Design, Fabrication and Evaluation of Nonconventional Optical Components

DISsertation

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By

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Abstract

The main focus of this dissertation is to seek scientific and fundamental knowledge of nonconventional optical components including its optical design, ultraprecision prototyping, precision molds making, transition into industrial production and efficient evaluation.

A nonconventional component in this dissertation is loosely defined as an optical component either that is not symmetric around its optical axis or that is aspherical surface with three or higher order coefficient. Nonconventional optics have broadened the vision of optical designers and enhanced the design flexibility and thus are becoming increasingly important as a core next-generation optical component. These optical components have gradually been implemented to replace conventional spherical and aspherical counterparts in the fields of imaging (Plummer, 1982), illumination (Fournier & Rolland, 2008), aviation (Spanò, 2008), and energy (Zamora, et al., 2009) where freeform optics have demonstrated excellent optical performance and high degree of system integration. However, design, fabrication and metrology of nonconventional optics have not been developed at the same pace. Due to the complex nature of nonconventional optics manufacturing processes, the production efficiency and finished quality of nonconventional optical components are difficult to be improved. To validate optical performance, in this dissertation ultraprecision diamond tooling is applied to prototype the optical design, which is capable of generating precision optical features.
both on polymer blank and metal mold without post grinding and polishing process. In addition, the prototyping process also paves the way to mold fabrication. To produce low cost high volume high quality nonconventional optical components, precision compression/microinjection molding has been combined with ultraprecision diamond machining and cleanroom manufacturing respectively for different size scale and application. Once the low cost molded nonconventional optical components and assembly are fabricated, their optical performance needs to be characterized to ensure quality in industrial production. The geometric feature and principle optical parameter, such as focal length, are two important aspects that influence the final optical performance considerably.

In order to solve the major problems in manufacturing affordable high quality nonconventional optical components, this dissertation will include several key steps: 1) Investigate nonconventional optics design that could be functionally and economically applied in various optical components or systems to further improve their performance; 2) Validate and evaluate nonconventional optics design by ultraprecision prototyping; 3) Develop the precision molds manufacturing process and the corresponding molding process both for miniaturized lens profile and micro scale diffraction structure; 4) Investigate the products quality by crucial optical parameters measurement and surface profiling.

Overall, this dissertation describes a comprehensive understanding of low cost high volume nonconventional optics manufacturing.
Dedication

This document is dedicated to my family.
Acknowledgments

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**Fields of Study**

Major Field: Industrial and Systems Engineering
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Chapter 1 Introduction

A nonconventional lens in this research is loosely defined as an optical component that is not symmetric around its optical axis or an aspherical surface with three or higher order coefficient.

1.1 Nonconventional optical design and its application

Nonconventional optical components are becoming increasingly important for next-generation optical systems. These optical components have gradually been implemented to replace conventional spherical and aspherical counterparts in the fields of imaging (Plummer, 1982), illumination (Fournier & Rolland, 2008), aviation (Spanò, 2008), and energy applications (Zamora, et al., 2009) where freeform optics have demonstrated excellent optical performance and high degree of system integration. Nonconventional optics have broadened the vision of optical designers and enhance the design flexibility. However, design, manufacturing and metrology of freeform optics have not been developed at the same pace. Nonconventional optics is generally reviewed by many optical designers as less feasible or economic to manufacture even though some nonconventional optical design theories have been established and different mathematical
models were created (Parkyn, 1998; Ries & Muschaweck, 2002; Winston, Minano, & Benitez, 2005).

In imaging systems, nonconventional optics integrates multiple lens or optimize optical surface at wavefront scale level to improve the optical performance by eliminating the optical aberration, increasing the depth of field and expanding the field of view. For example, Paolo et al. designed two nonconventional cylinder surface for an anamorphic collimator, which achieved diffraction limited images (Spanò, 2008). Sherif et al. designed a log phase plate by the help of wavefront coding and eventually improved the depth of field and allowed larger defocus in microscopes (Sherif, Cathey, & Dowski, 2004). Hicks et al. designed a nonconventional surface reflector and managed to enlarged the field of view of a driver-side mirror up to 45° so that this mirror has no blind sport (Hicks, 2008).

Non-imaging optics has been pioneered for illumination applications. Special illumination patterns are urgently required in optical lithography, such as annular, dipole, quasar, and so on. Wu et al. successfully designed a nonconventional lens array to increase the energy efficiency and reduce the complexity of the exposure system (Wu, Li, Zheng, & Liu, 2011). Li et al. used point-to-point mapping method to design a microlens array that is capable of redistributing a collimated light into a uniform pattern. This microlens array requires fewer optical components and thus reduces alignment difficulty compared with traditional uniform illumination system (Li & Yi, Design and fabrication of a freeform microlens array for uniform beam shaping, 2011).
Nonconventional optics is also used in laser beam shaping as well as other fields, such as solar energy concentration, where the goal is to collect the incident light from the large incident aperture in a small exit aperture. In conventional parabolic design, concentrator only accepts the coming rays of light that are perpendicular to the entrance aperture. To enlarge acceptance angles and improve the uniformity of the radiation on solar cell, a series of research and design work have been done through compound parabolic, Kohler integrator and finally to freeform optics. Minano et al. applied non conventional array optics using Kohler integration to Fresnel and off-axis concentrators. Their design achieves a larger acceptance angles and more uniform radiation concentration on solar cell and thus improve the overall solar to electric energy efficiency (Minano, et al., 2005).

1.2 Ultraprecision machining

Ultraprecision diamond tooling technology has been studied and developed for over 40 years and has been successfully applied to numerous fields. This technology can be categorized into fast tool servo (FTS) (Patterson & Magrab, 1985), slow tool servo (STS) (Yi & Li, Design and fabrication of a microlens array by use of a slow tool servo, 2005), diamond micromilling (Stoebenau & Sinzinger, 2009), diamond flycutting (Stoebenau & Sinzinger, 2009) and ultraprecision grinding (VanLigten & Venkatesh, 1985).

In the process of diamond turning, diamond cutter is controlled according to the angular position of the workpiece. However, the fabrication of a freeform surface by diamond turning requires tool movement at a bandwidth significantly higher than the rotational frequency of the workpiece. In FTS, the diamond cutter is generally mounted on a stack
of piezoelectric actuators. Thus, the frequency of tool actuation can be extremely higher compared to that of the mechanical slides. In contrast to FST, STS is based on the feedback control of the mechanical slides. Although STS has a significantly longer machining time compared to FTS, STS is capable of generating a better finished surface and traveling along azimuthal height more than 25 mm. In diamond micromilling, a diamond cutter is mounted on a high-speed spindle while the work piece is mounted on the main spindle of the diamond lathe machine to fabricate aspherical or complex lenses with small positive and negative curvatures. In flycutting setting, diamond tool is mounted on the main spindle while workpiece is on the mechanical slide. Thus, flycutting is commonly applied to fabricate features such as micro-groove. Diamond grinding is well suited to cutting brittle materials. In a grinding process, polishing process always follows because grinding alone cannot meet the required optical surface quality for a wide variety of geometrical profiles.

1.3 Precision compression molding and injection molding

For manufacturing of optical elements, precision compression molding and precision injection molding have been widely accepted as two common low cost high volume processes.

As early as in the 1980s, precision compression molding was first proposed for fabricating glass optical components with complicated surface geometries (Maschmeyer, Andrysick, Geyer, Meissner, Parker, & Sanford, 1983). Since its introduction, micro and miniaturized scale compression molding has become a very important manufacturing
technology for its low cost as well as high repeatability and reliability of the fabricated parts (He, et al., 2011). Conventional compression molding process also requires the heating of entire bulk glass blank above glass transition temperature (Tg) where the glass behaves like a viscoelastic material. In this arrangement, the glass mold, vacuum chamber where glass blank is placed and other mechanical components are heated up and then cooled down simultaneously. As such a long cooling cycle is generally required to ensure quality of the molded optics. Among the drawbacks of conventional glass molding process, one major issue is its low energy efficiency due to long thermal cycles. In addition, bulk heating/cooling cycle can also cause problems ranging from thermal expansion of the molds, a shorter mold life, residual stresses inside the molded glass and refractive index variation in molded glass optics. To overcome these problems, numbers of experimental studies and numerical simulations have been devoted into in previous research works, including geometry compensation (Dambon, et al., 2009), evaluation of residual stresses (Chen, Yi, Su, Klocke, & Pongs, 2008; Tao, He, & Shen, 2014), reducing refractive index variations (Su, Chen, A. Y. Yi, Klocke, & Pongs, 2008; Su, F.Wang, He, Dambon, Klocke, & Yi, 2014) and applying protective coating on the mold surfaces (Fischbach, et al., 2010). More recently, precision glass molding has also even been tested for wafer level molding process demonstrated by (Huenten, Hollstegge, Wang, Dambon, & Klocke, 2011) to improve glass molding efficiency. However, wafer level glass molding in principle is still a form of conventional precision glass molding. Most of the aforementioned studies
above failed to address the issues related to the prolonged and high degree of thermal cycles.

To cope with this issue, this dissertation presents a novel localized rapid heating process to effectively heat only very small part of the glass. This localized rapid heating study utilized a fused silica wafer coated with a thin graphene layer to heat only the surface of the glass. The graphene coating functions as an electrical resistant heater when a power source was applied across the thin film coating, generating heat on and near the coating. The feasibility of this process was validated by both experiments and numerical simulation. To demonstrate the advantages of the localized rapid heating, both localized rapid heating process and bulk heating process were performed and carefully compared. The uniformity and quality of the molded sample by localized rapid heating process was also demonstrated.

Injection molding uses a screw type reciprocating plunger to force molten material into a relatively cold mold cavity where the material solidifies into a shape that conforms to the contour of the mold cavity. As a subset of injection molding, precision injection molding process is considered as one of the significant technologies of manufacturing high precision micro or miniaturized features with mass-production capability. Precision injection molding offers molded parts more accuracy and less variability by means of its special design features, i.e., a) plasticizing screw and injection plunger are separated, and both are manufactured with high precision to provide stable and uniform polymer melt, b)
direct clamping pressure by central ram construction provides even distribution of clamping pressure on the platen.

1.4 Metrology of nonconventional optics

Metrology is an indispensable and fundamental part of the entire production of freeform optics. An accurate and traceable metrology in industry can either guide the improvement of freeform optics manufacturing by compensating profile errors caused by temperature variation, machine vibration, tool wear and structural errors of equipment or serve for the product quality inspection and verification generally in a statistical way. As Fang et al. presented in a recent overview of freeform metrology (Fang, Zhang, Weckenmann, Zhang, & Evans, 2013), most of the research work targeting at the former purpose have studied in detail and established different systems. Coordinate measuring machines (CMM) was applied on measurement of freeform optics as early as in 2001 (Jäger, et al., 2010). Apparently, the efficiency of this dot-by-dot contact scanning method diminishes for large number of measurements. Henselmans et al. mounted an auto focus laser probe on CMM and thus improved the rate of measurement dramatically (Rajamohan, Shunmugam, & Samuel, 2011). However, the time needed for the entire measurement strongly depends on the area of surface being tested and the point spacing.

Interferometric method, which is generally used to measure an entire interested surface in a single operation, inherently comes with high efficiency and low cost compared with the methods mentioned above (Moriyasu, Yamagata, Ohmori, & Morita, 2003). Unfortunately, conventional interferometry is not capable of testing freeform surfaces
simply due to large deviation of the tested surface from the reference wavefront. To overcome this problem, Computer Generated Hologram (CGH) have been proposed and successfully applied in aspherical (Burge & Wyant, 2004) and even freeform surfaces were suggested (Talha, et al., 2010). In their interferometric setup, if the test surface has the desired shape, the optical path difference (OPD) between CGH and the tested surface will be nulled by using wavefront of the CGH. There are some critical issues of the method based on CGH in that it limits its wide application in industrial freeform surface quality inspection. First, 6 degrees of freedom have to be precisely adjusted to align the CGH with the test surface. Next, CGH transforms wavefront by use of diffraction and reconstructs the interferometric image by spatial filtering. Its limited dynamic arrange prevents CGH method to be applicable for all freeform surfaces. In addition, CGHs are made using a method similar to CGH, Qiu and Cui (Qiu & Cui, 2013) replaced the CGH component and fabricated a null lens to compensate OPD by Fermat principle. Although they made some contribution to the measurement of freeform surface, the null lens used in their research was not a true nonconventional design.
Chapter 2 Research Objectives

The main focus of this dissertation is to seek scientific and fundamental knowledge of nonconventional optical components including its optical design, ultraprecision prototyping, precision molds making, transition into massive production and efficient evaluation. Overall, this dissertation describes a comprehensive understanding of low cost high volume nonconventional optics manufacturing.

