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Two-dimensional plastic microlens arrays by deep lithography with protons: fabrication and characterization

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Abstract

We present a quantitative study of the fabrication process of two-dimensional plastic microlens arrays fabricated using deep lithography with protons. Our process involves the proton irradiation of a PMMA (poly(methyl methacrylate)) sample in regions with a circular footprint followed by a diffusion of MMA vapour into the bombarded zones to cause a lens-shaped volume expansion. In the first part of this paper we give a detailed description of our fabrication technique and of the calibration procedure that goes with it. We demonstrate the flexibility of our approach with the fabrication of different types of array: highly uniform microlens arrays and arrays of microlenses with varying sags (maximum height of the spherical lenscap) and pitches. All lenses under test feature diameters of $200 \pm 2 \,\mu\text{m}$, root-mean-square (RMS) roughnesses on the top of the lenses of $\lambda/30@632$ nm and lens sags ranging from 10 to 70 μ m. We also present the optical performances and the aberrations of the microlenses, measured using a dedicated transmission Mach-Zehnder interferometer. The focal lengths of the lenses under study range from 166 to 1444 μ m, corresponding to a range of sags between 9.77 and 69.73 μ m and to focal numbers between 0.83 and 7.22. Typical values for the RMS and peak-to-valley aberrations of 0.209λ and 1.057λ respectively were observed. To conclude, we analyse and discuss the strengths and weaknesses of this fabrication method.

Keywords: Refractive microlenses, deep lithography with protons, vapour diffusion, characterization, interferometry, spherical abberation, replication

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

1. Introduction

The efficient integration of arrays of opto-electronic devices into photonic data handling systems calls for the development of high-quality, high-precision, low-cost microlens arrays [1]. Lens arrays made of glass have been studied for a relatively long time compared with those made in other materials. Over the years various fabrication techniques have been proposed for this purpose [2]: photothermal expansion [3], ion exchange [4], CO_2 laser irradiation [5] and reactive ion etching to transfer lens arrays into fused silica or related materials [6]. More recently, extensive studies on fabrication techniques of micro-optical components in new lightweight optical materials have been the research topic of interest of various research groups. Optical grade polymers in particular have attracted special attention because of the controllability of their mechanical and thermal properties. Several researchers have reported on fabrication methods of microlenses and lens arrays



Figure 1. Basic fabrication process for arrays of spherical microlenses with DLP.

with these materials. They include photoresist reflow [7], laser beam shaping [8], laser ablation [9], photopolymerization [10] and ink-jet printing [11]. Most of these fabrication methods satisfy many of the optical quality requirements of lens arrays but have a drawback in that they are less suitable either for rapid prototyping or for mass-fabrication.

In this paper we present the state of the art of deep lithography with protons, a technology which we have adopted [12] and optimized to prototype two-dimensional arrays of plastic refractive microlenses, featuring a wide range of numerical apertures, diameters and pitches. The uniqueness of our approach lies in the fact that this particular fabrication process is fully compatible with the other processing steps of the deep lithography with protons (DLP) technology [13]. As such it allows the monolithic integration of the microlens arrays with other plastic micro-optical components and mechanical features to form high-precision three-dimensional microoptical modules that can be replicated in large numbers and at low cost through injection moulding or vacuum casting [14], resulting in a rapid prototyping mass fabrication technology.

In section 2 of this paper we discuss the irradiation and swelling processes involved in the fabrication of the microlenses and we describe our experimental set-up. Next, in section 3, we highlight the geometrical and optical characteristics of the microlenses and we demonstrate the repeatability of the DLP fabrication process. In a fourth section we illustrate the prototyping flexibility of DLP by making arrays of microlenses with different sags and pitches and show an example where two-dimensional microlens arrays have been integrated with other micro-optical components fabricated by DLP. As a conclusion we briefly discuss the advantages and shortcomings of our technology.

2. The microlens fabrication process: irradiation and volume expansion

The lens fabrication process in DLP consists of two principal steps: the irradiation of selected areas of a poly(methyl methacrylate) (PMMA) substrate with high-energy protons and the volume expansion of these irradiated areas by indiffusion of an organic monomer vapour (figure 1).

