Achromatic design in the illumination system for a mini projector with LED light source

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Abstract: We provide a novel achromatic design in the illumination system for a mini projector with an LED light source. The lateral color aberration at the corners of the DMD active area can be reduced to 0.48 μm by our compact ATIR prism. The total prism size is 4091 mm^3. The spot sizes at the corner and the edge are also controlled under 198 μm. Moreover, we use a light pipe for color uniformity at the center of the DMD active area. Under the two components for color uniformity, the Δu' v' is well controlled under 0.016 by a 20 mm length of light pipe. The illuminance uniformity at the active area of the DMD chip is higher than 92.8%. The optical efficiency of the light pipe is 94.1%.

OCIS codes: (220.4830) Optical systems design; (230,3670) Light-emitting diodes; (220,2945) Illuminaiton design.

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1. Introduction

Light-emitting diodes (LEDs) are the new generation of light sources. LEDs are power-saving and environmentally friendly [1]. A long life and a small size are also common properties of LEDs. With the development of this technology various LED applications have been developed, and it also has created amazing business opportunities. In addition to well-known electronic products such as the LED indicator and signal lantern, there are many LED application products such as the backlight in a liquid crystal display (LCD) for mobile phones and other products. In projector products, an LED light source has been widely used for digital light processing (DLP) and liquid crystal on silicon (LCoS) projectors [2,3].

In DLP projectors [4], there are many advantages in replacing a conventional ultra-high-pressure (UHP) lamp with an LED light source [5–8]. Most of all, an LED light source has highly saturated color with a narrow bandwidth [9]. However, the red, green, and blue (RGB) LEDs are separate light sources in a DLP projector. According to our research, "Homogenized LED-illumination using microlens arrays for a pocket-sized projector [10]," we used an LED light source in our mini projector where there are serious color uniformity issues at the center and corner of the projection screen.

In this paper, we introduce novel achromatic prisms in the illumination system of a projector in order to solve the lateral color aberration at the corner of the digital micromirror device (DMD) active area and to control color uniformity at the center of the DMD active area with a light pipe. For lateral color aberration, a novel achromatic prism is designed to reduce lateral color aberration at the corner of the DMD active area to under 10 μm. We do not use any achromatic doublet lenses to reduce the lateral color aberration produced in the illumination system with a total internal reflection (TIR) prism [10]. We have a compact prism size of 4091 mm^3. The spot sizes (SPT) at the corner and the edge of the DMD active area are also controlled under 198 μm. For color uniformity we use a light pipe to control the color uniformity at the center of the DMD active area. There is a trade-off between the length of the light pipe and its optical efficiency. The longer light pipe brings us better color uniformity with lower optical efficiency. Finally, the Δu' v' is also controlled under 0.016 with a 20 mm length of light pipe. In addition to color uniformity, illuminance uniformity is also investigated. We can use a light pipe to enhance illuminance uniformity from a highly peaked distribution to a relatively uniform and flat distribution at the exit point of the light pipe. Moreover, we can also get illuminance uniformity at the DMD active area by choosing a suitable length of a hollow-mirrored light pipe with low-loss efficiency [11,12]. The illuminance uniformity at the DMD active area is higher than 92.8%.

2. The Achromatic TIR Prism for Lateral Color Aberration

There are two kinds of TIR prisms widely used in a DLP projector, especially in an LED mini projector [10,13]. The main difference between the two kinds of TIR prisms is the prism number for an incident ray passing through the TIR prism. For the first kind of TIR prism, the ray passes through two prisms before impinging the DMD active area, as shown in our previous research [10]. For the second kind of TIR prism, the ray passes through only one TIR prism before impinging the DMD active area in a convention design [13]. In the first kind of TIR prism, there is a compact-size TIR prism without an achromatic function and a micro-lens array as the homogenizer. We get serious lateral color aberration and low color uniformity [10] because we use the same material of N-BK7 as in the first kind of TIR prism. For the lateral color aberration issue at the corner of the DMD active area, the common way is to use an achromatic doublet in an illumination system with a TIR prism. However, a doublet lens increases the cost of an illumination system. In order to use plastic lenses due to cost issues, an achromatic function for the lateral color aberration issue will be added into the TIR prism. For reaching an achromatic function for the lateral color aberration issue, the ray must pass through two different optical materials before impinging the DMD active area. Deriving an idea from the first kind of TIR prism, we created a novel achromatic TIR (ATIR) prism with two different materials, as shown in Fig. 1.

