Polymer micro- and nanophotonic sensors realized using replication technologies

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Polymers are transparent in the visible, mechanically flexible, cost-effective, and therefore attractive materials for optical sensors. Furthermore, high-quality micro- and nanophotonic structures can be realized in polymers using replication-based technologies. This paper will demonstrate single mode waveguide Bragg grating sensors realized using various polymers, and as such illustrate the capabilities of replication technologies both for fabricating microstructures (waveguides with typical cross-sectional dimensions of a few micron) and nanostructures (gratings with typical pitch of a few hundred nanometer) using these technologies. Furthermore, we illustrate that the sensor properties can easily be tuned by selecting the appropriate polymer material.

Introduction

To lower manufacturing costs, there is a trend towards polymer-based technologies, such as roll-to-roll manufacturing or replication-based technologies, because of high throughput and low (material) costs [1]. Also in photonics, polymers are interesting materials because of their transparency in the visible and mechanical compliance allowing flexible [2] or even stretchable photonics [3]. A particularly interesting application is strain sensors based on Bragg gratings, for example for structural health monitoring, since polymer waveguides allow measuring larger strains compared to standard silica fiber sensors. Realization of such sensors requires fabrication of gratings with typical pitches in the order of a few hundreds of nanometers.

Recently, nanoimprint lithography (NIL) has received a lot of attention as a flexible and cost-effective technology for realizing the required nanometer-sized features in photoresist, as an alternative for (Deep-UV) lithography. The basic principle of NIL is straightforward: a thin layer of resist is spin-coated and a stamp with the inverse feature pattern is pressed into the resist layer. For UV-NIL, the resist layer in contact with the stamp is then hardened using UV illumination. Such a process is commercially available and already widely used to imprint dedicated resists in combination with dedicated stamp materials. After the NIL process, the resist is then used as a mask for etching underlying materials. However, it would be beneficial if this etching step can be omitted and the stamp pattern can directly be replicated in the material of interest. Although this is not possible for inorganic materials, it is possible for certain types of polymers which are UV-curable. This paper will therefore discuss the direct replication of micro- and nanostructures by imprinting in 2 classes of optical materials, epoxies (EpoCore and EpoClad from Microresist Technology [4]) and hybrid organic-inorganic polymers (OrmoCore and OrmoClad from Microresist Technology [4]). Although these polymers were initially developed for patterning using traditional photolithography, it is possible to use them as NIL resists by finding the appropriate process conditions.

First, the replication of nanostructures in optical polymers will be discussed, and then this process is optimized for replication of single mode optical waveguides. Finally, both technologies are combined to demonstrate their suitability for fabricating polymer waveguide Bragg grating sensors which are characterized in terms of strain and temperature sensitivity. The waveguides have cross-sectional dimensions of about 5x5 μm^2 to yield single mode behavior, as discussed elsewhere [5]. The gratings have a pitch of 505nm (duty cycle 50%, groove depth 200nm) resulting in a Bragg wavelength $\lambda_B=2n_{eff}\Lambda\approx1550$nm, in the desired telecom range.

Replication of nanostructures in optical polymers

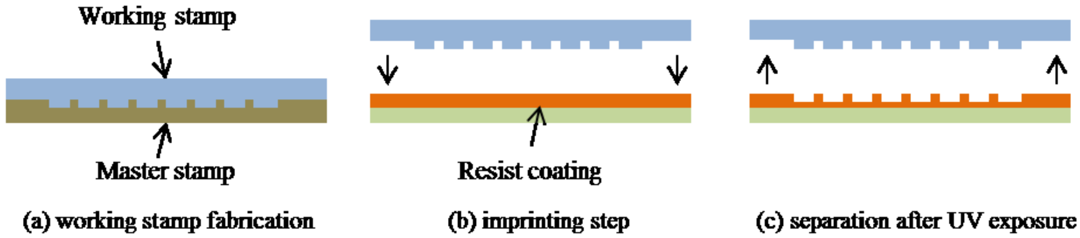

Fig. 1. Schematic illustration of the most important imprinting steps.

