Fabrication of large-scale infrared diffractive lens arrays on chalcogenide glass by means of step-and-repeat hot imprinting and non-isothermal glass molding

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Abstract
In this study, a new cost-effective and high-precision process chain for the fabrication of large-scale infrared (IR) diffractive lens arrays on chalcogenide glass is proposed. First, a positive diffractive lens array is fabricated on a polymethylmethacrylate (PMMA) master substrate by employing a step-and-repeat hot imprinting process. The direct hot imprinting can transfer micro-structures from a heated mold to the polymer substrate accurately. Repeating the hot imprinting process along a predetermined path, the desired diffractive lens array is obtained. Unlike photolithography and electron-beam writing, which are expensive technologies with sophisticated process steps, the hot imprinting is an easier, cheaper, and more eco-friendly method for fabricating diffractive features with continuous profile. Afterwards a casting process is applied to create a polydimethylsiloxane (PDMS) mold with negative features. The diffractive lens array is successfully transferred from the master substrate to the PDMS elastomer, which is used as a mold in subsequent precision glass molding. Finally, microstructures on the PDMS mold are replicated to the chalcogenide glass by non-isothermal glass molding. In this process, the PDMS mold and workpiece are set at different temperatures. Specifically the PDMS mold at low temperature maintains enough rigidity to press the features onto the softened chalcogenide glass, which is kept at a relatively higher temperature, resulting in a replica of high-fidelity diffractive lens array on the chalcogenide glass. Surface profiles and optical performance of the fabricated components are characterized quantitatively. Results showed that large-scale diffractive lens array can be successfully fabricated on chalcogenide glass by this proposed process chain with high quality and integrity.

Keywords Chalcogenide glass · Diffractive lens array · PDMS mold · Hot imprinting · Non-isothermal molding

1 Introduction

Diffractive lens arrays are important optical components in various applications, such as integral imaging, concentrator photovoltaics, and LED lighting [1–4]. The diffractive lens arrays are usually composed of a same diffractive lens feature in multiform arrangements. The focusing and imaging performance of diffractive lenses depend on the form accuracy and surface finish of its feature. Many methods for manufacturing of diffractive lens arrays have been extensively investigated, including laser direct writing [5–7], focused ion beam [8], and photolithography [9]. By increasing the number of orders, the optical properties of the multiorder diffractive optical elements fabricated by lithography can be improved. However, due to the influence of the straight edge diffraction in binary structure, light cannot be fully concentrated in the far field. Thus, in practice, the focusing ability obtained by discrete (step) profile cannot be compared with that of the continuous (smooth) profile. The continuous profile can be machined by laser direct writing and focused ion beam technology [6], but the pursuit of surface quality while maintaining a high machining efficiency in those processes proves to be challenging. In general, most of these techniques require expensive equipment and involve complicated process steps; in addition, these processes are usually time consuming as well. Accordingly, they are not the perfect solutions for manufacturing large-area
diffractive array optics, particularly those lenslets with intricate shapes and continuous profiles.

Precision molding is a high-efficiency and low-cost manufacturing process, suitable for optical elements at both macroscopic and micro/nano scale [10, 11]. It is becoming a promising alternative for high volume production of plastic and glass optics. In precision molding, both geometrical accuracy and surface quality of the workpieces are largely determined by the molds. Therefore, it is critical to fabricate the precision master molds with inverse microstructures. At present, material removal methods, such as precision grinding, polishing, and diamond turning, still play a dominant role in mold fabrication. Hard materials, such as metals (e.g., Ni, SiC, and WC), are usually the popular choices for precision molds for their excellent physical properties and inert chemistry at high temperature. However, the higher the hardness a material has, the more difficult its machining process is. Especially for large areas containing micro and nano-scale structures, the uniformity of the entire array is difficult to maintain due to tool wear. In addition, fabrication of intricate microstructures with sharp angles on hard materials, such as the diffractive lens array in this study, is also a technical challenge using existing manufacturing processes [12, 13]. These issues limit the wide applications of precision compression molding in replicating high resolution and complex surfaces.