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We used two optical materials to make up the ATIR prism. A is the prism angle of the first prism, as shown in Fig. 1. Then n_a and n_b are the indices at d light for the first and second prisms. θ_{in} and θ_{DMD} are the incident angles at the ATIR prism and the DMD active area. θ_{DMD} is 26.5 degrees for higher contrast and lower loss [12]. For an illumination system with an ATIR prism, the optical axis will pass through the ATIR prism and impinge on the DMD active area. θ_{in}, θ_{DMD}, and the index of two different materials for the optical axis will follow Eq. (1):

$$\sin\theta_{in} = n_a \sin\{\sin^{-1}[\frac{n_b}{n_a}\sin(45^\circ - \sin^{-1}\frac{\sin\theta_{DMD}}{n_b})] - A\}. \quad (1)$$

In order to use the same projection lens shown in our previous research [10], we only can use N-BK7 as our material for the second prism. At the ATIR prism, the second prism is an isosceles right-angle triangle. For the lateral color aberration, we choose four real optical materials with different Abbe numbers for the first prism. The four real optical materials are N-SK16 (N_d = 1.62, V_d = 60.32), N-LAK8(N_d = 1.71, V_d = 53.83), N-SF2(N_d = 1.65, V_d = 33.85), and N-SF57(N_d = 1.85, V_d = 23.78) as found in Schott optical glass catalogs. For the optical simulations, we use Zemax software [14] as our calculation platform. In this paper, we also use a 0.55 inch (13.97 mm) DMD panel for our design target.

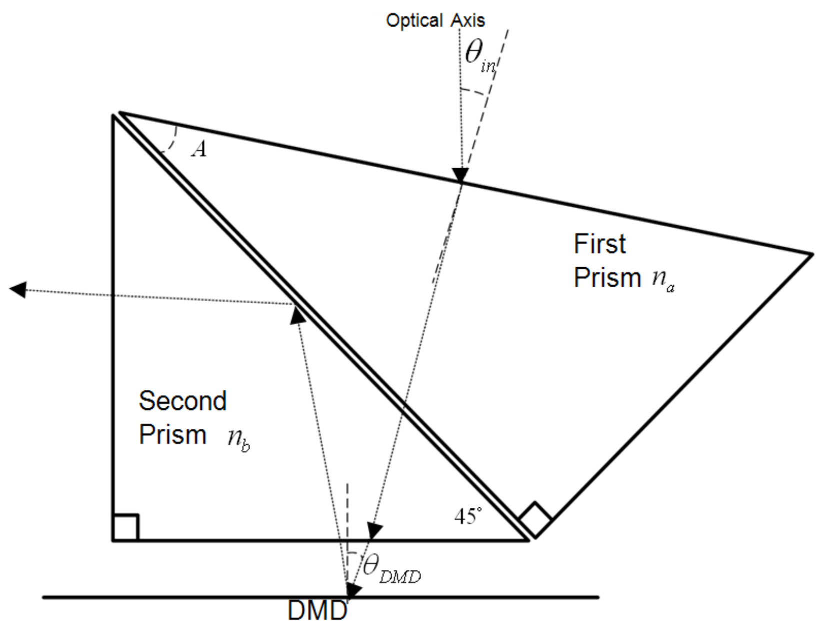

Fig. 1. Structure of the ATIR prisms with deferent materials.

