Chapter 11

Design and Fabrication of Ultra-Short Throw Ratio Projector Based on Liquid Crystal on Silicon

Jiun-Woei Huang

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.72670

Abstract

One of applications for liquid crystal on silicon (LCoS) could be an emitted light panel for display and projection. Among optical projectors, the most challenging work is to design ultra-short throw projection systems for LCoS projector for home cinema, virtual reality (VR), head-up display (HUD) in automobile. The chapter discloses the design and fabrication of such kind of projector. In fact, such design is not only to design wide angle projection optics but also to optimize illumination for LCoS in order to have high-quality image. The projector optical system is simply with a telecentric field lens and inlet optics of symmetric double gauss or a large angle eyepiece, with a conic aspheric mirror, thus the full projection angle large than 155°. Applying Koehler illumination, the resolution of image is increased; thus, the modulation transfer function of image in high spatial frequency is increased to form the high-quality illuminated image. Based on telecentric lens type of projection systems and Koehler illumination, optical parameters are provided. The partial coherence analysis has verified that the design is reached to 2.5 lps/mm within 2 × 1.5 m. The best performance of systems has been achieved. The throw ratio is less than 0.25 with HD format.

Keywords: LCoS, Koehler illumination, telecentric, ultra-short throw ratio

1. Introduction

The mass requirement for display as viewing accessory has been applied toward the smart phone, HUD, and computers, home games, and home cinema. Projector has been one of the display tools for classrooms, family rooms or theaters, while the LCD display cannot be fully replaced due to its unique characteristics of adjustable view angle and size, and environmental protection issue.

Since two decades ago, rear projection TV has been used the projection in the back to image in the back of screen then formed in the front screen, to the forward projection LCoS refractive projection systems, the throw ratio is 1.4 to 1.6, recently, Sony short throw projection LSPX-W1 has announced the throw ratio to less than 0.5 [2].

In the past decade, several companies [3] had announced reflective-type projectors could provide the short ratio projection under 0.5, and Sony [4] has announced the throw ratio to less than 0.2, even it is posted in **Figure 1**, yet it is still no unique solution for such kind design disclosure. Thales [5, 7] reports that several reflective design are suggested by using optical deviated and tilted method, yet the engineering is enable to be carried.

1.1. The advantage of LCoS applicable in show throw ratio projector

Digital light processing (DLP) has been a display device based on optical micro-electro-mechanical structures. In DLP projectors, the image is created by microscopically small mirrors laid out in a matrix on a semiconductor chip, known as a digital micro-mirror. In addition, it has been popularly used in the projectors, and due to each element in DLP mechanical driving, it has limited to drive in high-speed image display. However, LCoS display modulates the emitted liquid crystal, which is much faster than mechanical driving panel. The other evaluating factor is color contrast and duration. Based on reflective coating in silicon, the efficiency of true color and duration is superior to DLP. The typical LCoS is shown in **Figure 2**.

1.2. Short throw ratio projection optics

For those forward-projecting diffractive lens are quite popular, yet the throw ratios almost is above 1, thus, the project is especially to design and fabricate a lens for throw ratio under 0.5 or less and is hard to achieve. To design short throw ratio of projection lens which is different from other projection lens with refractive lens, the performance of system is short

Figure 1. Sony short throw ratio projector for home theater.

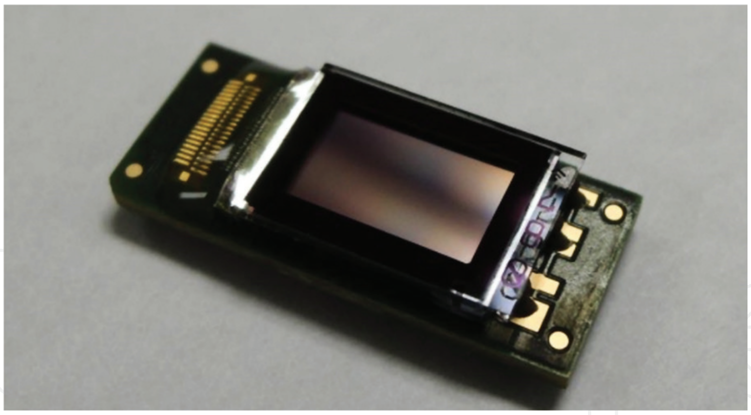

Figure 2. Typical LCoS panel and output circuit.

throw ratio and compact. Especially, for LCoS projector, the emitted panel, such as liquid crystal on silicon chip (LCoS), has to be emitted by light. The three panels of LCoS projector are shown in **Figure 3**. Emitted RGB panels, carrying modulated LCD video information, pass through di-chloic filters and polarized beam splitters into lens system to form image on screen. Obviously, the lens for delivering image is crucial part in the projector. Because reflective can reduce the size, enlarge the projection angle, and make system packed, it is the best for short throw projector. The image has to be delivered out from LCoS, the optical system, thus, it is proper to design projector by a reflective mirror to project a wide screen with very short distance and wide angle system.

1.3. The HD format and the short throw ratio

To classify the projectors' format, the standard video format for ultra-high definition television is shown in **Table 1**. In this case, the image format DCI 4K: 4096 × 2160 is applied.

1.4. The definition of throw ratio

Usually, the definition of throw ratio is D/W, but for the short throw projector, the throw ratio is defined W/D'. D' is the distance between the bottom side of screen to the last lens or mirror.

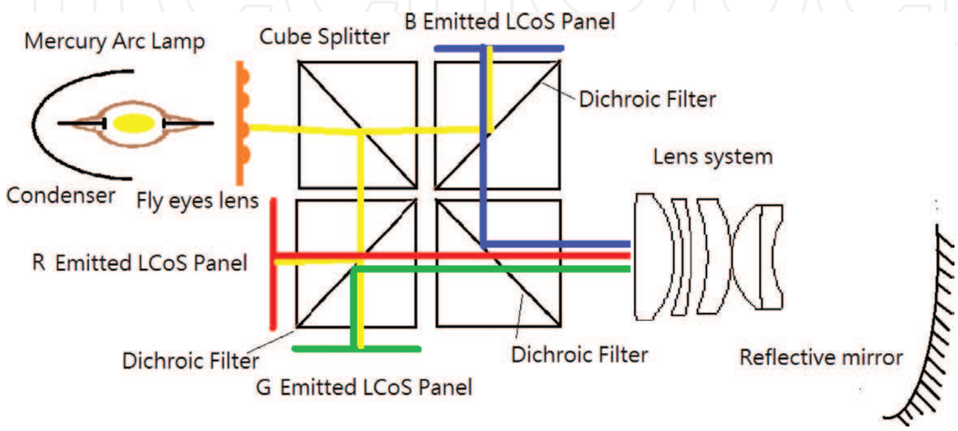

Figure 3. Three-panel LCoS projection diagrams.

