and fabricated to have a projection lens that produces a throw ratio under 0.5 or less.

The optical system requirements are listed in Table 2. In order to increase the projection angle of the short throw

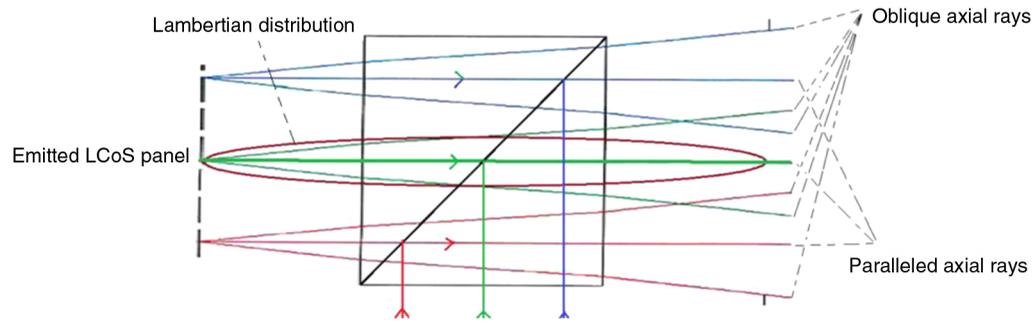


Fig. 5 The panel-emitted LCoS telecentric source.

Table 2 Specifications for theatre short throw factor lens.

| Specification for short throw factor lens | | |
|---|--|---------------------------|
| No. | Item | Specification |
| 1 | Projected screen in diagonal | 2500 mm |
| 2 | LCoS size | 1 in. |
| 3 | Pixels size square | 4 μm |
| 4 | Video format | 4K2K |
| 5 | Lens type | Refractive and reflective |
| 6 | Short distance to project between last mirror and screen | 666 mm |

projection, the LCoS image is formed on the screen in three steps. In the first step, an eyepiece lens delivers the LCoS image through the dichroic prisms to form the wide-angle curved image shown in Fig. 6. In the telecentric system defined in codeV, the principal rays from three fields of view that are parallel rays from all fields from the object are focused in one position as a common aperture, enabling all the rays to form an image. In the second step, the image is formed with a magnification greater than 1. The reflective mirror delivers the wide-angle curved image onto the screen or nonreflective wall as shown in Fig. 7. The enlarged and curved image is relayed to the final screen using a reflective mirror. Finally, in the third step, the image on the screen can be expanded and optimized by adjusting the conic value and radius of the reflective mirror as shown in Fig. 8.

It is worth mentioning that, in general, when designing a camera lens, the sight viewed is the object and the receiver is the image. However, in this design, the LCoS panel is

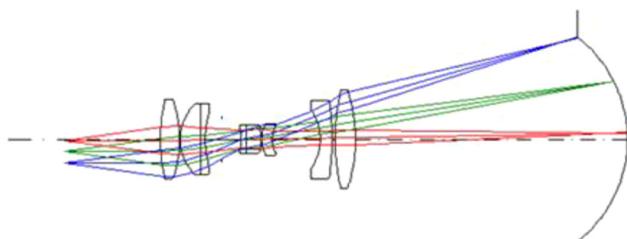


Fig. 6 The wide-angle eyepiece to broaden the field of view.

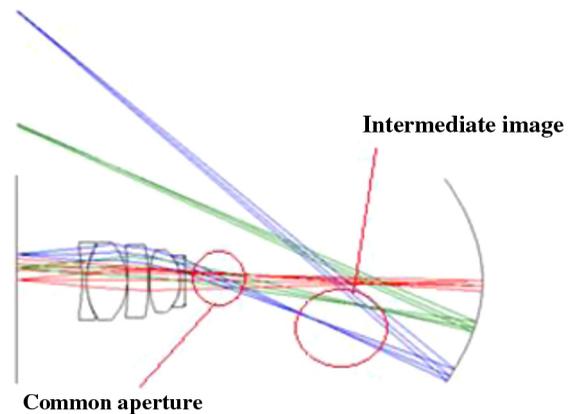


Fig. 7 The common aperture and intermediate image.

considered to be the object and the screen is displayed for viewers as an image. The advantage of this method is to directly evaluate the image quality and illumination on the viewer's side.

2.6 First Step

Because the LCoS panels are located separately at a relatively long distance from the last surface of the lens, a long back focal length lens is used to pull the image out of the panels. In the first step, an eyepiece-type lens used as a telecentric lens is selected to extract an instant image of the emitted panel. This is passed through a common aperture and spread out to form an enlarged and curved image. Figure 6 shows how to utilize a wide-angle eyepiece to broaden the field of view.