For the lateral color aberration issue, we discuss the relation between lateral color aberration, prism size, and incident angle. The relation is shown in Fig. 2. The hollow blue lines show the relation between the lateral color aberrations and the incident angles. For each optical material, there is a local lateral color aberration minimum at certain incident angles. The lateral color aberration minimum is at a range between 0.2 and 8.0 μm. For reducing the lateral color aberration, the Abbe number of the material decreases when the incident angle increases. In other words, a material with a lower Abbe number has a lateral color aberration minimum at a higher incident angle. Moreover, the solid black lines show the relation between the prism sizes and the incident angles. Due to Eq. (1), the incident angle increases when angle A decreases. The prism size increases when angle A increases. In other words, the incident angle increases when the prism size decreases. The phenomenon for prism size and

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incident angle is the same as in our previous research [10]. In other words, for reducing lateral color aberration, we can get a more compact prism size by choosing an optical material with a lower Abbe number. Under this condition, N-SF57 is the candidate for reducing lateral color aberration. Noticeably, we cannot reduce lateral color aberration to zero owing to the fact that θ_{DMD} must be 26.5 degrees.

Besides lateral color aberration, spot size on a DMD active area is a very important factor for an illumination system. We also discuss the relation between spot size, prism size, and incident angle for the four real optical materials, as shown in Fig. 3. We evaluate the spot size on the DMD active area by the rms value. The spot sizes located at the center, corner, and edge of the DMD active area are: a green triangle, a red square, and a blue counter triangle. The spot size increases when the incident angle increases. As we mentioned before, in Fig. 3 the prism size decreases when the incident angle increases. In other words, the spot size increases when the prism size decreases. In Fig. 3, for an incident angle around 7 to 10 degrees, the average spot size for the center, corner, and edge is at the lowest level and the minimum spot size is controlled under 100 µm.

Finally, we use conclusions drawn from the previous paragraphs. We can get the relation between the Abbe number, the spots size, and the prism size at the lateral color aberration minimum. At the lateral color aberration minimum for the four real optical materials, when the Abbe number decreases, the spot size increases and the prism size decreases.

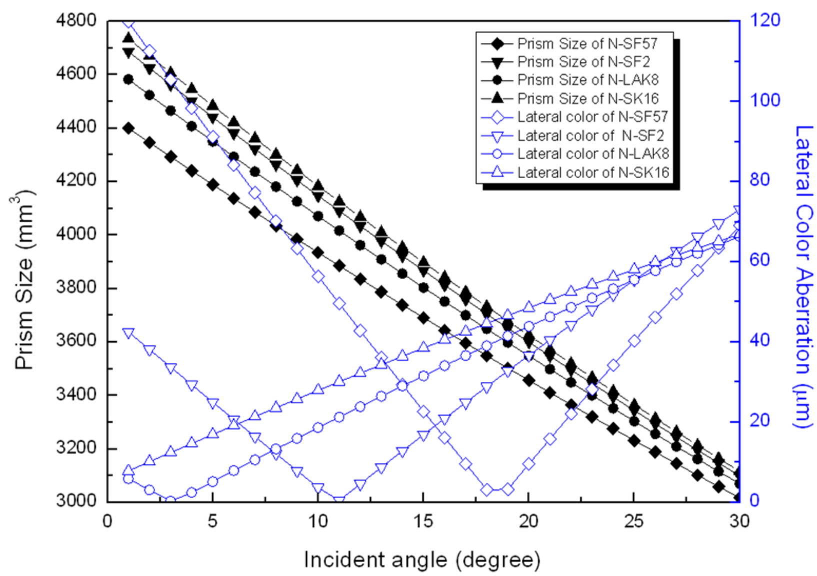

Fig. 2. Relation between lateral color aberration, prism size, and incident angle (θ_{in}).

