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Femtosecond inscription of fiber Bragg gratings through the coating with a Low-NA lens

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Abstract: Fiber Bragg grating (FBG) inscription in standard fibers with femtosecond (fs) laser pulses was first reported nearly two decades ago. FBG fs inscription through the fiber polymer coating was recently demonstrated with a phase mask (PM) and High Numerical Aperture (High-NA) cylindrical lenses. In this work, we report on a new technique for FBG inscription through the acrylate polymer coating of optical fibers using a Low-NA lens and the PM. The FBGs were inscribed through the polymer coating of the fiber after a suitable fs photo-treatment process that was done to the polymer coating. We experimentally demonstrate inscription of high-quality FBGs yet with some damage to the coating. We characterize the wavelength sensitivity to strain and temperature of the inscribed FBGs, and compare them to FBGs that were inscribed in fibers that have undergone stripping, inscription, and recoating. The technique may simplify FBGs inscription through the coating especially in large mode area fibers and double clad fibers for laser applications in the future.

1. Introduction

Fiber Bragg gratings (FBGs) were first demonstrated in the late 70's by Hill et al. [1]. Today, FBGs have found applications in various fields such as telecommunications, sensors, and fiber lasers [2]. Traditionally, FBGs are written by side illumination with Ultraviolet (UV) interference pattern onto the core of photosensitive fibers. Fiber preparation to FBG inscription with UV lasers involves several steps. Typically, hydrogen loading is used to increase the photosensitivity of the fiber core to UV light [3], followed by stripping its polymer coating [4]. The FBG is inscribed using UV laser [5] and undergoes thermal aging to outgas the hydrogen and to stabilize the index modulation for long-term operation [6]. Finally, the FBG is recoated for mechanical protection. All these steps must be performed with extreme care in order for the fabrication process to be reliable and repeatable [5]; consequently this limits the yield and increases both the time and the cost of the FBG fabrication process. Writing through the coating (WTC) is an attractive concept for improving the yield, cost and time of the fabrication process. Several attempts to WTC with traditional UV techniques have been made using special UV transparent coatings [7,8] or by using near UV sources where standard polymer coatings are partially transparent [9]. However, it was not possible to induce a significant refractive index modulation and a reflectivity of only 20% was achieved [9].

Femtosecond (fs) induced index modification and inscription of photonic devices has been under extensive research in the past two decades [10]. Numerous photonic devices such as waveguides and FBGs have been demonstrated. The latter were demonstrated in various types of fibers. Typical intensities of $\sim 10^{13}\,\mathrm{W/cm^2}$, in silica fibers, are used to initiate multiphoton absorption and refractive index modification. Index modification with fs laser has been used for writing FBGs without the need for sensitization in both the phase mask

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(PM) technique [11] and the point-by-point (PbP) technique [12]. In the last fifteen years, the PM technique was used to inscribe FBGs in various types of fibers including pure silica single mode fibers (SMF) [13,14]. Due to the nonlinear nature of the inscription process, the refractive index modification is confined to the focal volume only, where the intensity exceeds the modification threshold.

In order to inscribe gratings through the fiber polymer coating one need to use tight focusing such that the intensity at the fiber core is sufficient for refractive index modification, yet the intensity at the coating is low enough to avoid damage. While this is quite trivial in the PbP method where High-NA objective lenses are used, it is more challenging with the PM technique (mainly due to lack of suitable cylindrical objectives). WTC in silica fibers was successfully demonstrated using 800 nm fs pulses with both the PM [15] and the PbP techniques [16]. Since the PbP technique relies on the formation of void-like defects, the resulting FBGs were reported to present poor mechanical strength, with a mean breaking stress of only 15%–20% compared to that of a pristine fiber [17]. FBGs fabrication with the PM technique have been demonstrated through both acrylate [15,18] and polyimide coated [19] fibers, and the reported mean breaking stress was 75%–85% and 50%, respectively, compared to that of a pristine fiber. In both cases, optical damage to the coating was observed. There has been also a demonstration of WTC of FBGs in unloaded SMF-28 by using the PM technique and High-NA lens [20]. Only recently, excellent FBGs WTC of acrylate and polyamide coatings of single mode fibers (SMF) using the PM technique were demonstrated by Bernier et al. [21,22]. In these works, very short focal acylindrical lens with High-NA of 0.46 was used together with scanning of the fiber core to achieve FBGs WTC in pure silica core fibers, without noticeable degradation of the gratings mechanical strength. The mechanical strength of type I gratings were similar to that of a pristine fiber, while the mechanical strength of type II gratings had only a strength of ~10% compare to that of a pristine fiber. This inscription concept opens significant opportunities in the field of fiber sensors. However, due to the small focal spot size and the limited volume of index modification it would be more challenging to WTC FBGs in large mode area (LMA) fibers, double clad fibers, and graded index fibers for laser applications. In these cases, it would require scanning and stitching in both axes to induce a refractive index modification over the entire fiber core. Such a process will be time consuming and difficult to align.

