Polymer Fiber Bragg Grating Inscription using Phase Mask and 400 nm Femtosecond Laser

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This work highlights a setup based on a femtosecond laser system operating at 400 nm and using a phase mask technique to inscribe FBGs in CYTOP fibers without over-clad. The gratings are inscribed in a few seconds with a writing laser power as low as 80 µW. With this setup, 2 mm-long gratings with reflectivity up to 92 % were obtained in less than 10 s. Moreover, a 29.7 pm/°C temperature sensitivity of these FBGs is found, which is in agreement with results published elsewhere.

Introduction

To date, polymer optical fibers (POFs) have attracted more and more attention in the fields of communication and sensing due to their advantages such as high flexibility, low Young's modulus, biomedical compatibility and safety [1–4]. Nevertheless, polymer fibers present a high attenuation that is the main drawback for their wide deployment. The most widespread POFs are based on poly (methyl methacrylate) (PMMA) material and demonstrate an attenuation, caused by high absorption losses of the C−H bonds, of the order of 100 dB/km to 300 dB/km at wavelengths around 600 nm. This attenuation is also rapidly increasing with the wavelength shift towards the two standard telecom transparency windows around 1300 nm and 1550 nm [2]. The problem of high losses of PMMA has been significantly overcome with perfluorinated POFs, where hydrogen atoms are replaced by heavy fluorine atoms. These fibers are known as CYTOP fibers, and are available as graded-index multimode fibers with standard 50.0, 62.5 as well as 120.0 µm core diameters [2]. Actually, their theoretical attenuation limit is as low as 0.3 dB/km, but practical numbers now reach 20 dB/km at 1300 nm [2]. Such low losses made CYTOP fibers outstanding candidate for short-distance communication links and fiber sensing.

Due to low insertion loss, low polarization sensitivity, and an extremely concise design, it makes polymer gratings very attractive candidates for applications of complex filtering or precise chromatic dispersion compensation in telecommunications [5]. However, FBG inscription in CYTOP fibers is still a challenging task. Despite the early reports on CYTOP material photosensitivity achieved with frequency tripled Nd:YAG laser (355 nm) and Ar ion laser (457.9, 488.0 and 515.5 nm) [6,7], to date, there is a very limited number of reported techniques for successful FBG inscription in CYTOP fibers.

The first one, a phase mask technique, has been applied with KrF excimer laser (248 nm) for gratings inscription in CYTOP without over-clad [8–10]. However, either low reflectivity, or long exposure times ($\sim$ 1 hour) are the issues appearing with this FBG inscription method in CYTOP fibers. The second method consists in direct FBG inscription by femtosecond (fs) laser. The fs inscription was firstly realized by point-by-point and line-by-line techniques using a 517 nm fs laser providing reflectivity up to 70 % [11]. However, this technique requires an accurate control of the beam spot position in the core of the optical fiber through high precision three-dimension translation stages, which is both expensive and generally time-consuming, especially for the setup alignment.

In this work, we combine a phase mask technique with a femtosecond laser system operating at 400 nm to inscribe FBGs in CYTOP fibers. The inscription parameters, such as laser beam energy, exposition time, and grating length are investigated. In this inscription method, 2 mm-long gratings with reflectivity up to 92 % were obtained in less than 10 s.

POF Pretreatment

We used the commercially available (GigaPOF-50SR from Chromis) graded-index multimode perfluorinated POF, with an over-clad diameter, a core diameter and a numerical aperture of 490 µm, 50 µm and 0.185, respectively [12]. The over-clad of the CYTOP fiber is removed in this set-up to (1) position the phase mask closer to the fiber, and (2) to avoid its degradation by the laser beam.
Because the over-clad is made of polycarbonate material, it is removed by dichloromethane CH_2Cl_2 solution [13–15] for a few minutes; then the fiber is carefully cleaned to remove all residues that would distort the inscription pattern, and therefore lead to huge distortions of the grating spectrum.

