

High contrast ratio and compact-sized prism for DLP projection system

Yung-Chih Huang¹ and Jui-Wen Pan^{2,3,4,*}

¹Institute of Lighting and Energy Photonics, National Chiao Tung University, Tainan City 71150, Taiwan

²Institute of Photonic System, National Chiao Tung University, Tainan City 71150, Taiwan

³Biomedical Electronics Translational Research Center, National Chiao Tung University, Hsin-Chu City 30010, Taiwan

⁴Department of Medical Research, Chi Mei Medical Center, Tainan 71004, Taiwan

*juiwenpan@gmail.com

Abstract: In this paper, a novel light separator with contrast ratio enhancement but maintaining the optical efficiency of the DLP projection system is proposed. The main capability of the novel light separator is to direct the uncontrolled light away from the image system. The working theorem for the novel light separator is derived as well. Uncontrolled light is kept away from the image system by a total internal reflection surface, thereby effectively improving the image quality. Compared with the conventional contrast ratio enhancement method, the FO:FO contrast ratio can be improved from 839:1 to 48250:1, the ANSI contrast ratio can be improved from 180:1 to 306:1, while the image system efficiency remains at 76.2%.

©2014 Optical Society of America

OCIS codes: (220.4830) Systems design; (230.3670) Light-emitting diodes; (230.5480) Prisms; (330.1800) Vision - contrast sensitivity; (110.2945) Illumination design.

References and links

1. X. Zhao, Z. L. Fang, J. C. Cui, X. Zhang, and G.-G. Mu, "Illumination system using LED sources for pocket-size projectors," *Appl. Opt.* **46**(4), 522–526 (2007).
2. C.-M. Chang and H.-P. D. Shieh, "Design of illumination and projection optics for projectors with single digital micromirror devices," *Appl. Opt.* **39**(19), 3202–3208 (2000).
3. J. W. Pan, S. H. Tu, C. M. Wang, and J. Y. Chang, "High efficiency pocket-size projector with a compact projection lens and a light emitting diode-based light source system," *Appl. Opt.* **47**(19), 3406–3414 (2008).
4. J. W. Pan and S. H. Lin, "Achromatic design in the illumination system for a mini projector with LED light source," *Opt. Express* **19**(17), 15750–15759 (2011).
5. S. P. Marks, "Projector phones: Cool app or visual pollution," *New Sci.* **201**(2697), 18–19 (2009).
6. S. C. Shin, Y. Jung, T. J. Ahn, S. S. Jeong, S. G. Lee, and K. Y. Choi, "The compact systems design based on DMD and the straight line 2-channel LED for a mobile embedded pico projector," *J. Disp. Technol.* **8**(4), 219–224 (2012).
7. C. Zhang, P. S. Huang, and F. P. Chiang, "Microscopic phase-shifting profilometry based on digital micromirror device technology," *Appl. Opt.* **41**(28), 5896–5904 (2002).
8. P. F. Van Kessel, L. J. Hornbeck, R. E. Meier, and M. R. Douglass, "A MEMS-based Projection Display," in *Proceedings of IEEE Conference on Micro Electro Mechanical Systems Workshop* (IEEE, 1998), pp. 1687–1704.
9. Texas Instruments Incorporated, "Introduction to Digital Micro Mirror Device (DMD) Technology," *Appl. Rep. DLPA008* (2008).
10. Texas Instruments (TI), "DLP® Discovery Optics 101 Application Note," <http://focus.ti.com/lit/an/dlpa022/dlpa022.pdf>.
11. Texas Instruments (TI), "DMD 101: Introduction to Digital Micromirror Device (DMD) Technology," <http://www.ti.com/lit/an/dlpa008a/dlpa008a.pdf>.
12. J. W. Pan, C. M. Wang, W. S. Sun, and J. Y. Chang, "Portable digital micromirror device projector using a prism," *Appl. Opt.* **46**(22), 5097–5102 (2007).
13. Y. Meuret and P. De Visschere, "Contrast-improving methods for digital micromirror device projectors," *Opt. Eng.* **42**(3), 840–845 (2003).
14. W. J. Smith, *Modern Optical Engineering*, 4th ed. (McGraw Hill, 2008), pp.185–186.
15. J. W. Bowron and R. P. Jonas, "Off-axis illumination design for DMD systems," *Proc. SPIE* **5186**, 72–82 (2003).

16. Lighttools website: <http://optics.synopsys.com/lighttools/>.
 17. E. H. Stupp and M. S. Brennessoltz, "Characteristics and characterization," in *Projection Displays*, A. C. Lowe, ed., 2nd ed. (Wiley, 2008), Chap. 13, pp. 311–346.
 18. American National Standards Institute (ANSI), Website <http://www.ansi.org/>; document number: ANSI/NAPM IT7.228–1997.
 19. J. W. Pan and H. H. Wang, "High contrast ratio prism design in a mini projector," *Appl. Opt.* **52**(34), 8347–8354 (2013).
-

1. Introduction

Nowadays, the projector is an important feature of the devices people use in their daily life, and portability is an important factor, especially in small devices such as mobile phones [1]. Liquid Crystal Display (LCD), Liquid Crystal on Silicon (LCOS), and Digital Light Processing (DLP) are the main technologies used in the projectors. Each technology has its respective advantages, but the characteristics of the DLP system give it better light utilization, resolution, and image quality [2]. However, there is one disadvantage in that the size of a conventional lamp is bulky, so it is not suitable as a light source for mini projectors. For this reason, the light-emitting diode (LED) projector [1] came into being. The advantage of LEDs is that they are not only cheap, have a long life time, and are portable, but also generate less heat than conventional light sources to avoid extra energy loss. LEDs also have the ability of instantly powering on or off. Therefore, an illumination system with red, green, and blue (RGB) LED sources would be suitable as a light source in a compact-size projector [1, 3]. The development of the LED projector has led to numerous applications such as in computer monitors, laptops, or mobile phones [4–6].

