Design and application of new generation micro-lens arrays (MLA) with free-form surfaces and irregular arrangement of segments

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ABSTRACT

A Micro-lens Array (MLA) is an optical element in which multiple lens segments are integrated onto a single substrate. Traditional MLAs consist of segments with the same geometric shape arranged at regular intervals atop a planar surface. They are used for applications that include beam homogenization, to equalize light intensity distribution, and light field imaging to change post-exposure the optical configuration such as viewpoint and focal distance of the captured image data. However, the limitations imposed by the identical segment geometry and the regular arrangement pattern constrain the range of possible applications and their associated performance. In this paper, novel MLA geometries and design methods are introduced that enable new generation products. With this type of MLA, each segment can have a different free planar shape and freeform surface shape in height direction. The segments of MLA are designed with topology optimization method based on internal stresses, that allows unsupervised design of optical segments. The designed freeform segments can maximize the use of light the lens, according to the target illumination pattern and intensity defined by each segment.

Keywords: freeform illumination, micro-lens array, topology optimization

1. INTRODUCTION

Freeform illumination optics often consist in a continuously curved surface that achieves prescribed illumination patterns or intensity distributions. Researches were conducted for sag computation of single or multiple freeform surfaces of single lens, using ray mapping method including Monge–Ampere equation and ellipsoid algorithm [1, 2]. Lens surface points are inversely computed by ray transfer function relating given source rays distribution and target rays distribution and a continuous surface is obtained by optimization process. However, the surface area used for illumination is only a portion of the total lens area [3]. This is because in ray mapping method, constraints are not taken in account to control outline geometry of intermediate rays distribution: front and back surface of lens. This research therefore focuses on the process of optimization of the planar layout of segments on Micro-lens Array (MLA) surfaces, with the goal of maximizing the use of light irradiating the lens (Figure 1). We propose to optimize the planar topology of the MLA segments using finite element modelling of inner stress in elastic materials. This process is performed as a preliminary step of ray mapping computation and the freeform surfaces are constructed based on Construction–Iteration method [4].

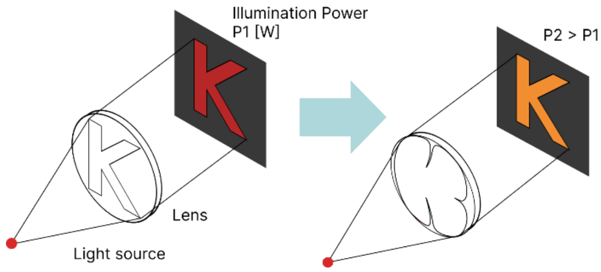


Figure 1 Increase of the irradiated area of lens leading to a more efficient use of light

2. METHODS

The optimization process for the topology of the planar shape of MLA segments consists of four steps. First, the outline of illumination patterns at the target plane is defined (Figure 2(a)), where each segment is responsible for illuminating one pattern. Second, these patterns are transferred and fitted within the circular outline of the base lens of the MLA, and segment domains are defined within the base lens domains (Figure 2(b)). Third, intensity weights w_I are defined for each segment domain to adjust the relative intensity of each pattern. Fourth, the computation of segment domain expansion is performed (Figure 2(c)). Virtual inner stresses σ_{vr} are applied on base and segments domains to expand the segment domains, as shown in Eq. 2. The outer boundary of base lens domain is fixed. The PDE of 2D linear elastic deformation shown in Eq. 1 is solved by finite element method (FEM)and segment planar topologies are optimized by iteration.