Experimental set-up

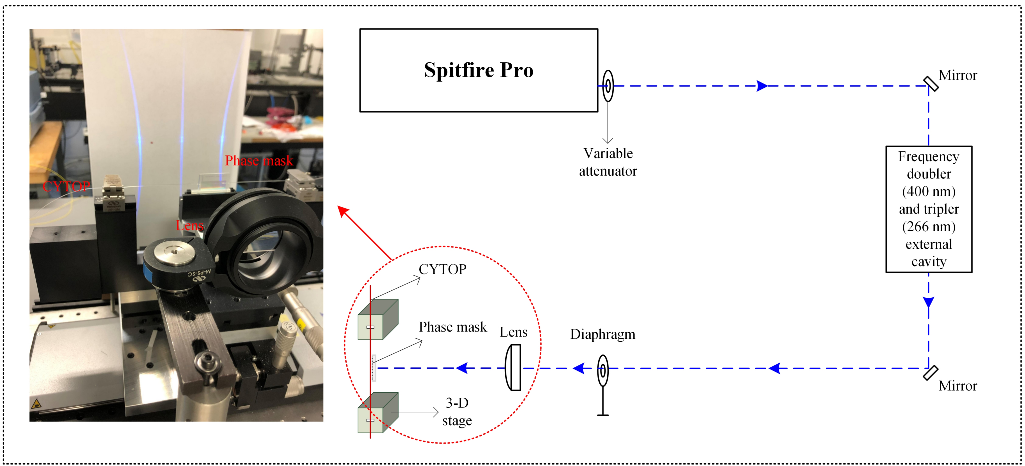

Figure 1 - *Experimental setup to inscribe FBG in CYTOP.*

Figure 1 represents the setup used to write the fiber Bragg gratings in CYTOP fibers. It consists of a femtosecond laser (Spitfire Pro amplifier from Spectra Physics company) producing 120 fs light pulses at 800 nm with a repetition rate of 1 kHz and an energy of 4 mJ. The laser is followed by a variable attenuator and a frequency doubler to have pulses at 400 nm. The laser beam is then reduced by a diaphragm to 2 mm, and focused onto the core of the CYTOP fiber through the phase mask by a plano-convex cylindrical lens with a focal length of 100 mm.
The phase mask technique is used to produce the grating as shown in the inset of Fig. 1. The phase mask has a period of 1158 nm, and a powermeter is inserted between the lens and the diaphragm to measure the power before focusing. An FBG interrogator (FS2200 from FiberSensing) with a spectral resolution of 1 pm and a spectral range from 1500 nm to 1600 nm is used to monitor FBG spectrum evolution. A butt coupling joint between a standard single-mode silica optical fiber pigtail (SMF-28) and the CYTOP fiber is used

as a link towards the interrogator. Moreover, a small drop of refractive index matching gel (n =1.4646 at 589.3 nm) is used between the two optical fibers to reduce Fresnel reflections from the end face of the SMF.
Figure 2 (a) shows spectra for a 2 mm-long grating inscribed in 10 s with a beam power as low as 80 µW. From the transmission spectrum, the reflectivity of the fundamental mode of the grating is computed to be 92 %.

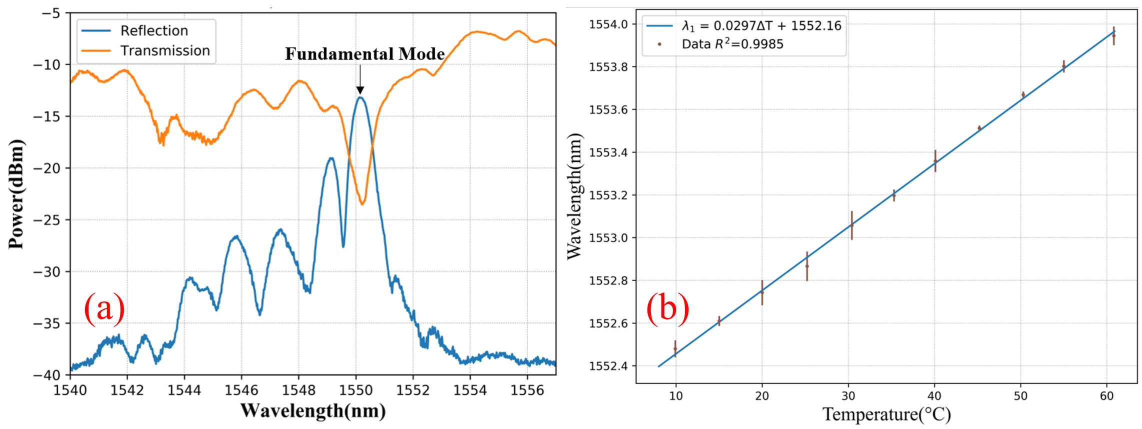

Figure 2 - *(a) Transmission and reflection spectra for grating in CYTOP (inscription parameters: grating length 2 mm, laser power 80 µW, and inscription time 10 s); (b) Temperature response of the fundamental peak of the FBG in CYTOP fiber.*

By comparing several FBGs spectra with the same grating length and different beam powers, such as 60 µW, 80 µW, 100 µW and 120 µW, it is shown that: (1) there are no FBG resonance peaks in the spectrum when the beam power is lower than 80 µW; (2) the reflectivity of the main resonance peak (fundamental mode group) decreases with the increase of the beam power; and (3) more and more subpeaks appear when the beam power is increased.
We have also produced gratings of different lengths with same beam power by adjusting the diameter of the diaphragm in Fig. 1, i.e., 2 mm, 3 mm, 4 mm and 5 mm. The main conclusions are: (1) the reflectivity of the main resonance peak increases with the increase of the grating length; and (2) all the spectra exhibit significant subpeaks.

