Illumination system using LED sources for pocket-size projectors

Xing Zhao, Zhi-liang Fang, Ji-cheng Cui, Xin Zhang, and Guo-guang Mu

An illumination system using LED sources for pocket-size projectors is designed. Its color gamut is much larger than the sRGB standard. The maximum theoretical efficiency of this system is 29.98% by nonimaging theory-based calculations. To analyze the system model, 1.5×10^6 rays are traced by using the LightTools software. The total light flux that illuminates the digital micromirror device is 44 lm and the American National Standards Institute 13-point uniformity on the surface is 91.55%, −91.15% with a system efficiency of 28.3%. The calculations are in good agreement with the simulation results. The illumination system can be used for personal pocket-size projectors providing a 15–20 in. (38–51 cm) color display with the brightness comparable with a laptop.

OCIS codes: 080.2740, 120.2040, 120.4820, 220.4830, 230.3670.

1. Introduction

Nowadays, liquid-crystal devices (LCD) and digital light processing (DLP) portable projectors are important pieces of equipment for business applications. However, these projectors are sometimes not very suitable for personal use or for small groups in informal settings, including projection of digital camera images for vacation trips, business dinner discussions from one's personal digital assistant, or reading e-mail via cell phone. For these applications, the use of projectors and laptops would be inconvenient and time consuming. Therefore a tiny pocket-size projector would be a promising candidate. But the conventional lamps used in current projectors are not designed for pocket-size projectors because they need high power and generate a great amount of heat and cannot be instantaneously switched on and off. In this paper, an illumination system with three red, green, and blue (RGB) LED sources suitable for a pocket-size projector is proposed. By using this illumination system, a pocket-size projector for personal use is set up. It is cheap and portable, generates less heat than current sources, and can be instantly powered on or off. It can produce a 15–20 in. (38–51 cm) image with sufficient brightness and can even be controlled by batteries.

2. Conventional Illumination System of a Single-Panel Projector

Owing to its simple and highly efficient architecture, a single-panel DLP optical engine is a suitable optical system for a pocket-size projector. A conventional illumination system with a single-panel optical engine includes a lamp with reflector, color wheel, integrator rod, relay system, and total internal reflection (TIR) prism.[1–3]

As for conventional illumination systems, the arc lamp operation is stable after having been powered on for several minutes. It cannot be powered on or off instantly and needs a large-power supply. When the system is working, a fan is needed to dissipate a great amount of heat given off by the lamp, which leads to much noise and a larger system size. Besides the above disadvantages, the use of an arc lamp and color wheel will also make the optical engine more complex and fragile. Owing to the short life of the arc lamp, it would be expensive for customers to replace the lamp.

From the above description it is apparent that a conventional illumination system cannot be used in the optical engine of pocket-size projectors for personal use. A pocket-size projector should have a small volume, a long life, and cheap power sources. It needs low power and can be instantly powered on or off. Fortunately, the development of the LED gives a solution to this problem. A LED is a new source that is compact, requires low power, generates less heat, and

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is cheap. With research and manufacture development in recent years, a single LED can provide more flux than before[4]; hence replacing the conventional source in an illumination system with LED sources is a good choice to develop pocket-size projectors. The detail of such systems is discussed in the following sections.

3. Design of the Illumination System Based on LED Sources

A. Optical Specification of the Illumination System

To give a 15–20 in. (38–51 cm) projection display with a single-panel DLP system, a 20 lm light flux is the minimal requirement. It is comparable with the brightness of a laptop.[5] After the light illuminates the digital micromirror device (DMD) chip, it will be reflected by the micromirror of DMD and propagate through the TIR prism and projection lens. The efficiency of the DMD, determined by the fill factor, switching time, and reflecting and diffraction factors, is about 61%, while the typical transmittance of the prism and the lens is about 85%. Then the efficiency of this projection system (including the DMD, TIR prism, and projection lens) is about 50%.[1] Therefore the light flux illuminating the DMD chip should be no less than 40 lm. Additionally, the uniformity of the illumination on the DMD, an important factor for the display, should be no less than 90% according to the American National Standards Institute (ANSI).