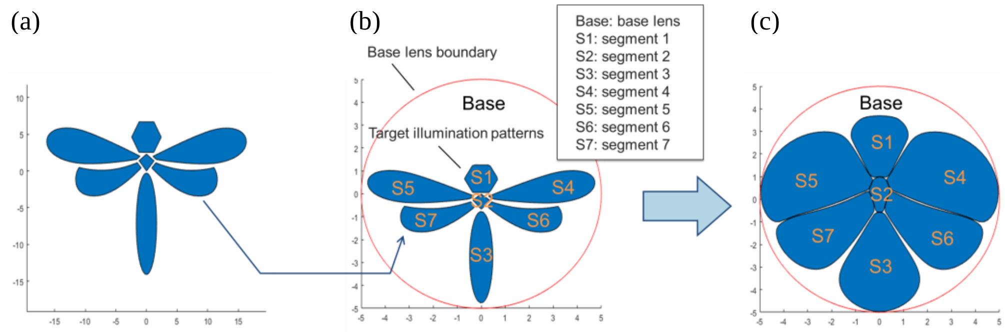


Figure 2 Sequence of segment domains expansion: (a) Outlines of target illumination pattern (7 patterns), (b) Assignment of base and 7 segment domains in base lens area, (c) Expansion of segment domains

$$\int_{\Omega} \sigma(u) : \varepsilon(v) dA = \int_{\Omega} \sigma_{vr}(u) : \varepsilon(v) dA \tag{1}$$

$$\sigma_{vr} = \begin{bmatrix} 3 \cdot \alpha \cdot B \cdot \Delta T \cdot \sqrt{w_I} & 0 \\ 0 & 3 \cdot \alpha \cdot B \cdot \Delta T \cdot \sqrt{w_I} \end{bmatrix} \tag{2}$$

In Equation 1, σ [N/m^2] represents stress states of base and segments domains and ε represents the deformation. u and v is the trial function and test function of PDE. Virtual inner stresses σ_{vr} is expressed as the foam of thermal expansion stress tensor multiplied by square root of intensity weight w_I and α represents virtual linear coefficient of thermal expansion [1/K], B is virtual bulk modulus [Pa], and ΔT is virtual temperature change of domains [K] in Equation 2. In order to induce the expansion of segment domains, lower Young modulus E and higher thermal expansion coefficients α are set to segment domains than the base lens domain, as shown in Table 1.

Table 1 Domain parameters and mean intensities of patterns

Domain	Base lens	Segment #1	Segment #2	Segment #3	Segment #4	Segment #5	Segment #6	Segment #7
E [e^{11}]	2.73	2.1	2.1	2.1	2.1	2.1	2.1	2.1
$\boldsymbol{\alpha}$ [1/K]	1e-12	1e-4	1e-4	1e-4	1e-4	1e-4	1e-4	1e-4

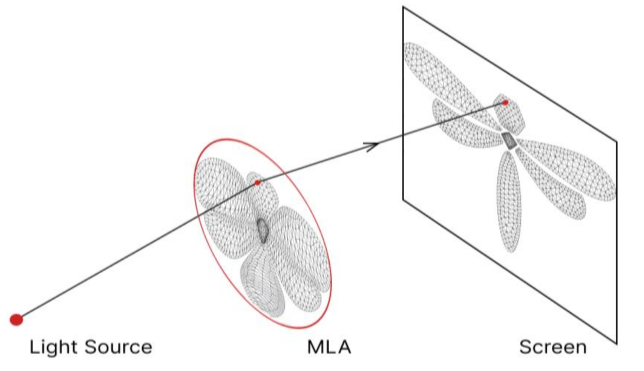


Figure 3 Construction of freeform surfaces using mesh nodes

Freeform surface computation is performed for each MLA segment after the topology optimization of its planar shape. Nodes of the triangular meshes generated for FEM are used as data points of MLA surfaces for ray mapping computation, which relate source distribution points and target distribution points, as shown in Figure 3.

3. RESULTS

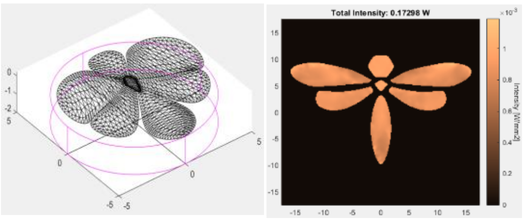
3.1 Adjustment of intensity of illumination by intensity weights

An MLA for logo projection is designed with different intensity weights. Intensities of illumination patterns at target plan was evaluated by ray tracing simulation. Side view of illumination system is shown in Figure 5(d). A MLA is irradiated by a point source of 590 nm of wavelength and creates a dragon fly pattern on the screen 410 mm away. The intensity of right forewing pattern was increased by a factor of 2.15 comparing to the other patterns when the weight of fourth segment domain is set to 2.0, as shown in the table of Figure 4(B).

