Bragg Gratings Written with Ultrafast Laser Pulses

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Abstract — This work describes the production of optical fiber Bragg gratings written using ultrafast laser pulses of the order of 100 fs through point-by-point and phase mask methods. Some samples were thermally regenerated and characterized at high temperatures. The obtained results do not show differences in the thermal behavior when compared to gratings recorded using an Excimer laser.

Index Terms— Bragg gratings, recording process, ultrashort laser pulses.

I. INTRODUCTION

The optical fiber Bragg gratings (FBGs) play one major role as optical fiber sensors in measuring and control applications [1], due to, among other characteristics, their inherent sensitivity to temperature and strain variations. Albeit the spectral sensitivity of FBG is larger for standard temperature changes (∼10 pm.K⁻¹) than the sensitivity to strain (∼1 pm.µstrain⁻¹), commercial applications are focused on strain measurements, particularly for large buildings and similar structures. One reason for such asymmetry is that a less saturated FBG – usually known as Type I – shows reduced lifetime at temperatures higher than a few hundred degrees, even if their spectral shape is better. Several features contribute to this drawback namely: the polymer primary coating of the optical fiber and the thermal bleaching of color centers associated to the changes in the glass photosensitivity.

Concerning high temperature applications, above ∼300-400 °C, there is intense effort in the development of Bragg gratings resisting those temperatures as well as temperature durable coatings like composites and metallic layers. FBGs for high temperature operation were obtained by several techniques like special dopants [2,3], thermal annealing [4], use of low photosensitivity optical fiber[5] or with femtosecond (fs) laser pulses [6], as well as thermal regeneration of seed FBGs [7,8].

FBG recording with femtosecond laser pulses can be performed using several well-established standard techniques, e.g., point-by-point inscription [9,10], conventional interferometry [11] and phase-mask assisted interferometry [12-14]. In the first method, the laser beam is focused on the fiber core while the sample is moved in relation to the focal point. This method requires accurate positioning and high spatial reproducibility. Power control is also necessary to prevent the cleaving of
the fiber. The spatial modulation of the refractive index composing the FBG can also be obtained from an intensity pattern resulting from optical interference. The use of a conventional interferometer implies a tight spatial tolerance for the optical path in each interferometer’s arm in order to obtain the spatial and temporal overlap of the optical pulse at the interference plane. The same drawback is also present in the phase-mask interferometric writing, but in this situation the distance from the wave front dividing mask to the sample is relatively small (a few tens of micrometer), which simplifies the optical alignment.

This paper presents the writing of FBG with femtosecond laser pulses using point-by-point and phase-mask assisted writing methods. Results about the thermal stability of the obtained gratings are also presented. This work extends the results previously reported by the authors [15] and has special significance due to being the first FBGs recorded by femtosecond laser pulses in Brazil.

II. MATERIALS AND METHODS

The optical source is a Ti:Saphire laser with regenerative amplifier (Coherent Libra-F-1K-HE) able to generate pulses with energy of 3.2 mJ, temporal half width of 100 fs and central wavelength of 800 nm at a repetition rate of 1 kHz. The laser pulses can be used at the fundamental wavelength for point-by-point writing method or illumination under the phase-mask. The pulses can also pump an optical parametric amplifier (Coherent OperaSolo option FH/SHSF) to generate light at other wavelengths, which permits to use the phase-mask technique over a large spectral band. Light from the parametric amplifier at 250 nm is particularly useful because the wavelength is close to that of the more traditional KrF Excimer laser (248 nm) usually used to record FBG. This permits to observe the differences of using the short fs pulses in comparison to the longer 5-10 ns pulses of the Excimer laser.

In point-by-point recording method, as depicted in the schematic in Fig.1(a), the laser beam is attenuated by neutral optical filters and focused over the sample using a microscope objective with 20X magnification. The sample is mounted over a MM3000 translation stage (Newport), which can move it relatively to the laser beam in a continuous sweep. The choice of the sweep speed and laser repetition rate set the spatial pitch, \( \Lambda \), of the induced refractive index changes.

When using the phase mask interferometry method, the laser beam is focused onto the fiber core with a cylindrical lens (focal length ~ 5 cm). The fiber is positioned perpendicularly to the laser beam propagation direction. Fig. 1(b) shows a scheme of the used set-up. Typically, the distance from the phase mask to the fiber external surface lies in the range from 60 \( \mu \)m to 70 \( \mu \)m. The phase masks were produced by Ibsen Photonics. Special phase masks, designed for operating wavelengths of 800 nm and 250 nm, were used with spatial pitch of 1057 nm and 1064.5 nm, respectively. The energy of the laser pulses, before the phase mask, is measured with a Coherent FieldMax II power meter, equipped with a thermal head PM-10X. Neutral density filters were used to adjust the optical power.

