Fabrication of periodic structures in optical fibers by femtosecond laser micromachining for sensing applications

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ABSTRACT

A femtosecond laser direct writing system was developed to explore the fabrication of periodic structures in optical fibers. The possibility to write type I first- and second-order Bragg gratings in the same single-mode fiber (SMF-28e), with reflectivities of 99.6 % and 59.3 %, respectively, is presented. The fabrication of structures (waveguides and grating) in a coreless and in a SMF-28e fiber was first demonstrated, and the gratings were then exposed to a thermal annealing up to 1000°C. The FBG inscribed in the SMF-28e fiber presents thermal stability at temperatures of 800 ºC and a temperature sensitivity of 14.34 pm/°C was determined.

Keywords: Femtosecond laser system, fiber Bragg gratings, fiber optics sensor

1. INTRODUCTION

Fiber gratings are employed as in-fiber optical filters and reflectors in telecommunication systems, fiber lasers, and sensors. Traditionally, fiber gratings are fabricated by ultraviolet (UV) laser exposure through periodic UV light pattern created by two-beam interference (with phase masks, for example) [1]. The importance of fiber gratings as devices for manipulating fiber guided light has led, in this work, to the development of a femtosecond laser direct writing system to explore the fabrication of periodic structures in optical fibers. The system is controlled in a LabVIEW® program that enables high design flexibility and precise control of all relevant experimental parameters (scanning velocity and optical writing power, fiber positioning, vision and alignment features). The system has been primarily designed for the fabrication of point-by-point first order Bragg gratings, made available due to the high spatial resolution resultant from a non-linear absorption process triggered by femtosecond laser exposure. Additionally, this writing technique can be used to write gratings through the fiber polymer coating [1], and in a variety of optical fibers without any special treatment for photosensitivity enhancement [2]. The influence of the writing parameters on the fabrication of gratings is discussed in detail. The femto-inscribed Bragg gratings were characterized in temperature and compared with the traditional UV-inscribed ones to verify their thermal stability, as femtosecond gratings offer higher thermal stability, withstanding temperatures up to 1000ºC [3]. This opens the possibility to address high-temperature thermal monitoring in, for example, nuclear power plants, aerospace industry, and steam turbines [2].

2. FEMTOSECOND LASER SYSTEM

To explore the fabrication of Fiber Bragg Gratings (FBGs) inside a standard single mode optical fiber (SMF-28e, Corning) and a coreless fiber (FG125LA, Thorlabs) through localized refractive index (RI) modifications, a femtosecond laser direct writing system was developed. The writing system uses a femtosecond fiber amplified laser (Satsuma HP, from Amplitude Systèmes) providing pulses with duration ~250 fs, and a repetition rate ranging from single shot up to 2 MHz. The maximum average power is 10.5 W in the fundamental wavelength (1030.3 nm), corresponding to 23 µJ per pulse. In the laser direct writing system presented in Figure 1, three different wavelengths can be chosen: 1030 nm (fundamental wavelength), 515 nm (second harmonic generation) and 343 nm (third harmonic generation). The second harmonic was chosen with a maximum energy per pulse of 1.1 µJ and a maximum average power of 5.5 W, at a repetition rate of 500 kHz.

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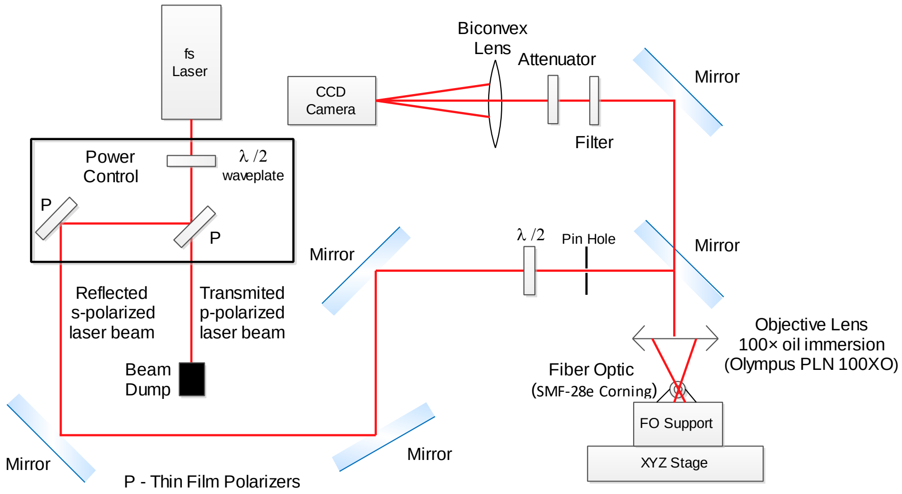


