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ABSTRACT

The unwanted light transmitting through the gap spaces of low fill factor lens array will deteriorate the signal contrast detected by the sensor. The high cost photolithographic techniques and optical coating technology have to be used to deposit a metallic film precisely filling these gap regions, which is only suitable for the lens array on flat substrate. In this paper, we will propose an efficient way for the fabrication of gap-masked lens array on a curved plastic substrate by using the direct diamond turning and spray coating process. The semi-finished lens array (SFLA) on a convex surface is first fabricated by rough cutting with fast tool servo. A paint film layer with mirror surface effect is then formed uniformly by spray coating on the SFLA which has a rotation speed controlled by the computer-numerically controlled (CNC) machine. At last, the lenslet surfaces are uncovered and regenerated by finishing cutting process. Without any re-loading or re-position error, this cost-effective method can generate various gap-masked array optics on curved substrate with customized period and grid pattern.

Keywords: Lens array, Diamond turning, Fast tool servo

1. INTRODUCTION

As a structured-feature surface with high integration, lens arrays are significant and useful in optical applications such as uniform illumination[1,2], wavefront detection[3], wafer-level camera[4] and integral imaging[5]. The common optical manufacturing methods such as femtosecond laser writing[6], photolithography[7], and 3D-printing[8] can be used to fabricate lens arrays on a flat substrate. Lens array on curved substrate usually relies on the ultraprecision machining process[9]. Both fast tool servo (FTS) and slow tool servo (STS) have high-precision controllability in efficient diamond turning of lens arrays[10,11] as well as molds with various filling factor. Lens array mold can be used in the precision injection molding process to achieve the batch manufacture of lens array with low cost. The main concern of lens array with low filling factor is the unwanted transmission through the gap spaces in-between lenslets. Photolithography and optical coating technology have to be used to produce the metallic film mask to cover these gap regions, which however is high-cost and only suitable for lens array on flat substrate. In this paper, a simple and efficient method is proposed for the fabrication of gap-masked lens array on curved substrate. The method is composed of three steps which are rough cutting of semi-finished lens array (SFLA), on-machine spray coating of mask film and finishing cutting of lens array. The whole process can be accomplished on machine without sample transfer, so high accuracy can be expected.

2. SURFACE DESIGN

The hexagonal patterned lens array will be designed on a convex spherical surface with a radius of curvature of 106 mm. The radius of curvature of the lenslet is 53 mm in order to generate an addition power of 5 diopters as compared to the spherical power of the convex substrate if a refractive index 1.53 is used for the lens material. The pitch of lens array is 12 mm. The lenslets have a circular aperture of 9.6 mm in diameter, so a fill factor of 58% is expected. The vault height of lenslet is calculated to be 0.218 mm. The gap spaces in-between lenslets must be blocked, otherwise the unwanted transmission in these areas will cause background noise. The conventional method is using photolithographic technique to generate a chrome mask to block the gap spaces, which however is unfeasible in the case of convex substrate.

The new method for the fabrication of gap-masked lens array on curved substrate has been depicted in Fig. 1. First, a SFLA with a larger vault height of lenslets should be fabricated. In our case, the radius curvature of the lenslet of SFLA is set to be 36.48 mm, which gives a vault height of 0.318 mm. The aperture of the these lenslets should be slightly

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enlarged. Then, a paint film layer is deposited uniformly by spray coating on the whole surface of SFLA which is rotated at high speed with the spindle on machine. At last, the surface of the lenslet covered by the paint film should be re-generated to remove the mask and give the desired surface curvature within the working aperture, leaving the remaining mask in the gap spaces untouched.

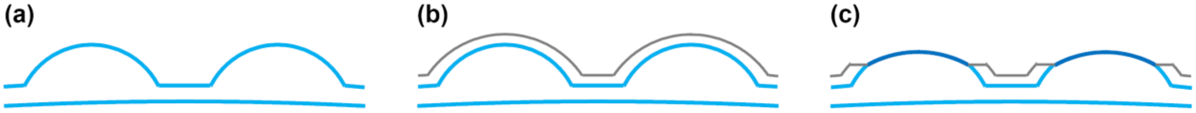

Fig. 1 Generation of gap-masked lens array on curved substrate. (a) SFLA; (b) spray coating on the SFLA; (c) finish cutting of lens array.

