Optical design of a micro DLP projection system based on LEDs and an innovative light pipe

Xiangbing Zhu[1, a ,*], Cheng Wang[1,b], Wenliang Hao[1], Liwei Tian[1], Ruofei Wang[2]

[1]Department of Physics, Anhui Normal University, Wuhu 241000, China

[2]Chery New Energy Automotive Technology Co., Ltd., Wuhu 241000, China

[a]asd05tx@126.com, [b]cheng0808066@163.com

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Abstract. Micro projection systems not only can be applied in portable display technology, but can also be applied to adaptive automobile headlamps. Present DLP technology cannot collect and utilize the light which is reflected by the micromirrors of the DMD in the "OFF" state. Aiming at this defect, a design scheme of a micro DLP projection system based on LEDs and an innovative light pipe is presented. First, the related parameters of each part are calculated according to the nonimaging optics theory. Second, the projection lens is optimized using ZEMAX software. Finally, we build a model and simulate it in TracePro software. The simulation results show that: when all the micromirrors of the DMD are in the "ON" state, the light efficiency is 36.13%; when half of the micromirrors are in the "OFF" state, the light efficiency is 27.23%.Compared with having no light pipe, the light efficiency is increased by 5.33%.

Introduction

Micro projection systems, which have a small and compact structure, have a growing share of the projection market with the rapid development of society [1-2]. By virtue of high precision accuracy, high efficiency and instant reactions, Digital Light Processing (DLP) display technology has become one of the mainstream projection display technologies [3-4]. The Digital Micromirror Device (DMD) developed by Texas Instruments is the core device of DLP technology [5]. Single-piece micro DLP projection systems can also be applied to automobile adaptive front-lighting systems. LEDs, which are seen as the light source of the 21st century, have the advantages of long life, energy saving, small volume and high degrees of design freedom, etc [6].

The defects of single-piece DLP technology

Most traditional single-piece micro DLP projection system is shown in Fig.1. The DMD has millions of individual micromirrors which can be independently swiveled to positive and negative angles, say±12°, at high frequency. When the micromirror is swiveled to +12°, the rays are reflected onto the projection lens; while the micromirror is swiveled to-12°, the rays are reflected onto the absorber. There is one major limitation involved in this kind of system. The light can not be utilized effectively when the mirrors in the state of -12°. This will reduce the light efficiency of the system and increase the heat of the system.

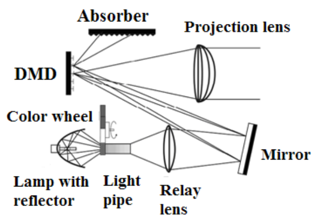


Fig.1 Optical structure of single-piece micro DLP projection

Optical design scheme

To address the above technical defect, we propose an optical design scheme, as is shown in Fig.2. The system is composed of LEDs, light pipe, color wheel, collimation system and projection lens. The scheme increases light efficiency by employing an innovative light pipe, adding a bending light pipe on the base of the tapered light pipe, and using a compound parabolic concentrator (CPC) in the input end to collect the extra light reflected by the DMD. The extra light is collected and then returned to the main light pipe, which recycles energy, improves efficiency and reduces the heat.

Selections of DMD chip and LED

In order to guarantee high resolution and compact structure, we select a DMD chip of dlp7000 type developed by Texas Instruments. When a DMD works, each mirror in the chip has two states: the “ON” state (+12°) and the “OFF” state (-12°). The light reflected by the mirrors in the “ON” state should be parallel into the projection lens, therefore the light is irradiated onto the DMD chip with a 33°angle of incidence, Fig.3 show the light on the DMD in the two states. CREE XLamp Q-E device is a white LED source with a small size of 1.6mm×1.6mm×1.44mm, 110°divergence angle and 252 lumens which is very suitable for the source of micro projection system. The numbers of required LED will be calculated by the following:

$\theta_{\frac{1}{2}}$ is angle of divergence, Etendue of a tablet such as a DMD, is:

$$E = n^2 \pi A \sin^2 \theta_{\frac{1}{2}} = \frac{\pi A}{4F^2} \tag{1}$$

NA is the numerical aperture of light, The F (f-number) of light irradiated to the DMD is:

$$F = \frac{1}{2NA} = \frac{1}{2n\sin\theta} = \frac{1}{2\times\sin 12^0} = 2.4 \tag{2}$$