DLP is a technology used in an all-digital projection display system that is based on Texas Instruments Digital Micromirror Device (DMD) [7–11]. The DLP projection system has many applications with better optical efficiency and a smaller system size than other display systems. This is possible because the DMD system does not use polarized light. However, the DLP-projector still cannot compare with other display systems in the terms of image quality which is affected by several factors such as the contrast ratio. Here, we are interested in how to increase the contrast ratio as affected by uncontrolled light. Uncontrolled light entering the image system is caused by scattered light. In order to achieve higher optical efficiency, more rays have to be collected in the pupil of the image system. A smaller f-number image system is thus usually used in a DLP projection system to increase optical efficiency [12]. However, more rays entering the image system also means more uncontrolled light entering the image system. This phenomenon leads to decreasing contrast ratios and worsening image quality. Adding an asymmetric aperture to the image system is one common method to increase the contrast ratio and maintain the optical efficiency of DLP projection systems [12, 13]. An asymmetric aperture has the ability to cut off uncontrolled light from the illumination system passing through the image system aperture. However, this method also has some disadvantages that have to be improved. One of the disadvantages is that it is difficult to align the lens with the asymmetric aperture, a problem which can increase manufacturing costs. In addition, the uncontrolled light is cut off by the asymmetric aperture. A decrease in the contrast ratio of the DLP projection system because the extra scattered light may impinge on the screen through multiple reflections within the image system.

In this paper, we propose a novel light separator design to be used instead of an asymmetric aperture to increase the contrast ratio and maintain the optical efficiency of the DLP projection system. The novel light separator design is able to reflect the uncontrolled light away from the image system without the asymmetric aperture and avoids its disadvantages. The novel light separator is designed mathematically while considering the critical conditions. Optical software is used to simulate the projection system to offer proof that this method can increase the contrast ratio and maintain the optical efficiency of a DLP projection system. In order to find out why there is an increase in the contrast ratio, we also analyze the optical ray path followed by the stray light. The proposed novel light separator

design does in fact effectively increase the contrast ratio and maintains the optical efficiency of the DLP projection system.

Comparison with the conventional contrast ratio enhancement method shows an improvement in the full-on/full-off (FO:FO) contrast ratio, from 839:1 to 48250:1, the ANSI contrast ratio can be improved from 180:1 to 306:1, while the image system efficiency remains at 76.2%. The test results show the system with the novel light separator to have an FO:FO contrast ratio of 4025:1 and an ANSI contrast ratio of 275:1.

2. The working principles of the novel light separator

Depending on the structure, there are two types of DLP projection systems, those with a telecentric structure and those with a nontelecentric structure. In the telecentric structure the exit pupil of the illumination system or entrance pupil of the projection system is located at or near infinity from the DMD chip. In the nontelecentric structure the exit pupil of the illumination system is located at a finite distance from the DMD chip. Moreover, for the energy translation between illumination system and image system in the projection system, the entrance pupil of the image system must be coincident with the exit pupil of the illumination system [10].

In the telecentric structure, a light separator is usually used to reduce interference between the illumination system and the image system. Telecentric structure has a higher uniformity of illumination than the nontelecentric structure because of the telecentric condition at the DMD's active area [14]. Also, the illumination system and image system can be designed independently, making system design easier. These advantages have made the telecentric structure a quite common design in the DLP projection system.

The light separator in the telecentric design can significantly affect the contrast ratio of the projection system. Removing light scattering in the flat-state is an important topic in contrast enhancement. A schematic diagram of the novel light separator is shown in Fig. 1. The novel light separator is composed of three light separators, labeled P1, P2, and P3, made of the same material, with air gaps existing between the joints. The $5\mu\text{m}$ air gaps are often used to prevent astigmatism and overcome the limitations of the manufacturing technology [10, 15]. However, because of the existence of the air gaps, the direction of the ray path will be altered by total internal reflection (TIR). In this design, there are two air gaps defined as the first TIR surface (orange line) and the second TIR surface (red line).

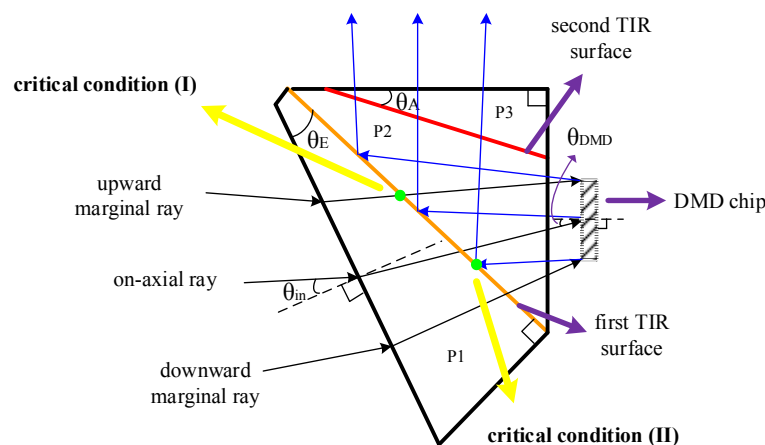


Fig. 1. Schematic diagram of the ray tracing sequence when the DMD chip is in the on-state and for critical conditions I&II.

In the DLP projection system, there are three states: the on-state, the flat-state and the off-state with corresponding tilt angles of the micromirrors of +12 degrees, 0 degrees, and -12 degrees, depending on the image ray path and the working conditions of the DMD chip [11]. The novel light separator design in terms of the angular space and spatial space is discussed below.