The designed surface of lens array on the convex sphere has been shown in Fig. 2. Within the whole aperture which is 72 mm in diameter, there are 36 lenslets uniformly arranged in hexagonal pattern. The lens array surface is well described with 8.64×10^6 supporting points in a uniform polar mesh. The point elements are equally spaced with an incremental size of 10 μm along radial direction and circumferentially spaced with a fixed angular increment of 0.15°. Therefore, the central lenslet is over-determined with more surface data than that of the lenslet on the outer diameter. In order to demonstrate the isolated profile of each lenslet, the basic surface profile of the spherical substrate has been subtracted in Fig. 2(b) and 2(c).

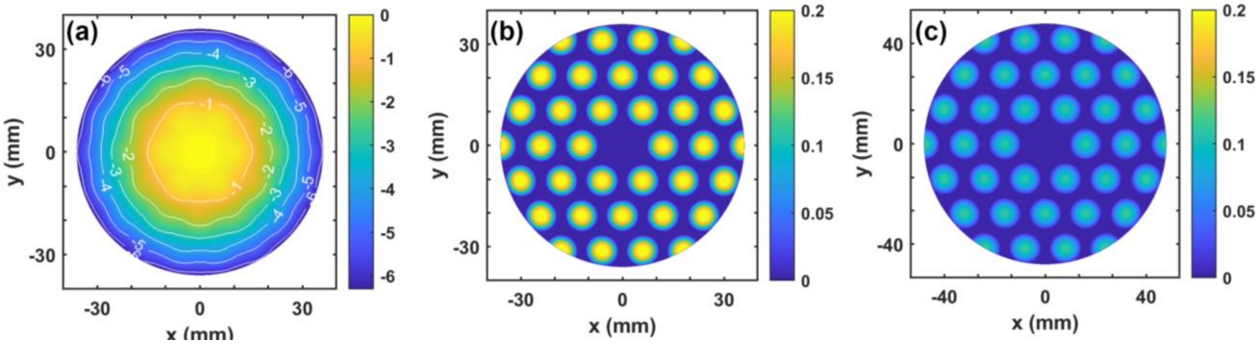

Fig.2 Design of lens array on curved substrate. (a) Surface of lens array; (b) isolated surface of semi-finished lenslets; (c) isolated surface of finished lenslets.

3. FABRICATION

3.1 Tool path generation

Based on the point cloud data of lens array surface, the tool radius compensation is made to account for the cutting-edge geometry especially in the radial direction. Figure 3 shows the tool radius correction for the radial profile at zero degree. Due to the discontinuities in the slope of the profile, the tool radius compensation is defined in the spherical substrate region and the lenslet region, respectively along the local normal directions. Then, the different segments are combined together the form the complete supporting points for the diamond tool center along the radial line. The boundary of lenslet is smooth after tool radius compensation as shown in Fig. 4, while the aperture of lenslet is enlarged. No additional interpolation is needed to fill the transition regions.

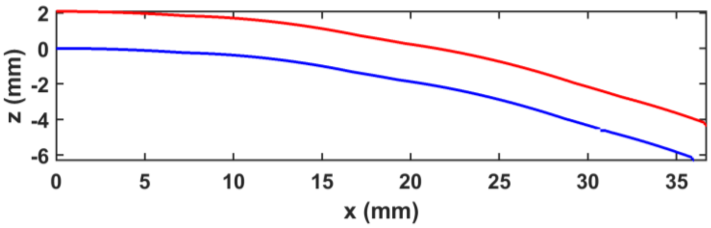

Fig. 3 Tool tip radius compensation in the radial direction. Blue line: the original surface profile; Red line: tool radius compensated profile.

