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Hot embossing of polymer optical waveguides for sensing applications

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Abstract

Micro-optical sensors integrated into polymer foils hold great promise for a wide range of applications. One major challenge to date is the reliable, large-scale and cost-effective manufacturing of the required waveguide structures. Several techniques are currently investigated in the field, hot-embossing being particularly promising. In this work, we discuss hot embossing of polymer optical waveguides. We present our recent results in the area of stamp manufacturing and waveguide fabrication. For the characterization of the waveguides, the refractive index, the transmission losses and the beam profile of the coupled light are measured. We also describe next steps towards more advanced waveguides.

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1. Introduction

The present work is a part of the Collaborative Research Center “PlanOS”. The aim of PlanOS is the integration of highly-functional micro-optical sensor networks into thin polymer foils and their application for large-area distributed sensing. Micro-optic polymer sensors have a very wide range of application. For example, an optical waveguide with grating structures integrated in its core can be used to form a temperature sensor. The transmitted wavelengths are dependent on the grating period, which varies with temperature due to thermal expansion [1]. Strain sensing is also possible using polymer optical waveguides. The applied strain on the sensor sheet can be derived from the change in the optical output signal, which results from the mechanical deformation of the waveguide structures [2][3]. Furthermore, polymer optical waveguides are utilized to fabricate interferometric sensors, such as

Mach-Zehnder interferometers. These devices are frequently used for detection of specific chemical or biological substances. An analyte changes the refractive index in one arm of the interferometer, inducing a change in the output intensity of the device due to interference. Thus, the described interferometers are capable of detecting the change in the composition of the analyte [4]. Another application area consists of the fabrication of whispering gallery resonators, which resonance frequency varies as a function of the surrounding analyte. These resonators have a high sensitivity and are even capable of detecting single molecules [5].

One of the most important building blocks of these sensors is the optical waveguide. Such waveguides can be fabricated using various techniques, such as photolithography [6], flexo- and inkjet-printing [7], nanoimprint lithography [8], processing with femtosecond lasers [9] and also hot embossing. Hot embossing is a replication process that is based on the transfer of a stamp structure onto a substrate. The process is suited for the replication of structures with dimensions from the millimeter- to the nanometer-scale. For optical applications, hot embossing is an attractive fabrication process because it potentially allows a large scale and cheap fabrication [10] and can be integrated in roll-to-roll processes [11].

In the past years, several research groups investigated the fabrication of optical waveguides through hot embossing. Different stamp fabrication techniques were examined such as LIGA-technology [12], photolithography [13], micro-machining [14] and etching [15]. Moreover, various polymer materials were investigated, including photoresists [16] and thermoplastics [10]. The fabricated waveguides operate in single-mode and multi-mode regime [16] and were used for optical communication [17] and sensing applications [18]. Depending on the embossing stamp and the polymer materials, the waveguide transmission loss ranges from several dB/cm to values under 1dB/cm [10].

In the present article, we present the hot embossing of optical waveguides using micro-machined mold inserts and optical adhesives as core material, which further increases the cost-effectiveness of the fabrication process. First, the hot embossing of polymer substrates is briefly reviewed and the application of the technique for fabrication of optical waveguides described. Then, first experimental results are presented. Finally, the technical challenges and next steps of the work will be discussed.

Nomenclature

PMMA	Polymethyl-methacrylate
PDMS	Polydimethylsiloxane
n_D	Refractive index at the wavelength of 589nm

2. Hot embossing of thermoplastic polymer

The hot embossing process is displayed in figure 1 and consists of four consecutive steps: In the first step, a structured mold and a thermoplastic substrate are heated to the molding temperature. The molding temperature where the thermoplastic is in the rubbery state lies between the glass transition temperature and the melting temperature of the polymer [19], and depends on the substrate material. The second step is the embossing which consists of pressing the stamp against the substrate with a certain force and for a defined period of time. During this step the stamp structure is transferred into the polymer. The third step consists of the cooling of the stamp and substrate to a temperature below the glass transition temperature of the polymer. In the fourth process step - the so-called demolding step - the stamp and substrate are separated.

In addition to its dependence on process parameters such as molding temperature, molding time and embossing force, the quality of the hot embossed structures depends mainly on the quality of the stamp. As described above, a multitude of mold fabrication methods are available. Depending on the fabrication technique, the molds are usually composed of metals, silicon or polymer materials [11]. Furthermore, elastomer stamps can be fabricated by casting an elastomeric material on the hard stamps manufactured by one of the above techniques and can be used to pattern polymer substrates. The most important advantages of using elastomer stamps are the increase in the lifespan of potentially expensive master stamps and the favorable anti-sticking properties of elastomers. The mold fabrication

technique is usually chosen with regard to the required structure dimensions, the mechanical and chemical properties of the stamp material, the mold surface quality, and the costs, among others [10].

