Production and characterization of all-polymer based optical waveguides and interconnects

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We present our recent work on the production of polymer waveguides using hot embossing, photolithography, and laser ablation techniques and discuss the feasibility for implementation in high-throughput reel-to-reel processes. We have also developed a method based on self-focusing of laser light in polymer to realize reliable and efficient optical interconnects between waveguides at will.

1 Introduction

Optical waveguides are key ingredients for integrated photonics and optical sensors. Integrated optics and photonics is widely used for sensing applications to measure quantities such as temperature, strain or molecular concentration [1,2]. If parts of such sensors are functionalized using suitable substances, optical sensors are also capable of selectively detecting biomolecules or biochemical reactions [2]. Common micro-geometries used to realize such sensors are ring resonators or whispering gallery mode resonators [2]. However, state-of-the-art technologies to fabricate these devices rely on silicon based processes, which are inherently expensive and time consuming. Therefore, in an attempt to meet modern demands, fast, low-cost and high throughput fabrication processes are essential, in particular also to ultimately enable a market entry of such sensors. To overcome the drawbacks of silicon photonics, polymers are an adequate alternative to standard materials such as Si, SiO_2 or Si_3N_4. Being less resistant against chemical and environmental influences compared to the latter materials, polymers are, however, cheaper, easier to process and enable the realization of disposable micro-sensors. In this work, we present our recent results on the fabrication of fully polymer based waveguides based on a hot embossing process and the implementation of coupling structures to couple light in and out of the waveguide arrays.

2 Waveguide fabrication and results

The fabrication process for fully embedded polymer waveguides is illustrated in Fig. 1 [3]. During an initial fabrication step, the under cladding of the waveguide is fabricated by hot embossing. A master stamp and a polymer substrate made from Polymethylmethacrylate (PMMA) are heated to the embossing temperature ϑ_E = 140°C, which is well above the glass transition temperature of the PMMA. Subsequently, the stamp is embossed into the PMMA by applying an embossing force of F_E = 10 kN. Then, stamp and cladding are demoulded by applying an undetermined demoulding force F_D manually.

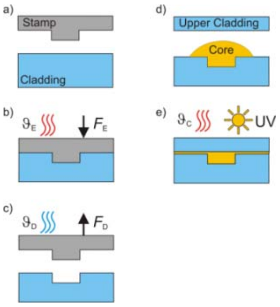

Fig. 1 *Fabrication steps for fully embedded waveguides; (a)-(c) hot embossing of lower cladding; (d)-(e) application of core material, embedding of waveguide an curing of core monomer.*

As stamp, we utilized silicon based microstructures, which were fabricated by etching technologies, maskless lithography, as well as metal stamps created by ultra-precision milling and laser ablation. After demolding, a core material is applied and covered with the upper cladding. Depending on the core material, the core monomer is cured either thermally at a temperature ϑ_C=80°C or by applying UV-radiation. The process was carried out using various Epoxi-based core materials (Epotec, NOA68, self-made).

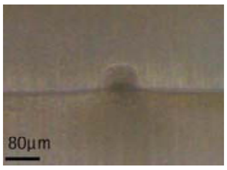

Fig. 2 *Cross-section of an embedded multimode waveguide integrated in a PMMA cladding*

Fig. 2 shows a cross-section of a fabricated multimode waveguide with a rectangular core of 50 x 50 μm^2. After fabrication, the attenuation of the wave-

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guides was determined by the cut-back method. We achieved a total loss of 4.6 dB/cm in the wavelength range of 850 nm using thermosetting Epoxy materials.

3 Coupling structures and interconnects

To realize integrated sensors based on optical waveguide arrays, low loss coupling structures and interconnects between waveguide and sensor elements as well as light sources and detectors are essential. The specific type of coupling structure depends on the waveguide dimensions, coupling direction and the optical components to be connected. For instance, vertical emitting laser diodes (VCSEL) require different structures compared to side emitting laser diodes (LD), the latter of which are utilized in this work.

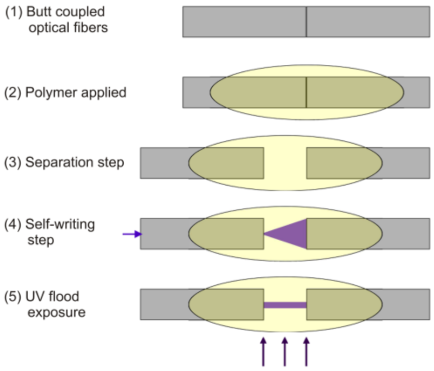

Fig. 3 *Process steps for creating self-written waveguide interconnects (from [4]).*

To create fiber-waveguide, waveguide-waveguide and LD-waveguide interconnects we developed a simple process based on self-written waveguides [4]. The process steps are exemplarily shown in Fig. 3 for a fiber-fiber interconnect. In an initial step, both fibers are positioned with respect to their optical axes (1) and an UV curable monomer is applied to the gap between the components (2). To proof that such interconnects are suitable for connecting micro-optical components over distances up to several millimeters, we separated both fibers (3). During step (4), the core of the waveguide is fabricated by coupling a beam of a laser source (Thorlabs, MCLS 1-405-30) with a wavelength of 405 nm into the launching fiber. Polymerization of the monomer starts at the end facet of the launching fiber and the waveguide core propagates to the receiving fiber due to a self-focusing effect of the beam inside the monomer. Subsequently, a rigid cladding is fabricated by UV flood exposure at a wavelength of 254 nm (5). The optical losses of the waveguides were determined using, again, the cut-back method, which yields total losses of 0.8 dB/cm at a wavelength of 850 nm. Furthermore, we achieved a coupling loss between the two fibers of below 0.01 dB, which corresponds to the detection limit of our attenuation measurement setup. The presented fabrication process is also suitable for coupling side emitting LDs to aveguides.

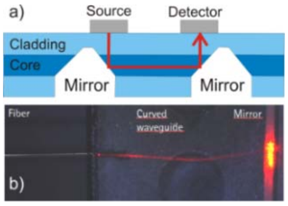

Fig. 4 *Micro-mirror coupling structure: (a) Sketch of the concept; (b) Proof-of-concept.*

To couple a laser beam emitted by a VCSEL into a multimode waveguide, micro-mirrors represent a simple but efficient method, as sketched in Fig. 4a. Here, the laser beam is coupled into the waveguide core by means of an air recess, which acts as a mirror and couples the laser beam in and out of the waveguide core due to total internal reflection. After waveguide production, the mirror was fabricated by a slotting process utilizing a diamond tool with an opening angle of 90° in a precision milling machine. Fig. 4b shows a proof-of-concept of the coupling structure, where a laser beam with a wavelength of 650 nm is launched into a bend waveguide from a fiber and coupled out of the waveguide using the micro-mirror. Optical loss measurements yield a coupling efficiency of 15%.

4 Summary

We presented a low-cost production process to fabricate fully polymer based multimodal waveguides. In addition, two coupling structure concepts and first proof-of-concepts were introduced, which are capable of being integrated in the hot embossing process. The coupling concepts rely on self-written waveguides for creating light source to waveguide and waveguide to waveguide interconnects as well as on mechanically machined micro-mirrors, which couple light vertically into the core of the waveguide due to total internal reflection.

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