Figure 1. Schematic diagram of the Femtosecond Laser System for FBGs Fabrication.

Before writing, the optical fiber coating was removed around the writing section, and the fiber was mounted on a XYZ stage. A 100× oil immersion lens (Olympus PLN 100XO) with a numerical aperture (NA) of 1.25 was used to focus the laser beam inside the fiber core. The polarization state at the focus was linear and adjusted, with a half waveplate (λ/2), to be parallel to the scanning direction. For writing gratings, the laser gate was externally controlled by a periodic square time function with a duty cycle of 50 % generated by a synthesized function generator (DS345, Stanford Research Systems). This simple arrangement allows the automated writing of gratings by simply translating the optical fiber at constant velocity with the signal modulation turned on. Using the Bragg relation, we can easily see that the Bragg wavelength is given by $\lambda_B=2n_{eff}\frac{V}{f_{mod}}$, where V is the velocity of the stage and n_{eff} the effective index of refraction of the guided mode. In turn, the Bragg wavelength can easily be controlled by simply tuning the modulation frequency, f_{mod}.

2.1 Fabrication of periodic structures

Various periodic structures in two types of optical fibers were fabricated with different parameters, which are summarized in Table 1, alongside the measured spectral properties: full width at half maximum (FWHM), dip attenuation and reflectivity.

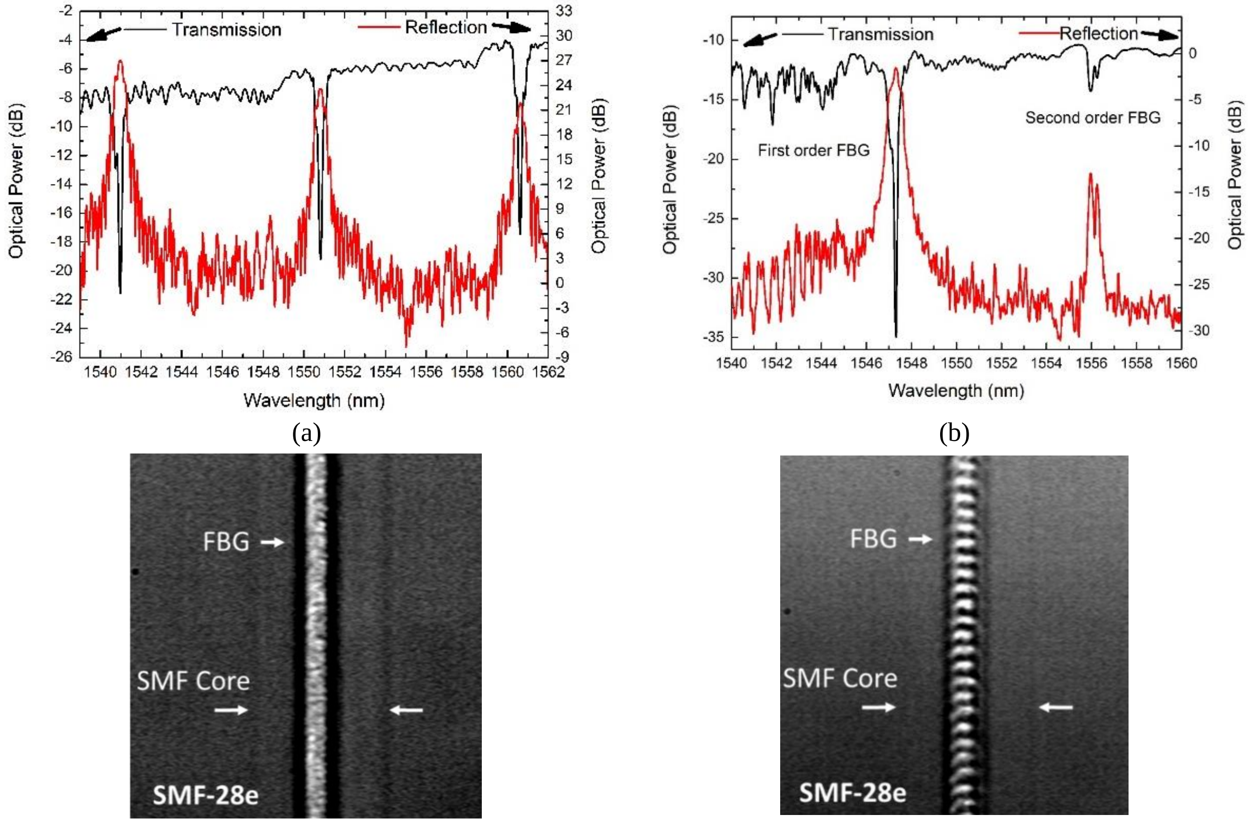
Table 1. Parameters of the femto-inscribed FBGs in an SMF-28e.