2.7 Second Step

In the second step, the curve that forms is optimized by selecting different types of lenses, such as an eyepiece and double Gauss. Each parallel axial ray forms a common aperture through the lens because of the telecentric effect. Light enters through the aperture, and the projection angle is enlarged. In accordance with mirror theory, the object is formed at a conic trajectory, broadening the field angle to achieve the best fit for magnifications larger than 1 as shown in Fig. 7. Thus, the final image on the screen is formed through the reflective mirror reimaged into the intermediate image.



Fig. 8 The LCoS image is formed on the screen through the refractive lens and reflective mirror.

2.8 Third Step

In the third step, the aspheric mirror is optimized to deliver the intermediate image such that it forms a broader image on the screen as shown in Fig. 8. The conic constant and radius of the aspheric mirror are adjusted iteratively until the spot sizes of each field are reduced. The parameters of the wide angle and short projection distance are then calculated.

2.9 Image Evaluation

Image evaluation will be carried out using spot diagrams and image distortion diagrams to instantly adjust the lens size, space, and material. This will generate the smallest and least amount of aberration spots. The third-order aberration for each lens provides instant information needed to adjust lens shape and other parameters to the best MTF.

2.10 Partial Coherence

According to partial coherence theory, the relative numerical aperture was introduced in the paper “On the diffraction theory of optics image” by Hopkins.⁶ The “phase-coherence” factor was introduced here. The correlation of phases

between wave disturbances at any two points of an illuminated surface may be specified. Thus, the optical image can be calculated accordingly. Using the codeV program, the partial image is calculated with the FFT of summation for the wave-front on the aperture for the lens and the wave-front on the aperture for the light source. By optimizing the optics formation and illumination, the image quality is enhanced. For the current evaluation of the image, the MTF is not able to describe the image quality in the minimum pitch. However, the partial coherence does describe this image form clearly. In the current research, the condenser and collimated lens using the Koehler model have been designed by optimizing the uniformity of illumination of the LCoS. The light of the interface of the integrator is uniform in amplitude and random in phase. When the Koehler model light source is applied, the light passing and reflecting back through each neighbor element can be aligned with the optical axis. This forms spatial coherence that can easily interfere in the image because the total pixels in the panel are formed as a two-dimensional grating with a fixed pitch.

For the calculations for image formation, each pixel in the image corresponds to individual ones in the LCoS. Two pixels in the same vicinity of a single LCoS have the phase correlation factor. Each pixel of an image corresponds to individual ones in the LCoS, and this is calculated. If we consider the coherence and noncoherence of an individual LCoS as a single pitch of the LCoS array, the light hitting the center of the LCoS could create interference in the image and coherence. The light hitting one edge of the LCoS could interfere with the vertical light to form the partial coherence. These two kinds of light may pass through the optics to form an image.

By applying the analysis of partial coherence to the LCoS projector, we can visualize each pixel in every field of the projected screen. By adjusting the RNA, the contrast of the smallest pitch in the image can be emphasized. The RNA is defined as the ratio of the diameter of the pupil of the light source to the diameter of the pupil of the lens as shown in Fig. 9.

An ideal module demonstrates the partial coherence effect in the smallest pitch. The module carries the same aberration with a different RNA. As shown in Fig. 10, if the RNA equals 0.0, the coherent images are blurry and the MTF is less than 0.1. If the RNA is 0.6, the partial images are clear and the MTF is 0.45.

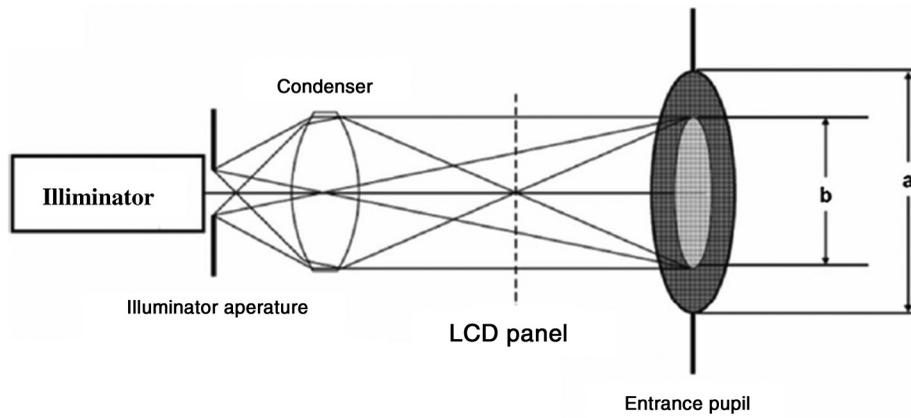
2.11 Fabrication

The system will be installed and tested in a three-panel LCoS system. In the Utmost Co. LCoS projector, the original lens is replaced, and the projector is mounted with newly designed optics to display the image. An optomechatronic mount between the LCoS engine and short throw ratio projection has been designed and fabricated. Several trials have been carried out in order to achieve an optimized image.