The specific objectives of this research are to:

a) Establish nonconventional optics design that could be functionally and economically applied in various optical components or systems to further improve their performance

b) Validate and evaluate nonconventional optics design by ultraprecision prototyping

c) Develop the precision molds manufacturing process and the corresponding molding process both for miniaturized lens profile and micro scale diffraction structure

d) Investigate the products quality by crucial optical parameters measurement and surface profiling
Chapter 3 Nonconventional Optics Design

Nonconventional optical elements are becoming increasingly important as a core next-generation optical component. These optical components have gradually been implemented to replace conventional spherical and aspherical counterparts in the fields of imaging, illumination, aviation, and energy where nonconventional optics have demonstrated excellent optical performance and high degree of system integration. A nonconventional lens in this research is loosely defined as an optical element either that is not symmetric around its optical axis or that is aspherical surface with three or higher order coefficient. Nonconventional optics have broadened the vision of optical designers and enhance the design flexibility. Some nonconventional optical design theories have been established and different mathematical models were created. Therefore, this chapter is to seek fundamental understanding of nonconventional optics design that could be functionally and economically applied in various optical components or systems to further improve their performance.

3.1 Nonconventional optics design of an endoscope with oblique view

Miniature endoscopes are becoming increasingly important as an optical inspection tool that expands the applicability of minimally invasive surgery (MIS). Fiber-optic
endoscopes quickly have proven to be useful medical devices since their invention in 1957 (Edmonson, 1991). Although the fiber-optic imaging endoscopic devices exhibit high flexibility in manufacturing and miniaturization, its low illumination and color reproducing capabilities often result in poor image quality. As cleanroom technology matures, expensive optical imaging fibers have been replaced by low cost CMOS imagers. This technological leap has improved the resolution dramatically for small diameter endoscopes but has come at the expense of a reduction in their field of view. Additionally, CMOS imagers need to be placed coincident with imaging plane. This combination of tight packaging constraints and strict optical requirements present significant challenges for manufacturing.

Wippermann et al. (2010) (Wippermann, Beckert, Dannberg, Messerschmidt, & Seyffert, 2010) developed a disposable low cost video endoscope that is capable of viewing in both straight and oblique directions. The configuration of their endoscope consists of an aspherical polymethylmethacrylate (PMMA) lens, a BK-7 glass prism with double reflections at two angled surfaces, a gradient index rod lens (GRIN) and a spherical PMMA lens assembled sequentially. The prism is used to tilt the optical axis of the object with respect to the mechanical axis of the packaging tube, achieving an 18° off-axis view. The GRIN lens was installed to enlarge the field of view (FOV) to 110° in the straight viewing direction. In order to lower fabrication cost, they also demonstrated a diamond turning process to fabricate the two polymer lenses, which could be mass produced by molding in the future.
However, the fabrication process of Wippermann’s endoscope may not be readily adopted by the optical industry due to the use of the glass prism and GRIN lens. Generally speaking, glass prism fabrication requires grinding and polishing processes that can prolong the production cycles, especially when optical lenses have complicated shapes. GRIN lens fabrication on the other hand involves with ion exchange and diffusion techniques in high volume manufacturing. The diffusion process is difficult to control and only produces an approximation of a parabolic or hyperbolic secant surface (Sinzinger & Jahns, 1999).

Moreover, since freeform surfaces were not included in Wippermann’s original design, aberrations due to large changes of optical paths/directions are difficult to control. In their design, had freeform optics been used, these optical aberrations would have been effectively reduced while still achieving a large depth of field and a larger field of view (Fang, Zhang, Weckenmann, Zhang, & Evans, 2013). In terms of optical fabrication, diamond machining is an efficient method to fabricate a small number of freeform optics with high optical surface finishing, a useful feature in developing prototypes where freeform optics are required. Additionally, the manufacturing process study of the endoscope helps to establish process steps for precision mold fabrication (He, et al., 2011). These molds can then be used in injection molding or hot embossing for high volume production. These molding processes provide an alternative method by creating high quality and low cost optical lenses and therefore are becoming promising manufacturing methods.
As discussed earlier, the design in this chapter of the miniature endoscope with a large off-axis view is a variation of an off axis endoscope initially developed by Wippermann et al. (Wippermann, Beckert, Dannberg, Messerschmidt, & Seyffert, 2010). The optical design was performed using CODE V as shown in Figure 3.1. The major optical prescription is listed in Table 3.1. The materials of all the optical components are polymers.

![Figure 3.1](image)

*Figure 3.1* An off axis endoscope design using a prism with freeform optical surface

In the design of this endoscope, a freeform surface having negative power was chosen as the front face of the prism to eliminate the first aspheric lens in Wippermann’s design. The prescription of the freeform surface is represented by a Zernike polynomial in polar coordinate as follows:
where \( c, r \) and \( k \) are listed in Table 1, \( A_i \) are listed in Table 3.2.

Unlike Wippermann’s design, the optical axes of the following lenses are parallel with the mechanical axis of the packaging tube. This arrangement reduces the level of complication for assembly at the expense of volume of the optical system. Two aspherical lenses behind the prism, one made of PMMA and one made of polycarbonate (PC), are acting as an achromatic doublet to reduce chromatic aberration. A high order aspherical lens surface was designed on the front face of the rear field lens to further correct spherical aberration. The design of the aspherical lens can be described as:

\[
z = \frac{cr^2}{1 + (1 - (1 + k)c^2r^2)^0.5} + \sum_{i=1}^{15} A_i + B_1r^4 + B_2r^6 + B_3r^8 + B_4r^{10} + B_5r^{12} + B_6r^{14} + B_7r^{16} + B_8r^{18} + B_9r^{20}
\]  

(2)

where \( c, r \) and \( k \) are listed in Table 3.1, \( B_i \) are the higher order coefficients and their values are listed in Table 3.3. Units in Table 3.1 are in millimeters. Surface 2 and 3 are reflective surfaces. Surface 5, 6, 7 and 9 are represented by the equation:

\[
z = \frac{cr^2}{1 + (1 - (1 + k)c^2r^2)^0.5}
\]  

(3)
The object distance was 100 mm and the object heights in X and Y direction were set at \(+/-\ 34\) mm. The aperture of the left surface on the doublet was set as stop as shown in Figure 1. The weights of three wavelengths 700 nm, 550 nm and 400 nm were assigned as 4:5:1 since less blue color could be detected in medical operation. The off-axis viewing angle is 16.7°.

Table 3.1  The optical prescription for the endoscope

<table>
<thead>
<tr>
<th>Surface</th>
<th>Radius (1/c)</th>
<th>Thickness</th>
<th>Material</th>
<th>Semi-aperture (r)</th>
<th>Conic const.(k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>object</td>
<td>—</td>
<td>100.000</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>1</td>
<td>-5.172</td>
<td>2.900</td>
<td>PMMA</td>
<td>2.328</td>
<td>-0.634</td>
</tr>
<tr>
<td>2</td>
<td>—</td>
<td>-4.500</td>
<td>PMMA</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>—</td>
<td>7.500</td>
<td>PMMA</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>—</td>
<td>2.000</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>5</td>
<td>2.130</td>
<td>1.900</td>
<td>PMMA</td>
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<tr>
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<td>-6.113</td>
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<td>PC</td>
<td>0.960</td>
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<td>7</td>
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<tr>
<td>8</td>
<td>2.276</td>
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<td>PMMA</td>
<td>1.083</td>
<td>-4.373</td>
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<tr>
<td>9</td>
<td>3.030</td>
<td>3.500</td>
<td>—</td>
<td>1.064</td>
<td>-4.015</td>
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<tr>
<td>sensor</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1.507</td>
<td>—</td>
</tr>
</tbody>
</table>

A variety of analyses have been conducted in CODE V to validate the performance of the endoscope. This miniature endoscopic system has a 4.326 mm effective focal length. Its entrance pupil and exit pupil are 1.000 mm and 1.301 mm in diameter. The diagrams of imaging spot sizes from different object positions were plotted in Figure 3.2 to
demonstrate the capability of the freeform surface. The left spot diagram was generated under the same optical arrangement as the right spot diagram except that its Zernike coefficients were truncated. The root mean square (RMS) spot radius of the endoscope without freeform surface would have increased from 3.8 m to more than 110 m, indicating that an image could barely be formed. Additionally, the modulation transfer function (MTF) curves, illustrated in Figure 3.3, were studied for quantitative comparison among different object positions. For each position, the MTF of the incident beam is calculated in both sagittal and tangential orientations. 50% contrast at 110 LP/mm was feasible for all objective positions and the optical system is only 10% less than the diffraction limit.

**Table 3.2 Zernike coefficients for the freeform surface**

<table>
<thead>
<tr>
<th>$A_i$ term</th>
<th>Value</th>
<th>$A_i$ term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$ 1</td>
<td>-3.639 E-2</td>
<td>$A_9$ $(3\rho^3-2\rho)\sin(\theta)$</td>
<td>2.680 E-5</td>
</tr>
<tr>
<td>$A_2$ $\rho\cos(\theta)$</td>
<td>-2.454 E-7</td>
<td>$A_{10}$ $\rho^3\sin(3\theta)$</td>
<td>-5.023 E-6</td>
</tr>
<tr>
<td>$A_3$ $\rho\sin(\theta)$</td>
<td>8.705 E-3</td>
<td>$A_{11}$ $\rho^4\cos(4\theta)$</td>
<td>-1.452 E-5</td>
</tr>
<tr>
<td>$A_4$ $\rho^2\cos(2\theta)$</td>
<td>3.400 E-6</td>
<td>$A_{12}$ $(4\rho^4-3\rho^2)\cos(2\theta)$</td>
<td>-1.789 E-8</td>
</tr>
<tr>
<td>$A_5$ $2\rho^2-1$</td>
<td>1.309 E-2</td>
<td>$A_{13}$ $6\rho^4-6\rho^2+1$</td>
<td>-6.399 E-6</td>
</tr>
<tr>
<td>$A_6$ $\rho^3\sin(2\theta)$</td>
<td>-3.798 E-8</td>
<td>$A_{14}$ $(4\rho^4-3\rho^2)\sin(2\theta)$</td>
<td>1.139 E-9</td>
</tr>
<tr>
<td>$A_7$ $\rho^3\cos(3\theta)$</td>
<td>-8.779 E-10</td>
<td>$A_{15}$ $\rho^4\sin(4\theta)$</td>
<td>-8.661 E-10</td>
</tr>
<tr>
<td>$A_8$ $(3\rho^3-2\rho)\cos(\theta)$</td>
<td>1.560 E-10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.3 Higher order coefficients for aspherical surface

<table>
<thead>
<tr>
<th>$B_i$</th>
<th>Value</th>
<th>$B_i$</th>
<th>Value</th>
<th>$B_i$</th>
<th>Values</th>
<th>$B_i$</th>
<th>Values</th>
<th>$B_i$</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_1$</td>
<td>2.271E-2</td>
<td>$B_3$</td>
<td>-5.201E-2</td>
<td>$B_5$</td>
<td>-3.518E-2</td>
<td>$B_7$</td>
<td>-1.341E-3</td>
<td>$B_9$</td>
<td>-8.130E-5</td>
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<tr>
<td>$B_2$</td>
<td>2.657E-2</td>
<td>$B_4$</td>
<td>5.685E-2</td>
<td>$B_6$</td>
<td>1.237E-2</td>
<td>$B_8$</td>
<td>-1.734E-4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.2 Comparison of imaging spot size between optical designs using aspherical surfaces and freeform surface
3.2 Nonconventional optics design of an endoscope with dual channel

The goal of the dual channel endoscope design is to achieve a near 90° lateral field of view to visualize the surrounding anatomy appropriately as well as a clear straight view. Due to the large amount of light bending, a single freeform surface does not have enough power to refract the light beams even with oblique view angle. Therefore, the design starts with a dome lens cleaved by an anamorphic surface whose optical center coincides with that of the front aspherical surface of the dome lens. The angle between the optical axis of the endoscope and the normal vector at the pole of the anamorphic surface is 70° such that the lateral channel can reach from. The rear aspherical surface and the

Figure 3.3 Computational MTF in tangential direction and sagittal direction
following aspherical lens are designed to converge the ray of lights from two straight and lateral views and reduce the spherical aberration. Both of the first two lens are made of polymethylmethacrylate (PMMA), which allows much design freedom and machining feasibility. The final element is a doublet made of SLAL9 working as crown glass and SNPH2 as flint glass to further reduce achromatic aberration. In order to allow the endoscope to access remote and cramped areas of the body, the design attempts to keep the optical elements under 10 mm diameter. The optical design was performed using CODE V as shown in Figure 3.4. The major optical prescription is listed in Table 3.4. All dimensioned units are in millimeters.

Figure 3.4 An endoscope design with dual channel
The design of the anamorphic surface can be described as:

$$Z = \frac{c_y x^2 + c_y y^2}{1 + (1 - (1 + k)c^2 r^2)^{0.5}}$$

(4)

where $c_x$ and $c_y$ are the curvatures in x and y direction at the pole of the surface, $r$ is the radial distance $(x^2+y^2)^{0.5}$, $k$ is the conic coefficient.

