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Fabrication of micro-optical components in polymer using proton beam micro-machining and modification

A.A. Bettiol *, T.C. Sum, J.A. van Kan, F. Watt

Department of Physics, Research Centre for Nuclear Microscopy (RCNM), National University of Singapore, Blk S12, 2 Science Drive 3, Singapore 117542, Singapore

Abstract

Proton beam micro-machining (PBM) is a direct write lithographic technique that utilizes a high energy (MeV) sub-micron focused proton beam to machine or modify a material, usually a polymer. The technique has been developed in recent years at the Research Centre for Nuclear Microscopy, National University of Singapore where structures with feature sizes of well below 1 μm have recently been demonstrated. The PBM technique has several desirable features that make it suitable for rapid prototyping of micro-optical components. Structures made using PBM have very smooth side walls, high aspect ratio, and a scale that can be easily matched to existing optical fiber technology (0.1–1000 μm). Furthermore, PBM can also be used to modify the optical properties of polymers, particularly if the end of range is used. In this paper we demonstrate the use of proton beam micro-machining and modification for manufacturing micro-optical components in positive and negative resist. The structures that are fabricated can be used for both rapid prototyping and for large scale replication.

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1. Introduction

Micro-optical components are structures that are less that 1 mm in size, that are able to alter either the state or direction of light through reflection, refraction or diffraction. Micro-lens arrays and gratings are an important part of many micro-optical systems. Gratings can be used for dispersing light onto a detector for spectrometry, or for wavelength selection in an integrated demultiplexer [1]. Bragg type gratings have found numerous applications in optical filtering and optical sensing [2]. Some applications for micro-lens arrays include coupling light onto an optical fiber core [3], and wavefront analysis in a Shack–Hartmann sensor [4]. Micro-lenses and gratings are two examples of micro-optical components that can be easily fabricated using PBM. Knowledge of how to fabricate both is important for developing an integrated polymer based hybrid system for bio or chemical sensing. This work describes various methods of fabricating gratings and micro-lenses in polymer using proton beam micro-machining and modification.

* Corresponding author. Tel.: +65-6874-4138; fax: +65-6777-6126.
E-mail address: phybaa@nus.edu.sg (A.A. Bettiol).

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The two polymers chosen for this study, SU-8 and PMMA, have been extensively used for PBM in previous work [5]. Consequently many of the irradiation and chemical development parameters for PBM are well known and are described elsewhere [6]. SU-8 is a negative photoresist that has a high optical transparency in the visible part of the spectrum, and an exposure dose for protons of 30 nC/mm^2. PMMA behaves as a positive resist for proton doses between 80 and 100 nC/mm^2 (proton energy 2 MeV). There are two methods in which PBM can be used to prototype a micro-optical system. The first method involves the direct modification of a material to produce a change in the optical properties. In the case of PMMA, previous studies have shown that the refractive index of PMMA can be modified by proton implantation. This change has been used to fabricate buried waveguide structures in PMMA [7,8], and fused silica [9,10]. The second method of fabricating micro-optical components is achieved by micropatterning and subsequent development of the latent structure. This method can be applied to either of the polymers used in this study, depending on the fabrication requirements.

2. Experiment

The proton beam micro-machining and modification experiments for this work were performed at the Research Centre for Nuclear Microscopy, using a focused beam of 2 MeV protons. For micromachining experiments, a Si wafer was first sputter coated with a layer of Au. A 10 μm layer of SU-8 photoresist was then spin coated onto the wafer from which small samples were then cut to approximately 0.5×1 cm. The Au sputter coated layer can be later used as a seed layer for electroplating. A metallic replica of any structure in the SU-8 can be then used as a hot embossing stamp. For modification experiments, a bulk sample of 2 mm thick PMMA obtained from Röhm (Plexigas® GS233), was cut to approximately 1×2 cm in size. Transmission measurements were performed with a UV–VIS spectrophotometer on the bulk PMMA, and a sample consisting of a layer of 20 μm SU-8 spin coated onto a glass microscope slide.

3. Results and discussion

In order for a polymer to be useful for micro-optical applications it needs to have a high degree of transparency in the wavelength range of interest. The UV–visible transmission spectrum of a bulk PMMA sample and a 20 μm SU-8 layer on a glass microscope slide was measured. Fig. 1 shows that both samples have approximately 90% transmission for the wavelength range of 400–1100 nm for PMMA, and 380–1100 nm for the SU-8 on glass sample. Both these sample are therefore suitable for applications in the visible to near IR range.

