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Bragg grating sensors in laser-written single mode polymer waveguides

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Abstract

We present a technology for integrating Bragg gratings with single mode polymer waveguides fabricated in the EpoCore/EpoClad material system. The gratings were inscribed in a photosensitive polymethyl methacrylate (PMMA) coating using a phase mask and then transferred in the lower cladding layer using reactive ion etching maintaining compatibility with standard waveguide fabrication technologies. Subsequently, the waveguide core was patterned on top using laser direct-write lithography of a spin-coated polymer layer. When exciting the waveguides with a broadband spectrum around 1550 nm, 2 reflection peaks around 1580 nm were found corresponding to the fundamental TE and TM mode in the polymer waveguide. Eventually, this technology will be used for structural health monitoring in concrete constructions or composite materials.

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Keywords: Bragg grating; polymer waveguide; single mode waveguide; strain sensor; structural health monitoring.

1. Introduction

Fiber Bragg grating based sensors are increasingly used in “smart” structures for various applications such as robotics, biomedical devices [1] or structural health monitoring of concrete or composite based materials [2]. This technology has proven to be very reliable because the parameter information is encoded in a wavelength shift of a reflection peak, which is neither prone to electromagnetic interference nor fluctuations in absolute intensities.

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Nomenclature

λ	Wavelength
λ_B	Bragg wavelength
Λ	Grating pitch
n_{eff}	Effective index of a mode propagating in a waveguide

Although Bragg grating sensors are very attractive, the integration of silica fibers in all kinds of structures is not always straightforward. For example, for monitoring composite structures, the fibers need to be accurately kept in place during production, especially when a certain orientation is critical. In biomedical devices, the brittle silica fiber may not comply due to a risk for tissue punching. Furthermore, the sensing range of a silica fiber is limited due to its limited fracture strain.

Although their optical loss is higher, the use of polymer based waveguides provides opportunities for tackling the above-mentioned challenges. Compared to glass, polymer waveguides can be elongated to a large extent [3], are less prone to breaking and can easily be processed on planar substrates. This allows fabrication of a multitude of sensing structures, with an orientation fixed during fabrication which is ideal for multi-axial sensing. Such polymer waveguides can be fabricated on a thin flexible patch that can also have light sources and detectors integrated [4].

Therefore, this paper demonstrates the integration of Bragg gratings with a very flexible and scalable (up to 20 x 20 cm^2 substrates can be processed with the current equipment) single mode polymer waveguide direct-write technology. The functional polymer layer is very thin (a few tens of microns) and can be released to obtain a freestanding foil making it eventually easy to orient and integrate inside or on top of structures [5].

2. Methods

Various techniques can be used to fabricate gratings in optical fibers or planar waveguides, typically resulting in either volume gratings (i.e. a periodic refractive index modulation in the waveguide core) or periodic surface relief structures at the core-cladding interface. When a grating with period Λ is present in a waveguide, the reflected wavelength λ_B is defined by $n\ \lambda_B = 2n_{eff}\Lambda$, where n takes integer values and indicates the order of the grating. For maintaining compatibility with standard waveguide fabrication processes, a surface relief grating was chosen, which was fabricated using UV-exposure of a photosensitive polymethyl methacrylate (PMMA) material through a phase mask obtained from Ibsen Photonics (+1/-1 order phase mask, 1 x 1 cm^2 grating area, 1010 nm period). These parameters where chosen to yield Bragg reflections around λ_B = 1550 nm for compatibility with telecom and existing sensor readout equipment.

The PMMA layer was obtained by spin-coating a solution of PMMA A1 950 (MicroChem) on glass at 3000 rpm for 60 s and subsequently baking on a hotplate for 3 min at 180 °C. Then, the phase mask was placed in direct contact with the PMMA layer and was exposed using a Hamamatsu LC8 mercury lamp with a 365 nm filter for 20 min at 70 mW/cm^2. Subsequently, the sample was developed in a solution of (7:3) IPA:H2O for 35 s, revealing the grating structures [6].

