Refractive elements produced in photopolymer layers

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Micro-optical elements are an important enabling technology for many hightech products including 3-D displays and backplanes [1, 2]. We note that there is a wide range of different fabrication methods each with its own advantages and disadvantages [3]. Techniques such as the photoresist reflow method [4] have been examined and have been shown to be excellent for a range of microlenses (f number between 1.5 and 4 for lens diameters from 25 to 800 μm), however difficulties arise when attempting to produce combined large focal length and small diameter lenses [5]. We note that there has been a large number of studies on the production of relief elements using patterned exposures in a wide variety of materials. These include IR radiation focusing elements by Boiko *et al.* [6], exposure of dichromated gelatin in printing applications [7], UV exposure of sol gels by Soppera *et al.* [8], surface relief elements in methacrylate photopolymers by Kojima *et al.* [9] to name just a few.

In the present work we examine the possibility of producing lenses using a fabrication method that takes advantage of the change induced in acrylamide-based holographic recording materials during and after exposure to intense light. In order to study the production of lenses using this method it is necessary to first perform a temporal study of the evolution of the optically induced surface relief pattern. In this study we examine the effects of coherent exposure energy and mask pattern on the final surface relief pattern. Both single and double beam (interferometric/holographic) exposures are examined to determine the implications of material volume change for holographic recording.

The acrylamide-based photopolymer layers were produced by drop casting the material onto microscope slides. The thickness of the layers being controlled by the volume of material applied.

Different types of exposures were carried out including single and double beam exposures and single beam exposure through a patterned mask. A range of exposure energies were examined. The resulting layer profiles were examined using a number of profilometry techniques including TalySurf (model: Talysurf Series 2, Ametek (Taylor-Hobson), USA), AFM (model: Nano-R, Pacific Nanotechnology, USA), SEM (model: JSM-5410LV, JEOL, Tokyo) and optical profilometry

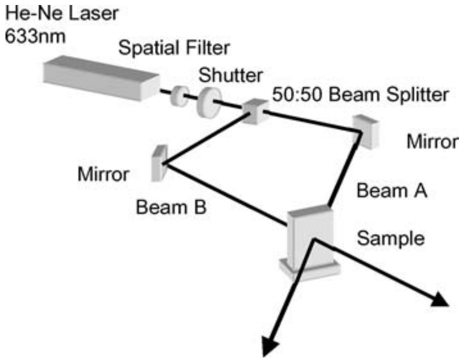

Figure 1 Two beam unslanted transmission holographic recording geometry.

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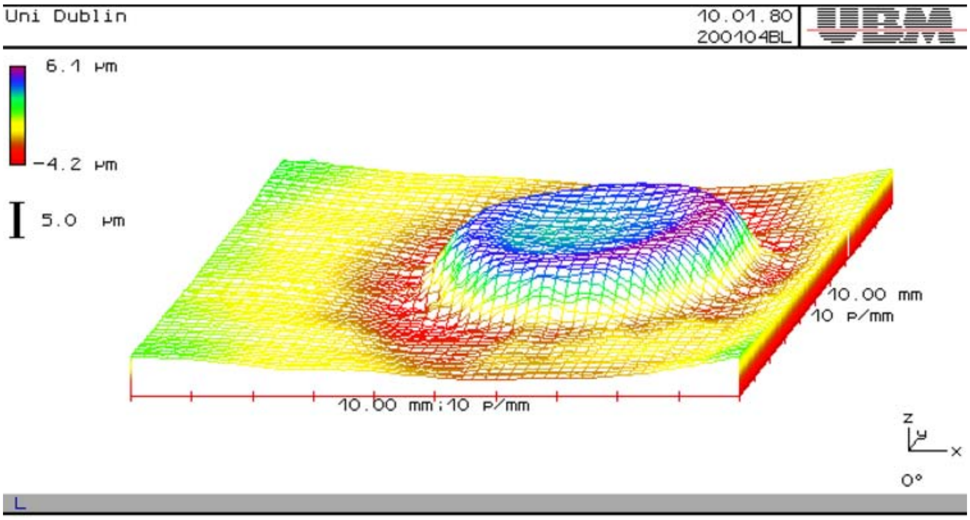

Figure 2 Single-beam exposure of acrylamide-based photopolymer layer. (∼430 mJ/cm^2, 120 μm layer).