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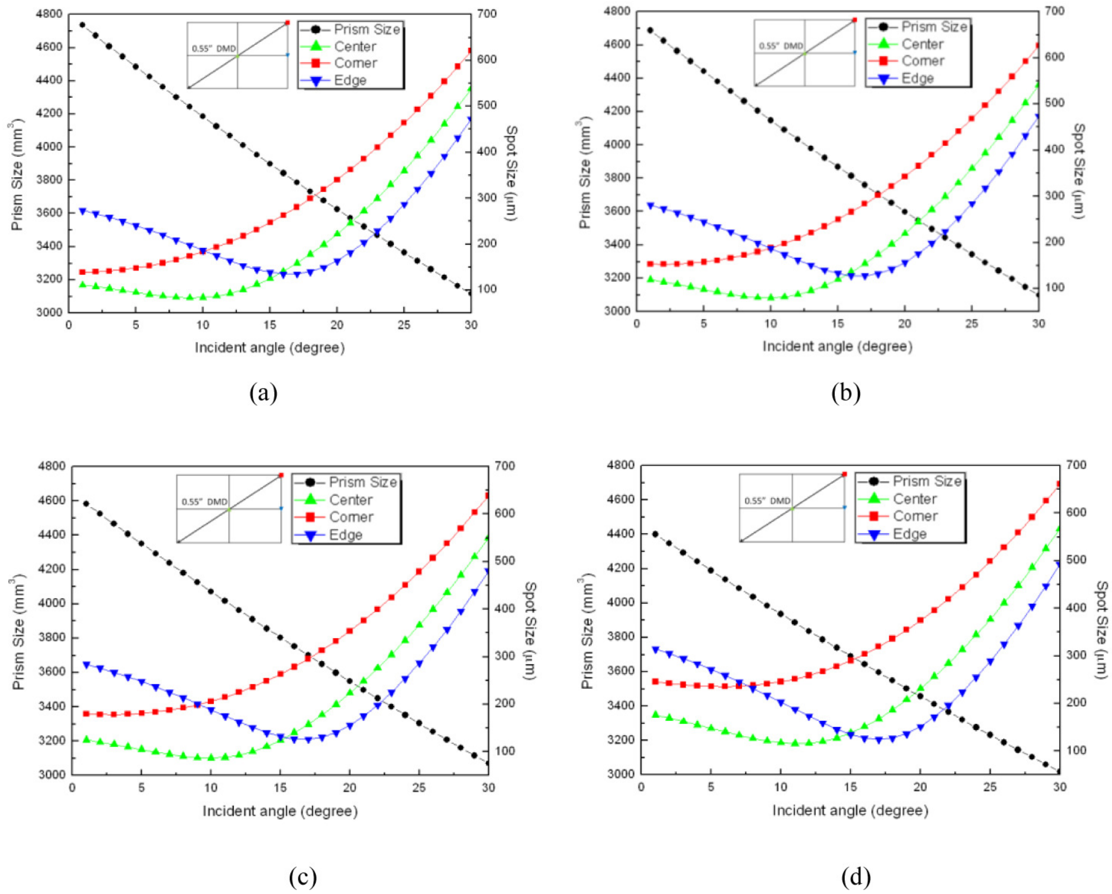

Fig. 3. Spot size on the DMD active area and the prism size for a series of incident angle (θ_{in}). (a) Spot size of SK16. (b) Spot size of SF2. (c) Spot size of LAK8. (d) Spot size of SF57.

In addition, we must consider the cost issue for an ATIR prism. An expensive material is not practical for a manufacturer. In order to get the lowest lateral color aberration for the color uniformity issue at the corner of a DMD active area, we summarize all of the optical properties for the four used materials in Table 1. For each achromatic material, Table 1 shows spot size, prism size, and glass price. The Schott glass price data in Table 1 refers to Ohara's reference sheet with the corresponding glass catalog [15]. Overall in Table 1, N-SF2 is the optical material with the best balance between low lateral color aberration, small spot size, compact prism size, and low cost. For lateral color aberration and compact prism size, we can choose N-SF57 for the first prism with a high incident angle, but the price for N-SF57 is too expensive. Moreover, the spot size is largest at the corner of the DMD chip. For the lateral color aberration, small spot size and cost issue, we can choose N-SK16 for the first prism with a low incident angle. However, the prism size of N-SK16 is the largest. The lateral color aberration of N-SK16 is the highest, because the Abbe number of N-SK16 is too close to the Abbe number of N-BK7. In this paper, N-SF2 is our final choice for the ATIR prism.