First, a working stamp is prepared as a first replica of a master stamp (Fig. 1a). In this case, the master stamp was a silicon wafer in which the grating grooves were etched. To form the replica, a Photocurable perfluoropolyether-based (PFPE) polymer was cast against the master stamp and polymerized using UV exposure (60s at 30mW/cm^2). After peeling off, this working stamp with replicated grating lines was used to imprint the polymer materials. This is achieved by placing the working stamp on top of a spin-coated layer while being careful not to introduce air voids at the interface (Fig. 1b). Upon contact, the small features of the working stamp are capillary filled with the material which is subsequently polymerized using UV exposure, after which the stamp can easily be released (Fig. 1c). The hybrid polymers OrmoCore and OrmoClad are solvent-free solutions which after spin-coating form a liquid layer and therefore the working stamp can directly be placed onto this layer. However, EpoCore and EpoClad are formulations which are diluted in a solvent, and after spin-coating need a soft-baking step to evaporate the solvent and solidify the layer. This process step is required in case of lithography where a mask is in contact with the resist layer, but prevents the layer form being patterned using NIL. This can be solved by performing the imprinting step on a hotplate, since the epoxy material is not yet polymerized and therefore returns to a liquid state at elevated temperature.
Since the working stamp material is relatively soft, it allows a conformal contact over large areas, which is very challenging to achieve when using hard working stamps. Furthermore, owing to the perfluorinated nature of the material, no extra anti-release coating is required on the working stamp.

Replication of single mode waveguides

Although the imprinting process flow is the same as depicted in Fig. 1, and the features are larger, the replication of single mode waveguides is more challenging than the process for imprinting gratings. The reason is that previously only a surface corrugation at the top of the polymer was required, but for achieving waveguides, the residual layer between adjacent cores needs to be minimized to avoid additional losses. This can be accomplished by optimizing the spin-coated layer thickness and the stamp design. Fig. 2a shows a cross-section of OrmoCore waveguides imprinted onto a uniform

OrmoClad cladding layer. It can be seen that wider dummy structures are present between the individual cores. These structures act as reservoirs for the excess material, so that during imprinting and upon capillary filling of the stamp grooves the material is squeezed into these channels and therefore only leaves a very thin residual layer.
An alternative approach for achieving waveguides is to imprint grooves at the top surface of the undercladding layer, then spin-coating the core material and finally placing an unpatterned (flat) working stamp on top. Placing this stamp again helps in forcing the material into the channels by capillary action. A typical resulting waveguide cross-section is shown in Fig. 2b.

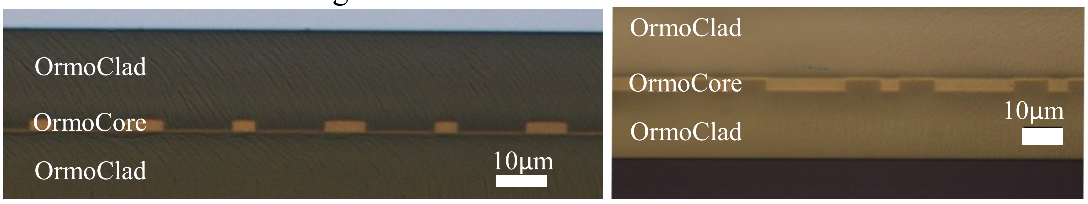

Fig. 2. Cross-sectional view on waveguides replicated in OrmoCore (a, left) and inverted rib waveguides in OrmoCore (b, right). In both cases, the OrmoCore waveguides are surrounded by OrmoClad cladding.

Polymer waveguide Bragg grating sensors

To combine both processes, in a first approach, a grating is imprinted at the surface of the undercladding and then a waveguide is fabricated on top. Fig. 3a illustrates this approach for an EpoCore waveguide on top of an EpoClad layer with imprinted grating. The waveguide shown in the figure was patterned using Direct Write Lithography, but it can also be applied using imprinting. In a second approach, a grating is imprinted at the top surface of an inverted rib waveguide by placing a working stamp with a grating instead of a flat stamp on top of the spin-coated core layer during fabrication. This is illustrated in Fig. 3b for an OrmoCore/OrmoClad inverted rib waveguide.

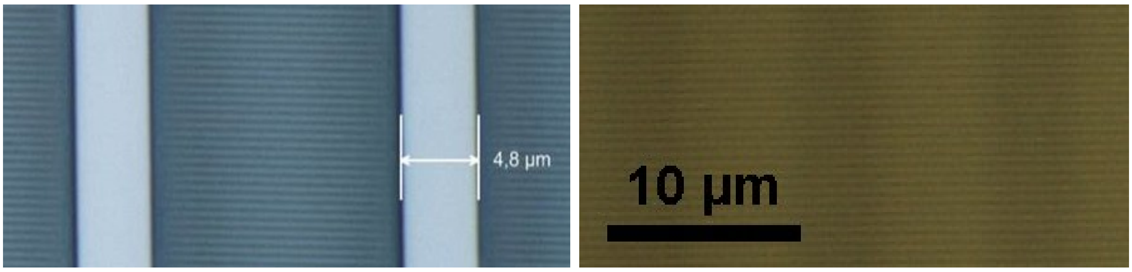

Fig. 3. Top view on EpoCore waveguides on top of Bragg gratings imprinted in EpoClad (a, left) and imprinted Bragg gratings on top of inverted rib OrmoCore waveguides (b, right).