Format	Resolution	Display aspect ratio	Pixels
Ultra high definition television	3840 × 2160	1.78:1 (16:9)	8,294,400
Ultra wide 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

Table 1. The format for ultra-high-definition television.

In **Figure 4**, the throw ratio is the ratio of the distance from the lens to the screen (throw) to the screen width. A larger throw ratio corresponds to a more tightly focused optical system.

This projection lens is to reimage of each pixel of LCoS to the projected screen truly, the performance is emphasized the image of LCoS elements, and the size of the object less one LCoS element becomes less important. In three pieces LCoS Panels system, the pixel is 4 μm, and the minimum size is for 2048 × 1080 mm DCI 4K2K projected screen.

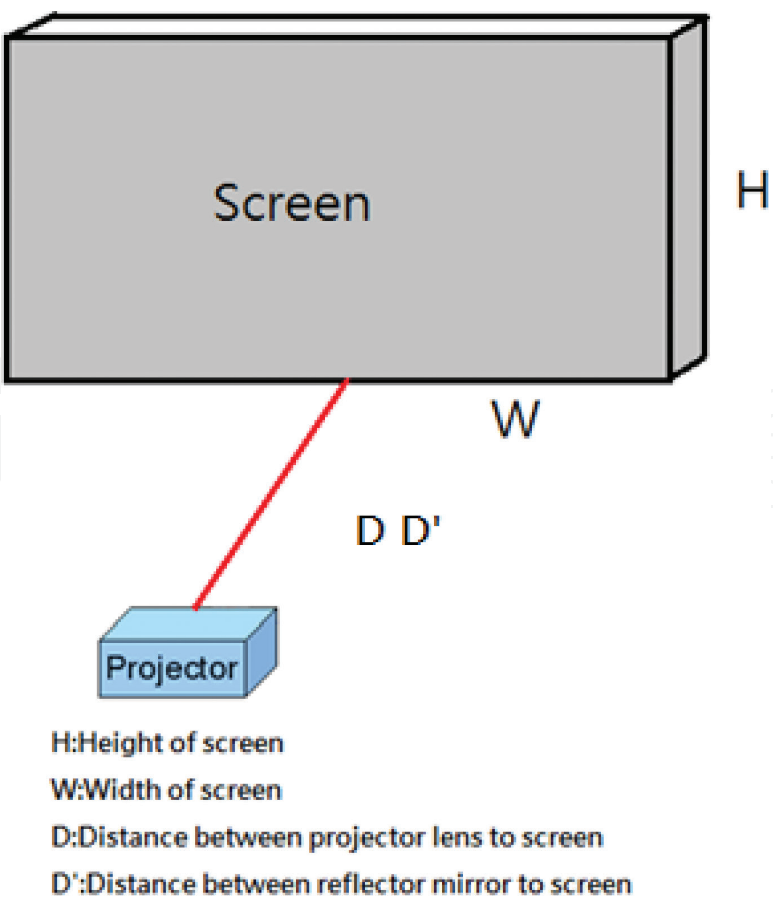

Figure 4. The view to show throw ratio.

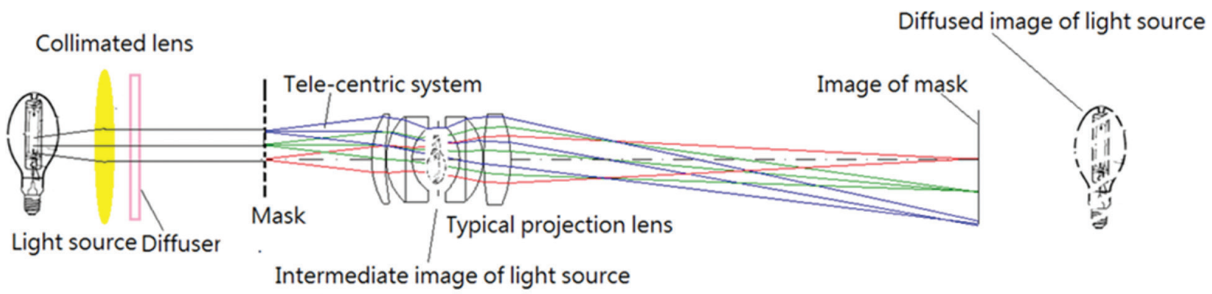

Figure 5. Projection system with illumination and optics.

1.5. The projection system

To design and fabrication of projection system has included two parts: one is imaging, and the other is illumination, [1] and it is desirable that the deterministic optical parameters to optimize the contrast of image requirement must be considered with full consideration of illumination and imaging. **Figure 5** is an illustration of projection system with illumination and optics.

2. Theory

To design projection system has considered two aspects: one is imaging, and the other is illumination, [1] and the theories are explained in the following [6].

2.1. Koehler illumination and telecentric

The liquid crystal on silicon (LCoS) projector includes a cube formed RGB panel with collimated source and projection lens. The illumination requires a cube formed RGB collimated source to introduce the light into pattern by the LCoS module. By a projection lens, the meaningful video information in LCoS is projected into a wall or screen with large field of view, up to throw ratio less than 0.4. In the design, illumination and image require the optimized parameters to form highly demanded images. In order to optimize these systems, the theory of Koehler illumination and telecentric optical system are chosen.

2.1.1. Telecentric system

The telecentric is best fitted for short throw projection system because telecentric in the object side can separate the central object rays and margin rays with different optical path and increase the contrast of image plane [10, 12, 14]. Moreover, the telecentric system can provide the non-distorted image or object along optical axis, and the projection system is easy to be optimized.

2.1.2. Koehler illumination

Koehler illumination [1] is the light source imaged in aperture, while the rays are collimated in LCoS panel. Due to the panels requiring uniform intensity in optical axis in order to keep polarization and coherence, the high performance platform often selects Koehler illumination.

Being designed by telecentric and Koehler illumination, the best performance of systems, having the optimized optical parameters, could be achieved.

2.2. Model of components build up

First, the emitted panel is stimulated by using a paralleled light bundle of mercury light source to hit LCoS panel. Rays, spreading as an emitted object, are shown in **Figure 4**. In the system, three LCoS panels are combined paths as one object, which is pseudo Lambertian distribution in ray field. It acts as telecentric source, shown in **Figure 6**.