In this paper, we study the feasibility of FBG inscription through the acrylate coating in a standard SMF using a Low-NA lens with 800 nm fs pulses and the PM technique. We apply a fs pre-photo-treatment to the fiber coating polymer and show it enables energy penetration to the fiber core and inscription of high quality gratings with a transmission dip of –30 dB. We measure the wavelength sensitivity of our FBGs WTC to both strain and temperature and evaluate their mechanical strength. We note that without this photo-treatment, we did not succeed to inscribe gratings due to damage to the polymer coating which leads to scattering. Appliance of photo-treatment to the polymer coating modifies it properties and enables grating inscription in the fiber core. Further investigation of the modification to the polymer is required.

FBGs WTC with Low-NA lenses have its advantages. Low-NA lenses have longer focal lengths (Raleigh range) to induce index modification, which makes them preferable to use with LMA fibers. Inscription through the coating of LMA fibers (e.g. 20/400) with a High-NA lens would require significant time consuming scanning (and stitching of grating planes), while a Low-NA lens would cover the whole fiber core with stationary illumination. In addition, it is easier to align the inscription beam to the fiber core, as the alignment sensitivity is reduced compared to High-NA lenses.

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2. Experimental setup and methodology

Our experimental setup is typical for FBG inscription with the PM technique and is shown schematically in Fig. 1. The inscribing source is an amplified Ti-sapphire laser system (Coherent Legend Elite) producing 3.5 mJ, 35 fs pulses at a 1 kHz repetition rate, at a center

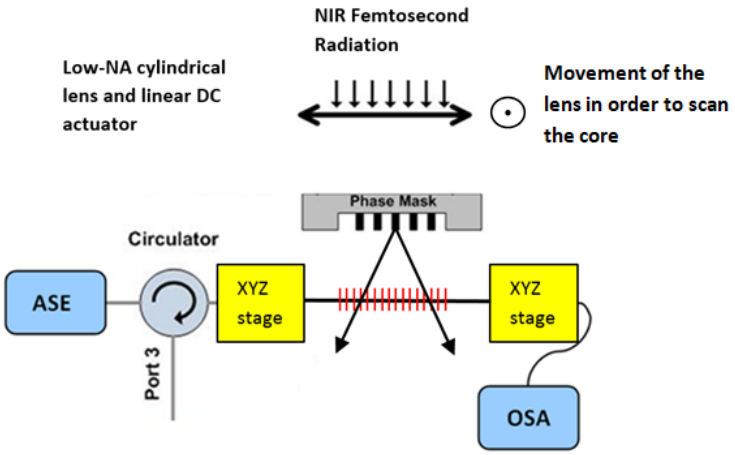

Fig. 1. Experimental setup.

wavelength of 800 nm. The Gaussian beam diameter is ~8 mm and it is focused on the fiber core, through the PM by a 40 mm cylindrical lens corresponding to NA of 0.1. The PM, made by Ibsen LTD, has a pitch of 2140 nm, corresponding to a second-order Bragg grating at a center wavelength of 1550 nm. Less than 5% of the energy diffracts to the zero order, while ~80% of the energy diffracts to the first diffraction orders (± 1 orders). These diffraction specifications are better than a first order PM (pitch of 1070 nm) for 800 nm illumination. The PM is positioned ~2 mm in front of the fiber to ensure pure two-beam interference [23]. The fiber is held in two grooves, each on a three-axis stage and under controlled tension, which provides high repeatability of our inscription system. The pulse energy of the inscription beam is adjusted by using a rotating half wave plate in front of a polarizer. The grating size in the fiber core is calculated to be ~5 μm × 6 mm, covering only part of the mode field diameter, which is ~9 μm in SMF fibers. Therefore, we scan the fs Gaussian beam with a linear DC actuator (PI M-230) ± 10 μm around the core, perpendicular to both the fiber axis and the optical axis of the inscription beam. The scanning corresponds to a movement of the cylindrical lens up and down within the plane that includes the lens (see Fig. 1). This ensures proper coverage of the fiber core and maximum reflectivity. In the other dimension, the extent of the Rayleigh range is much larger than the mode field diameter. Hence, we do not need to scan the beam in the focusing axis in order to cover the whole mode field diameter. The fiber is connected to an amplified spontaneous emission (ASE) source via a circulator on one end and to an optical spectrum analyzer (Yokogawa AQ6370D OSA) on the other end. The FBG transmission spectrum is monitored during the inscription process with 20 pm resolution and a 4 pm sampling interval.

