Design and fabrication of nanoimprinted polymer optical devices

Nikolaos Kehagias, Vincent Reboud, Marc Zelsmann, Clivia M. Sotomayor Torres

University College Cork, Tyndall National Institute, Lee Maltings, Prospect Row, Cork, Ireland

Beatriz Hernandez Juarez, Isabelle Ledoux, Joseph Zyss

Ecole Normale Superieur de Cachan, Avenue du President Wilson, Cachan 94235, France

The need for accessible, flexible and low-cost functional optical devices and integrated optics is becoming increasingly acute as the optical communication network is expanding very fast. Polymer optical devices are expected to meet these requirements because they can be fabricated using a low-cost process with high manufacturing output. Polymer optics feature sizes down to 100 nm which could potentially meet key challenges in high quality optical communications systems. We report on the feasibility and process parameters of nanoimprint lithography (NIL) to fabricate waveguides, gratings, splitters and interferometers. This technique is very promising for the fabrication of complex polymer optical devices.

Keywords: polymer optical devices, nanoimprint lithography

1. INTRODUCTION

Due to their low cost fabrication and their high-volume manufacturing production, polymer nanoimprinted optical devices are becoming an optional solution to silicon based optical communication systems. Nanoimprint lithography[1] also known as hot embossing lithography seems to be the leading technique among all. Fig. 1 shows a schematic of this process. In the first step the stamp is pressed into a thin polymer film, which is spin-coated on a substrate. The imprinting is carried out for a few minutes at a temperature well above the glass transition temperature T_g (generally between 70 and 110 ºC) of the polymer, where the polymer has relatively low viscosity and can flow under force[2]. Then, the pressure is maintained during the cool down procedure and demolding and separation of the stamp and substrate takes place when the temperature is just under T_g. A further anisotropic etching process, such as reactive ion etching (RIE), can be used to remove the residual resist in the compressed area. The polymer thickness contrast left on the substrate after imprinting can be used for fabrication purposes (mask for dry etching or lift off) but can also be used as a device itself.

The NIL technique is particularly suitable for the fabrication of integrated polymer optical devices due to its high resolution and parallel processing of polymer layers. Furthermore, NIL can deliver a surface roughness compatible with the demands of light guiding. Passive devices such as diffraction gratings[3], waveguides[4] and micro ring resonators[5] have been fabricated as well as active devices like Mach-Zehnder interferometers[6] and lasers[7, 8].
In this paper we report first on the fabrication of some passive polymer optical devices (gratings, waveguides, splitters, interferometer) using the nanoimprint technique.

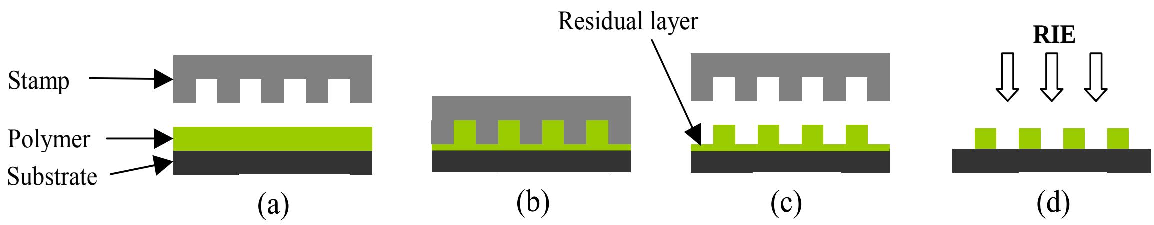

FIG. 1: Nanoimprint process: (a) sample and rigid stamp are heated to $T>T_g$, (b) stamp and sample are pressed together, (c) imprinted sample after cool-down and separation, (d) residual layer removal by Reactive Ion Etching (RIE).

2. FABRICATION DETAILS

Polymer optical devices where fabricated by nanoimprint lithography using the silicon stamp. Throughout our experiments we have been using polymers from *micro resist technology GmbH* (Germany). All experiments are done on an *Obducat* nanoimprinting equipment that allows the use of samples with diameters up to 2.5 in., temperatures up to 250 ºC and pressures up to 70 bars. A 300nm film of mr-L 6000 was spin coated on a Si substrate followed by baking at 120 ^{o}C for 5 min. Stamp and polymer where brought into contact at a temperature of 70 ^{o}C and a pressure of 60 bars for 5 min was applied. The separation of the stamp and the substrate was made at

45 ^{o}C. A typical result is shown in Fig. 2 (top part). The features from the silicon stamp are very well reproduced in the polymer layer. Even the smallest features (100 nm silicon lines on the stamp) are reported correctly (top left). The residual layer is about 150 nm thick in this case. By optimizing the process (thinner spin-coated polymer layer) this height could eventually be reduced, but for optical applications, this layer is not a crucial issue.