3 Experimental Setup and Simulation

3.1 LCoS Projection System

The LCoS projection system is shown in Fig. 11. Illumination requires a cube-formed RGB collimated source to shape the light into a pattern by the LCoS module. With pixel sizes as small as $4\ \mu\text{m}$, partial coherence becomes an important



$$\text{RNA} = \text{Relative Numerical Aperture} = \sigma \equiv \frac{b}{a} = \frac{\text{NA}(\text{illuminator})}{\text{NA}(\text{projection optics})}$$

Fig. 9 The diagram of relative numerical aperture.

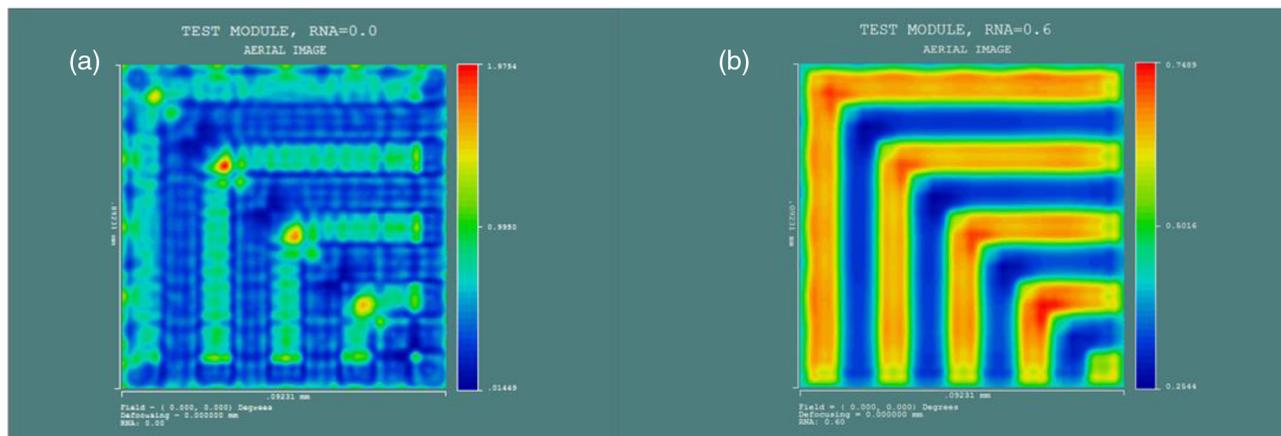


Fig. 10 Simulated images for (a) RNA = 0.0 and (b) RNA = 0.6.

factor for enhancing the minimum figure of a pixel for display on the screen. The emitted panel of the LCoS modulates the image reflector while the collimated rays propagate through the open-state liquid crystal and reflect back to the lens system. Thus, the emitted LCoS paralleled axis rays are the coherent light with pseudo-Lambertian illumination. The oblique axial rays are formed as incoherent light and as a partial coherence image. By using a projection lens, video information from the LCoS is projected onto a wall or screen with a large field of view and with a throw ratio of less than 0.3.

3.2 Numerical Calculation

CodeV 10.8 has MTF, wave-front, coupling efficiency, and longitudinal aberration methods that help achieve an optimized solution. Once the constrained conditions are defined, at least 100 runs of optimization are performed. The results for specification requirements are reached. The tolerance for tilting has also been determined by tilting different elements. The results are displayed in MTF graphs. CodeV can trace each point in space through the lens system to the target.

4 Results and Analysis

The design is shown in Fig. 12. The refractive lens applies a double Gauss to introduce the emitted spread because of the symmetric structure and minimal aberration induced.

4.1 Optical Evaluation

The conic aspheric mirror is used to relay the intermediate image to the screen. The conic constant ranges from 1.55 to 1.8 to form the image, and the distortion is less than 1%. An optical system for a 2048 mm × 1080 mm DCI 4K2K projected screen with a projecting distance of 666 mm and a throw ratio 0.3 has been designed. A minimum size of 500 μm for a 4-μm pixel in the LCoS is achieved, except for the pixels at the bottom of the screen.

4.2 Image Quality

Figure 13 shows the input object and output image. The image accurately represents the object. The relative illumination is shown in Fig. 14 before and after tuning the shape of the lens. It shows that the full screen is above 85%, which is the most optimized image for viewers.

