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ScienceDirect
Procedia Technology 26 (2016) 309 – 315
Procedia Technology

3rd International Conference on System-integrated Intelligence: New Challenges for Product and Production Engineering, SysInt 2016

Flexible and low-cost production of waveguide based integrated photonic devices

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Abstract

We present a process to fabricate fully polymer based integrated optical devices which is based on maskless lithography and hot embossing. Using the maskless lithographic setup, we are able to create a hot embossing stamp in a flexible and fast manner. We demonstrate that our process is capable of creating linear optical waveguides, Y-splitters and Mach-Zehnder interferometers designed by preliminary optical simulations. The fabricated structures are analyzed with respect to optical smoothness and line edge roughness. In the future, our process will greatly enhance a fast design and fabrication of complex optical sensor structures.

Peer-review under responsibility of the organizing committee of SysInt 2016

Keywords: Integrated photonics; maskless lithography; waveguides; polymer photonics; hot embossing

1. Introduction

Optical sensors based on integrated photonic devices have already made the transition from research laboratory into daily life use. While telecommunication applications are the largest market for integrated photonics and established production techniques for such devices are at hand, latest applications focus on, e.g., biomedical and bioanalytical applications [1,2]. Sensors which are especially suited for the latter application class, however, are highly specific in terms of materials utilized for sensor fabrication as well as the optical design and layout due to the

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Peer-review under responsibility of the organizing committee of SysInt 2016
doi:10.1016/j.protcy.2016.08.040

high diversity of the application field. Hence, a fabrication technique which is capable of fabricating such sensors on a short time scale as well as in a flexible manner is highly desirable to meet modern industrial demands often referred to as “Industry 4.0”. Commonly, integrated photonic devices are fabricated by means of semiconductor technologies based on inorganic materials such as silicon or silica. These technologies deliver low-cost products if throughput rates are high such as in the case of computer technology but they are distinguished by a lack of flexibility. Therefore, another material class namely polymers have gained increasing interest for integrated photonics due to their excellent optical properties, comparably low asset costs for fabrication devices and the flexibility of the available fabrication processes [3]. As most optical integrated sensor devices rely on optical waveguides, manufacturing techniques to create integrated light guiding structures are essential. An elegant and flexible way to create waveguides in bulk polymers such as polymethylmethacrylate (PMMA) is achieved by altering the refractive index through exposure to ultraviolet light utilizing photolithographic processes [4]. Alternatively, a waveguide can be directly inscribed into PMMA by means of fs-laser radiation which is focused into the bulk polymer [5]. Both techniques provide a high flexibility with regard to the structure’s geometry to be created. However, core and cladding materials are essentially the same in both cases which does not allow for including other core materials with, e.g., active optical properties such as electro-optical characteristics [6]. To employ different core materials, hot embossing is a suitable fabrication process. Commonly, trenches are created by embossing a master mold into a polymer substrate at an embossing temperature above the glass transition temperature of the substrate material. Waveguides are formed by inserting a core material into the trenches subsequent to the hot embossing step [7].

Prominent application examples of integrated optical sensor systems are Mach-Zehnder interferometers (MZI), which are utilized to detect chemical or biological substances [1]. Fabrication of such devices was demonstrated utilizing various processes including UV direct structuring [4] and hot embossing [6,8,9]. The latter process was also employed to include electro-optical materials in one of the interferometer arms to create optical switches [6].

