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Illumination optics design for DMD Pico-projectors based on generalized functional method and microlens array

Dan Li¹, Baolong Zhang^{1*} and Jiawei Zhu²

Abstract

The influence of incident angle and aberration of the microlens array on the optical efficiency in pico-projector is analyzed. By modifying the relevant parameters, a method to optimize the optical efficiency and uniformity of the illumination system is proposed. By changing the profile of the freeform double lens used for the concentrator of LED source, the incident angle can be reduced, thus the efficiency loss caused by large angle incident can be reduced. In addition, two spherical relay lenses instead of the Fourier lenses are used as integral component after the microlens array, which is not only low cost, but also more flexible in controlling aberrations. After system optimization, the illumination efficiency and uniformity of the pico-projector system can reach 60.51% and 86.2%, which verifies the feasibility and validity of the theoretical analysis.

Keywords: Non-imaging optics, Microlens array, Pico-projector, LED

Introduction

Recently, pico-projector is becoming a very hot topic with numerous potential applications [1–3]. Small volume, ultra-thin thickness and lightweight are the inexorable tendencies to modern pico-projectors. The optical engine of pico-projector is mainly composed of two parts, which are imaging system and non-imaging illumination system. In the imaging system, digital micromirror devices (DMD), liquid crystal display (LCD), and liquid crystal on silicon (LCoS) microdisplay are always adopted as the display panel. Among them, DMD is popular in the market because of its high definition, high brightness and saturated color. With the trend of portability of pico-projector market, compact illumination source has become a key technical requirement in the non-imaging illumination system. As a result, light emitting diode (LED) is chosen due to its outstanding performance such as high energy efficiency, small size, simple driving scheme and so on. However, as the radiant angle of LED is too large as 180°, a compact non-imaging optics is required to increase the illumination efficiency and uniformity.

In this paper, the concept of imaging method is introduced into the design of non-imaging illumination system to correct the spherical aberration, which plays a great role in improving the brightness and uniformity. As a result, a double-row microlens array with two spherical lens as relay lens and two aspherical lens as collecting unit are designed in the illumination system to achieve the compact structure and uniform illumination. By controlling the angle of incident of the microlens array, the loss of light energy caused by large angle incident is reduced.

Non-imaging illumination optics design

The non-imaging illumination system designed in this work was mainly divided into two parts, which are microlens array system and double lens concentrator system. In between these two systems, relay lens are usually adopted to adjust the optical path and avoid the structural interference.

Microlens Array system

Principle and design

When light passes through the first row of microlens arrays in the illumination system, the broad beams are divided into several fine beams. These fine beams are imaged on the second row of microlenses, and the

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uniformity of each fine beam is improved compared with that of the wide one. These fine beams are integrally superposed as secondary light sources by the modulation of the following concentrator. The superposition compensates for the slight difference in the uniformity of the imaging spot of the fine beam. Then, with the magnification of the relay lens, a uniform illumination spot is obtained. Figure 1 shows the architecture of microlens array system, in which P_a is the periodical of the microlens array, D_{DMD} is the diagonal size of DMD panel, f_a and f_{Relay} are the focal lengths of microlens array and relay lens, respectively [4, 5]. In order to obtain the most efficient illumination spot, the size of P_a should be proportional to the diagonal size of DMD panel, that is

$$D_{\text{DMD}} = K \cdot P_a \quad (1)$$

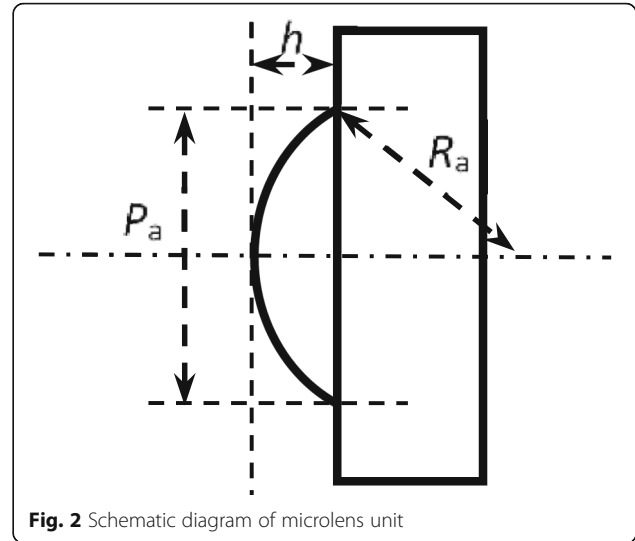
where K is a constant.