B. Design of the Illumination System

Three high-power RGB 3 W Luxeon LEDs are employed in the scheme.[6] The typical parameters of these LEDs are listed in Table 1. Color display can be obtained as the LEDs are driven in a temporal duty-cycle mode instead of using the color wheel.[5]

As is well known, a LED has a large divergence angle, which is a challenge to the design of the condenser system, because light emitted from the source must converge into the integrator rod as much as possible. To achieve high collection efficiency, a collimator specially designed for Luxeon LEDs is utilized. Combined with the collimator, the divergence angle of the LEDs becomes $\pm 6°$ and contains 52% of the total energy.[7] The collimator used here is the SO20XA module manufactured by Illumination Management Solutions (IMS). The diameter of the collimator is 20 mm and its height is 18.4 mm.

A condenser system is designed to collect the light coming from the collimator within $\pm 6°$ into the integrator rod. To mix the red, green, and blue light into the integrator rod, an X-cube is placed between the LEDs and the rod. There are two diagonal planes in the cube with coatings to reflect red and blue light. Moreover, these two planes are transparent to green light. Therefore, a confluent light path for the mixed color light is established. The integrator rod is a hollow pipe with the same aspect ratio of its cross section as for the DMD chip. A telecentric relay system following the rod makes the light uniformly illuminate the DMD. The design result of this illumination system displayed in LightTools software is shown in Fig. 1.

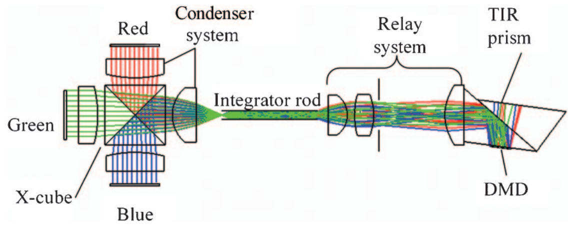

Fig. 1. (Color online) Design of the illumination system with LED sources for a pocket-sized projector.

In Fig. 1, red, green, and blue are the sources combining LEDs with collimators. The diameter of the source is 20 mm, which is determined by the collimator size. The rod dimensions are 4.8 mm $\times$ 3.6 mm $\times$ 40 mm. The DMD chip used here is 0.55 in. (1.40 cm) with a 12° tilt angle of the micromirrors. The total length of the system is about 210 mm. If a folded mirror were added to the light path, the system would be more compact.

The major difference between a conventional system and our design lies in the source and color mixing system. A conventional system uses an ellipsoidal reflector and a white arc lamp as its source; our proposed system utilizes LEDs and collimators as its source, and uses a condenser system to collect light from the source. In a conventional system, the color wheel is used as its color division device to separate the white light into temporal duty-cycle primary colors; in the design system, an X-cube is utilized as the color mixing system to mix temporal duty-cycle primary colors into the successive optical system. In fact, the X-cube is often used as a color mixing device in the optical engine of LCD projectors and is often placed between the LCD and the projection lens.[8] Considering the requirement for mixing colors here, the X-cube is placed between the sources and the rod and designed as a part of the condenser system, which is not used in the single-panel DLP optical engine in this way yet. Such an illumination system has no color wheel or other mechanical devices, which makes the system more reliable.

Table 1. Parameters of Luxeon III LEDs

Color	Central Wavelength (nm)	Current (mA)	Typical Lumens (lm)	Radiation Pattern
Red	627	1400	140	Lambertian
Green	530	1000	80	Lambertian
Blue	470	1000	30	Lambertian

4. Evaluation

A. Colorimetric Characteristics

In the illumination system, the colorimetric performance is determined by LEDs and the coatings in the X-cube. According to the spectrum of the RGB LED, reflectance coatings in the X-cube are theoretically

Table 2. Colorimetric Characters of the Illumination System[a]

Item	Illumination System		sRGB	
	x	*y*	*x*	*y*
Red (R)	0.69744	0.30247	0.64	0.33
Green (G)	0.2404	0.71406	0.3	0.6
Blue (B)	0.1439	0.034609	0.15	0.06
White field chromaticity coordinate	0.31064	0.33126	0.3127	0.3290
CCT	6605 K		6500 K	