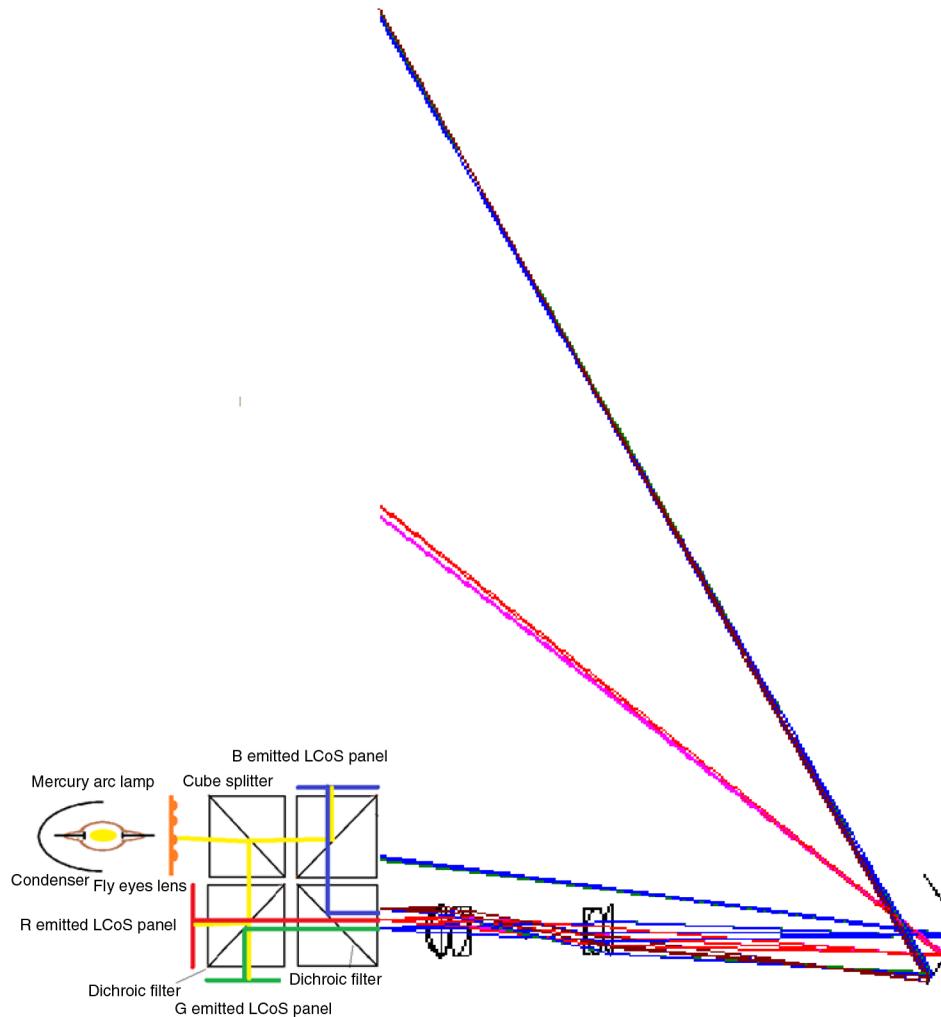


Fig. 11 The short throw ratio LCoS projection system with telecentric optics and Koehler illumination.

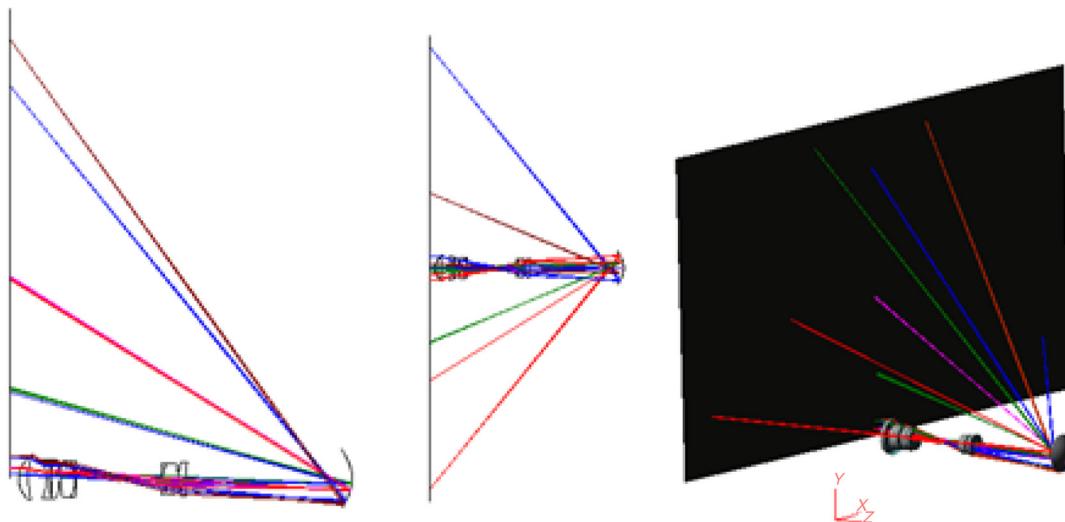


Fig. 12 The optical design for the short throw ratio projector.