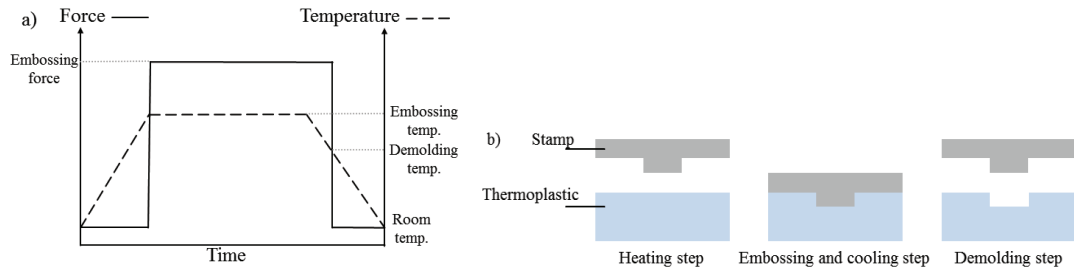


Fig.1. Schematic illustration of the hot embossing process (a) Main process parameters: Temperature and molding force as function of time; (b) The process steps of hot embossing consist of the heating and embossing step, followed by the cooling and demolding step.

In the present work, an aluminum master stamp was fabricated through micro-milling. Several microchannels were engraved on the stamp surface. The microchannels have a depth of $60\mu\text{m}$ and a width of $100\mu\text{m}$ and $500\mu\text{m}$. Figure 2 shows a photograph of the stamp surface which was analyzed using a confocal laser scanning microscope, in order to determine the surface roughness of the sample. The surface roughness is a very important quantity for the fabrication of optical waveguides and should be as small as possible to avoid light scattering at rough surfaces [20]. The measured average surface roughness varies between 150 and 250 nm depending on the individual microchannels. In the next step, the aluminum stamp was replicated in PDMS and used as the actual embossing stamp, which in turn was replicated in the thermoplastic PMMA. The thickness of the patterned PMMA foils is $175\mu\text{m}$.

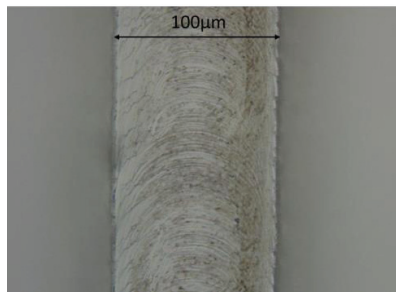


Fig.2. Aluminium stamp fabricated through micro-milling: Photograph of the microchannel structure on the stamp. The average surface roughness varies between 150 and 250nm, as measured with a confocal microscope.

For the described replication process, a commercial hot embossing machine HEX03 from Jenoptik Mikrotechnik GmbH was used. The machine has a plate-to-plate configuration and delivers a maximum embossing force of 200kN and a maximum embossing temperature of 300°C . It also includes a vacuum chamber and a stamp positioning system. It can be used to pattern substrates with diameters of up to 4 inches.

3. Hot embossing of optical waveguides

The patterned thermoplastic substrates were then used to fabricate optical waveguides. These PMMA substrates serve as the waveguide undercladding. The other two components required are the overcladding and the core material: The overcladding consists of the same material as the undercladding, whereas the core material consists of

a thermosetting polymer. We used commercial thermosetting epoxies and thermosetting polymers provided by our collaborators within PlanOS. Table 1 summarizes the core and cladding materials used in the present work.

Table 1. Polymer materials utilized for waveguide fabrication.

Polymer	Material type	n_D	Manufacturer
PMMA	Cladding	1.491	ThyssenKrupp
SB40	Core	1.555	PlanOS
Epotek 301	Core	1.519	Epotek
Epotek 310-M2	Core	1.4947	Epotek
Polytec EP601	Core	1.5645	Polytec
Polytec EP610	Core	-	Polytec

The hot embossing of optical waveguides is similar to the hot embossing of thermoplastics, as it has a heating and an embossing step. The structured undercladding serves as a stamp to pattern the waveguide core layer. At the beginning of the process, the core material is liquid. A second thermoplastic layer is also needed to build the overcladding. The first process step consists of pouring the liquid core material between both cladding layers and applying a pressing force between them, thus, removing the excess polymer material and reducing residual layer. In the second step, the samples are heated to the curing temperature of the thermosetting polymer, which should not exceed the glass temperature of the cladding in order to prevent any structure deformation of embossed patterns. After the curing time, the pressing force is released. The core polymer acts as an adhesive, which glues the three layers. The whole process is summarized in figure 3. In the following chapter, the experimental results obtained are discussed in detail.