For characterizing the grating, the diffraction efficiency of the different diffraction orders was measured when the grating was perpendicularly illuminated with a He-Ne laser (λ = 632.8 nm) and compared with the theoretically expected values. For simulating the diffraction efficiency, the Rigorous Coupled-Wave Theory was implemented in Matlab (assuming a sine grating amplitude) and extended to include multiple layered structures [7]. As such, the grating depth can be estimated by simulating the diffraction efficiency of the different diffraction orders as a function of grating depth and comparing this with the measured diffraction efficiencies.

For integrating grating structures with polymer waveguides, a grating fabricated in PMMA was transferred in the lower cladding layer and then the core of the waveguide was patterned on top, as illustrated in Fig. 1. The commercially available EpoCore/EpoClad material system (MicroResist Technology) was used for fabricating the polymer waveguides on a Borosilicate glass substrate. First, the lower cladding layer was applied (a) by spin-coating a solution of EpoClad at 4500 rpm for 30 s and soft baking at 85 °C for 60 min. Afterwards, the material was UV-exposed for 50 s at 10 mW/cm^2, followed by a post bake step (85 °C for 15 min) and hard bake step (150 °C for 90 min in an oven). Then, a PMMA layer was applied in which a grating was fabricated (b-c-d) as described above.

This PMMA grating structure was transferred (e) into the EpoClad layer by reactive ion etching (RIE) for 6 min (CHF3:O2, 5 sccm:15 sccm, 150 W, 150 mTorr). Secondly, a 5 µm core layer was applied (f) by spin-coating a solution of EpoCore 2 at 1250 rpm for 30 s followed by a soft bake step (50 °C for 2 min and then 85 °C for 3 min).

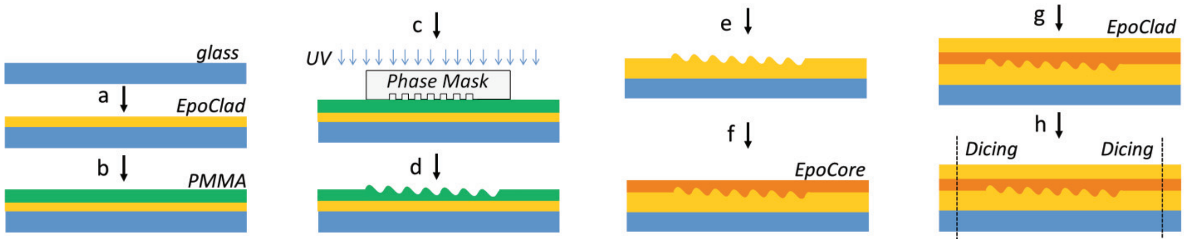

Fig. 1. Illustration of the process for fabricating single mode polymer waveguides with grating structures.

Waveguide structures with a varying width were defined using laser direct-write lithography (DWL) and afterwards the sample was baked on a hotplate (50 °C for 2 min and then 85 °C for 3 min), developed using MrDev-600 (Microresist Technology) and hard baked (150 °C for 90 min in an oven). Finally, a cladding layer of EpoClad was applied (g) using similar process steps as for the lower cladding layer. After fabrication of the polymer waveguide stack, the sample was diced on both sides (h) perpendicular to the waveguides using a wafer dicer resulting in 2.5 cm long waveguides with exposed end-faces.

The insertion loss of the waveguides was measured by coupling light in the waveguides using a 1550 nm laser diode connected to a SMF-28 single mode fiber. At the output, a fiber with a 50 µm diameter core connected to a power meter was used to measure the transmitted light. The propagation losses were obtained using the cut-back technique. To measure the reflection spectrum, a fiber-coupled source (Thorlabs ASE FL-7002) with a broadband spectrum between 1530 nm and 1610 nm (random polarization) was used to couple light in port 1 of a circulator (Thorlabs 6015-3-APC); port 2 was connected to a fiber which was aligned with the end-face of the waveguides and port 3 was connected to an optical spectrum analyzer (OSA) (Agilent 86142B).

3. Results and discussion

Since it is not possible to completely eliminate the higher diffraction orders of a phase mask, interference of these orders may lead to doubling of the fabricated grating period [8]. We observed this effect when fabricating PMMA gratings, so that a grating period of 1010 nm (second order Bragg grating) was obtained. In Fig. 2, the simulated diffraction efficiency (PMMA grating with a sine amplitude and a 1010 nm period) of the different diffraction orders is plotted as a function of grating depth. By fitting the measured diffraction efficiencies with these graphs, a grating depth of approximately 260 nm was found.

