Wide-range and accurate temperature sensing with micro-lens-array

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Abstract: A multi-focal depth (10-80 mm) micro-lens-array is designed for use as objective lens in a remote temperature measurement system. System performance is evaluated by ray tracing simulation and experiment, comparing favourably against an aspheric system.

Keywords: lens array, freeform optics, remote measurement, multi-depth objective

1. Introduction

A method for accurate remote temperature measurement consists in inferring the temperature of an excited fluorescent gel from its correlation with the polarization degree of fluoresced light [1], as illustrated in Fig. 1. Excitation light is sent onto a heat source coated with a fluorescent gel, and the fluoresced light is then split and passed through a pair of polarizing plates to measure the polarization degree. When compared to infra-red spectrum based systems [2], this method is characterized by insensitivity of the degree of polarization with measurement distance and high repeatability of the measurement. By using a micro-lens-array (MLA) as the objective lens of the measurement system, it is possible to receive a significant amount of the fluoresced light irrespective of distance to the gel. This method improves the range of the temperature measurement system.

Zhu et al. established a freeform surface construction algorithm for MLA with hexagonal shape segments [3]. In this paper, the method is applied to design a freeform-spherical MLA collecting light from 6 different focal depths. The intensity collection and degree of polarization are evaluated by ray tracing simulation and experiment.

2. Design of Objective Lens Array

2.1 Measurement System

The layout of temperature measurement system is shown in Fig. 2(a). System is composed of a hexagonal MLA shown in Fig. 2(b) and two plano-aspheric condenser lenses (Edmund Optics #16-960). Each segment of MLA is assigned a different focal distance on the optical axis as shown in Table 1, and generates a virtual image on the optical axis at [0, 0, -8.0]. These virtual images then generate real images through the pair of condenser lenses at a point on the axis located at [0, 0, 102.9]. A linear polarizer can be placed between the condenser lenses to select the polarization direction.

The MLA material is polymethyl methacrylate (PMMA) with refractive index n=1.495 at the operating wavelength of 530 nm. The centre is planar on both sides, with a thickness of 0.8384 mm and 1.9 mm diameter, to allow transmission of the excitation light (through a fold mirror placed between the condenser lenses). The outer diameter is 6.0 mm. This array consists of 6 hexagonal lens segments, with diagonal length of 1.30 mm. On the front surface of the array, each segment features a different freeform shape, while the back surface adopts a concave spherical shape with the curvature radius of 440.9 mm.

2.2 Design Method of Freeform Surfaces

For the first step, before computing the freeform surfaces, the initial curvature radii are calculated for both the front and back surfaces of each segment, denoted as R_1 and R_2. Approximating the lens surfaces with spherical shapes that minimize spherical aberration enhances the

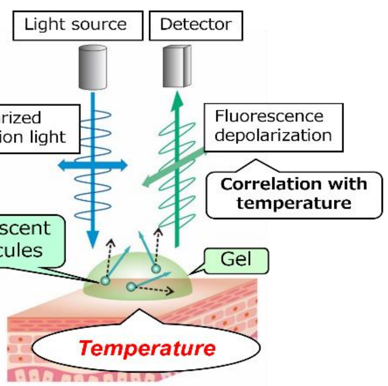

Fig.1. Temperature measurement using the variation of polarization degree

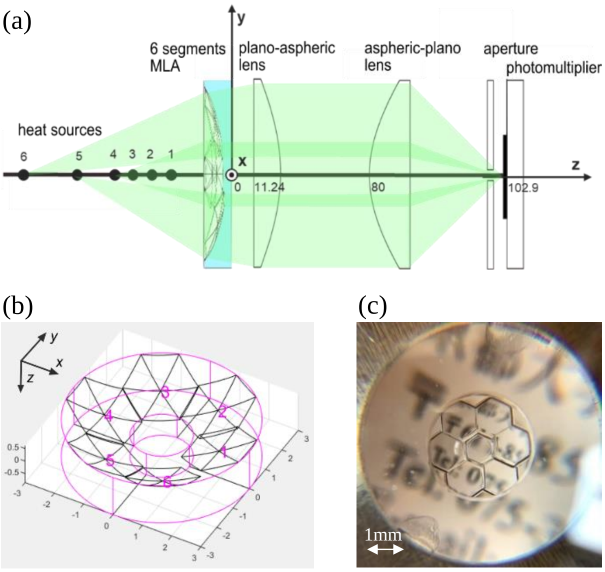

Fig.2. (a) Layout of temperature measurement system in Y-Z plane, (b) 3D view of hexagonal lens segments, and (c) Top view of fabricated MLA

initial guess for the subsequent step. The curvature radii R_1 and R_2 of each segment are obtained by solving the following five simultaneous equations: (1,2) relationships of object, image and lens distance, (3) thin lens formula, (4) lens-maker equation, and (5) aberration minimizing Coddington shape factor relation [4], where s_o, s_i, d_o and d_i are the distance from object to front principal plane, image from back principal plane, object to front surface, and image to back surface, respectively. As the refractive index n and the center thickness T of MLA are fixed, the effective focal length (*EFL)*, front focal length (*FFL)* and back focal length (*BFL)* are functions of R_1 and R_2.