2.3. Optical design

The optical system requirement is listed in **Table 2**. In order to enlarge the projection angle, the optical system of the short throw projection includes two parts, one is refractive lens system, and the other is reflective mirror. In **Figure 7**, a telecentric system is defined, and the principal rays from three fields as parallel rays, from the object, will be focused in one position as common aperture, while the other rays form image. Thus, the image will be formed with reduction value greater than 1. The intermediate image is relayed to the final screen with a

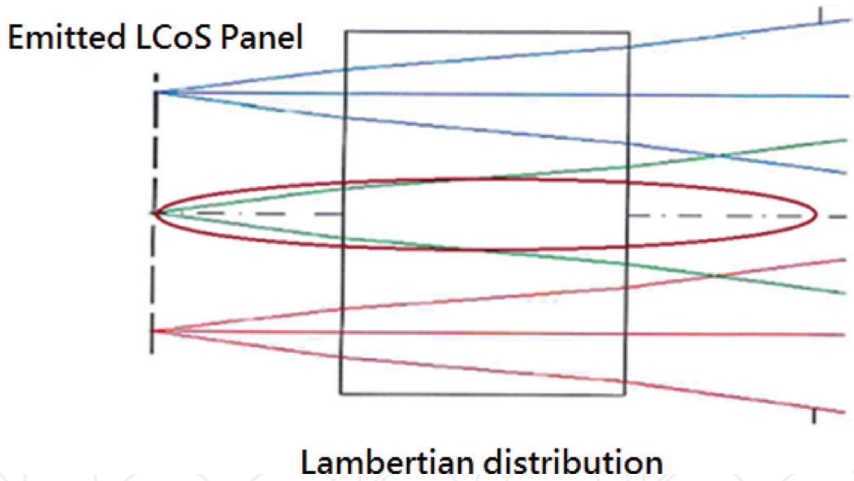

Figure 6. The common aperture and intermediate image.

Specification for short throw factor lens	
Items	**Specification**
Projected screen	2500 mm in diagonal
LCoS size	1 inch
Pixels size	4 μ^2
Video format	4K2K
Lens type	Refractive and reflective
Short distance to project between last mirror and screen	666 mm

Table 2. The specification for theater short throw factor lens.

similar method by adjusting the conic curvature of reflective mirror. The image on screen can be expanded and optimized by adjusting the conic value and radius of reflective mirror.

In a typical case, the design has passed through three stages, which are given as follows.

2.3.1. Initial stage

The initial stage is setup delivering optics. The lens, such as double gauss or eyepiece types in **Figure 8**, will pull instant image of emitted panel out to pass through common aperture and spread out to form an intermediate image and to broad the field of view, as shown in **Figure 9**.

2.3.2. Middle stage

In **Figure 10**, each principal rays formed common aperture due to telecentric effect. Light passing through the aperture and convergent, the projection angle can be enlarged. Because

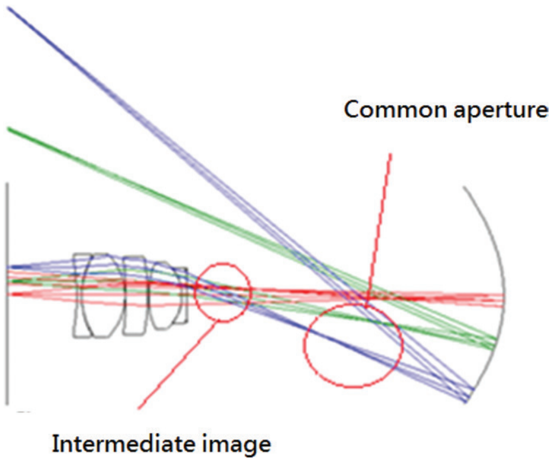

Figure 7. The common aperture and intermediate image.

Figure 8. Symmetric double gauss and wide eye-piece types.

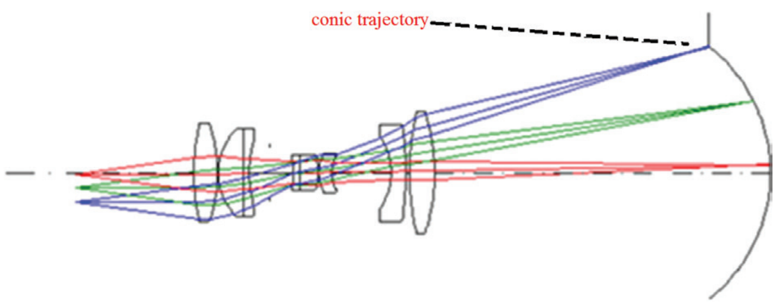

Figure 9. The wide-angle eyepiece to broad the field of view.

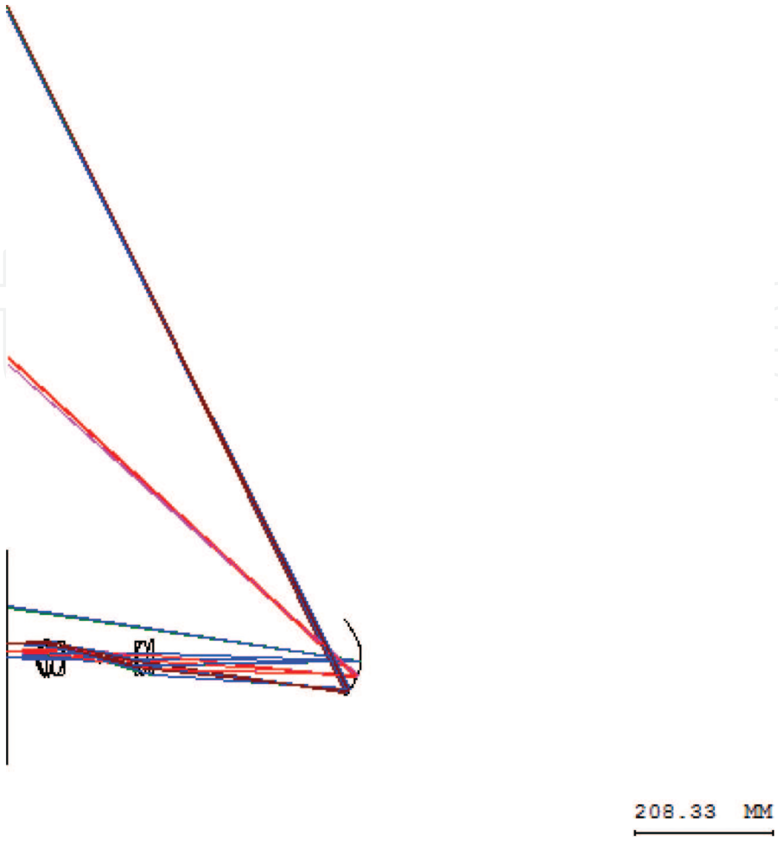

Figure 10. Design in middle stage.

the final image has to be formed in plane, the previous intermediated image has to be a conic trajectory. By mirror theory, the object forms a conic trajectory to broaden the field angle, as in **Figure 10**. Thus, the final image will be placed through the reflective mirror.