We have imprinted bended waveguides and interferometers in an 800 nm thick mr-L 6000 layer. The imprinting temperature was 80 ^{o}C while the pressure applied was 60 bars for 7 minutes. Details of some imprinted features are given in Fig. 2 (bottom), as well as in Fig. 3. We can see that the polymer waveguides are very well reproduced and that the chips have uniform colours indicating that the residual layer is very uniform. The bended waveguides are designed to make losses measurements using the cutback method (waveguides of different length). This is under progress at the moment as we are also working on the fabrication of an upper cladding in order for these waveguides to become monomode. For the use of the Mach-Zehnder interferometer, an upper cladding is also necessary and we are actually also investigating the imprinting of a polymer loaded with dyes in order to have an active device.

Nanoimprint lithography seems to be a very promising fabrication technique for polymer optical devices due to its parallel (low-cost) and high-resolution properties. Our results prove the simplicity of this technique and show how well the replicated structures could be formed in a polymer.

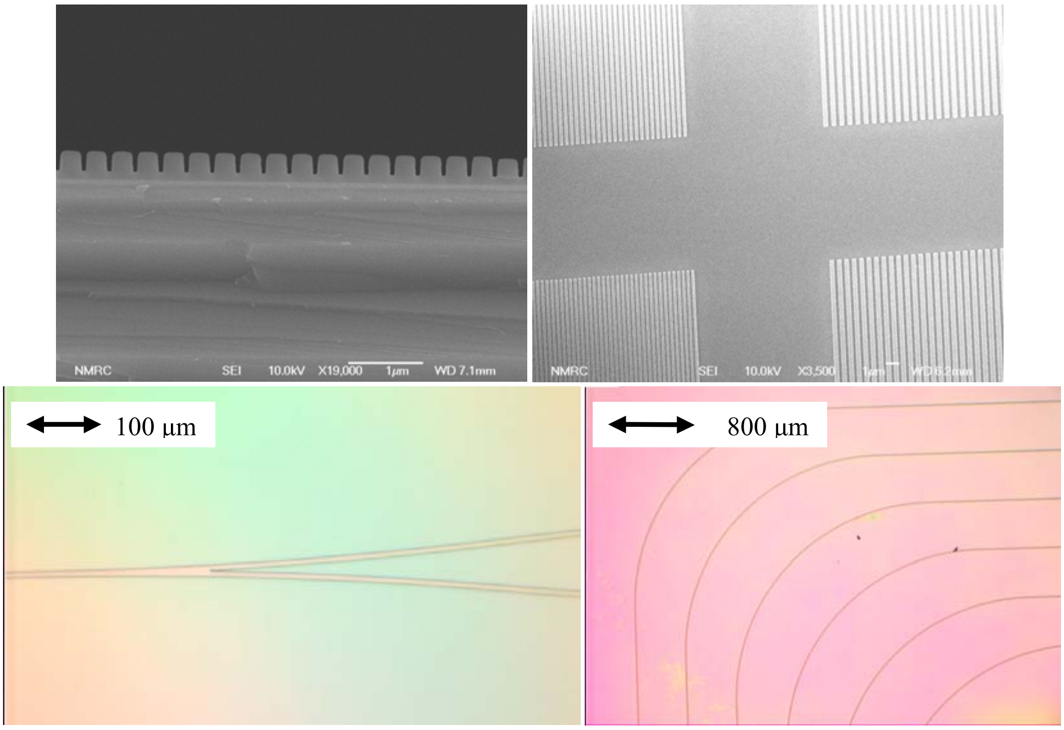

FIG. 2: SEM images of gratings imprinted in mr-L 6000 (top) and optical microscope image of a section of an interferometer (splitter, bottom left) and of bended waveguides (bottom right) imprinted in mr-L6000.