The design of the aspherical surface can be described as:

$$Z = \frac{cr^2}{1 + (1 - (1 + k)c^2 r^2)^{0.5}} + B_1 r^4 + B_2 r^6 + B_3 r^8$$

(5)

where $c$ is the curvature at the pole of the surface, $r$ is the radial distance, $k$ is the conic coefficient and $B_i$ are the higher order coefficients and their values are listed in Table 3.5.

The object distance was 100 mm and the object heights in X and Y direction were set at +/- 34 mm. An aperture stop was following the surface 5 with a diameter of 0.909 mm shown in Figure 3.4. The weight of five wavelengths 642.73 nm, 590.86 nm, 542.02 nm 500.48 nm and 465.61 nm were assigned as 7:36:42:13:2 since less blue or purple color could be detected in medical operation.
Table 3.4 Optical prescription for the redesigned endoscope

<table>
<thead>
<tr>
<th>Surface</th>
<th>Type</th>
<th>Radius (1/c)</th>
<th>Thickness</th>
<th>Material</th>
<th>Conic constant (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>object</td>
<td>Flat</td>
<td>—</td>
<td>50</td>
<td>WATER</td>
<td>—</td>
</tr>
<tr>
<td>1</td>
<td>Asphere</td>
<td>3.33</td>
<td>0</td>
<td>PMMA</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Anamorphic</td>
<td>147/108</td>
<td>2.5</td>
<td>PMMA</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Asphere</td>
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<td>1</td>
<td>—</td>
<td>-4.240</td>
</tr>
<tr>
<td>4</td>
<td>Asphere</td>
<td>3.1</td>
<td>2.8284</td>
<td>PMMA</td>
<td>7.907</td>
</tr>
<tr>
<td>5</td>
<td>Asphere</td>
<td>1.58</td>
<td>0.3582</td>
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<td>-0.841</td>
</tr>
<tr>
<td>6</td>
<td>Sphere</td>
<td>-1.73</td>
<td>1.500</td>
<td>SLAL9</td>
<td>—</td>
</tr>
<tr>
<td>7</td>
<td>Sphere</td>
<td>1.25</td>
<td>0.750</td>
<td>SNPH2</td>
<td>—</td>
</tr>
<tr>
<td>8</td>
<td>Sphere</td>
<td>4.3</td>
<td>0.5874</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>9</td>
<td>Flat</td>
<td>—</td>
<td>0.4476</td>
<td>NK5</td>
<td>—</td>
</tr>
<tr>
<td>10</td>
<td>Flat</td>
<td>—</td>
<td>0.056</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>sensor</td>
<td>Flat</td>
<td>—</td>
<td>—</td>
<td>—</td>
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</table>

Table 3.5 Higher order deformation coefficients for aspherical surface

<table>
<thead>
<tr>
<th>Surface</th>
<th>$B_1$</th>
<th>$B_2$</th>
<th>$B_3$</th>
</tr>
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<tbody>
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<td>1</td>
<td>-3.599 E-4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>-2.943 E-1</td>
<td>1.439 E-1</td>
<td>-1.048 E-1</td>
</tr>
<tr>
<td>4</td>
<td>1.374 E-2</td>
<td>2.998 E-2</td>
<td>-1.535 E-2</td>
</tr>
<tr>
<td>5</td>
<td>1.131 E-2</td>
<td>-2.718 E-3</td>
<td>-</td>
</tr>
</tbody>
</table>

A variety of analyses have been conducted in CODE V to validate the performance of the endoscope. This endoscopic system has a 4.326 mm effective focus length. The diameter
of its entrance pupil is 0.4 mm for both channels. The exit pupils are close to each other, 1.120 mm for straight view and 1.226 mm for the lateral view in diameter. The diagrams of imaging spot sizes from different objective positions were plotted in Figure 3.5 to demonstrate the capability of the anamorphic surface. The left spot diagram was generated under the same optical arrangement as the right spot diagram except that the anamorphic surface was substituted by a flat reflect surface. The spot root mean square (RMS) radius of the endoscope without anamorphic surface diffused from 1.5 m to more than 6 m; comatic aberration can be readily observed in the flat reflect surface design, both of which indicate that a low imaging fidelity could be achieved. Additionally, the modulation transfer function (MTF) curves, illustrated in Figure 3.6, were studied for quantitative comparison among different objective positions of both channels. For each position, the MTF of the incident beam is calculated in both sagittal and tangential orientations. 50% contrast at 175 LP/mm was achieved for all objective positions and optical system is only 20% less than the diffraction limit.
<table>
<thead>
<tr>
<th>imaging position</th>
<th>flat</th>
<th>anamorphic</th>
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<tbody>
<tr>
<td>0.4, -0.6</td>
<td>3.4 µm</td>
<td>1.4 µm</td>
</tr>
<tr>
<td>0.4, -0.4</td>
<td>6.3 µm</td>
<td>1.5 µm</td>
</tr>
<tr>
<td>0.2, -0.2</td>
<td>8.3 µm</td>
<td>1.2 µm</td>
</tr>
<tr>
<td>0, -0.7</td>
<td>2.4 µm</td>
<td>1.5 µm</td>
</tr>
<tr>
<td>0, -0.6</td>
<td>3.5 µm</td>
<td>1.6 µm</td>
</tr>
<tr>
<td>0, 0.1</td>
<td>7.4 µm</td>
<td>0.7 µm</td>
</tr>
</tbody>
</table>

Unit: mm

50 µm

**Figure 3.5** Contrast of imaging spots size under flat reflect surface and anamorphic reflect surface
Figure 3.6 Computational MTF of tangential direction and sagittal direction
Chapter 4 Prototyping of Nonconventional Optical Components

Nonconventional optical components are generally reviewed by many optical designers as less feasible or economic to manufacture. As ultraprecision machining and related manufacturing processes continue evolving, the methods to fabricate nonconventional optics have extended from single point diamond turning (Yi & Raasch, Design and fabrication of a freeform phase plate for high-order ocular aberration correction, 2005) to ultraprecision milling (Brinksmeier, Riemer, & Osmer, Tool path generation for ultraprecision machining of free-form surfaces, 2008) to ultraprecision grinding (Brinksmeier, Mutlugünes, Klocke, Aurich, Shore, & Ohmori, 2010), to injection molding (Li & Yi, Design and fabrication of a freeform microlens array for a compact large-field-of-view compound-eye camera, 2012) and hot embossing (Gao, Fabrication of Large-area Microlens Arrays with Fast Tool Control, 2008).

Diamond turning machines assisted by slow tool servo or fast tool servo have been successfully employed in laboratory for nonconventional optics fabrication for its 3D ultraprecision machining capability. Diamond machining is an efficient method to fabricate a small number of freeform optics with high optical surface finishing quality. However diamond turning machine is still an expensive tool for mass industrial
production of freeform optics. On the other hand, molding technologies such as injection molding or hot embossing provide an alternative by creating high quality and low cost parts therefore becoming a promising industrial manufacturing method. Precision components for roller embossing, for an example, have already been commercialized by companies such as Moore Nanotech and Precitech.

4.1 Diamond turning for lenses
In single point diamond turning processes, slow tool servo (Yi & Li, Design and fabrication of a microlens array by use of a slow tool servo, 2005), fast tool servo (Gao, Araki, Kiyono, Okazaki, & Yamanaka, 2003), high speed diamond milling (Scheiding, et al., 2011) and broaching (Li & Yi, Design and fabrication of a freeform prism array for 3D microscopy, 2010) are commonly used to fabricate freeform optical components for use in prototypes and for optical mold fabrication. Because the freeform surface on the prism in the endoscope optical design has large slopes, neither slow tool servo nor fast tool servo diamond turning in spiral cutting path can be easily applied without getting part of the diamond tool collided with the machined surface. On the other hand, high speed milling will require a separate setting up and therefore will interrupt the continuation of the machining process. At the end, broaching was selected to ensure that a single, non-interrupted machining process was used for fabrication.

In addition to the freeform optical surface, every other lens in the endoscope was machined on the 350 FG (Freeform Generator from Moore Nanotechnology, Inc., Keene,
New Hampshire) as well. This process could be further developed for mold fabrication for low cost, high volume and high precision optical components.

All three following aspherical lenses were machined on larger size PMMA or PC discs for easy handling during fabrication. Specifically, the diamond turned outside diameter surfaces of the discs were used as the datum surfaces for both fabrication and assembly.

The thicknesses of three finished discs are 3.900 mm, 1.568 mm, and 1.924 mm. The thickness of these lenses were designed such that the need for spacers between the lenses is eliminated. Thus, the final thickness of each lens is the sum of the distance between adjacent surfaces of two lenses and the thickness of the original design. Once the three lenses were machined, they were assembled by simply stacking face to face as shown in Figure 4.1. No translational alignment in the axial direction is needed for the optical test because all three lenses are circular in shape. Lens 1 and lens 3 were turned by a diamond tool with 2.606 mm tool nose radius while lens 2 was turned by a smaller diamond tool with 0.379 mm tool nose radius. The nose radii of the diamond tool were compensated offline in the calculation for tool path trajectory. The rough cutting feed rate and cutting depth were 20 mm/min and 10 μm. The finishing cut feed rate and cutting depth were 2 mm/min and 2 μm.
The PMMA and PC discs were first rough machined on a lathe. 100 μm extra stock for finishing process was left in both axial (for disc thickness) and radial directions for all the discs (for outside diameter). The disc was then waxed on an aluminum mandrel which was already diamond machined on both ends. The circumferential surface and the flat surface were turned using the same diamond tool with a sweep angle larger than 90°. This process ensures the perpendicularity between the circumferential surface and the flat surface – a critical step for optical assembly. Afterwards, the disc was flipped to be vacuum chucked to machine the opposite surface. It was centered around the spindle axis within 1 μm accuracy by indicating on the circumferential surface. A rough and a finishing diamond turning process were subsequently performed for the first side of the lens surface after facing the flat. Finally, the disc was flipped again and vacuum chucked.

**Figure 4.1** Assembly of the three aspherical lenses
The other side of lens surface was also diamond turned by a similar rough and finishing process.

4.2 Diamond broaching for prism

It would be extremely challenging to grind and polish the prism since it contains a freeform and two reflective flat surfaces. The angles and distances between each two surfaces are crucial parameters for the prism. In contrast to the conventional lens manufacturing process, diamond machining is much more capable of fabricating optics with complex 3D profiles, which could be further developed for micro precision injection molds or compression molds. Although ultraprecision diamond machining is a capable and versatile process, there are some issues associate with this process, especially when slow tool servo or broaching are used. One of the issues is the higher magnitude of the residual tool marks (Li, Jr., & A. Y. Yi, Optical effects of surface finish by ultraprecision single, 2010) compared with grinding. By optimizing the machining conditions and parameters, the effects of the residual tool marks can be minimized.

In order to shorten the rastering process and therefore minimize the environmental influence such as temperature variation and floor vibration, the prism was first roughed out on a Haas VF3 vertical milling machine. This blank was roughed out with material on all sides with an extra stock of 300 μm, to be subsequently diamond machined. Additionally, the rough prism shape boss sits on a tapered base that could be firmly vacuumed on the chuck of 350 FG. A square shoulder was machined into the tapered
surface of the blank and is parallel with the first rastered surface of the prism. This was used for orientation of the diamond tools at the beginning of the rastering process.

Figure 4.2 (a) Diamond broaching setup for the prism (b) Interference problem can be resolved by tilting the freeform optical surface

The rough prism was mounted on the vacuum chuck of the 350 FG as shown in Figure 4.2 (a). The diamond tool with a tool nose radius of 400 μm and 0° rake angle was installed in the X axis (horizontal direction). The feed of the tool moves upward in the Y direction while horizontal stepping along the Z direction. The tool path was compensated based on the freeform surface profile and the diamond tool nose radius. During rastering, the spindle on the machine (C axis) was held in a constant position. After the rastering of each face of the prism was completed, the spindle was rotated sequentially according to the angle between two adjacent surfaces on the prism. The rastering feed rate for the flat surfaces was set at 500 mm/min. For rough rastering, the cutting depth was 10 μm and
the cross-feed step along Z axis was 40 µm. For finishing rastering, the cutting depth was 2 µm and the cross-feed step along Z axis was 10 µm.

The entire process consists of the aforementioned rough machining and freeform surface machining by rastering. The maximum slope of the concave freeform surface on the prism is 28.8°, which means a tool with a clearance angle of less than 28.8° would interfere with the freeform surface during the rastering process. To cope with this issue, the face where freeform surface was to be rastered was tilted -20° along Z axis such that it could be machined with a tool of 10° clearance angle as shown in Figure 4.2 (b).

Figure 4.3 shows the color map and the contour lines of both the original and the tilted freeform surface.