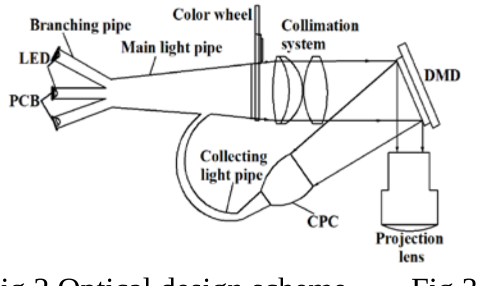
The incident angle θ^* is 33° and the F value is substituted into Eq.(1):

$$E_{DMD} = \frac{\pi A}{4F^2}\cos\theta^* = \frac{3.14\times 20.736\times 11.664}{4\times 2.4\times 2.4}\times\cos 33^0 \approx 27.645\ mm^2\cdot sr \tag{3}$$

Finally, the light-emitting area of the LED should be:

$$A_{LED} \le \frac{E_{DMD}}{n^2\pi\sin^2\theta_{\frac{1}{2}}} = \frac{27.645}{3.14\times\sin^2 55^\circ} \approx 13.121 mm^2 \tag{4}$$

Therefore we select three white CREE XLamp Q-E device LEDs.



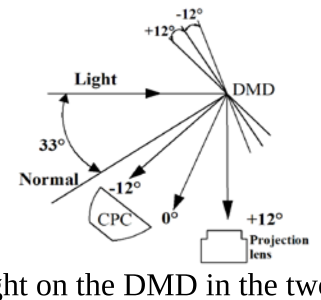


Fig.2 Optical design scheme Fig.3 The light on the DMD in the two states

Design of the light pipe

Design of the main light pipe. The main light pipe employs a positive tapered structure. The aspect ratio of the output end should accord with the aspect ratio of the DMD chip, therefore we make 16mm×9mm the cross-section of output end and 37mm as the length for the main light pipe, which has a hollow structure and is coated with high reflectivity film. The cross-section of the input end is 8mm×2mm.

Design of the branching pipe. Three LEDs mounted in three PCBs are coupled with three branching pipes respectively to improve light efficiency. The length of the branching pipes is 5mm and the cross-section area is 3mm×2mm. The two side light pipes are tilted at 60°.

Design of the collecting light pipe. A Compound Parabolic Concentrator (CPC) is a nonimaging concentrator. If the radius of the input end and the output end are b and a, respectively, and the maximum collecting angle of the CPC is $\theta_{\max}$, the relationship between b, a and $\theta_{\max}$ is:

$$\sin\theta_{\max} = \frac{a}{b} \tag{5}$$

The focal length f and length L of the CPC can be expressed by the following equations:

$$f = a(1+\sin\theta_{\max}) \tag{6}$$

$$L = \frac{a(1+\sin\theta_{\max})\cos\theta_{\max}}{\sin^2\theta_{\max}} = \frac{f\cos\theta_{\max}}{\sin^2\theta_{\max}} \tag{7}$$

Then, according to Fig.3 and Eq. (5) to Eq. (7) we can get the parameters of the CPC: $\theta_{\max}$ is 30°; a is $5mm$; b is $10mm$; f is $4.5mm$; L is $15.6mm$.

When the light pipe is bent, bending loss will occur, which is similar to that in optical fiber. According to the theory of LucB.Jeunhomme, the greater the bending radius is, the smaller the bending loss will be. We make the proportion 13:1for the bending radius and the aperture. The radian of the bending pipe is 200 °. Fig.4 shows the overall schematic.

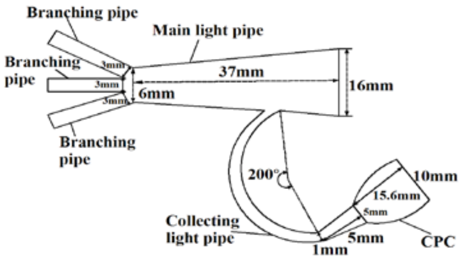
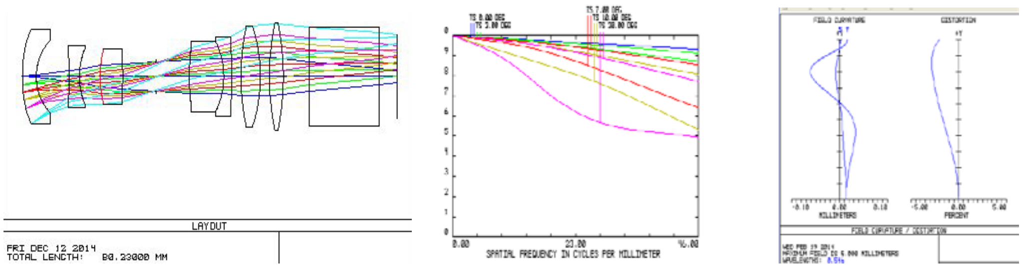


