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Fabrication and Sensing Applications of Multilayer Polymer Optical Waveguides

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Abstract

For sensing applications in structural health monitoring, process technology or life sciences polymer micro-optical sensors are highly promising as they offer several advantages in comparison to other sensor types. In this work, a fabrication process of low-cost planar polymer optical waveguides based on hot embossing and doctor blading is presented. Such waveguides represent one of the main building blocks of micro-optical systems. The refractive index and propagation losses of several waveguide materials are characterized. In order to increase the integration density of optical components, the fabrication of multilayer waveguides is investigated. Finally, potential applications of the fabricated waveguides are outlined.

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1. Introduction

In recent years, micro-optical devices and their deployment in different sensing applications have been subject of intense research. Based on advances in microelectronics, constant progress in silicon photonics was achieved. Due to the high fabrication costs of silicon based materials, alternative materials are being investigated. Polymer materials carry many advantages compared to silicon based materials, such as their inherent low costs and their compatibility with high throughput manufacturing techniques. Polymer optical waveguides are among the most important and elementary components of polymer micro-optical devices. Several fabrication techniques of polymer optical

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waveguides have been reported, such as laser direct writing [1], two-photon-polymerization [2], printing [3] and hot embossing [4]. Polymer micro-optical devices are used in a large variety of applications such as sensing applications in structural health monitoring and process monitoring. For example, polymer optical strain sensors were demonstrated, where the intensity of the sensor output varies with the applied force [5]. Other examples are temperature sensors, which rely on the determination of the spectrum reflected by a Bragg grating [6]. Polymer micro-optical devices can also be used to detect the composition of liquids based on the change of their refractive indices [7].

In this work, we present a fabrication process for low-cost foil-integrated all-polymer multimode optical waveguides, which is based on hot embossing, doctor blading and UV curing. We characterize the fabricated waveguide with respect to refractive index and propagation losses and we achieve low-loss optical waveguides with propagation losses down to 0.74 dB/cm at a wavelength of 633 nm and 0.30 dB/cm at a wavelength of 850 nm. We also investigate the fabrication of multilayer waveguides using thermal and adhesive assisted bonding. Finally, we discuss potential sensing applications of the investigated multilayers and present future steps of our research.

Nomenclature

PMMA	Poly(methyl methacrylate)
POF	Polymer optical fiber
MZI	Mach-Zehnder interferometer

2. Fabrication of multimode optical waveguides

For the fabrication of low-cost all-polymer planar optical waveguides, we present a process, which is based on three main steps. These steps consist of hot embossing, doctor blading and UV-curing. Figure 1 summarizes the consecutive fabrication steps. We choose these specific steps because they are compatible with reel-to-reel fabrication techniques, which represent the long term goal of our research.

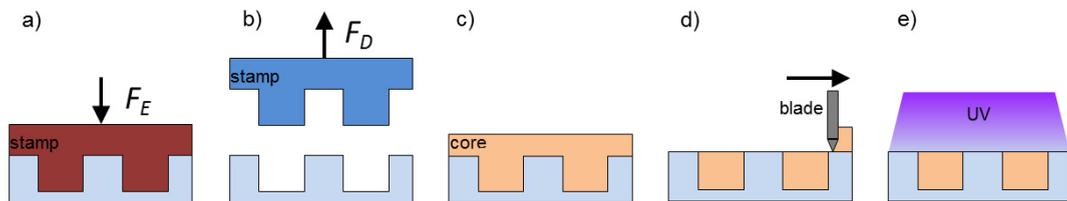


Fig. 1. Waveguide fabrication process: (a) heating and embossing step; (b) cooling and demolding step; (c) deposition of core material; (d) doctor blading; (e) UV curing.

