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Modified Köhler illumination for LED-based projection display

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ABSTRACT

Common projection optics use Köhler illumination to achieve a required lighting. These systems always prevent the realization of a compact optical configuration along with a high lumen output. Based on conventional Köhler illumination, a modified Köhler illumination system for LED-based projection display is presented in this paper, which can significantly reduce the system volume while allowing for adequate and homogeneous illumination. Equipped with the proposed system, a pocket-sized CF-LCoS projector with a physical dimension of 27.4 mm × 19.4 mm × 9.6 mm is designed, simulated and analyzed. Compared to conventional approaches, this design could offer an average 43% volume reduction with acceptable tolerance. To the best of our knowledge, the screen uniformity of 90.2% and the light efficiency of 56.5% are competitive as compared with those of the currently commercialized pocket-sized CF-LCoS projectors.

1. Introduction

Currently, the development of communication systems and portable devices greatly enriches our daily lives. These communication approaches make the information transfer simple and convenient. However, miniaturization of portable devices is still urgently needed. Projection display system is certainly one of them. Up to now (to our knowledge), there have been two types of widespread adopted pocket-sized projectors: the LCoS-based projector [1] and the DMD-based projector [2]. Small imager size and high pixel count are of vital importance to the pocket-sized projectors. Both of these features are required for high-resolution and small-footprint display application that suitable for next generation of digital projection systems. For commercial applications, a tiny CF-LCoS based pocket-sized projector would be a promising candidate due to its inherently simple optical structure and color production. Nowadays, a compact light emitting diode (LED) light source is used in place of conventional lamps, which makes for power conservation and faster on–off delay time [3,4]. By combining an LED with a CF-LCoS projection system, a reduction in the size of the whole optical engine becomes possible. Moreover, the color filters integrated on the LCoS chip mean that primary colors can be created by a single white LED instead of being laboriously filtered.

Given a vested luminous efficiency of light source, the illumination system is the key factor in deciding the optical performance and the physical dimension of the projector [5]. An illumination system always includes a source, integrator components, a prism and an image storage panel. The goal of an illumination system is to produce an adequate and homogeneous illumination on the display panel, for which Köhler illumination is the most commonly adopted. Conventional Köhler illumination develops two approaches for projection display: the light-integrator method and the lens-array method. Based on the light-integrator method, the uniformity of a projector is proportional to the length of its light integrator [6,7]. Similarly, a homogenizer with a lens array will determine the system uniformity by the number of micro lens [8,9]. But it is more difficult to process a lens array and ensure the machining accuracy. Analyzing the two conventional illumination systems, one can find that they have one thing in common: a relay lens system is needed insides. The source's intermediate image produced by the homogenizer is located at the end of the light integrator or a micro-lens array. The relay lens system is applied to transfer the intermediate image and realize the overlapping illumination on the display panel. In other words, the requirement of compactness and simple optical architecture makes conventional Köhler illumination an inappropriate choice for a pocket-sized projector.

To offer an appropriate solution to improve conventional Köhler illumination, we present an effective illumination system design approach, namely modified Köhler illumination. It can greatly reduce the system complexity and satisfy the optical requirements synchronously. Only two compact lenses are applied in the illumination part of the optical engine to replace conventional Köhler illumination optics. The relay lens system is no longer needed. A condensing lens is first designed to collect the LED's

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Lambertian light and limit the illuminating beam width, and then a beam-reshaping lens is introduced to control the illumination field and the semi-view-angle for the CF-LCoS panel. The condensing lens is the common entrance of incident ray bundles for the following system. The beam-reshaping lens can further direct more incident ray bundles to the destination and increase the system efficiency. The mapping of the LED's uniform intensity distribution and the illumination on the LCoS panel is established that the emitting rays from every point of the LED surface can fill the active area of a CF-LCoS panel. This ensures the homogeneity of the projection display. By using this modified Köhler illumination system, a pocket-sized projector for personal use is designed and demonstrated to offer both high performance and low space utilization.

2. Modified Köhler illumination system description

As shown in Fig. 1, the components of the CF-LCoS illumination system includes an LED source, a lens group, a polarization beam splitter (PBS) and a CF-LCoS image storage panel. Even though the LED source's illuminance distribution may be non-uniform, there has uniform intensity distribution of the source indeed. This characteristic is used in the design of a modified Köhler illumination system. The LED emitting rays are collected by the Lens I (i.e., condensing lens). The aperture of the lens limits the width of the collected ray bundles. It also determines the amount of light entering the illumination system and reaching any given point of the destination plane. Lens II (i.e., beam-reshaping lens) is located behind the Lens I to control the illumination field and the semi-view-angle of the LCoS panel. The surface curvature and aperture size of Lens II limit the extent of the field at which the incident bundles can get through to the destination plane. Although the above system still follows the Köhler illumination principle, one can find that such an appropriate design can reduce the system volume while allowing for adequate and homogeneous illumination. This is just the reason that we present this improved system.