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Table 1. Comparison for Novel ATIR Prism with Different Material

Material for first prism	N_d	V_d	Incident angle (θ_{in}) (degree)	Prism size (mm^3)	SPT (corner) (μm)	SPT (edge) (μm)	Lateral color aberration (μm)	Price (relative to N-BK7)
N-SF57	1.85	23.78	18	3549	336	128	1.00	4.5
N-SF2	1.65	33.85	11	4091	198	174	0.48	2.0
N-LAK8	1.71	53.83	3	4466	178	267	0.32	3.0
N-SK16	1.62	60.32	1	4735	139	274	7.88	2.0
N-BK7	1.52	64.17	17	3925	195	145	30.64	1.0

3. Light Pipe for Color Uniformity

In an illumination system there are: the homogenizer, the relay lens system, and the TIR prism [13]. For reaching the goal of an illumination system without a color uniformity issue, the ATIR prism is suitable for lateral color aberration at the corner of a DMD active area, and the homogenizer is an important element for color uniformity at the center of a DMD active area. Until now, the ATIR prism is designed well for lower cost. For the homogenizer, we can use a micro-lens array or a light pipe. In our previous research [10], we had designed the double-side micro-lens array as a compact-size homogenizer. However, there was a serious drawback in using the micro-lens array. The incident beam was split into many cell beams by each lens cell in the micro-lens array. Each cell beam produced lateral color aberrations on the DMD chip. All lateral color aberrations from the 124 × 146 micro-lens array overlapped on the DMD chip [10]. We could not use the ATIR prism to reduce so many lateral color aberrations produced by the micro-lens array. In this paper, we use a light pipe as the homogenizer for color uniformity.

The light pipe is formed by four silver mirrors with a cross section of 5.0 × 3.8 mm. The magnification between the exit of the light pipe and the DMD active area is 2.4 × with a 10% over-fill loss for mass production [11]. The typical reflectivity for four silver mirrors is 98%. The length of the light pipe is relative to the uniformity degree at the DMD active area. In order to find a suitable length of light pipe, we must define some parameters to evaluate optical performance. First, we define over-filled efficiency as the ratio of the flux in the DMD active area and the flux in the entire DMD chip [10]. The mathematical equation is shown in Eq. (2), where F_{active} is the flux at the DMD active area, and F_{DMD} is the total flux of the entire DMD chip. Second, color uniformity is one of our main issues in an achromatic design. Color uniformity is relative to Δu' v', so we chose nine points on the receiver and use the average value of Δu' v' to represent color uniformity. Δu' v' is defined by Eq. (3) [16]; u' and v' are the color coordinates for the current output color; and u'_{ref} and v'_{ref} are the color coordinates for the reference color. We use Osram Ostar SMT LEA_S2W, LET_S2W, and LEB_S2W LEDs as our light sources [17]. RGB LEDs are driven under a duty cycle of Red = 32.0%, Green = 37.6%, and Blue = 30.4% [16]. The reference chromaticity coordinate is (u', v') = (0.190, 0.450), which represents a color temperature of 8500K [11,16]. In addition to color uniformity, we also investigate illuminance uniformity. We can use a light pipe to redistribute illuminance uniformity from a highly peaked distribution to a relatively uniform and flat distribution at the exit of the light pipe. We can get illuminance uniformity by choosing a suitable length of a hollow-mirrored light pipe with low-loss efficiency [11,12]. Illuminance uniformity at the DMD active area is defined by Eq. (4). $L_{i\min}$ is the minimum illuminance and $L_{i\max}$ is the maximum illuminace in the illumination area. In addition, we must check the optical efficiency of the light pipe to maintain the optical efficiency of the light pipe. The optical efficiency of the light pipe is defined by Eq. (5), where F_{input} is the flux on the input of the light pipe and F_{output} is the flux on the exit of the light pipe.