As the first fabrication step, hot embossing relies on a replication process. Therefore, a replication stamp, which includes the desired microstructures, is necessary. For the fabrication of channel waveguides, we opted for silicon stamps that include rib-structures. The stamp was fabricated by Micromotive GmbH through photolithography, deep reactive-ion etching and plasma etching. The fabricated rib structures have a height of 28 μm and a width of 25 μm . As waveguide cladding, which is to be microstructured through hot embossing, we chose a 500 μm thin PMMA sheet (Plexiglas XT 99524, ThyssenKrupp, Germany). We performed the replication process using a commercial hot embossing machine (HEX03, Jenoptik Mikrotechnik GmbH, Germany). During the heating step of hot embossing, the stamp and the PMMA sheet were heated to the embossing temperature ϑ_E of 140°C. During the subsequent embossing step, an embossing force F_E of 4kN was applied between stamp and the PMMA and maintained for 120

seconds. After cooling to the demolding temperature ϑ_D of 50°C and releasing the applied embossing force, stamp and PMMA were separated manually. The result obtained consists of trench structures in PMMA.

The next waveguide fabrication step consists of doctor blading. In this step, UV curing materials in liquid form were deposited on the PMMA trenches. Using a sharp razor, the excess material was removed, leaving material only in the trench. The used UV curing materials are NOA68 (Norland, USA), OG198-54 (Epotek, USA) and OG142 (Epotek, USA) and represent the waveguide core materials. To cure the applied materials, we performed a UV flood exposure for 60 seconds. For the later waveguide characterization, the fabricated waveguide sheet was cleaved using an in-house polymer optical fiber (POF) cleaver. The obtained waveguide cross section is presented in Figure 2, which shows satisfactory cladding replication, the absence of a cladding residual layer and smooth end facets.

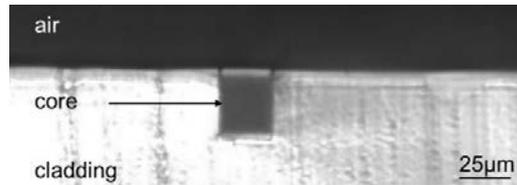


Fig. 2. Cross section of fabricated waveguide structures with PMMA as cladding material and NOA68 as core material.

3. Optical characterization of the fabricated waveguides

After fabricating the waveguide single layers, their refractive index profiles and propagation losses were measured. Using a refractive index profiler (Rinck Elektronik GmbH, Germany) we determined the refractive index of the waveguide core materials at a wavelength of 638 nm and a temperature of 20°C. The refractive index measurement is based on the refracted near field method [8]. An example of the obtained profiles is presented in Figure 3. The obtained refractive indices of NOA68, OG198-54, and OG142 are summarized in Table 1.

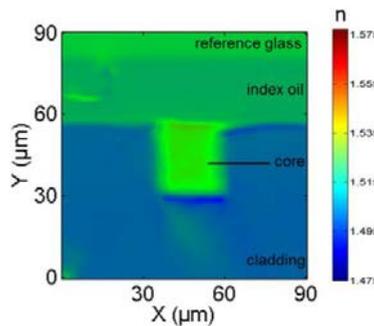


Fig. 3. Measured refractive index profile of a fabricated waveguide using NOA68 as core material.

Table 1. Measured refractive index of different UV curing core materials.

Material	Refractive index ($\lambda = 638 \text{ nm}$)
OG198-54	1.524
OG142	1.568
NOA68	1.525

The final waveguide characterization step consists of the measurement of the optical propagation losses of the different core materials. As light sources, we used a helium-neon laser (25-LHP-991, Melles Griot, USA) at a wavelength of 633 nm and a fiber coupled laser diode (MCLS1-850, Thorlabs, USA) at a wavelength of 850 nm. As detector at the output of the investigated waveguides, we used a photodiode power sensor (S151C, Thorlabs, USA). Based on the cutback method [9], we measured the output power of waveguides with different lengths and determined the dependence of propagation losses on the sample length. Table 2 summarizes the obtained propagation losses of the different core materials in dB/cm. The measurement shows that OG198-54 is most suitable for applications in the infrared wavelength range, whereas NOA68 is more suitable for applications in the red wavelength range (633 nm). The obtained low losses enable the use of these UV curing core materials in different sensing applications and are much lower than the losses of the thermosetting materials that we investigated in earlier work [10].