These limitations of the hard material mold in machining, in principle, can be overcome by using soft material molds. Recently, PDMS, one of the soft material molds, has been adopted as the mold for precision molding for its simple, mature, and low-cost manufacturing process, as well as the flexible mechanical properties [14, 15]. Compared with hard materials, PDMS has the following advantages as a mold: (1) PDMS can be easily obtained over large areas with good reproducibility and high accuracy, by casting a liquid onto a master substrate followed by thermal curing. (2) PDMS has low surface energy, which promotes separation from the workpiece, and prevents damage to the workpiece during separation stage. (3) A PDMS mold is also less sensitive to surface defects and contamination. However, PDMS, when used as a precision mold, also encounters some problems. The first one is the difficulty of fabricating master substrate with large-area intricate features. Inkjet printing technologies is a popular flexible fabrication method of microlens array, but the structures of the microlens are limited to spherical and aspheric shapes [16]. Other batch technologies, including photolithography, e-beam lithography, and wet-etching process [17, 18], are good at creating complex features with high precision. However, these processes are relatively complicated and time consuming. For example, repeated exposures with multiple masks are required for lithography process in order to secure the accurate construction of binary structures. The second one is the rigidity of PDMS. PDMS is softer than that of chalcogenide glass at room temperature, and its hardness decreases with the increase of working temperature [19]. Although the rigidity can be improved by changing the components of pre-curing PDMS [20] and adjusting the processing parameters of PDMS, such as mixing ratio [21], curing time, and thermal aging temperature [22–24], these enhanced methods have limited performance improvements. In addition, by increasing the molding temperature [25], the workpiece can be softened to the point that it can flow into the mold cavities without much pressure. As expected, the deformation of the PDMS mold was almost avoided in the molding stage under this condition. However, high temperature sometimes leads to loss of sulfur elements in chalcogenide glass [26], which directly affects the optical properties of the lens. The higher the working temperature, the shorter the lifespan of the mold. As such in the current research using PDMS as mold, most workpieces are limited to plastic material, such as PMMA and polycarbonate (PC) [15, 27, 28]. An attempt to imprint a bulk chalcogenide glass at 225 °C resulted in only partial feature transfer, and the imprinted depth was less than a half of the mold feature height [25]. Although full transfer of features on chalcogenide glass was realized by increasing molding time [29], the PDMS molds need to be pressed and kept for 2 h at 200 °C. In such an environment, the lifespan of the PDMS molds may be considerably shortened. Therefore, although the existing manufacturing methods can replicate the features of the PDMS mold onto chalcogenide glass, a new manufacturing process with better energy efficiency, stable, and longer life of the mold is required for industrial applications.

Focusing on the above problems, in this research, a non-isothermal molding technology for fabricating large-scale complex microstructures on chalcogenide glass by PDMS soft molds was investigated. As compared to the hard molds normally used in glass molding processing, this design allows a faster cycle time while maintaining high replication precision. This new process addresses one of the issues associated with PDMS soft molds, namely, the difficult nature of filling the mold completely due to its tendency to deform in the molding process. Three major process steps are needed in the proposed process chain: the first step is the fabrication of a diffractive lens array on plastic master substrate used in hot imprinting. A single diffractive feature with continuous profile is machine on a brass mold by diamond turning. The continuous profile diffractive feature is copied completely to the polymer substrate by hot imprinting consecutively until the entire lens array is obtained. The direct hot imprinting ensures that the continuous feature of the mold is replicated with high fidelity, and the accuracy of the entire array can be guaranteed by the stability of imprinting temperature and high motion accuracy of the servo platform. At the end of this process, an optical PDMS mold is generated by pouring uncured PDMS into the master substrate followed with curing. Lastly, the diffractive lens array is fully replicated on chalcogenide glass using non-isothermal glass molding. The non-isothermal molding
process allows the PDMS mold to maintain enough rigidity at lower temperature, to press into the softened chalcogenide glass at relatively high temperature. To demonstrate the feasibility of the proposed process chain, a 30 \times 30 square diffractive lens array was fabricated on As$_2$S$_3$ glass. Each fabrication step and the quality of the molded lens arrays are carefully described throughout the whole process chain. The results showed that the proposed method has the potentials for manufacturing optics elements with better optical performance and a much lower cost and higher efficiency.