In all experiments we use standard single mode fiber (Corning SMF-28) without hydrogen loading. Our inscription procedure is as follow: We first scan the acrylate polymer coating (perpendicular to both the fiber axis and the optical axis of the inscription beam) with relatively low pulse energy of 30 μJ, corresponding to an intensity of $\sim 2.5 \cdot 10^{12}$ W / cm^2. This intensity is slightly lower than the reported damage threshold of $\sim 3 \cdot 10^{12}$ W / cm^2 for acrylate polymer with multiple pulses of 790 nm and 30 fs pulse duration [24]. We scan the fiber polymer coating 600 times with the linear DC actuator ± 23 μm around the core (~2.4M pulses), during which the cylindrical lens is focused on the fiber polymer coating, ~80 μm

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from the core. Following this pre-photo-treatment, we adjust the focus of the cylindrical lens to the fiber core, increase the pulse energy and inscribe an FBG through the acrylate polymer coating. We stress at this point that without the fs pre-photo-treatment to the polymer coating we did not manage to inscribe FBGs through the coating with a 40 mm cylindrical lens. Without the pre-treatment the coating doesn't allow for the beam to focus into the fiber core and reach the threshold intensity needed for refractive index modification. This can be due to either scattering/absorption or a change/aberration of the focus due to the curvature of the polymer coating that prevents from reaching the intensity threshold. We speculate that the pre-treatment somehow changes the attenuation of the polymer coating enabling refractive index modification of glass in the core during inscription (due to increased intensity at the focus). After the pre-treatment procedure, we use the Vytran GPX-3400 microscope to inspect the coating of the fiber. We noticed that there is a slight black coloring that can be seen in Fig. 2. However, there is no shrinkage of the coating as can be seen in Fig. 3. The acrylate polymer coating diameter remains 240 μm – 250 μm through all the pre-treatment inscription area and the black coloring is visible only on one side; the side of the pre-treatment area.

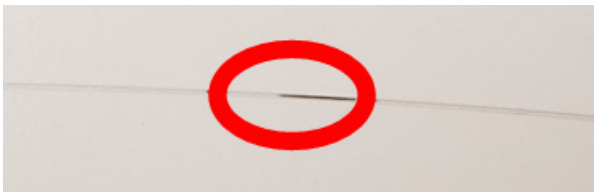

Fig. 2. Black coloring is observed on the fiber polymer coating in the pre-treatment area. This black coloring is observed with the naked eye only from the side of the fiber polymer coating where the pre-treatment procedure was.

3. Results and discussion

Following the fs pre-photo-treatment described above in the experimental setup and methodology section, we adjust the focus of the cylindrical lens to the fiber core, increase the pulse energy to 0.4 mJ and inscribe through the acrylate polymer coating of the fiber a FBG for 5 min at a repetition rate of 1 KHz. The result is a FBG with a transmission loss dip of −27 dB at a center Bragg wavelength of ~1548.4 nm as can be seen in Fig. 4. During the inscription process, severe damage occurs to the fiber coating. This damage is clearly visible with the naked eye; a very clear dark coloring in the inscription area is observed. The damage area is clearly seen with the Vytran GPX-3400 microscope in Fig. 5. The polymer coating size reduces from a diameter of 250 μm to less than 150 μm in some of the FBG inscription areas and there are some places were some ablation of the polymer coating is observed. We believe that this damage and shrinkage is mainly a result of heat accumulation. During the inscription process the center of the grating wavelength measured on the OSA is ~1554-1555 nm while the center grating wavelength at the end of the inscription process when the inscription beam is blocked is only ~1548.4 nm. This ~6 nm of red-shift is a result of a heat accumulation in the fiber core of the order of ~600 °C occurring during the FBG inscription process when we use both high repetition rate and high pulse energy. It was already reported that the acrylate polymer coating deteriorates above 150 °C after a short term [22]. Moreover, at these inscription conditions (high repetition rate and high pulse energy) we even observe sometimes smoke coming out from the fiber during the FBG inscription process. We believe that this smoke indicates that the fiber coating is burned, shrinks, and some of the material coating is ablated. Yet, according to the FBG inscription monitoring with the OSA there is still growth of the FBG even after the smoke is observed.

