Flexible thin polymer waveguide Bragg grating sensor foils for strain sensing

Jeroen Missinne, Nuria Teigell Benéitez, Gabriele Chiesura, Geert Luyckx, Joris Degrieck, Geert Van Steenberge

In: Proceedings of the SPIE, Volume 101010, page 101010X (6 pages), 2017.

https://doi.org/10.1117/12.2250823

To refer to or to cite this work, please use the citation to the published version:

Jeroen Missinne, Nuria Teigell Benéitez, Gabriele Chiesura, Geert Luyckx, Joris Degrieck, Geert Van Steenberge (2017). “Flexible thin polymer waveguide Bragg grating sensor foils for strain sensing.” *Proceedings of the SPIE, Vol. 101010.* 101010X. 10.1117/12.2250823

Flexible thin polymer waveguide Bragg grating sensor foils for strain sensing

Jeroen Missinne*[a], Nuria Teigell Benéitez[a], Gabriele Chiesura[b], Geert Luyckx[b], Joris Degrieck[b],
Geert Van Steenberge[a]
[a]Centre for MicroSystems Technology (CMST), imec and Ghent University,
Technologiepark 914-A, B-9052, Ghent, Belgium;
[b]Department of Materials Science and Engineering, Technologiepark 903-B 9052, Ghent, Belgium.

ABSTRACT

This paper demonstrates that epoxy-based single mode polymer waveguides with Bragg gratings can be realized in very thin (down to 50 micron) polymer foils which are suitable for strain sensing when integrated inside glass fiber reinforced polymer composite materials. The single mode waveguides were fabricated using laser direct-write lithography and the gratings were realized using nanoimprint lithography. These steps were performed on a temporary rigid carrier substrate and afterwards the functional layers were released yielding the thin, flexible sensor foils which can be laser-cut to the required dimensions.

The Bragg grating-based polymer waveguide sensor foils were characterized before and after embedding into the composite. As expected, there was a blue shift in the reflection spectrum because of residual strain due to the embedding process. However, the quality of the signal did not degrade after embedding, both for 50 and 100 micron thick sensor foils. Finally, the sensitivity to strain of the embedded sensors was determined using a tensile test and found to be about 1 pm / microstrain.

Keywords: Bragg grating sensor, composite, epoxy, flexible, foil, polymer waveguide, nanoimprinting, strain sensing.

1. INTRODUCTION

Similarly as in electronics, there is a trend towards flexible polymer photonics because of low (material) costs and high-throughput fabrication [1-4]. Furthermore, in case of sensors, the optical and mechanical material properties of the polymers themselves lead to interesting sensor attributes. For example, highly-sensitive temperature sensors can be obtained making use of the high thermo-optic coefficient of the hybrid polymer Ormocer® [5]. On the other hand, the flexibility of polymers allows e.g. measuring very large mechanical deformations or elongations before breaking. Such deformations are a.o. the topic of investigation in the field of structural health monitoring. For that application, the sensors can be applied on top of the structure, although it may be better to embedded them inside the structure, e.g. to protect them from the harsh operating environment.

Fibers with Bragg grating sensors have been used extensively for this purpose [6, 7], but polymer waveguides with Bragg gratings realized on a flat substrate are a promising alternative in certain use cases. Compared to silica fibers, they allow larger elongations and their planar configuration allows precise positioning of the sensor and allows using more complex layouts, e.g. sensors in various well-defined directions. However, the sensor foils need to be unobtrusive (very thin and flat) and compatible with the host material.

The sensors reported in this paper implement the Bragg grating sensing concept on a thin epoxy foil with a single mode waveguide which has a grating imprinted at the cladding/core interface. When broadband light is launched in the waveguide, the grating will reflect a particular so-called Bragg wavelength λ_B given by the Bragg equation $\lambda_B = 2n_{eff}\Lambda$ (for a first order grating), where n_{eff} is the effective index of the waveguide mode and Λ the pitch of the grating. Epoxy foils with thicknesses of 35 µm, 50 µm and 100 µm were realized and their operation was characterized after embedding in glass fiber reinforced composite, a light-weight and high strength material which is increasingly replacing traditional materials (such as metals) in mechanical constructions.