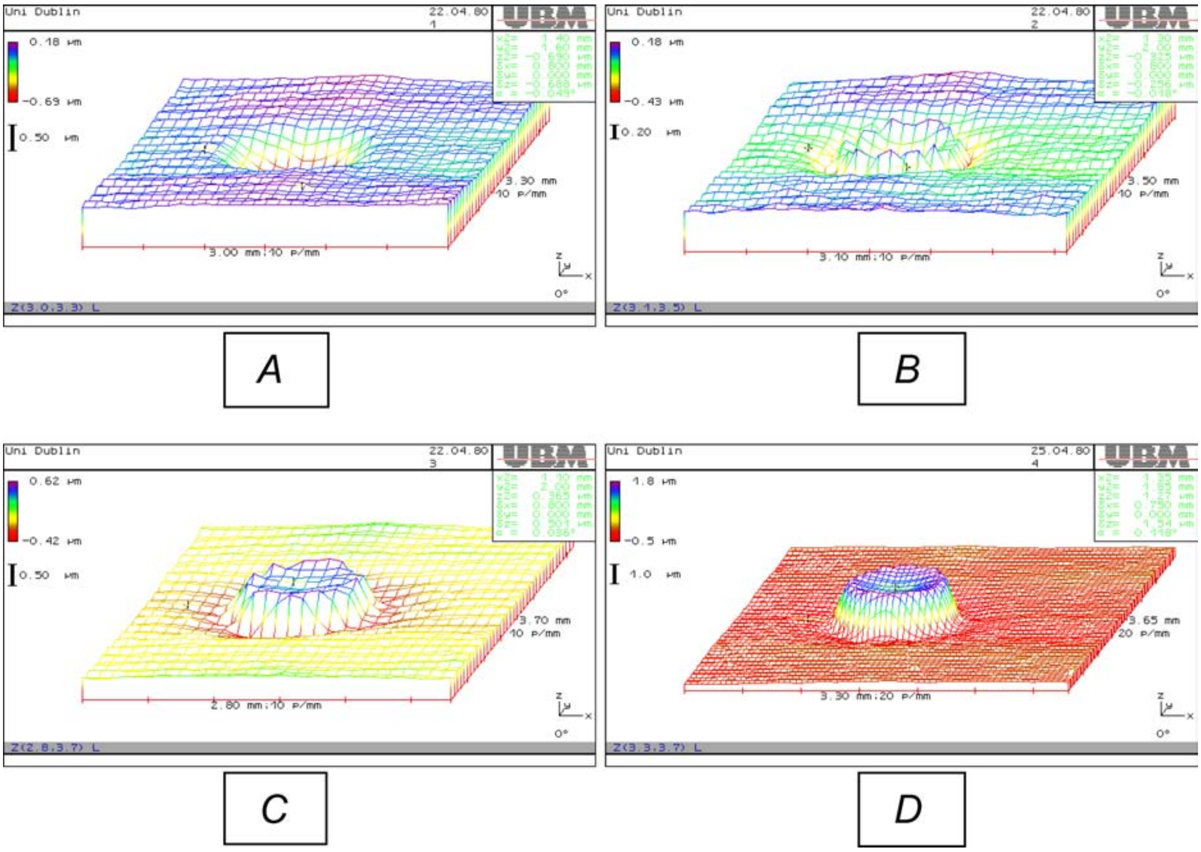

Figure 3 Range of figures showing the development of a layer exposed with a single beam over a period of 69 hr. (A) 7 min post-exposure, (B) 60 min, (C) 3 hr and (D) 69 hr. The exposure energy was 100 mJ and the layer was 46 μm thick.