2.3.3. Final stage

In the final stage, the intermediate image, coupling with a mirror, forms a broad view image on the screen. The intermediate image relays on the final screen with a similar method by a reflective mirror, shown in **Figure 11**. The whole system has to be optimized in the constraint optical parameters. The optimized condition can be reached [8].

2.4. Image evaluation

Image evaluation has been carried out by evaluation of spot diagrams, image distortion diagram, to instant adjust the lens size, space and material in order to reach the small and less aberration spot. The third aberration for each lens provides the instant information to adjust lens shape and other parameters to the final stage.

2.5. Partial coherence

Illumination could be calculated by illumination program. The condenser and collimated lens could be designed by optimizing the uniformity of illumination of LCoS. For detailed calculation

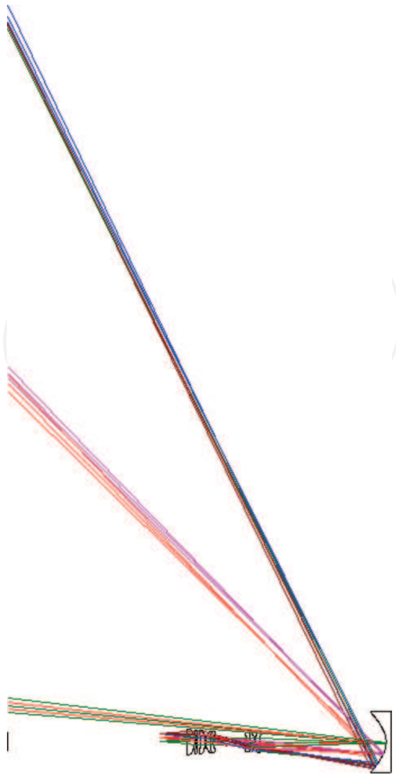

Figure 11. Design in the final stage.

of image formation, each emitted element in LCoS, two vicinities will not be correlated according to the calculation. If the polarization is considered, two coherence sources may just be passing through, and two bundles of coherent photo will never be interfered. In practical condition, this always happens, that is, once the two bundle groups of photo are partially coherent, the partial coherence should be calculated.

2.6. Fabrication

The system has been verified in a projector, without lens, by a 3-panel LCoS system. The optics system totally replaces the previous lens to demo the function.

3. Simulation

Simulation is mentioned below [3, 5, 6].

3.1. LCoS projection structure

LCoS reflective-type projection system is shown in **Figure 12**. The illumination requires a cube formed RGB collimated source to introduce the light into pattern by LCoS module.

The emitted LCoS panel as modulate image reflector, while the collimated rays propagate through the open-state liquid crystal and reflecting back to lens system, thus it can be modified type Koehler illumination. By a projection lens, the meaningful video information in LCoS is projected on a wall or screen with large field of view, up to throw ratio less than 0.3 [9, 11, 13].

3.2. Numerical calculation

codeV (an optical design software) is used in the study [5]. codeV provides MTF, wave-front, coupling efficiency and longitudinal aberration methods to reach the optimized solution. The program-constrained conditions are defined, and at least 100 runs of optimization are performed. The result for requirement of specification is reached. The tolerance of tilted optics has also performed by tilting different elements. The results are expressed in MTF graphs. codeV almost can trace each point in the space through the lens system to target.

3.3. Image quality

The design is shown in **Figure 13**. The refractive lens is to apply double gauss delivering the emitted to spread out due to the symmetric structure and less aberration induced. **Figure 14** shows the comparison between input object and output image, and the output image could truly describe the object with slight pincushion distortion. **Figure 15** shows