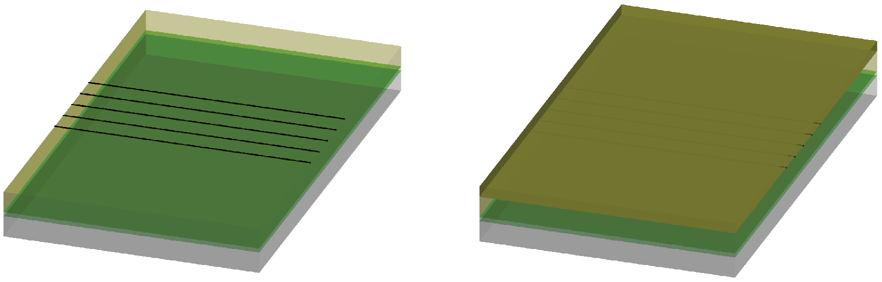
*jeroen.missinne@ugent.be; phone 32 9 264 5621; cmst.be

2. METHODS

2.1 Thin polymer sensor foil fabrication

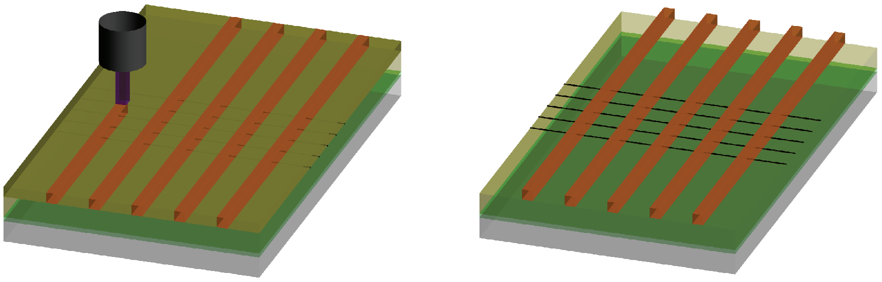
Traditionally, polymer waveguides are realized on a glass, silicon or FR-4 substrate, but in order to allow embedding in a later stadium, free-standing flexible sensor foils without any carrier need to be fabricated. This can be achieved by adding a release layer on a rigid temporary processing carrier which allows lifting off the flexible epoxy sensor stack after fabrication. On top of this release layer the typical cladding-waveguide-cladding stack is realized and to implement Bragg grating sensors, a grating is imprinted in the lower cladding layer at the interface with the waveguide core.

The most important fabrication steps are summarized in Figure 1 and detailed below. First, a polyimide (PI2611, HD Microsystems [8]) release layer is spin-coated on a temporary glass carrier and the required baking steps are performed. Then, the cladding layer (EpoClad, Microresist Technology [9]) is spin-coated on top followed by a baking step on a hotplate to evaporate the solvent. Different spin-coating parameters are employed to realize final sensor foil thicknesses of 35 µm, 50 µm and 100 µm. The adhesion of the EpoClad material onto the polyimide layer is sufficient to ensure reliable fabrication, but is low enough to allow release afterwards. After the baking step, the grating is applied using imprinting. To this end, a fluorinated stamp with about 200 nm deep grooves on a pitch of 505 nm (duty cycle 50 %) is brought in contact with the cladding layer while still on the hotplate. To polymerize the material, it is illuminated using a broadband UV-lamp (30 s at 30 mW/cm^2) after which the stamp is peeled off (Figure 1 (a)). After subsequent hotplate and convection oven baking steps, this layer is plasma-treated (gas used: air) and the core layer (EpoCore Microresist Technology) is spin-coated (thickness 5 µm) and baked on a hotplate (Figure 1 (b)). Then, 5 µm wide waveguide structures are defined by selective UV exposure using Direct-Write Lithography (DWL, Heidelberg DWL 66+), see Figure 1 (c). Afterwards, the unexposed material is removed in a dedicated developer (mr-DEV600, Microresist Technology) and final baking steps are performed. Finally, the waveguides are covered with another EpoClad layer using the same parameters as for the lower cladding layer (omitting the imprinting step).



(a) Cladding with imprinted grating lines

(b) Spin-coating of core layer



(c) Selective UV exposure using DWL

(d) Develop unexposed material

Figure 1. Illustration of the most important steps to realize flexible Bragg grating sensor foils.

