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# Diamond turning and soft lithography processes for liquid tunable lenses

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**Abstract**
Making use of the capability of high precision diamond turning in producing 3-dimensional free form optical surfaces with excellent surface finish, molds for various types of liquid tunable microlenses are fabricated. Subsequently, a rapid prototyping process known as soft lithography is applied to the fabricated mold to replicate multiple lens structures. This method provides an efficient and reliable way of generating rotationally symmetric free form optical surfaces that are otherwise difficult to produce with conventional methods such as lithography and etching methods. Using atomic force microscopy, white light interferometry and a mechanical profiler, it is verified that the surface quality and dimensional accuracy of the replicas are preserved. We demonstrate the practical usefulness of the proposed fabrication methods by developing and experimentally testing three different liquid tunable lenses, namely (1) a diffractive/refractive hybrid lens that reduces chromatic aberration within the visible spectrum, (2) a double focusing lens and (3) an aspherical lens that minimizes spherical aberration.

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Producing three-dimensional (3D) free form surface relief is important in the field of optics, especially when the demand for optical quality and versatility continue to increase. At the same time, optical systems are continuing to strive for compactness, with many working with light sources that can range from x-rays to IR [1–5]. This drives the active research on microlenses, which increasingly requires design of free form surface relief to optimize the optical performance of the lens systems targeted for a specific application. Applications that have benefited from the use of free form optical surfaces include beam shaping [6–8], imaging systems [9, 10], optical data storage systems [11, 12] and aberration reduction [5, 13–15]. In many instances, free form optical elements can also reduce lens count, thereby enabling the miniaturizing of optical systems.

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There are a number of fabrication methods that have been developed to fabricate free form micro-optical elements. Among them is a method that makes use of selective wet etching on a boron-doped silicon substrate [16]. Alternatively, lithography and etching techniques can be used to fabricate micro-refractive [17] and micro-diffractive lenses such as Fresnel lens [3, 18, 19]. If binary optic masks are used, stepped profiles will result. Each time the number of phase levels is doubled with an additional cycle of photolithography with a binary optic mask, there is a mask alignment error introduced [20]. Thus, to keep the alignment error within a reasonable limit, the number of phase levels fabricated has to be small. This in turn limits the efficiencies of the lenses. The use of gray scale masks and high-energy-beam-sensitive (HEBS) glass has provided alternatives that address some of the fabrication issues associated with binary optic masks. In contrast to binary optic masks, the use of gray scale masks and HEBS requires just a single exposure-etching process to produce multiple phase levels that can closely approximate continuous profiles. There is also a research team that modified the conventional lithography cum etching method to produce various structures with sloping walls. Instead of using a stationary mask, the team put the mask in continuous motion during UV exposure [21]. By taking into consideration the motion of the mask, the light propagation characteristics and variation in refractive index across the depth of the photoresist it is possible to design various 3D structures with smooth continuous profiles. Other alternatives developed include excimer laser ablation techniques which can be used to write 3D lens structures on polymeric substrates [22]. Photoresist thermal reflow methods have also been successfully implemented to produce various lens structures that can achieve high fill factors [23, 24].

Thus far, the fabrication methods discussed all involve clean room processes which use non-contact methods such as lithography and laser ablation to define the lens structures. There is another class of fabrication process that uses mechanical methods to produce 3D microstructures. Single-point diamond turning (SPDT) and diamond shaping are prominent examples. Typically, with the use of either high frequency response piezoelectric actuators for a fast tool servo [25] or mechanical slides with a feedback response for a slow tool servo [26], diamond turning processes can be very precisely controlled. With the proper selection of rotational speed, feed rate, depth of cut, geometry of the diamond tip on the cutting tool and substrate material, microstructures with surface quality suitable for optical purposes can be fabricated with diamond machining methods [15, 27].

There has been increasing emphasis on variable focusing lenses as many optical systems now require dynamic tuning to sense and acquire data. Most of the liquid tunable lenses in the literature focus on developing different methods to improve the actuation methods and frequency response of tunability. For instance, the electrowetting effect has been used to change the surface energy and hence the radius curvatures of liquid lenses on dielectric surfaces and capillaries [28, 29]. There is also a type of liquid lens that makes use of pressure to harmonically oscillate a liquid lens to improve the response times [30]. Alternatively, liquid pressure can be used to deform an elastic membrane of either uniform [31, 32] or radially varying thickness [33, 34].

Here we present a fabrication process that combines diamond machining and soft lithographic replication to produce various liquid tunable lenses. Instead of solely focusing on the design of the actuation method of liquid lenses, there are also special considerations to enhance targeted aspects of optical performances of the liquid lenses. We demonstrate that it is possible to exploit the main strengths of the diamond machining technique, which are its versatility in fabricating genuine 3D free form structures and the precision in dimensional control, to generate continuous optical surface relief in combination with liquid tunability capabilities with an elastomeric membrane.