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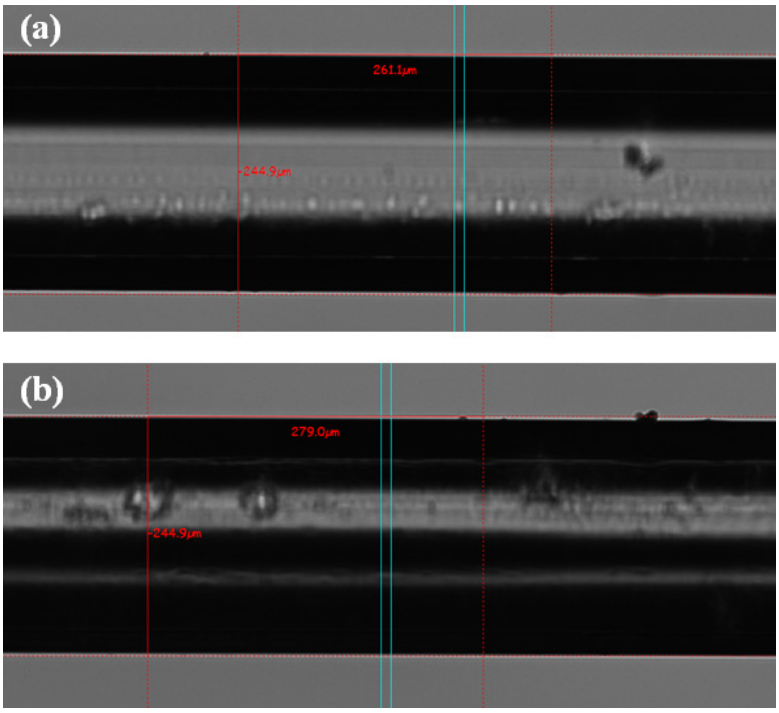

Fig. 3. Inspection of the fiber polymer coating after the pre-treatment procedure with the Vytran microscope imaging system. (a) Back side, the fiber looks similar to a pristine fiber. There is no shrinkage of the polymer coating. (b) Front side, there is no shrinkage of the polymer coating, but the black coloring of the coating is present.

Therefore, our next step was to reduce the repetition rate of the inscription fs beam in order to reduce heat accumulation. When we reduce the repetition rate of the inscription beam to 200 Hz, 250 Hz or 500 Hz (during the FBG inscription), the measured red-shift is always less than ~2.5 nm (<1551 nm) during the FBG inscription. This significantly smaller red-shift is a result of lower heat accumulation in the fiber during the FBG inscription process, compared to that in the case of 1 KHz repetition rate.

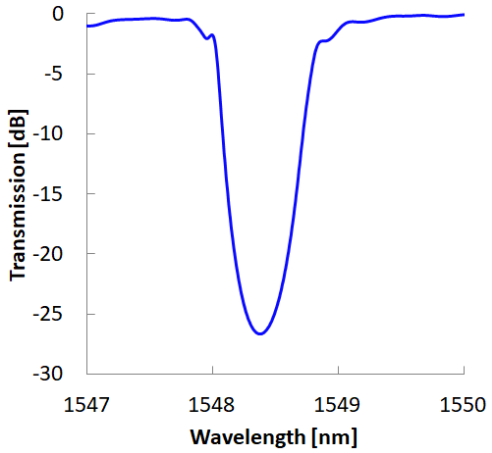

Fig. 4. Transmission spectra of a FBG inscribed through the acrylate coating after fs pre-photo-treatment. A transmission dip loss of –27 dB at a center Bragg wavelength of ~1548.4 nm is measured after ~5 min of inscription with pulse energy of 0.4 mJ and a repletion rate of 1 KHz.

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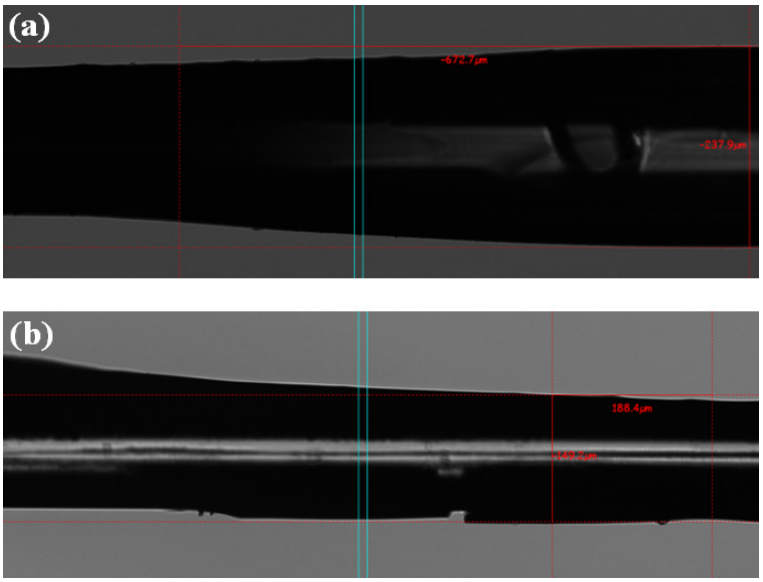

Fig. 5. Severe damage is visible in the FBG coating. (a) The acrylate polymer coating shrinkage from its original 240-250 µm diameter is clearly visible. The coating original size (seen on the right side) starts to shrink at the edge of the exposure. (b) Some of the polymer coating is removed and there is shrinkage of the polymer coating thickness to less than 150 µm in the center of the FBG exposure.