The details of the process can be described as follows. In a first step a cast PMMA sample, with a molecular weight higher than 10^6 g mol⁻¹ and an optical transmission of 94%, is bombarded with an 8.3 MeV proton beam which is shaped by a high-aspect-ratio non-contact metal mask, featuring a high-precision circular aperture. The shape of this aperture



Figure 2. The one-dimensional absorbed fluence profile in PMMA after a proton irradiation $(1.2 \times 10^6 \text{ particles}/\mu\text{m}^2)$ for different entrance energies [13].

is directly projected onto the PMMA sample, where the impinging high-energy protons break polymer chains and create free radicals [15, 16], resulting in a polymeric material with a reduced molecular weight. This process is based on the fact that, while the ions propagate through the substrate, they transfer energy to the PMMA molecules. In the early part of their trajectory the swift ions will transfer less energy to the material than slow ions and therefore they will deposit a lower fluence. This energy transfer will gradually slow the ions down and their interaction density with the PMMA molecules will increase significantly. This will result in a maximum absorbed fluence when the impinging ions have velocities equal to those of the electrons in the amorphous material. Below this energy level, the ion energy transfer will decrease immediately and after a further penetration of some micrometres the ions will come to a full stop at a depth called the penetration depth [13] (see figure 2). As the molecular weight decreases proportionally with the absorbed fluence in the PMMA, the molecular weight reduction will not be homogeneous in the direction of the proton beam.

The shape of the irradiated volume is a cylinder with a circular footprint of diameter D, equal to the circular aperture in the mask, while the height of the cylinder is determined by the penetration depth of the protons, or if the protons cross the sample by its thickness. The cylindrical volumes thus created feature a lower molecular weight and will be more receptive to an in-diffusion process of an organic monomer than the non-irradiated bulk material. During the diffusion



Figure 3. Experimental diffusion set-up.

process a polymerization reaction occurs between the broken polymer chains and the in-diffused monomer molecules, but more importantly the in-diffusion of the monomer causes a volume expansion, which results, because of the circular footprint of the irradiated zones, in hemispherical surfaces. In our very first diffusion experiments we used styrene as the monomer [17, 18]. A change to MMA however made it possible to eliminate the cracks in the sample as the physicochemical properties of the latter monomer are much closer to those of the polymer material PMMA. Thus refractive microlenses can be fabricated over a wide range of diameters D corresponding to the circular apertures available on the high-aspect-ratio mask. The mask that we use features hole diameters ranging from 20 μ m to 1 mm. In this paper we focus on the fabrication of spherical microlenses with a diameter of 200 μ m. Three aspects of the above-mentioned irradiation procedure influence the lens characteristics: the average molecular weight, the number of free radicals in the irradiated region and the volume of this region. Both the molecular weight and the number of free radicals can be controlled by the number of deposited protons per surface area or by the proton fluence. We have observed that when the proton fluence is too low (e.g. a proton fluence of 10^4 particles/ μ m² for a typical diffusion at 90 °C for 50 min) the molecular weight of the irradiated region remains too high to allow a sufficient in-diffusion of the MMA monomer to cause a volume expansion. Too high a fluence, on the other hand (e.g. a proton fluence of 4×10^5 particles/ μ m² for a typical diffusion at 90 °C for 50 min), results in a local temperature increase during the irradiation and destroys the optical surface quality of the sample. The volume expansion itself strongly depends on the amount of monomer diffused into the irradiated zones. This can be controlled through the concentration of monomer (typically 0.01 ml cm^{-3}), through the diffusion time and through the temperature of the chemical reactor in which the diffusion takes place. However, both the diffusion time and the diffusion temperature will also limit the range in which lenslike shapes are practically achievable.

Too short a diffusion time leads to an insufficient volume expansion, too low a polymerization and hence a depressed lens surface, while too long a diffusion time will destroy the lens shape. Moreover the temperature within the chemical reactor must be sufficiently high to create the monomer vapour phase and to increase the polymerization and diffusion rate, while for too high a temperature $(T > 95 \,^{\circ}\text{C})$ the substrate material will start to flow and deform. Figure 3 shows the temperature-controlled reactor that is used for the practical fabrication process. The irradiated sample, the backside of which is covered during the diffusion process, is placed in the reactor. When the desired diffusion temperature of 90 °C is reached, the MMA monomer is injected with a syringe while a pressure probe is used to detect a possible leakage of the reactor. Diffusion and swelling then take place for a well defined period of time, the optimum of which lies between 20 and 60 min. Finally a thermal stabilization procedure, inducing a full polymerization, prevents the out-diffusion of the monomer and fixes the shape of the microlenses. This stabilization procedure consists in reducing the temperature to 70 °C and keeping the sample in the reactor for 4 h.