In the used spectral ranges, the residual zeroth order beam exiting from the phase masks still has
2% and 17% of incoming energy for the laser wavelengths of 250 nm and 800 nm, respectively. Due to the high peak power of the laser pulses, the residual energy is enough to induce changes in the refractive index of the core over the illuminated region. Thus, an increase in the DC term of the refractive index change appears, reducing the index modulation efficiency of the ±1 interference pattern. In terms of the measured optical spectrum, the DC term also rises the optical background due to greater values of the Fresnel coefficients at the optical interfaces between the optical fiber non-exposed and exposed sections of the optical fiber.

![Fig. 1](image)

Fig. 1 – Schematic designs of the used set-ups for FBG writing: (a) point by point process, and (b) illumination under a phase mask, top and side views, fom top to bottom.

Optical reflection spectra from the FBGs were measured by a FBG interrogator (Micron Optics SM125) or using an optical spectrum analyzer (Yokogawa 6375). The results are presented in reflection mode, this situation is more usual and advantageous in the FBG sensing applications. Thermal studies were carried out with the sample inside a tubular furnace Jung model 0112, equipped with a Nuvus N1100 controller. The sample was positioned within a stainless steel capillary tube at the center of the furnace. An additional thermocouple was placed close to the sample to measure the temperature during the thermal cycle.

The optical fiber samples were standard telecommunications G. 652 fibers provided by Draktel. Photosensitive fibers, model GF1 (Nufern), were obtained from a commercial provider (Thorlabs Inc.). Some samples were previously hydrogenated at 100 atm, room temperature, for a few days before the grating writing.

### III. Results and Discussion

#### A. Bragg Grating Recording

Fig. 2(a) presents the reflection spectrum of a Bragg grating written in standard G.652 optical fiber using the point-by-point method with laser pulse energy of 14.8 µJ at the fundamental wavelength (800 nm), sweep speed of 1070 µm/s, grating length of 10 mm and six writing cycles. The sweep
speed was chosen to induce a grating operating at the second-order wavelength, that is, $2\lambda_B = 2n_{\text{eff}}\Lambda$, where $\lambda_B$ is the (1st order) Bragg wavelength, $n_{\text{eff}}$ is the effective index of the propagated mode in the fiber core and $\Lambda$ is the spatial pitch of the index modulation.

Using a second-order grating enhances the modulation index along the propagation direction as the writing spots will be spaced by a greater distance, reducing the overlap region caused by the focal point cross section. It can be seen in Fig. 2(a) that the contrast obtained in the spectrum is still very weak, with an amplitude of ~ 3.4 dB above the average noise level and full width at half maximum (FWHM) of 0.43 nm. Due to the strong noise level at the baseline, this FBG presents a low signal to noise (S/N) ratio. This noise level could be caused by light scattering at the local refractive index changes and material densification in the illuminated regions, due to the high peak power of the fs pulses. It should be noted that, due to the sweep of the focal point, the illuminated regions are partially overlapped, as the focal diameter of the used objective is greater than the distance travelled between two successive pulses. A larger number of sweeps did not allow obtaining gratings with better S/N ratio as it is cumbersome the synchronization between the spatial movement of the sample and the lasers pulses. This lead to an illumination outside the previously illuminated regions and thus reducing the refractive index modulation and increasing the scattering zones.
Fig. 2 Optical reflection spectra of FBG written with ultrafast laser pulses: (a) using point-by-point method on standard G.651 optical fiber; (b) using the phase-mask method at 800 nm; (c) same method at 250 nm, initial spectrum on non-hydrogenated standard fiber and, (d) grating written in photosensitive fiber, same method and wavelength.

In Fig. 2(b) it is possible to see the optical reflection spectrum of a Bragg grating written using the phase mask interferometry method at the illumination wavelength of 800 nm in the NIR (Near Infra-red) spectral range. The inscription used a standard single mode fiber, previously hydrogenated, the laser energy was 370 µJ per pulse and the exposure time was 30 min. The dose (pulse energy × exposure time) is considerably greater than that used at a more usual UV (ultraviolet) wavelength, as discussed later in this paper. The peak lies approximately 12 dB above the first minima at each side of the reflection band and the FWHM is 0.42 nm. From the shape of the spectrum, it appears that a strong, saturated grating was yet not obtained, even with a high exposure dose. However, the grating peak amplitude is considerably greater in this recording method than that obtained with point-by-point writing.