![Figure 4.3 Color map and contour line of the original and tilted freeform surface on the prism](image-url)
4.3 Hybrid diamond machining for dome lens

It would be extremely challenging to grind and polish the dome lens since it contains an angled anamorphic reflective surface and an aspherical surface. The angles and distances between two surfaces are also crucial parameters for the dome lens. In contrast to the conventional lens manufacturing process, diamond machining is much more capable of fabricating optics with complex 3D profiles, which could be further developed to precision injection molds or compression molds. However, one of the major issues of ultraprecision diamond machining is the magnitude of the residual tool marks [9] compared with grinding. By optimizing the machining conditions and parameters, the effects of the residual tool marks can be minimized.

Figure 4.4 Assembly of the polymer lenses
In order to shorten the entire diamond machining process and therefore minimizing the environmental influence such as temperature variation and floor vibration, we first milled out a puck-like blank as shown in Figure 4.5 (a) on a CNC machine. This blank has a rough cylindrical stock at the central area with a milled slot aside for the further tool clearance. The blank was mounted on an aluminum mandrel that was sucked on the vacuum chuck of the 350 FG as shown in Figure 4.5 (b). The flat surface of the aluminum was diamond turned beforehand. Firstly, the annular surface as shown the top on the blank in Figure 4.5 (a) was diamond turned. The blank was flipped to be mounted on the aluminum mandrel. Afterwards, the circumferential surface and the flat surface were turned with the same diamond tool with a sweep angle larger than 90°.

Figure 4.5 (a) Diamond broaching setting up for the prism (b) Diamond broaching tool path for the freeform surface on the prism (the total number of passes was reduced for clarity)
The maximum slope angle of the rear lens surface is 57.3° that is much larger than the clearance angle of any diamond turning tool. In order to avoid the diamond tool interfering the machined surface, diamond milling process was performed. A ball end mill tool with 500 μm circular radius was chosen and the tool path was compensated according to the circular radius. The spindle speed is 50,000 RPM. The rough cutting feedrate and cutting depth were set at 50 mm/min and around 25 μm. The finish cutting feedrate and cutting depth were set at 25 mm/min and around 3 μm. After the rear lens surface was finished, the blank was flipped to be mounted on the aluminum mandrel.

The blank was set up for diamond turning and broaching as illustrated in Figure 4.5 (a). A 381 μm nose radius diamond tool with a larger than 70° sweep angle and 0° rake angle was installed in the X-Z plane (horizontal direction). The tool was tilted along Z axis such that no tool switching or adjusting operation was needed when turning phase transited into broaching phase. In this configuration, the aspherical surface and anamorphic surface share the same datum. The tool path was compensated based on the aspherical and anamorphic profiles and the diamond tool nose radius. For the turning phase, the rough cutting feedrate and cutting depth were set at 20 mm/min and around 11 μm. The finish cutting feedrate and cutting depth were set at 5 mm/min and around 3 μm. For the broaching phase, the feed of the tool is in the Y direction while stepping along the X direction and the spindle of machine (C axis) was locked. The broaching feedrate for the flat surfaces was set at 300 mm/min. The cutting depth was 30 μm and the crossfeed was 5 μm.
4.4 Evaluation of the Miniature Endoscope

4.4.1 Geometry measurement of the lens surface

The geometry measurement was performed on a white light noncontact interferometer, Wyko NT9100. Surface 6 in Table.1 was chosen for its mild curvature such that more light could be reflected into objective lens of Wyko under the same condition compared with the other surfaces. Therefore it is less likely to lose information during scanning. For the measurement, the magnification was set at 27.4x and the stitching function was used to obtain a high resolution scan of the entire lens surface. The tilt angle of the scanned surface was automatically removed. The complete profile of surface 6 was shown in Figure 7 (a). A cross-section profile was drawn in Figure 7 (b). The solid line and the dashed line represent the design surface profile and the measured surface profile. According to the corresponding deviations between the two surface profiles plotted in Figure 7 (b), the absolute deviation was within +/- 2 μm.
The geometry measurement was performed on a white light noncontact interferometer, Wyko NT9100. Surface 4 in Table 3.4 was chosen for its mild curvature such that more light could be reflected Wyko under the same condition compared with the other surfaces. Therefore it is less likely to lose information from the scanned surface. During the measurement, the magnification was set at 27.4x and the stitching was used to obtain a high resolution view of the central lens surface with half aperture. The tip/tilt angle of the scanned surface was automatically removed. A cross-section profile with full aperture was drawn in Figure 4.7 (a) to study the surface quality. The solid line and the dashed line represent the designed surface profile and the measured surface profile. According to
the corresponding deviations between the two surface profiles plotted in the Figure 4.7 (b), the absolute deviation was within +/- 4 µm.

Figure 4.7 (a) Measured surface 4 using Wyko Profilometer (b) Cross section profiles of the design and measured surface 4 and its deviation

4.4.2 Imaging performance

The optical performance of the off-axis endoscope was tested on a home-built setup. A CCD camera (PL-B957F, pixeLINK, 8.98 mm by 6.70 mm) with a 6.45 µm pixel pitch was employed. A zoom lens (VZTM 450i, Edmund Optics) with magnification range from 0.75x to 4.5x was mounted onto the camera to observe the images through the endoscope. A USAF test target was used to evaluate the imaging performance of this endoscope as in Figure 4.8. To measure the field of view (FOV), an aluminum block (24 mm by 24 mm) was used as a target in the following imaging test. When it was around 90
mm away, the block was circumscribed by the aperture of the endoscope. Thus, the half angle of the FOV of this endoscope is $10.7^\circ$ according to:

$$\text{half of FOV} = \arctan\left(\frac{24\times\sqrt{2}}{90 \times 2}\right) \times \frac{180}{\pi}$$

(6)

**Figure 4.8** Imaging test of the endoscope

The optical performance of the endoscope with split view was tested on a home-built setup. A CCD camera (PL-B957F, pixeLINK, 8.98 mm by 6.70 mm) with a 6.45 µm pixel pitch was employed. A zoom lens (VZMTM 450i, Edmund Optics) with the
magnification range from 0.75 X to 4.5 X was connected onto the camera to observe the images through the endoscope in a water tank to simulate the practical environment. To investigate the angle of the split view, a USAF test target was used to evaluate the imaging performance of this endoscope as in Figure 4.9. The left half of the image was collected from the lateral split channel while the right half of the image was from the front dome surface. When the target was around 36.7 mm away, the distance between two object area was 34.9 mm. Thus, the angle of the split view is 43.56° according to:

\[ \text{lateral angle} = \arctan \left( \frac{34.9}{36.7} \right) \times \frac{180}{\pi} \]  \hspace{1cm} (7)

**Figure 4.9** Imaging test of the endoscope: (a) the practical imaging test in water (b) object position on the target
4.4.3 MTF measurement

The MTF of the entire lens assembly was measured to evaluate the optical performance of the endoscope. In this experiment, a slanted edge target test was performed. A snapshot of a checker board with 5° rotation was collected and calculated in Quick MTF (www.quickmtf.com), an image quality test program. In this program, the combination of centroid calculation and hamming window was selected to minimize edge detection error. In addition, in the measurement, the linear regression was turned off for geometric distortions of the slanted edge. The experimental MTF results are depicted in Figure 4.10. The contrast falls to 15% around 30 - 40 LP/mm in both tangential and sagittal directions. Although the experimental results show the real endoscope system has lower resolution than the plot from the original design in Figure 3.3, this result is still considered to be acceptable given that the Nyquist frequency of the test camera is 77.5 LP/mm. The causes of less MTF value may include several possible sources: low and/or non-uniform illumination, residual tool marks, other fabrication errors and misalignments of optical components.
Secondly, the straight view of the endoscope was tested using a home-built imaging setup. A USAF 1951 test target, assembled lenses fixed on a multi degree of freedom stage, a zoom lens (VZMTM 450i, Edmund Optics) and a CCD camera (PL-B957F, pixeLINK) were sequentially set up on an optical table. The MTF was calculated by analyzing the contrast of each line pair of the tested image shown as in Figure 4.9 (a) as follows:

\[
\text{Contrast} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \tag{8}
\]

where \(I_{\text{max}}\) and \(I_{\text{min}}\) are the maximum and minimum intensity within one line pair element, respectively. The experimental and predicted MTF results are depicted in Figure 4.11.
Respectively, the contrast falls to 10% around 30 - 40 LP/mm in both tangential and sagittal directions compared with Figure 3.3; the contrast falls to 20% around 15 - 20 LP/mm in both tangential and sagittal directions compared with Figure 3.6. The reasons are various, including imaging environment, the nonuniform illumination, the residual tool marks, fabrication errors and misalignment of optical components.

Figure 4.11 MTF test result of tangential direction and sagittal direction

4.4.4 Discussions and conclusions

Refractive indices of optical polymers are slightly lower in comparison with most optical glasses. Therefore the PMMA prism has less power to steer light than its glass counterparts. The diameter of this endoscope will be slightly larger than 3 mm as compared to Wippermann’s design, from which our optical design was originated. The
usage of a GRIN lens also drastically converged the light rays in Wippermann’s design, which was important for reducing the overall length of the endoscope. In Wippermann’s design, the optical axis was also bent after leaving the prism. This results in a more compact structure and a larger off-axis angle but brought about a lot of difficulties for testing and assembly of the endoscope.

In this paper, a freeform surface was designed and integrated with the prism. The freeform optical surface helps to shrink the imaging spot from more than 110 μm if only aspherical lenses were used to less than 4 μm and therefore improves the overall resolution of the endoscope. According to its MTF, this endoscope is only around 5% below the diffraction limit at half Nyquist spatial frequency of the imaging sensor and therefore is more than sufficient to avoid aliasing effects.

An integrated diamond machining process was developed to fabricate a prototype of the endoscope for optical test. In this research the absolute deviation was discovered to be almost symmetric along the optical axis of the lens, a result of the diamond turning process used. Apart from the random factors of the environment such as temperature variations, vibration, structural deflection of the ultraprecision machine due to its weight and uneven heating, machining process variations also affect the finish quality of the optical components. Moreover, to achieve a larger clearance angle during the broaching of the freeform entrance surface on the prism, the diamond tool was purposely tilted -20° along Z axis. Therefore, the diamond tool machined the large part of the freeform surface with a very large negative rake angle, resulting in a slightly lower surface roughness.
In addition to the aforementioned errors in fabrication, the misalignment of the optical components always results in performance loss. In this endoscopic configuration, during test the freeform based prism was mounted on a fixture while three lenses were concentrically aligned to each other and mounted on a separate multi degree of freedom stage. Any misalignment from the optimal position between the prism and the following lenses could have affected the imaging. In this assembly, wedge, de-centration of the lenses and tilt of the lenses in assembly could all have introduced errors during the testing. Optical aberrations are another source of errors during the imaging test of this endoscope. For example, the chromatic aberration still existed although a doublet was installed in the assembly. The chromatic aberration causes blurs in the image and thus brings degradation in MTF. Moreover, the separation between sagittal and tangential MTF was also partially caused by lateral chromatic aberration as in Figure 9.
Chapter 5 Industrialized Fabrication of Nonconventional Optical Components

Miniaturization of optical elements and optical system have become increasingly popular in medical devices, smart phone and laser technology. The accelerating miniaturization trend and high demands for affordable compact optical products require optical industry to develop a process featured with high throughput and adequate quality optics. In recent years, various techniques including lithography process and hot embossing process have been investigated in order to achieve low cost high volume production of miniaturized or micro-structured optical components. These efforts include, for example, ultraviolet (UV) imprint lithography or UV molding (Schmitt, 2010; Dannberg, 2014; Kooy, 2014), injection molding (Li & Yi, Design and fabrication of a freeform microlens array for uniform beam shaping, 2011), and compression molding (He P. L., 2014).

As semiconductor industry is fully developed, lithography process has become a mature technology, especially considering its capabilities of shaping precise micro or sub-micro structure, fabricating large number of optical elements on wafer level scale and packing the components by stacking. However, there are some limitations for lithography based wafer level fabrication process. Lithography based process is not ideal at creating profiles with high degree of flexibility for micro lens that always plays a crucial role in optical
performance. Generally speaking, either dry etching or wet etching can be used to fabricate the simple grooves or similar features that are subsequently used for the following molding. Reflow process is also widely accepted to generate the profile with compromised parameters. However all these methods can only create spherical geometry not suitable for aspherical or freeform lenses. Also due to the nature of etching processes, clean room processes work well with micro scale features thus their products are used more common in the form of micro lens array rather than individual module, such as compound eye (Zhang, 2012) and fiber or diode lighting and display (Zeng, 2011; Liu, 2010). Besides, lithography based processes are limited to selected UV cured photoresists. Injection molding macro or meso scale polymer lenses is a popular high volume fabrication method. However, injection molding is not usually used to create wafer level components due to the thermal related issues rather than molding of individual lenses. For macro size optics, handling and assembly are not difficult. But for meso scale packaging process, cost of production dramatically increases due to the size reduction. To this end, compression molding provides an alternative methodology for its high efficiency and relatively low equipment requirement (Huenten, Hollstegge, Wang, Dambon, & Klocke, 2011; Li L. H., 2011). In Li et al.'s research work (Li L. H., 2011), P-SK 57 glass and polycarbonate were used together to form an achromatic doublets array. The success of this process relies on the two optical materials used in the assembly. This process also eliminates the assembly stage for the doublets array by positioning on two chisel-shaped cavities during molding stage. More recently, Huenten et al. proposed a precision glass molding process on wafer level scale (Huenten, Hollstegge, Wang,
Dambon, & Klocke, 2011). Their description of the entire process includes a detailed view on each step however the process steps are all based on computer simulation.