In Fig. 6 we show the transmission dip of an FBG inscribed through the polymer coating, after the pre-photo-treatment procedure, with pulse energy of 0.4 mJ, a repetition rate of 500 Hz and for ~10 min (~500K pulses). As evident, a transmission loss dip of −30 dB at a center Bragg wavelength of ~1548.5 nm is obtained.

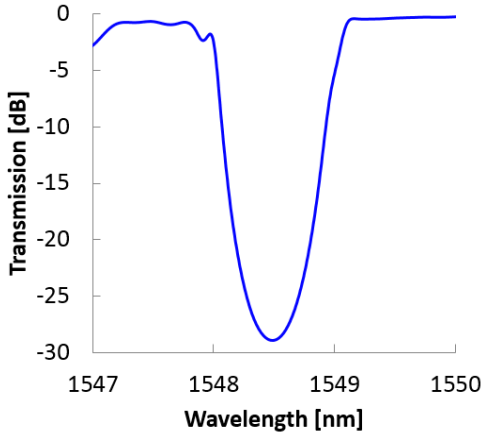

Fig. 6. Transmission spectra of a FBG inscribed through the acrylate coating after fs pre-photo-treatment. A transmission dip loss of −30 dB at a center Bragg wavelength of 1548.5 nm is measured after ~10 min of inscription with pulse energy of 0.4 mJ and a repletion rate of 500 Hz.

After applying the fs pre-photo-treatment mentioned above, we inscribe through the polymer coating many FBGs with various transmission dips up to −30 dB with repetition rates of 200 Hz, 250 Hz and 500 Hz. The typical pulses energies and the FBG inscription duration were 0.4-0.5 mJ and 10-20 min, respectively, keeping in each case the total number of pulses ~500K. For all inscription cases, there was a significant reduction of the red-shift

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observed during inscription and we didn't observe any smoke or burning of the fiber. The original black coloring due to the fs pre-treatment procedure was always observed. Yet, again we inspected this damage / black coloring with the Vytran GPX-3400 microscope imaging system. The black coloring is observed, however with these inscription conditions (200 Hz, 250 Hz and 500 Hz), there is no shrinkage of the coating as can be seen in Fig. 7. The acrylate polymer coating diameter remains 240 μm – 250 μm through all the FBG inscription area and the black coloring is visible only on one side; the side of the illumination.

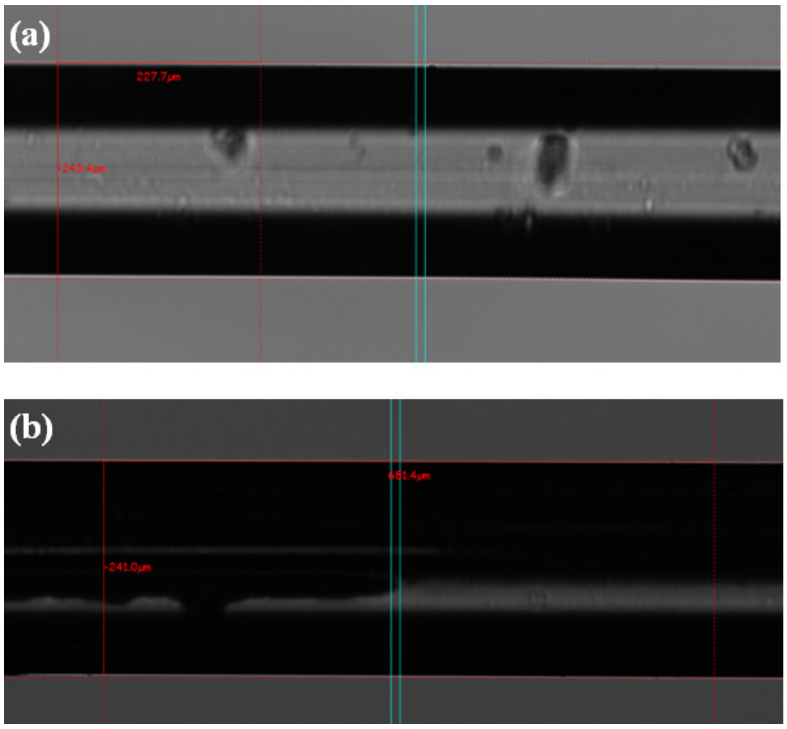

Fig. 7. Inspection of the FBG inscribed through the fiber polymer coating with the Vytran microscope imaging system. (a) Back side, the fiber looks similar to a pristine fiber. There is no shrinkage of the polymer coating. (b) Front side, there is no shrinkage of the polymer coating, but the black coloring of the coating is present.