To allow releasing, the contours of the sensors are cut out using a Nd:YAG laser (λ = 355 nm). Because of the low adhesion of the polyimide to the glass carrier, the flexible sensors easily come off and finally the polyimide layer can be peeled off from the epoxy sensor stack.

2.2 Embedding of sensor foils in composites

The flexible epoxy sensor foils are integrated in a glass fiber reinforced composite during its production. Such a composite is realized by impregnating reinforcement fiber sheets (500 g/m^2 UDO E S500 unidirectional glass fiber from SGL Group [10]) with an epoxy resin (two-component epoxy system RIMR135+RIMH137 from Hexion [11]) in a mold under vacuum conditions (vacuum assisted resin infusion process [12]). In the current work, a large plate was realized containing four layers of unidirectional reinforcement fibers in which various sensor foils (with the 3 different thicknesses) were integrated between the second and third layer. Upon impregnating, the composite is formed after 24h curing at room temperature and post-curing for 15 hours at 80°C in an oven. Finally, the large plate was diced in smaller specimen, each containing a single sensor foil. To expose the waveguide for characterization, a cut was made through the embedded sensor foil and its end-face was polished to improve the coupling efficiency.

2.3 Characterization of the embedded sensor foils

The reflection spectrum of the waveguide Bragg grating sensors was characterized before embedding (i.e. flexible sensor foils) and after embedding in the composite using a typical setup with an optical circulator and spectrum analyzer (OSA) as shown in Figure 2. After characterization, the specimen was pigtailed with a fiber by actively aligning and gluing a dedicated connector.

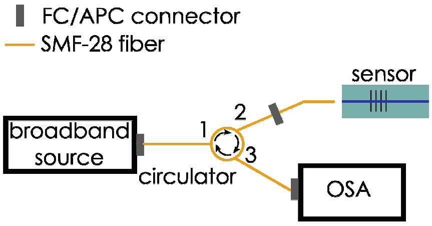


Figure 2. Setup used to characterize the waveguide Bragg grating reflection spectrum.

The tensile tests were performed using a servo-hydraulic tensile tester from Instron® (model 8801) with a crosshead speed of 0.2 mm/min and a 100 kN load cell. A 10 mm gauge length dynamic extensometer with a strain range of 10 % was mounted on the specimen to record the actual strain at the grating sensor location. To allow clamping of the pigtailed specimen, 2 steel blocks were glued on both sides of the fiber connector. The Bragg wavelength reflection peak was tracked using a dedicated optical fiber sensor interrogator (FBG-Scan 804 interrogator from FBGS Technologies GmbH) operating from 1510 nm to 1590 nm and having a resolution of 1 pm.

3. RESULTS AND DISCUSSION

3.1 Thin polymer sensor foil fabrication

We found that with contact mask lithography, it is difficult to realize low-roughness waveguides on top of an underlying grating, probably because of scattering of (broadband) UV-light at the grating during illumination. On the other hand, using the DWL technology and after optimizing exposure parameters, it was possible to reliably define such single mode waveguides on top of grating grooves, as illustrated in Figure 3 (left). The EpoCore waveguides measure about 5 µm x 5 µm and taking into account the refractive index contrast between EpoCore and EpoClad materials, this yields single mode operation around 1550 nm [13].

Figure 3 (right) shows several sensor foils cut out from a 5 cm x 5 cm glass carrier. When lifting off from the carrier, the foils slightly curl because of the CTE (coefficient of thermal expansion) mismatch between the epoxy and the polyimide release layer which is still attached to the sensor foil. After peeling off this polyimide layer, the flexible sensor foils become virtually flat. Sensor foils with final thicknesses of 35 µm, 50 µm and 100 µm were successfully realized and released without damaging, however, the 35 µm foils were so thin that they were very difficult to handle especially before embedding them in the composite.