2.1 Angular space

2.1.1 DMD chip in the on-state

In Fig. 1, the optical ray path is divided into two main paths: the black line indicates the illumination ray path and the blue line indicates the image ray path. Based on the working theory, the illumination rays strike the first TIR surface at an angle smaller than the critical angle θ_c , so they will pass through the first TIR surface and directed toward the DMD chip. After the rays are reflected by the DMD chip, they become image rays at the on-state. These rays strike the first TIR surface at an angle larger than the θ_c , so are reflected due to TIR condition. As shown in Fig. 1, there is a limitation of θ_E at P1 to correspond to the above condition.

Equation (1) shows the limitation of θ_E . Here, the rays impinge on P1 at an incident angle θ_{in} , n_p indicates the index of the light separator, and θ_{DMD} represents the incident angle between the DMD normal line and on-axial ray before impinging on the DMD chip. The relationship between θ_{in} and θ_E is shown in Eq. (1) below:

$$\sin \theta_{in} = n_p \sin[45^\circ - \sin^{-1}\left(\frac{\sin \theta_{DMD}}{n_p}\right) - \theta_E]. \quad (1)$$

There is a balance between θ_{in} and θ_E because of the aberration and the size of the light separator, so we can acquire a suitable angle θ_E [12].

When the DMD chip is in the on-state, the incident angle of the upward marginal ray is the highest in the illumination system. In critical condition (I), the upward marginal ray strikes the first TIR surface without TIR and the other rays will be able to pass through. The critical condition (I) is formulated as in Eq. (2) below:

$$\sin^{-1}\left\{\frac{1}{n_p} \sin[\theta_{in} + \sin^{-1}\left(\frac{1}{2F/\#}\right)]\right\} + \theta_E < \sin^{-1}\left(\frac{1}{n_p}\right), \quad (2)$$

where $F/\#$ indicates the f-number of the illumination system. In critical condition (II), the downward marginal ray strikes the first TIR surface with being reflected by TIR and the other rays will be reflected. Critical condition (II) is formulated as in Eq. (3) below:

$$\sin^{-1}\left(\frac{1}{n_p}\right) + \sin^{-1} \frac{\sin[\sin^{-1}\left(\frac{1}{2F/\#}\right) - \theta_{DMD} + 2\theta_t]}{n_p} < 45^\circ, \quad (3)$$

where θ_t indicates the tilt angle of the micromirrors on the DMD chip. From Eqs. (2) and (3), we can obtain the interval of n_p for critical condition (I) and critical condition (II).

Among the three states of DMD chip operation, the flat-state is the major cause of uncontrolled light scattering [12]. In order to reduce the scattering of uncontrolled light, a second TIR surface is designed. After being reflected from the first TIR surface, the on-state rays easily pass through the second TIR surface. The flat-state rays are reflected away from the image system at the second TIR surface by TIR.

2.1.2 DMD chip in the flat-state

As shown in Fig. 2, when the DMD chip is in the flat-state, the illumination rays will also pass through the first TIR surface without TIR into the DMD chip. After the rays are reflected by a DMD chip in the flat-state, the rays will become flat-state rays. The flat-state rays strike the first TIR surface at an angle larger than the θ_C , so will be reflected. The existence of flat-state rays will reduce the contrast ratio, so P3 is designed at θ_A to direct the flat-state rays from the image system by the second TIR surface.

There are two critical conditions in the design of the θ_A at P3 as shown in Fig. 2. Here, we want the flat-state rays to be reflected at the second TIR surface, while the on-state rays just pass through. In critical condition (III), the downward marginal rays strike the second TIR surface and are reflected while the other rays are reflected at the second TIR surface. Critical condition (III) is formulated as in Eq. (4) below:

$$\theta_A > \sin^{-1}\left(\frac{1}{n_p}\right) - \sin^{-1}\left\{\frac{1}{n_p} \sin[\theta_{DMD} - \sin^{-1}\left(\frac{1}{2F/\#}\right)]\right\}. \quad (4)$$

In critical condition (IV), the upward marginal ray strikes the first TIR surface without TIR, while the other rays will be able to pass through the first TIR surface. Critical condition (IV) is formulated as in Eq. (5) below:

$$\theta_A < \frac{1}{2} \left\{ \sin^{-1}\left(\frac{1}{n_b}\right) - \sin^{-1}\left\{\frac{1}{n_b} \sin[\theta_{DMD} + \sin^{-1}\left(\frac{1}{2F/\#}\right)]\right\} + 45^\circ \right\}. \quad (5)$$

From Eqs. (4) and (5), we can acquire the interval of θ_A for critical condition (III) and critical condition (IV).

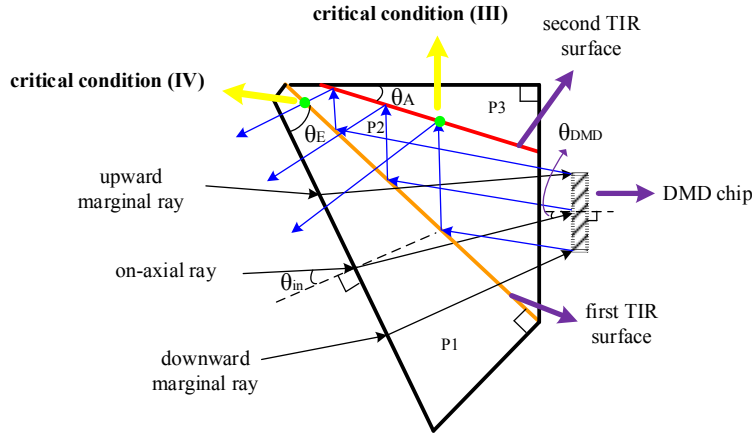


Fig. 2. Schematic diagram of the ray tracing sequence when the DMD chip is in the flat-state for critical conditions III&IV.