4. Measurement of the FBGs mechanical strength and sensitivity to strain and temperature

Next, the inscribed fibers were pull-tested to evaluate their mechanical strength after the FBG inscription process. All the fibers broke at a force of ~0.55 Kg, which means a breaking stress of ~450 MPa and we didn't see any difference between the fibers inscribed at different repetition rates (200 Hz, 250 Hz or 500 Hz). This breaking stress is only about ~10% compared to that of a pristine fiber and to the fibers inscribed through the polymer coating with the 8 mm acylindrical lens in [21,22], by Bernier et al. This breaking stress is similar to the breaking stress reported for Type II FBGs in [22]. Finally, we compared our FBG inscribed through the acrylate coating with FBGs inscribed on a bare fiber after the polymer coating was stripped. Several FBGs were also recoated before measured for comparison. We didn't observe any significant difference in the mechanical strength between those three cases. All fibers broke under approximately the same mechanical stress, indicating that our stripping procedure also degrades the fiber strength.

We also measured the FBGs wavelength sensitivity to both strain and temperature of those three types of inscribed FBGs. The FBG wavelength sensitivity to strain can be seen in

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Fig. 8. The measured strain sensitivity for all three FBGs shows a linear dependence on strain with similar sensitivities of ~0.8 pm/με. This measured sensitivity to strain is slightly higher than the one reported in [22] and quite similar to the theoretical value of 0.78 pm/με reported for silica fibers in [25].

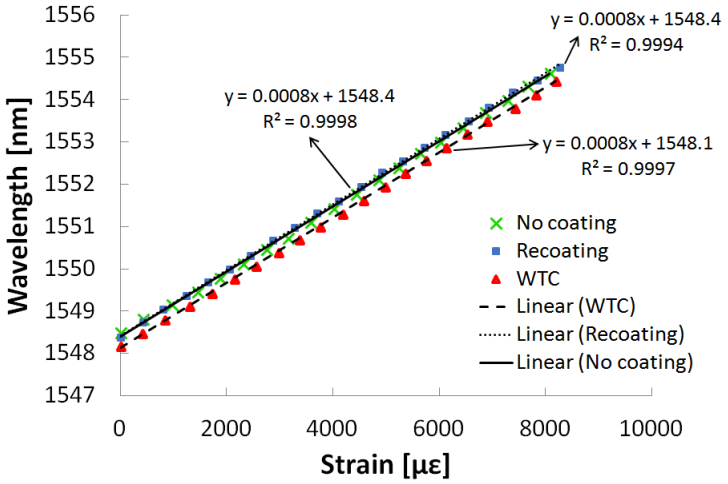

Fig. 8. Measured wavelength sensitivity to strain for all three FBGs inscribed. All three FBGs show a linear dependence on strain and a similar sensitivity of ~0.8 pm/με (green x – with no coating, blue square – with recoating, red triangle – WTC).

The measured wavelength sensitivity to temperature for all three FBGs is shown in Fig. 9. All three FBGs show a linear dependence on temperature. We also measured similar sensitivities of ~10.7 pm/°C and ~10.5 pm/°C for the FBG WTC and the FBG inscribed with the coating removed, respectively. These sensitivities are quite similar to the typical sensitivity value of ~10 pm/°C reported in the literature for silica fibers [26]. However, the FBG with the recoating has a slightly higher sensitivity value of ~12.4 pm/°C. This ~15% increase of sensitivity compare to our FBGs inscribed with the coating removed and through the coating is most likely due to the recoating. The recoating induces a slight strain (red-shift) and a slight increase of sensitivity to temperature. We removed the coating from the recoated fiber and found that without the coating the sensitivity is reduced by ~15% back to the sensitivity value of a FBG without coating.