Table 2. Measured propagation losses of waveguides fabricated using different UV curing core materials.

Material	Loss dB/cm at ($\lambda = 633$ nm)	Loss dB/cm ($\lambda = 850$ nm)
OG198-54	0.97	0.30
OG142	2.56	1.05
NOA68	0.74	0.81

4. Fabrication of multilayer optical waveguides

After fabricating and characterizing single layer optical waveguides on PMMA foils, we investigated the fabrication of multilayer structures. One of the advantages of multilayer structures is the increase in the integration density of optical components. For this work, we investigated thermal and adhesive assisted bonding of two waveguide layers.

In the case of thermal bonding, a waveguide stack was placed in the above mentioned hot embossing machine. Next, the layers were heated to a temperature of 140°C. Subsequently, a bonding force of 50 N was applied and maintained for 60 seconds. Finally, the bonded layers were cooled and removed from the machine. After cleaving the multilayer end facets, the cross section of the fabricated samples were photographed under a microscope, as presented in Figure 4. In Figure 4(a), two bonded 500 μm thin waveguide layers are shown: A waveguide layer is capped by a second layer, which means that the top layer waveguides can interact with the environment, while the buried waveguides are protected. For sensing applications, a signal in the surface layer can be altered by environment conditions, such as humidity or gas composition. In contrast, a signal propagating in the buried waveguides remains unaltered. This effect can be potentially used to automatically calibrate optical sensor structures. For other applications, an environment interaction can be undesirable. In that case, an additional PMMA layer can be bonded to protect the underlying waveguides. Figure 4(b) shows such a structure, where two 175 μm thin waveguide layers are capped with an additional protecting PMMA layer.

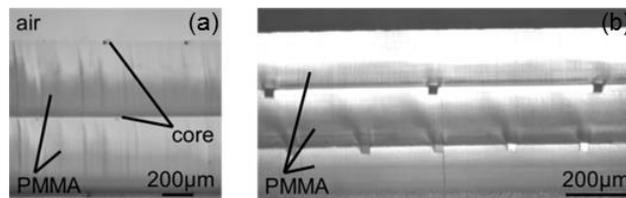


Fig. 4. Cross section of multilayer waveguides fabricated through thermal bonding: (a) Multilayer with a capped waveguide cores; (b) Multilayer with exposed top layer.

As alternative to thermal bonding, we investigated adhesive assisted bonding of two waveguide layers. In addition to providing a good adhesion between PMMA layers, the used adhesive should not alter the function of the optical waveguides. An example of such an alteration consists of light leaking from the core material to the adhesive layer due to inadequate refractive indices of the used materials. Therefore, we chose an optical adhesive, whose refractive index is lower than the index of the core materials used, i.e. OG675 (Epotek, USA) [11]. The adhesive layer was applied on top of the first waveguide layer through spin coating. Then, another waveguide layer was deposited on top of it. Finally, UV flood exposure was performed to cure the adhesive layer. The cross section of the resulting multilayer is shown in Figure 5. In contrast to the thermally bonded layers, where PMMA separates the waveguide cores of the different layers, the waveguide cores are separated with an intermediate adhesive layer. Using appropriate spin coating parameters, very thin adhesive layers can be fabricated, thus allowing evanescent light coupling between both waveguide layers. As an example, this effect can be used for light coupling between a cascade of sensor structures on different waveguide layers. Another potential use consists of bonding a layer that includes sensor structures with an optical signal processing layer that includes light sources, detectors and spectrometers.

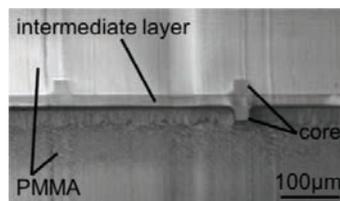


Fig. 5. Cross section of multilayer waveguides fabricated through adhesive assisted bonding.

5. Sensing applications of multilayer waveguides

As mentioned above, polymer micro-optical devices can be used for sensing of different physical and chemical quantities, such as temperature, strain and chemical composition. The simplest method to take advantage of the presented multilayer waveguides is to use each layer to sense a different parameter, thus increasing the integration density of the micro-optical device.