2.2 Spatial space

As can be seen in Fig. 3, in the flat-state, the position of the second TIR surface is an important factor influencing the ray tracing sequence. The upward marginal ray indicates the top edge of the illumination rays and the downward marginal ray represents the bottom edge of the illumination rays. The illumination rays will pass through the first TIR surface without TIR into the DMD chip. After they are reflected by the DMD chip in the flat-state, the flat-state rays are reflected away from the image system by the second TIR surface. If the position of the second TIR surface overlaps limit point 1, the upward marginal rays cannot be directed

The position of the second TIR surface is easily described using a coordinate axis as shown in Fig. 3. The original point (0, 0) (marked in red) is located at the bottom of the first TIR surface. Equations (6) and (7) below is used to calculate the positions of limit point 1 (L, a) and limit point 2 (b, 0) (both marked orange). In Eqs. (6) and (7), L is the edge length of an isosceles right triangle at P2 and P3; d1 is the distance which the downward marginal ray is traced in the novel light separator at P1 and P2; d2 is the distance between the DMD chip and the novel light separator; k is the distance between the top of the first TIR surface and the intersection of the downward marginal ray and the first TIR surface. The limit point is:

$$a = L - \left\{ \frac{1}{1 - \tan[\theta_{DMD} + \sin^{-1}(\frac{1}{2F/\#})]} [k \sin(45^\circ + \theta_A) - \frac{2d_1}{n_p} \sin[\theta_{DMD} + \sin^{-1}(\frac{1}{2F/\#})]] - 2d_2 \tan[\theta_{DMD} + \sin^{-1}(\frac{1}{2F/\#})] \right\} \quad (6)$$

and

$$\begin{aligned} b = L - (L - \{ \frac{1}{1 - \tan[\theta_{DMD} + \sin^{-1}(\frac{1}{2F/\#})]} [k \sin(45^\circ + \theta_A) - \frac{2d_1}{n_p} \sin[\theta_{DMD} + \sin^{-1}(\frac{1}{2F/\#})] - \\ 2d_2 \tan[\theta_{DMD} + \sin^{-1}(\frac{1}{2F/\#})] \}) \tan \theta_A. \end{aligned} \quad (7)$$

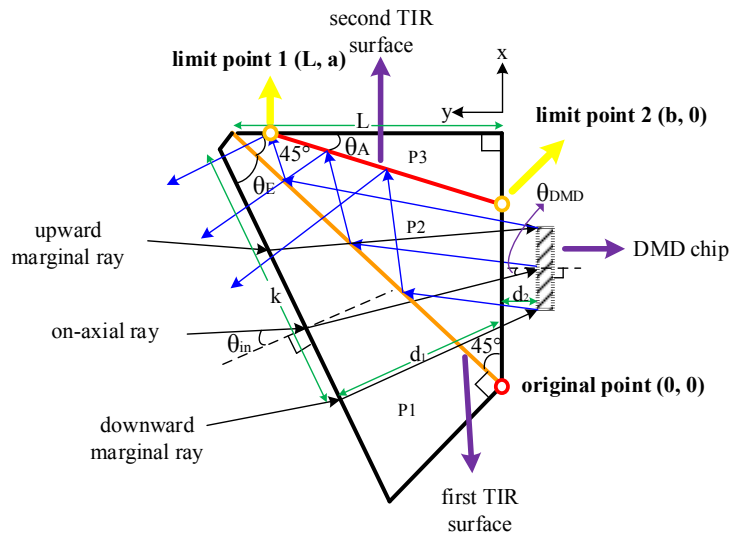


Fig. 3. Schematic diagram of the ray tracing sequence when the DMD chip is in the flat-state and limit points 1&2.

The novel light separator can be modeled using Eqs. (1)–(7) for the three states of DMD chip operation, as shown in Fig. 4. The on-state rays are directed into the image system without TIR by the second TIR surface, as shown in Fig. 4(a). The flat-state and the off-state rays are directed away from the image system by the second TIR surface, as shown in Figs. 4(b) and 4(c), respectively.