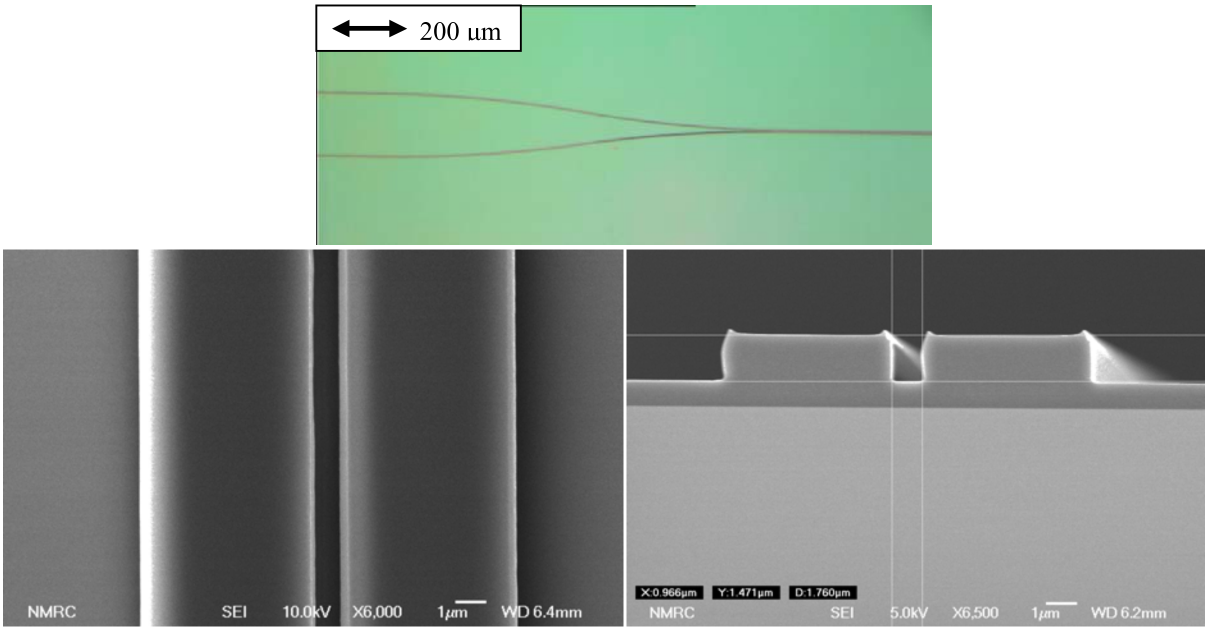

FIG. 3: Optical microscope image of a section of an interferometer (the two waveguides comes in near interaction, top) and SEM images of the two interfering waveguides (bottom).

3. Waveguide tests

First tests of optical waveguiding were performed using a simple experimental setup consisting of an Ar-laser (514 nm), optical fiber to transmit light from the laser to the edge of the sample, and optical elements such as mirrors and lenses to couple the laser light into the fiber. The output radiation from the waveguide structures was imaged in the near- field with a digital camera attached to a microscope and, in the far-field, by taking images on a screen located at a far-field zone. At this stage we did not achieve a good optical quality of the cut edge of waveguides, thus the coupling losses from fiber to this waveguide are too high. Therefore, below only tests of guiding in mr-L 6000 are presented.

The 514 nm light from an Ar-laser was coupled to the film slab waveguide by placing an optical fiber end as close as possible to the input edge of the mr-L 6000 sample. The near- field image of the output sample edge was obtained with a microscope.