3.1. Gratings

In this study, two types of diffraction gratings were fabricated using PBM. The first type of grating was machined by directly modifying the refractive index of a PMMA sample. The refractive index change modifies the phase of light traveling through the irradiated regions of the sample resulting in a diffraction pattern. A scan size of 2×2 mm was used to write 682 lines with a beam spot size of the order of 1×1 μm. A dose of 100 nC/mm^2 was used in the exposure to produce a series of lines approximately 3 μm apart. Fig. 2(a) shows a differential interference contrast (DIC)

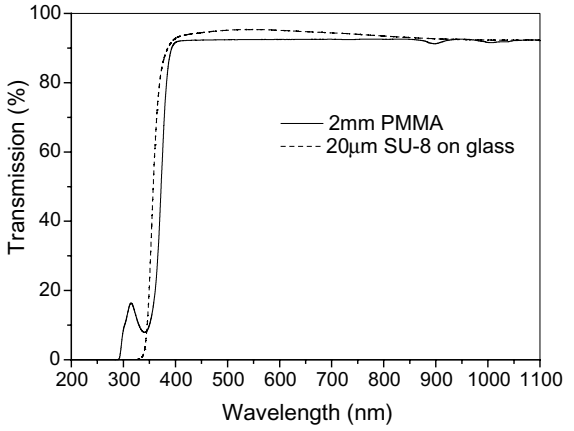

Fig. 1. Optical transmission spectrum measured from a 2 mm thick sample of PMMA and a 20 μm unexposed layer of SU-8 spin coated on a glass substrate.

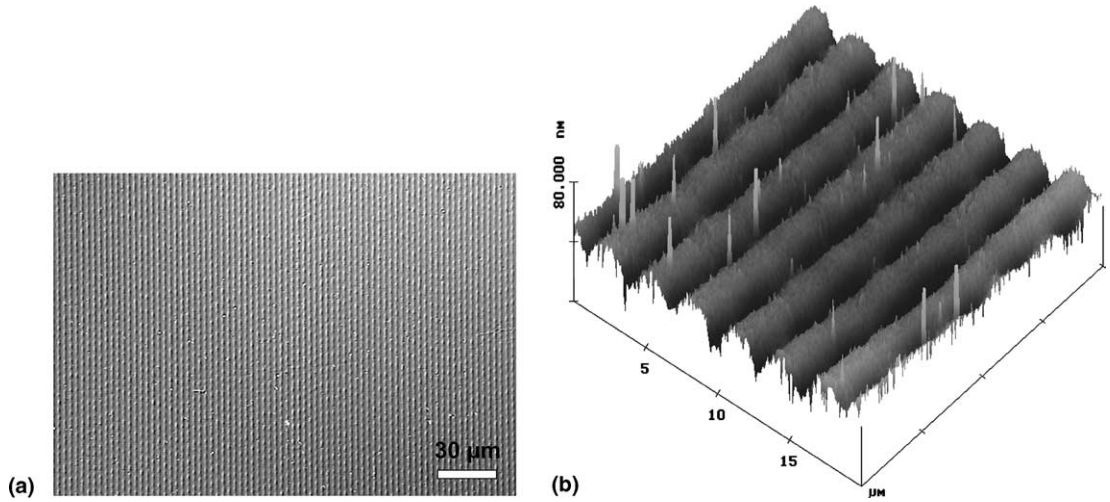

Fig. 2. (a) Differential interference contrast (DIC) optical image of an implanted line grating in PMMA. (b) AFM image of a section the same grating structure. The PMMA sample is modified using 2 MeV protons and a dose of 100 nC/mm^2.

optical image of the grating structure. The refractive index change in the PMMA is caused by a local increase in density at the end of range of the ion beam. This density increase is accompanied by a slight compaction of the surface which can be directly imaged in high resolution by an atomic force microscope (AFM). Fig. 2(b) shows an AFM image of the implanted transmission grating. It is also possible, if desired, to develop this sample to form a square wave type surface grating. If light is incident on the grating perpendicular to the beam irradiation direction and the ''ruled'' line direction; the grating can be used as a Bragg grating.

For applications that require gratings for light traveling in the plane of the sample, a second type can be fabricated using PBM. To illustrate this application, a blazed grating with a 1.5 μm period was machined in a SU-8 on Si sample. Fig. 3 shows