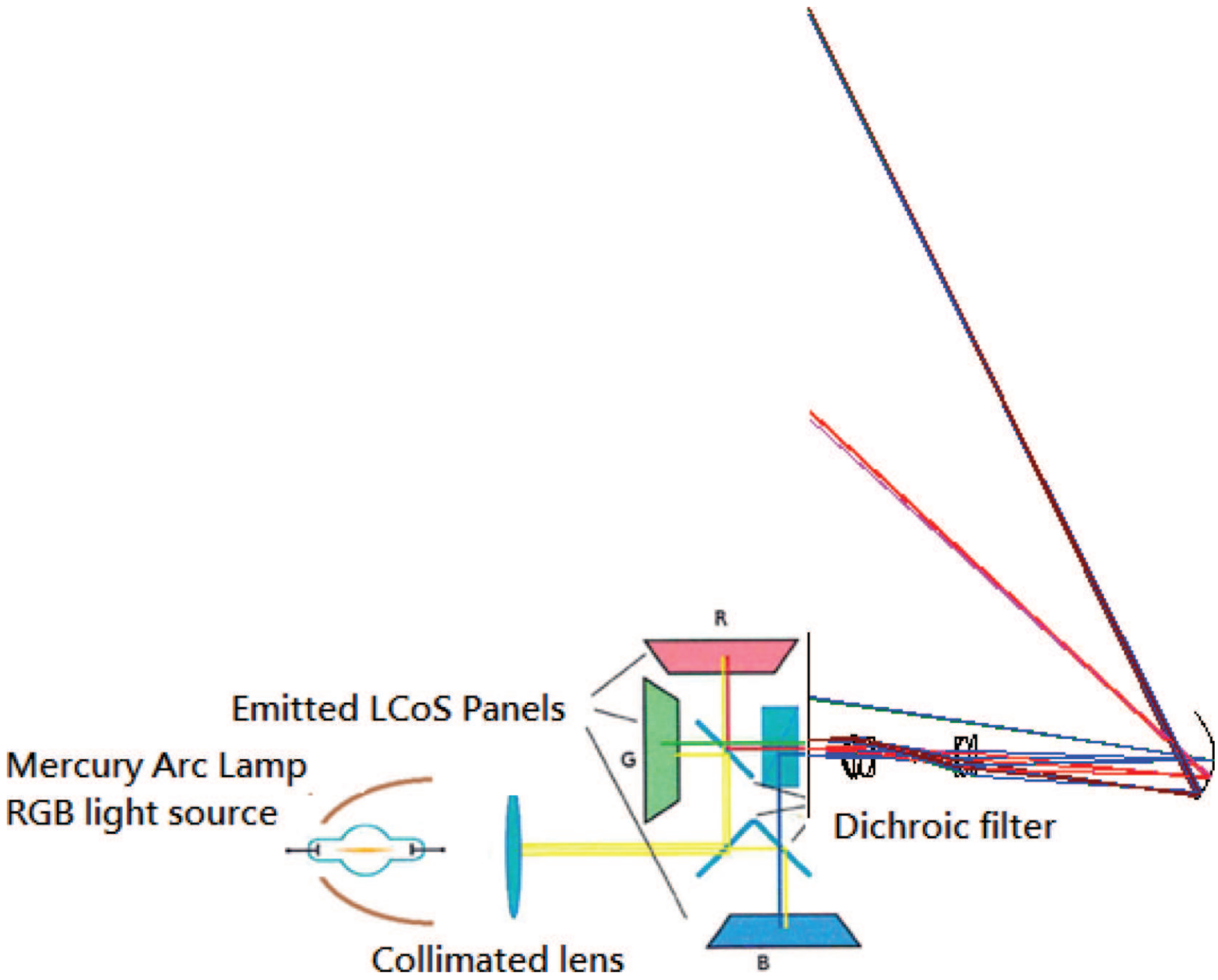

Figure 12. The short throw ratio LCoS projection system with Koehler illumination and telecentric optics.

http://dx.doi.org/10.5772/intechopen.72670

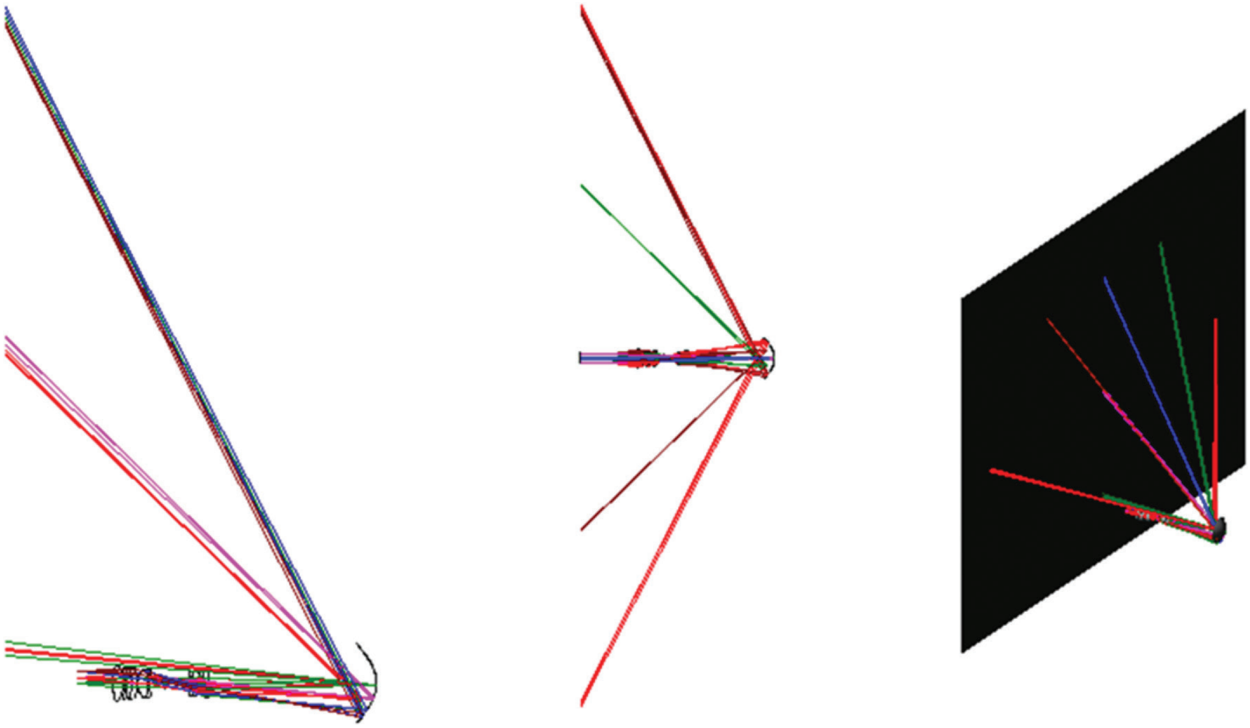

Figure 13. The optical design for short throw ratio projector.

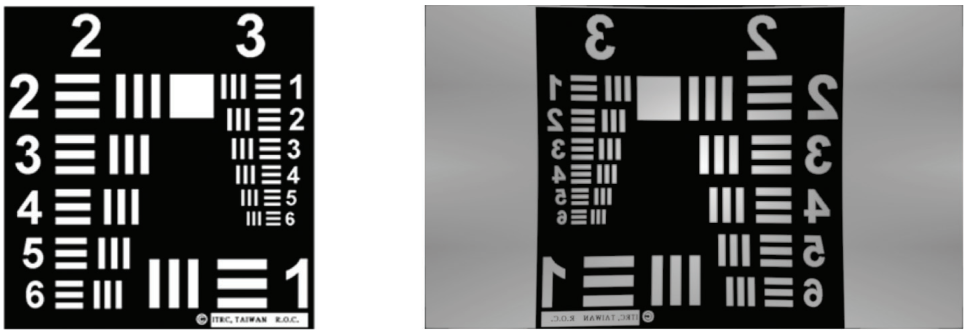

Figure 14. The simulated object and image.

