Optik 125 (2014) 3864–3867

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Design of fly's-eye lens for LCOS laser display

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ARTICLE INFO

Article history:
Received 3 August 2013
Accepted 28 January 2014

Keywords:
Laser display
Étendue
Fly's-eye lens
Optical engine
Ray tracing
Sub-light sources

ABSTRACT

Design of optical system in laser display has always been an important research topic. From the aspect of decreasing the system volume and improving the light efficiency, it can be found that when the size of fly's-eye lens and the value of *f*/# are definite, the more fly's-eye arrays there are, the more useful it will be to the decrease of the optical engine size, which means that more honeycombs on fly's-eye lens and better dodging effect can be more beneficial for the decrease of the system size. After the optimal design for the rectangular elements on sub-fly's-eye lens and then doing 4000 ray tracing, the light transmittance turns out to be good with little parasitic light and scattering light.

1. Introduction

In the previous display device optical engine design, one mature imaging system is ordinarily adopted. Decompose the optical path into several object and image relationships along path, optimize the optical system according to imaging requirements, and then we can obtain the best imaging quality. However, this method cannot reach the goal of optical energy transmission maximization [1–4]. According to the need of laser display engineering application, the luminous energy utilization efficiency in the illumination and imaging optical path should be raised as far as possible to reduce the cost of optical engine which will be propitious to reducing the high cost of lasers. Étendue is the measure of the optical energy transmission rate. Étendue can be used to analyze the energy utilization rate of optical elements in the whole optical system so as to obtain high luminous energy utilization efficiency, get more reasonable optical structure and realize matching of étendue between two elements. This article employs a new design method: étendue will be estimated on every optical surface in order to ensure that étendue can be amplified as little as possible to prevent the optical energy loss in the premise of ensuring good imaging effect during the transmission process.

2. Calculation of fly's-eye lens étendue

Considering the effect to étendue, fly's-eye lens is the best scheme for dodging in laser projection display. Due to the small amount of laser étendue, the uniformity of optical field needs to meet high requirements. The light source is separated into the same number sub-light sources with fly's-eye lenses by the fly's-eye lens arrays. These sub-light sources run through the next overlapping lenses, focusing lenses, overlapping illumination LCOS chip, and then image through the subsequent light path. Fig. 1 shows the optical engine light path structure using fly's-eye as the homogenization element.

Étendue of different optical elements can be calculated by the following formula.

$$E = 4A\ \sin(\theta_{1/2})\ \sin(\phi_{1/2}) \tag{1}$$

In formula (1), A represents the area contacting optical surface. $\theta_{1/2}$ and $\phi_{1/2}$ stand for the half-included angle with optical surface in horizontal and vertical direction separately. Assume that $a_{L\cos}$ represents the width of LCOS chip, $b_{L\cos}$ the height, and $\sin\varphi_{L\cos}$ the aperture angle of the illuminating beam. Due to the low numerical aperture of laser source, it can take the approximation

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http://dx.doi.org/10.1016/j.ijleo.2014.01.172
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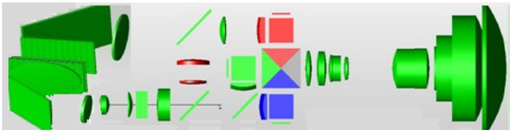

Fig. 1. Fly's-eye path of optical engine.

$\sin\phi \approx \phi$ from the aspect of mathematics. The étendue of LCOS can be expressed as follows.

$$E_{Lcos} = \pi a_{Lcos} b_{Lcos} \sin^2 \varphi_{Lcos} \approx \pi a_{L\cos} b_{Lcos} \varphi^2_{Lcos} \quad (2)$$

From the analysis, for the projection chip:

- When étendue(LCOS) > étendue(Laser), the system allows the entire beam to run through with no energy loss and high luminous energy utilization efficiency.
- When étendue(LCOS) < étendue(Laser), optical elements will prevent part of the étendue passing with low luminous energy utilization efficiency.

In order to increase the optical energy projected on the chip, the beam projected on the chip should be reshaped to rectangle and its size should be the same as that of LCOS chip.

The fly's-eye lens is designed in the shape of rectangle due to the shape of LCOS chip. Fly's-eye lens arrays are arranged in small uniformity lens arrays. Assume that '*a*' and '*b*' represent the width and height of fly's-eye lens (unit mm). *M* and *N* stand for the number of lens in horizontal and vertical direction. For the reason that the illuminating beam is in round shape, $aM = Nb$, so the étendue of fly's-eye lens can be calculated as follows.

$$E_{flyeye} = \sum_{MN} \pi W(i,j) ab \sin^2 \phi_{max}(i,j) \quad (3)$$

In formula (3), $\phi_{max}(i,j)$ represents the maximum aperture angle of the (i,j) fly's-eye lens. $W(i,j)$ is one variable, which represents the area weight of single fly's-eye lens (the ratio of the beam area on the lens to the total area). We can obtain the following relation from the path in Fig. 4.