Fabrication Parameters					**FWHM (nm)**	**Dip Attenuation (dB)**	**Reflectivity (%)**
Grating order	**Pulse Energy (nJ)**	**Write velocity (µm/s)**	**Bragg Wavelength (nm)**	**Length (mm)**			
First-order	60	50	1540.96	4	0.21	-14.67	97.0
			1550.82		0.22	-13,22	95.0
			1560.63		0.21	-13.65	96.0
First-order	63	50	1547.32	10	0.17	-24.04	99.6
Second order			1555.97		0.49	-3.90	59.3
			1556.26				

The writing process introduces birefringence to the SMF-28e fiber, which splits the Bragg resonance into two polarization modes, as observed in the case of the second order FBG, Table 1. The two Bragg resonances are separated by 290 pm, yielding a birefringence value equal to 1.35×10^{-4}.

As shown in Figure 2 (a), three FBGs with the same length (4 mm) and different periods: 531.983, 535.437 and 538.891 nm, respectively were serially inscribed in the core of an SMF-28e fiber and axially separated by 1 mm. In this case, all the FBGs inscribed are first-order FBGs, but with our system it is also possible to inscribed second-order FBGs by just changing the period of the grating. We have fabricated first- and second-order Bragg gratings (the latter with a fundamental reflection near to 3110 nm) around 1550 nm with the periods of 533.710 nm and 1074.328 nm, respectively.

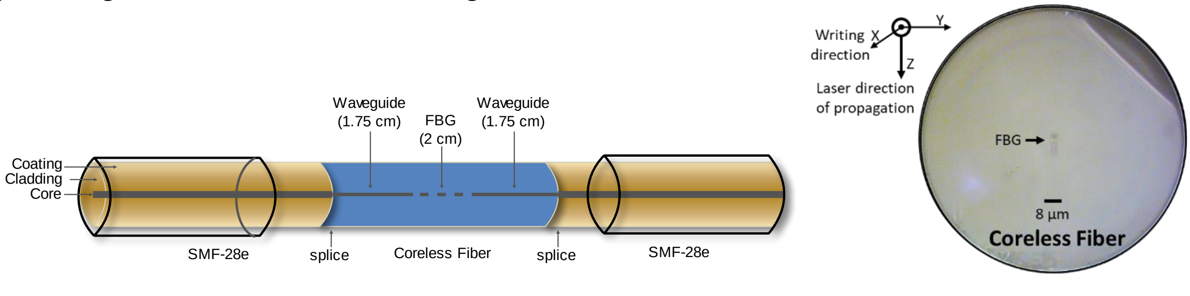
Analyzing the top view section images presented in Figure 2 (c) and (d), it is possible to verify the increase of the grating period in the refractive index modification for the case of the second order grating.