In this work, we present a flexible and low-cost fabrication process for entirely polymer-made integrated photonic devices which is based on an initial maskless lithography and a subsequent hot embossing process step. We demonstrate that the process is capable of creating feature sizes even in the sub-micron range on an area of several square centimeters. Thus, the process even lends itself for the fabrication of large-area waveguide sensing structures which are operated in the single mode regime. To fabricate such polymer based integrated photonic devices, we initially created a hot embossing step consisting of a silica substrate which is coated with Ormocer, a hybrid organic-inorganic polymer. To transfer an inverse of the waveguides and other relevant microstructures of the sensor devices to be fabricated into the Ormocer layer, we utilized a self-made maskless lithography setup. The setup is based on a digital-mirror-device (DMD) projector technology and a standard microscope setup, which generates a two-dimensional intensity distribution at a wavelength of 405 nm and transfers the DMD image into the Ormocer. After a development process step, the glass substrate contains superficial Ormocer microstructures and is used as hot embossing stamp. The microstructures are transferred into a PMMA substrate which serves as waveguide cladding. Subsequently, the microstructures are filled with liquid monomer, which is cured by applying UV radiation and acts as waveguide core material.

Nomenclature

d_w	waveguide diameter
$d_{\parallel}$	separation of Mach-Zehnder interferometer arms
L_Y	Y-splitter length
$L_{\parallel}$	length of Mach-Zehnder interferometer arms
λ	vacuum wavelength
NA	numerical aperture
n_{core}	refractive index of the waveguide core
n_{clad}	refractive index of the waveguide cladding
PMMA	polymethyl methacrylate
MZI	Mach-Zehnder interferometer

2. Fabrication process

2.1. Waveguide fabrication by hot embossing

The waveguide fabrication process consists of four consecutive steps as shown in Fig. 1. First, we carried out a hot embossing step, where a master stamp containing an inverse of the optical structures to be created is transferred into a polymer substrate which serves as waveguide cladding. As master stamp, we utilized a microscope silica cover slide (Carl Zeiss) with an Ormocer (Microresist Technology) coating which was microstructured by maskless lithography as described in detail in Sec. 2.2. We chose polymethyl methacrylate (PMMA) as substrate material, which is a thermoplastic with a glass transition temperature of 105°C. For pattern transfer, the PMMA substrate and the cover slide were heated to 130°C, which is well above the glass transition temperature of PMMA.

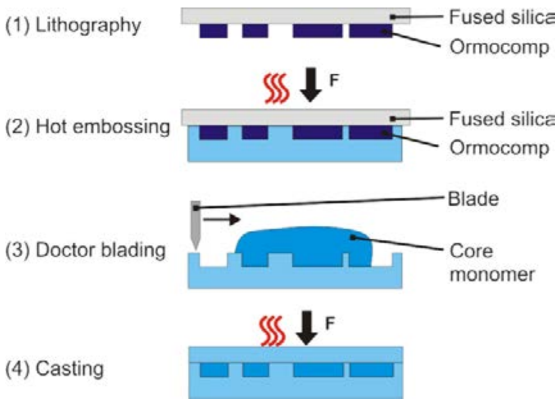

Fig 1. Fabrication process for fully polymer based photonic devices.

Subsequently, an embossing force of approximately 2 kN was applied for 2 min. For hot embossing we utilized a self-made hot embossing machine described in detail in [10]. After cooling to room temperature, the stamp and polymer substrate were removed from the hot embossing machine and separated manually. In the current process stage, the PMMA substrate contains grooves which need to be filled with core material to achieve waveguiding. As core material we used a liquid commercially available printing ink (390119 UV Supraflex, Jänecke+Schneemann Druckfarben) which was applied manually onto the substrate and spread by a doctor blading process. Subsequently, the core material was cured by UV exposure at a wavelength of 365 nm.