## 2 Material and method

Materials and methods of the entire process chain are illustrated in this section. The material of the master substrate is PMMA, a material with a low transition temperature, suitable for large area hot imprinting. Chalcogenide glass used in the experiment is AMITIR-6 (As$_2$S$_3$), and the PDMS prepolymer is prepared from an elastomer kit (Sylgard 184, Dow Corning). The thermal and mechanical properties of PMMA, PDMS, and As$_2$S$_3$ are listed in Table 1.

The whole process chain is illustrated in Fig. 1. (a) First, a single diffractive optical surface is machined using diamond turning on a brass cylinder, which is used as the master mold for subsequent imprinting. Afterwards, the step-and-repeat hot imprinting is introduced to duplicate the diffractive feature of the mold repeatedly on the polymer substrate, creating a diffractive lens array on PMMA master substrate. (b) The diffractive lens array on PMMA master substrate is then transferred successfully onto the PDMS mold by using a casting process. (c) Non-isothermal precision glass molding is used to replicate the entire microstructures form the PDMS mold to chalcogenide glass.

### 2.1 Step-and-repeat hot imprinting

The PMMA master substrate was fabricated by using step-and-repeat hot imprinting. In this process, a brass mold was first machined by single point diamond turning using a half-radius tool, as shown in Fig. 1a and b; a continuous surface diffractive feature with negative focal length was obtained on the surface of the brass mold. The overall dimensions of this diffractive feature are 1.2 \mu m in height and 1 mm in diameter. Then, the continuous profile diffractive feature was copied completely to the polymer substrate by imprinting consecutively until the entire array is obtained. As shown in Fig. 2, the imprinting process of the diffractive lens array was conducted on an ultraprecision 5-axis CNC turning machine. A self-developed imprinting device was mounted on the tool post, while a polymer substrate was clamped on the center of vacuum chuck.

The self-developed imprinting device consists of a brass mold, a band heater, an insulation washer, and a mounting bracket, as shown in Fig. 2c. The band heater is fastened to the outer surface of the brass mold. Heat generated by the band heater can be transferred quickly to the mold through surface contact. Between the mold and the mounting bracket is an insulation wafer, which is used to prevent heat spreading from the mold to the tool post. A K-type thermocouple installed on the brass mold next to the heater measures and sends temperature data in real time to a solid-state temperature controller. Using the temperature controller, the imprinting device can achieve rapid heating and closed-loop control of temperature in real time during hot imprinting process. In addition, there is no force sensor designed in our self-developed imprinting device. Instead position control rather than imprinting force is used to complete imprinting process. The reasons for not considering imprinting force are as follows: from experience, the force for imprinting micro-scale features on PMMA material is very small, and this has been verified by the smooth current fluctuation in the feedback signal on the Z-axis drive. In addition, Z-axis feedback resolution is 8.3 nm, critical to achieving precision imprinting of microstructure features. As such the forming force during the imprinting process was not monitored.

The fabrication procedure works for diffractive lens array as follows: first, the brass mold temperature is heated to 130 °C by the band heater, while the PMMA substrate is maintained at room temperature. The heated mold structure is then pressed into the PMMA substrate surface. After one diffractive lenslet was imprinted, the PMMA substrate moves along the X and Y axes to the next position for the next lenslet fabrication. By repeating the above process 900 times, a 30 \times 30 square diffractive lens array is then obtained on the PMMA substrate. To ensure that microstructures are fully filled often requires higher imprinting depth, higher temperature, or longer holding time, which may soften the PMMA material. Raising molding temperature and increasing holding time usually result in deterioration of the temperature field in the surrounding area, which will inadvertently affect the deformation of other lenses. Therefore, the method of increasing