(c) (d)

Figure 2 Femtosecond laser FBGs inscribed in an SMF-28e: (a) spectra of three first-order FBGs in sequence and (b) sequence of two FBGs fabricated with different orders; (c) and (d) Top-view section images of the first and second order FBGs, respectively.

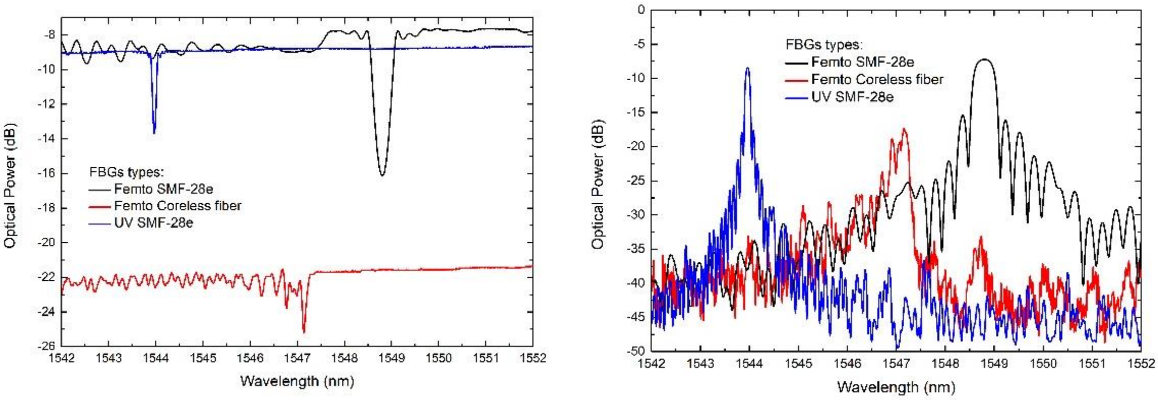
In order to fabricate gratings in a coreless fiber, a section of this fiber was spliced between two single-mode fibers (SMFs) forming an SMF- multimode fiber (MMF) -SMF structure. This structure was a Multimode Interference (MMI) based optical device. After with the femtosecond laser, the two SMF was connected by a waveguide with a grating in the middle performing a coreless FBG was shown in Figure 3.



(a) (b)

Figure 3. Femtosecond laser structures inscribed in a coreless fiber: (a) Schematic diagram; (b) End-view optical micrograph.

Figure 4 shows three different FBGs, one written with a UV-laser on a SMF-28e fiber, and two with the femtosecond laser direct writing system in a SMF-28e fiber and in a coreless fiber.



(a) (b)

Figure 4. Femtosecond and UV laser FBGs: (a) Transmission spectra and (b) Reflection spectra.

The femto-inscribed structure in the coreless fiber presents higher attenuation and the Bragg resonance is not well defined, when compared with the previously mentioned gratings. The fabrication parameters and the measured optical properties, such as the FWHM, dip attenuation and reflectivity are presented in Table 2.

Table 2. Parameters of the FBGs for characterization.