The recording parameters were critically close to the threshold damage of the glass fiber, slight changes in the pulse energy, exposure time or even focal point caused the fiber to shatter under the laser light. It was also observed that the glass in the grating region turned very brittle, even a gentle handling after the writing induced a break.

The spectrum of a FBG written by the same method using light pulses at 250 nm can be seen in Fig. 2(c). The used fiber (standard G.652) was not hydrogenated and the exposure time is ~ 1 min. Although the peak spectral amplitude is barely over 1 dB, the S/N ratio is clearly greater than that of point-by-point reported grating, due to the reduced noise level at the baseline. A possible cause is that the homogeneous illumination over the grating length (roughly 1 mm) changes also homogeneously the refractive index due to the remaining zeroth order light (~2%), resulting in less scattering. The FWHM for this FBG is 0.25 nm.

In the graph in Fig. 2(d) it is presented, for comparison, the optical reflection spectrum of a FBG recorded on a photosensitive fiber under the same exposure conditions, which allows obtaining a grating with high reflectivity (spectral peak amplitude ~ 13 dB, bandwidth 0.26 nm) than that shown in Fig.1(c).

The graphs in Figs. 3 and 4 present some features of the writing dynamics for the fs induced gratings. The graph in Fig. 3 (a) displays the amplitude and FWHM evolution during the grating writing process in a previously hydrogenated standard telecommunications fiber, when lasers pulses at the fundamental wavelength are used. The grating was written in the same batch as that whose spectrum was shown in Fig. 3(b), using pulses with 385 µJ and exposure time of 30 min. It is observed that the writing tends to saturate the spectrum of the optical reflection band, whereas the spectral broadening has a more conservative behavior and there is no evidence that a longer exposure time would lead to a strongly saturated grating.
Fig. 3 Evolution of growth parameter of two FBGs written using the phase-mask method: (a) at the fundamental, 800 nm, wavelength and, (b) at 250 nm. Lines are only guides for the eye.

A different growth dynamics is observed when laser pulses of 23.5 μJ at 250 nm were used to record the grating on the same optical fiber, as depicted in the graph in Fig. 3(b). A fast growth is detected with a saturation time under 30 s. The observed bandwidth also increases in a steady way towards a saturation plateau. It should be recalled the difference in the time scale of the last two described grating inscription. To about the same amplitude level, the writing at the NIR wavelength requires a time interval ~ 60 times greater than that at the UV wavelength, even with pulse energy 10 times greater.

The graph in Fig. 4 shows the wavelength shift of the grating whose spectrum was depicted in Fig. 2 (d), with a consistent shift for longer wavelengths and a slight tendency for saturation. The used fiber is a commercial photosensitive fiber. The grating amplitude (not displayed), over the same time interval (130 s), did not show a possible saturation, but increased at an approximately constant rate after the initial 40 s of inscription. The aforementioned behavior for both fibers is consistent with type II grating recording, the so-called damage gratings. The obtained results agree with previously published results of FBGs written by fs pulses using the same method at the near-IR wavelength of
800 nm [14].

Fig. 4 - Peak position of the spectral band of a FBG written on photosensitive fiber as a function of the exposure time.

The influence of the illumination wavelength implies that, even at the high peak energy of fs laser pulses, which gives rise to strong non-linear interactions with the glass constituents, the color center model for Bragg grating production is still dominant. It was possible to write gratings with better amplitudes in shorter times, using lower pulse energies, when the illumination wavelength was in the UV spectral range (250 nm) than when in the NIR (800 nm). The former wavelength is close to the peak of the main absorption band of Ge related defects in silica glass.

B. Thermal Regeneration

For thermal regeneration studies strong and saturated FBGs were written in previously hydrogenated G.652 optical fibers using higher pulse energies with recording times in the order of 10 min. The gratings were heated up to ~ 900 °C. Results from two similar gratings are presented in Fig. 5. The first one was recorded with pulse energy of 45 µJ and the optical reflection spectrum shows saturated features with a peak reflection power of -15.4 dBm (baseline at ~ 50 dBm), FWHM of ~ 1 nm and central wavelength of 1534.5 nm. This grating was submitted to thermal regeneration for a time interval of ~ 2 h. The minimum in the reflected amplitude occurred approximately 70 min after the insertion of the sample in the high temperature set-up, as can be seen in the graph in Fig. 5(a), with a subsequent increase in the reflected signal, typical of the regenerated gratings.

A similar behavior was seen for the second grating, which was written with a pulse energy of 30 µJ and an exposure time 10 min. Its optical reflection spectrum showed several lateral sidebands and flattening of the central peak, as expected in saturated gratings. The flat top reflected power measured ~ -23 dBm whereas the noise baseline in this situation lied at ~ -48 dBm. The regeneration profile of this sample is shown in the graph in Fig. 5(b). The reflected peak amplitude practically vanished about 95 min after the heating and further signal regeneration stabilized in about ~ 20 min.

