Temperature-insensitive birefringent FBG in standard optical fibre induced by UV femtosecond pulses.

K. Chah,[1] D. Kinet,[1] C. Caucheteur,[1] Patrice Mégret,[1] and M. Wuilpart[1]

[1] Department of Electromagnetism and telecommunications, Faculty of Engineering, University of Mons, Bld Dolez 31, 7000 Mons, Belgium

Fibre Bragg gratings (FBGs) are widely used in a huge number of applications. Thanks to the development of ultrafast lasers and high precision positioning systems new generation of micromachined gratings has emerged. In point-by-point (PbP) FBGs the modified zone in each period is relatively small (2×0.5 μm) and may induce a significant scattering. This limitation is overcome in the line-by-line (LbL) writing process since the size of the inscribed region can be selected. In this work we report on the first LbL femtosecond UV inscription of polarization dependent FBGs in standard single mode optical fibre (SMF). Due to the ultralow thermal sensitivity of the SMF we show that this type of gratings can be exploited as temperature-insensitive strain sensor, eliminating the requirement for temperature compensation.

1. Introduction

The femtosecond laser pulses has become the essential tool for FBGs and waveguide inscription in various optical materials since the photosensitization process can be avoided which is not the case with conventional UV radiation. With the help of high precision (sub-micron) translation stage and by tightly focusing the 800 nm IR femtosecond beam to the core of the fibre, the PbP inscription technique has been first employed to inscribe highly reflective second order grating for 1550 nm wavelength [1], then improved with reflective microscope objective [2] to allow first order FBG inscription. By using the femtosecond radiation in the UV range, it has been demonstrated a first order gratings inscription in silica slabs with even smaller periods (down to 250 nm) [3]. However, due to the focus size (500 nm for IR down to 250 nm for UV) compared to core diameter (~8 μm) only a fraction of the core of the fibre is modified inducing a significant scattering [4]. Nevertheless, depending on the energy level and the polarization of the femtosecond pulses, the refractive index modulation is found to be not uniform across the entire core and can be regarded as elliptical micro-voids in the middle of the modified zone surrounded by a densification [5]. This type of refractive index modulation results in birefringent gratings where the magnitude of birefringence depends on the shape and the position of the modified zone in the core and is found to be in the range of 10^{-4} [5]. In the LbL inscription technique [6], the grating occupies the entire core diameter reducing the alignment requirements compared to the PbP one. The vertical offset which is more dependent on the autofocusing and the pulse energy will remain as the parameter to control. According to [5], we can predict that in the IR LbL inscription process the modified area will result in holly micro-channel surrounded by very high densification (Fig. 1(c)). A vertical shift of the channel location in the core may induce very high birefringence. The size of the line (micro-channel and surrounding densification) will depend on the pulse energy.

In our experiments we have combined the advantage of the 266 nm femtosecond radiations (very low focusing and high absorption coefficient in silica) with the LbL inscription technique to have the possibility to inscribe FBGs with the highest birefringence. Different gratings were inscribed with different orders. To inscribe first order LbL gratings few minutes were required and the reflectivity of the grating was moderated, more over the induced damage to create the birefringence is more concentrated rendering the fibre more fragile at the grating location. The 10^{th} order FBG was then selected as a trade-off between highly birefringent grating with good mechanical stability and high reflectivity coefficient. Temperature and transversal stress characterizations of such FBGs reveal that these type of gratings achieve very high transversal load birefringence sensitivity up to 178 pm/(N/mm) which is the same order of magnitude as standard highly birefringent bow Tie fibre (160 pm/(N/mm) [7] with the additional advantage of being inherently temperature-insensitive.

2. Experiment and discussion

For the FBGs inscription we used the 266 nm femtosecond pulses produced by the femtosecond laser from Spectra-Physics. The laser system composed by a Maitai oscillator and a Spitfire pro. amplifier delivers 4 mJ pulses with 120 fs duration and 1kHz repetition rate at 800 nm. After the amplifier the frequency of the laser is tripled via a third harmonic generation (THG) setup to reach 266 nm wavelength. A diffractive variable attenuator is used at the output of the amplifier so as to control both the IR and the UV beams powers. The UV laser beam was focused with a 50× long working distance microscope objective (OFR) with numerical aperture of 0.5. The microscope objective is fixed on a translation stage with piezo positioning system to allow precise position of the focus along y direction of the fibre (Fig. 1). The standard SMF fiber used for the experiments is clamped and fixed on a two-axis air bearing translation stage from Aerotech (Fig. 1(a)) to achieve precise displacement of the fiber along its x and z directions.