[a]sRGB standard is co-developed by Microsoft and Hewlett-Packard. It is widely used to solve most of the color communication problem for office, home, and Web users (http://www.srgb.com/aboutsrgb.htm).

designed. The reflectance of the coatings to the dominant wavelength of the LED is 99%, and these coatings can reflect over 95% spectral energy of the LEDs. Therefore the CIE1931 chromaticity coordinates of the primary colors can be calculated by using the colorimetric theory.[9] Meanwhile, a different temporal duty cycle determines the chromaticity coordinates and correlated color temperature (CCT) of the white field. By programming and calculating, the optimal duty cycles of the LEDs are obtained. The optimal duty cycles of the RGB LEDs are 42%, 25%, and 33%. As the RGB LEDs are driven in this temporal duty cycle, the CCT of the white field is 6605 K. The colorimetric characteristics of the illumination system are illustrated in Fig. 2 and Table 2.

In Fig. 2, the color gamut of the design illumination system is very large, exceeding the color gamut of sRGB system. This means that the illumination system using LED sources can easily generate more vivid colors than the sRGB standard. In a conventional system, the complicated color wheel system with more primary color filters has to be involved to achieve the above aim

B. Collection Efficiency Analysis of the Illumination System

Nonimaging theory is a useful theory for illumination system design. By calculating the ratio between the étendue of the light bundle and the optical device, the maximum theoretical collection efficiency of the optical system can be obtained.[10] As we know, the étendue of a circular shape device is

$$E = \pi A \sin^2 \theta, \tag{1}$$

where A is the area of the device, and θ is the half-angle of the light bundle. The étendue of a rectangular shape device is

$$E = \pi A \sin \alpha \sin \beta, \tag{2}$$

where A is the area of the device, and α and β represent the half-angles of the light bundle along the direction of length and width, respectively.

Using Eqs. (1) and (2), the étendue of light beams and some devices in the illumination system can be calculated. Then the maximum light collection efficiency of the corresponding devices can be calculated according to nonimaging theory. The analysis of the light collection efficiency of the illumination system is listed as Table 3, neglecting the absorption and scattering in the system.

The maximum collection efficiency of the condenser system, listed in Table 3, is the ratio of the light collected by the condenser system to the output light of the collimator. As mentioned in Subsection 3.B, our proposed condenser system can collect only the light coming from the collimator within a ±6 divergence

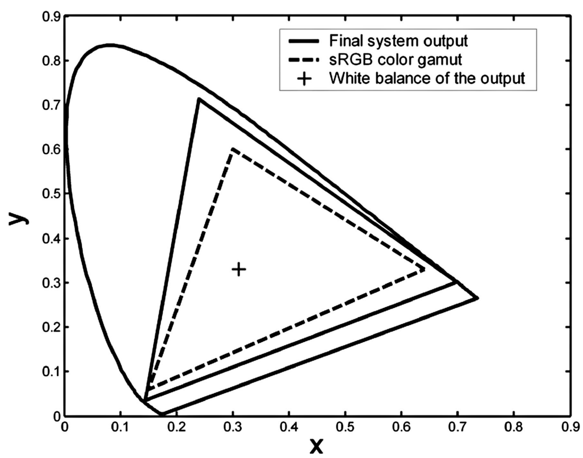

Fig. 2. Colorimetric characteristics of the illumination system in CIE1931 color space.

Table 3. Analysis of the Optical Engine Efficiency

Item	Trends (mm^2 sr)	Maximum Collection Efficiency
Condenser system (X-cube prism included)		49.4%
Input end of the rod		70.83%
Rod		100%
Light beam exiting from the rod	13.3	100%
Relay system	21.76	
Light beam exiting from the relay system	14.91	85.68%
DMD	12.78	
Total		29.98%