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$$Over-Filled-Efficiency=\frac{F_{active}}{F_{DMD}}\times 100\%, \tag{2}$$

$$Average(\Delta u'v')=\frac{\sum_{i=1}^{9}\sqrt{\left(u_i'-u'_{ref}\right)^2+\left(v_i'-v'_{ref}\right)^2}}{9}, \tag{3}$$

$$Illuminance\ \ Uniformity=\frac{L_{\min}}{L_{\max}}\times 100\%, \tag{4}$$

$$Optical\ Efficiency\ of\ \ Light\ Pipe=\frac{F_{output}}{F_{input}}\times 100\%. \tag{5}$$

For the optical simulations in this section, we used LightTools software [18] as our calculation platform. The relation between illuminance uniformity, the optical efficiency of a light pipe, and the length of the light pipe are shown in Fig. 4. The optical efficiency of a light pipe decreases linearly when the length of the light pipe increases, so we have to choose a suitable length of light pipe with low-loss efficiency [11,12]. The illuminance uniformity increases when the length of the light pipe increases. Importantly, the illuminance uniformity at the DMD active area and the optical efficiency of a light pipe are higher than 90% when the light pipe is longer than 16 mm. Owing to this condition, we can choose a length of light pipe of 16 mm for illuminance uniformity. Figure 5 shows the relation between Δu’ v’, the optical efficiency of the light pipe, and the length of the light pipe. The Δu’ v’ decreases when the length of the light pipe increases, which means the color uniformity increases when the length of the light pipe increases. In Fig. 5, the Δu’ v’ at the DMD active area with an ATIR prism stabilizes under 0.016 when the light pipe is longer than 20 mm. For color uniformity, we can choose a length of light pipe of 20 mm with 94.1% optical efficiency. Moreover, the difference between the Δu’ v’ at the DMD active area with the TIR prism [10] and the ATIR prism is shown in Fig. 5. The ATIR prism contributes to color uniformity and reduces Δu’ v’. At the DMD active area Δu’ v’ with the ATIR prism is 0.001 lower than Δu’ v’ with the TIR prism [10]. In Fig. 4 and Fig. 5, the optical efficiency of a light pipe decreases only 0.8% when the length of the light pipe is from 16 mm to 20 mm. We can control both the illuminance uniformity and the color uniformity well with an optical efficiency of light pipe higher than 90%.

As our final decision, we choose a length of light pipe of 20 mm for illuminance and color uniformity. The illuminance uniformity at the DMD active area is 92.8%. The average Δu’v’ is controlled under 0.016. The chromaticity coordinate is (u’, v’) = (0.192, 0.455). Both the color uniformity and illuminance uniformity are under control, and the optical efficiency of the light pipe is 94.1%. The over-filled efficiency is 90%. The schematic diagram for the mini projector with an LED light source is shown in Fig. 6. The system is separated into two parts: illumination system and projection system. The illumination system consists of the RGB LEDs, the dichroic filters, a condenser, a light pipe, the relay lens system, a novel ATIR prism, and a DMD chip. The projection lenses are designed well in our previous research [10]. Figure 7 shows the illuminance chart at an active area of the DMD chip and the distribution is uniform.

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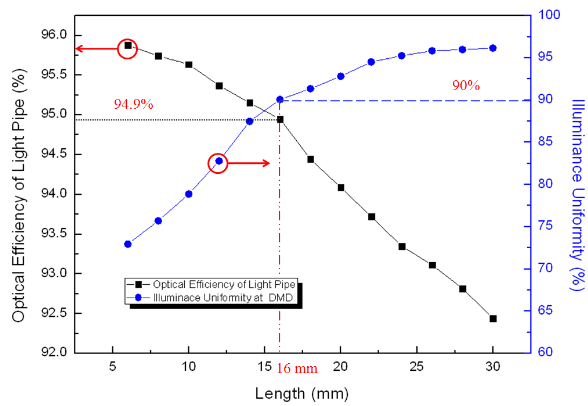

Fig. 4. Efficiency and illuminance uniformity.