2.2. Stamp fabrication by maskless lithography

For stamp fabrication, we utilized a maskless lithography setup which is shown in Fig. 2 and described in detail in [11]. The essential component of the device is a digital-mirror-device (DMD) with a pixel pitch of 13.6 µm (Texas Instruments DLP7000). An image of the microstructure to be created is uploaded onto the DMD prior to pattern generation. As light sources for the DMD we utilized two LED which are used for autofocusing and lithography and run at wavelengths of 650 nm and 405 nm, respectively. Both LED are collimated by plan-convex lenses and can be controlled by an Arduino microcontroller board. Additionally, the UV LED which runs at 405 nm is homogenized using a diffractive flat top diffuser (Thorlabs) to achieve a homogeneous illumination of the DMD during the lithographic process. The intensity distribution generated by the DMD is imaged and demagnified by a standard microscope setup (Carl Zeiss) onto the silica substrate covered with photosensitive resist or liquid monomer. For imaging we utilized an apochromatic microscope lens (Carl Zeiss Epiplan) with a numerical aperture of NA = 0.3 and a magnification of ten. Therefore, the minimal feature size which can be generated by the setup equals 1.36 µm. The area which can be illuminated by a single exposure shot is limited due to the field of view of the microscope of 1.9 mm x 1 mm. To extend the structurable area to several square centimeters, the substrate is placed on a two-axis linear translation stage (two SLC-1780-S, Smaract, Germany) which allows for carrying out several exposure runs sequentially. After each single exposure, the substrate is moved by the translation stage to perform a stitching process. However, the focal position of the lithography setup needs to be precisely constant with respect to the substrate surface to obtain a sharp image of the DMD during each exposure run. Therefore, the microscope lens is attached to an additional linear stage (SLC-1780-S, Smaract, Germany) which is oriented vertically along the optical axis of the microscope. To determine the optimal focal position of the lens, the image being projected onto the substrate is captured by a camera (Pike 421, AVT) via a beam splitter which is place inside the beam path of the microscope setup. The best focal positon is obtained by projecting a checkboard-like pattern onto the substrate and moving the microscope lens until the optimal position is determined from the camera image by a variance based autofocus algorithm as described in [12]. During each autofocus run, the LED with a center wavelength of 650 nm is used for illumination to avoid undesired exposure of the resist. During each lithographic exposure run, the LED with a wavelength of 405 nm is switched on for 180 seconds.

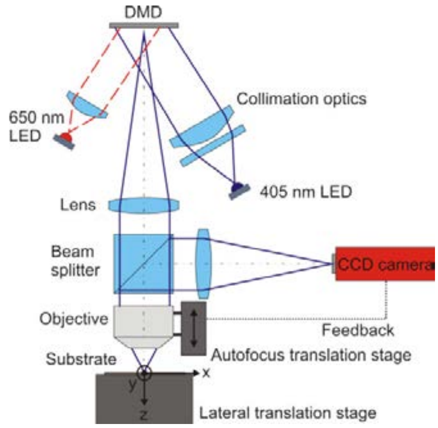

Fig 2. Sketch of the maskless lithographic setup used for hot embossing stamp fabrication.

For stamp fabrication, first we coated a silica made microscope cover slide (Carl Zeiss) with a thin layer of Ormocomp hybrid polymer (Microresist Technology). To achieve a coating thickness of approximately 4 µm, we diluted 5 ml Ormocore in 5 ml Ormothin (Microresist Technology) thinner to reduce its viscosity and spin coated the resist onto the silica slide at a rotational speed of 4000 rpm. During the lithographic process we carried out two bake steps: first, we applied a prebake at 80°C for 2 min. After exposure, another bake was applied to the slide at 150°C for 10 min. The microstructures were developed by placing the slide in an OrmoDev developer (Microresist Technology) bath for 1 min and rinsing the slide with pure water subsequently.

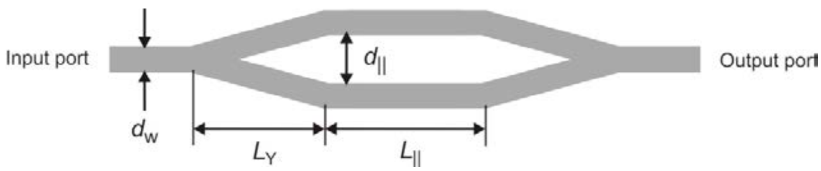

Fig 3. Layout of the Mach-Zehnder interferometer and relevant geometrical parameters of the interferometer.