$$s_o = d_o + (EFL - FFL) \quad (1)$$

$$s_i = d_i + (EFL - BFL) \quad (2)$$

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{EFL} \quad (3)$$

$$\frac{1}{EFL} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) + \frac{(n-1)^2 T}{n R_1 R_2} \quad (4)$$

$$\frac{R_2+R_1}{R_2-R_1} = \frac{-2(n^2-1)}{n+2} \cdot \frac{s_i+s_o}{s_i-s_o} \quad (5)$$

For ease of fabrication, the back curvature radius is set to the mean value R_2 of all segments. For the second step, individual freeform shapes are computed for each front surface of lens segment. The surface computation is performed using a reverse surface construct-iterate algorithm [3]. In this method, the surface is expressed with XY polynomials $\left(z(x,y) = \sum_{sx=1}^{s}\sum_{sy=1}^{s} P_{sx,sy} \cdot x^{sx} \cdot y^{sy}\right)$ and the computation consists of deriving the optimal polynomial coefficients $P_{sx,sy}$ by iteration, based on the target object and image coordinates. For the first step, it is computed for each data points of front surface, including the point coordinates and surface normal which minimize the optical path length. Computation starts with the nearest data point from optical axis and moves to the next data points whose intersection between a ray and computed planes is nearest. For the second step, using computed points coordinates and surface normals as initial guess, the polynomial surface fitting is performed.

2.3 Simulation of Light Collection

To evaluate the spot size and irradiant power of the spot formed by each segment when it is located at the designed distance from the gel, ray tracing simulation is performed independently for each segment with a point light source at the designed location, shown in Table 1. The power of light source is set to 100 W, homogeneously distributed over a 360-degree angle and each lens segment receiving irradiant power proportional to its solid angle. The wavelength is set to 530 nm.

Table 1. Predicted light collection of MLA

Segment Index	Object Position Z [mm]	Solid Angle [sr]	RMS Spot Size [mm]	Irradiant Power [mW]
#1	-20	8.937e-3	0.03344	46.46
#2	-30	3.899e-3	0.03953	20.26
#3	-45	1.707e-3	0.04193	8.875
#4	-70	6.974e-4	0.04294	3.629
#5	-120	2.351e-4	0.04335	1.222
#6	-300	3.732e-5	0.04350	0.194

3. Experimental Measuring of Degree of Polarization

Using the fabricated MLA shown in Fig. 2(c), a degree of polarization measurement experiment was carried out with the system. Excitation light of 530 nm wavelength is irradiated onto a gel coated heat source and the polarization degrees of fluoresced light is measured under a set temperature of 21 ℃ (equivalent to 0.2 polarization degree), while shifting the object distance from 10 mm to 80 mm in 5 mm step. The results are then compared with a system using an aspheric objective lens (Edmund Optics #16-960) instead of the MLA. As shown in Fig. 3, the polarization degree measured with MLA is stable against the object distance. This is because the MLA has five focal points in the defined object distance range, and can thus produce well focused spots on the light sensor.

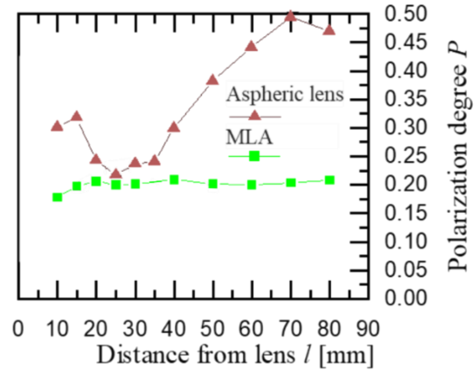

Fig.3. Measured polarization degrees with single focus aspheric lens and MLA, as function of distance to the gel (nominal temperature 21 °C)

4. Conclusion

A freeform mirco-lens-array was designed and fabricated using the reverse surface construct-iterate method and used as an objective lens in a temperature measurement system based on polarization degree of fluorescent light. Through experiment, it was confirmed that the system measures the polarization degrees of light stably over an object distance range of 10 to 80 mm.

5. References

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