According to the characteristics of microlens array, we can assign the characteristics of the whole microlens array to each microlens unit, and obtain the design method of microlens unit, which is shown in Fig. 2, where h and R_a stand for the thickness, and the spherical radius of microlens unit, respectively.

It is well known that the focal length of a real lens is as

$$f = \frac{n \cdot r_1 \cdot r_2}{(n-1) \cdot [n \cdot (r_2 - r_1) + (n-1) \cdot d]} \quad (2)$$

where f is the focal length of a real lens, n is the refractive index, d is the thickness of the lens, r_1 and r_2 are the spherical radius of front and rear surface of the lens, respectively. For microlens unit discussed in this work, $f = f_a$, $r_1 = R_a$, and $r_2 \approx d = \infty$. As a result, the spherical radius of microlens unit can be expressed as



$$R_a = (n-1) \cdot f_a \quad (3)$$

Also, the relationship between numerical aperture and focal length of the microlens unit is as

$$N_A = \frac{1}{F/\#} = \frac{P_a}{f_a} \quad (4)$$

According to geometric relationship, the thickness of the microlens unit can be solved as

$$h = R_a - \sqrt{R_a^2 - P_a^2} \quad (5)$$

In this work, polycarbonate (PC) is selected to fabricate the microlens array due to its outstanding characteristics on small shrinkage (0.5–0.7%), high accuracy, and good stability. The refractive index of PC is $n = 1.59132$ [https://www.plastics.covestro.com/en/Products/Makrolon.aspx]. The diagonal of DMD panel selected in

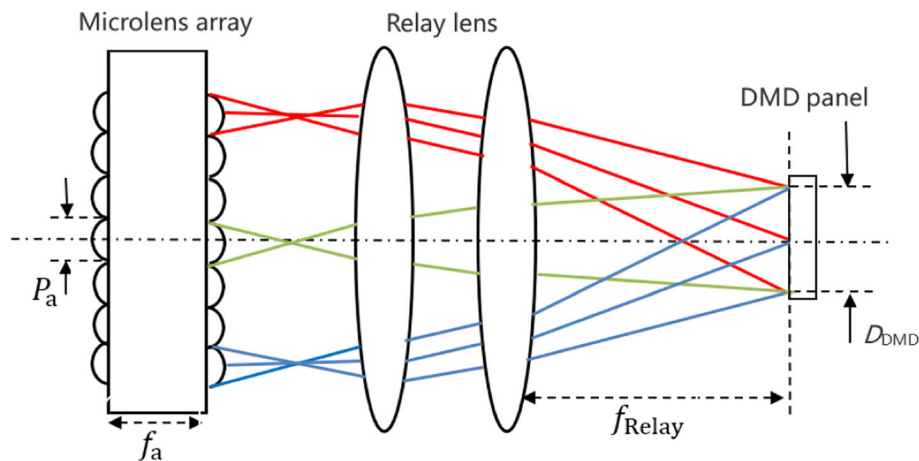


Fig. 1 Architecture of microlens array system

this design is 0.45 in.. To compromise the contrast and brightness, the $F/\#$ of the system is set as 1.8, and the constant $K = 4$. Substitute these values into above formulas, the design parameters of microlens unit can be obtained as $P_a = 2.8575\text{mm}$, $f_a = 5.1435\text{mm}$, $R_a = 3.0414\text{mm}$ and $h = 2\text{mm}$.

It is worth mentioning that the early microlens arrays are two discrete components in cascade. The physical properties of the two components were identical. However, when assembling, the front and back sides of the microlens arrays should be kept strictly symmetrical, which requires a high assembling accuracy [6]. Due to the misalignment introduced in the assembly process, the fine beams segmented from the first row of microlenses cannot be fully imaged on the corresponding second row of microlenses, which will cause the eccentricity of the illumination system. As a result, the segmented beam cannot be concentrically superimposed on the target DMD panel, so that the illumination efficiency and uniformity will be dramatically decreased. The overflowing light will show bright lines on one side of the panel, which results in the flare when it is displayed on the projection screen. This phenomenon is similar to the large incident angle effect discussed in the following section. To avoid this phenomenon, two separated microlens array are combined into one integrated component, which is shown in Fig. 3. This structure increases the complexity of die processing and injection molding process, but greatly reduces the assembly error, and improves the illumination efficiency dramatically.