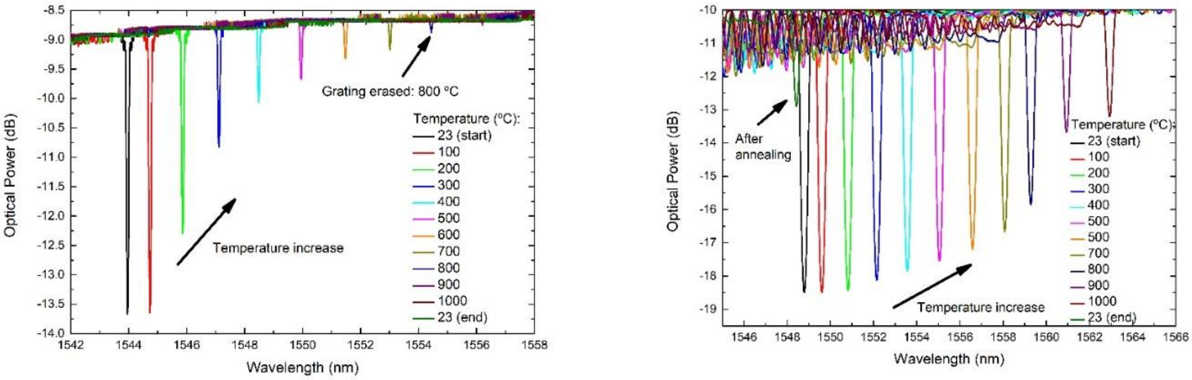
FBGs	Fabrication Parameter				FWHM (nm)	Dip Attenuation (dB)	Reflectivity (%)
	Pulse Energy (nJ)	Write velocity (μm/s)	Bragg Wavelength (nm)	Length (mm)			
Femto SMF-28e	20	200	1548.80	30	0.41	-8.42	86.0
Femto Coreless fiber	130	200	1547.14	20	0.10	-3.64	57.0
UV SMF-28e	N.A.	N.A.	1543.97	N.A.	0.09	-4.75	67.0

3. RESULTS AND DISCUSSION

The annealing process leads to modifications in the FBGs spectral response, affecting its dip attenuation that reduces the grating reflectivity. The results of the spectral variations with the annealing temperature are presented.

3.1 FBGs Temperature Characterization

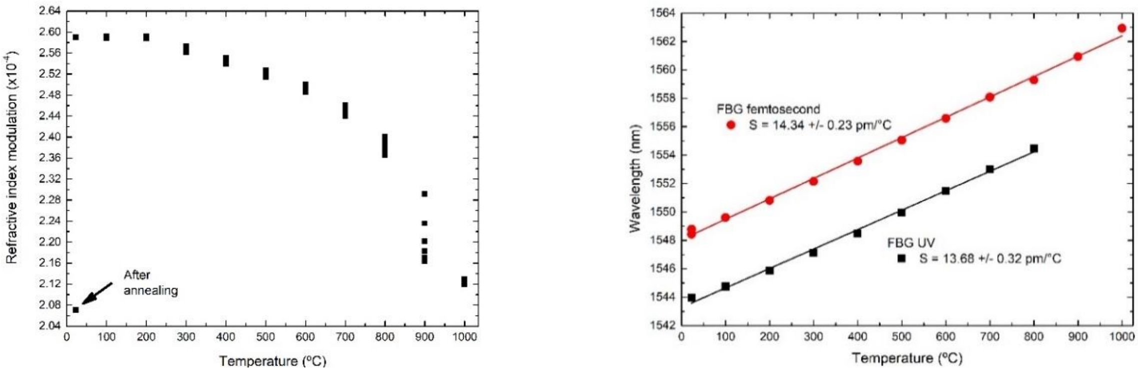
The UV-inscribed FBG and the femto-inscribed FBGs in an SMF-28e and in a coreless fiber were placed in an oven and annealed at constant temperatures (100˚C to 1000˚C) with steps of 100˚C, for a period of 1 h. The grating spectra were monitored every 10 minutes by a continuous swept laser scanning interrogator specifically designed to interrogate FBGs (FS22 HBM BraggMETER) with a resolution of <0.5 pm. After the annealing period, the oven was switched off and the gratings were allowed to cool down to room temperature and the grating spectra was recorded. Figure 5 (a) and (b) represents the Bragg wavelength, at room temperature, of the UV-inscribed FBG and femto-inscribed FBG in an SMF-28e fiber after a one hour annealing at constant temperatures.



(a) (b)

Figure 5. Spectral evolution of: (a) the UV-inscribed FBG and (b) femto-inscribed FBG during the annealing cycle.