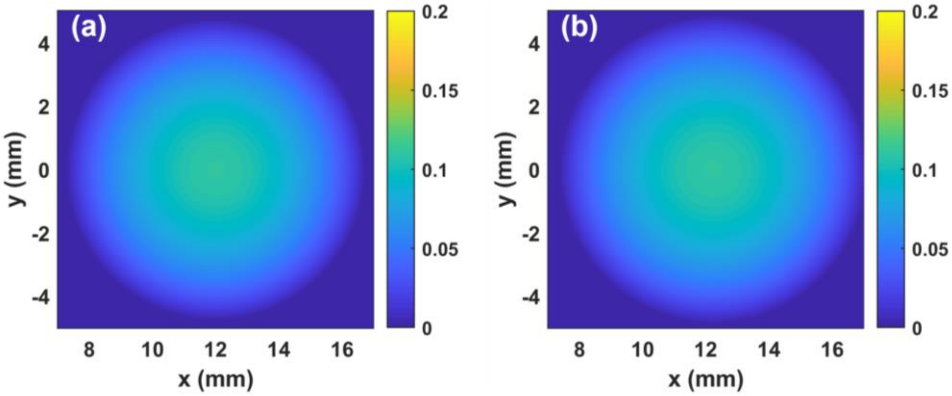

Fig. 4 The isolated lenslet profile (a) before and (b) after tool tip radius compensation.

In order to transfer the three-dimensional surface data with the high frequency freeform features into an appropriate format of computer-numerically controlled (CNC) data for machining, a proprietary software using Matlab programming is developed to calculate the control nodes with the supporting points of tool tip center. As mentioned above, the surfacing process comprises the rough cutting of SFLA and the finishing of the final lens array. Therefore, two different tool paths both following spiral trajectory are required as shown in Figure. 5. The control nodes are spaced with a fixed angular increment of 0.5° along circumferential direction. The required tool center points are calculated by using a linear interpolation with the nearest four supporting points. The computation time of tool path for final surface finishing is 123 seconds based on a desktop computer equipped with an Intel i7 processor of 1.8 GHz clock frequency.

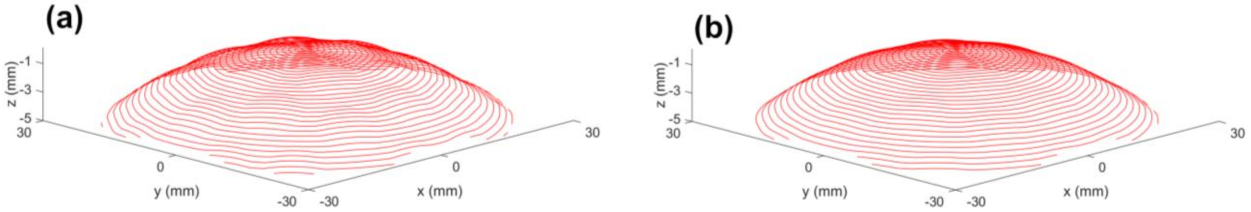

Fig. 5 Tool path generated for diamond turning of lens array on a spherical substrate. The feed rate is set to be 1 mm per revolution just for demonstration. Tool path for (a) SFLA and (b) surface finishing of lens array.

3.2 Diamond turning and measurement

Lens array surfacing is performed with a self-developed CNC freeform generators[12]. To fabricate the lens array, the surfaces of a lens blank made of CR39 is subjected to a two-stage cutting process which uses a polycrystalline diamond tool for the rough cutting of SFLA with a cutting depth of 0.5 mm and a natural diamond tool for the high-quality finishing of lens array with a cutting depth of 0.1 mm. This two-tool configuration is mounted on an FTS unit. The required total FTS stroke is 0.2 mm and 0.1 mm for the rough cutting and the surface finishing, respectively. Limited by the working bandwidth and the tracking error of tool motion, a constant spindle speed of 100 rpm is used.