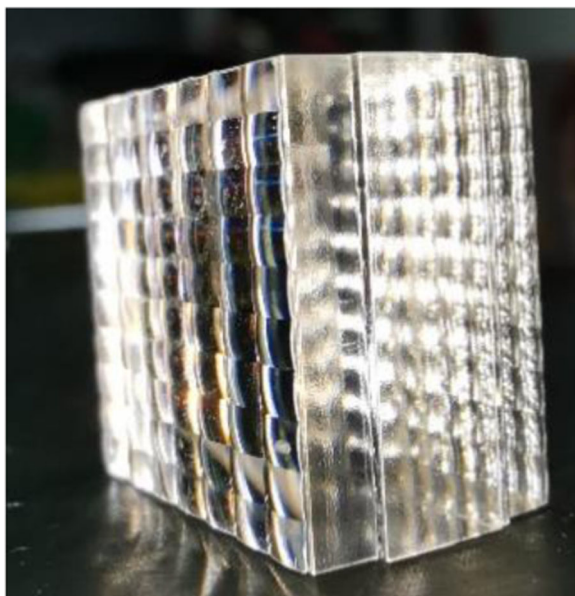


Fig. 3 The fabricated prototype of the integrated microlens array

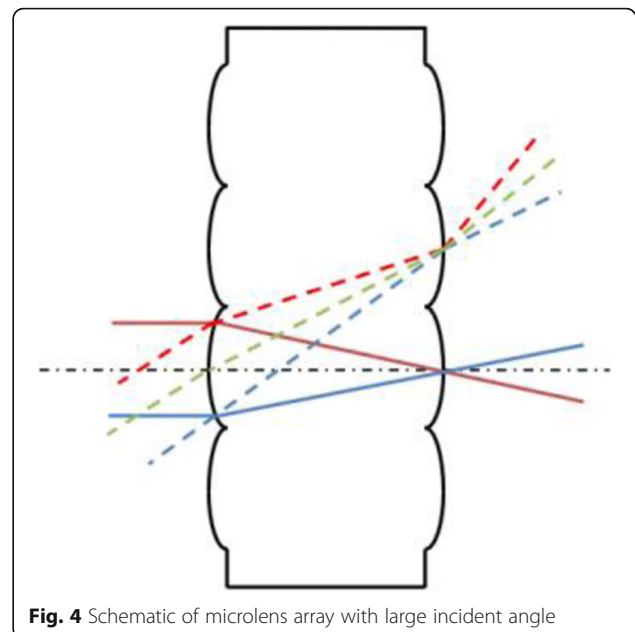


Fig. 4 Schematic of microlens array with large incident angle

Large incident angle analysis

When the incident light was irradiated on and refracted by the first row of the microlens arrays, it should be collected by the corresponding second row of microlenses, ideally. However, when the incident angle is too large, it cannot be imaged on the second row of microlenses. As a result, it emits as a spurious spot around the target DMD surface and reduces the optical utilization of the microlens arrays [7, 8], which is shown in Fig. 4.

In order to improve the system efficiency, the angle of the incident beam can be reduced by modifying the surface profile of the freeform optical lens, or the numerical aperture can be accordingly increased based on the optical conservation principle of etendue [9] as

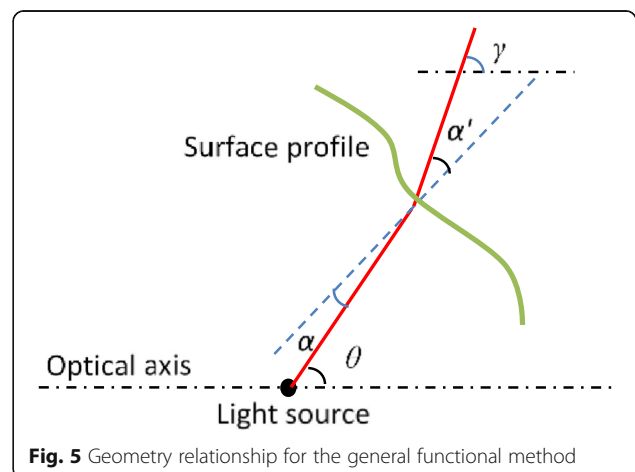


Fig. 5 Geometry relationship for the general functional method

Table 1 The optical parameters used in the simulation

Parameters	Value
LED areas	2.09 mm × 1.87 mm
LED Luminous angle θ	120°
Material	Polycarbonate
Index of refraction	1.59132
Target surface areas	10 mm × 10 mm
Output angle γ	12°

$$E = \pi \cdot A_s \cdot \sin^2 \theta_i \quad (6)$$

where, A_s is the spot area and θ_i is the incident angle of light. According to the design specifications, increasing the numerical aperture means reducing the F number, which is expressed as