$$\frac{f_{flyeye}}{f_{relay}} = \frac{a}{a_{Lcos}} = \frac{b}{b_{Lcos}} \quad (4)$$

In formula (4), f_{flyeye} is the focal length of lens, and f_{relay} the equivalent focal length of the lens group in lighting path. The numerical aperture of laser is small enough to make the expression $\sin\phi \approx \phi$ true. Meanwhile, we can assume the beam angles of light traveling into all fly's-eye lens are all the same. Then we can simplify the formula (3) to formula (5).

$$\begin{aligned} E_{flyeye} &= \sum_{MN} \pi W(i,j) ab \sin^2 \phi_{max}(i,j) \\ &\approx \pi \phi^2_{max} ab \sum_{MN} W(i,j) \\ &\approx \frac{\pi^2}{4} MNab\phi^2_{max} \end{aligned} \quad (5)$$

In the fly's-eye lens arrays, it meets the following formulae.

$$a_{L\cos}\varphi = (M-1)a\phi_w \quad (6)$$

$$b_{L\cos}\varphi = (N-1)b\phi_H \quad (7)$$

In the above formulae, ϕ_w and ϕ_H represent the aperture angles of fly's-eye lens on the LCOS chip in width direction and height direction of the spatial light modulator. Combine formula (6) and (7) with (2), we can get formula (8).

$$\begin{aligned} E_{L\cos} &= \pi a_{L\cos} b_{L\cos} \sin^2 \varphi_{L\cos} \\ &\approx \pi a_{L\cos} b_{L\cos} \varphi^2_{L\cos} \\ &\approx \pi (M-1)(N-1) ab\phi_w\phi_H \end{aligned} \quad (8)$$

Through formula (5) and (8), we can get formula (9).

$$\frac{E_{flyeye}}{E_{L\cos}} = \frac{\pi ab\phi^2_{max}}{4(M-1)(N-1)\phi_w\phi_H} \quad (9)$$

We can get the following points from formula (9).

- When $E_{flyeye} = E_{L\cos}$, the étendues of LCOS and fly's-eye lens are the same. There is no energy loss in system.
- When $E_{flyeye} > E_{L\cos}$, fly's-eye lenses do not accept all the light, and those beams with large solid angle are not used in the LCOS system, which leads to low energy efficiency.
- When $E_{flyeye} < E_{L\cos}$, it is possible that fly's-eye lens accepts all the light of source, but the LCOS chip is not rationally utilized. After the laser beams run through fly's-eye lens, the subsequent optical path need to increase optical étendue, which may increase the cost and complexity of the projection system.

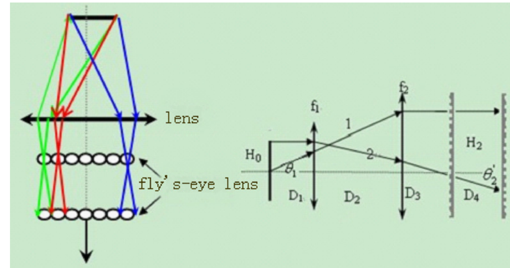

Fig. 2. Operational principle diagram of two fly's eyes.

3. Calculation of aperture and aperture angle θ'_2

Many shapes of fly's-eye lens elements can be used in uniform light, such as square, rectangle, spiral, variable radius shape, and so on. Among these shapes, square and rectangle are frequently used. From Fig. 1, we can see that the light path uses two fly's-eye lenses [5–9] to make uniform illumination. Its operational principle is shown in Fig. 2.

According to Fig. 2, we can get formula (10) through analyzing light beam 1 with imaging theory of geometrical optics.

$$\frac{1}{D_3} - \frac{1}{f'_1 - D_2} = \frac{1}{f'_2} \quad (10)$$

To light beam 2,

$$\frac{1}{f_2 + D_2} - \frac{1}{(-D_1)} = \frac{1}{f'_2} \quad (11)$$

In formula (11), f_1 and f'_1, f_2 and f'_2 represent the object side and image side focal length of lens 1 and lens 2. D_1, D_2, D_3 and D_4 stand for the distances between different lenses. The constant H_0 represents the size that system will display. Through calculating formula (10) and (11), we can get formula (12).

$$A_2 f'^2_2 + B_2 f'_2 + C_2 = 0 \quad (12)$$

In formula (12), $A_1 = \frac{D_1D_2 - D_2D_3}{D_1 + D_2 - D_3}$, $A_2 = B_1 = \frac{D_2 + D_3 - D_1}{D_1 + D_2 - D_3}$, $B_2 = A_1 - B_1D_1 - B_1D_2 - D_1$, $C_2 = D_1D_2 - A_1D_1 - A_1D_2$.