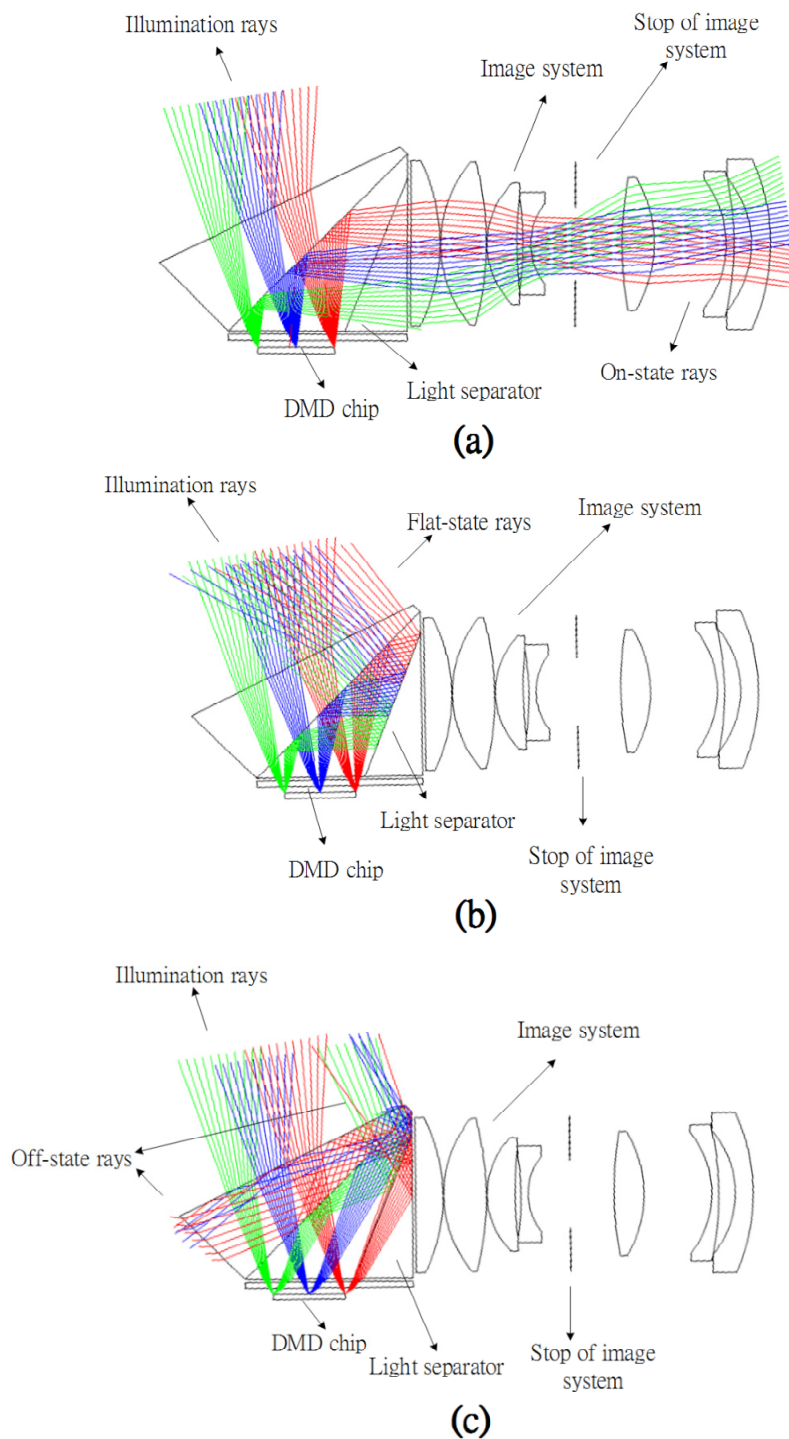


Fig. 4. Arrangement of the novel light separator, the DMD chip, and the image system when: (a) on-state rays are directed into the image system; (b) flat-state rays and (c) off-state rays are reflected away from the image system.

3. Optical simulation of the projection system

3.1 Novel light separator for a projection system

The DLP projection system with the novel light separator is shown in Fig. 5, and the whole system is set up by the optical software “LightTools” [16]. The DLP projection system is composed of three major subsystems: an illumination system, a relay system and an image system [2]. An RGB LED is used as the light source in the illumination system, one condenser lens is used to collect light, and one integration rod is used to get uniform light. After the illumination system, the rays strike the DMD chip after passing through the relay system. Micromirrors on the DMD chip are used to control the progress of the image rays toward or away from the image system. In this design, the θ_{DMD} is set at 26 degrees and the f-number of the illumination system is 2.4. The size of the DMD chip is 0.3 inch (7.62 mm) and the tilt angle of the DMD chip is ± 12 degrees. The f-number of the image system is 2.0 to collect more light [12].

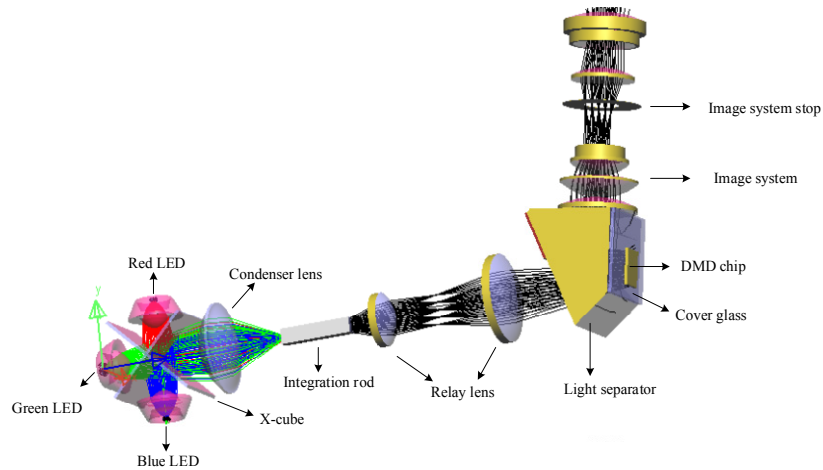


Fig. 5. Schematic diagram of the novel light separator for the DLP projector.

3.2 Analysis of the contrast ratio for the novel light separator

There is a trade-off between the contrast ratio and optical efficiency in the DMD based projector [12]. The two common methods for measuring the contrast ratio of the projection system are the FO:FO contrast ratio [10, 17] and ANSI contrast ratio [17, 18]. The FO:FO contrast ratio is defined as a ratio between the darkest dark (which represents a 100% dark level) and the whitest white (which represents a 100% white level) that the display is able to produce. The ANSI contrast ratio is measured using a 4×4 checkerboard pattern that shows black and white at the same time. The image system efficiency is defined as the luminous flux on the screen divided by the luminous flux on the receiver set between the cover glass and the novel light separator.