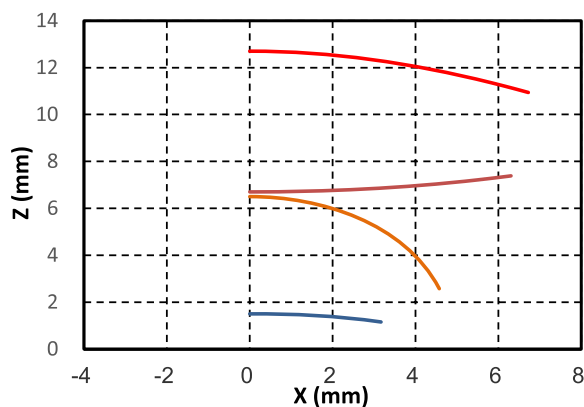
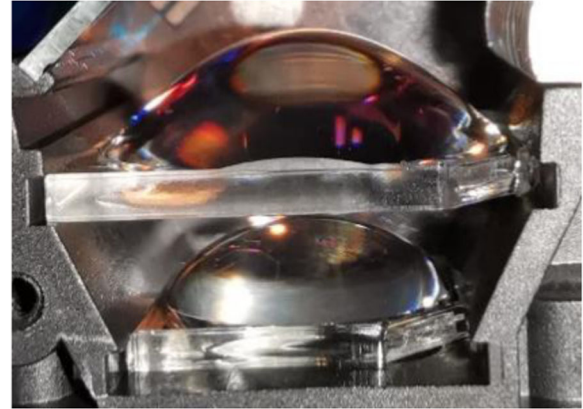
$$F/\# = \frac{1}{2 \tan \theta_i} \quad (7)$$

As a result, the area of the illumination spot should be reduced. However, since the illumination area of the DMD is fixed, the only solution is to increase the focal length of f_{Relay} , which will increase the volume of the pico-projector. Therefore, tradeoff must be adopted in the design for the purpose of optimization.

Double Lens concentrator system

Lambert-shaped light emitted by LED source usually diverges at an angle of about 120 degrees, which is over-dispersed and affect the optical efficiency seriously. For this reason, the optical concentrator must be designed for LED source. As the requirement of DMD panel, most of the energy of the illumination source needs to be concentrated in the range of 12 degrees.

Freeform double lens concentrator is a group of aspheric lenses. They are designed on the basis of generalized functional method [10]. The lens is a centrosymmetric entity. Its profile of cross section is a freeform curve

**Fig. 6** The simulated freeform surface profile**Fig. 7** The fabricated prototype of double lens concentrator

composed of discrete points, which cannot be expressed by analytic formula. This freeform profile can realize the given functional correlation between the output angle γ of the illumination system and the output angle θ of the LED source. Figure 5 illustrates the Geometry relationship for the general functional method.

From the geometry, it is apparent that the output angle γ as a function of source angle θ can be expressed in the form

$$\gamma(\theta) = \theta - \alpha + \alpha' \quad (8)$$

where α and α' are the incident and refracted ray angles, respectively, measured counterclockwise relative to the local surface normal. Using Snell's law to eliminate α' in eq. (8), we can find α as

$$\alpha(\theta) = \tan^{-1} \left\{ \frac{n' \sin[\theta - \gamma(\theta)]}{n' \cos[\theta - \gamma(\theta)] - n} \right\} \quad (9)$$

which is an expression of required incident ray angle as a function of source emission angle. In this equation, n and n' are the refractive index on the incident and refractive side of the optical surface, respectively.