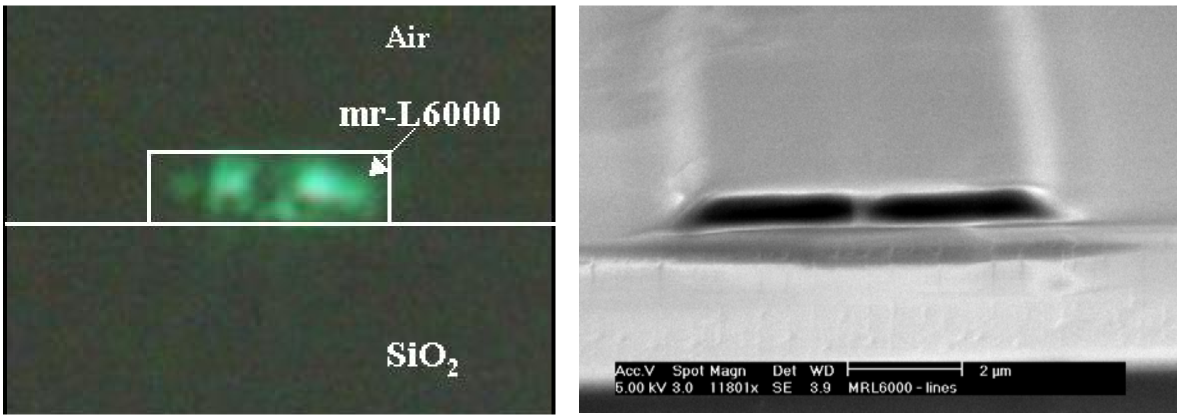

FIG. 4: Image of light guided in a mr-L 6000 slab polymer waveguide. White lines show the cross section of the polymer waveguide with dimension 1 µm × 6 µm (left). SEM cross-section image of the 1 µm wide strip written on a film of mr-L 6000 film-thickness on the line written sample. This is a typical mr-L 6000 waveguides written on silicon oxide substrate, by electron beam writing (right).

Fig. 4 shows the near-field power distribution of light propagation, as captured from direct imaging. Taking the far-field distribution image we are able to distinguish single mode propagation. The non-homogeneous intensity in the horizontal direction is ascribed to the poor quality of edge-cut, which can be clearly seen as an undesired feature on the SEM cross-section image (Fig. 4, right). Tests are in progress and particularly cutting and polishing the waveguides must be improved.

4. CONCLUSIONS AND PERSPECTIVES

Silicon stamps with several types of optical devices have been fabricated and these patterns have been successfully transferred into a polymer film by nanoimprint lithography. Nanoimprint lithography is shown to be a suitable fabrication technique for polymer integrated optics due to the high resolution and low-cost provided. Optical characterization of these waveguiding devices will be performed in the next months using a tunable laser at near-infrared wavelengths. Then, a study of the fabrication of a Mach-Zehnder modulator nanoimprinted in electro-optic will be performed with a functionalized PMMA material.

ACKNOWLEDGEMENTS: Financial support from the EU/IST project APPTECH (IST-2000-29321) and the German Research Council DFG is acknowledged. This work was partially funded by EC through project NaPa (Contract no. NMP4-CT-2003-500120) and the network of excellence PHOREMOST.

---

[1] C. M. Sotomayor Torres, “Alternative Lithography - Unleashing the Potentials of Nanotechnology”, Kluwer Academic / Plenum Publishers, New York (2003).

[2] L.J. Heyderman, H. Schift, C. David, J. Gobrecht, and T. Schweizer, “Flow behaviour of thin polymer films used for hot embossing lithography”, Microelectron. Eng. **54**, 229–245 (2000).

[3] J. Seekamp, S. Zankovych, A. H. Helfer, P. Maury, C. M. Sotomayor Torres, G Bottger, C. Liguda, M. Eich, B. Heidari, L. Montelius, and J. Ahopelto, “Nanoimprinted passive optical devices”, Nanotechnology **13**, 581–586 (2002).

[4] N. Kehagias, S. Zankovych, A. Goldschmidt, R. Kian, M. Zelsmann, C.M. Sotomayor Torres, K. Pfeiffer, G. Ahrens, G. Gruetzner, “Embedded polymer waveguides: design and fabrication approaches”, Superlattices and Microstructures **36**, 201–210 (2004).

[5] C.–Y. Chao, and L. J. Guo, “Polymer microring resonators fabricated by nanoimprint technique”, J. Vac. Sci. Technol. B **20 (6)**, 2862–2866 (2002).

[6] G. T. Paloczi, Y. Huang, A. Yariv, J. Luo, and A. K.-Y. Jen, “Replica-molded electro-optic polymer Mach-Zehnder modulator”, Appl. Phys. Lett. **85 (10)**, 1662-1664 (2004).

[7] M. Meier, A. Dodabalapur, J. A. Rogers, R. E. Slusher, A. Mekis, A. Timko, C. A. Muray, R. Ruel, and O. Nalamasu, “Emission characteristics of two-dimensional organic photonic crystal lasers fabricated by replica molding”, J. Appl. Phys **86 (7)**, 3502-3507 (1999).

[8] D. Pisignano, L. Persano, P. Visconti, R. Cingolani, and G. Gigli, “Oligomer-based organic distributed feedback lasers by room-temperature nanoimprint lithography”, Appl. Phys. Lett. **83 (13)**, 2545–2547 (2003).