## 2. General structure of the tunable liquid lenses

Figure 1 shows the overall design of the liquid lens proposed in this work. It consists of a cylindrical lens cavity which has a certain lens profile of interest integrated on its bottom surface. On both sides of the lens cavity are narrow and long liquid channels, one acting as an inlet and the other acting as an outlet. This structure is hermetically sealed by a thin and elastic film of polydimethylsiloxane (PDMS) with only two small holes punctured above the ends of the liquid channels to allow the delivery of liquid from an external source to the lens cavity. When distilled water, the working liquid of choice, is pumped into the cavity, the uniform pressure created will deform the PDMS film and that constitutes the tunable liquid refractive lens.

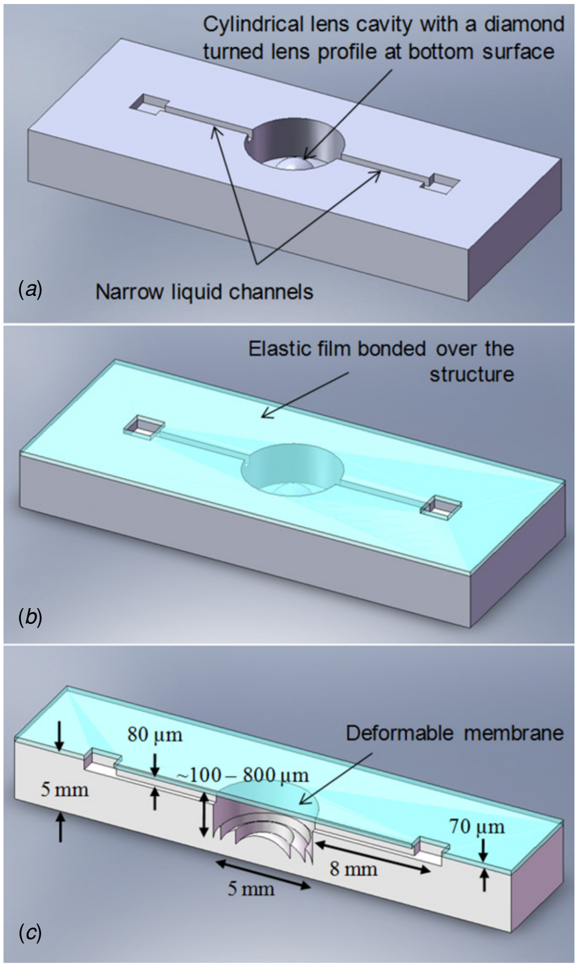


**Figure 1.** The overall device consists of two parts. (*a*) The first is a thick slab of PDMS consisting of a lens profile of interest, a lens cavity and two liquid channels. (*b*) The second part is a thin film of PDMS bonded over it. (*c*) A cross-sectional view of the device with the approximate dimensions of the structural features.

The deformation of the PDMS film is subjected to a fixed boundary condition due to the permanent bonding of the film to the slab. As a result, the deformation does not follow an exact spherical shape. Nevertheless, as a rule of thumb, if only within 80% of the central region of the lens is considered, it can be safely assumed that the deformation is spherical [35]. Moreover, considering the small thickness–diameter ratio of the elastic film used in this work, there is little rigidity at the circular boundary. An 80% or smaller aperture is used in the experiments carried out in this work to ensure that the boundary effects do not affect the experiments.

The tunable refractive lens, together with the lens integrated at the bottom of the cavity, form an optical lens system that can be designed to improve imaging qualities over a range of focal lengths. The actuation of the liquid lens involves the pumping of just one liquid. Although in the experiments of this work a digitally controlled syringe pump was used to control the volume of injection, pressure sensors could be used to tune the focal length of the liquid lens instead, as demonstrated in [36, 37].

There are a number of advantages of using diamond machining techniques to fabricate molds of liquid lens devices of such a design as indicated in figure 1(*c*). Firstly, the feature sizes of the lens device range between the orders of micrometers and millimeters. The aspect ratios of the different features are also vastly varied. Devices with these characteristics typically cannot be easily fabricated with the use of lithography and etching techniques. Moreover, these techniques would not be able to efficiently remove the large volume of material that is required to create the cavity that can be as large as 12 mm in diameter and 800 $\mu$m in depth. The large depth of the lens cavity is sometimes necessary to accommodate an optical surface that has large height variation across its diameter. In addition, it is also likely that the walls of the cavity could not be vertically etched for depths in that range. In contrast, the versatility of diamond machining enables it to create such features with ease without compromising the surface integrity and dimensional accuracy. The depth and size of the structure fabricated by diamond turning are limited only by the geometry and size of the diamond tip on the inset, which is typically in the order of a few hundreds of microns to a millimeter.