With this function, numerical solution of freeform surface profile can be obtained by MATLAB simulation. The optical parameters used in the simulation is shown in Table 1. By setting the linear relationship between the input angle θ and the output angle γ , four refractive optical surface have been resulted. The refracted beam from each surface has smaller angle difference compared to the incident light beam. The contour of the fourth refractive surface, which is near to the illumination target, is determined by the requirements that the output light must be within 12°. The optical efficiency of the system reach the theoretical limit when the etendue of LED light source and the irradiated surface are equivalent [11]. The simulated freeform surface profile is shown in Fig. 6. By rotating these profiles around the optical axis (Z-axis,

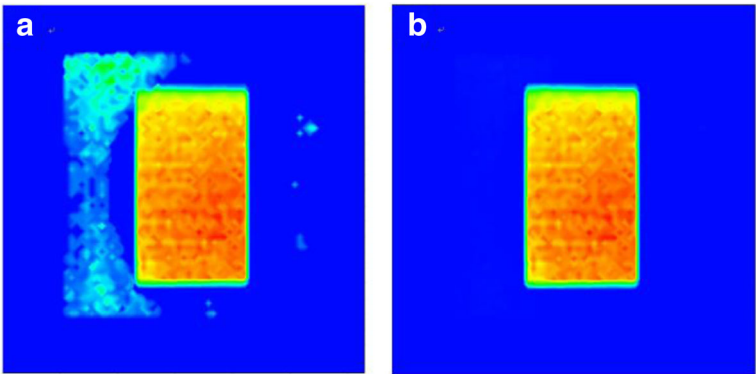


Fig. 8 The ray tracing results of the illumination system at output angles of (a) 15°, and (b) 12

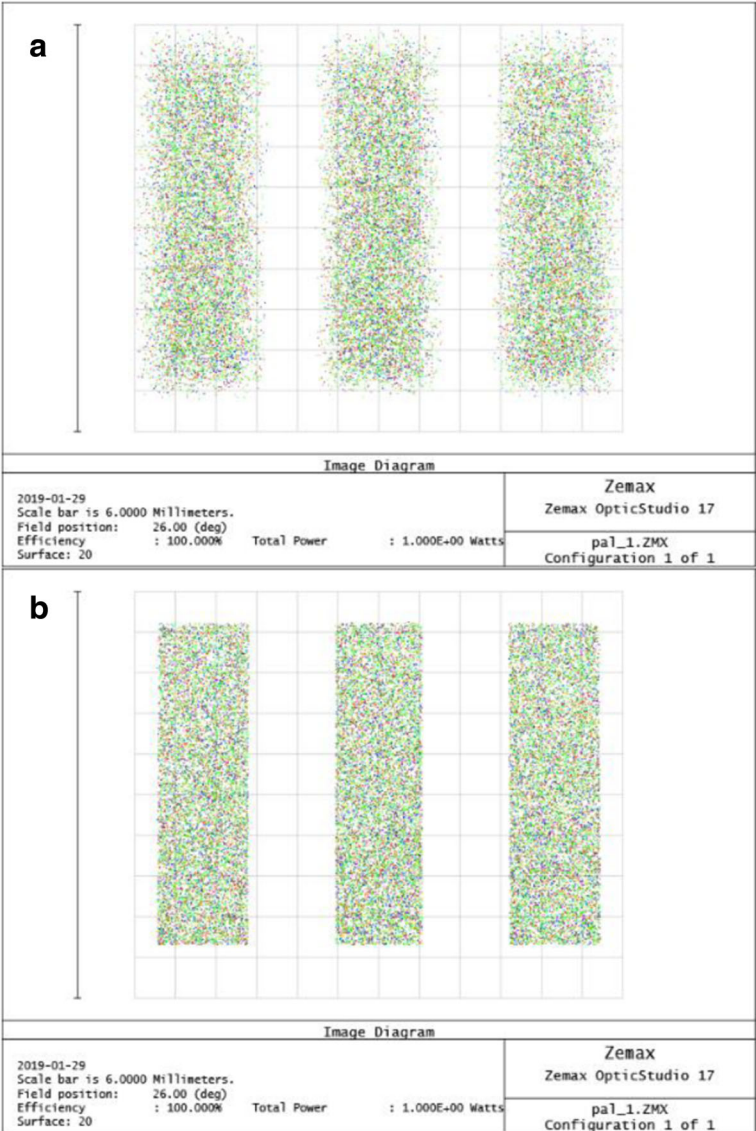


Fig. 9 The illumination spot (a) before and (b) after the aberration correction

where $x = 0$), the entity of freeform double lens concentrator is generated. Figure 7 shows the fabricated prototype of double lens concentrator.