angle. The energy of this portion of light is 52% of the total energy emitted by LED sources. Therefore the maximum collection efficiency of the condenser system is also 52%. Considering the reflectance coatings in the X-cube, it will reflect 95% spectral energy of the LEDs (mentioned in Subsection 4.A); the maximum collection efficiency of the total condenser system (X-cube prism included) is 49.4%. The collection efficiency of the input end of the rod is the area ratio of the light spot within the input end of the rod to its counterpart at the input end of the rod. According to the optical design of the condenser system and the cross-sectional dimension of the rod, the collection efficiency should be 70.83%. The theoretical efficiency of the rod will be 100%, since the energy loss induced by the reflectance of the hollow rod is negligible. After the light beam propagates through the integrator rod, it has a definite divergence angle and will enter the relay system, as shown in Fig. 1. The étendue of the exit beam is 13.3 mm^2 sr, calculated based on Eq. (2). According to the design result, the étendue of the relay system should be 21.76 mm^2 sr, which means the exit beam of the rod can be collected by the relay system without any energy loss. Therefore the theoretical collection efficiency of the relay system will be 100%. According to the optical design of the relay system, the étendue of the exit beam of the relay system is 14.91 mm^2 sr, while based on Eq. (2), the étendue of the 0.55 in. (1.40 cm) DMD chip (12° tilt angle of the micromirrors) should be 12.78 mm^2 sr. Therefore the theoretical maximum collection efficiency of the DMD is 85.68%, which is the étendue ratio of the DMD to that of the exit beam of the relay system. Multiplying the collection efficiency of all the devices described above, the maximum collection efficiency of the total illumination system is 29.98%.

Considering the demands of color display, all the LEDs will be driven in temporal duty-cycle mode. The duty cycles of the RGB LEDs are 42%, 25% and 33%. It is completely the same as what is used in Subsection 4.A. When the LEDs are driven in a duty-cycle mode with their average power constant, the current will increase nonlinearly, and then the output lumens correlate with the duty cycle nonlinearly, just as is mentioned in Ref. 5. According to this nonlinear relationship, the output flux of the RGB LEDs is 101, 36, and 19 lm. Hence the light flux on the DMD surface will be 46.77 lm after the output flux of three LEDs is multiplied by the maximum efficiency of the illumination system. This can totally reach the flux specification mentioned in Subsection 3.A. At the same time, this theoretical analysis can testify to the validity of the proposed illumination system for the pocket-size projector.

C. Ray Tracing Simulation

The optical simulation software LightTools developed by Optical Research Associates (ORA) can be used to analyze various types of illumination system.[11] It is used here to analyze the characteristics of the illumination system designed above.

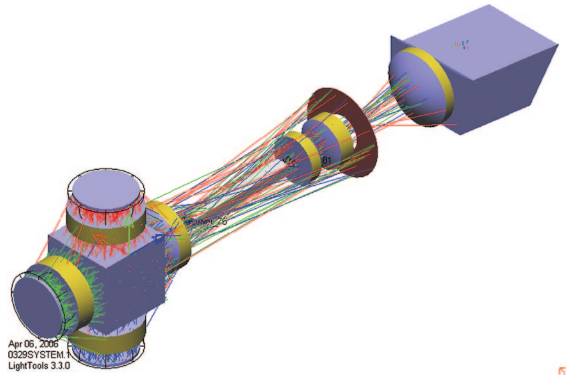

Fig. 3. (Color online) Model of the design system in LightTools.

In LightTools, the LED and collimator are modeled as a surface source. To set up a model close to the real situation as much as possible, the source apodization function is used to simulate the distribution of the source intensity versus angle. The setup of the source apodization is based on the datasheet of the SO20XA module collimator provided by IMS. The driven mode and the flux of the LEDs are the same as those mentioned in Subsection 4.B. After modeling all the devices by LightTools, the illumination system is shown as Fig. 3.

By using the simulation function of LightTools, 1.5×10^6 rays are traced. The illumination distribution of the output end of the rod and DMD with contour lines is shown in Fig. 4. The upper part of Fig. 4 is the illumination distribution for the DMD, and the lower part corresponds to the output end of the rod. Total light flux illuminating on the DMD is 44 lm with a system efficiency of 28.3%. The ANSI 13-point illumination uniformity on this surface is 91.55%,