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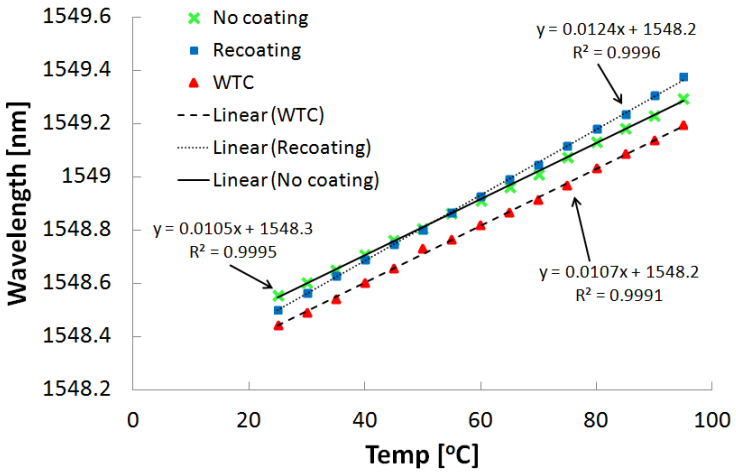

Fig. 9. Measured wavelength sensitivity to temperature for all three FBGs inscribed. All three FBGs show a linear dependence on temperature (green x – with no coating, blue square – with recoating, red triangle – WTC). The measured sensitivities are ~10.7 pm/°C for FBG WTC, ~10.5 pm/°C for FBG with no coating, and ~12.4 pm/°C for the recoated FBG.

5. Conclusions

In this paper we have demonstrated an approach to inscribe FBGs through the acrylate polymer coating of SMF with Low-NA lens (40 mm cylindrical lens) using 800 nm fs pulses and the PM technique. The FBG inscription through the polymer coating was obtained only after a suitable fs pre-photo-treatment was done to the fiber acrylate polymer coating. High quality FBG written through the acrylate polymer coating of the fiber with a transmission dip loss of −30 dB at a center Bragg wavelength of ~1548.5 nm in SMF is demonstrated. We found that there is some damage (black coloring) to the fiber coating. Some of the damage can be reduced by decreasing the repetition rate of the inscription beam during the FBG inscription process. However, though we reduced the damage of the coating, the measured mechanical strength of the FBG is only about ~10% compare to that of a pristine fiber. The measured wavelength sensitivity to strain of ~0.8 pm/με and the measured wavelength sensitivity to temperature of ~10.7 pm/°C were very similar to the measured sensitivities in a fiber with the coating removed as well as to the reported results in the literature. This new approach for inscribing FBGs through the coating with Low-NA lens may open the door for inscribing FBGs in LMA fibers and in double clad fibers for laser applications. In LMA fibers and double clad fibers, we believe that the damage to the polymer coating may be even reduced since the diameter of the fiber is larger hence, resulting in a lower intensity on the fiber polymer coating during the pretreatment and during the FBG inscription process. Future work may include applying this inscription technique on different fiber diameters and coatings (e.g. 20/400 and polyimide, respectively) as well as a first order PM and further investigation of the modification to the polymer during the pre-photo-treatment.

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Disclosures

The authors declare that there are no conflicts of interest related to this article.