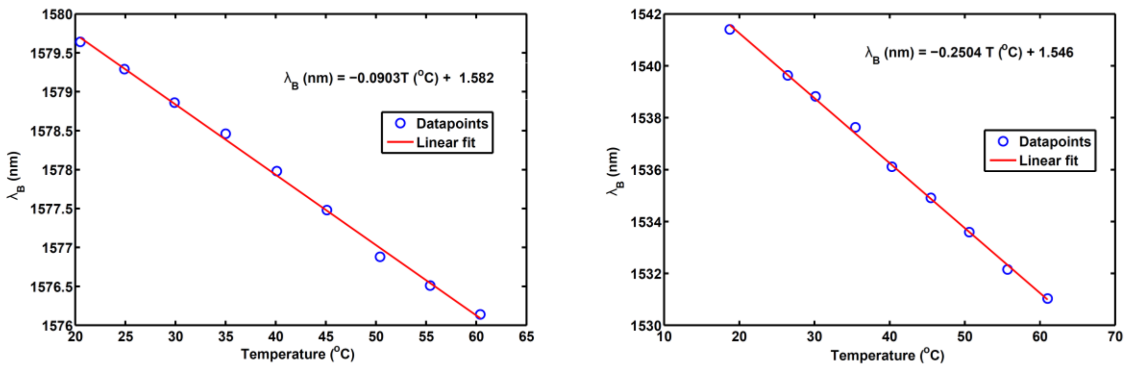

Fig. 4. Bragg wavelength shift as a function of temperature for EpoCore/Clad (left) and OrmoCore/Clad (right) waveguide Bragg grating sensors.

The 2 sensor implementations based on different materials, as illustrated in Fig. 3, were each implemented on top of an FR-4 substrate and characterized in terms of their strain and temperature sensitivity. Therefore, a fiber was attached to one of the waveguides in the array and the grating was read-out in reflection using a commercial interrogator. A tensile test revealed a similar strain sensitivity of about 1 pm per με (microstrain) for both materials. For assessing temperature sensitivity, both sensors were placed in a temperature-controlled oven and a measurement was performed after stabilization at 5°C intervals. A thermocouple placed directly on top of the Bragg grating was used as a reference sensor. The results of this test are shown in Fig. 4 and it can be seen that the OrmoCore/Clad sensor is almost 3 times more sensitive (250 pm/°C) as compared to the EpoCore/Clad sensor (90 pm/°C). Furthermore, this is about 25 times higher compared to standard silica fiber Bragg grating sensors, which can be explained by the very large (negative) thermo-optic coefficient of the OrmoCore/Clad materials [6].

Conclusions

The potential of replication technologies, in which optical polymers are directly structured without a need for an extra resist layer, has been demonstrated for fabrication of single mode waveguides and Bragg grating sensors. The resulting sensors were implemented using epoxy materials and hybrid organic-inorganic materials characterized in terms of strain and temperature sensitivities. Both materials showed similar sensitivity to strain, but the hybrid organic-inorganic materials showed a much larger sensitivity to temperature as compared to the epoxy materials.

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References

[1] S. Aikio, J. Hiltunen, J. Hiitola-Keinänen, M. Hiltunen, V. Kontturi, S. Siitonen, *et al.*, "Disposable photonic integrated circuits for evanescent wave sensors by ultra-high volume roll-to-roll method," *Optics Express,* vol. 24, pp. 2527-2541, 2016/02/08 2016.

[2] J. Hu, L. Li, H. Lin, P. Zhang, W. Zhou, and Z. Ma, "Flexible integrated photonics: where materials, mechanics and optics meet [Invited]," *Optical Materials Express,* vol. 3, pp. 1313-1331, 2013/09/01 2013.

[3] J. Missinne, S. Kalathimekkad, B. Van Hoe, E. Bosman, J. Vanfleteren, and G. Van Steenberge, "Stretchable optical waveguides," *Optics Express,* vol. 22, pp. 4168-4179, 2014/02/24 2014.

[4] "Microresist Technology," http://www.microresist.de.

[5] A. Elmogi, E. Bosman, J. Missinne, and G. Van Steenberge, "Comparison of epoxy- and siloxane-based single-mode optical waveguides defined by direct-write lithography," *Optical Materials,* vol. 52, pp. 26-31, 2// 2016.

[6] N. Teigell Benéitez, J. Missinne, Y. Shi, G. Chiesura, G. Luyckx, J. Degrieck, *et al.*, "Highly Sensitive Waveguide Bragg Grating Temperature Sensor Using Hybrid Polymers," *IEEE Photonics Technology Letters,* vol. 28, pp. 1150-1153, 2016.