Simulations and optimizations

The non-imaging illumination system designed in previous sections is simulated by Tracepro for ray tracing analysis. Figure 8 shows the ray tracing results of the illumination system at different output angles. For the compatibility of following assembly process, the bright green border in Fig. 8 is an illumination redundancy, which is 10% larger than the DMD panel. Figure 8(a) is the ray tracing result of the illumination system at output angles of 15° . Obviously, due to the leakage of refracted light caused by large incident angle, flare is formed on left side of the DMD panel, and the energy loss is about 20%. Figure 8(b) is the ray tracing result of the optimized illumination system at output angles of 12° . Because the beam segmented by the first row of microlens array imaged on the corresponding second row of microlens array effectively, the energy loss of the illumination system is only about 10%, and the system efficiency is significantly improved.

Analysis of imaging aberration on illumination system

Generally, in the illumination system with large effective aperture and compact structure, it is necessary to quickly reduce the illumination spot area of the light source to the effective area of the microdisplay device. This requires that the relay lens has a shorter rear focal length, which will inevitably introduce large aberration and reduce the optical utilization efficiency of the illumination system [12]. According to the theory of imaging aberration, the spherical aberration, coma and astigmatism will affect the size and shape of diffuse speckles, which results in blurred edges and reduces the brightness of the projected image. Also, the field curvature and distortion cause the distortion of the image plane, which makes the aberrations of the secondary light source equivalent to the microlens array superimpose on each other. This will result in non-uniform illumination, and the edge field of view is the most obvious. Figure 9 shows the illumination spot before and after the aberration correction, which are simulated by Zemax.

It is obvious that the optical utilization of illumination system is significantly affected by the aberration of edge field of view, but not by its central counterpart. Therefore, in the optimization process, the imaging constrains for central field of view should be relaxed, and the imaging constrains for each aberration in edge field of view should be emphasized [13]. Zemax is used to optimize the aberrations of two spherical relay lenses. In the design, the diffuse speckle diameter of the edge field of view should be less than 0.3 mm, and the counterpart of the central field of view should be less than 0.04 mm.

Figure 10 shows the MTF curve before and after the aberration correction. The MTF curve before optimization is less than 0.1 at 36 line pairs as shown in Fig. 10(a), while the optimized MTF curve is still larger than 0.4 at 60 line pairs as shown in Fig. 10(a), which means that the optical performance has been significantly improved.

Experiments and discussions

Based on the above discussion, the influence of incident angle and large aberration on the optical efficiency of illumination system is analyzed, and a set of optimized design schemes is proposed. Relay lenses are replaced by two spherical lenses, which makes it easier to correct aberrations and reduce image height quickly in short distance to avoid large aberrations. Compared with Fourier lenses, the design of two spherical relay lenses is much simpler, aberrations are easier to adjust and costs are greatly reduced [14].

The optical layout of the whole pico-projector is shown in Fig. 11. The prototype uses a 0.45 in. DMD from Texas Instrument (TI) as display panel and a PT39 LED from Luminus as illumination source. The beam radiated by the LED source passes through the freeform double lens

