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Global solution of achromatic Total Internal Reflection prism in projection system

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ABSTRACT

In this paper, an achromatic total internal reflection (TIR) prism set, consisting of two stacked prisms, is designed to reduce the lateral color aberration of a mini projector with light-emitting-diode (LED) light sources. Two different types of the prism set are proposed. Type 1 prism set is the first prism with a small Abbe number material stacked with the second prism with a large Abbe number material. By analyzing the optical properties of the proposed ATIR prism sets, we are able to choose an appropriate optical material combination of the prism set. For type 1 prism set, the corresponding lateral color aberration is 0. 65 μm and the size is 2306 mm^3. Nevertheless, the type 1 suffers from efficiency loss of 15.5%. For type 2 prism set, the corresponding lateral color aberration is 0. 61 μm and the compact prism size is 3000 mm^3. Although the size of type 2 prism set is larger than that of type 1, the efficiency loss can be as low as 1 %.

1. Introduction

Nowadays, solid-state light sources, such as LED and Laser, are widely utilized as a light source of a projection system. In a Digital Light Processing (DLP) projection display, a light source is separated into three primary colors by a color wheel with a traditional broadband light source [1]. As a solid-state light source is applied, an additional component to generate RGB light is no more needed. This is a great difference between the traditional light source and solid-state light source. For a color display, three Lasers respectively with red, green, and blue wavelengths are necessary [2]. However, currently, the green laser generated from the second-harmonic generation (SHG) is difficult to be mass-produced. Therefore, the green laser is more expensive than the other two lasers. In addition, the laser speckle affects the quality of the display image. For eliminating the laser speckle, an extra component is needed [3]. Consequently, the cost increases. Compared to the laser, LEDs as light source has some advantages [4–11], for example, its low cost and long lifetime. Therefore, in this paper, the LEDs is chosen as our light source for the projection system.

However, there is chromatic uniformity issue such as the lateral color aberration at the corner of the projection screen when LED light source is used. In order to solve this issue, an achromatic design is necessary. Conventionally, an achromatic doublet lens is usually added into the relay lens system of the illumination system [12]. Although a doublet can reduce color aberration, the total cost will increase. In order to reduce color aberration without extra lenses, an achromatic total internal reflection (ATIR) prism set is proposed to replace the achromatic doublet lens [13]. By using an ATIR prism set can avoid the extra cost of achromatic doublet lens and eliminate the lateral color aberration. However, some issues still exist. In previous ATIR prism, only one solution is considered [13]. The solution is when the right-angle prism is the second prism, the material of the second prism is kept the same. In this paper, we extensively consider the combination of the prism set. Additionally, the ATIR prism exists angle loss due to its optical material and propagation angles. The angle loss will cause part of efficiency loss. Originally, it is an unavoidable disadvantage in previous ATIR prism. In this paper, we extensively consider the combination of the prism set consisting of different optical materials to find a global optimized solution for a low efficiency loss.

Additionally, the chromatic aberration of the relay lens is considered as well. The global solution of ATIR prism set design can be divided into two types. Type 1 is the first prism with five small Abbe number materials stacked with the second prism with a large Abbe number material design. Type 2 prism set is an opposite design to type 1 prism. Type 2 use large Abbe number material as the first prism. Five small Abbe number materials are utilized as the second prism. We analyze the optical performance of the two type of ATIR prism sets and choose appropriate optical materials. For type 1 prism, it is found

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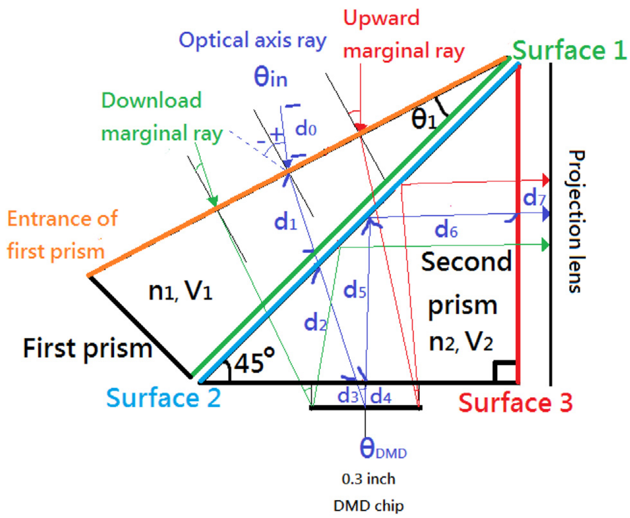

Fig. 1. Schematic of the optical path of the ATIR prisms with different materials.

that the lateral color aberration is 0.65 μm and the size is 2306 mm^3. Nevertheless, the type 1 suffers from efficiency loss of 15.5%. For type 2 prism set, the corresponding lateral color aberration is 0.61 μm and the compact prism size is 3000 mm^3. Although the size of type 2 prism set is larger than that of type 1, the efficiency loss can be as low as 1%.