5.1 Compression Molding and Assembly on Wafer Level Scale

In this section, we have attempted to implement an integrated approach that could be used as an alternative process for the miniaturized optical elements fabrication and assembly at lens array level scale. To demonstrate this process, three lenses, a polymethylmethacrylate (PMMA)-polycarbonate (PC) doublets and a PMMA rear field lens, in a layout similar to the endoscope in reference (Li, Yu, Lee, & A. Y Yi, 2015) were fabricated and assembled in a wafer level manner. As discussed in (Huenten, Hollstegge, Wang, Dambon, & Klocke, 2011), one of the major challenges is the alignment of the upper and lower mold die to guarantee the concentricity of the optical surfaces. To cope with this problem, we designed a special pair of molds to minimize the eccentricity. A slow tool servo (STS) diamond turning process was developed to fabricate the molds. PMMA and PC lens arrays were separately formed in molding operation with fiducial feature designed for subsequent alignment and assembly. The entire compression molding process was simulated using finite element method (FEM) to study the molded surface profile and the maximum residual stress in the sample. The quality of the molded lenses was also evaluated including their geometrical profile, critical optical parameters and fabrication errors. The assembly process of three lenses was performed in a wafer level manner under a white light interferometer. The assembly error was also measured to investigate the quality of the assemble process. Finally, MTF was measured for
quantitative comparison between practical assembled lenses and their analytical model for different tolerances.

5.1.1 Mold fabrication

In recent years, various micro precision machining techniques have been developed and commercially applied in success, such as photolithography, precision grinding and polishing, laser micro machining and ultraprecision diamond machining. Compared with other approaches, diamond machining provides a high simplicity and flexibility and therefore is an efficient method to fabricate a small number of precision compression molds with high optical surface finishing quality. In this research, the compression molds were firstly roughed out on a common CNC milling machine from a 6061 aluminum alloy rod. Next, the rough molds are machined by the slow tool servo machining technique on the 350 FG (Freeform Generator from Moore Nanotechnology, Inc., Keene, New Hampshire). To demonstrate the idea of wafer level fabrication and packaging, two molds are diamond machined for each two by two lens array. The diamond tool has a 0.393 mm tool nose radius that was compensated in the generation for spiral tool path trajectory. For all the molds, initial cutting depth was 10 - 20 μm and finish cutting depth was 2 μm. The feedrates for rough and finish cutting were set at 20 and 5 mm/min, respectively.

The three lenses used to demonstrate the wafer level scale fabrication and assembly origin from the endoscope design (Li, Yu, Lee, & A. Y Yi, 2015). This endoscope has a large off-axis view integrated with a freeform entrance prism. The following three lenses
were used to reduce the chromatic aberration and further correct spherical aberration. The second lens is made of PC and acts as flint glass forming a doublet with the first lens.

In the endoscope design, a high order aspherical lens surface was designed on the front face of the rear field lens, that is, surface 4. It is described as equation (2).

Table 5.1 Optical prescription for the three lenses

<table>
<thead>
<tr>
<th>Surface</th>
<th>Radius $(1/c)$</th>
<th>Thickness</th>
<th>Material</th>
<th>Semi-aperture $(r)$</th>
<th>Conic constant $(k)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.130</td>
<td>1.900</td>
<td>PMMA</td>
<td>1.021</td>
<td>-0.170</td>
</tr>
<tr>
<td>2</td>
<td>-6.113</td>
<td>1.300</td>
<td>PC</td>
<td>0.960</td>
<td>13.318</td>
</tr>
<tr>
<td>3</td>
<td>3.027</td>
<td>0.500</td>
<td>—</td>
<td>0.922</td>
<td>5.456</td>
</tr>
<tr>
<td>4</td>
<td>2.276</td>
<td>1.500</td>
<td>PMMA</td>
<td>1.083</td>
<td>-4.373</td>
</tr>
<tr>
<td>5</td>
<td>3.030</td>
<td>3.500</td>
<td>—</td>
<td>1.064</td>
<td>-4.015</td>
</tr>
</tbody>
</table>

For every lens array, each lens offsets from the center of the array 25 mm horizontally and vertically. According to the Table 5.1, a gap exists between the second and the third lens. Generally, a spacer is used in the common lithography process. Here, four fiducial dome bosses with specific height were designed on the mold to minimize the cost of fabrication and eliminate the unnecessary steps for assembly, functioning as the spacer between the second and the third lenses as shown in Figure 5.1. However, the intersection edge between each dome boss and each lens surface does not have a continuous derivative that is necessary to achieve a continuous compensated tool path. The sudden shift of the cutting point generally induces an impact force on the cutting diamond tool. To avoid the worn of the tool, the fabrication of the mold was divided into
two steps: the dome bosses were firstly diamond turned out from a blank; each lens profile was diamond turned on its dome boss. As shown in Figure 5.2, one curved slide rib and its opposite flat slide rib were designed to secure the centricity of top and bottom optical surfaces of the lens array.

![Figure 5.1 Tool path of lens surface sitting on fiducial feature](image)

**Figure 5.1** Tool path of lens surface sitting on fiducial feature
5.1.2 Simulated and compression molding process

Precision compression molding is a hot forming process of replicating optical elements from mold to softened material at elevated temperature. In this research, precision compression molding of lens array was conducted on a commercial molding machine, DTI bench top GP-10000HT glass press. The configuration of the machine is shown in Figure 5.3 (a). The molding assembly consists of an upper mold, a lower mold, two ring-shape infrared heater, two thermal couples inserted into the molds and a tungsten carbide sleeve which guides the upper mold and also maintains the thermal uniformity around the molding space from possible turbulent airflow. A small piece of polymer blank with double faces preliminarily diamond turned was placed on the top surface of the lower mold. Three cycles of purge between vacuum and nitrogen were conducted. As illustrated

Figure 5.2 A pair of molds for wafer level fabrication
in Figure 5.3 (b), after the temperature monitored by the thermal couples reached the molding temperature, the upper mold descended and pressed onto the polymer blank with a forming load. To ensure the cavity was fully filled, the upper mold was continuously being pushed downward until its position unvarying for a while. Next, the entire molding assembly was cooled down by an external fan until the temperature dropped to around 50 °C. Detailed parameters of compression molding process for three lenses are listed in Table 5.2. A molded lens sample was shown as in Figure 5.3 (a).

![Diagram of compression molding assembly](image)

**Figure 5.3** (a) Compression molding assembly (b) Entire molding process of a wafer

continued
Figure 5.3 continued

![Graph showing temperature and molding force over time.]

(b)

<table>
<thead>
<tr>
<th>Lens</th>
<th>Molding temp. /°C</th>
<th>Forming load /N</th>
<th>Initial thickness /mm</th>
<th>Pushing time /mins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens 1</td>
<td>140</td>
<td>650</td>
<td>2.1</td>
<td>~30</td>
</tr>
<tr>
<td>Lens 2</td>
<td>155</td>
<td>400</td>
<td>1.6</td>
<td>~20</td>
</tr>
<tr>
<td>Lens 3</td>
<td>140</td>
<td>550</td>
<td>2.0</td>
<td>~15</td>
</tr>
</tbody>
</table>

Table 5.2 Compression molding conditions for three lenses

A simulated molding process for lens 1 was established on the base of the experimental data in ABAQUS. The process steps include heating, pressing and cooling stages. First the PMMA blank was heated above its transition temperature ($T_g = 109$ °C) and molded as viscoelastic material. A generalized Maxwell model was adopted for its viscoelastic
behavior. The shear modulus at transition temperature is expressed as Prony exponential series. The parameters were used from reference (Kim, 2008) for thermal rheology simple behavior using WLF equation. Only a quarter of the model was analyzed based on symmetry. In the pressing stage, a constant force was applied until the desired displacement is reached. At the beginning of this stage, the displacement increased rapidly with time, and then crept very slowly to the desired value until the two molds touched each other. An overview of the molded lens was illustrated in Figure 5.4 (a) that indicates the surfaces were well formed. The nodal stress in the center of the sample increased sharply to the maximum value when touching, and then decreased slightly during the pressing stage. In the cooling stage, the position of the upper mold was fixed. The stress relaxed with time to a small value during the transition range. After separation between the sample and the upper mold due to thermal shrinkage, the residual stress within the sample almost remained constant. The maximum residual stress in the sample after cooling to the room temperature is less than 1 MPa as shown in Figure 5.4 (b).
Figure 5.4 (a) Practical molded lens array (b) Overview of a quarter of simulated lens array

5.1.3 Assembly in a wafer level manner

Generally, for injection molding and hot embossing processes, the assembly process involves with manually assembling lenses into a barrel-like housing structure. The procedure is not efficient and labor intensive. On the other hand, wafer level packaging has been widely accepted and applied in semiconductor industry. The industry uses wafer bonding equipment platforms to bond wafer level lens array with spacers or a second wafer level lens array with thermal or UV curable adhesives. Here, we use the similar strategy to assemble the lenses by using the white light interferometer (NT 9100 Wyko).
First, a wafer of lens array with smaller aperture was stacked onto another with larger aperture and under the microscope objective lens of Wyko. Because of the transparency of the material, the coordinates at the center of upper and lower apertures can be recorded by aiming the crosshair of the objective lens. The relative planar deviation and rotation can be calculated by the coordinates of one diagonal pair of the stacked apertures. With the upper wafer laterally restricted by a 2D positioner as shown in Figure 5.5, the lower wafer was fixed on and moved with the Wyko stage. Due to the uneven friction between two wafers, the upper wafer could rotate in plane as well as translate along the reverse moving direction with respect to the lower wafer. Finally, a UV adhesive (Norland Optical Adhesive 65) was dripped on the lateral side of the assembled lenses and cured by a UV light source at 365 nm wavelength.
5.1.4 Surface profile and focal length measurement

The entire surface profiles of molded lenses were measured under Wyko. During the measurement, the magnification was set 27.4 X and the stitching function was enabled to get a high resolution scan of the entire surface. The tip/tilt angle of the scanned surface was automatically removed. A cross-section profile was extracted from the measurement. For example the back surface of lens 1 was shown in Figure 5.6. To investigate the surface quality quantitatively comparing with the mold profile, the solid line and the dash line represent the molded lens surface profile and the mold surface profile. According to the deviation plotted in Figure 5.6, the maximum absolute deviation was 4 µm at the rim of the aperture, which results from the different cooling rates of the mold and the polymer.

Figure 5.5 Assembly process of wafers of lens array

![Assembly process of wafers of lens array](image-url)
There are many methods for measuring optical focal lengths. For miniaturized lens arrays, especially with high order aspherical surface, conventional methods based on geometrical measurement cannot fulfill the requirements with high precision. To better evaluate the fabrication quality of the molded lens array, a Twyman-Green interferometer was set up as shown in Figure 5.7. A collimated beam from He-Ne laser source (632.8 nm) was split into two beams: the reference beam was reflected by the standard plat mirror and received by the CCD; the test beam propagated through 4 times microscope objective lens and lens array and was reflected backwards. The focal length measurement was divided into two steps. First, the lens array was moved along the horizontal direction until the focal point of the objective lens arrived at the surface of the lenslet. The position,
which is generally called the Cat's eye position, was recorded. Second, the lens array was moved along the horizontal direction until the focal plane of the objective lens overlaps with that of the lenslet. In the two situations, the straight fringes were observed because both the reference and test beams were collimated. Both front focal length (FFL) and back focal length (BFL) of a wafer for lens 1 were tested as listed in Table 5.3.

![Schematic of the Twyman-Green interferometer](image)

**Figure 5.7** Schematic of the Twyman-Green interferometer

<table>
<thead>
<tr>
<th>Lenslet 1</th>
<th>Lenslet 2</th>
<th>Lenslet 3</th>
<th>Lenslet 4</th>
<th>Computational Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFL (mm)</td>
<td>3.121</td>
<td>3.115</td>
<td>3.069</td>
<td>3.050</td>
</tr>
<tr>
<td>BFL (mm)</td>
<td>2.453</td>
<td>2.428</td>
<td>2.436</td>
<td>2.430</td>
</tr>
</tbody>
</table>

**Table 5.3** Measured focal length of lens 1
5.1.5 Fabrication error and assembly error measurement

Eccentricity and wedge are two other errors that are important for lens fabrication. The measurement of these two errors contributes a lot to the following computational MTF curve. A better evaluation of these errors also benefits for reasonable tolerance distribution of optical system for optics engineers. First, the white light interferometer was applied to detect the flatness and tip/tilt angle between front and back molded wafer surface. The uniform white and black fringes indicate the molded wafer is only slightly warped. Next, the lens aperture was observed under the microscope objective lens of Wyko. The coordinates at the center of upper and lower apertures were recorded to calculate the rotation ($R$) and translation ($T$) errors between front and back lenslet. Two coordinate systems respectively attached to front ($W$) and back ($W'$) surface can be described as follows:

$$\mathbf{W} = \mathbf{R} \mathbf{W}' + \mathbf{T}$$  \hspace{1cm} (8)

where $\mathbf{R} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$, $\mathbf{T} = \begin{bmatrix} X_0 \\ Y_0 \\ 1 \end{bmatrix}$. The eccentricity and wedge errors, for example three samples of lens 2, are listed in Table 5.4.