4.3 Aberration

The field distortion is shown in Fig. 15. Initially, the distortion is high. However, by adjusting the conic constant of the reflective mirror, the distortion at the margin can be

minimized. Figure 16 shows the third-order aberration of the surfaces. The image aberration is almost eliminated in the image plane. The MTF is shown in Fig. 17. This shows that when the corresponding spatial frequency for the smallest

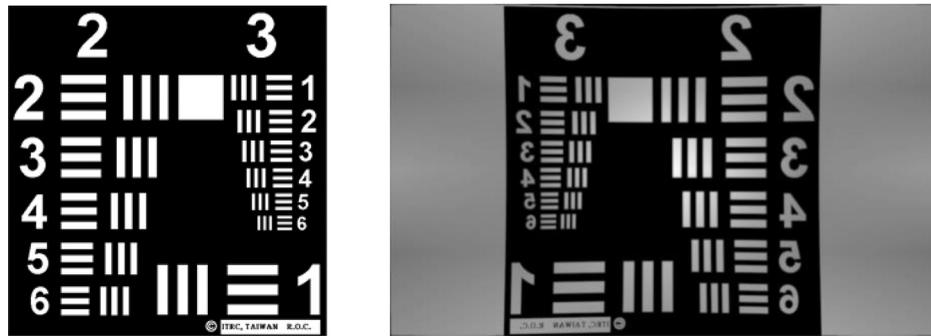


Fig. 13 The simulated object and image.

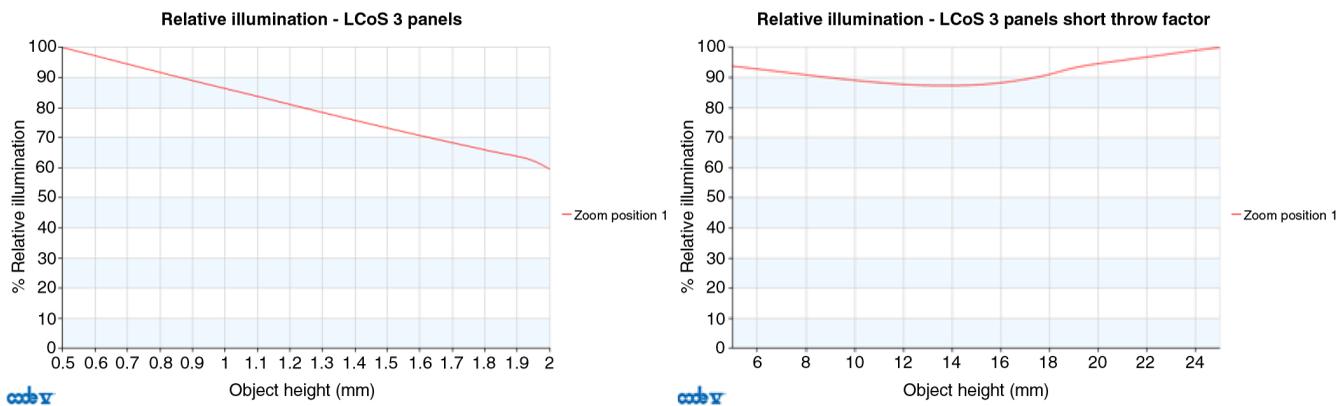


Fig. 14 The relative illumination before and after tuning the lens shape.

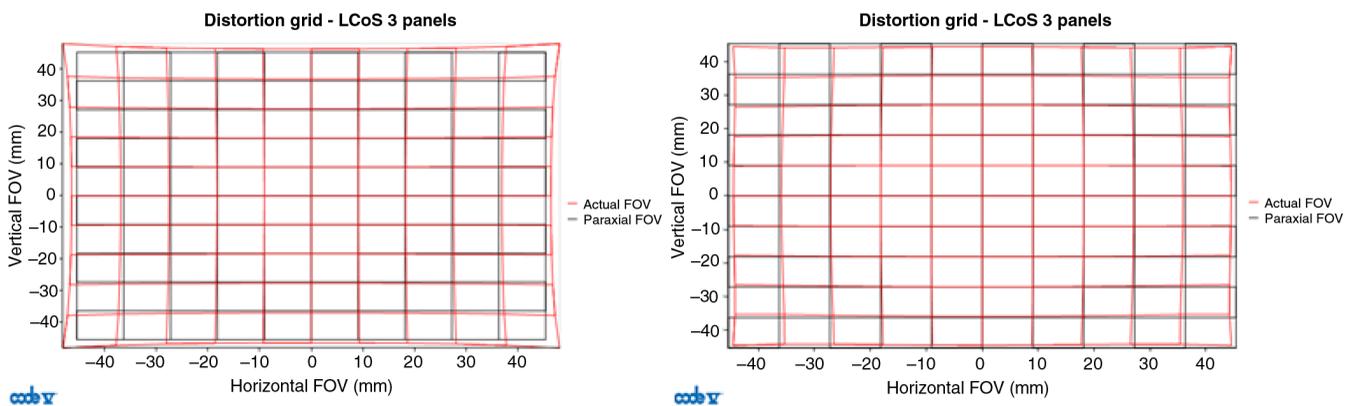


Fig. 15 The distortion before and after tuning the optical parameters.

size of the LCoS (2.5 lps/mm) is achieved, the MTF is still above 0.25.