### Table 1  Material properties needed for this research

| Material properties | PMMA  | PDMS  | As$_2$S$_3$ |
|---------------------|-------|-------|-------------|
| Density, $\rho$/(kg·m$^{-3}$) | 1.190 | 965  | 3,200       |
| Elastic modulus, $E$/Pa  | 3.3E+9 | 1.50E+6 | 1.58E+10   |
| Poisson’s ration, $\nu$ | 0.3   | 0.3   | 0.24        |
| Thermal conductivity, $k_c$/[W·(m·k)$^{-1}$] | 0.19 | 0.15 | 0.167       |
| Coefficient of thermal expansion, $\alpha$ | 6.0E−05 | 9.6E−04 | 2.14E−05 |
| Specific heat, $C_p$/(J/kg°C) | 1,466 | 1,460 | 456.36      |
| Transition temperature, $T_g$/°C | 105  | 180  | 208         |
| Softening point, $S_f$/°C |       |       |             |
imprinting depth was adopted in this case. Specifically, imprinting depth of 2 \( \mu m \) is the result of multiple tests of the process parameters. Relevant hot imprinting parameters are illustrated in Table 2. These parameters have been optimized based on previous hot imprinting experiments [30]. Furthermore, the hot imprinting process is carried out at room temperature, and the polymer substrate does not need to be heated and cooled repeatedly, which greatly reduces the thermal cycle time, demonstrating that the proposed process for fabrication of large-scale diffractive lens arrays on polymer substrate is robust and cost-effective.

2.2 PDMS casting

PDMS has been tested as a versatile and low-cost mold material. PDMS has stable mechanical properties. To create a
flexible mold for precision glass molding, a casting process is formulated to generate the PDMS mold, and the imprinted PMMA master is used as the casting substrate. PDMS prepolymer was prepared from an elastomer kit (Sylgard 184, Dow Corning), which consists of a prepolymer base (part A) and a crosslinking curing agent (part B). Relevant process parameters are illustrated in Table 3. Detailed casting process is as follows. First, mix two parts in a beaker thoroughly for 5 min. The ratio of the two parts is 5:1 as recommended for high rigidity and hardness [21]. Fully mixed liquid PDMS was poured directly into the PMMA master substrate to form a negative replica of the microstructures. A circular frame was attached to the PMMA substrate serving as a boundary to form the PDMS mold into a disk shape and also prevent leakage during curing. The PDMS mold was thoroughly degassed in low vacuum for 20 min until bubbles were completely removed. The PDMS mold is then cured using a precision furnace with temperature control. Since the mechanical properties of PDMS are largely determined by the curing temperature and time, to achieve better rigidity and hardness, the operating temperature of 150 °C and a curing time of 10 min are chosen as the curing parameters [22]. Finally, a cured PDMS mold, patterned with diffractive lens array features on one side, was separated from the PMMA master substrate.

### 2.3 Non-isothermal precision glass molding

After the PDMS mold is completed, the next step is to copy the microstructures on the PDMS mold to chalcogenide glass. The Young’s modulus of PDMS is around 2.59 MPa at room temperature [19], which is lower than conventional polymers. This value will significantly decrease with the increase of working temperature. Therefore, it is a challenge to ensure that the features of the PDMS mold are completely pressed into the glass substrate. In view of this, a non-isothermal molding process is proposed. The workpiece and the mold are set at different temperatures. The PDMS mold is kept at a low temperature to maintain a higher stiffness and lower thermal expansion rate, while the workpiece is heated to a higher temperature, above its transition temperature for molding. Stiffer molds will have less deformation hence improve replication fidelity. The mold at lower temperature is then pressed on the glass substrate that was kept at a higher temperature, completing the transfer of the surface features. Due to the low thermal conductivity of PMDS and glass material, as well as the short molding time for micro-scale structures, thermal exchange in the contact interface between glass and mold during molding stage remains low. In addition, vacuum in the molding chamber impedes convection heating, which helps slow down temperature changes in glass and mold. As expected, the small temperature difference between mold and glass does not have much effect on the rigidity of PDMS mold and the viscosity of the glass. The microstructures of PDMS mold can be replicated to the glass substrate with high integrity as demonstrated next.