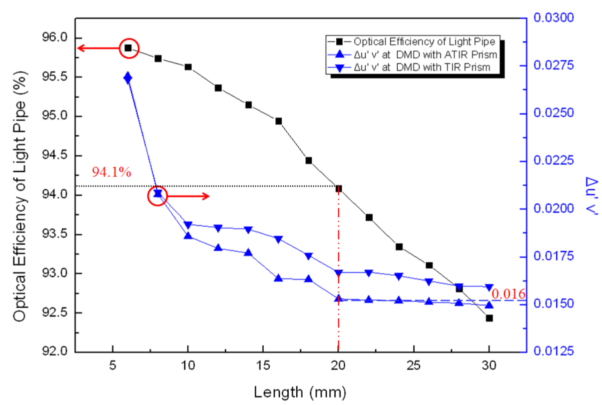

Fig. 5. Efficiency and average Δu' v'.

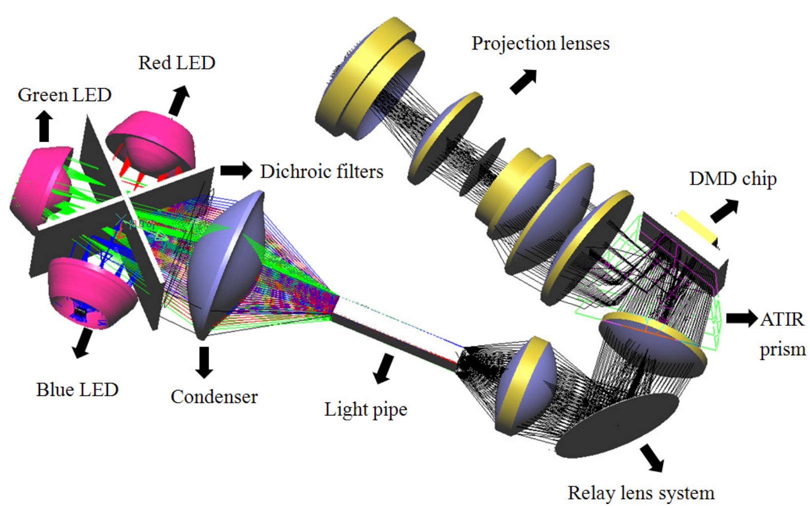

Fig. 6. Schematic diagram for the mini projector with LED light source.

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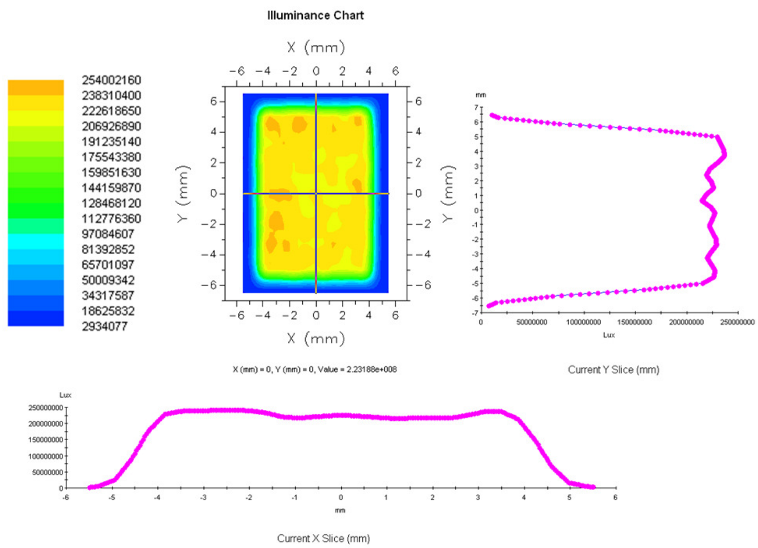

Fig. 7. Illuminance chart at the DMD active area.