4.4 Throw Factor Ratio

The short throw, wide-angle projection lens is different from other lens systems. According to Eq. (1), D' is the distance between the bottom side of the screen and the last lens or mirror.

$$\text{Throw ratio} = D'/W. \quad (1)$$

In this case, the throw ratio is 666 mm/2000 mm = 0.3.

4.5 Illumination and Partial Coherence Analysis

A partial coherence analysis has been applied in this case. Because the MTF cannot provide the full view to verify the requirements for 4K2K, the partial coherence distribution can fully display the pixels of the LCoS in each field to fulfill the requirements of the 4K2K. A four-bar pattern with a pitch of 0.004 mm corresponds to one pixel of the LCoS. This is projected in each field. The width of a pixel projected onto the screen is 500 μm , and the full screen is 2000 mm \times 1000 mm. For each pair, the resolution is 2.5 lps/mm, and it has 5K2.5K fulfilled to 4K2K, in addition to the field 0 deg. The RNA is set to 0.6 as shown in Fig. 18. The optical

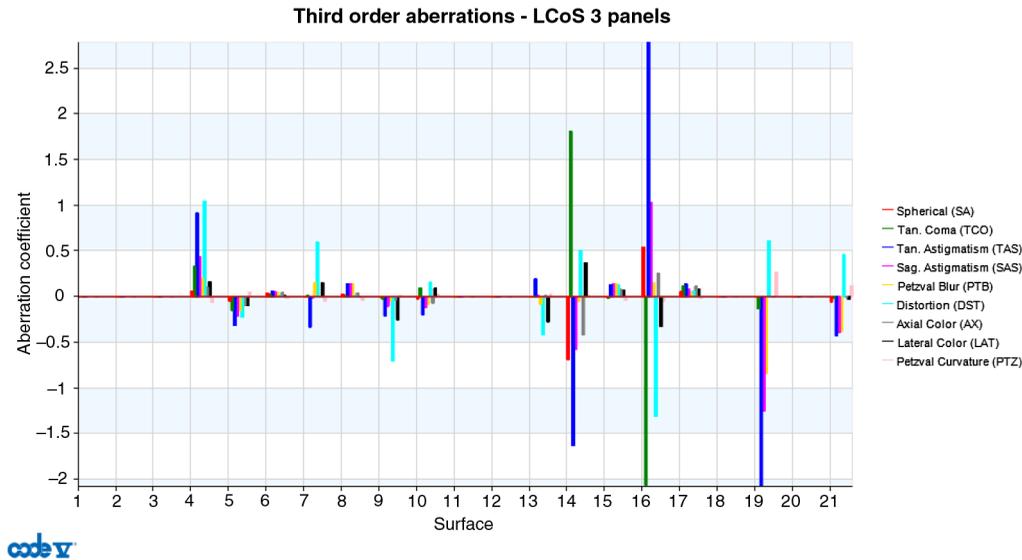


Fig. 16 The third-order aberration for each surface.