Another possibility consists of using two layers containing one dimensional sensor elements to achieve two dimensional sensing. As an example, a 1D-strain planar optical sensor [12] can be fabricated orthogonally to a second strain sensor, thus enabling an integrated distributed 2D strain measurement, as shown in Figure 6.

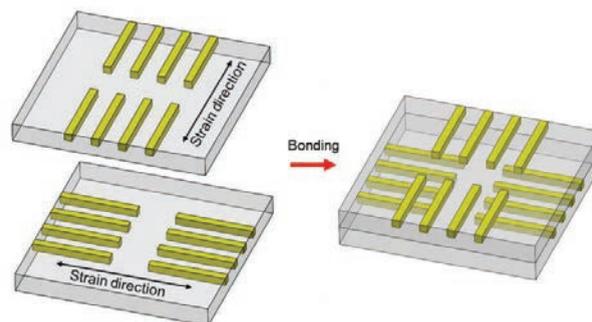


Fig. 6. Multilayer configuration enabling 2D strain sensing using orthogonal 1D strain sensors: Arrows designate the strain direction that can be measured.

Multilayers can also be used to calibrate sensor signals and increase their accuracy. In the case of interferometric chemical sensors, which detect chemical composition of liquids or gases through changes in the refractive index of the surrounding material [7], a first interferometric structure can be enclosed between two cladding polymer foils. The output signal of a second interferometric device on the foil surface is altered by the refractive index change in the surrounding medium. The signal of the surface structure can then be compared to the unaltered signal of the buried structure. The result of the comparison can be used to constantly monitor the change in signal amplitude. As an example, a multilayer implementation of such a refractive index change sensor, which is based on asymmetric Mach-Zehnder interferometers (AMZI), is shown in Figure 7.

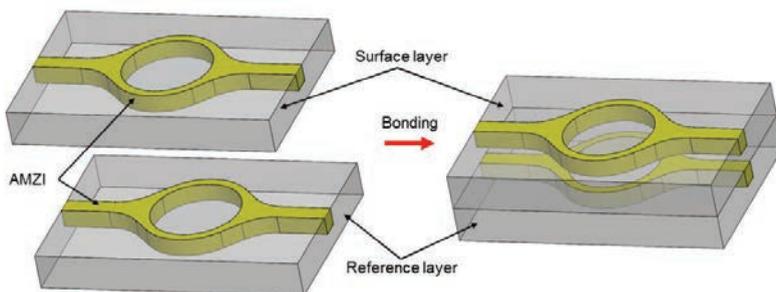


Fig. 7. Multilayer configuration enabling signal calibration of an interferometric sensor using the buried waveguide layer to transmit a reference signal.

To demonstrate the functionality of the described AMZI sensor, optical simulations were performed through the beam propagation method using the software “RSoft’s Photonic Component Design Suite”. Since operation in the single mode regime increases the sensitivity of AMZIs [7], we used single mode structures, having a width and depth of $3\ \mu\text{m}$. In this example, core and cladding materials have a refractive index of 1.495 and 1.49 at a wavelength of 850 nm. The optical power at the output of the reference and surface AMZI was simulated as a function of the refractive index of the surrounding medium. The dimensions and the simulated results of the AMZI structures are summarized in Figure 8: The output power of the surface AMZI increases with increasing refractive index of the surrounding material, while the output power of the buried AMZI is constant, thus enabling the use of its signal as a reference for the signal of the surface AMZI.