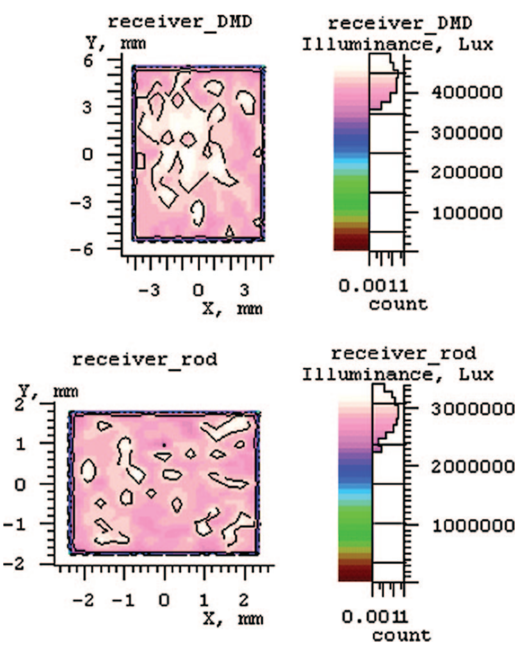

Fig. 4. (Color online) Illumination distribution at the exit end of the rod and DMD with contour lines.

-91.15%.[12] Considering the absorption, scattering, and error between the source apodization model and the real intensity distribution of the LED, the simulation results are in good agreement with the theoretical analysis. The above result can also prove the validity of the design system.

D. Discussion

Compared with the efficiency of the ellipsoidal reflector in conventional systems, the efficiency of the condenser system is a little lower. (As mentioned above, the maximum efficiency of the condenser system is 52%, while the typical efficiency of the ellipsoidal reflector is 70%.[1]) The explanation is described as follows. In such a system, the length of the integrator rod is determined by the angle of the light bundle converging into the rod, while the product of the rod end dimension and the angle of the light bundle is fixed after the size and the tilt angle of the DMD are defined, according to the Lagrange Invariant. To make the system more compact, we have to use the shorter rod, which requires that the light bundle converged into the rod has a larger divergence angle. This will make the rod end dimension small. To collect more light into the rod, the spot size of the light bundle converged by the condenser system has to be smaller than the rod end dimension. As is well known, the image spot size of the system is determined by the effective focal length for a specific field of view. Therefore a short rod requires the condenser system to have a short effective focal length and a large divergence angle of the light bundle in image space, which means that the condenser system should be a system with a small *f*-number. However, it is a big challenge to design such a system by using a simple optical system. Thus we need a balance between high efficiency and compactness for the condenser system.

Thus the collimator with stronger collimating ability is expected to be developed in the future. Using such a collimator can increase the system efficiency and make the condenser system design simpler. Obviously, more efficient LEDs that are being developed by many manufacturers will provide more light flux. However, improving the efficiency of the optical system is still the most important issue to be resolved. Both the theoretical analysis and the simulation results show that our design of the illumination system with an LED source can definitely reach the optical specification mentioned in Subsection 3.A. Our work has proved the feasibility of the above design. It is a good start even though there is still much work to do to commercialize our design. The proposed system can be used to make a pocket-size projector that can be used to provide a 15–20 in. (38–51 cm) color display with sufficient brightness. It may cost about \$500–\$600, but the expense of daily maintenance will be very low. With advantages such as small size and compactness, little heat emission, and instant switching, the pocket-size projector would be suitable for personal use.

5. Conclusion

An illumination system based on an LED source has been designed. It is composed of three RGB Luxeon III LEDs driven in temporal duty-cycle mode, three IMS SO20XA collimators, an X-cube, a hollow integrator rod, a relay system, a TIR prism, and a 0.55 in. (1.40 cm) DMD chip. The illumination system has a larger color gamut than the sRGB standard, which can produce more vivid colors. The maximum efficiency of the system calculated with nonimaging theory is 29.98%, and the light flux on the DMD surface is 46.77 lm. After the system is modeled via the optical simulation software LightTools, 1.5×10^6 rays are traced. The total flux illuminating the DMD is 44 lm and the uniformity on the surface is 91.55%, -91.15% with a system efficiency of 28.3%. The theoretical calculation and simulation results coincide well with each other, which proves that the design of the illumination system can reach optical specifications. By using this illumination system for a pocket-size projector, a 15–20 in. (38–51 cm) color display with a brightness comparable with that of a laptop can be obtained. It is compact, emits little heat, is instantly powered, and is convenient to set up. This pocket projector will be suitable for personal use.

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