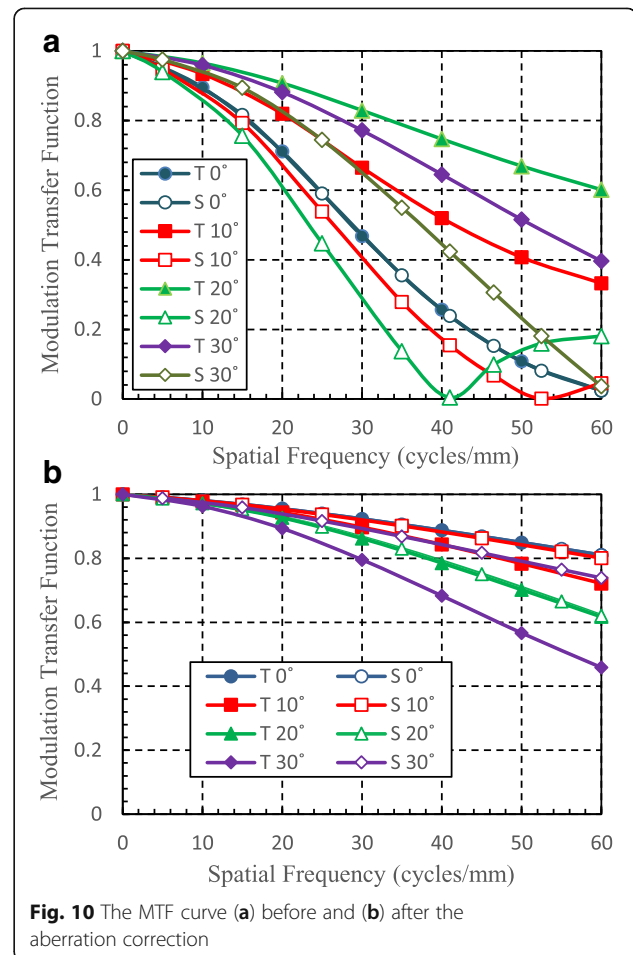


Fig. 10 The MTF curve (a) before and (b) after the aberration correction

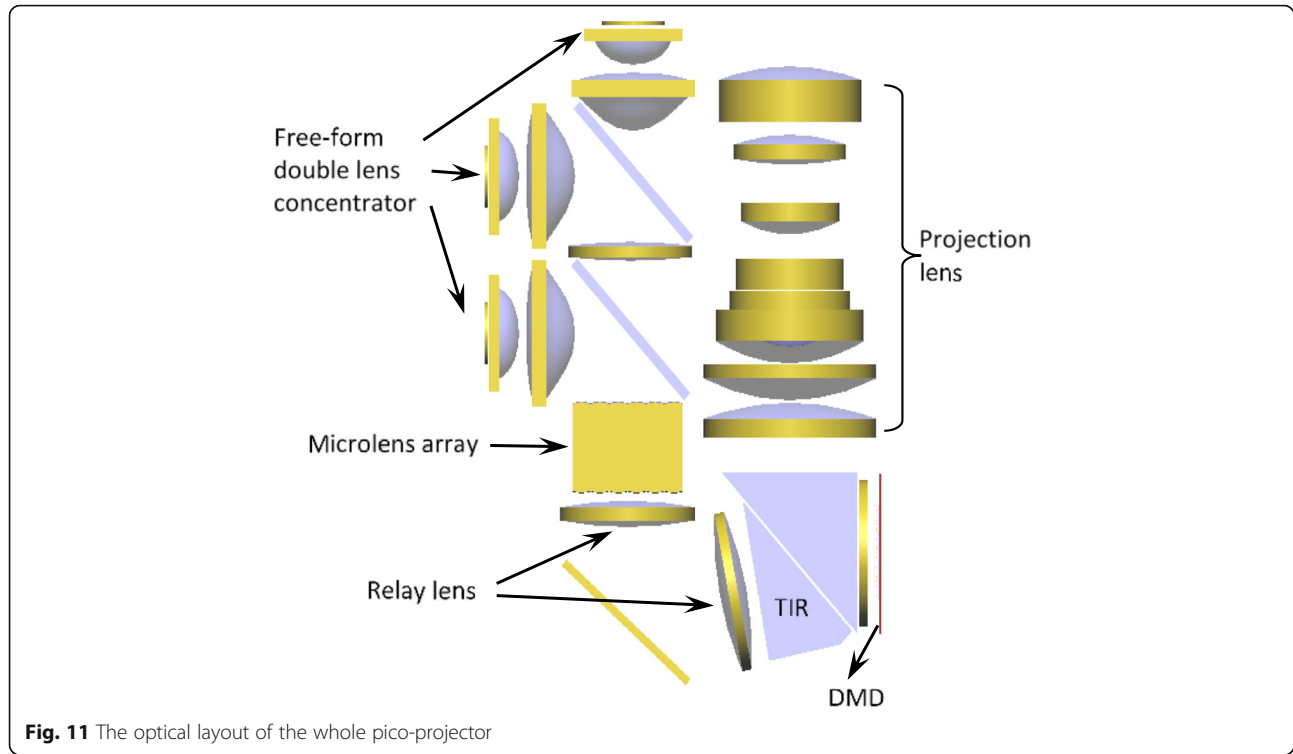


Fig. 11 The optical layout of the whole pico-projector

concentrator and incidents to the microlens array at an angle less than 12 degrees. The ratio of the area of the microlens unit to the effective area of the DMD panel is 1:4, at which the system uniformity is the best [15]. According to the conservation principle of optical extension, the F/# of microlens array is set to 1.8. The illumination efficiency is as high as 60.51%. Figure 12 shows the prototype of the pico-projector in operation.