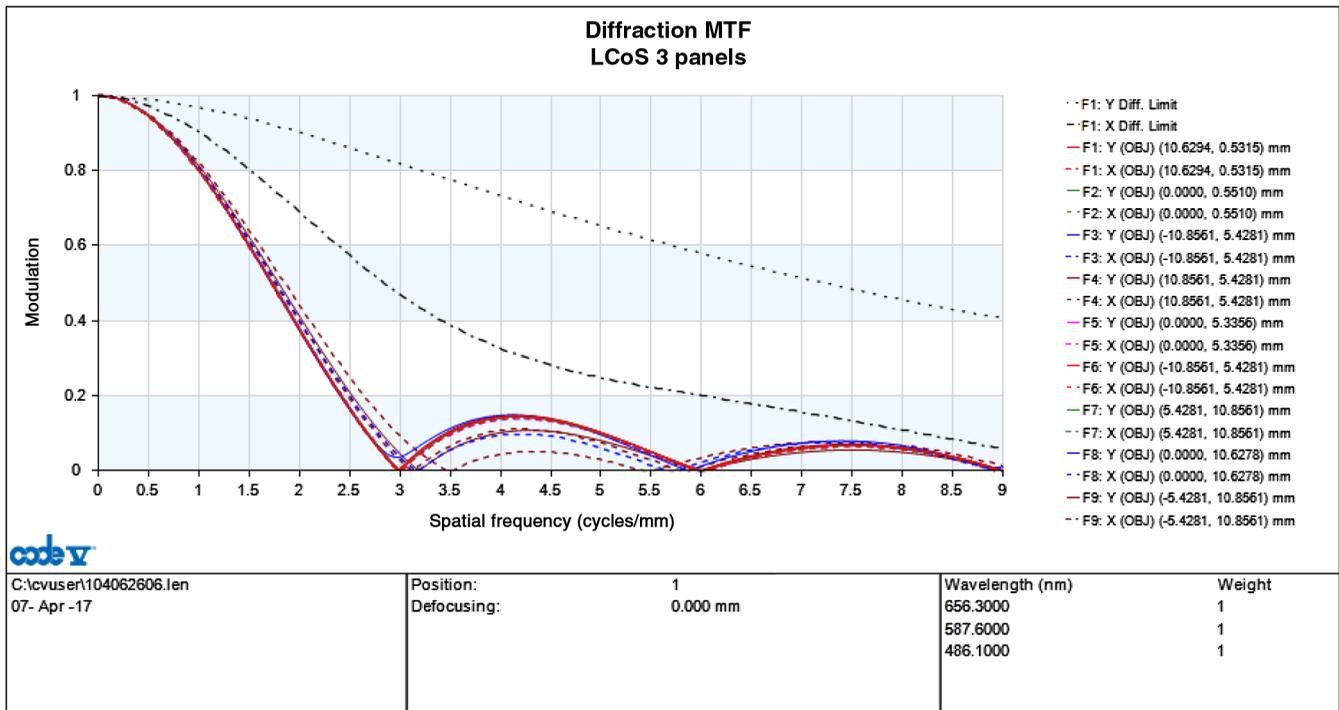


Fig. 17 The MTF of the short throw ratio projector.

system for a 2048 mm × 1080 mm DCI 4K2K projected screen with a projecting distance of 666 mm and a throw ratio of 0.3 has been designed. The minimum size is 500 μm to generate a 4-μm pixel in the LCoS, except at the bottom of the screen.^{6,7}

4.6 Relative Numerical Aperture and F/#

The F/# for the short throw wide-angle projection is different from other lens systems. There are two types of F/# that we consider. One is projection optics and the other is

illumination. Here, the LCoS has a light source that projects into the screen to form an image utilizing the Koehler model. If the LCoS is considered to be the object, the F/# of the projection lens is 3. However, if the screen is considered to be the object, the F/# of the lens will be the projection distance divided by the size of the aperture, which is about 40.

Cumulatively, our design fulfilled the requirements shown in Table 2. We fabricated and tested two configurations (one consisting of a seven-piece lens and the other an eight-piece lens) to produce a short throw ratio projection lens.