The rotationally symmetrical lens cavity and the integrated lens profile are generated by diamond turning while the rectangular liquid channels are produced by the shaping process. To ensure affordability and efficiency of the fabrication process, a rapid prototyping method known as soft lithography is used on the diamond machined mold. It is a replication process that utilizes an elastomeric material to replicate structures with features as small as in the nano scale with high reliability [38]. Because soft lithography preserves the main strength of diamond machining, which is the tight dimensional control that accompanies the generation of 3D surface relief, the two processes complement each other well.

Apart from being able to achieve rapid replication, there are other advantages of combining soft lithography with PDMS and diamond turning on a rigid PMMA plate. Any cutting tool has a limited tool life and toward the end of the tool life, there might be geometrical changes on the tool tip that affect the dimensional accuracy of the machining and surface quality of the work piece produced. Thus, it would be advantageous to first fabricate a high-quality lens device on a rigid substrate with diamond machining before using the soft lithographic process to obtain multiple replicas. This method enables a larger number of usable lens devices to be produced within the inset's tool life.

In addition, hermetic sealing can be easily achieved between a PDMS replica and a PDMS membrane with the use of oxygen plasma, which gives the proposed fabrication flow process an added advantage.

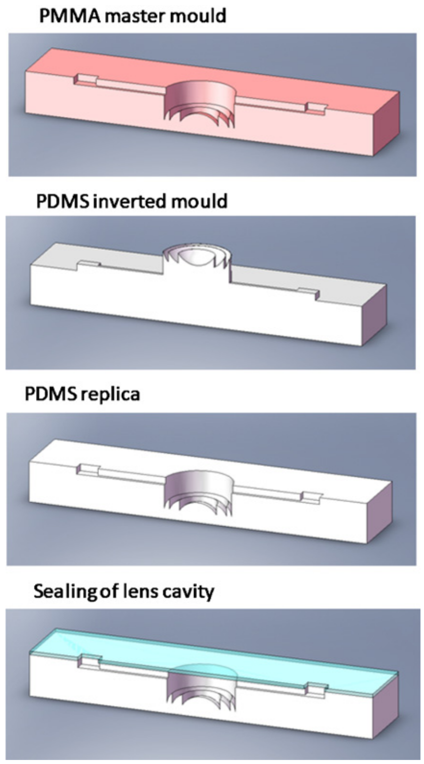


**Figure 2.** The cross-sectional views of the tunable lens device at each stage of the fabrication process are shown. Firstly, diamond turning of a certain lens profile and cavity on a PMMA substrate was carried out. After shaping of liquid channels, the PMMA mold was completed. After a cycle of soft lithography, a PDMS inverted replica was obtained. The desired PDMS device was obtained after a second cycle of soft lithography. A PDMS membrane was bonded to the slab of PDMS replica, sealing the cavity. Holes are punctured at the ends of the liquid channels to enable the pumping of the refractive lens.

## 3. General fabrication process flow

Here, three different types of liquid lenses will be presented. The general structures of the lenses are all similar to those shown in figure 1 and so are the fabrication processes. The only difference between them is the integrated lens profile generated by diamond turning at the bottom of each lens cavity. The three different integrated lens profiles explored in this work are namely (1) a diffractive Fresnel lens, (2) a double focusing lens and (3) an aspherical lens.

The proposed general fabrication process flow, as summarized in figure 2, combines high-precision single-point diamond machining on a polymethylmethacrylate (PMMA) substrate and the soft lithographic replication process with an elastomeric material known as PDMS. Firstly, the required mold has to be produced by diamond machining methods. The reverse of the mold will be replicated through a cycle of soft lithography and that serves as a PDMS mold for the next cycle of soft lithography. The second PDMS replica, which takes on the exact shape of the PMMA mold, will then be hermetically sealed with a PDMS film to complete the fabrication of the required lens device. The fabrication process at each stage will be described in greater detail in the subsequent sections.

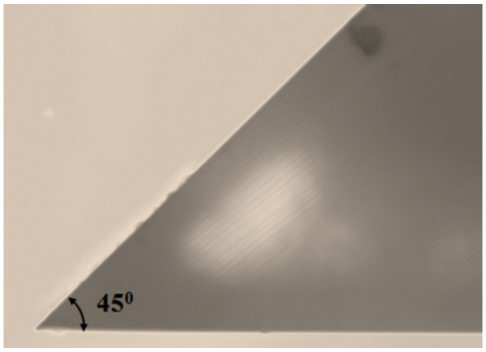


**Figure 3.** Image of the 0–45° facet-cut single crystalline diamond-tip cutting tool under an optical microscope.

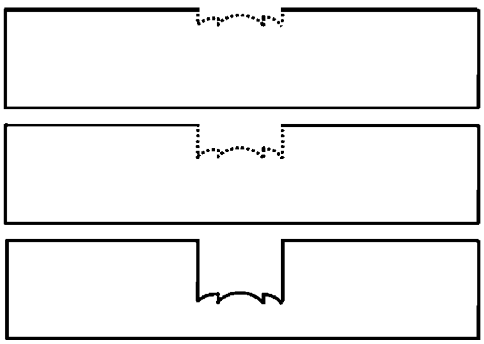

**Figure 4.** Depth of cut is maintained at 5 $\mu$m and the profile is progressively cut until the required depth of the feature is reached.