The relationship between the FO:FO contrast ratio, image system efficiency and θ_A is illustrated in Fig. 6. As the θ_A increases gradually, more and more flat-state rays are reflected by the second TIR surface and the FO:FO contrast ratio will also get larger until reaching the maximum value at an θ_A of 29.8 degrees. On the other hand, when the θ_A increases, fewer and fewer on-state rays are able to pass through the second TIR surface. Therefore, the image system efficiency decreases gradually. From the above results we can see that there is a trade-off between FO:FO contrast ratio and the image system efficiency. As shown in Fig. 6, we can get the maximum FO:FO contrast ratio when the θ_A is set at 29.8 degrees; the FO:FO contrast ratio can increase to 48250:1 and the image system efficiency is about 76.2%.

However, if the θ_A is too large, the flat-state rays are reflected at the second TIR surface and there is a gradual decrease in FO:FO as shown in Fig. 7.

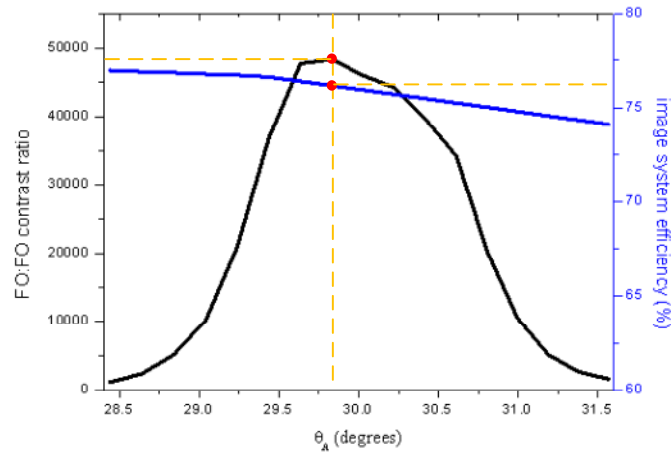


Fig. 6. The relationship between the FO:FO contrast ratio, image system efficiency and θ_A .

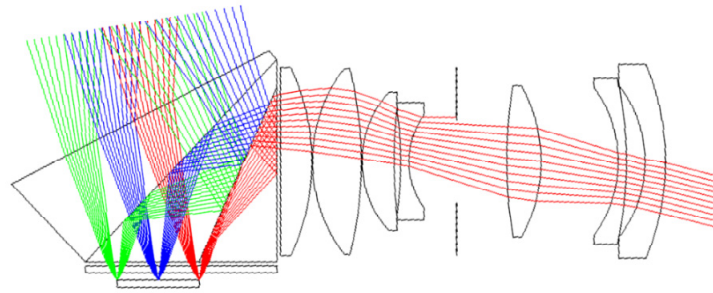


Fig. 7. Schematic diagram of the ray tracing sequence with θ_A set to 31.0 degrees when DMD chip is in the flat-state.

3.3 Comparison of the traditional light separator with an asymmetric stop

When the f-number of the image system F/2.0 is smaller than that of the illumination system F/2.4, the pupil of the image system will be slightly larger than the pupil shown in Fig. 8. The overlap between the image system pupil and the flat-state pupil implies a flat-state light leakage into the image system which causes the contrast ratio to decrease. One common method of contrast ratio enhancement is to use asymmetric stops to block flat-state light leakage [12]. Here, γ is the distance from the edge of the asymmetric stop to the edge of the image system pupil. If $\gamma = 0$ the asymmetric stop is located at the edge of the image system pupil, and does not block any light passing into the image system. As γ increases gradually, the asymmetric stop will move closer to the center of the image system pupil.

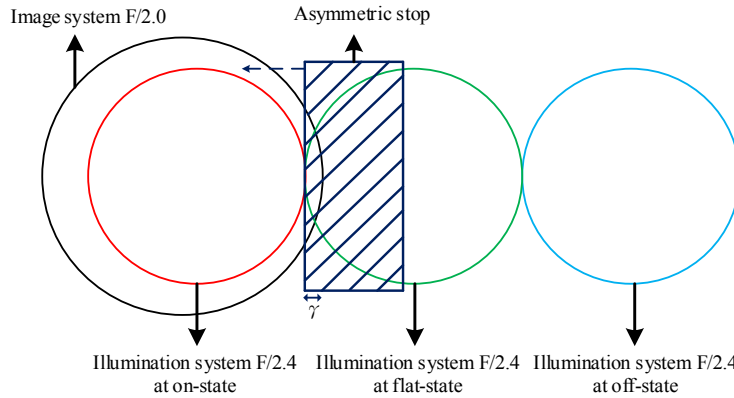


Fig. 8. Schematics of the pupils. The pupil of the image system F/2.0 is slightly larger than the pupil of the illumination system F/2.4. The deep blue board presents an asymmetric stop. The overlapping area between the projection and flat-state pupil shows the flat-state light leakage into the image system.

The relationship between the FO:FO contrast ratio, image system efficiency and asymmetric stop position is illustrated in Fig. 9. As can be seen from the figure, when the asymmetric stop position γ is at 0.4mm, there is a balance between the FO:FO contrast ratio and image system efficiency. Here, the image system efficiency is 82.04%, and the FO:FO contrast ratio is 839:1.