The time for signal stabilization after regeneration is similar for regenerated gratings produced by a KrF Excimer laser at 248 nm [4,5], typically a few tens of minutes at 850 °C. The final amplitude change after regeneration is also similar to those of gratings obtained with the Excimer laser and provides an additional clue that the writing process induces a type II grating. Another feature of the reported gratings is that the reflected signal did not show significant drop for temperatures up to ~ 750 °C. Although long term annealing at lower temperatures has not been performed with these samples, that feature is expected to be similar to the reported stability of similar gratings written at 800 nm, namely a few weeks at 300 °C [14].
Fig. 4 Thermal regeneration profiles of gratings written with fs laser pulse energy of (a) 45 µJ and (b) 30 µJ. The depicted lines are only guides for the eye.

C. Thermal Sensitivity

Heating and cooling of the recorded gratings during or after the regeneration process allows measuring the temperature dependence of the wavelength shift. The graphs in Fig. 6 show the heating process of two gratings heated to 850 °C and 950 °C, respectively. The experimental data are plotted with the marks and the best-fit results displayed by the lines.

The graph in Fig. 6(a) corresponds to the grating whose regeneration is depicted in Fig. 5 (a). A second order polynomial best fit – shown by the dashed line in the graph – results a first order coefficient of 12.8 pm.K\(^{-1}\), whereas the second order coefficient measures 1.05 \(\times\) 10\(^{-6}\) pm.K\(^{-2}\) (adjusted \(R^2=0.9991\)). In the low temperature range, \(T<200\) °C, it is also possible to apply a simpler linear best fit \((R^2=0.9923)\), from which it is possible to determine a thermal sensitivity of 11.5 pm.K\(^{-1}\).

Fig. 6 Thermal characterization of the FBG written by fs laser pulses. Details are given in the text.

The graph in Fig. 6(b) presents data from another grating (writing energy 26 µJ, 20 min, hydrogenated G.652 optical fiber), which didn’t show the spectral regeneration when heated, so
results only depict the spectral shift during the heating cycle. For this grating the results of the best fit procedure are: first order coefficient 9.74 pm.K$^{-1}$, second order coefficient 2.92 $\times$ 10$^6$ pm.K$^{-2}$ ($R^2 = 0.9995$), and linear thermal sensitivity ($T< 200$ °C) 8.38 pm.K$^{-1}$ ($R^2 = 0.99741$). The used grating was heated from 20 °C until 950 °C with a ramp lasting 45 minutes, and its spectrum showed a continuous amplitude drop, vanishing after a few tens of minutes at the high temperature. As the recording time was long, the accumulated optical energy dose of the inducing laser pulses was comparable with other gratings presenting regeneration (recorded at higher energies but in shorter exposition intervals). This implies that the grating type, which determines the regeneration characteristic, is energy related. It should be stressed that this later grating did not show any special thermal resistance, even if recorded by fs laser pulses. Bragg gratings with long thermal resistance at temperatures in the order of 1000 °C have been reported previously [6]. They were recorded with very high energy pulses (~ 1 mJ) and using short exposition intervals with optical scanning over the fiber core. With the results discussed above, this suggests that the thermal survival characteristics of the gratings are related to the pulse energy.

IV. CONCLUSION

Bragg gratings were written in conventional and photosensitive optical fibers with the use of femtosecond laser pulses, using both point-by-point and phase mask methods. To our best knowledge, this is the first time that such methods were employed in Brazil for FBG recording. The method of moving the sample under the laser beam has low efficiency in single pass whereas multiple sweeps require reproducible positioning of the sample with high accuracy and synchronization to the pulse temporal position. Illumination under the phase mask provided better results with the used parameters, which allowed the writing of weak gratings on hydrogenated and photosensitive optical fibers during short exposure times (< 1 min) and with good amplitude and S/N ratio. The grating growth is faster when the illumination wavelength lies in the UV spectral region. The obtained gratings also presented typical thermal sensitivities in the order of 10 pm.K$^{-1}$, whereas the increase of the amplitude and peak wavelength points to type II gratings. Thermal regeneration was also observed in strong, saturated, gratings. It should be noticed that the obtained results are not different from those obtained with conventional Excimer lasers in the same spectral range of the illumination wavelength. The obtained results also corroborate the dependence of the thermal characteristics with the laser pulse energy in femtosecond laser writing of fiber Bragg gratings.

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