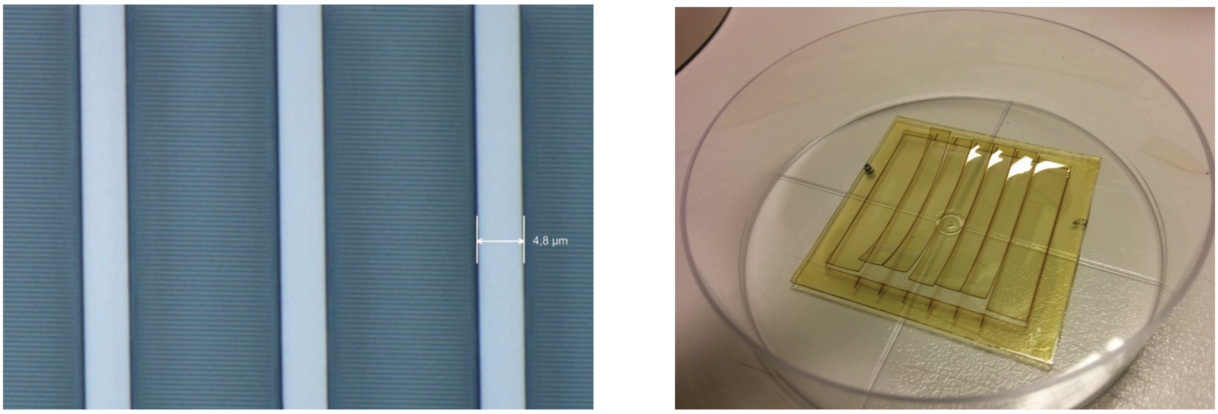


Figure 3. (left) Microscope top view image showing 5 µm x 5 µm waveguides realized on top of the imprinted grating before applying the top cladding (image processed using 'Enhanced Depth of Focus' software to show both gratings and waveguides in focus). (right) Flexible sensor foils after laser cutting and before peeling off the polyimide layer.

3.2 Embedding of sensor foils in composites

Figure 4 shows one of the sensor foils after embedding in the composite material. It can be seen that the sensor was positioned towards the edge of the specimen to allow connecting it to an external fiber for tracking the reflection peak in situ during tensile testing. The grating itself was located about 2 cm from the specimen edge.

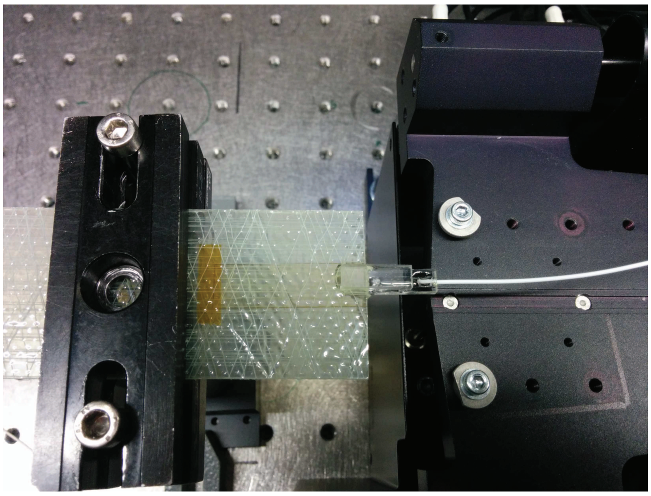


Figure 4. Fiber reinforced composite test specimen with embedded flexible sensor, pigtailed to an external fiber.

3.3 Characterization of the embedded sensor foils

The correct operation of the 35 µm, 50 µm and 100 µm thick sensor foils were investigated after embedding. From the cross-section, it could be seen that the embedded 35 µm thick sensor foil showed quite some deformation, probably because it was too thin to withstand the composite production process. Also the recorded sensor signal was very low and the spectrum was heavily distorted. However, both for the 50 µm and 100 µm thick sensor foils the signal strength was comparable before and after embedding and also the reflection spectrum did not seem to show significant distortion due to the embedding process, which is an important aspect to take into account when embedding Bragg grating sensors [7].

The graph in Figure 5 shows reflection spectra of the 50 µm thick sensor foil. The values shown on the ordinate should be interpreted as the total reflectivity taking into account contributions of grating reflectivity, fiber-waveguide coupling losses and waveguide propagation losses (about 2.2 dB/cm for EpoCore/Clad waveguides at 1550 nm [13]). As a reference signal for calculating these reflectivity values, the Fresnel reflection at a perpendicularly cleaved fiber end-face was considered (without touching the FC/APC connections). The reflectivity has slightly decreased after pigtailing due to misalignment during the gluing process, but the signal is strong enough to allow reliable tracking of the peak location during tensile testing. The Bragg wavelength λ_B is found at the expected spectral position, considering a grating pitch of 505 nm and n_{eff} of about 1.56 for EpoCore/EpoClad waveguides at this wavelength. However, it can be seen that there is a slight asymmetry in the spectra which may be caused by a slight deformation of the grating sensor. Since the same distortion is present in the spectra before and after embedding, we assume it is caused by the grating imprinting process and not during embedding in the composite. However, after embedding, the Bragg wavelength shows a blue shift of about 3 nm indicating a residual strain due to the embedding process.