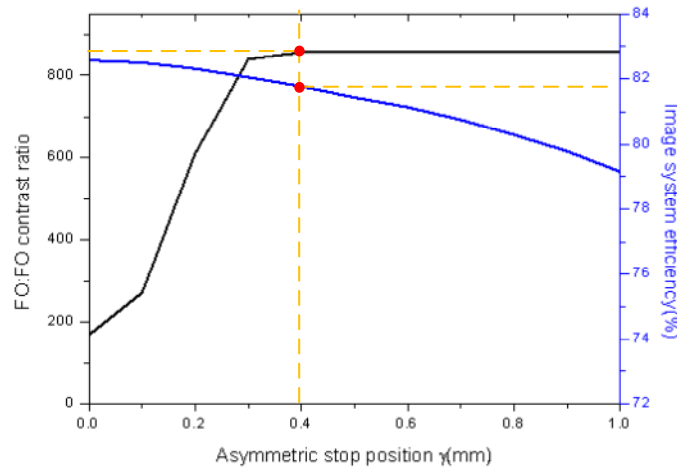


Fig. 9. The relationship between the FO:FO contrast ratio, image system efficiency and asymmetric stop position γ

The ANSI contrast ratio is also a common factor considered for ensuring image quality. We compare the ANSI contrast ratios obtained for the novel light separator and the conventional asymmetric stop in Fig. 10. The results indicate that the ANSI contrast ratio is roughly greater with the novel design than that under the asymmetric stop. For the novel light separator, when θ_A increases from 28.4 to 29.8 degrees, the ANSI contrast ratio will increase from 260:1 to 306:1. For the conventional light separator with an asymmetric stop, when the asymmetric stop is moved from 0.0 mm to 1.4 mm, the contrast ratio will increase from 96:1 to 180:1. Obviously, the novel light separator would offer a higher contrast ratio than the conventional light separator with an asymmetric stop in a LED projector system.

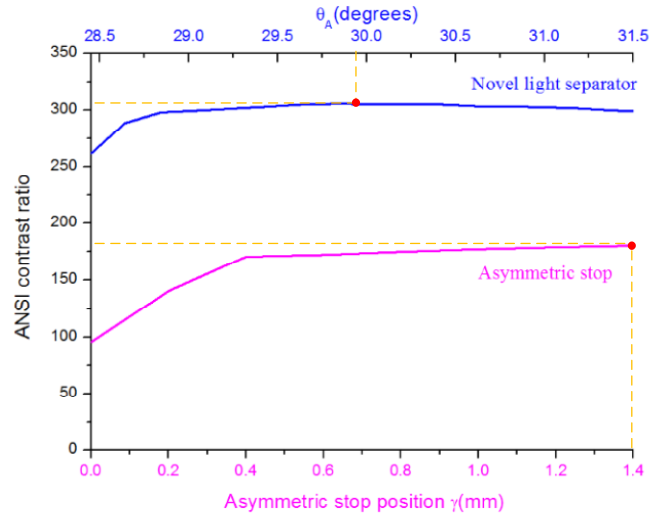


Fig. 10. Comparison of the ANSI contrast ratios for the novel light separator and asymmetric stop.

A comparison of the FO:FO contrast ratios, ANSI contrast ratios and image system efficiency obtained with our design and the traditional design is shown in Table 1. A photograph of the novel light separator is shown in Fig. 11. The testing results of the system with the novel light separator show an FO:FO contrast ratio of 4025:1 and an ANSI contrast ratio of 275:1.

Table 1. Comparison of the novel light separator and the traditional asymmetric stop method

Condition	Novel light separator with $\theta_A = 29.8$ degrees	Asymmetric stop conventional light separator with $\gamma = 0.4$ mm
FO:FO contrast ratio	48250:1	839:1
ANSI contrast ratio	306:1	180:1
Image system efficiency	76.2%	82.0%

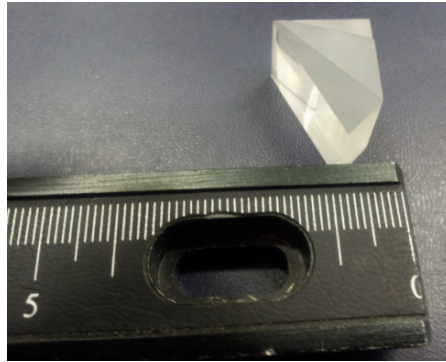


Fig. 11. A sample of the novel light separator.

4. Ghost ray analysis

As noted in the above results, the contrast ratio of the novel light separator is higher than that of the conventional light separator with an asymmetric stop. The higher contrast ratio indicates that the novel light separator should have smaller amounts of ghost rays. In order to find the reason for this high contrast ratio, the ghost rays are analyzed using ray path analysis.

As shown in Fig. 12, there are three main ghost ray paths, labeled 1, 2, and 3, in the projection system in the conventional light separator with an asymmetric stop, named Design 1. Paths 1, 2, and 3 are caused by Fresnel reflection when the flat-state light passes through the image system. In the flat-state, Fresnel reflection happens in the rear part of the image system. In Design 1, ghost ray path 1 produces about 1.885 lm (51.01%), ghost ray path 2 produces about 0.840 lm (22.73%), and ghost ray path 1 produces about 0.689 lm (18.65%), as shown in Table 2. These three paths comprise 92.39% of the ghost rays' total power in Design 1. The only method to remove the ghost rays before they hit the rear part of the image system is to use the novel light separator to change their path.

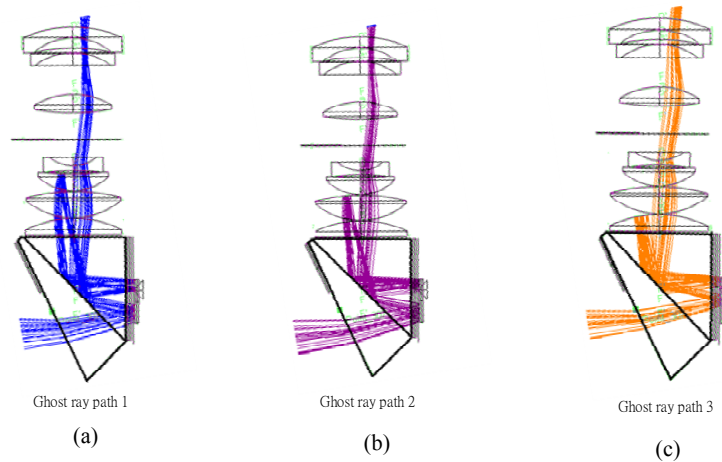


Fig. 12. Three main ghost ray paths in Design 1: optical engine with conventional light separator: (a) path 1, (b) path 2, and (c) path 3.