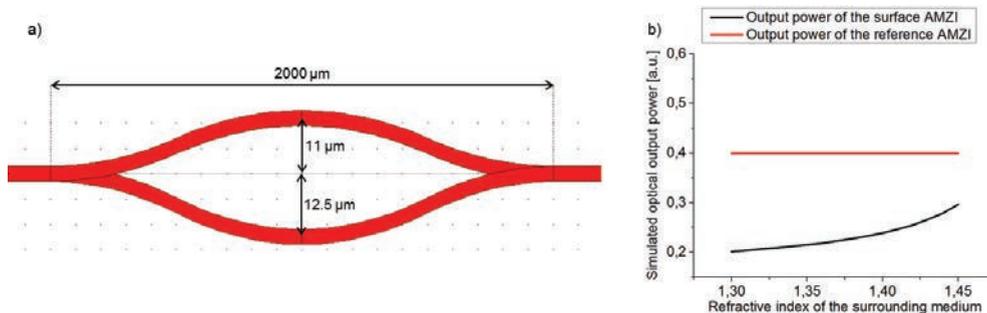


Fig. 8. Simulation of a multilayer AMZI sensor structure: (a) Dimensions of the simulated structures, (b) Simulated optical output power as a function of the refractive index of the surrounding material.

6. Summary and outlook

In summary, we presented a fabrication process for all-polymer low-cost optical waveguides embedded in thermoplastic foils. The fabrication process is based on hot embossing, doctor blading and UV curing. We measured the refractive index of the UV curing core materials used and characterized their propagation losses based on the cutback method. Depending on the core material, we demonstrated low-loss waveguides, which have propagation losses down to 0.74 dB/cm and 0.30 dB/cm at wavelengths of 633 nm and 850 nm, respectively. Furthermore, we fabricated multilayer waveguides in different configurations through thermal and adhesive bonding. We finally presented approaches towards micro-optical sensing applications for the fabricated multilayers, which can be used in the fields of structural health monitoring, process technology or the life sciences. The next steps of our work consist of the fabrication and characterization of the discussed optical sensors and the implementation of the presented fabrication process in reel-to-reel configuration, thus enabling the fabrication of low-cost large scale foil-embedded optical sensors for various applications.

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References

- [1] Krchnavek RR, Lalk GR, Hartman DH. Laser direct writing of channel waveguides using spin-on polymers. *J Applied Physics* 1989;66: 5156–5160.
- [2] Klein S, Barsella A, Leblond H, Bulou H, Fort A, Andraud C, Lemercier G, Mulatier JC, Dorkenoo K. One-step waveguide and optical circuit writing in photopolymerizable materials processed by two-photon absorption. *Applied Physics Letters* 2005;86:211118.
- [3] De Gans BJ, Duineveld PC, Schubert US. Inkjet printing of polymers: State of the art and future developments. *J Advanced Materials* 2004;16:203-213.
- [4] Choi CG. Fabrication of optical waveguides in thermosetting polymers using hot embossing. *J Micromech Microeng* 2004;14:945-949.
- [5] Kelb C, Rahlves M, Reithmeier E, Roth B. Realization and performance of an all-polymer optical planar deformation sensor. *IEEE Sensors Journal* 2015;15:7029-7035.
- [6] Sherman S, Zappe H. Printable Bragg Gratings for Polymer-based Temperature Sensors. *Procedia Technology* 2014;15:702-709
- [7] Hofmann M, Xiao Y, Sherman S, Gleissner U, Schmidt T, Zappe H. Asymmetric Mach-Zehnder interferometers without an interaction window in polymer foils for refractive index sensing. *J Applied Optics* 2016;55:1124-1131
- [8] Göring R, Rothhardt M. Application of the Refracted Near-Field Technique to Multimode Planar and Channel Waveguides in Glass. *J Opt Commun* 1986;7:82-85
- [9] Tong X. *Advanced Materials for Integrated Optical Waveguides*. Springer; 2014.
- [10] Rezem M, Guenther A, Rahlves M, Roth B, Reithmeier E. Hot Embossing of Polymer Optical Waveguides for Sensing Applications. *Procedia Technology* 2014;15:514-520
- [11] Epoxy Technology. EPO-TEK OG675, datasheet, Sep 2013.
- [12] Kelb C, Reithmeier E, Roth B. Planar integrated polymer-based optical strain sensor. *SPIE 8977 MOEMS and Miniaturized Systems XIII Conference Proceedings*; 2014;89770Y