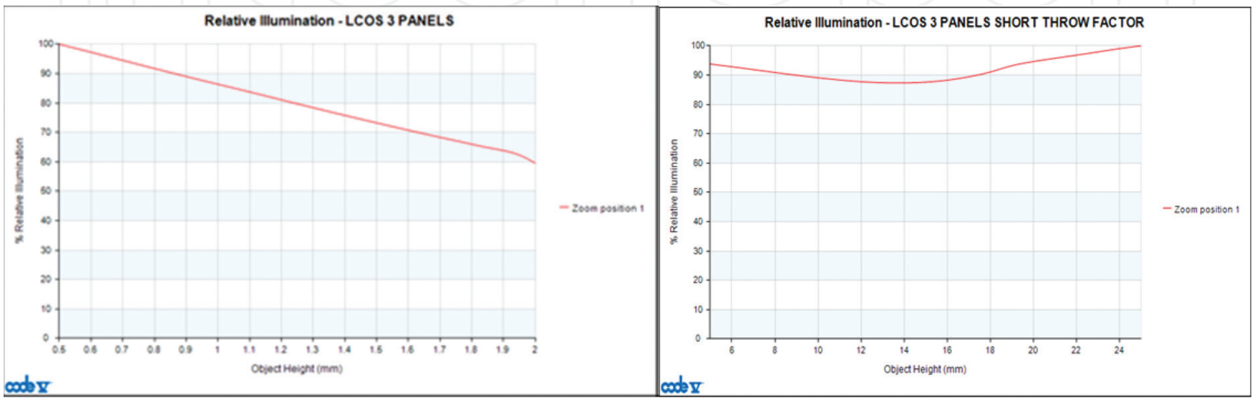

Figure 15. The relative illumination between before and after tuning the lens shapes.

the relative illumination between before and after optimization. Optimize illumination shows that the full screen is above 70%, for the the full field of view is fitted for human eyes.

3.4. Aberration

Figure 16 shows the field distortion between before and after optimization. Initially, the distortion was high, and after adjusting the conic constant of reflective mirror, the distortion in the margin becomes straight and less distorted. **Figure 17** shows the third-order aberration of surfaces. The image aberration is almost reduced to the least in the image

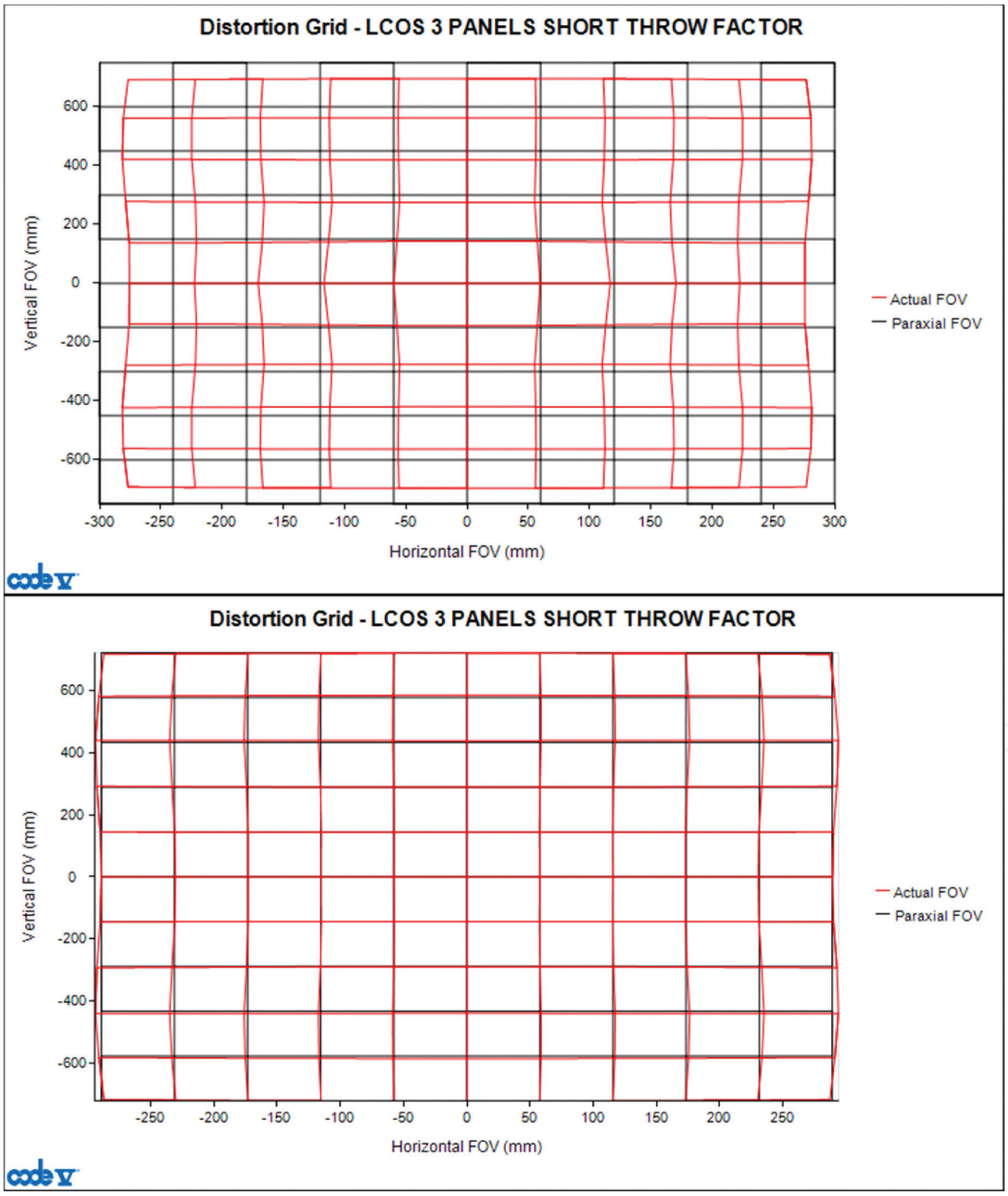

Figure 16. The distortion before and after tuning the optical parameter.

http://dx.doi.org/10.5772/intechopen.72670

plane. The MTF is shown in **Figure 18**. It shows the corresponded spatial frequency for the LCoS is still above 0.25.

3.5. Optical evaluation

The conic aspheric mirror is used to relay the intermediate image on screen. The conic constant keeps in 1.55–1.8 to form image and distortion is less than 1%. The optical system for 2048 mm × 1080 m DCI 4K2K projected screen with projecting distance 670 mm with throw ratio 0.33 is designed, and the minimum size 500 μm for the corresponded 4 μm pixel of LCoS is reached, except for the bottom of the screen.