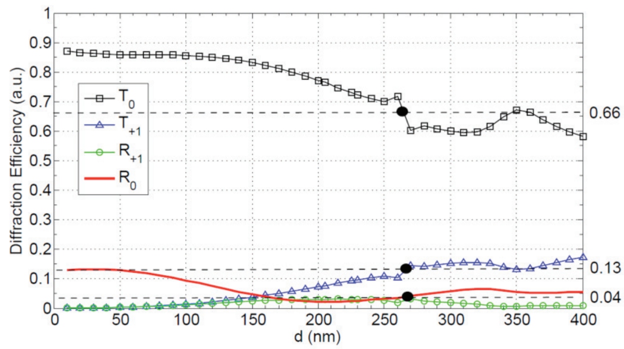

Fig. 2. Simulated diffraction efficiencies of the 1010 nm period PMMA grating as a function of grating depth and measured diffraction efficiencies (solid markers) plotted at the grating depth matching the values (i.e. 260 nm).

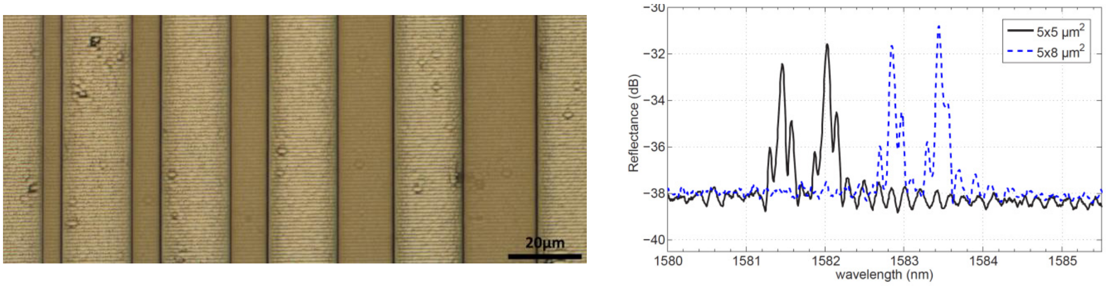

Fig. 3. (left) Microscope image of 5 µm, 8 µm, 10 µm, 15 µ m, 20 µm wide waveguides (5 µm thick) patterned on top of grating structures inscribed in the cladding layer. (right) Reflection spectrum of the 5 µm and 8 µm single mode waveguides, normalized to the source spectrum.

Fig. 3 (left) shows a top view of waveguides having different widths (all 5 µm thick) patterned on top of grating structures in the cladding layer. The propagation loss of the single mode EpoCore/EpoClad waveguides at 1550 nm was found to be 2.2 dB/cm and the coupling loss per waveguide-fiber transition about 0.75 dB. The reflection spectra (normalized to the source spectrum) obtained for 5 µm x 5 µm and 8 µm x 5 µm waveguides are plotted in Fig. 3 (right). This plot was obtained using a resolution bandwidth of 60 pm and averaging over 20 sweeps. For each waveguide, 2 closely spaced reflection peaks are observed, corresponding to the reflected fundamental TM and TE mode, having slightly different n_{eff}. This peak separation is due to the relatively large material birefringence induced by molecular orientation and internal stress during fabrication using spin-coating and several baking steps. The reflection peaks corresponding to the 8 µm x 5 µm waveguides are found at longer wavelengths due to the higher n_{eff} in these larger core waveguides.

4. Conclusions and future work

An approach for integrating Bragg gratings with single mode polymer waveguides was presented. Waveguides were patterned using laser direct-write technology and gratings were integrated as surface relief structures in the cladding. The reflection spectra were recorded and revealed the expected reflection peaks around 1580 nm. Although the absolute reflection values are currently relatively low, the addition of gratings to the standard waveguide fabrication process is promising for sensing applications. We are currently looking at increasing the reflected power by optimizing the grating transfer and investigating the use of a more coherent UV-source, an anti-reflection coating and other types of photosensitive materials for grating fabrication.

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