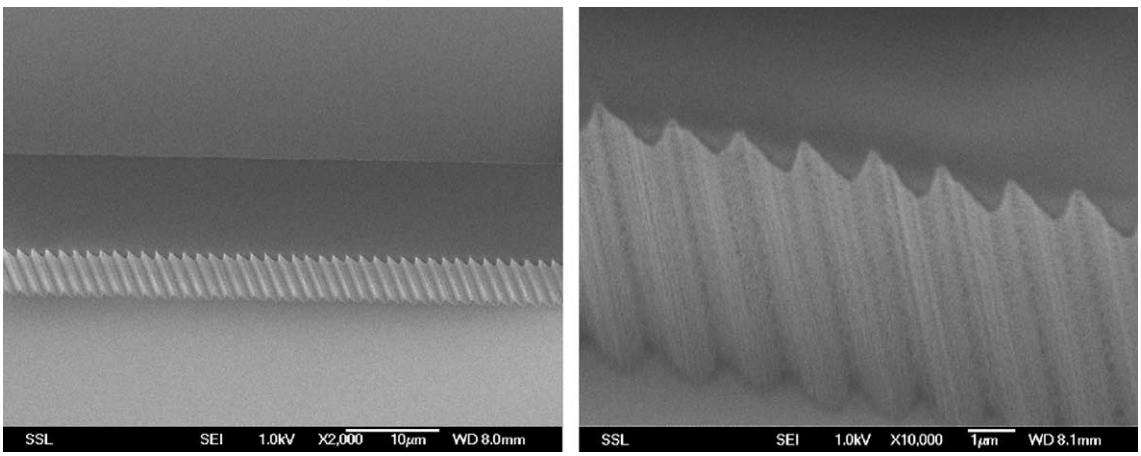

Fig. 3. SEM images of a blazed grating micromachined in a 10 μm layer of SU-8 on a Si substrate.

an SEM image of the grating. This type of gratings can be easily integrated with other micro-structures forming a hybrid micro-optical system. Some typical applications for a blazed grating of this type include a micro-spectrometer or a wavelength de-multiplexer.

3.2. Micro-Fresnel lens arrays

Two types of micro-Fresnel lens elements are demonstrated here. The first type is micro-machined in a 10 μm SU-8 layer on a Si substrate. Both the positive and negative image of this structure are shown in Fig. 4. Such structures on Si can be used as polymer templates for electroplating. Once these structures are electroplated, a stamp can be produced that can be used to replicate micro-lens arrays over a large area by nano-imprinting or hot embossing. In order to achieve the high degree of side wall smoothness that is observed in these structures, a sub-micron beam spot was necessary. The beam resolution used to machine these micro-Fresnel lens arrays was approximately 0.5×0.5 μm, and the scan figure was designed with a 100 nm pixel size over a 200×200 μm scan area.

Micro-Fresnel lenses can also be fabricated by direct modification of PMMA. An array of five lenses was machined into a 2 mm sample of PMMA. Fig. 5 shows several optical DIC images of the PMMA lens array. The surface of these structures was also imaged with an AFM. Fig. 6 shows an image measured in one region of the Fresnel lens. A line scan through the image reveals that the surface compacts about 150 nm for the 100 nC/mm^2 irradiation used in this example.

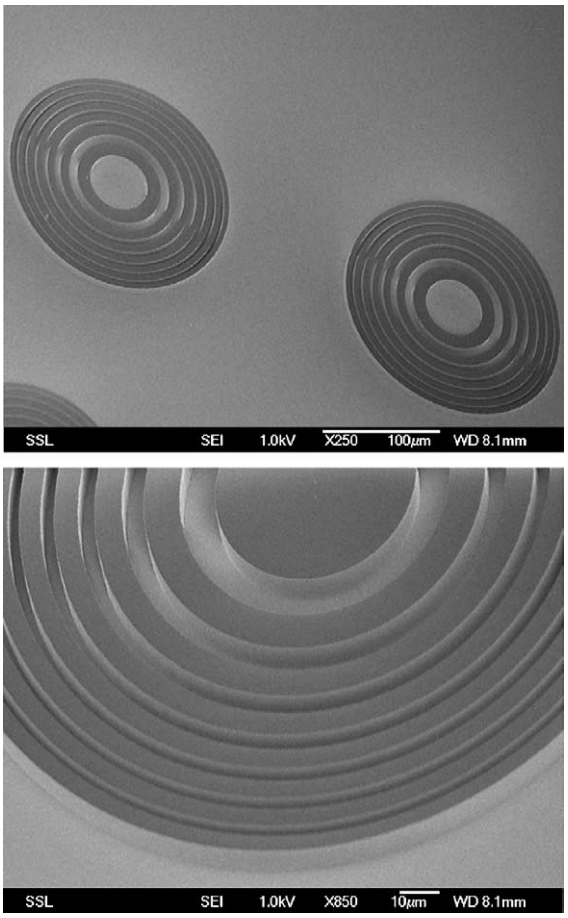

Fig. 4. SEM images of some micro-Fresnel lens elements micromachined in a 10 μm layer of SU-8 on a Si.