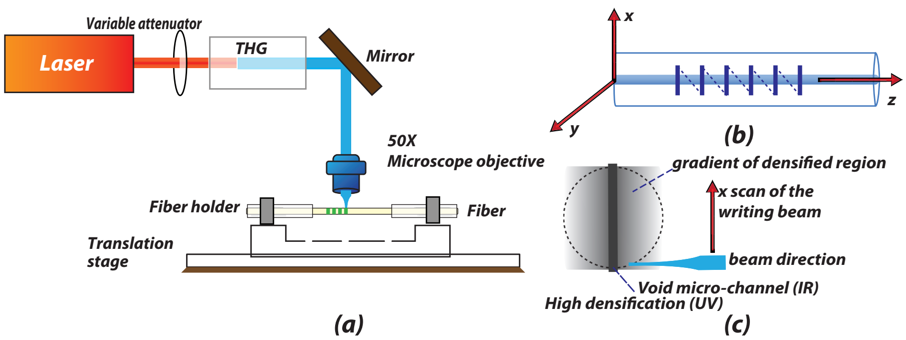

Figure 1. (a) Experimental setup for FBG inscription (b) schematic of top view LbL FBG inscription (c) transversal schematic view of the induced modification in the core (circle) and surrounded cladding area.

All the FBGs realized for the study were inscribed by the LbL technique. The principle of this process consists of scanning the focused writing beam perpendicular to the fibre axis (z) through the core to inscribe one line before displacing the fibre in the xz plane to inscribe the second parallel line and so on until the required length of the grating is reached (Fig.1 (b)). For our FBGs, the velocity of the x scan was fixed to $V_1= 60\ \mu m/s$, the diagonal translation speed to $V_2=800\mu m/s$ and the length of the lines to 30 µm. The UV pulse energy for inscription was set to 2µJ.

First up to fourth order gratings achieved very low transmission spectra. This effect has been reported for LbL FBGs inscribed with 120 nJ IR pulses where the highest reflectivity was recorded for the fourth order grating and the width of the lines measured to be less than 1 micron [6]. In our experiments, the focusing should be tighter (250 nm) because of the UV radiation and the lines narrower. Nevertheless, we expect that in our

case the high energy doses deposition at the focus induces more extended densification area which overlap for low gating orders.
To have higher reflectivity and less fragile gratings, we inscribed the gratings with higher order. In Fig. 2(a), we show the reflection and transmission spectra for the fifth and the tenth order LbL FBGs. From the peak separation values of the gratings we determine the birefringence to be 4.8 10^{-4} and 1.14 10^{-3} for the 5th and 10th order respectively. These values are the highest reported up to now in FBGs written with femtosecond laser. The microscope image of the side view of the 5th order FBG (Fig.2 (b)) shows that the inscribed grating is not centered with respect to the fibre core (straight dot line). In the insets of Fig. 2 we show a close up of the two gratings. In the case of these FBGs no micro-voids or void micro-channels were observed. According to [8], we assume that the high UV pulses used for the inscription should be responsible for high densification and radial asymmetrical stress in the core of the fibre. The FBG offset induces a shift of the high-density line from the center of the core increasing the birefringence of the fibre at the grating location.

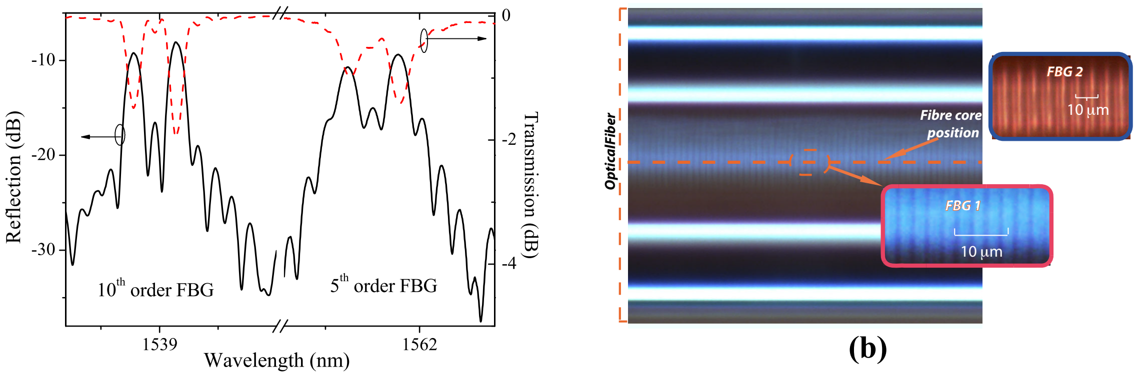

Figure 2. (a) Reflection and transmission spectra for 5th and 10th order 6 mm LbL FBG written with 2 µJ UV femtosecond beam. (b). Microscope image of the 5th order LbL FBG. Insets: close-up for 5th order FBG1 and 10th order FBG2.

Temperature characterization of the 10th order LbL FBG (Fig. 3 (a)) shows that the sensitivities of the slow and fast axis of the grating are identical in the investigated temperature range. Their values are 10.29 pm/°C and 10.25 pm/°C for slow and fast axis respectively. These sensitivities are equivalent to that obtained for FBG in standard SMF with conventional UV inscription techniques.
For the transversal stress characterization, we have used a test bench where the FBG with dummy fiber were disposed parallel and crushed between two metal plates. The line load was applied on the fibres and the spectra monitored.