3. Calibration of the swelling process and optical characterization of the microlenses

An accurate calibration of the swelling process is necessary to predict the sag *h* and the radius of curvature *R* of the lenses, and hence their focal length *f*, focal number f/# and numerical aperture (NA). All these parameters are related by the formulae

$$R = \frac{h^2 + (\frac{D}{2})^2}{2h}, \qquad f = \frac{R}{n-1},$$

 $f/\# = \frac{f}{D} \qquad \text{and} \qquad \text{NA} = \frac{1}{2f/\#}$

in the paraxial approximation, where *D* represents the diameter of the microlenses.



Figure 4. (*a*) Vertical scanning non-contact optical profiler (WYKO NT2000); (*b*) transmission Mach–Zehnder interferometer [19].



Figure 5. Profile of three microlenses (column 2—proton fluence of 4×10^4 particles/ μ m²) of the studied 10 × 10 microlens array measured with a non-contact optical profiler (WYKO NT2000).

For calibration purposes we have fabricated a 10×10 array of microlenses, all of which feature a 200 μ m diameter. Each column of the array consists of ten identical microlenses created with the same proton fluence. We thereby increased with increasing column number the proton fluence from 2×10^4 to 2×10^5 particles/ μ m² in steps of 2×10^4 particles/ μ m². Details of the irradiation set-up and the irradiation procedure can be found elsewhere [13]. After irradiation of this 10×10 array, the sample was placed in a 90 °C temperature-controlled reactor, which has a volume of 1000 cm³. Next 10 ml MMA was injected with a syringe. We then allowed diffusion to take place for 50 min. Finally the microlenses were stabilized by reducing the temperature to 70 °C and sustaining this condition for 4 h.

We measured the geometrical dimensions, the sag and the surface roughness of the microlenses with a vertical scanning non-contact optical profiler working in reflection mode (figure 4(a)). The vertical resolution of this profiler is 3 nm RMS, while the maximum error of 1.3% in lateral resolution is a function of the accuracy of positioning of the cursors by the observer, the total magnification and the detector array size.

All the lenses of this 10×10 array showed a diameter of $200 \pm 2 \mu m$, a pitch of $250 \pm 3 \mu m$ and an RMS roughness on the top of the lens of $\lambda/30@632$ nm. As explained before, the deviation in pitch of $3 \mu m$ is not due to a positioning error of the translation stages. It mainly reflects the limited lateral resolution of our profiler, which is a function of the total magnification, the accuracy of positioning of the cursors by the observer and the detector array size. The real error in pitch is estimated to be 50 nm, corresponding to the positioning



Figure 6. Sag (μ m) and focal length (μ m) as a function of the proton fluence (particles/ μ m²).

accuracy of our piezo-driven translation stages. In table 1 we give for each column of ten microlenses the average sag and its respective standard deviation. The uniformity of the microlens characteristics in each column of the array under study is better than 0.5%, as shown in figure 5. The sags range from 9.77 to 69.73 μ m, as plotted in figure 6 (see \blacklozenge , experiment 1). From this figure we can conclude that the sag of the microlenses increases linearly with the proton flux up to a flux of 10^5 particles/ μ m² and levels off for higher proton fluences. This saturation can be understood as being due to a decrease of the MMA in-diffusion rate as the number of free radicals decreases. We have repeated this calibration experiment and made a second 10×10 array on a different sample using the same settings for the irradiation and diffusion parameters (see \triangle , experiment 2). From figure 6 we can conclude that the results of the two experiments (1 and 2) are identical within the error margin of the instrumentation (0.7%), which confirms the reproducibility of our DLP-based lens fabrication method.

To investigate the optical characteristics of the microlenses we applied the accurate and reliable technique of interferometry to measure the wavefront aberrations and the focal lengths of the microlenses with the aid of a dedicated Mach-Zehnder transmission interferometer [19] (figure 4(b)). For the microlenses with average sags from 9.77 to 69.73 μ m the corresponding focal lengths were found to range from 166 to 1444 μ m (see figure 6). Their standard deviations are displayed in table 1. The focal numbers and NAs were calculated using the equations mentioned earlier in this section. Figure 7 shows the transmission interferogram of a part of this 10×10 lens array as well as the RMS and peak-to-valley (PV) aberrations for a 200 μ m lens, revealing typical values of 0.209 λ and 1.057λ respectively. These values indicate that our lenses are not yet diffraction limited, which can be mainly ascribed to deviations from a perfect spherical lens shape both at the vertex and at the rim of the lenses (see figures 8(a) and 9(a)). The former deviation can be caused by an angular misalignment of the mask with respect to the sample. The deviations at the rim of the lens are due to a local defect in the 200 μ m diameter mask.