Temperature Measurements

It is well-known that temperature affects the Bragg wavelength, so the gratings were tested against temperature. A climate chamber (Weiss SB 22) is used to control the temperature and humidity with a temperature range of –40 °C to 180 °C and a relative humidity range of 10 % to 98 %. Considering the maximum temperature tolerance of CYTOP fiber (<70 °C), we use a range of temperatures from 10 °C to 60 °C, and the humidity is kept approximately constant around 80 %.
In this test, we cycle the temperatures from 10 °C to 60 °C with steps of 5 °C for 10 min per step. Fig. 2 (b) displays the main peak evolution, and by a linear fit a temperature sensitivity of 29.7 pm/°C (coefficient of determination $R^2 = 0.99$) is obtained .

Conclusions

In this work, we combine a phase mask technique with a femtosecond laser system operating at 400 nm to inscribe CYTOP FBGs with reflectivity up to 92 % in less than 10 s exposure time. The main advantages of the proposed method is the fast and repeatable inscription of highly reflective CYTOP FBGs utilizing standard precision mechanical equipment. To characterize the properties of the inscribed gratings in CYTOP fibers, we investigate their temperature sensitivities in the fundamental mode group of the FBG spectra. It is found that the temperature sensitivity of the fundamental mode group of a FBG in CYTOP without over-clad is approximately 29.7 pm/°C.

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References

[1] L. Bilro, N. Alberto, J. L. Pinto, and R. Nogueira, “Optical sensors based on plastic fibers,” *Sensors*, vol. 12, pp. 12184–12207, Sept. 2012.

[2] Y. Koike and M. Asai, “The future of plastic optical fiber,” *NPG Asia Materials*, vol. 1, pp. 22–28, Oct. 2009.

[3] J. Zubia and J. Arrue, “Plastic optical fibers: An introduction to their technological processes and applications,” *Optical Fiber Technology*, vol. 7, pp. 101–140, Apr. 2001.

[4] Y.-G. Nan, D. Kinet, K. Chah, I. Chapalo, C. Caucheteur, and P. Mégret, “Ultra-fast fiber bragg grating inscription in CYTOP polymer optical fibers using phase mask and 400 nm femtosecond laser,” *Optics Express*, vol. 29, p. 25824, jul 2021.

[5] I. Riant, “Fiber Bragg gratings for optical telecommunications,” *Comptes Rendus Physique*, vol. 4, pp. 41–49, Jan. 2003.

[6] H. Y. Liu, G. D. Peng, P. L. Chu, Y. Koike, and Y. Watanabe, “Photosensitivity in low-loss perfluoropolymer (CYTOP) fibre material,” *Electronics Letters*, vol. 37, no. 6, p. 347, 2001.

[7] H. Y. Liu, G. D. Peng, and P. L. Chu, “Thermal stability of gratings in PMMA and CYTOP polymer fibers,” *Optics Communications*, Apr. 2002.

[8] M. Koerdt, S. Kibben, O. Bendig, S. Chandrashekhar, J. Hesselbach, C. Brauner, A. S. Herrmann, F. Vollertsen, and L. Kroll, “Fabrication and characterization of Bragg gratings in perfluorinated polymer optical fibers and their embedding in composites,” *Mechatronics.*, p. 137, 2016.

[9] Y. Zheng, K. Bremer, and B. Roth, “Investigating the strain, temperature and humidity sensitivity of a multimode graded-index perfluorinated polymer optical fiber with Bragg grating,” *Sensors.*, p. 36, 2018.

[10] R. Min, B. Ortega, A. Leal-Junior, and C. Marques, “Fabrication and characterization of Bragg grating in CYTOP POF at 600-nm wavelength,” *IEEE Sensors Letters.*, p. 1, 2018.

[11] A. Lacraz, M. Polis, A. Theodosiou, C. Koutsides, and K. Kalli, “Femtosecond laser inscribed Bragg gratings in low loss CYTOP polymer optical fiber,” *IEEE Photonics Technology Letters.*, p. 693, 2015.

[12] *Information on the detail of CYTOP fiber (https://chromisfiber.com/products/gigapof-50sr/).*

[13] R. Min, B. Ortega, and C. Marques, “Fabrication of tunable chirped mPOF bragg gratings using a uniform phase mask,” *Optics Express*, vol. 26, p. 4411, Feb. 2018.

[14] R. Gravina, G. Testa, and R. Bernini, “Perfluorinated plastic optical fiber tapers for evanescent wave sensing,” *Sensors*, vol. 9, pp. 10423–10433, Dec. 2009.

[15] A. G. Mignani, R. Falciai, and L. Ciaccheri, “Evanescent wave absorption spectroscopy by means of bi-tapered multimode optical fibers,” *Applied Spectroscopy*, vol. 52, pp. 546–551, Apr. 1998.