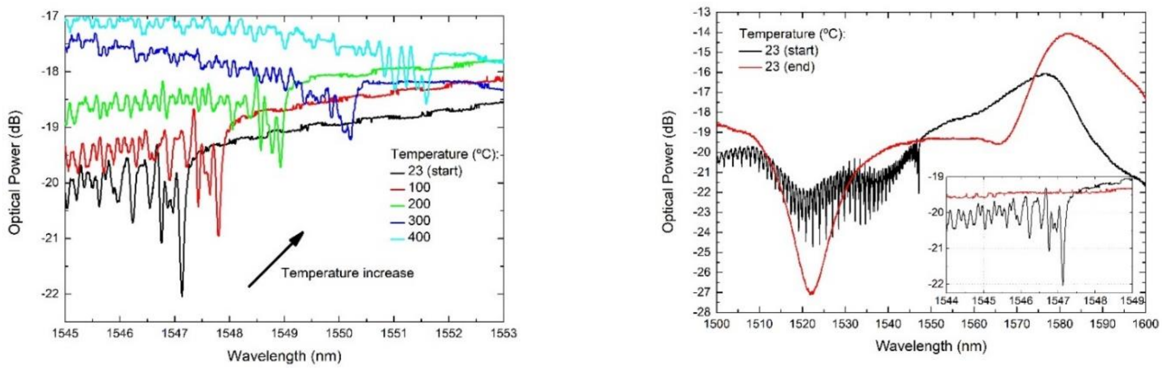
While the UV-inscribed FBG were erased as the temperature exceeded 800 °C, the femto-inscribed FBG were almost unaffected by thermal exposure at temperatures of 800 ºC. Above this temperature, a portion of the refractive index change of the femto-inscribed FBG was annealed out, resulting in a degradation of grating reflectivity as presented in Figure 6 (a). A 0.36 nm-shift of the Bragg resonance to the lower wavelength side was detected at the end of the annealing.



(a) (b)

Figure 6. (a) Decrease of refractive index modulation as a function of temperature and (b) Bragg wavelength as a function of temperature.

Temperature sensitivities of 14.34 and 13.65 pm/°C were achieved for the femtosecond-written FBG and for the UV-laser written FBG respectively. Comparing the achieved results with similar FBGs reported in literature **[1 – 3]** we can affirm that our FBGs are of Type I. Figure 7 represents the shift of the femto-inscribed FBG in an coreless fiber spectra after one hour at constant temperatures.



(a) (b)

Figure 7. Spectral evolution of femto-inscribed FBG Coreless fiber: (a) during the annealing cycle and (b) at room temperature.

It can be seen from Figure 7 (a) that, unlike, SMF-28e femto-inscribed FBG which became thermally stable at temperatures of 400 ºC, the FBG inscribed in a coreless fiber was almost erased as the temperature exceeded 400°C. This could be a result of a different index modification. When the FBG is inscribed in the core, the index is further increased compared to the index inscribed in the coreless fiber, resulting in a more thermally stable grating [3]. Figure 7 (b) shows the spectra of the structure before and after the annealing, where it can be seen that the grating is erased after annealing.

4. CONCLUSION

In this work, a femtosecond laser direct writing system was developed to explore the fabrication of periodic structures, namely fiber Bragg gratings, in optical fibers. The optimum conditions to write FBGs in SMF-28e were attained with 63 nJ on-target pulse energy, 50 μm/s scan speed and a grating length of 10 mm. The possibility to write first- and second-order Bragg gratings in the same fiber with reflectivity's of 99.6 % and 59.3 %, respectively was showed. The fabrication of several FBGs in the same fiber with different periods was demonstrated, which opens the possibility to explore different types of sensors configurations and multiplexing schemes. The fabrication of structures in a coreless fiber was also proven and, the written gratings were characterized in temperature. After annealing the FBGs at high temperature, only the femto-inscribed FBG in an SMF-28e showed thermal stability at temperatures of 800 ºC presenting a temperature sensitivity of 14.34 pm/°C. At these temperatures, UV-laser written gratings and gratings inscribed in a coreless fiber are erased. The fabricated FBGs can be classified as Type I.

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