3. Mach-Zehnder interferometer design

As photonic device to be fabricated and to demonstrate the capability of our process, we chose a Mach-Zehnder interferometer (MZI). The layout of the device and all relevant geometrical parameters are summarized in Fig. 3. The physical principle of the interferometer is based on a variation of the refractive index of one of the interferometer arms as the refractive index of the other stays constant. Assuming a coherent beam is being coupled

into the input port of the interferometer and the geometrical path length in both interferometer arms is the same, the intensity which is measured at the output port is only dependent on the optical path length difference (OPD) between both interferometer arms due to interference. The OPD is determined by the arm length as well as the refractive index of both interferometer arms. If the refractive index of only one arm varies due to changing environmental conditions, the measured intensity at the output port depends on these conditions and is determined by the interferometric contrast of the interferometer. A detail description of the physical principle of the MZI is given in [1].
To give an example of a suitable selection on the MZI design, we consider the sensor geometry shown in Fig 3. The waveguide width d_w determines, in addition to the refractive indices n_{core}=1.52 and n_{clad} =1.49 of the core and the cladding materials, respectively, the number of modes propagating inside the interferometer. Best interferometric contrast is obtained when the waveguide is operated in the single-mode regime. However, since our fabrication process is limited to a feature size of 1.36 µm, we chose a waveguide width of five DMD pixels which corresponds to a waveguide width of 6.4 µm. Hence, the interferometer is operated in the few-mode regime. Other important parameters are the Y-splitter length L_Y and the separation distance between the interferometer arms $d_{||}$. These parameters determine the opening angle of the Y-splitter which influences optical losses due to optical splitting. In our case, we chose $L_Y = L_{||} = 1$ mm and $d_{||} = 10$ µm. The performance of the MZI was simulated by means of the beam propagation method using the commercial software RSoft (Synopsis). As input signal we assumed a Gaussian beam with its beam waist being located at input port of the interferometer as indicated in Fig. 3. The beam waist diameter was 6 µm and we assumed a wavelength of 633 nm.

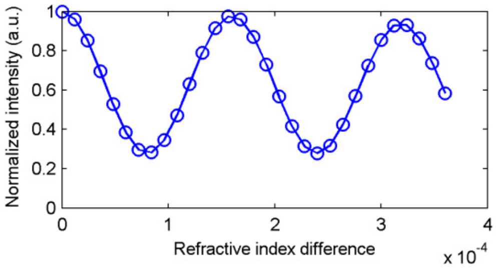

Fig 4. Simulated normalized intensity at the interferometer output port as function of a refractive index difference between both interferometer arms.

From Fig. 4 it can be seen that even if the interferometer is operated in the few-mode regime, one obtains a significant interference contrast up to 0.73, being defined as the difference between highest and lowest intensity. Hence, the chosen waveguide diameter of 6.4 µm is suitable for the fabrication of the MZI.

4. Fabrication results

To demonstrate the capability of our fabrication process, we fabricated linear waveguides, Y-splitters and MZI. The waveguide diameter of $d_w = 6.4$ µm was chosen according to the simulation presented in section 3. However, since the emphasis of the paper is on the fabrication technology rather than on the optical performance of the waveguides and MZI, we chose $L_Y = L_{||} = 200$ µm and $d_{||} = 150$ µm. This is a suitable selection to estimate the influence of the discretized DMD pixels since we are not able to fabricate microstructures with continuous edges which might lead to a significant line edge roughness.

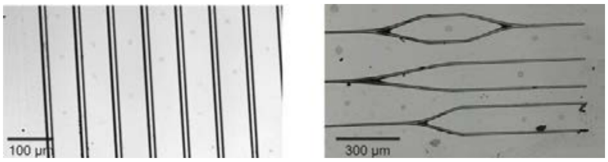

Fig 5. Fabricated optical elements in a PMMA substrate: linear waveguides (left) and Y-splitter and Mach-Zehnder interferometers (right).