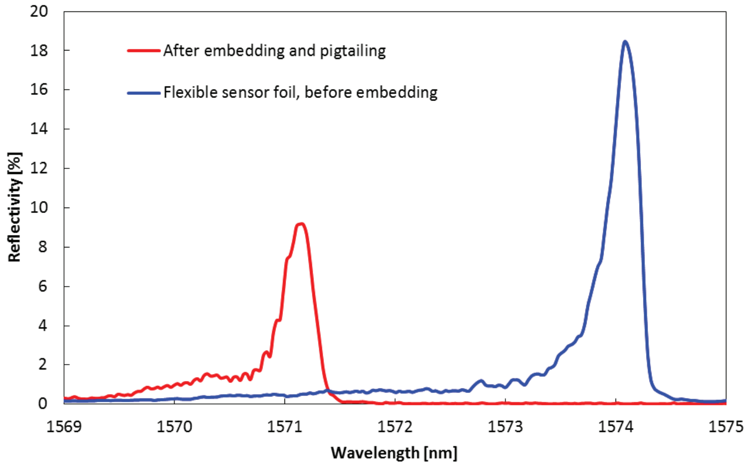
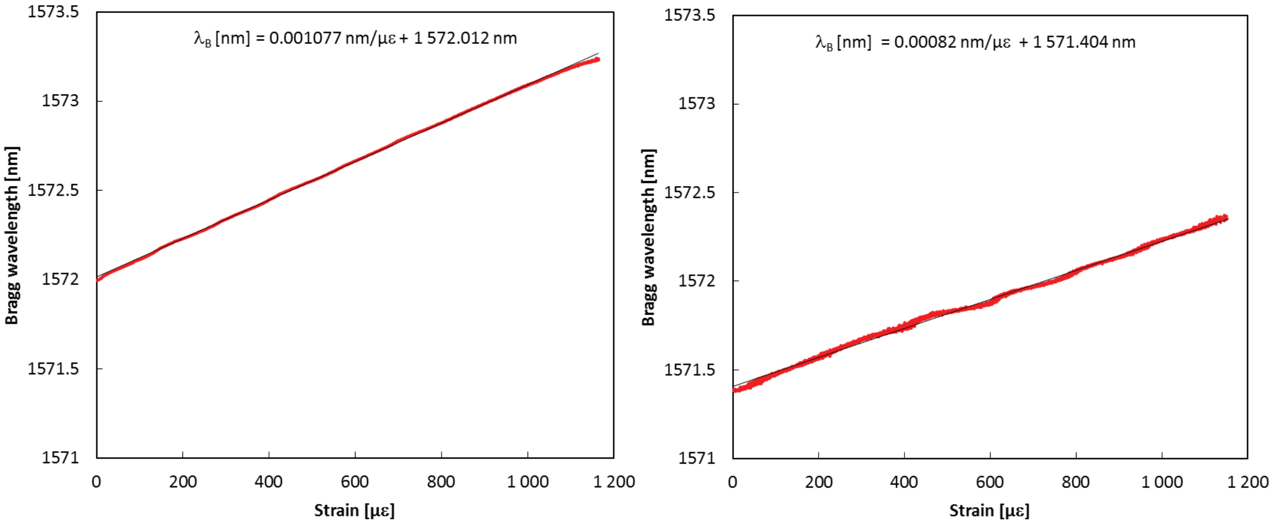


Figure 5. Reflection spectrum of the 50 µm thick sensor foil after embedding (and pigtailing) and before embedding in the composite specimen.

Figure 6 shows the recorded Bragg wavelength λ_B as a function of strain recorded by the extensometer for the 50 µm thick (a) and 100 µm thick (b) embedded sensor foils. The sensitivity of the embedded 50 µm thick sensor was found to be about 1 pm/µε. For the 100 µm thick sensor, the sensitivity appears to be slightly lower, however, this is likely due to non-ideal testing conditions, i.e. the steel bars were glued a bit too close to the sensor location, having an impact on the proper sensor operation.