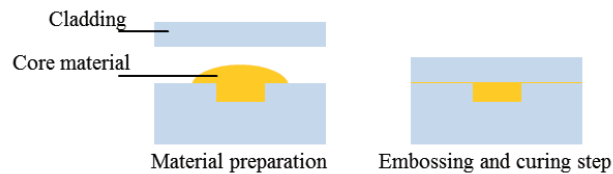


Fig.3. The main steps of the hot embossing of planar optical waveguides: After deposition of the liquid core material, a force is applied on the cladding layers. The sample is then heated to the curing temperature of the core material and the pressing force is released after the curing time.

4. Experimental results and waveguide characterization

After fabrication, the polymer waveguides were cut into sheets with a waveguide length of $L_1=7\text{mm}$ and $L_2=5\text{mm}$. The side facets were polished to provide optically smooth surfaces. Figure 4 shows a microscope image of a cross section of the polished waveguides.

The residual layer is caused by the hot embossing process itself during the production of the core and has a thickness of less than $10\mu\text{m}$. The smaller this layer is the less light is lost during propagation through the waveguides. This is because the residual layer is made of the same material as the core itself. If this layer is too thick, the light from the waveguide leaks into this layer. The yellow color of the core material originates from the material itself.

For optical characterization, the light transmission through the waveguide is measured and the attenuation deduced. Furthermore, the guided modes were examined by using a beam profiler (Thorlabs) and the refractive index was measured by using a refractive index profilometer (RINCK elektronik).

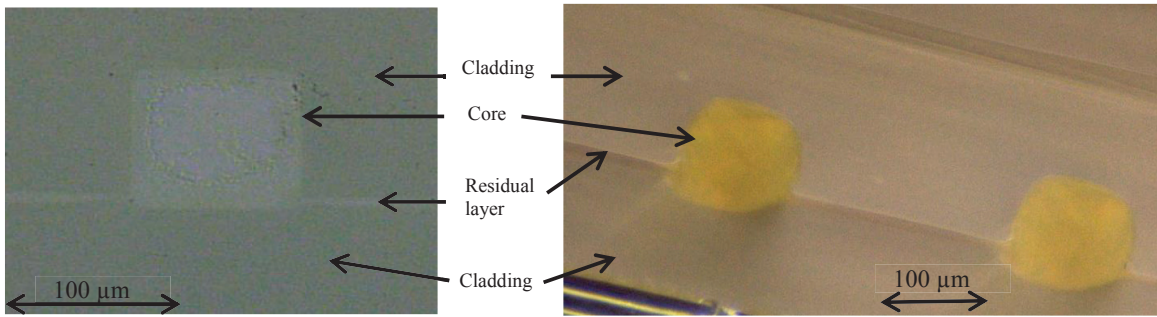


Fig.4. Cross section of the hot embossed polymer waveguides. Cladding material of both waveguides is PMMA. Core materials are Epotek 301 (left structure) and SB40 (right structure).

For the mode profile measurement, the coupling of the light was realized by butt coupling of a 50 μ m fiber and the waveguide under study. The fiber in turn is connected to a diode laser module. In order to quantify the near field intensity distribution, the beam profile was registered by a Spiricon BM-USB-SP620 beam profiler following a 4x-Re-imaging beam expander.

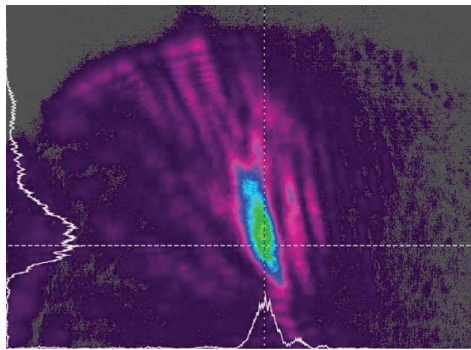


Fig.5. Near field intensity distribution at the end of the SB40 waveguide.

The intensity distribution in figure 5 shows wave guiding through the hot embossed waveguide structure. The purple shadows in the picture are attributed to scattering effects at the end of the waveguide. The white lines on the left and on the bottom of the picture show the intensity distribution along the vertical and horizontal marker lines, respectively.