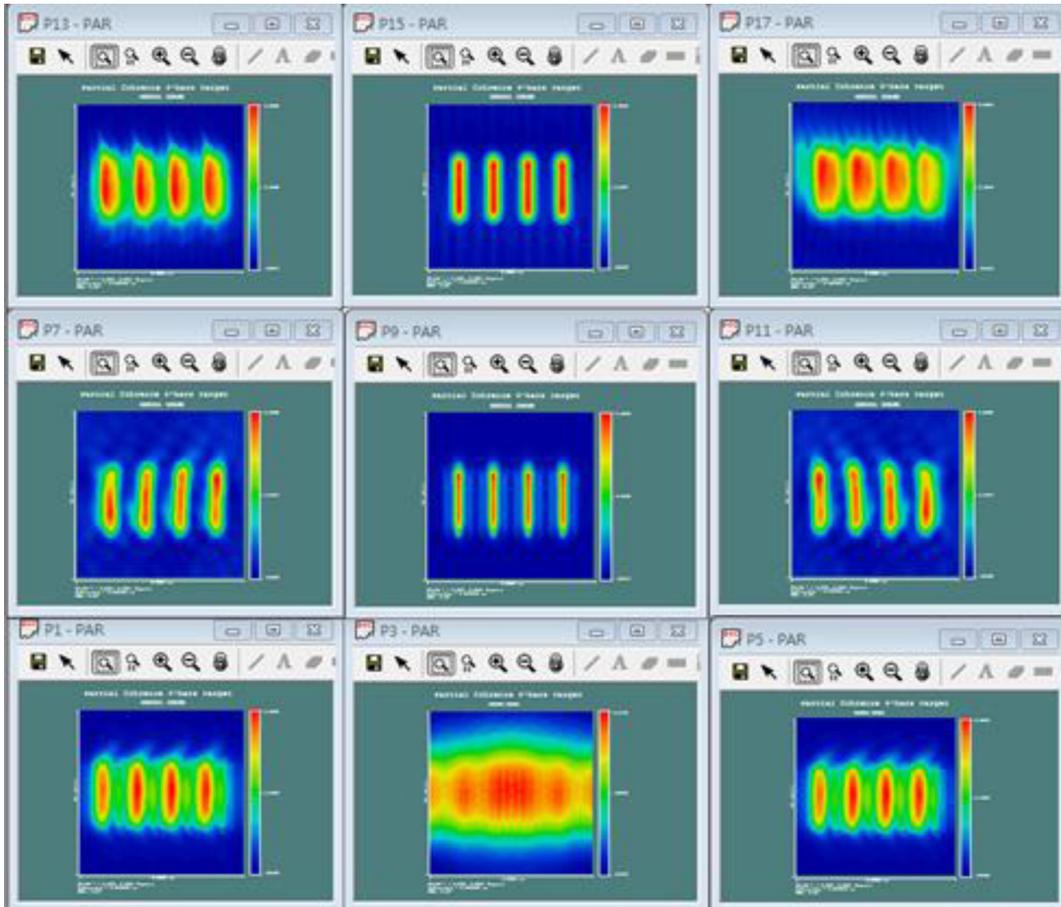


Fig. 18 Four-bar patterns with a pitch of $4 \mu\text{m}$ projected in each field with respect to each field.

4.7 Fabrication for Demonstration

For the Utmost Co. LCoS projector, the previous lens has been removed, and an ultrashort throw lens has been installed and tested as shown in Fig. 19. The optomechatronic mount between the LCoS engine and the short throw ratio projection has been designed for statically adjusting the focus. The performance is shown in Fig. 20 with an indoor light on and in Fig. 21 with an indoor light off. Figure 20 shows the image

produced for a movie projection and Fig. 21 displays the contrast characters on the screen. The throw ratio is 0.3. However, the image is blurred and out of focus because the manufacturing of the mirror is not precise. Further improvements in metrology are still needed. After a slight adjustment of the conic constant, lens radius, and spaces, the final image can be generated.

The analysis of the system is shown in Table 3. The throw ratio of the projection is less than 0.3, and it meets the requirement. The contrast of the projected image can be enhanced using the telecentric system. By modifying



Fig. 19 Utmost Co. LCoS projection engine with self-designed optics and optomechatronic mount.



Fig. 20 With an indoor light on.



Fig. 21 With an indoor light off.

Table 3 Comparison between design specifications and actual values.

| Optical specification for short throw factor lens | | | |
|---|--|---------------------------|---------------------------|
| No. | Item | Design specification | Actual |
| 1 | Pixels size in 1 m | 1 mm | <0.5 mm |
| 2 | Lens type | Refractive and reflective | Refractive and reflective |
| 3 | Short throw ratio | <0.4 | <0.3 |
| 4 | Illumination uniformity for all fields | >70% | 85% |
| 5 | Distortion | <4% | <2% |

Koehler illumination in the reflective LCoS panel, a clear image with high contrast can be displayed.

5 Conclusion

Using a design involving telecentric optics and Koehler illumination integrated into the projection, optimized optical parameters can be achieved to produce the best performance. The result is better than that of other projectors. As these systems continue to be manufactured, further optimizations should be expected. The partial coherence analysis has been used to verify the 4K2K system.

This study presents the design of a short throw projector optical system. The throw ratio is 0.3 with a single aspheric mirror and the smallest number of sphere lenses. This system consists of a wide-angle projection lens with a partial coherence source parameter. The procedures used to design the system and optimize illumination are presented.

5.1 Very Short Projecting Distance Optical System

The throw ratio is less than 0.2, whereas the tilt in the mirror is at an angle of 8 deg. In Fig. 22, the throw ratio is 0.186663. However, the image may be a keystone, and it can be corrected using the Scheimpflug effect. The image may be corrected by slightly tilting the object to form an undistorted image.

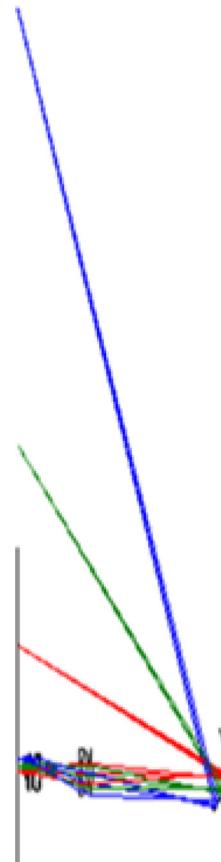


Fig. 22 Tilt-mirror projector.

5.2 Other Issues

The system can zoom to various distances using the first lens, and the zoom ratio is 1:1.33. The optical system will be fabricated and installed in a three-panel forward-facing projector system. The tolerances for this design are provided for the adapted optical mechanism. Other projectors, such as the automobile HUD, virtual reality, glass-type display, and smart phone external display, can easily be adapted.

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