(a) 50 µm thick sensor foil

(b) 100 µm thick sensor foil

Figure 6. Recorded Bragg wavelength λ_B as a function of recorded strain during tensile testing of sensor foils embedded in composite.

4. CONCLUSIONS

We have shown that epoxy-based flexible waveguide Bragg grating sensor foils (operating around 1570 nm) with a total thickness down to 50 µm can be realized and that those sensors can be embedded in a glass fiber reinforced composite during an infusion process without degradation in sensor signal. However, after embedding, a blue shift in the reflection spectrum was observed, indicating a compressive residual strain but this did not lead to spectral distortion. The flexible foils were realized on a temporary rigid carrier and afterwards released; the sensors themselves were fabricated by defining a single mode waveguide (using direct-write lithography) on an imprinted grating in the cladding layer. After embedding 50 µm thick and 100 µm thick sensor foils in composite specimens, a fiber was attached to those specimens and the sensor sensitivity to strain was determined through tensile testing. The sensitivity of the embedded 50 µm thick sensor foil was found to be about 1 pm/microstrain; the sensitivity of the 100 µm thick sensor foil was slightly lower but this was likely due to non-ideal testing conditions, rather than due to intrinsically different sensor behavior.

ACKNOWLEDGMENTS

This work was conducted in the framework of the project Self-Sensing Composites (SSC), funded by the Flemish Government through the SBO project IWT-nr 120024 and in the framework of the project NextDx (EU-FP7). We also thank the Hercules foundation to provide funding for the APPLIE4MOS polymer prototyping line used in this research.

REFERENCES

[1] Missinne, J., Kalathimekkad, S., Van Hoe, B., Bosman, E., Vanfleteren, J., and Van Steenberge, G., “Stretchable optical waveguides,” Optics Express, 22(4), 4168-4179 (2014).

[2] Hu, J., Li, L., Lin, H., Zhang, P., Zhou, W., and Ma, Z., “Flexible integrated photonics: where materials, mechanics and optics meet [Invited],” Optical Materials Express, 3(9), 1313-1331 (2013).

[3] Li, L., Lin, H., Michon, J., Huang, Y., Li, J., Du, Q., Yadav, A., Richardson, K., Gu, T., and Hu, J., “A new twist on glass: A brittle material enabling flexible integrated photonics,” International Journal of Applied Glass Science, n/a-n/a (2016).

[4] Aikio, S., Hiltunen, J., Hiitola-Keinänen, J., Hiltunen, M., Kontturi, V., Siitonen, S., Puustinen, J., and Karioja, P., “Disposable photonic integrated circuits for evanescent wave sensors by ultra-high volume roll-to-roll method,” Optics Express, 24(3), 2527-2541 (2016).

[5] Benéitez, N. T., Missinne, J., Shi, Y., Chiesura, G., Luyckx, G., Degrieck, J., and Steenberge, G. V., “Highly Sensitive Waveguide Bragg Grating Temperature Sensor Using Hybrid Polymers,” IEEE Photonics Technology Letters, 28(10), 1150-1153 (2016).

[6] Majumder, M., Gangopadhyay, T. K., Chakraborty, A. K., Dasgupta, K., and Bhattacharya, D. K., “Fibre Bragg gratings in structural health monitoring—Present status and applications,” Sensors and Actuators A: Physical, 147(1), 150-164 (2008).

[7] Luyckx, G., Voet, E., Lammens, N., and Degrieck, J., “Strain Measurements of Composite Laminates with Embedded Fibre Bragg Gratings: Criticism and Opportunities for Research,” Sensors, 11(1), 384 (2011).

[8] HD Microsystems, http://www.hdmicrosystems.com.

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

[10] SGL Group, http://www.sglgroup.com/.

[11] Hexion, http://www.hexion.com/.

[12] Summerscales, J., and Searle, T. J., “Low-pressure (vacuum infusion) techniques for moulding large composite structures,” Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 219(1), 45-58 (2005).

[13] Elmogi, A., Bosman, E., Missinne, J., and Van Steenberge, G., “Comparison of epoxy- and siloxane-based single-mode optical waveguides defined by direct-write lithography,” Optical Materials, 52, 26-31 (2016).