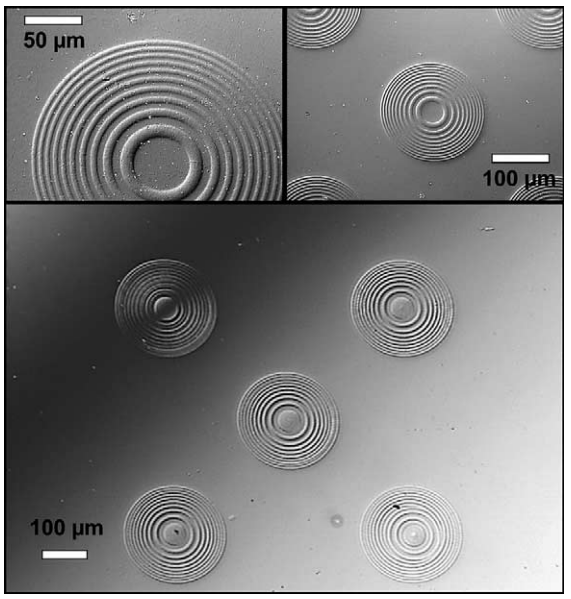

Fig. 5. DIC images of some micro-Fresnel lens elements micromachined in a bulk PMMA sample.

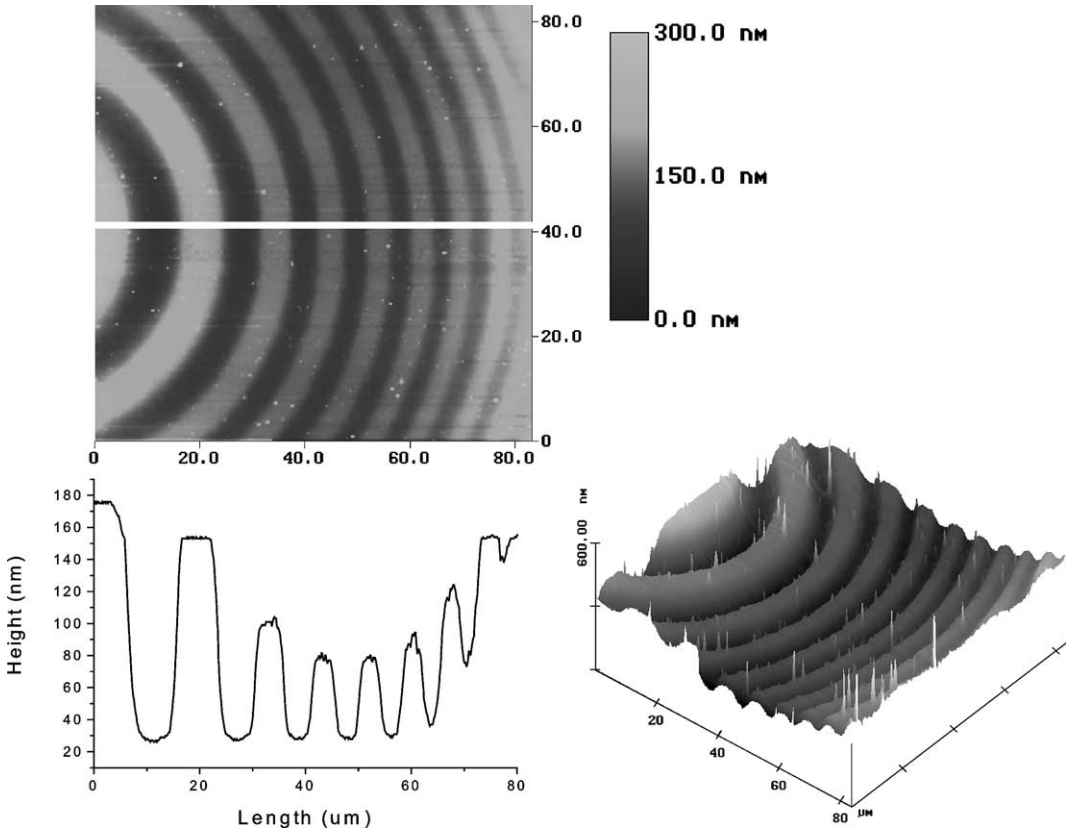

Fig. 6. AFM image of a section of one of the micro-Fresnel lens elements in Fig. 5. A line scan showing the surface compaction is also shown.

4. Conclusion

This paper demonstrates several methods for fabricating micro-optical components in polymer, either by micro-machining or micro-modification. In both cases it is important to work with a beam spot of the order or better than 1 μm in size. This ensures that the structures have the required smoothness and that the feature size matches that of optical components, like for example optical fiber core sizes. PBM can be used for rapid prototyping of a hybrid system that incorporates a micro-optical component, or for making metallic stamps for replication in polymer. Future work will involve the integration of micro-lenses and gratings with other systems like detectors and micro-fluidic channels to form complete micro-optical bio or chemical sensor systems.

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