The mapping of the LED's uniform intensity distribution and the illumination on the LCoS panel is depicted in Fig. 1. The ray bundles from every point of the LED emitting surface can fill the whole image panel through the lens group. Given the three-dimensional space that far from the source, the illuminance distribution over a small area is independent of where the flux originated. This tends to provide uniformity over portions of the source's intensity distribution. The direct radiation and the flux from the LED source become an effective mapping source for a modified Köhler illumination system. Consequently, this mapping approach ensures the homogeneity of the projection display.

The optical simulation software of the TracePro® [10] is used to describe the characteristics of the proposed system. Owing to the nature of the extended Lambertian light source, the emission angle of an LED chip is still so large that a traditional optical element cannot collect the light effectively. The light source file referred to is from the company of LumiEngin® [11]. The LED chip is a standard size, 1 mm × 1 mm. Tailoring the surfaces of Lens I can provide a desired center-to-edge uniform illumination [13]. The fundamental specifications of the CF-LCoS panel include the diagonal dimension, the active area and aspect ratio, which are 0.29 in., 6.39 mm × 3.6 mm and 16:9, respectively. The destination illumination is determined by these specifications. To keep simple and easy-fabricated, the front surface of Lens II is designed as a planar surface, and the back surface is a cylindrical one. The Lens II is different from other cylindrical lens that compresses light beam [12]. One is that Lens II contains only a cylindrical surface to directly reshape the incident light beam, but the cylindrical surface can be flexibly replaced by other freeform surface based on the principle of modified Köhler illumination; the other is that Lens II could not only compress light beam, but also control the system *NA*, which reveals that the uniformity of the lighting pattern should be insensitive to the beam-reshaping lens design. The cross-section of the designed lenses and the corresponding illumination system are shown in Figs. 2 and 3(a), respectively. Obviously, high spatial utilization ratio is obtained. The ray-tracing perspective is shown in Fig. 3(b), in which two important phenomena can be observed: the aperture of Lens I that limits the size of the collected ray bundles defines the collection efficiency of the projection system indeed; the illumination field is finally determined by Lens II, which can well match the active area of the CF-LCoS panel. The simulation results coincide well with the fundamental principle of the modified Köhler illumination.

3. Optical performance of the complete projection display system

To evaluate the modified Köhler illumination, a type of pocket-sized projection system is designed, simulated and analyzed. As shown in Fig. 4, the whole projection system mainly includes the LED source, the illumination lens group, the polarization beam splitter, the CF-LCoS panel and the projection lenses. In place of conventional Köhler illumination, this illumination system that only employs two compact lenses can compress the optical engine's size down to 27.4 mm × 19.4 mm × 9.6 mm. The TracePro simulation function is used to trace 10^6 rays. The output lighting patterns emergent from the condensing lens and the beam-reshaping lens are shown in Fig. 5. The circular illumination with a diameter of 8 mm is compressed into an output elliptical spot by

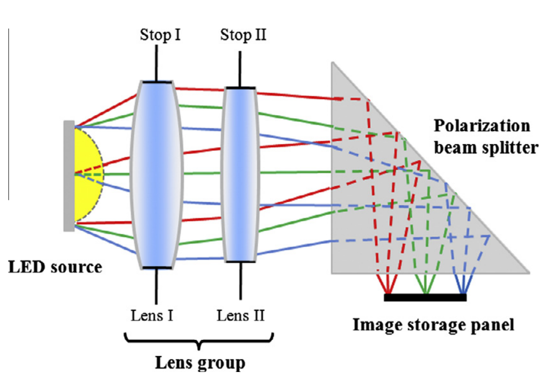

Fig. 1. Schematic diagram of a CF-LCoS illumination system based on a modified Köhler illumination.

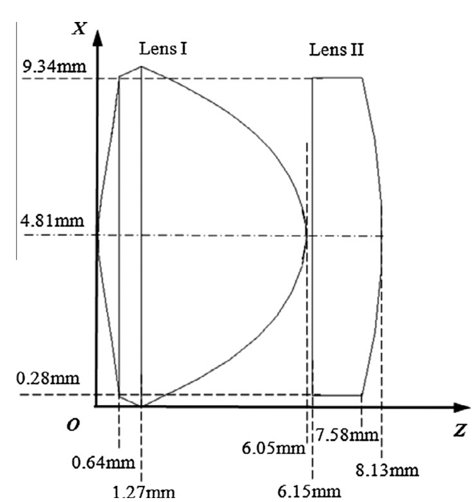

Fig. 2. Cross-section of the two illumination lenses.