As shown in Figure 6, following the rough cutting, a paint film layer is deposited uniformly by spray coating on the SFLA which is rotated at speed of 600 rpm with the spindle. In order to remove the film layer within the lenslet aperture and keep the gap spaces to be blocked, the surface finishing is performed with the diamond tool tip repositioned 3 μm backward. Therefore, the actual cutting depth of surface finishing applied on the lenslets is 0.097 mm. The feed per revolution in finishing is adjusted to 20 μm.

A two-dimensional contact surface profile measurement instrument (Veeco, Dektak 150) is used to measure the surface of a single lenslet as shown in Fig. 7. The measured form error is 5.2μm (PV) and 1.5 μm (RMS). The surface deviation observed between the measurement and the calculation is mainly caused by the tilt error of the lens array substrate on the measurement stage.

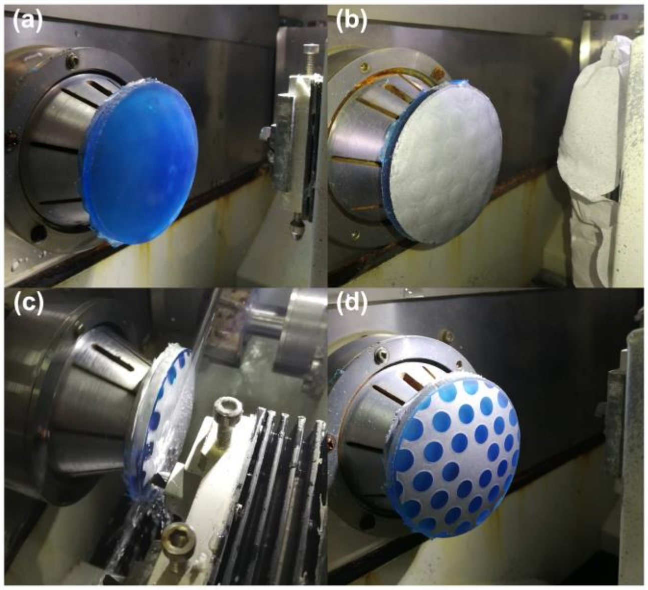

Fig. 6 Fabrication of lens array on convex spherical surface. (a) Rough cutting of SFLA; (b) on-machine spray coating on SFLA; (c) surface finishing cutting; (d) gap-masked lens array on spherical surface after finishing cutting.

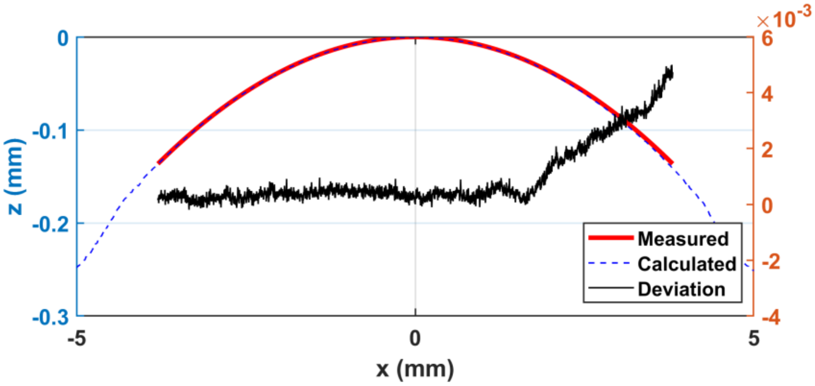

Fig. 7 Surface profile of a single lenslet and the measured form error.

4. CONCLUSION

We present an efficient solution for the design and fabrication of gap-masked lens array on a curved substrate. The gap spaces in-between the lenslets are covered by film layer deposited by spray coating on the SFLA on machine. The final surface finishing is performed solely within the aperture of lenslets for the purpose of removing the local mask and generating the required lenslet profile simultaneously. The working aperture of lenslet or the actual filling factor of lens array can be adjusted in the surface finishing process. The measured results verified the effectiveness of the proposed method. This method is applicable to the fabrication of various patters of gap-masked array optics and can be extended to the field of segment-masked optics for aperture coding and amplitude modulation.

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