(UBM microfocus measurement system ver. 1, UBM, USA). The use of optical profilometry provided a non contact alternative to the Talysurf method of inspection.

The optical setup used to carry out the exposure of the photopolymer was a standard holographic recording geometry for transmission gratings [10] as shown in Fig. 1. The beams are set up so as to produce 1000 lines per mm gratings. This spatial frequency is chosen for simplicity and because it is known to be within the materials spatial frequency response range [11]. A detailed comparison of the resulting surface relief profiles is discussed later. The exposure energy is controlled with a Uniblitz [12] shutter and the laser used was a He–Ne (20 mW, 633 nm). The angle of incidence of the beams is 18.45 degrees. An iris was used to shut off one of the beams in the case of the single beam exposures.

During exposure, the acrylamide-based photopolymer layers undergo a photoinduced polymerisation reaction [13]. Polymerization of acrylamide occurs via a mechanism known as free radical polymerization [13]. On polymerization each carbon double bond is converted into a carbon single bond lowering the molar refractivity from approximately 4.16×10^3 to 2.15×10^3 mm^3 [14]. This lowers the refractive index of the

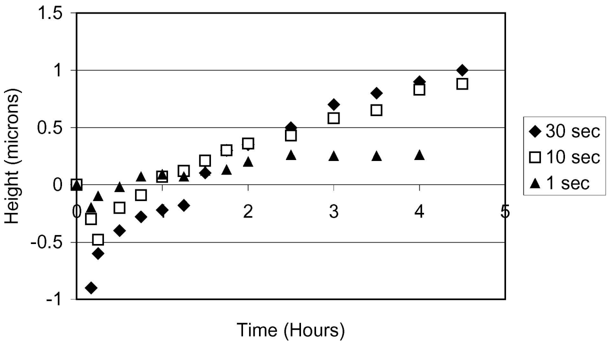

Figure 4 Temporal evolution of the surface relief profile. The layers are 46, 44 and 50 μm for the 30, 10 and 1 s exposures respectively and the exposure beam power was 2.4 mW/cm^2. The exposure beam was normal to surface.

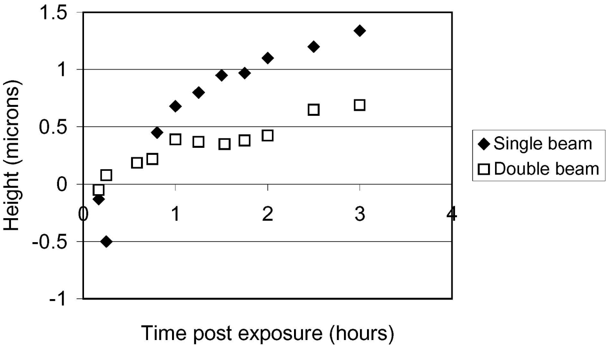

Figure 5 Resulting surface modulation from both single and double beam exposure are shown. The exposure energy for each is equal.

material. This is usually accompanied by an increase in density (10–15%), which leads to an increase in refractive index [14]. The combination of these two processes results in a higher refractive index in polymerized regions compared to unpolymerized regions so that a refractive index modulation exists between exposed and unexposed areas. During exposure monomer diffuses into bright regions as a result of the concentration gradient induced by the depletion of these components [15]. This causes a further difference in density (and so refractive index) between bright and dark regions. These two processes result in an initial reduction in surface profile as can be seen experimentally at short times post-exposure followed by a swelling over time. Although there are a range of diffusion-based models [16, 17] that describe the formation of holographic elements in these materials the process involved in the swelling stage in photopolymer layers is currently not well understood. It is possible that material mass transport occurs causing the exposed area to swell [18].

Attempts to characterize the performance of the material in order to fabricate lens structures are now shown. In Fig. 2 we give an example of a surface profile modulation caused by a focused beam (~430 mJ/cm^2, 120 μm layer, single beam exposure). It is clear that large modulation of the surface (~8 μm) is possible.