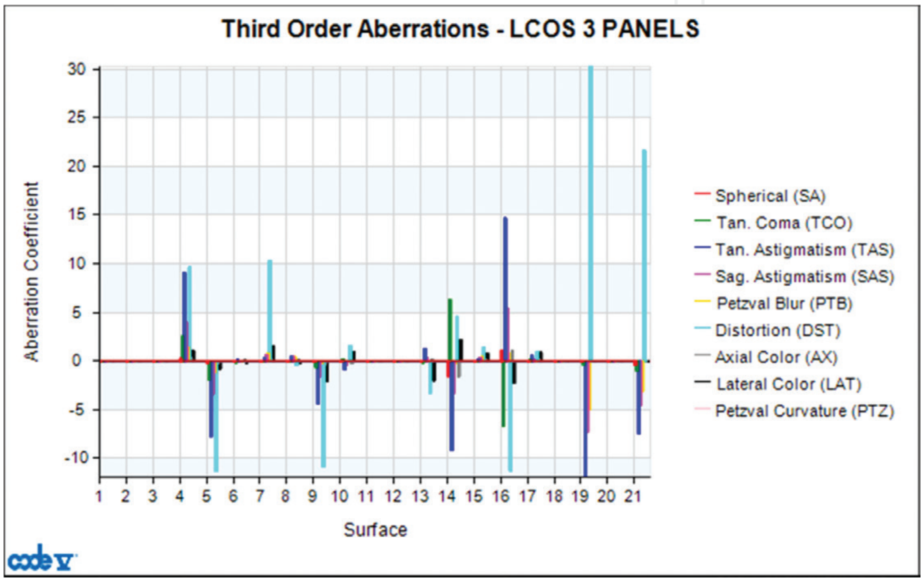

Figure 17. The third-order aberration for each surface.

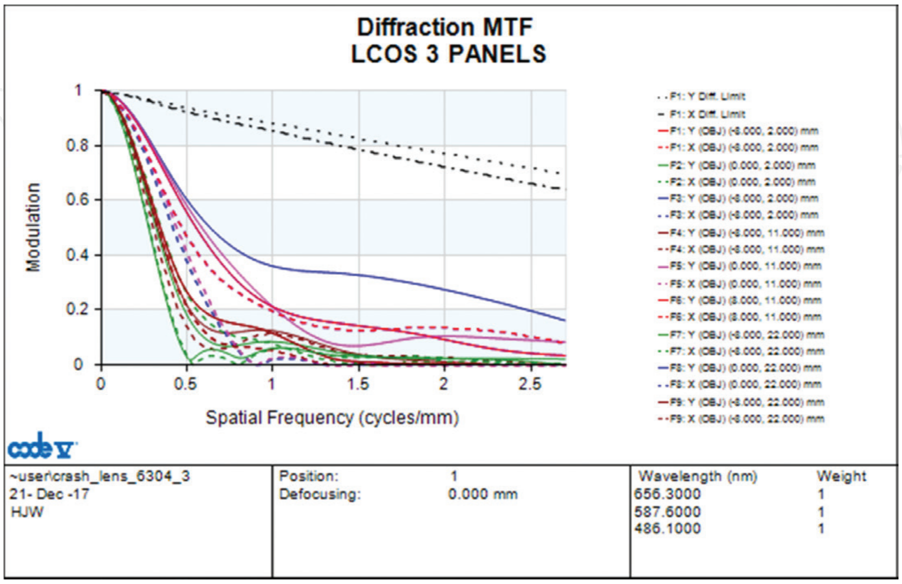

Figure 18. The MTF of short throw ratio projector.

4. Prototype and analysis

4.1. Fabrication for demonstration

In **Figure 19**, the utmost Co LCoS projector with the lens is adapted as emitted panel or effective light source. The opto-mechatronic mount between LCoS engine and short throw ratio projection are built. The performance is ready to be verified at room light on and at room light off, as shown in **Figures 20** and **21**, respectively.

In this case, 2048 mm × 1080 m DCI 4K2K projected screen with projecting distance 670 mm with throw ratio 0.3 is designed, and the minimum size 500 μm for the corresponded 4 μm pixel of LCoS is reached, except for the bottom of the screen.

In **Table 3**, the analysis of the system is explained as follows:

1. The throw ratio of projection is less than 0.3 and reaches the requirement.
2. The contrast of projected image can be enhanced by using telecentric system.
3. By modifying Koehler illumination in reflective LCoS panel, the clear image with high contrast will be viewed.

4.2. The throw factor ratio

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

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

In this case, the throw ratio 666/2000 mm = 0.333.

4.3. Illumination and partial coherence analysis

The partial coherence analysis has been applied to this case. Because MTF cannot provide the full view to verify the requirement of 4K2K, the partial coherence distribution can fully

Figure 19. Utmost Co. LCoS projection engine with the self-designed optics and opto-mechatronic mount.

Figure 20. At room light on (day).

present pixels of LCoS in each field to fulfill the requirement of 4K2K. A 4-bar pattern with the pitch of 0.004 μ corresponded to one pixel of LCoS is projected in each field respect to each field. The width of pitch projected on screen is 0.5 mm, and with the full screen, it is 2000 × 1000 mm^2. For each pair, the resolution has reached 2.5 lps/mm, and has 5K2.5K fulfilled 4K2K, beside the field 0°. By setting relative numerical aperture (RNA) 0.6, the partial coherence analysis is shown in **Figure 22**. All the fields are resolvable except blur bottom of the screen.

4.4. The number aperture and F/#

The F/# for the short throw and wide-angle projection, different from other lens systems, has considered two f/#; one is optical system and the other is illumination. Here, the LCoS as light source projects onto the screen to form image, as the source of the Koehler model. The F/# of projection lens is 3 and F/# of each pixel of as effective light source is 40, thus the relative numerical aperture is applied.

Figure 21. At room light on (night).

No.	Specification for short throw factor lens		
	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

Table 3. The comparison between design specification and actual value.

The result and analysis are mentioned as follows: The design has fulfilled the requirement as shown in **Table 2**. Two configurations of short throw ratio projection lens are fabricated and under test.