The feasibility of this method is tested by molding a 30 × 30 square diffractive lens array from PDMS mold to chalcogenide glass. The experiment was conducted on a precision glass molding machine (OSU-PGM100), as shown in Fig. 3. The molding device consists of a rapid heating unit, a loading unit, and a cooling system. The device can be operated under vacuum or with nitrogen. The heating unit in this press is divided into upper and lower heating components; the mold and workpiece are mounted in the middle of the upper and lower heaters. The lower heater is fixed while the upper heater can move vertically with the pressure loading system to work with different thickness of the workpieces. Heating is provided by ten cartridge heaters with a total power of 5,000 W. Equipped with precise thermocouples and a temperature controller, the rapid heating system can achieve real time closed-loop temperature control in a wide range from 26 to 900 °C, with an accuracy of 0.1 °C. An integrated linear actuator provides loading pressure for smooth vertical movement of the upper heater with a micron-level position control. The maximum load is 3,800 N. In addition, the pressure loading system combines the bidirectional force sensor and the linear optical encoder to realize dual closed-loop control of position and pressure. The molding device constructed with the above configuration is capable of molding optical elements of various shapes and materials.

The implementation steps of non-isothermal glass molding are as follows: first, the PDMS mold is fixed in the center of the upper heating plate, and the As₂S₃ glass is installed in the lower heating plate directly below the mold. A vacuum pump is used to purge the working area, and temperatures of the upper and lower heating plate are heated to 150 and 200 °C, respectively.
Second, after the PDMS mold and the As$_2$S$_3$ glass preform are heated to the designated temperatures, the upper mold is slowly pressed into the glass sample at a speed of 0.5 $\mu$m/s and a displacement of 1.2 $\mu$m under position control. The maximum molding force was 200 N. Finally, when the molding force reached to a stable value, the mold was moved upward and slowly separated from the glass. Subsequently, the microstructures on the PDMS mold are replicated to the As$_2$S$_3$ glass. Relevant non-isothermal molding parameters are illustrated in Table 4. In addition, to reduce possible damages to the PDMS mold, firstly, the physical and mechanical properties of the mold were improved by optimizing the compound ratio, curing temperature, and other parameters in the preparation of the mold as mentioned before. Secondly, in the process of performing non-isothermal molding, low mold temperature and short molding time are beneficial to minimizing the damage of the PDMS mold. In the future, the PDMS mold can also be coated with a nanoscale protection layer to further improve its heat insulation and wear resistance.

3 Results and discussion

3.1 Characterization of the PMMA master substrate

The feasibility of the step-and-repeated hot imprinting process was demonstrated by generating a large-scale diffractive lens array on a PMMA substrate. The photographs of the brass mold and the imprinted PMMA master substrate are shown in Fig. 4a and b, respectively. In Fig. 4b, a 30 × 30 diffractive lenslets is closely aligned in the form of a square on PMMA substrate. And the central regions of the patterns are captured by optical microscope and shown in Fig. 4c. The outer edge of each lenslet is adjacent immediately to that of the others, showing a high spatial filling rate. The diffractive lens array is fully formed; no visible scratches, damage, deformation, and incomplete features were discovered on the surface. It indicates that a uniform diffractive lens array covering the relatively large area is formed on PMMA by the hot imprinting process.

To investigate contour replication accuracy of the imprinted lenslets, the microstructure on the brass mold and an arbitrary lenslet from the PMMA microlens array are captured by white-light interferometer (Wyko NT9100, Bruckner, Tucson, AZ, USA), and the corresponding 3D structures are shown in Fig. 5a and b, respectively. As shown in the figures, the diffractive lens on the brass mold has a negative focal structure, while the lenslet on the PMMA master substrate has a positive (or inversed) focal structure. Both of the lens surfaces are very smooth without breaks or steps, showing the advantages of the imprinting process over the existing material removal process. Furthermore, the central cross-section profiles on brass mold and PMMA master substrate (in Fig. 5a and b) are measured and compared, as shown in Fig. 5c. In the comparison figure, the height of the central