Figure 13 shows the illumination uniformity obtained by simulation and the projected bright field image obtained by experiment. Optical uniformity of pico-projectors is defined as

$$u = \frac{P_{cor_avg}}{P_{center}} \times 100\% \quad (10)$$

where P_{cor_avg} stands for the average brightness of the four display corners and P_{center} stands for the central brightness of the projected image. The calculated uniformity of the pico-projector is 86.2%, which coincides with the experimental results.

Conclusion

In this work, the influence of incident angle and system aberration of microlens array on optical utilization efficiency in illumination system is analyzed. The freeform double lens is designed based on general functional



Fig. 12 The prototype of the pico-projector in operation

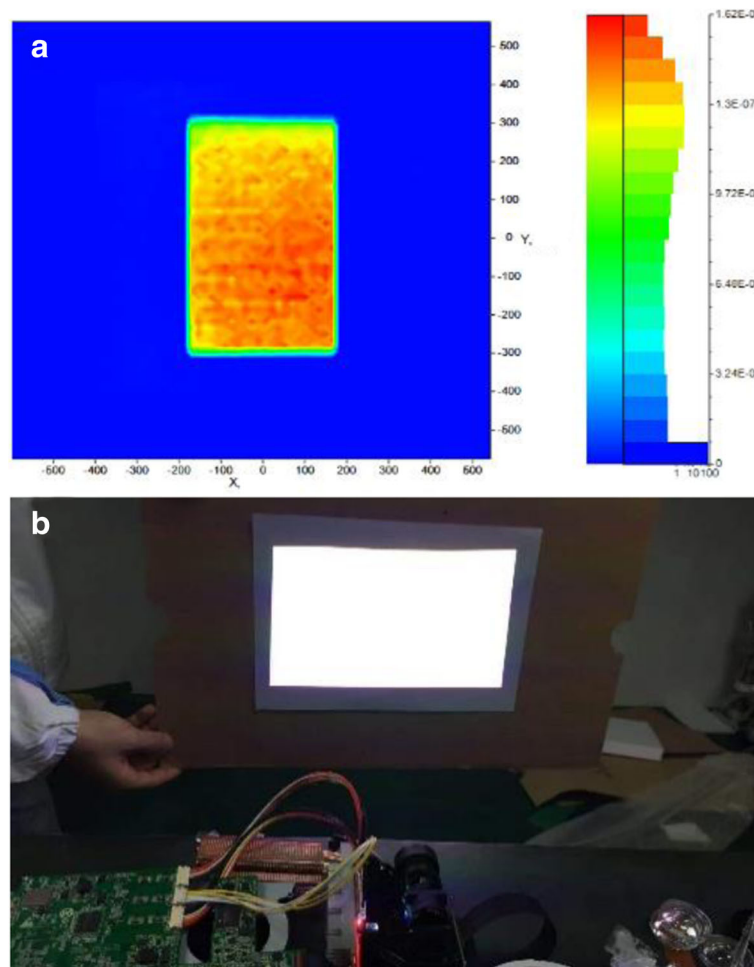


Fig. 13 (a) The simulated illumination uniformity, and (b) the projected bright field image

method and used as the concentrator for LED source. By calculating and modifying the lens profile, the angle of incident to the microlens array is reduced, and the efficiency loss caused by this large angle incident is reduced, which finally results in the improvement of the system efficiency. After the microlens array, two spherical relay lenses are designed to control the aberration more flexibly, optimize the effective spot shape, and improve the optical efficiency and uniformity. A 0.45 in. DMD panel is used in the pico-projector discussed in this work for the design of illumination system. The diameter of diffuse speckle in the edge field of view is controlled within 0.3 mm, and that of the central field of view is controlled within 0.04 mm. After optimization, the illumination efficiency and uniformity of the system can reach 60.51% and 86.2% respectively.

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Authors' contributions

Dr. DL contributes the design and simulation of the pico-projector system. Dr. BZ contributes the fabrication and characterization of the pico-projector prototype. All authors read and approved the final manuscript.

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Availability of data and materials

The supporting data is already provided in this paper work.

Competing interests

The authors declare that they have no competing interests.

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