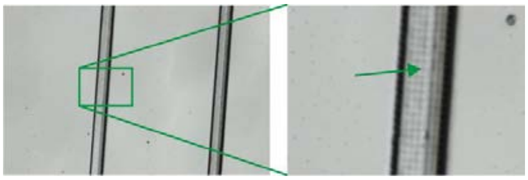

Fig 6. Enlargement of the microscope images of the linear waveguides shown in Fig. 5.

Microscope images of the fabricated linear waveguides as well as the Y-splitter and Mach-Zehnder interferometer are shown in Fig. 5. Fig. 6 shows an enlargement of the linear waveguides in Fig. 5, which indicate that the waveguides show a checkboard-like structure on top due to the discrete pixels of the DMD. However, confocal topography measurements yielded a waviness of 20 nm, which is small compared to an optical wavelength of 633 nm. An enlargement of the splitter region is displayed in Fig. 7. The splitter region shows a remaining side wall

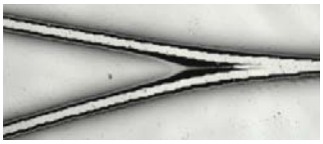

Fig 7. Enlargement of the microscope images of the linear waveguides shown in Fig. 5.

roughness after the fabrication process which is also due to the discrete pixels of the DMD. However, the influence of the pixels is larger in the structures shown in Fig. 6 and 7 due to the large opening angle of the Y-splitter compared to the simulation parameters used in section 3. We expect a negligible influence of the side wall roughness when fabricating interferometric structures which exhibit significant smaller opening angles. However, first preliminary optical performance tests were carried out by launching laser light with a wavelength of 635 nm from a single mode fiber (Thorlabs) into the Y-splitter as shown in Fig. 8.

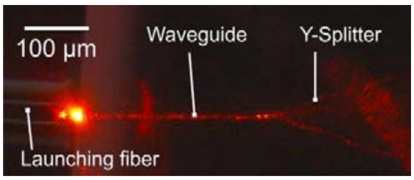

Fig 8. Laser light with a wavelength of 635 nm launched into the Y-splitter fabricated by hot embossing and doctor blading.

However, since the emphasis of this paper lies on the fabrication, we will carry out fabrication and optical characterization of MZI as simulated in section 3 in future work.

5. Discussion

We demonstrated a fabrication process for fully polymer based integrated photonic devices such as embedded linear waveguides, Y-splitters and Mach-Zehnder interferometers. The process relies on a hot embossing process step to generate grooves in a polymethyl methacrylate made thermoplastic substrate. The grooves were filled with a liquid monomer by a doctor blading process and cured by exposure to UV light subsequently. The hot embossing stamp was made from a silica cover slide coated with an Ormocer hybrid polymer which was structured by means of a self-made lithographic setup. Furthermore, we carried out optical simulation of a Mach-Zehnder interferometer to estimate the influence of the waveguide width on the interferometric contrast. The simulation results showed that even when fabricating waveguides with a diameter of 6.4 µm, which work in the few-mode regime, one obtains interferometric contrasts up to 0.7 which is still suitable for most sensing application. Linear waveguides, Y-splitter and Mach-Zehnder were fabricated according to these simulation results. The optical elements were characterized by light microscopy images and confocal topography measurements, which indicate a remaining waviness of 20 nm on top of the fabricated waveguides and a remaining line edge roughness. Both effects are due to the lithographic process but are expected to be negligible in the optical performance of the sensors. Future work will therefore focus on the optical characterization of the fabricated optical structures. In future applications, our process enables a fast and flexible fabrication of small series and optical sensors at the proof-of-concept stage. Especially, since no photolithographic mask is needed, the proposed method allows for the fabrication of sensors without expensive and/or time consuming mask production which is a significant matter of expense at the small series or research level.

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