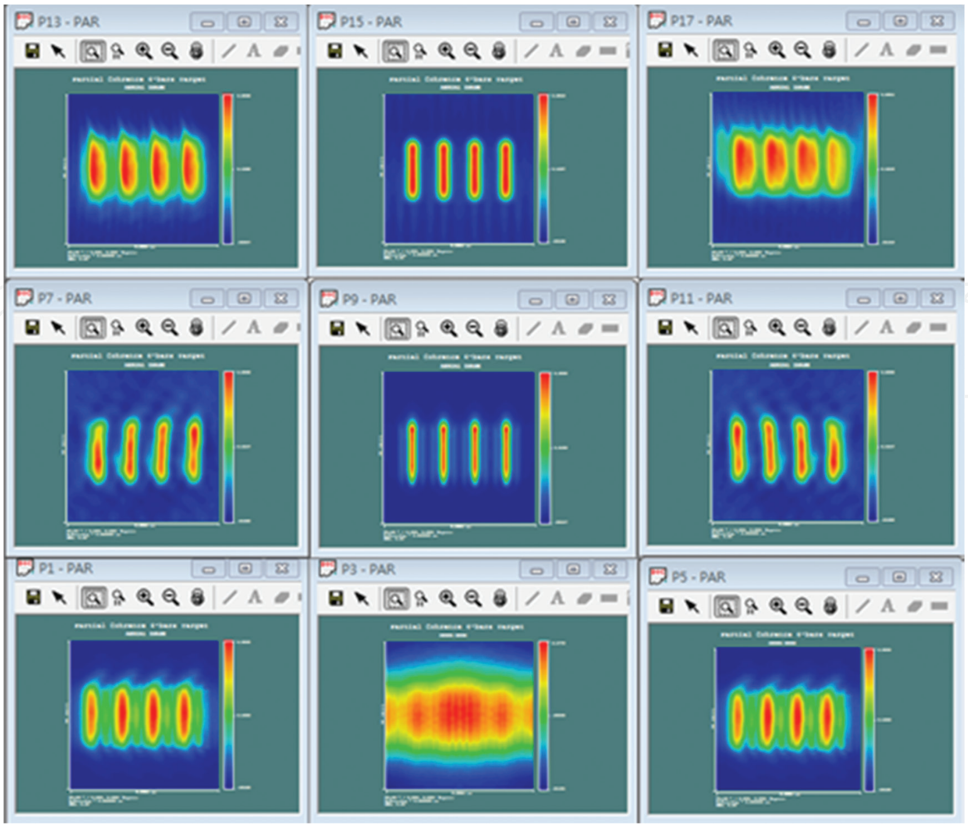

Figure 22. 4-bar pattern with the pitch of 0.004 μ is projected in each field.

5. Conclusion

Being designed by Koehler illumination and telecentric optics, the systems, having the optimized optical parameters, could be achieved. The results for two system requirement are promising, better than other structures. As the systems are built, the optimized performance should be expected. The partial coherence analysis has been applied to verify the system reaching 4K2K.

The chapter presents the design of a short throw projector optical system, and the throw ratio is 0.3, with a single aspheric mirror and the least number of spherical lens. It provides a wide angle projection lens system with partial coherence source parameter provided. The throw ratio is less than 0.3. The procedures of the optical design and illumination are presented.

5.1. Very short projecting distance optical system

With regard to throw ratio that can be less than 0.2, the design has also been carried out. While tilting the mirror at 8°, the throw ratio is 0.186663, as shown in **Figure 23**. However, the image may be keystone, and it can be corrected by the Scheimpflug effect. The image may be corrected by slightly tilting the object, and the corrected nondistorted image may be formed.

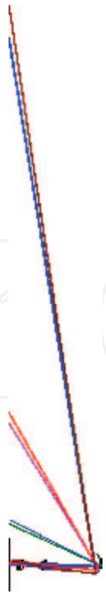

Figure 23. The tilt-mirror projector.

5.2. Other issues

The zoom system can be done. It could be zoomed by various distance of first lens, and the 1 to 1.33, by replacing with zoom optics of relay lens.

In conclusion, the optical system has been fabricated and installed in a three-panel forward looking projector system. It has been demonstrated and reached to 4K2K format. The application can be used for other projections such as automobile HUD, VR, glass-type display, smart phone external display, and others can be easily applied.

Acknowledgements

The study is supported by the grants from Ministry of Science and Technology, Taiwan, Republic of China (MOST 104-2221-E-492-040-)and(MOST-2622-E-492_029-CC3). We thank the cooperation of Professor C.H. Chen, and Mr. Wei-Cheng Lin. We deeply thank Dr. Shih-Feng Tseng for his sincerely instruction and encouragement.

Author details

Jiun-Woei Huang[1,2]*

*Address all correspondence to: jwhuang@narlabs.org.tw

1 National Applied Laboratories, Instrument Technology Research Center, Hsin Chu, Taiwan, R.O.C

2 Institute of Applied Mechanics, National Taiwan University, Taipei, Taiwan, R.O.C

References

[1] Chung F-C, Ho F-C, Wu Y-L. High-resolution 60-in liquid crystal rear-projection TV. In: Projection Displays 2000: Sixth in a Series", Proc. SPIE 3954. 2000

[2] http://www.sony.net/Products/4k-ultra-short-throw/

[3] Matsumoto S, Amano R, Okuda M, Adachi T, Okuno S. Ultra-short Throw Distance Front Projector with Mirror-Lens Hybrid Projection Optical System. 9.4-2 Consumer Electronics, 2008. ICCE 2008. Digest of Technical Papers. In: International Conference on Date 9-13 January 2008

[4] Abe T, Mashitani K, Kanayama H. Floor-Projected 3D system by 3D ready Ultra Short Throw Distance Projector. In: IEEE International Conference on Consumer Electronics (ICCE); 2011. pp. 757-758

[5] DLP, https://en.wikipedia.org/wiki/Digital_Light_Processing

[6] Sidney F. Ray, Applied Photograpic Optics, Ch.64. London: Focal Press; 1988. pp. 453-468

[7] Charbonneau M. Short throw projector system. Thales Co; 2012

[8] Code V 11. Optimization: Synopsys Co; 2017

[9] Huang J-W. The optical design of ultrashort throw system for panel emitted theater video system. In: International Conference on Optical and Photonic Engineering (icOPEN 2015), Proc. SPIE 9524-134; 2015

[10] Huang J-W. The design and fabrication of common optical components lithography lens. In: International Conference on Optical and Photonic Engineering (icOPEN 2015) Proc. SPIE 9524-69; 2015

[11] Huang J-W. Optical design of ultra-short throw LCoS projection system. In: ODF2016 International Conference on Optics-Photonics Design & Fabrication 2S3-05. Weigarten Germany; 2016

[12] Huang J-W. Optical design of a 1-to-1lithography projection. Optical Review. 2016;**23**(5): 870-877

[13] Huang J-W. Optical design of ultrashort throw liquid crystal on silicon projection system. Optical Engineering. 2017;**56**(5):051408

[14] Huang J-W. Chap.15.7.2 and Chap. 38. Design and fabrication of optro-mechatronics system. Taipei, Taiwan, R.O.C.: Wunan Bookstore Co. http://www.wunan.com.tw/bookdetail.asp?no=11702

IntechOpen