2. Definitions of achromatic TIR prism

The schematic of ATIR prism is shown in Fig. 1. ATIR prism set consists of the first prism, the second prism stacking with a Digital micromirror device (DMD) chip, DLP® 0.3 WVGA DMD [14]. The first prism has an apex angle of θ_1 as shown in Fig. 1. The second prism is a isosceles right-angled triangle, i.e., the angles of second prism is 45°, 45°, 90°. The refraction index of the first prism and the second prism is denoted by n_1 and n_2, respectively. The optical axis ray passes through the ATIR prism set and impinges on DMD chip with an angle of θ_{DMD}. The relation between θ_{in}, θ_{DMD}, and the refractive index of two different materials will follow Eq. (1) [13].

$$\sin\theta_{in} = n_1 \sin\{\sin^{-1}\left[\frac{n_2}{n_1}\sin\left(45° - \sin^{-1}\left(\frac{\sin\theta_{DMD}}{n_2}\right)\right)\right] - \theta_1\} \tag{1}$$

θ_{in} is the incident angle of optical axis ray at the first prism and θ_{DMD} is the incident angle at the DMD active area. As θ_{DMD} is 26.5°, the projection image presents higher contrast ratio and lower loss [15]. The angle of θ_{in} is positive while the optical axis ray is rotated clockwise to reach the normal of the entrance of the first prism. Moreover, the prism size decreases when θ_{in} increases due to the relation among prism size, θ_{in} and θ_1 as shown in Eq. (1) [1].

The ATIR prism is designed to reduce the lateral color aberration. The lateral color aberration is defined as ray height difference of the peak wavelength of red LED and blue LED at edge of the projection screen because the chromatic aberration can be easily distinguished at the edge region. We choose an appropriate prism combinations to eliminate the lateral chromatic aberration. V_1 and V_2 represent the Abbe number of the first prism and the second prism, respectively. The difference of Abbe number are responsible to eliminate the lateral color aberration of the ATIR prism set [16]. As mentioned before, type 1 prism set consists of a small Abbe number prism stacked with a high Abbe number one. In order to optimized the achromatic capability of the ATIR prism set, five optical materials with Abbe number lower than 50 are considered. The five optical materials are N-SSK8 (N_d = 1.62, V_d = 49.83), N-BAF10 (N_d = 1.67, V_d = 47.11), N-LAF2 (N_d = 1.74, V_d = 44.85), N-SF2 (N_d = 1.65, V_d = 33.85) and N-SF57 (N_d = 1.85, V_d = 23.78) [17]. The material of the second prism is N-BK7 (N_d = 1.52, V_d = 64.17). For type 2 prism set, the material of the first prism is assumed to be N-BK7. The considered small Abbe number materials for the second prism are N-SSK8, N-BAF10, N-LAF2, N-SF2 and N-SF57. The optical performance of the various prism set is simulated and analyzed by using optical ray tracing software, Zemax [18].

When optical axis ray travels in ATIR prism, the optical path is also considered. The optical path in illumination system is shown in Eq. (2).

$$d_0 + n_1 \cdot d_1 + n_2 \cdot d_2 + d_3 = \text{const.} \tag{2}$$

where d_0 is the length of the optical axis ray during traveling between rear relay lens and the first prism. d_1 is the traveling length when optical axis ray propagates inside of first prism. d_2 is the traveling length while optical axis ray travels inside of the second prism. d_3 is the traveling length at the air gap between the second prism and DMD chip. Different optical materials lead to optical path changes. Consequently, the optical path in the illumination system is affected by n_1 and n_2. In order to keep the optical path at constant, the traveling length of optical axis ray is adjusted. Because d_1 is related to θ_1, d_1 is not a suitable parameter to adjust the optical path. Conventionally, d_0 is commonly used to adjust the optical path in illumination system. On the other hand, the optical path in projection lens system is shown in Eq. (3).

$$d_4 + n_2 \cdot (d_5 + d_6) + d_7 = \text{const.} \tag{3}$$

where d_4 is the traveling length while the optical axis ray propagates from the DMD chip to the second prism. d_5 and d_6 are the traveling length while the optical axis ray passes through the second prism. d_7 is the traveling length between second prism and the projection lens. This optical path is affected by n_2. In order to keep the geometric size of the second prism at constant, d_5 and d_6 are not suitable to modify the optical path. According to different n_2, we adjust d_7 for keeping optical path at constant in projection lens system.

In type 1 prism, the variable parameters are d_1 and n_1. They only affect the optical path in illumination system. When different materials are used as the first prism, the first prism varies and the second prism keeps constant. In type 2 prism, both of the illumination system and projection lens system are affected the different n_2. In the illumination system, d_0 is used to compensate the optical path variation causing from n_2. In the projection lens system, d_7 is responsible to compensate the optical path variation causing from n_2 for keeping optical path at constant.

3. Schematic of relay lens system

To analyze the optical performance of the ATIR prism set in both of the paraxial system and the real system, different relay lens system are designed. The relay lens system consists of two relay lenses. The theorem of relay lens system in illumination system has been shown in [19]. The schematic of relay lens system is shown in Fig. 2 for the two prisms with BK7. The spot size and the lateral color aberration of the relay lens systems are listed in Table 1. Ideal relay system indicates the simple relay system, as shown in Fig. 2(a). This relay system ignores all aberrations and lateral color aberration. Therefore, the spot size at different region at the image plane and the corresponding lateral color aberration are both zero.

In Fig. 2(b), paraxial relay system indicates the combination of ideal relay system and ATIR prism. When ideal relay system combines the ATIR prism, the optical path is considered and kept at constant. In

Table 1
Optical performance of relay lens system.

Specifications item	Ideal	Paraxial	Real
Spot size (center) (μm)	0	41.64	152.56
Spot size (corner) (μm)	0	143.94	260.41
Spot size (edge) (μm)	0	41.64	204.74
Lateral color aberration (μm)	0	0.63	10.70