Fig.4 The overall schematic of the light pipe

Design of the projection lens

According to the size of the DMD and the basic requirements of a micro projection system, the projection lens should meet the following specifications:(1) Relative aperture is above $1/2.0$;(2) Field angle 2ω is around 60°;(3) Effective focal length $EFFL$ is around 9mm, total length is less than 100mm;(4) The value of MTF is greater than 0.5 on the 46lp/mm. (5) The distortion is less than 3%. The projection lens employs an inverted telephoto structure with a short focal length and a long latter working distance, which can project a large area in a short distance. We select a projection lens with a7 chip lens as the initial structure. Using ZEMAX software, we optimized the initial structure and got a projection lens which conforms to the design specifications, as shown in Fig.5.

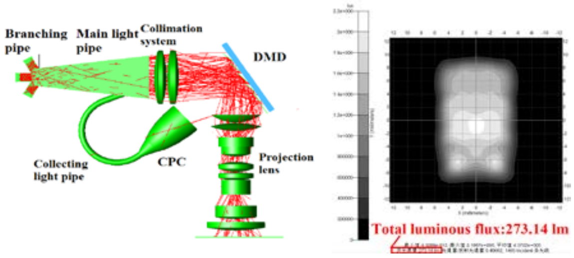


(a) (b) (c)

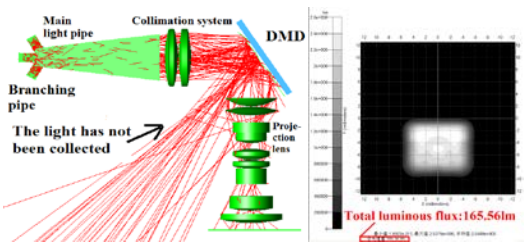
Fig.5 (a) Schematic of the projection lens (b) MTF (c) Distortion

Simulation and analysis

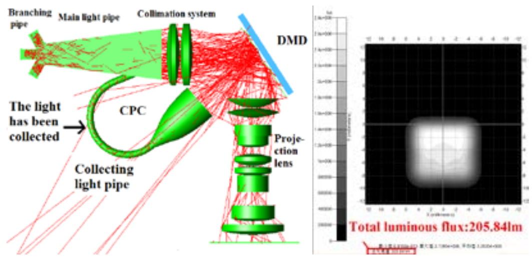
We built the model of the micro DLP projection system in TracePro software according to the relevant parameters calculated and simulated above. The whole volume of the system is controlled within 100mm×80mm×50mm. We found the optical pathway and illuminance distribution of system after repeated adjustment, as shown in Fig.6. In Fig.6 (a), all the mirrors of the DMD chip are in the “ON” state (+12°), therefore the rays are all reflected onto the projection lens. The total luminous flux of screen is 273.14lm and the total luminous flux of the three LEDs is 756lm, therefore the light efficiency of the system is 36.13%. Half of the mirrors are adjusted to the “OFF” state (-12 °), as shown in Fig.6 (b) and Fig.6 (c), we simulate the two situations respectively without a collecting pipe and with a collecting pipe. In Fig.6 (b), some rays are not reflected to the projection lens but are wasted in the absence of a collecting pipe. The light efficiency of the system is only 21.90%. In Fig.6 (c), the rays that are not reflected to projection lens are collected by the CPC. The rays return to the main light pipe again through the bending pipe and the light transmission can be clearly seen in the bending pipe. The light efficiency is 27.23%.Compared with no light pipe, the light efficiency increases by 5.33%.



(a)



(b)



(c)

Fig.6 (a) Optical pathway and illuminance distribution with all the micromirrors in the “ON” state. (b) Optical pathway and illuminance distribution with half the micromirrors in the “OFF ” state with no collecting light pipe.
(c) Optical pathway and illuminance distribution with half the micromirrors in the “OFF” state with a collecting light pipe.

Summary

In this paper, we proposed a compact structure micro DLP projection system with high light efficiency based on LEDs and an innovative light pipe. We add a bending light pipe and a compound parabolic concentrator (CPC) on the basis of the tapered light pipe that will collect the extra light reflected by DMD. We simulate the two situations respectively without collecting pipe and with a collecting pipe. The simulation results show that: when half of the micromirrors are in the “OFF” state, the light efficiency is 27.23%.Compared with no light pipe, the light efficiency increases by 5.33%.

Acknowledgments

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