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Direct patterning of polymer optical periodic nanostructures on CYTOP for visible light waveguiding

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ABSTRACT

Optical waveguides and grating couplers based on polymer nanostructures are now considered as promising technologies for integrated biophotonic sensing systems. Commonly, structuration and patterning of polymers at the submicron scale requires the use of time and cost-consuming equipments such as electron beam lithography. Direct patterning of high refractive index polymer devices on CYTOP is now achievable and provides symmetric waveguides with top water-like claddings. In addition, transparency of polymers makes them suitable for operation in the visible range, being of major interest for biophotonic applications. In this paper, we report on the fabrication process of polymer submicronic single-mode waveguides on CYTOP for visible light operation. Subwavelength grating couplers with a pitch lower than 300 nm were fabricated to couple the input light into a 350 nm square cross-section waveguide. The whole device is imprinted in a single step using soft stamp lithography with a minimal residual layer. Finally, optical characterizations demonstrate a state-of-the-art transmission efficiency (around 1.5%) at the selected operating wavelength of 507 nm for different coupling angles in good agreement with simulations.

1. Introduction

Optical waveguides are now widely used components in integrated photonics, independently of the final application. Extensive research has been carried out for infrared and near-infrared applications mainly addressing silicon photonics for high-speed data communications but also increasingly for sensing purposes. Particularly, semiconductor materials as Silicon-on-insulator (SOI) and III-V are widely accepted as mature and efficient technologies for photonics. Compared to these inorganic materials, optical polymers bring some substantial benefits such as low cost and ease of processing to meet a broad range of application-specific requirements. Moreover, their suitability to low-temperature and wet-coating processes over large areas for almost all sorts of substrates are recognized as key requirements for mass production. Polymer waveguides are also highly transparent, with typical absorption losses of 0.1 dB/cm or less at all key communication wavelengths. However, the low refractive index contrast between core and cladding limits the light confinement, and consequently limits the miniaturization of integrated polymer devices [1].

Up to now, integrated photonics working in the visible range has captured less attention than infrared or near infrared photonics. This is mostly due to the high industrial maturity of the semiconductor microfabrication technology but also to the high absorption losses of these materials in the visible spectrum. However, visible integrated photonics based on polymer materials is being increasingly recognized as very promising in various applications, as for example bio/chemical sensing, on-chip spectroscopy, visible light communication, satellite laser ranging or on-chip quantum processing [2]- [3]. Among advantages, polymer optical materials are transparent in the visible spectrum and are compatible with fast and low-cost embossing methods [4]. Additionally, the relative wide range of low refractive index ranging from 1.33 to 1.7 is of great interest for MOEMS and sensing applications [5]-[6]. Particularly, the use of low-index polymers as CYTOP ($n = 1.339$, $\lambda = 580$ nm) enables enough core-cladding index contrast when paired with other high index polymer materials such as SU8, PMMA or Ormocore. With CYTOP, symmetric waveguides can be designed with water-like refractive index top claddings. Potential applications of polymer platforms on CYTOP focus currently on hybrid photonic microfluidic devices with optical resonances to analyze water samples [7]. The main benefits of working in the visible range lie in the lower absorption of water at these wavelengths and the availability of selective colorimetric solutions.

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Nevertheless, two major drawbacks can occur when fabricating polymer optical devices for visible operation. First, building blocks such as grating couplers, waveguides and ring resonators require sub-wavelength features that are obviously more challenging to obtain at shorter wavelengths. The second limitation deals with the high sensitivity of polymeric photonic nanostructures to fabrication tolerances at the selected wavelengths. Up to now, these dimensions have been reliably achieved only with dedicated nanofabrication equipments such as Electron Beam Lithography (EBL) and NanoImprint Lithography (NIL). Specific parts such as waveguides and resonators have been successfully fabricated on CYTOP platforms for operation at visible wavelength with EBL, this technique dedicated to prototyping still remains time consuming and costly [8]. In contrast, soft-NIL is more appropriate for fast and low-cost processing of polymers at the nanoscale. This technique has been successfully applied to direct patterning of polymer waveguides, grating couplers and ring resonators on SiO_2 claddings as reported in Ref. [9]. However, very few studies have been published on nanoimprinting polymers for visible operation. For instance, M. Hiltunen et al. reported relevant results on optical sensors based on polymeric slot waveguides with an integrated Young's interferometer operating at 633 nm [10]. Additionally, M. H. M. Salleh et al. have shown a gapless resonator integrated with a microfluidic chip operating at the upper limit of the visible spectrum ranging from 740 nm to 780 nm [11]. Nevertheless, to our knowledge, full polymer (i.e. core and cladding) platforms on CYTOP using soft-NIL have not yet been addressed in the visible range. Using nanoimprint lithography, will definitively represent a significant step forward for future disposable low-cost on-chip biosensors.