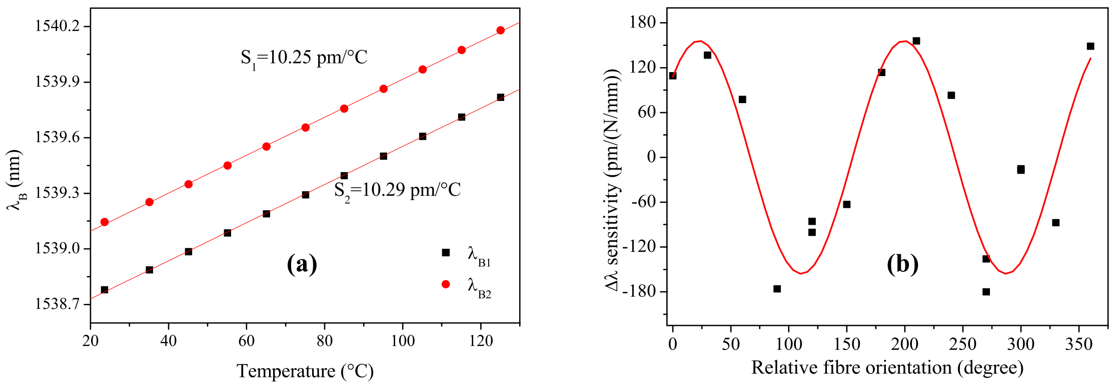

Figure 4. (a) Temperature and (b) transversal load of the 10th order LbL FBG.

Since the axes of the birefringent FBG were not determined, the fiber was oriented relatively to one initial position. In fig. 5 we show the Bragg peak separation sensitivities versus the relative orientation of the optical fibre. We can see clearly that the sensitivity can reach 178 pm/(N/mm) and show angular dependency as in conventional high birefringent fibers [7]. This behavior can be linked to the high radial concentration of the stress in the core of the fiber associated with the high densification.

Conclusion

We have realized very highly birefringent LbL FBG in standard SMF by UV femtosecond inscription. The birefringence of the FBG show no temperature dependence from room temperature up to 125°C. The transversal load sensitivity of the Bragg peak separation show angular dependence with the highest value of 178 pm/(N/mm) comparable to standard PM bow-tie fibre. This type of gratings can be exploited as temperature-insensitive strain sensor in structural health monitoring and many other applications.

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References

[1] A. Martinez, M. Dubov, I. Khrushchev and I. Bennion, "Direct writing of fibre Bragg gratings by femtosecond laser," Electron. Lett., vol. 40, 1170–1, 2004.

[2] T. Geernaert, K. Kalli, C. Koutsides, M. Komodromos, T. Nasilowski, W. Urbanczyk, J. Wojcik, F. Berghmans, and H. Thienpont, "Point-by-point fiber Bragg grating inscription in free-standing step-index and photonic crystal fibers using near-IR femtosecond laser," Opt. Lett., vol. 35, 10, 1647-1649, 2010.

[3] M Dubov, Bennion, D N Nikogosyan, P Bolger and A V Zayats, "Point-by-point inscription of 250 nm period structure in bulk fused silica by tightly focused femtosecond UV pulses," J. Opt. A: Pure Appl. Opt. vol. 10, 025305, 2008.

[4] R.J. Williams, N. Jovanovic, G.D. Marshall, G.N. Smith, M.J. Steel, M.J. Withford, "Optimizing the net reflectivity of point-by-point fiber Bragg gratings: the role of scattering loss," Opt. Express, vol. 20, 12, 13451-13457, 2012.

[5] N. Jovanovic, J. Thomas, R. J. Williams, M. J. Steel, G. D. Marshall, A. Fuerbach, S. Nolte, A. Tünnermann, and M. J. Withford, Polarization-dependent effects in point-by-point fiber Bragg gratings enable simple, linearly polarized fiber lasers," Optics Express, vol. 17, 8, 6082-6095, 2009.

[6] K. Zhou, C. Mou, M. Dubov, L. Zhang, and I. Bennion, "Line by Line Fiber Bragg Grating by Femtosecond Laser," IEEE Photon. Technol. Lett., vol. 22, 16, 1190-1192, 2010.

[7] E. Chehura, C.C. Ye, S.E. Staines, S.W. James, R.P. Tatam, "Characterization of the response of fibre Bragg gratings fabricated in stress and geometrically induced high birefringence fibres to temperature and transverse load", Smart Mater. Struct. 13, 888-895, 2004.

[8] F. Dürr, H. G. Limberger, R. P. Salathe, F. Hindle, M. Douay, E. Fertein and C. Przygodzki, "Tomographic measurement of femtosecond-laser induced stress changes in optical fibers," Appl. Phys. Lett., vol. 84, 4983-4985, 2004.