(*a*)

Table 1. Sags and focal lengths of the microlenses and their standard deviations, and the calculated focal numbers and NAs for different proton fluences.

Column number	Proton fluence (particles/ μ m ²)	Sag (µm)	STDV sag (µm)	Focal length (µm)	STDV focal length (μ m)	Calculated f/#	NA
1	2.00×10^{4}	9.77	0.41	1443	3.18	7.215	0.0693
2	4.00×10^{4}	17.79	0.91	607	0.53	3.035	0.1647
3	6.00×10^{4}	26.47	0.59	371	0.32	1.855	0.2695
4	8.00×10^{4}	34.32	1.13	342	0.34	1.71	0.2924
5	1.00×10^{5}	41.18	1.28	290	0.31	1.45	0.3448
6	1.20×10^{5}	47.02	1.40	231	0.27	1.155	0.4329
7	1.40×10^{5}	52.25	1.71	204	0.27	1.02	0.4902
8	1.60×10^{5}	56.86	1.77	183	0.26	0.915	0.5464
9	1.80×10^{5}	61.85	1.72	166	0.27	0.83	0.6024
10	2.00×10^5	69.73	1.45	256	3.20	1.28	0.3906





Figure 7. (a) Mach–Zehnder transmission interferogram of a part of the 10×10 array of microlenses illuminated with a plane wave, where the column numbers are identical to those in table 1; (b) contour plot of the aberrations for a 200 μ m diameter lens.



Figure 8. (*a*) 3×3 microlens array with different sags and constant diameter ($D = 200 \ \mu$ m) and pitch ($P = 250 \ \mu$ m) measured with a non-contact optical profiler (WYKO NT2000); (*b*) X cross-section of the microlens array; (*c*) fitting of the lens profile with a perfect sphere; (*d*) SEM picture of one of the microlenses.



Figure 9. (a) SEM picture of 3×3 array of 200 μ m lenses with different sags and various pitches; (b) WYKO plot of the microlens array (the arrows indicate the defects in the circular aperture of our mask).



Figure 10. Assembled optical bridge.

4. Flexible prototyping of various microlens arrays

Using the calibration curve of the microlens swelling process as derived in the previous section, we now demonstrate the prototyping flexibility of DLP for the fabrication of microlenses with different characteristics on one sample. As a first example we fabricated a 3 × 3 array where every lens featured a different sag ranging between 5 and 24 μ m, while the lens pitch was fixed at 250 μ m (figure 8). As a second example we show a similar 3 × 3 array of microlenses but this time with pitches varying between 230 and 300 μ m (figure 9).

The above-mentioned results demonstrate the flexibility of the DLP process for prototyping microlens arrays. In the near future we shall go one step further and fabricate microlens arrays not only with different sags and pitches, but also with different lens diameters by selecting circular mask apertures with different sizes from 200 μ m.

5. Discussion and conclusion

We have shown that DLP is a valuable tool for flexible prototyping of refractive microlenses and microlens arrays. What is more, these microlenses can also be integrated with other DLP-fabricated micro-optical components. As an illustration of the generic character of DLP we show in figure 10 a multi-channel free-space optical interconnection module [20] that consists of micro-prisms and a base plate, containing two 2×8 microlens arrays (diameters of 200 μ m and sags of 21 μ m) and rectangular alignment holes to accommodate the micro-prism mounting pins.

An important drawback however of using DLP to produce microlenses is the time consuming irradiation and diffusion

processes. We can on average fabricate five different customdesigned microlens arrays on a PMMA substrate, each with a size of 2.5×2.5 cm², in one day. Although this can be considered as rapid prototyping we realize that DLP is as such unpractical and too slow for large-scale manufacturing. Recently we have remedied this issue by showing that DLP can be made fully compatible with LIGA (German acronym for Lithographie, Galvanik und Abformung) [14] and can therefore take advantage of injection moulding or hotembossing techniques when low-cost mass fabrication of twoand three-dimensional micro-optical components in general and microlens arrays in particular is needed.

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