For conventional assemble process of miniaturized lenses in a barrel-like structure, the assembly error can be directly derived from the tolerances of the structure design and its manufacturing. Here, the assembly error measurement was inserted between every assemble step. The coordinates at the center of each upper and lower aperture can be
recorded by the help of the crosshair of the objective lens. This one-by-one measurement was inefficient but needed for an accuracy result to investigate the quality of the assembled module. The relative eccentricity was calculated by the center coordinates of each upper and lower apertures as listed in Table 5.5. The assembly error between lens 1 and lens 2 is much less than that of lens 2 and lens 3, which is largely determined by the self assembly features between the doublets.

**Table 5.4** Fabrication errors of three samples for lens 2

<table>
<thead>
<tr>
<th>Sample #</th>
<th>$\Theta$ (°)</th>
<th>$x_0$ (μm)</th>
<th>$y_0$ (μm)</th>
<th>wedge (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.125</td>
<td>4.375</td>
<td>28.343</td>
<td>0.34</td>
</tr>
<tr>
<td>2</td>
<td>0.149</td>
<td>-4.000</td>
<td>-20.341</td>
<td>0.14</td>
</tr>
<tr>
<td>3</td>
<td>0.051</td>
<td>6.500</td>
<td>-22.830</td>
<td>0.30</td>
</tr>
</tbody>
</table>

**Table 5.5** Assembly error of a lens module

<table>
<thead>
<tr>
<th></th>
<th>Lenslet 1</th>
<th>Lenslet 2</th>
<th>Lenslet 3</th>
<th>Lenslet 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens 1 and 2 (μm)</td>
<td>10.472</td>
<td>17.248</td>
<td>18.656</td>
<td>12.898</td>
</tr>
<tr>
<td>Lens 2 and 3 (μm)</td>
<td>19.049</td>
<td>21.245</td>
<td>35.526</td>
<td>18.784</td>
</tr>
</tbody>
</table>

5.1.6 MTF test of the assembly

MTF is the image modulation as a function of spatial frequency, which is generally used to describe lens imaging performance. First, an on-axis simulated MTF curve was derived from the ray tracing software CODE V to evaluate the impact of the tolerances on the imaging performance. In the MTF simulation, radius delta (DLR), thickness delta (DLT)
and surface displacement (DLZ) are respectively set as the mean value of each measurement. For surface tilt (DLA and DLB) and surface displacement (DLX, DLY) were evenly divided according to the fabrication error and assembly error. Decentered tolerance was set as Gaussian distribution and scalar tolerance was set as uniform distribution. Curves with 50% and 97.7% cumulative probability were shown in Figure 8 (b).

The three lens layers assembly was also tested using a home-built imaging setup. A USAF 1951 test target, assembled lenses fixed on a multi degree of freedom stage, a zoom lens (VZMTM 450i, Edmund Optics) and a CCD camera (PL-B957F, pixeLINK) were sequentially set up on an optical table. The lenslets of the assembly were individually evaluated. The MTF was calculated by analyzing the contrast of each line pair of the tested image shown as in Figure 8 (a).

where $I_{\text{max}}$ and $I_{\text{min}}$ are the maximum and minimum intensity within one line pair element, respectively. As shown in Figure 8 (b), the sagittal direction has a mildly better resolution than the tangential direction. The predicted curves were also depicted based on the curve fitting of the mean MTF value of four lenslets. The most part of the predicted curves locates between the simulated curve with 97.7% cumulative probability and the one with 50% cumulative probability. It indicates the simulation integrated with fabrication and assembly errors is reliable.
Figure 5.8 (a) Captured image of USAF 1951 target (b) Measured and simulated MTF curves of the assembly module

5.1.7 Conclusions

Through fabrication and assembly of three aspherical lens arrays and measurement of molded lens samples both for geometrical profile and focal length, we have demonstrated the integrated approach to fabrication and assembly of meso scale camera lens assemblies using precision compression molding process as a promising process for high precision and high efficient replication of miniaturized lens arrays. Moreover, the measurements of fabrication errors and assembly errors as well as the MTF curves of the molded samples validate the capabilities of wafer level compression molding process. Successful completion of this method will provide an alternative to manufacturing of precision wafer level miniaturized lens array, particularly in applications where high order aspherical or even freeform surface are needed or applications where low cost high quality miniaturized lens made of polymer are indispensable.
To demonstrate the wafer level fabrication and assembly process, three pairs of molds were diamond machined with high precision and optical surface quality. Special fiducial feature was designed to eliminate the usage of spacer between lenses. The three polymer lens arrays were respectively compression molded from each corresponding pair of molds. A simulation was conducted to further investigate the molded surface profile and the maximum residual stress in the samples. A live lens array assembly process was developed by the help of the white light interferometer. As a result, the efficiency of fabrication and assembly of miniaturized lens modules are improved compared with the conventional injection molding or other hot embossing process. The geometrical and optical measurement were both carried out to evaluate the finish quality of the molded lenses and its assembly. The fabrication error and assembly error were introduced into the MTF simulation. The comparison of the simulated MTF curve and practical MTF curves validated the imaging quality of the assembled modules.

This research validated a high efficiency and low cost integrated approach to fabricate and assemble high quality lenses module on wafer level scale. The advantage of this process combines high efficiency from lithography process and high profile precision from compression moldings process. In addition, by compensation of the molds profile according to the simulation of the entire molding process, the deviation of the molded profile can be further reduced. Therefore, the quality will be improved both for single lens array and the assembly of lens modules. Future work would also include the fabrication of various molds that could be compatible with more common materials. The coat techniques will be applied to improve wear ability and life time cycle of the molds.
5.2 Localized Rapid Heating Process for Precision Glass Molding

In this section, We have attempted to implement a graphene coating in precision glass molding in order to utilize its high hardness, low friction and high thermal conductivity (Soldano et al., 2010). For example, He et al. (2013) conducted a comparative molding test between a silicon wafer mold with carbide-bonded graphene coated and a silicon wafer mold without graphene coating. Their investigation demonstrated that graphene coating enables silicon to be used as a mold material by preventing silicon to glass adhesions at elevated temperature. Additionally, graphene (Sui et al., 2011) or graphene based material (Kang et al., 2011), has gained more popularity for its combination of excellent thermal and electrical property and successfully applied in flexible electrothermal heating element. Sui et al. (2011) annealed graphene oxide films at three different temperatures and revealed the electrothermal performances in diagram. They also investigated the mechanical stability and flexibility of these films by repeatedly bending to validate the heating function. Kang et al. (2011) increased graphene resistance using lay-by-lay doping methods. However, according to their studies, neither graphene film heater from the two groups could reach 210 °C, which barely reaches the $T_g$ for most common infrared glass materials.

This localized rapid heating mold was design to only elevate the temperature of area where micro features need to be replicated In this way, less thermal variation on mold and molding assembly is introduced comparing with conventional bulk heating glass molding equipment. This setup will reduce the undesired thermal expansion of the mold and molding assembly and thus will increase the life time of the molds and molding
equipment. Moreover, the heating and cooling cycles will be significantly shortened since only the target area on the glass sample and its immediate surroundings will be heated above $T_g$.

5.2.1 Mold fabrication

Fused silica was selected as the mold material for its low thermal expansion coefficient, ability to withstand rapid temperature change without cracking and its high electrical resistance even at elevated temperature. Standard lithography techniques were employed to transfer micro patterns to glass mold by reactive ion etching. The starting material is a 50 mm diameter and 500 μm thick fused silica wafer. First this wafer was cleaned using acetone and isopropanol sequentially. Hexamethyldisilazane (HMDS) prime oven was used to improve adhesion between photoresist and fused silica wafer. Afterwards, a layer of 1.4 μm thick S1813 photoresist was deposited on the fused silica wafer. The density of UV radiation for photoresist exposure was set at 15 mW/cm² with a duration of 2.4 second on an EV Group 620 advanced contact aligner. After the UV exposure, the wafer was developed for 2 minutes in MF-319 solvent and then rinsed in deionized water. Next the wafer was etched in Plasma Therm SLR-770 using CCl₄ at a flow rate of 20 cm³/min. The two RF (radio frequency) power supplies were set at 29 W and 500 W, respectively. The pressure was set at 5 mTor during the entire etching process. The etching rate was set at 0.1 μm/min. Finally the remaining photoresist was stripped and the wafer was cleaned in the ultrasonic bath. Figure 5.9 (a) shows the finished wafer.

Generally speaking, weak van der Waals force limits the atomic layer graphene building, especially for two-dimensional cross-linked coatings such as graphene because it can be
easily damaged or even wiped out. Therefore the carbide-bonded graphene method developed by (Huang, et al., 2013) was employed to coat a much thicker graphene network on the fused silica wafer. To do this, a piece of P-SO₃H nanopaper and a piece of high temperature silicone rubber were placed in a quartz tube furnace where the fused silica wafer was placed. Initially, vacuum was created in the furnace while the temperature inside the furnace was rapidly increased from room temperature to 600 °C in 20 minutes. Next, after vacuum was established, the furnace was sealed and continuously heated up to 1,000 °C in 10 minutes. During this stage, the pressure inside the furnace was gradually increased due to the decomposed gas from the nanopaper and the silicone rubber.

![Figure 5.9](image)

(a) Etched fused silica wafer before graphene coating (b) graphene coated fused silica wafer with copper electrodes
When the pressure reached atmosphere pressure, the vacuum valve was turned on under the protection of high purity nitrogen. At the elevated temperature, -Si or -SiO radicals are thermally generated by the silicone rubber. Simultaneously, the graphene sheets exfoliated from the nanopaper due to gas bubbles that were thermally decomposed from benzene sulfonic acid groups and reactively formed the carbon radicals at the edge. These graphene sheets were bonded either with themselves by C-Si and C-O-Si or on the fused silica wafer surface by C-O-Si and eventually formed a three-dimensional cross-linked graphene networks. The furnace was held at the highest temperature for 30 minutes before cooling to room temperature. Finally the fused silica wafer was rinsed with water and acetone and dried in a vacuum oven at 100 °C overnight. The resistance of this coating is subjected to the coating thickness and the coating electrical conductivity. The coating electrical resistance can be adjusted by changing the ratio of C and Si.

To connect the fused silica wafer with a power supply, two electrodes were fabricated as shown in Figure 5.9 (b). 597-A electrically and thermally conductive adhesive (Aremco Products Inc) was applied onto the two opposite areas using copper foils. After the electrodes were constructed, the wafer was dried at room temperature for 2 hours, followed by baking in vacuum oven at 93°C for 2 hours.

5.2.2 Molding experiments

Localized heating demonstration was experimentally performed as shown in Figure 5.10. In this experimental setup, a 3.8 mm thick infrared glass, arsenic trisulfide glass (As₄₀S₆₀) with $T_g$ of 180 °C, was placed on a small fused silica wafer coated with the graphene layer. Three small K type thermocouples were used to monitor the temperature variation,
as shown in Figure 5.10, two (node 1 and node 2) mounted near the edge of the glass and one (node 3) at the middle of the cylindrical side face. A direct current (DC) was applied on two copper electrodes in ambient environment during the heating test. Figure 5.11 plots the temperature measurements during a typical molding experiment. According to this figure, the middle layer of infrared glass was only heated up to 72.7 °C when the fused silica mold had reached 271 °C.