Freeform-plano MLA   Intensity Distribution

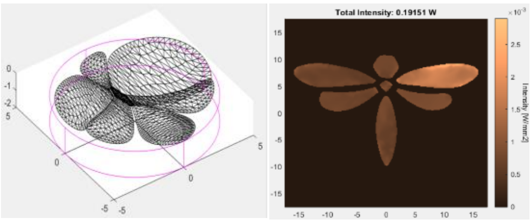
Mean intensities of pattern I_{mean} $[\mathrm{mW/mm^2}]$

(A)



Domain	S1	S2	S3	S4	S5	S6	S7
w_I	1.0	1.0	1.0	**1.0**	1.0	1.0	1.0
I_{mean}	0.922	0.921	0.853	0.852	0.863	0.871	0.872

(B)



Domain	S1	S2	S3	S4	S5	S6	S7
w_I	1.0	1.0	1.0	**2.0**	1.0	1.0	1.0
I_{mean}	0.794	0.809	0.730	1.68	0.730	0.879	0.748

Figure 4 Intensity change of right forewing as function of intensity weight

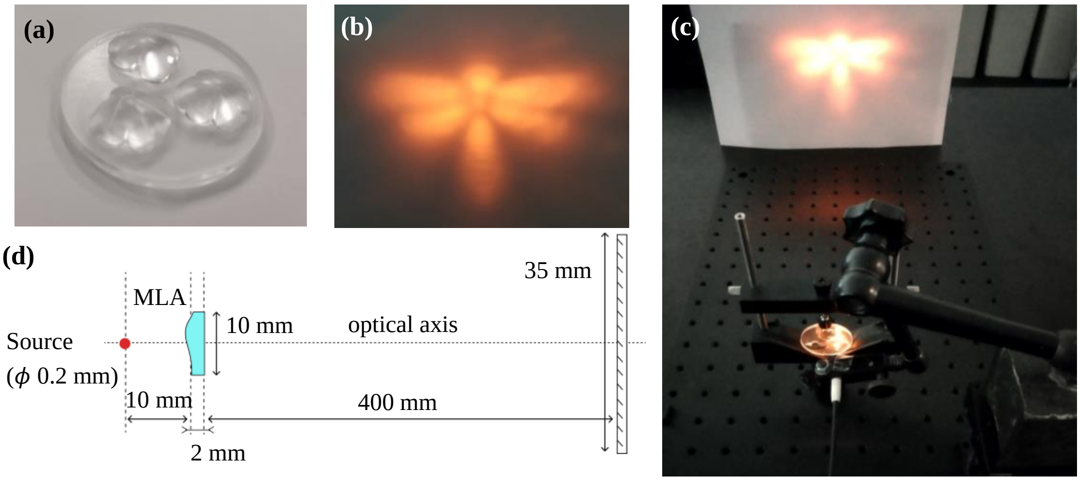


Figure 5 Experiment set up: (a) fabricated MLA (b) illumination of dragon fly logo (c) top view (d) side view

3.2 Evaluation of illumination pattern by experiment

The illumination pattern was evaluated by experiment. A MLA made of PMMA was fabricated using Makino machining center D200Z with a ball end mill of R 0.25 mm. Segment planar shapes were designed with the configuration of weights shown in the table of Figure 4(A). Seven patterns were observed on the screen. Image cannot maintain its sharp edges of patterns and it is mainly because a LED of 0.2 mm of aperture was used instead of point source.

4. CONCLUSIONS

The topology of planar shape of MLA segments are optimized by inner stress based - expansion method in FEM. We have confirmed that the lens area used for illumination can be increased to up to 85% of the base lens area, while adhering to the constraints of triangular mesh inversion. Distribution of irradiant power of multiple illumination patterns can be adjusted by inner stress weights set on each MLA segments.

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