| Parameter | Value |
|-----------|-------|
| Imprinting material | As$_2$S$_3$ |
| Temperature of the PDMS mold, $T_m$ | 150 °C |
| Temperature of the As$_2$S$_3$ substrate, $T_w$ | 200 °C |
| Heating rate, $v_h$ | 3 °C s$^{-1}$ |
| Imprinting rate, $v_i$ | 0.5 $\mu$m s$^{-1}$ |
| Imprinting depth, $d_i$ | 1.2 $\mu$m |
Curvature and outer prism edges on the lenslet are $1.20 \pm 0.05 \, \mu m$, matching the mold geometry well. The deviation between brass molds and molded lenslet is within $0.05 \, \mu m$. The profiles along the A-A direction have a good agreement with that of along the B-B direction, showing a good imprinting quality.

To evaluate the uniformity of the imprinted diffractive lens array, an arbitrary set of $2 \times 2$ lenslets on the PMMA substrate is further examined. Figure 6a shows the 3D structure on the PMMA master substrate. The diffractive lenslets, which have the same microstructures, are uniformly distributed on the view. There is no obvious deformation or defects on the array. Although a portion of the material in the outermost area of the lenslet is raised due to the extrusion of the mold during imprinting, the convex area is very small, accounting for a small proportion of the lens, so the effect on the optical performance is negligible. Figure 6b presents the corresponding profile along the A-A direction (in Fig. 6a). The height of the lenslet is $1.2 \pm 0.05 \, \mu m$ with $1 \pm 0.01 \, mm$ diameter. The distance between two successive lenslets is also $1 \pm 0.01 \, mm$. The diffractive lens features, including central circle and nine concentric grooves, are continuous, complete, and symmetrical, showing that the well-defined diffractive feature with continuous profile can be obtained by the step-and-repeated hot imprinting process.
3.2 Characterization of PDMS mold and chalcogenide glass

PDMS casting process is a mature technology with high replication accuracy. The contour error between PMMA master substrate and the PDMS mold can usually be predicted and compensated. Therefore, the molding quality of non-isothermal molding process is mainly discussed here, and the characteristics of the PDMS mold and molded chalcogenide glass are analyzed in detail. Figure 7a and c shows the photographs of PDMS mold and chalcogenide glass, respectively. The corresponding central regions of the patterns are captured by optical microscope with a magnification of 5× (shown in Fig. 7b and d, respectively). The structures on chalcogenide glass are clear, complete, and consistent, and the arrangement of the lenslets is also consistent with the PDMS mold, which visually shows a high molding quality.

To investigate the contour replication accuracy quantitatively, an arbitrary set of 2 × 2 diffractive lens arrays are extracted from the PDMS mold and chalcogenide glass by using the Wyko optical interferometer profiler, respectively. Similar to the aforementioned profile measurements, the corresponding 3D structures are illustrated in Fig. 8a and b, respectively. In these figures, diffractive features are complete and clear, and have a good consistency. Fig. 8c plots the profiles of the central region of the lens array by both PDMS mold and chalcogenide glass along the radial direction. The lenslet features on both surfaces consist of a central circle and nine concentric rings, showing a perfectly continuous topography. The height of the central region of the glass lenslet is about $1.15 \pm 0.05 \, \mu m$, slightly lower than that of the PDMS mold. It indicates that the PDMS mold still has a very small deformation under the molding pressure, although the adoption of non-isothermal molding process has improved the overall rigidity of the PDMS mold. Some of the grooves are also slightly less than $1.2 \, \mu m$ in height, and there is some bending on the glass surface, resulting in a $0.1-\mu m$ discrepancy between PDMS mold and chalcogenide glass. Several reasons may have contributed to this result: the main reason for the difference is that the thermal stresses caused by the non-
Isothermal temperature distribution resulted in slight shrinkage in the lenslets. Since the difference is consistent through the entire lens surface, it can be compensated by offsetting the PDMS mold by a small amount before molding.