Table 2. Ghost Ray Analysis of the Projection System with the Conventional Light Separator

Type	Luminous flux (lm)	Percentage (%)
Ghost ray path 1.	1.885	51.01
Ghost ray path 2.	0.840	22.73
Ghost ray path 3.	0.689	18.65
Total ghost rays	3.695	100

As shown in Fig. 13, there are three main ghost ray paths labeled 1, 2, and 3 in the projection system with the novel light separator, named Design 2. Paths 1, 2, and 3 are caused by Fresnel reflection at the second surface of the novel light separator and the rear part of the image system. Here, ghost ray path 1 produces about 0.066 lm (72.41%), ghost ray path 2 produces about 0.008 lm (13.79%), and ghost ray path 3 produces about 0.005 lm (8.62%) for a total in model 2 of 0.141lm, as shown in Table 3. These three paths comprise 94.82% of the ghost rays' total power in Design 2.

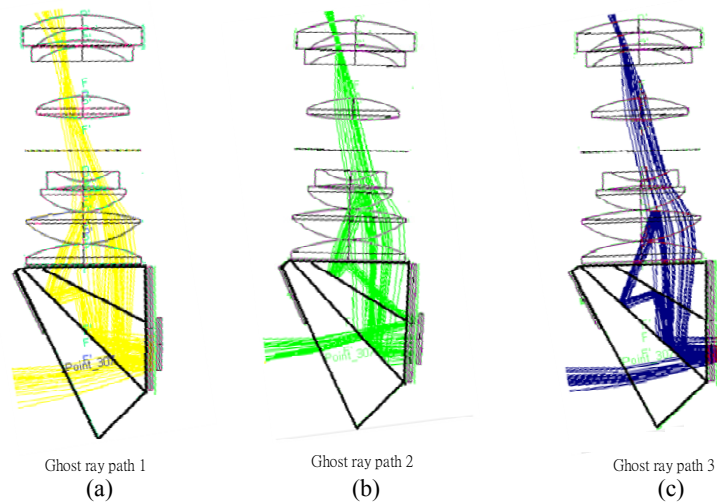


Fig. 13. Three main ghost ray paths in Design 2, the optical engine with the novel light separator: (a) path 1, (b) path 2, and (c) path 3.

Table 3. Ghost Ray Analysis for the Projection System with the Novel Light Separator

Type	Luminous flux (lm)	Percentage (%)
Ghost ray path 1.	0.066	72.41
Ghost ray path 2.	0.008	13.79
Ghost ray path 3.	0.005	8.62
Total ghost rays	0.058	100

Comparison of the ghost ray analysis results between the two designs shows that ghost ray paths 1, 2, and 3 in Design 1 can be removed by using the second TIR surface, as is done with the novel light separator in Design 2. The three ghost ray paths are caused by Fresnel reflection as the flat-state rays pass through the image system. However, in the novel light separator, the flat-state light is removed away from the image system; therefore paths 1, 2, and 3 do not happen in Design 2. In other words, the three main ghost ray paths in Design 1 can be efficiently removed by using the novel light separator, so that better contrast ratio enhancement can be easily achieved in Design 2.

5. Comparison to a previous design

A comparison of the novel light separator design to a previous design [19] under the same illumination system and image system appears in Table 4. The novel light separator has 80% the volume of the previous design. Obviously, the novel light separator design is more compact and has a higher contrast ratio, so it is also more suitable to be a component in a DLP projection system. Although there may be a slight decrease in the system efficiency of the novel light separator's image, the improvement in the image efficiency is still enough to warrant its use.

Table 4. The Comparison of Novel Light Separator and Previous Work

Condition	previous work [19]	novel light separator
FO:FO contrast ratio	46296:1	48250:1
ANSI contrast ratio	295:1	306:1
Image system efficiency	79.3%	76.2%
Prism volume	16 mm × 23 mm × 17 mm	16 mm × 21 mm × 15 mm
Weight	15.7g	12.6g
Light path in the illumination system	TIR surface → DMD chip	DMD chip → TIR surface
Prism number	3	3
Testing result for FO:FO contrast ratio	2050:1	4025:1
Testing result for ANSI contrast ratio	206:1	275:1

6. Conclusion

In this paper, we present a novel light separator that offers an enhancement of the contrast ratio while maintaining the optical efficiency of the DLP projection system. The novel light separator has the ability to direct the uncontrolled light away from the image system when the DMD chip is in the flat-state. This novel light separator design can achieve contrast ratio enhancement over that obtained using the asymmetric stop design. Compared with the conventional design, the FO:FO contrast ratio can be improved from 839:1 to 48250:1, and the ANSI contrast ratio can be improved from 180:1 to 306:1, while the image system efficiency remains at 76.2%. The test results for the system with the novel light separator show and the FO:FO contrast ratio of 4025:1 and ANSI contrast ratio of 275:1. Also, through ghost ray analysis, we know that the ghost rays can be removed effectively away from the image system. The difference between the novel light separator and asymmetric stop designs can be easily understood. With the advantage of a high contrast ratio, the mini projector can project a more vivid image and the image quality can be effectively improved.

Acknowledgments

This study was supported in part by the Ministry of Science and Technology, under project numbers MOST103-2220-E-009-009, MOST103-2220-E-009-008, NSC 103-2923-E-009-003-MY3, and in part by the "Aim for the Top University Plan" of the National Chiao Tung University and Ministry of Education, Taiwan, Republic of China.