Figure 6 shows a refractive index measurement of a produced waveguide obtained by using the above refractive index profilometer [21, 22]. For this case, the waveguide core material consists of SB40. The measurement implies a refractive index difference of approximately 0.055.

The numerical aperture NA of the waveguide can be calculated using formula (1) and gives information about the half angle of acceptance θ_A , i.e. the maximum angle of the incoming rays that are able to propagate inside the waveguide.

$$NA = \sqrt{n_{co}^2 - n_{cl}^2} = \sin \theta_A \quad (1)$$

The refractive index of the core is denoted as n_{co} and that of the cladding as n_{cl} . In the case discussed here the waveguide has a numerical aperture of 0.41 and $\theta_A = 24.24^\circ$. The whole cone of acceptance has an opening angle of 48.48° . A large angle of acceptance is necessary in order to increase light coupling through the waveguide.

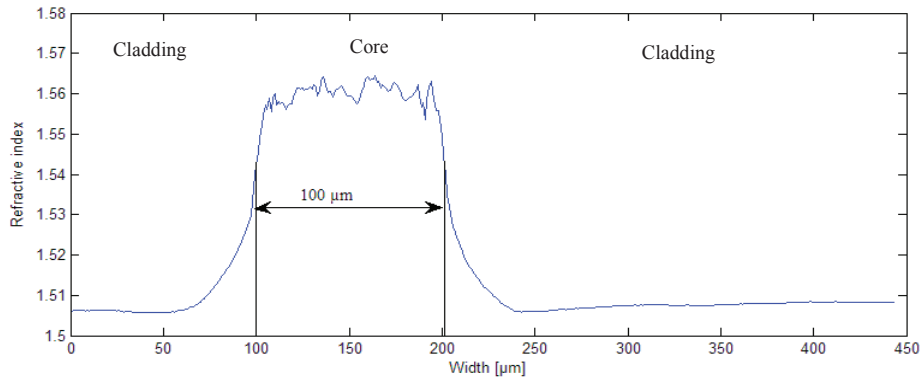


Fig.6. Refractive index line measurement of the SB40 waveguide.

The attenuation of the produced SB40 waveguides was measured with a setup consisting of a diode laser system operated at four different wavelengths, an optical powermeter and two fibers. Each of these fibers was butt-coupled to the waveguide and was adjusted for maximum intensity. The attenuation of two waveguides with different lengths was measured. This allows the subtraction of the coupling losses. The core diameter of the coupling fibers was 50 μm . The results of the attenuation measurement are given in table 2. Table 2 indicates that the attenuation decreases with wavelength which is characteristic for polymers and glasses.

Table 2. Measured attenuation at different wavelengths.

Wavelength [nm]	Attenuation [dB/cm]
406	25.4
638	14.1
685	9.0
850	6.4

The attenuation α was calculated using the formula (2) [23]:

$$\alpha = \frac{10}{\Delta L} * \log \left(\frac{I_{L1}}{I_{L2}} \right) \quad (2)$$

where ΔL is the length difference between the measured waveguides and I_{L1} and I_{L2} are the measured intensities at the exit port.

A reason for the relatively large attenuation measured is the wavelength selective absorption in the core material, as indicated by its yellow color. Furthermore, the roughness of the waveguide surface leads to scattering which also increases attenuation. A third factor is the residual layer which enables leakage of the light out of the core. The roughness and the thickness of the residual layer are affected by the hot embossing process and can be reduced by improved stamps and process parameters. Material absorption on the other side can be decreased by chemical modification of the core material.

5. Conclusion and outlook

Hot embossing is a promising manufacturing process for the integration of optical sensors in polymer foils. In this paper the hot embossing process was briefly reviewed with specific emphasis to our application. The manufactured stamp was characterized and used to fabricate polymer optical waveguides. Different polymer materials were used as waveguide core and cladding. The refractive index of the waveguide and the beam profile of

the transmitted laser beam were investigated. Furthermore, waveguide transmission losses were measured at different wavelengths.

In the next steps we will concentrate on manufacturing polymer optical waveguides using stamps with a lower surface roughness. Furthermore, the application of an UV-embossing machine will be investigated, in order to access the wide range of UV-curing polymer materials. The goal is the fabrication of polymer waveguides that have lower transmission losses, thus, improving the efficiency of polymer integrated optical sensors. The integration of light coupling structures, optical sources and detectors will also be investigated in order to manufacture entire sensor systems in the long term.

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