Furthermore, in order to evaluate the form accuracy of the lenslets on chalcogenide glass, an arbitrary lenslet is extracted from Fig. 8b. The corresponding 3D structure of the lenslet and the 2D profiles are illustrated in Fig. 8d and e, respectively. PDMS mold and chalcogenide lens profiles match well with each other, showing no distortion in the lenslet. And the resulted geometrical errors are less than 0.1 μm. In addition, there are still some protrusions at the junction of the lenslets, as shown in Fig. 8f. These protrusions are originally derived from the imprinting process and then transferred to the glass through the casting and molding process. The height of the protrusions on the glass was measured to be approximately 2 μm. Although these protrusions are higher than the lens height, they are located outside of each lenslet’s clear aperture therefore considered safe for optical performance. In general, the continuous morphology and complete groove features of the array indicate that the soft PDMS mold features can be completely copied to chalcogenide glass by non-isothermal compression molding.

3.3 Optical setup and measurement

To evaluate the shape uniformity and the focusing function of the diffractive lens array on chalcogenide glass, an optical setup was built. As shown in Figure 9, it consists of a blackbody infrared source (HawkEye Technologies, Infrared Source IR-35, Milford, CT, USA), a pair of polarizers, the molded diffractive lens array, and an infrared camera (Lynelby Sofradir & ULIS, Avenue de la Vauve, Palaiseau, France). The light source, whose wavelength range is around 6–14 μm...
based on the input power, provides a collimated infrared light beam using a parabolic reflector. During the experiment, the input power to IR-35 was controlled so that the wavelength generated by the light source is around 8 \( \mu \text{m} \), the working wavelength of this lens array. To prevent possible damage to the infrared camera, two polarizers were used to reduce the infrared beam intensity. The molded diffractive lens array was placed after two polarizers to focus the incident light on the IR camera’s image plane. The spot pattern of the diffractive lens array and the focal point light intensity distribution of a randomly selected row of microlenslets are shown in Fig. 10a and b, respectively. In the picture, the focal spots are clear and evenly distributed. The lens array successfully focused the incident plane waves into many convergent spherical waves. During the experiment, some background noise was observed in the spot pattern. The main reason is that the microlens array works in long wave infrared band. Objects in the testing environment, including the sensor itself, are sources of the background noise. Figure 10b shows that the focal spots still possess good intensity profiles despite the background noise, which validates the focusing ability of these diffractive lenses with continuous surfaces.

The design of each zone of the diffractive lens was based on chalcogenide glass molding process. For visible diffractive lens array, the focus efficiency of each lens may reduce; therefore, this process may not be a good candidate. A possible solution is to develop an achromatic harmonic diffractive lens array, which has a large geometry scale and supports multiple working wavelengths with a lower chromatic aberration, to replace the original diffractive lens array.

4 Conclusions

This paper provides a new manufacturing method by combining step-and-repeat imprinting, PDMS casting and non-isothermal glass molding for fabrication of large-scale diffractive lens array. A square 30 \( \times \) 30 infrared diffractive lens array on chalcogenide glass was successfully obtained. Each diffractive lenslet consists of nine concentric prism rings, all of which are maintained at a height of 1.2 \( \pm \) 0.05 \( \mu \text{m} \). In addition, each lenslet has a nearly perfect continuous profile, which matches well with design. Moreover, the step-and-repeat imprinting method offers an economical, environmentally friendly, and high-quality manufacturing choice for creating complex feature array on polymer substrates. The non-isothermal molding makes it possible to transfer microstructures from the soft mold (PDMS) to hard substrate (As\(_2\)S\(_3\) glass, becomes softer at molding temperature) with high fidelity. The entire process time of the non-isothermal molding is less than 15 min (including heating for 2 min, soaking for 4 min, pressing for 5 s, and cooling for 8 min). It is five times more efficient than the conventional molding process and can be further shortened with more process improvements. Finally, the optical properties of As\(_2\)S\(_3\) glass were evaluated using an optical testing setup. Optical performance of the infrared diffractive lens array demonstrates a promising high precision and low-cost process.

For future work, the protrusion in the outermost area of lens can be reduced by optimizing the process parameters to keep all of the diffractive features to design, so as to further improve molded diffractive lens array’s optical performance.

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Declarations

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