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References

1. K. O. Hill, Y. Fujii, D. C. Johnson, and B. S. Kawasaki, "Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication," Appl. Phys. Lett. **32**(10), 647–649 (1978).
2. R. Kashyap, *Fiber Bragg Gratings*, 2nd ed. (Academic Press, 2009).
3. M. J. Matthewson, C. R. Kurkjian, and J. R. Hamblin, "Acid stripping of fused silica optical fibers without strength degradation," J. Lightwave Technol. **15**(3), 490–497 (1997).
4. P. J. Lemaire, R. M. Atkins, V. Mizrahi, K. L. Walker, K. S. Kranz, and W. A. Reed, "High pressure H2 loading as a technique for achieving ultrahigh UV photosensitivity and thermal sensitivity in GeO2 doped optical fibres," Electron. Lett. **29**(13), 1191–1193 (1993).
5. D. Varelas, D. M. Costantini, H. G. Limberger, and R. P. Salathé, "Fabrication of high-mechanical-resistance Bragg gratings in single-mode optical fibers with continuous-wave ultraviolet laser side exposure," Opt. Lett. **23**(5), 397–399 (1998).
6. T. Erdogan, V. Mizrahi, P. J. Lemaire, and D. Monroe, "Decay of ultraviolet□induced fiber Bragg gratings," J. Appl. Phys. **76**(73), 73–80 (1994).
7. L. Chao, L. Reekie, and M. Ibsen, "Grating writing through fibre coating at 244 and 248 nm," Electron. Lett. **35**(11), 924–926 (1999).
8. R. P. Espindola, R. M. Atkins, N. P. Wang, D. A. Simoff, M. A. Paczkowski, R. S. Windeler, D. L. Brownlow, D. S. Shenk, P. A. Glodis, T. A. Strasser, J. J. DeMarco, and P. J. Chandonnet, "Highly reflective fiber Bragg gratings written through a vinyl ether coating," IEEE Photonics Technol. Lett. **11**(7), 833–835 (1999).
9. D. S. Starodubov, V. Grubsky, and J. Feinberg, "Efficient Bragg grating fabrication in a fibre through its polymer jacket using near-UV light," Electron. Lett. **33**(15), 1331–1333 (1997).
10. R. R. Gattass and E. Mazur, "Femtosecond laser micromachining in transparent materials," Nat. Photonics **2**(4), 219–225 (2008).
11. S. J. Mihailov, C. W. Smelser, D. Grobnic, R. B. Walker, P. Lu, H. Ding, and J. Unruh, "Bragg Gratings Written in All-SiO2 and Ge-Doped Core Fibers With 800-nm Femtosecond Radiation and a Phase Mask," J. Lightwave Technol. **22**(1), 94–100 (2004).
12. A. Martinez, M. Dubov, I. Khrushchev, and I. Bennion, "Direct writing of fibre Bragg gratings by femtosecond laser," Electron. Lett. **40**(19), 1170–1172 (2004).
13. S. J. Mihailov, D. Grobnic, C. W. Smelser, P. Lu, R. B. Walker, and H. Ding, "Induced Bragg Gratings in Optical Fibers and Waveguides Using an Ultrafast Infrared Laser and a Phase Mask," Laser Chem. **2008**, 1–20 (2008).
14. S. J. Mihailov, D. Grobnic, C. W. Smelser, P. Lu, R. B. Walker, and H. Ding, "Bragg grating inscription in various optical fibers with femtosecond infrared lasers and a phase mask," Opt. Mater. Express **1**(4), 754–765 (2011).
15. S. J. Mihailov, D. Grobnic, and C. W. Smelser, "Efficient grating writing through fibre coating with femtosecond IR radiation and phase mask," Electron. Lett. **43**(8), 442–443 (2007).
16. A. Martinez, I. Y. Khrushchev, and I. Bennion, "Direct inscription of Bragg gratings in coated fibers by an infrared femtosecond laser," Opt. Lett. **31**(11), 1603–1605 (2006).
17. A. Martinez, Y. M. E. Shazly, S. N. Kukureka, K. Sudgen, I. Y. Khrushchev, and I. Bennion, in European Conference on Optical Communications, Cannes, France, paper We3.P.13 (2006).
18. D. Grobnic, S. J. Mihailov, C. W. Smelser, and R. T. Ramos, "Ultrafast IR laser writing of strong Bragg gratings through the coating of high Ge-doped optical fibers," IEEE Photonics Technol. Lett. **20**(12), 973–975 (2008).
19. S. J. Mihailov, D. Grobnic, R. B. Walker, C. W. Smelser, G. Cuglietta, T. Graver, and A. Mendez, "Bragg grating writing through the polyimide coating of high NA optical fibres with femtosecond IR radiation," Opt. Commun. **281**(21), 5344–5348 (2008).
20. C. W. Smelser, F. Bilodeau, B. Malo, D. Grobnic, and S. J. Mihailov, "Novel phase mask apparatus for 'through the jacket'inscription of FBG's in unloaded SMF-28 fiber," in *Advanced Photonics & Renewable Energy, OSA Technical Digest* (Optical Society of America, 2010), paper BThD3.
21. M. Bernier, F. Trépanier, J. Carrier, and R. Vallée, "High mechanical strength fiber Bragg gratings made with infrared femtosecond pulses and a phase mask," Opt. Lett. **39**(12), 3646–3649 (2014).
22. J. Habel, T. Boilard, and F. Jean-Simon Frenière, "Trépanier, and M. Bernier, "Femtosecond FBG Written through the Coating for Sensing Applications," Sensors (Basel) **17**(2519), 1–11 (2017).
23. C. W. Smelser, D. Grobnic, and S. J. Mihailov, "Generation of pure two-beam interference grating structures in an optical fiber with a femtosecond infrared source and a phase mask," Opt. Lett. **29**(15), 1730–1732 (2004).
24. J. Krüger, S. Martin, H. Mädebach, L. Urech, T. Lippert, A. Wokaun, and W. Kautek, "Femto- and nanosecond laser treatment of doped polymethylmethacrylate," Appl. Surf. Sci. **247**(1-4), 406–411 (2005).
25. Y. Wang, X. Qiao, H. Yang, D. Su, L. Li, and T. Guo, "Sensitivity-improved strain sensor over a large range of temperatures using an etched and regenerated fiber Bragg grating," Sensors (Basel) **14**(10), 18575–18582 (2014).
26. J. Albert, L.-Y. Shao, and C. Caucheteur, "Tilted fiber Bragg grating sensors," Laser Photonics Rev. **7**(1), 83–108 (2013).