In this paper, we aim to demonstrate the direct patterning of grating couplers and polymer waveguides fabricated on CYTOP by soft-NIL for visible wavelength applications. The first part describes the whole process addressing the main fabrication concerns of the imprint process while the second part allows to characterize and analyze the impact of fabrication tolerances on optical efficiency. As the devices are imprinted from a soft stamp, different soft stamp materials including thermoplastics and hardened recipes of PDMS are used and compared to each other. The master stamp consists in a multi-height Silicon-On-Insulator (SOI) structure including both tapered submicron waveguides (350 nm square cross-section) and grating couplers (with a pitch Λ equal to 290 nm). It allows a direct imprint process of the multi-height structure in a single step with a minimal residual layer (RL) since its thickness can degrade the optical performances of the overall structure. In addition, optical coupling efficiency measured as a function of the input angle is also presented for different thicknesses of CYTOP. By using such a direct patterning technique, we demonstrate state-of-the-art efficiency and the large angular acceptance width obtained allowing an easy source alignment, that could facilitate the packaging process of future microfluidic chips for sensing applications.

2. Design and simulation results

2.1. Soft-imprint lithography technique

Soft nanoimprint lithography (soft-NIL) is a technique consisting in patterning nanostructures in a polymer by using a flexible and transparent stamp, usually made of poly(dimethylsiloxane) elastomer or thermoplastic materials, corresponding to the counterpart of the single hard master mold. The process enables to define submicron patterns with different thicknesses over large areas in a single step process and appears as an optimal technique to create large waveguides with subwavelength grating on polymers [12]. Depending on the polymer, the cross-linking is achieved from thermal nanoimprint lithography (T-NIL), UV nanoimprint lithography (UV-NIL) or a combination of both. Some UV photoresists such as SU-8 rely on thermal heating to enhance the cavity filling before the cross-linking effect. Fig. 1 summarizes the main steps of a full soft-NIL process. In Fig. 1a the intermediate soft stamp is fabricated with the mentioned soft stamp materials. In Fig. 1b the soft stamp is used to transfer the pattern polarity of the master stamp to the uncured polymer. Once the polymer is hardened, the soft stamp is released as shown in Fig. 1c.

When fabricating polymer nanostructures with soft-NIL, a critical issue lies in the fabrication of the master and intermediate stamps. The master stamps are fabricated with conventional lithography techniques that are usually based on EBL for submicron structures. Intermediate soft stamps allow conformal high-resolution imprints over large surfaces even at low pressures with the additional advantage of preventing master mold damage. Another issue is the RL of photoresist remaining between the mold and the substrate. This layer is due to the difficulty to hold the mold in full contact with the substrate during the imprint process and several strategies have been considered in this paper to overcome such an issue.

2.2. Design of the structure

The structure considered here is a single mode polymer submicron rib waveguide formed atop a thin (500 nm) CYTOP layer acting as the bottom cladding. For the waveguide core, we use a homemade negative photoresist NILUV-394 with a refractive index equal to 1.52 (λ = 532 nm). Based on methacrylate, the absorption coefficient is very low in the visible region as other transparent polymers (PMMA, SU8). The waveguide cross-section is 350 nm square onto a 50 nm residual layer (total height h of 400 nm). The residual layer must be managed depending on the final application. For straight waveguides, a thin residual layer can be accepted as long as the single mode condition is fulfilled. In order to achieve the best effective coupling of light from the laser source into the submicron waveguide, both a grating coupler and a taper were fabricated on to the same master stamp.

Fig. 2a shows the 4 mm length tapered waveguide including the grating coupler. This important length facilitates simultaneously the future integration of microfluidic circuitry and the handling of future packaged microsystems. The grating coupler surface area is 35 μm × 35 μm. The grating period is set to 290 nm achieving one single counter-propagative diffraction order, thus reducing the probability of parasitic modes or unwanted diffraction beams. Grating couplers are highly polarization dependent. The propagation constant is modified to match the effective index of the fundamental TE waveguide mode. The grating depth (h_g) is set to 164 nm with a fill factor of 0.5. A moderate groove depth was chosen allowing low backward reflection maintaining an easy release of the master stamp which avoids groove detachment. The cross-section view of the 3D structure is shown in Fig. 2b.

2.3. Simulation results of optical propagation

Simulation is performed by using the MODE solver from LUMERICAL© Finite difference eigenmode FDE software which solves the Maxwell equation on a cross sectional mesh of the waveguide. A 1.5 μm × 1.5 μm simulation region, larger than the physical dimensions of the waveguide, was selected as well as reflective layers for the transversal boundary conditions. The MODE solver is used to study the spatial variations of the mode profile depending on the RL thickness. We have studied the waveguiding conditions for single-mode operation in the green region of the visible spectrum. This wavelength region is of main interest in biophotonics, lab on chip analysis and flow cytometry [13]. The simulation results are displayed in Fig. 3a. In the case of air cladding, a RL thickness over 18 nm enables single-mode propagation of the TE-like mode while below this value, only the fundamental TM-like mode can propagate. For water top cladding, a multi-mode propagation is demonstrated over a 110 nm thick RL. Therefore, assuming a homogenous RL on the wafer is of major importance since large RL variations lead to wide effective index changes that can affect the properties of the mode propagation. Fig. 3b and c shows respectively