The temporal evolution of the exposed spot is shown in Fig. 3. The 44 μm thick photopolymer layer was exposed using a 24 mJ/cm^2 beam. We can clearly see that there is an initial shrinkage, ~0.34 μm, followed by a period during which swelling occurs. The resulting profile is a pedestal ~1.2 μm in height.

The effects of varying the exposure energy on the resulting temporal behavior of the central height is shown in Fig. 4. The height parameter is defined as the difference between the edge and the center of the exposure. The material variation increases with increasing intensity as is expected.

We now examine the effects of exposing the layer with both single beam and double beam illumination. We can see that although the swelling is less for the two beam recording, it is still appreciable. An example of this behavior is shown in Fig. 5. In this figure the layers are 47 and 50 μm thick for the double beam and single beam exposures, respectively. The exposure energy in both cases was ~240 mJ/cm^2. This result has implications for holographic recording in this material as shrinkage/swelling of the material can result in Bragg detuning effects. We note that the attempts to control this volume change have previously been examined [19]. Furthermore, the general trends observed regarding shrinking/swelling of the material are in agreement

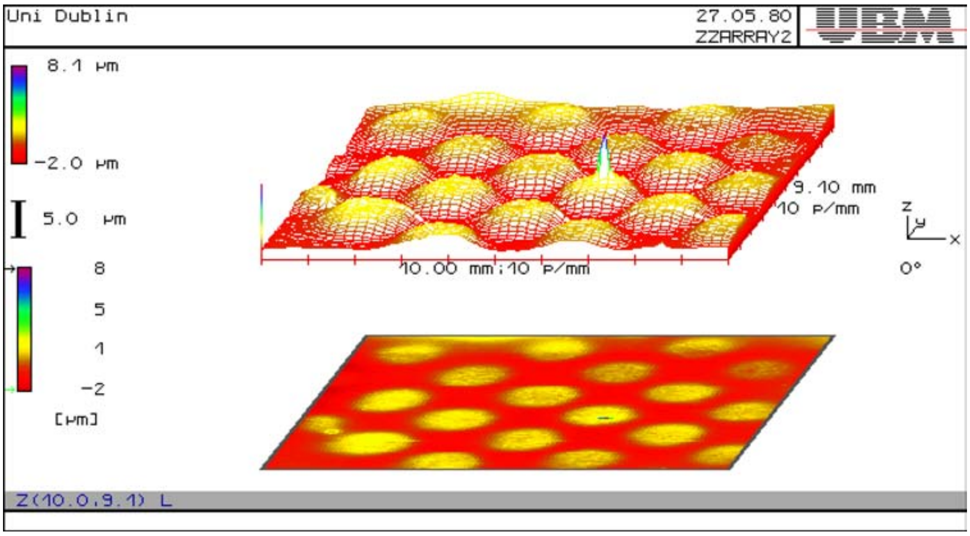

Figure 6 Array of microlenses produced in a 50 μm thick acrylamide-based photopolymer layer by exposing to a 2.4 mW/cm^2 beam for 5 min.

with those found using an electromagnetic inverse scatter fitting method to obtain shrinkage/swelling information from holographically recorded gratings [20].

We now examine the use of a mask to record arrays of elements. The experiment used a 4 by 4 gray scale circular lens mask. In this case the layer was exposed through the mask. The exposure energy used was 720 mJ/cm^2. The layer was $\sim$50 μm thick and the optical profilometry was carried out 24 hr post-exposure. From the surface profile as shown in Fig. 6, we can see that the elements are $\sim$4 μm, high and 1 mm diameter.

Attempts to reduce the size of the array have been carried out using an imaging lens. This method has been used to produce arrays of lenses with a diameter of $\sim$500 μm. However uniformity of the resulting lenses was poor. Work is currently going on for the improvement of these lenses.

In conclusion this study has shown that it is possible to use the volume change in holographic recording materials to produce patterned surfaces. In doing so we have also highlighted the difficulty involved in producing holographic elements using recording materials based on the polyvinylalcohol-acrylamide-polyacrylamide system.

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