4. Fabrication Tolerances of the LED Chip

Fabrication tolerance is an important consideration for a real optical manufacturer. RGB LEDs are installed in the light source respectively. In this case, there must be tolerances in fabrication. Tolerance for the linear dimension of an LED chip position is ± 0.25 mm [19]. In this paper, we keep the illumination uniformity at the active area of a DMD chip higher than 90.0% and control the average Δu' v' at the DMD active area under 0.016, so we have to find tolerance under this condition. Human eyes are most sensitive to a green LED, so we fix the position of the green LED and shifted the positions of red and blue LEDs, respectively, in the linear dimension. Figure 8 shows the relation between illuminance uniformity and the displacement of the LEDs. The displacement of the LEDs can slightly influence illuminance uniformity at the DMD active area when we shift the positions of red and blue LEDs about 0.30 mm in the vertical and horizontal directions. Figure 9 shows the relation between the Δu' v' at the DMD active area and the displacement of the LEDs. When we shift the positions of red or blue LEDs from 0.05 mm to 0.30 mm, the average Δu' v' at the DMD active area is well controlled under 0.016.

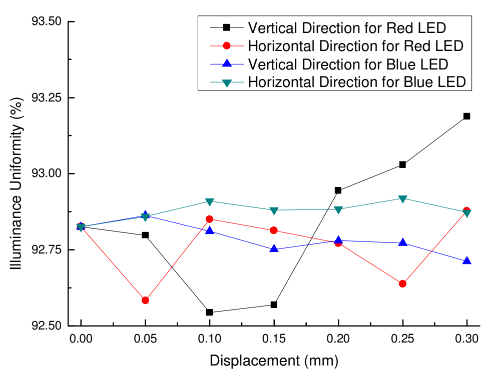

Fig. 8. Tolerance for illumination uniformity.

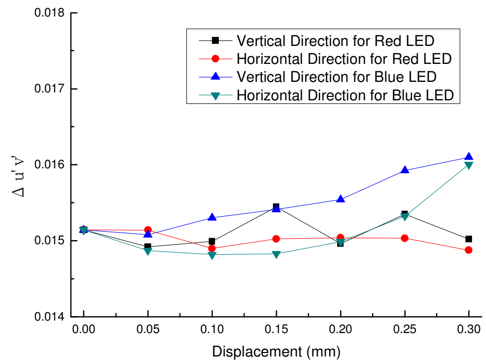

Fig. 9. Tolerance for the average Δu' v'.

5. Conclusion

In this paper, we demonstrate a novel design without a color uniformity issue in an illumination system. For reducing the lateral color aberration at the corner of the DMD active area, a novel ATIR prism is designed. We choose N-SF2 for the first prism and N-BK7 for the second prism. The lateral color aberration can be reduced to 0.48 μm. The spot sizes at the corner and the edge are controlled under 198 μm. We also get a compact prism size of 4091 mm^3 with low cost.

For improving color uniformity at the center of the DMD active area, a light pipe with a suitable length is designed. The average Δu'v' at the DMD active area can be controlled under 0.016 by a length of light pipe of 20 mm. We have controlled the color uniformity well. Moreover, illuminance uniformity at the DMD active area is higher than 92.8%. The illuminance distribution is uniform and flat. The optical efficiency of a light pipe is 94.1%. The over-filled efficiency is 90%.

We also simulate fabrication tolerances of an LED chip. When we shift the positions of red or blue LEDs from 0.05 mm to 0.30 mm, illumination uniformity at the DMD active area is still higher than 90.0% and the average Δu'v' at the DMD active area remains under 0.016. Tolerance for the linear dimension can achieve a commercial level of ± 0.25 mm [19]. Finally, a compact-size illumination system with an achromatic function is made by assembling the light pipe and the novel ATIR prism.

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