Figure 5.10 Localized heating test
Localized rapid heating glass molding was performed on a home-built machine (only the heating assembly is drawn) is shown in Figure 5.12. A specially designed polymer base plate is placed under the graphene coated fused silica wafer and a K type thermocouple, mechanically mounted on the lower mold. The thermocouple was fixed on the fused silica wafer at the corner of the infrared glass without touching the glass. Two copper electrodes were sandwiched between the edge of the polymer base plate and a piece of metal shim stock and fastened using a bolt. A 3.8 mm thick arsenic trisulfide glass from the same batch was placed on the fused silica wafer. The lower mold was moved up by a linear drive until the top surface of the infrared glass touched the bottom of the tungsten carbide. The force on the glass sample was preloaded at 49 N before heating and the positions of the molds remained the same during the heating cycle.
Figure 5.12 Localized rapid heating assembly

After this preliminary setting the chamber was closed. Two cycles of purge using vacuum and nitrogen were performed. During heating, a 60 V 0.84 A direct current was applied on the copper electrodes. The surface of the fused silica wafer was heated up rapidly as shown in Figure 5.13 (a). Once the temperature on the surface of the fused silica wafer reached approximately 240 °C, the output voltage of the power supply was reduced to zero. After the entire mold assembly was naturally cooled down to 150 °C, nitrogen flow was subsequently introduced into the chamber to accelerate the cooling. Afterwards, the load was released and the finished infrared glass was manually removed from the chamber.
Figure 5.13 (a) Localized rapid heating process (cycle time 240 sec) (b) Conventional bulk heating process (cycle time 3,600 sec)

A conventional bulk heating glass molding process was also performed on a commercial molding machine, DTI bench top GP-10000HT glass press. The cross section view of only the molding assembly is shown in Figure 5.14. The molding assembly consists of an upper mold, a lower mold and a tungsten carbide sleeve which guides the upper mold and also maintains the thermal uniformity around the molding space from possible turbulent airflow. A fused silica wafer without electrodes from the same batch of the aforementioned wafer was placed on the lower mold. A small piece of 3.8 mm thick arsenic trisulfide glass was placed on the fused silica wafer. Three cycles of purge between vacuum and nitrogen were conducted. The ramp rate of heating was set at 150 °C/min, following the study of (Wachtel, Mosaddegh, Gleason, Musgraves, & Richardson, 2013).
As illustrated in Figure 5.13 (b), after the temperature inside reached the set point, 240 °C, the upper mold descended and pressed onto the infrared glass with a forming load of 66 N. To maintain this forming load, the upper mold was continuously being pushed downward for 4 minutes. The cooling consisted of two stages: the entire molding assembly was cooled down to 180 °C in 5 minutes by nitrogen flow; then an external fan was turned on to accelerate the cooling process. The mold chamber was opened around 73 °C.

![Figure 5.14 Conventional bulking heating assembly](image)

5.2.3 Molded geometry comparison

As illustrated in Figure 5.15 (a) and Figure 5.15 (c), the molded surfaces of the infrared glass samples using localized rapid heating and conventional bulk heating molding
The process were investigated under a white light profilometer (NT 9100 Wyko) to evaluate the quality of imprinted features. Two molds each containes a matrix of 10 μm x 10 μm squares with a depth of 0.8 μm were fabricated in the same lithography process and were coated with graphene layers in the same batch as shown in Figure 5.15 (b) and Figure 5.15 (d). According to the measurements, both the molded infrared glass samples resembled the fused silica molds with slight discrepancy on the edges of the squares. Using a line scan, the average height of the molded squares is 0.72 μm for localized rapid heating process and 0.69 μm for conventional bulk heating process as in Figure 5.16.

**Figure 5.15** (a) Molded features from localized rapid heating process (b) Mold for localized rapid heating process (c) Molded features from bulk heating process (d) Mold for bulk heating process
As illustrated in Figure 5.16 (a) and (b), in both conventional and localized rapid heating process the infrared glass filled precisely into the features on the mold. However, for the localized rapid heating process, the features were replicated better as indicated by straight edges other than the slanted using conventional bulk heating. This is because most part of the infrared glass maintained the solid status as demonstrated, providing better support during pressing. The closer the infrared glass is from the mold, the higher the temperature and easier it flows under pressure. This shows that only the shallow surface layer close to interested area is heated up above $T_g$ and formed into the mold.
Figure 5.16 (a) Line scans of the mold and molded features from localized rapid heating process (b) Line scans of the mold and molded features from bulk heating process

For conventional bulk heating process, the entire glass is softened and becomes viscoelastic. The glass flows in all directions when the pressure was applied. Therefore, it is more difficulty for the softened infrared glass to fill up the features under the same load. This is confirmed by the comparison of final thickness of two glass samples: the thickness in the localized rapid heating process remained approximately 3.8 mm while in the conventional bulk heating process the glass thickness was pressed down to 3.5 mm. For surface roughness, $R_a$ values of the area that was made contact with glass and the unmolded area on the fused silica wafer are identical, i.e., 8 nm, which is equal to the $R_a$ value of the molded surface on the infrared glass. In this experiment, we have demonstrated that localized rapid heating process produces a more consistent and higher fidelity surface than the conventional bulk heating process.
5.2.4 Processes comparison

The bulk and localized heating process conditions are summarized in Table 5.6. As illustrated in Figure 5.13 and Table 5.6, the localized rapid heating molding was completed in 4 minutes, much more efficient than the hour-scale conventional glass molding process. For the heating phase, the localized rapid heating only increases the temperature of the shallow surface layer of the glass near the mold as well as the surface of the mold allowing the ramp rate of the localized rapid heating reach near 300 °C /min. The commercial equipment used in the bulk molding generally needs to heat up the entire molding assembly and everything else in the heating chamber. The maximum heating ramp rate in a conventional molding is around 150 °C /min as demonstrated by Wachtel et al., 2013. During the molding phase, the applied load dropped slightly as shown in Figure 5.13 (a), an evidence that only the top surface layer of glass is viscoelastic. For bulk heating process, the upper mold has to apply continuous pressure downward to maintain the applied load due to the softening of the entire glass piece.

<table>
<thead>
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<th>Bulk heating</th>
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<tr>
<td>Heating ramp rate</td>
<td>300 °C/min</td>
<td>150 °C/min</td>
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<tr>
<td>Replication fidelity</td>
<td>High</td>
<td>low</td>
</tr>
</tbody>
</table>

Localized rapid heating process also means a shorter cooling cycle because only very small volume of glass material was heated up. In addition, the graphene coating absorbs
the heat accumulated from the glass and its high thermal conductivity allows rapid transmit of the heat to the entire wafer substrate therefore increases the cooling rate. On the other hand, the cooling rate of a conventional bulk heating is dictated by the amount of heat stored in every part inside the glass molding chamber. The only way to shorten this cycle in a conventional molding process is to enforce convection by forcing the inert gas flow to cool the chamber down from molding temperature to ambient temperature. This approach can introduce unintended consequences, such as high residual stresses and high refractive index change (Chen, Yi, Su, Klocke, & Pongs, 2008; Su, Chen, A. Y. Yi, Klocke, & Pongs, 2008; Tao, He, & Shen, 2014; Su, F. Wang, He, Dambon, Klocke, & Yi, 2014).

To investigate the localized heating performance, a numerical model was developed in ABAQUS. The model was axisymmetric as shown in Figure 5.17 (a). The material properties and dimensions of the infrared glass are consistent with that of the glass sample used in experiments. The thermal conductivity, density and specific heat of the infrared glass used in this study are 0.167 W/m/K, 3.2 g/cm³ and 456 J/kg/K. According to the experiment in section 5.2.2, the temperature variation curve at node 1, shown in Figure 5.10, was applied directly onto graphene film as boundary condition. The convection boundary condition was applied the side and top face of the infrared glass with a coefficient of 5 W/m²/K. The thermal conductance between the graphene film and the infrared glass was set at 10⁶ W/m²/K to accommodate the extremely high thermal conductivity of the graphene layer.
This simulation can be approximately modeled as a one-dimension heat transfer process. A series of the interior points along the central axis of the infrared glass with 0.5 mm spacing away from the graphene film were evaluated. As illustrated in Figure 5.17 (b), the time required at these points to reach maximum temperature increases with their distance to the graphene film. The simulation also shows that only 0.5 mm thick layer of infrared glass right next to the graphene film was heated up above 180 °C. The maximum temperature at the middle layer of the infrared glass reached is 94 °C or 20 °C greater than the experiment. This error may be due to the method used to attach the tiny thermocouples to the wafer substrate. The thermocouple of node 3 as shown in Figure 5.10 was securely sandwiched between two pieces of thermal conductive tape, one of which was directly glued on to the infrared glass to prevent the thermocouple from falling off under the tension in the wire. Additionally, the radiative heat transfer was ignored to
simplify the simulation. Because the infrared glass is relatively thick, radiative heat transfer inside the glass also plays a small role in the cooling cycle (Loch & Krause, 2002; Sarhadi, Hattel, Hansen, Tutum, Lorenzen, & Skovgaard, 2012). Last but not least, some parameters and thermal boundary condition set in this simulation overestimated the temperature inside the infrared glass. Typically, thermal contact conductance falls between 2,000 to 200,000 W/m²/K and varies with surrounding temperature, air pressure and applied loads. In this paper, a high value that could be considered infinite, i.e., 10⁶ W/m²/K, was used as thermal contact conductance to simplify the simulation. This means that more heat was conducted off the graphene layer than what occurs in the real experiment, which resulted in a higher temperature inside the infrared glass in the simulation. Temperature at node 1 was used as a uniform thermal boundary condition on the entire graphene layer may also have contributed to the error. Because of the small thickness, the heat was concentrated on the graphene layer, which means that the temperature close to the edge of the infrared glass is higher than the temperature beneath it.

5.2.5 Molded sample by localized rapid heating process

To validate the uniformity of the molded sample and conformity of the molded lens shape, localized rapid heating process was also applied to larger scale molding area as shown in Figure 5.18 (a). The matrix of 20 μm by 20 μm squares has a 0.88 μm height in average while the micro feature on the mod has a depth of 1 μm. A close view of one of the squares is illustrated in Figure 5.18 (b). The $R_a$ value of optical surface roughness on the
mold is 3 nm and the $R_a$ value on the molded surface is near 4 nm, demonstrating an optical quality surface.

![Image of molded square dots](image1.png)

Figure 5.18 (a) Matrix of molded square dots on IR glass (b) Close view of a square dot on IR glass

5.2.6 Conclusion

Through fabrication of graphene coated fused silica wafer and measurement of molded glass samples from two comparative precision glass molding processes, we have demonstrated that localized rapid heating for glass molding can be a promising process for high precision replication of micro scale features on infrared glass. Moreover, the uniformity of the molded samples and overall molded feature quality illustrated the capabilities of localized rapid heating process. Successful completion of this method will provide an alternative to manufacturing of precision glass molding process, particularly
in applications where only micro surface features are needed or applications where large deformation in glass cannot be tolerated.

To demonstrate the localized rapid heating, an electric current was created in the graphene coating layer using a DC power supply. The direct heating of the mold surface to molding temperature provides a much higher heating rate as compared to conventional bulk molding. As a result, the localized rapid heating process eliminates the need to heat the entire glass and the mold assembly. This in turn will reduce the thermal expansion of both the mold and the molding equipment. Because the rapid heating occurs only on the surface layers of the mold and glass, this method can be used to more efficiently modulate the temperature right next to glass material therefore allows the control of the material property at a higher precision.

In addition, graphene coating has attractive mechanical properties such as high thermal conductivity, low friction, and stability under high temperature. These properties made graphene an ideal coating for high temperature molding of glass optics. The current work has shown molding temperature up to about 250 °C. This temperature has to be increased to about 500 °C in order to mold oxide glass. According to the preliminary tests, the current electrical power supply can reach about 400 °C. Future work would include further improvements to the power supply and particularly the electrode design, two areas that were largely responsible for heat loss during molding.
Chapter 6 Evaluation of Injection Molded Nonconventional Optical Component

Today nonconventional optical component affords more degrees of freedom that can be used to reduce the size and number of lens, implement smart integration mechanical and optical architecture and optimize performance in optical system. However, metrology in particular is a significant bottleneck of the development of nonconventional optical component. Thus, the lack of an efficient inspection techniques for nonconventional optical components inherently hinders the its huge potential commercial application not only for in the aforementioned cost-effective production but also for the traditional cold fabrication techniques.

In this chapter, the interferometric metrology technique was extended from conventional optical component to its nonconventional counterparts by designing and adding nulling optics, particularly as a demonstration of industrial inspection and verification of molded freeform optics. A simulation of free space optical arrangement in CODE V was performed to optimize the null lens profile. Then the fabrications of the null lens and its fixture were explained in details. A micro injection molded polymer Alvarez lens with large surface variation was measured by this system. Repeatability and accuracy of this
system were tested and evaluated. Finally, the application and the prospect of this system in industrial domain were also discussed.