### *3.1. Fabrication of the PMMA mold*

All diamond machining processes are carried out on a three-axes diamond machining lathe, Toshiba-ULG-100A(HY), which requires a 10 nm least input increment in the $x$-, $y$- and $z$-axes. To obtain the vertical walls, a 0–45° facet-cut single crystalline diamond-tip cutting tool (Osaka Diamond Industrial Co., Ltd) was selected, as shown in figure 3. The substrate material is a 3 mm thick and 10 cm wide PMMA plate. Since the diamond tip on the inset is a facet-cut tool, it is brittle and can be easily chipped if the depth of cut is large. Therefore, the profile is machined out progressively in numerous cycles, with the depth of cut maintained at 5 $\mu$m each time. This is illustrated in figure 4.

The rotationally symmetrical lens cavity and the integrated lens profile at the bottom surface are both generated by SPDT in a single, continuous step. This has an important implication of ensuring the optical centers of the lens integrated on the bottom surface of the lens cavity and that of the tunable refractive lens as defined by the deformable membrane are automatically aligned. This is because the optical center of the tunable refractive lens is defined by the circular opening of the lens cavity. As opposed to traditional manual alignment of individual adjacent lenses, this fabrication method could significantly minimize the human error that could arise during manual alignment of the adjacent lenses. Much time and effort could also be saved during optical testing because of the auto-alignment of the lenses.

**Table 1.** Machining parameters used to fabricate the PMMA mold.

| | Infeed rate (mm min$^{-1}$) | Crossfeed rate (mm min$^{-1}$) | Spindle speed (rpm) | Depth of cut ($\mu$m) |
|---|---|---|---|---|
| Turning | 5 | 5 (for rough cut)<br>1 (for last cut) | 1000 | 5 |
| Shaping | 150 | 150 | 0 | 5 |

The machining parameters used are summarized in table 1. Since only the crossfeed rate for the final cut determines the surface roughness, a higher crossfeed rate is used for the cutting cycles that precede the final cut to expedite the machining process. Only during the last cycle of diamond turning will the crossfeed rate be lowered to 0.1 mm min$^{-1}$ to obtain a smooth surface suitable for optical purposes. As opposed to the crossfeed rate, the infeed rate does not have a significant effect on the surface finish and it is arbitrarily chosen to be the same as the crossfeed rate.

When diamond turning has completed, the vacuum chuck that holds the PMMA plate stops rotating and the shaping of the non-rotationally symmetrical liquid channels commences immediately after. It should be noted that since turning and shaping commenced one after the other without releasing the workpiece from the vacuum chuck, they share the same machining referencing point.

As opposed to the integrated lens surface, there is no requirement for the surface finish of the water channels since their sole purpose is to transport fluid in and out of the lens cavity. Therefore, even if the high crossfeed rate of 150 mm min$^{-1}$ during the shaping process results in rough surfaces of the water channels, it is an acceptable speed. Moreover, the high speed does not cause perceptible damage to the diamond tool tip, partly because the depth of cut is merely 5 $\mu$m. The PMMA workpiece is released from the chuck after the fabrication of lens cavity and liquid channels on the diamond cutting lathe are both completed.

Since the opening of the lens cavity defines the boundary condition of the tunable lens, the channels that deliver water to it must be sufficiently narrow such that the deformation of the PDMS film remains spherical. For all the tunable lens devices presented, 80 × 80 $\mu$m$^2$ liquid channels are used. Similar to the turning of the lens cavity, the two liquid channels are shaped in steps of 5 $\mu$m until the desired depth is reached.

### *3.2. Soft lithographic replication processes*

With the PMMA master mold at hand, two cycles of soft lithographic replication processes need to be performed to obtain the PDMS lens device with the required structure. PDMS (Dow Corning Corp's Sylgard 184), a silicone elastomer, is chosen to be used for the replication process due to its high transmittance over a wide spectral range [39] and its elasticity ($E \approx 750$ kPa) [40].

Firstly, a PDMS pre-polymer is prepared by mixing a dimethylsiloxane monomer base and curing agent in a ratio of 10:1. In the presence of platinum-based catalyst, silicon hydride groups in the curing agent bond with the vinyl groups

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