6.1 Alvarez lens geometry and its fabrication

As a demonstration, an Alvarez lens with a circular aperture of 6 mm was chosen as shown in Figure 6.1. The height of its surface is governed by the following equation:

\[ z = 0.019583063x^2y + 0.0062879497y^3 \]  

(10)

where \( x \) and \( y \) are the coordinates within the aperture of the lens.
A hybrid process of diamond machining and microinjection molding was developed to fabricate this freeform lens. The fabrication processes were carefully controlled to achieve high quality whose details can be found elsewhere (Sieber, Yi, Li, Beckert, Steinkopf, & Gengenbach, 2014). An optical grade polymethylmethacrylate (PMMA), Plexiglas V825, was used in the experiment. The conditions of experimental molding are listed in Table 6.1.
Table 6.1 Microinjection molding conditions

<table>
<thead>
<tr>
<th>Molding parameters</th>
<th>Values</th>
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</thead>
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<td>Melt temperature (°C)</td>
<td>250</td>
</tr>
<tr>
<td>Mold temperature (°C)</td>
<td>35</td>
</tr>
<tr>
<td>Injection velocity (mm/s)</td>
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<tr>
<td>Maximum injection pressure (MPa)</td>
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<td>Velocity/pressure switch (vol %)</td>
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<td>Packing pressure (MPa)</td>
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<tr>
<td>Packing time (s)</td>
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</tr>
<tr>
<td>Cooling time (s)</td>
<td>50</td>
</tr>
<tr>
<td>Coolant temperature (°C)</td>
<td>25</td>
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</tbody>
</table>

Because of the rheological properties and uneven cooling of the melt polymer in microinjection molding process, profile deformation on the molded parts could be a noticeable symptom. In order to accurately predict the part deformation and thus alleviate this problem, the entire microinjection molding process was simulated in the environment of a commercial FEM software package Moldex3D (http://www.moldex3d.com/en/). The freeform lens was meshed into a 3D layer-by-layer structure to accurately model the molding process. Besides the lens itself, the runner, mold base and cooling pipes were also included in the modeling. In the simulation, the material properties and molding conditions were identical with those in the real injection molding process. After finishing the numerical analysis of filling, packing and cooling stages of the microinjection molding process, the surface deformation information was obtained and exported. The difference between the simulated deformed surface and the nominal surface was recorded, which was used in an iteration of a mold surface design in order to compensate lens deformation under the selected process conditions.
6.2 Null lens design

A null lens is capable of reconstructing the distorted wavefront by varying the optical path along which the wave of light propagates. The principle behind the design is to let the wavefront of the light that is passing the tested surface return back as its originally coming way while keep the conditions of equal optical path. Due to the superposition of this nulled wavefront and the reflected wavefront from a reference surface, interferometric fringes can be observed on the imaging plane. Further, analytical measurement was enabled by phase shift technique. In CODE V, the Alvarez lens and the null lens were initially assembled in free space under afocal optical configuration. The surface profile of the null lens which was governed by a $x$ and $y$ polynomial and the distance along the optical axis between null lens and the Alvarez lens were optimized to achieve a flat or near flat wavefront by using ray-tracing method as in Figure 6.2.

![Figure 6.2 Assembly of null lens and the freeform in Code V simulation](image)
The distance at the center of the freeform lens and the null lens is 0.98 mm. The assembly was validated by the wavefront result as illustrated in Figure 6.3.

The final optimized surface is described by the following polynomial:

\[ z = A_1 \times x + A_2 \times y + A_3 \times x^2 + A_4 \times xy + A_5 \times y^2 + A_6 \times x^3 + A_7 \times x^2 y + A_8 \times xy^2 + A_9 \times y^3 + A_{10} \times x^4 + A_{11} \times x^3 y + A_{12} \times x^2 y^2 + A_{13} \times xy^3 + A_{14} \times y^4 + A_{15} \times x^5 + A_{16} \times x^4 y + A_{17} \times x^3 y^2 + A_{18} \times x^2 y^3 + A_{19} \times xy^4 + A_{20} \times y^5 + A_{21} \times \]
\[x^6 + A_{22} \times x^5y + A_{23} \times x^4y^2 + A_{24} \times x^3y^3 + A_{25} \times x^2y^4 + A_{26} \times xy^5 + A_{27} \times y^6 + A_{28} \times x^7 + A_{29} \times x^6y + A_{30} \times x^5y^2 + A_{31} \times x^4y^3 + A_{32} \times x^3y^4 + A_{33} \times x^2y^5 + A_{34} \times xy^6 + A_{35} \times y^7 + A_{36} \times x^8 + A_{37} \times x^7y + A_{38} \times x^6y^2 + A_{39} \times x^5y^3 + A_{40} \times x^4y^4 + A_{41} \times x^3y^5 + A_{42} \times x^2y^6 + A_{43} \times xy^7 + A_{44} \times y^8 + A_{45} \times x^9 + A_{46} \times x^8y + A_{47} \times x^7y^2 + A_{48} \times x^6y^3 + A_{49} \times x^5y^4 + A_{50} \times x^4y^5 + A_{51} \times x^3y^6 + A_{52} \times x^2y^7 + A_{53} \times xy^8 + A_{54} \times y^9\] (11)

where \(x\), and \(y\) are the normalized coordinates in the position within the aperture of the lens with a 3 mm normalized radius; \(A_i (i = 1, 2...54)\) are the coefficient of the polynomial whose values are listed in Table 6.2.

<table>
<thead>
<tr>
<th>(A_i)</th>
<th>Value</th>
<th>(A_i)</th>
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6.3 Machining of the null lens and its fixture

According to the design mentioned above in section 6.2, the null lens can be considered as a variation of the Alvarez lens. On the other hand, this null lens needs a more precise manufacturing process acting as a standard lens to test surface. In this research, the null lens was machined using slow tool servo on the 350 FG (Freeform Generator from Moore Nanotechnology, Inc., Keene, New Hampshire). Rotational slow tool servo process was preferred since the null lens has a similar spherical aperture as the test lens. The diamond tool has a 2.6924 mm tool nose radius that was compensated in the generation for spiral tool path trajectory. To be consistent with the test lens, the null lens was also made of PMMA, Plexiglas V825. The entire machining process was divided into two phases: rough and finishing cutting. In the former phase, the depth of cut and the pitch of spiral were 14.3 \( \mu \text{m} \) and 50 \( \mu \text{m} \). In the latter phase, the cutting depth and the pitch of spiral were 5 \( \mu \text{m} \) and 5 \( \mu \text{m} \). Figure 6.4 (a) shows the finished null lens.

![Figure 6.4](image)

Figure 6.4 Metrological components (a) the null lens (b) the fixture and a piece of Alvarez lens

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In addition, a fixture was designed to provide the convenience for operator to mount and release the null lens and thus to ensure the precision of the measurement. It was featured with one end connecting and holding the cylindrical base of the null lens while the other end engraved into the contour of the Alvarez lens to accommodate the tested lens as shown in Figure 6.4 (b). The basic features, such as stepped hole, were fabricated on a cylindrical 6061 aluminum alloy bar stock by using conventional machine tools. The contour on the end was precisely machined on a Haas VF3 vertical milling machine.

6.4 Metrology

Because of the geometrical complexity of the Alvarez lens, the wavefront coming from the surface under test has large variations over the entire measurement aperture. In turn, the distorted wavefront could barely be used to reconstruct geometry of the Alvarez lens. Even a conventional interferometer with flat reference null lens is not applicable.

6.4.1 Interferometer setup

The Twyman-Green interferometer (TGI) is an essential instrument for measuring the surface defects and properties of optics, such as planar mirrors and spherical lenses. The surface of the micro injection molded Alvarez lens inevitably deviates from the ideal designed surface due to various fabrication errors. A typical TGI metrology setup was built as illustrated in Figure 6.5. In this setup, one beam from the laser source (He-Ne laser of 632.8 nm wavelength) is collimated by a pinhole and a lens. Then this beam is split by a beam splitter into two parallel beams: one serves as the reference beam and the
other is the test beam. The reference beam is reflected by a mirror that is actuated by a piezo transducer (PZT) as the phase-shifting element. The test beam passes through a combo of Alvarez lens and the null lens and coincides with the reference beam before entering a charge-coupled device (CCD). Thus, interference fringes can be detected on the CCD, which could be used to quantitatively evaluate the surface quality of the freeform lens under test. The light intensity distribution of the interference fringes can be expressed in the equation as follows:

\[ I_1(x, y) = I_0 + I' \cos (\phi(x, y) + \phi(t)) \]  \hspace{1cm} (12)

where \( \phi(x, y) \) is the phase difference of the two beams and \( \phi(t) \) is the phase change generated by the reference beam. By using the conventional phase-shift fringe analyzing technique, the optical path deviation (OPD) can be obtained.
6.4.2 Experiments and the results

The experimental testing consists of two main parts. The initial freeform surface test demonstrates the repeatability of this metrology and the following comparison test explores the accuracy that eventually can be obtained and the feasibility to be used in industry for surface quality control.

In the evaluation of repeatability, one micro injection molded Alvarez lens, which is called freeform lens in Figure 6.5, was randomly selected. Three iterations of mounting on, testing and removal from the fixture were performed. The interval between each iteration was one minute. Figure 6.6 (a) is the mean profile of the freeform lens from the three tests. Its peak-to-valley (PV) value is 20.26 µm. Figure 6.6 (b) - (d) show...

Figure 6.5 Layout of test of a molded freeform lens using a null lens

![Diagram of test setup]

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wavefront deviations between any two different tests under the same height scale of (a). Their PV values are 5.70 μm, 5.70 μm, and 1.27 μm.

Figure 6.6 Wavefront of repeatability test (a) average wavefront of three tests, (b) wavefront difference between the first test and the second test, (c) wavefront difference between the second test and the third test, (d) wavefront difference between the third test and the first test
In accuracy test, to exclude systematic error in this setup, the simulation results mentioned in section 6.1 was introduced into this experiment to evaluate the accuracy of this metrology. According to the simulation results, we exported the wavefront difference of a theoretical designed Alvarez lens and a simulated micro injection molded Alvarez lens whose profile has some deviation from the original design as shown in Figure 6.7 (a). Its peak-to-valley (PV) value is 6 μm. Then, we tested practical micro injection molded Alvarez lenses. Three Alvarez lens samples, namely, lens 1, 2 and 3, were chosen from the same batch of micro injection molding process. After three tests, we calculated the wavefront difference between the molded Alvarez lenses and its original design. The results are depicted in Figure 6.7 (b) - (d). Both (c) and (d) have a wavefront profile deviation whose PV value is around 10 μm whereas the PV value of (d) is more than 25 μm, which indicated large defect might exist in lens 3.
Figure 6.7 Wavefront difference of a micro injection molded and theoretical designed Alvarez lenses (a) simulation result, (b) difference between lens 1 and original design, (c) difference between lens 2 and original design, (d) difference between lens 3 and original design
6.5 Discussions

According to the repeatability test, large systematic deviation was discovered in this interferometer setup as shown in the examples in Figure 6.6. The reasons for this systematic deviation are various. In addition to the random environmental factors such as temperature variations, vibration, structural deflection of the ultra-precision machine due to its weight and uneven heating, machining process variations, such as following error of tool position, also affect the final profile and finish quality of the null lens. In addition to the errors in fabrication, the misalignment of the optical components always results in performance loss. In this interferometer configuration, any misalignment from the optimal position between the nulled lens and the tested lenses could have affected the results from the measurement. In this assembly, wedge, de-centration of the lenses, tilt of the lenses in assembly and position variance along the optical axis could all have introduced errors during the testing. Last but not the least, the tested Alvarez lens could also deform in various magnitudes under different mounting forces.

In both simulation and practical measurements of the accuracy test, the significant wavefront difference occurred at the gate location as the small red regions shown in Figure 6.7. This phenomenon confirms the fact that defects are commonly located around injection gate where flow rate is the highest and fluid turbulence is complicated when melt polymer enters the mold cavity. Apart from some wavefront variance at the central areas, the measurement of lens 1 is approximately consistent with simulation result. Lens 1 and 2 share a similar wavefront difference with the simulated Alvarez lens as illustrated in Figure 6.7 (b) and (c). The mild difference on the rim could be explained
by the fluid turbulence mentioned earlier. However, there is a significant difference in Figure 6.7 (d) compared with others that demonstrates large defect might exist in lens 3. The reason behind the defect could be complicated. First of all, the fluctuation of thermal flow rate could strongly impact the final product quality. Compared with lens 1 and 2, lens 3 has a smaller thickness along the direction of the melt polymer flow, which likely resulted from erratic flow rate. Second, the environmental variation of the molding process, especially in long-term production run, could induce surface quality degradation in Alvarez lenses. These three lenses were randomly sampled from an entire batch such that the production intervals of any two lenses are unknown. Perhaps, lens 3 has a significant discrepancy mainly due to larger interval between lens 1 or 2. Next, any environmental vibration and internal flux fluctuation could also influence the final quality of the molded Alvarez lenses.

6.6 Conclusions

Quality inspection is an indispensable sector of in freeform optical manufacturing. Before wide implementation of nonconventional lenses to replace more conventional optical components in the future, adequate quality inspection of nonconventional lenses to verify the features and functionalities of the optical design objectives is urgently needed to developed to prevent defects in production. In this section, we proposed a interferometric measurement system based on null lens for high volume production quality inspection. The system that was investigated in this study is based on a Twyman-Green interferometer metrology, a low cost and flexible metrology system that can be adapted to
different measurement requirements. The null lens was identified using a commercial optical design software and afterwards it was fabricated by ultraprecision diamond machining, slow tool servo. A special fixture was also designed to assist the alignment between the null lens and the Alvarez lens and thus allow easy loading and unloading of the Alvarez lens under test. Repeatability and accuracy tests of this system were performed to validate its possibility for industrial implementation for nonconventional optical component surface inspection. Limitations and error resources of the proposed technique has also been thoroughly discussed.
References


