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Dynamics of thermal annealing of fiber gratings directly written by an infrared femtosecond laser

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ABSTRACT

The inscription of fibre Bragg gratings using infrared femtosecond laser offers a number of advantages over conventional methods based on UV inscription. The refractive index modification in femtosecond inscription is independent on defect formation and therefore should not experiment the defect-related thermal decay of UV inscribed gratings. In this paper, the response to thermal annealing of fiber Bragg gratings inscribed using a tightly focussed femtosecond laser is investigated. Experimental results reveal a vastly improve thermal stability compared to gratings inscribed using conventional methods based on UV light. Erasure was not observed until temperatures in the range between 900ºC and 1000º. These devices are therefore particularly suited to work in hostile environments and as high temperature sensors.

Keywords: Fiber Bragg gratings, femtosecond inscription, thermal annealing

1. INTRODUCTION

Fibre Bragg gratings are spectrally selective reflectors directly inscribed in the core of the fibre. The volume of research in these devices have been ever-increasing since the advent of side exposure inscription[1], and they are considered for a number of applications such as; wavelength division multiplexers and dispersion compensation in telecommunications, narrow band reflectors in fibre lasers or for sensing applications, pulse compression, wavelength selective filters. The number of applications has been enhanced by the ever-increasing quality of grating inscription towards highly complex structures, which may be specifically designed to fulfil the individual requirements for each application.

Most methods used for the inscription of this devices use UV light to create a periodic modulation in the refractive index along the fibre core. A main concern in fibre grating fabrication is the low tolerance to high temperatures. The thermal decay of fibre Bragg gratings has been studied in depth in UV inscribed fibres[2,3], significant decay of the grating strength takes place at modestly high temperatures, and is even evident at room temperature. This decay is observed both in hydrogenated and non-hydrogenated fibre. The dynamics of this decay have been thoroughly study and it has been demonstrated that its effect can be control and reduce by post-annealing. This is possible since the rate of the decay is a function of temperature and time. By annealing the grating, the initial period in which the grating significantly deteriorates is accelerated, this way the device only suffers minor bleaching during its working lifetime. Pre-annealing offers an accurate and useful solution for gratings that are design to work at room temperature allowing a stable performance throughout the lifetime of the device. At higher temperatures however, UV inscribed gratings are destroyed limiting significantly their functionality. Inscription of fibre Bragg gratings with high thermal stability is highly desirable, particularly in thermal sensing applications. It will also increase the reliability of multiplexing devices, where a small difference in the reflectivity of the device would prevent the accurate response of the system. It is been reported that inscription in special fibres such as codoped Sb-Ge fibre significantly improved stability over standard fibres, but even for this fibres the decay implies that only 18% reflectivity would remain after 24 hours at 900ºC[4].

The inscription of fibre Bragg gratings by infrared femtosecond laser on the other hand offers in this area a significant advantage. Thermal studies both in FBG inscribed by a phase-mask[5] and point-by-point have proved to be stable up to temperature where the actual molecules of silica start to diffuse at approximately 1000ºC. Furthermore inscription have been demonstrated using a phase-mask in graphite fibre, this way temperature sensors stable to temperatures up to 1500ºC had been demonstrated.

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The extremely high thermal stability is a result of the mechanisms that produce the refractive index change. While in femtosecond inscription, the modification appears after localized melting in the bulk of the material follow by densification, UV inscription relies strongly in defect formation and compaction, those defects are prone to recombine at high temperatures, and this relaxation of the defects leads to a reduction in the refractive index modulation and the erasure of the device.

In order to demonstrate the expected thermal stability of fibre Bragg gratings inscribed point by point by an infrared femtosecond laser an number of experiments were carried out in which gratings were subjected to temperatures as high as 1050ºC. Results demonstrated that the grating is stable temperatures up to temperatures in the range between 900ºC and 1000º. The decay observed at higher temperatures was likely due to the degradation of the fibre characteristics rather than decay of the grating structure.

2. FABRICATION PROCESS

The set up used for the inscription of gratings is illustrated in Figure 1. An amplified laser system, operating at a wavelength of 800nm, is used in the inscription procedure. This laser system produces 150fs-long pulses at a repetition rate of 1 kHz, reaching a maximum average power of 1W.

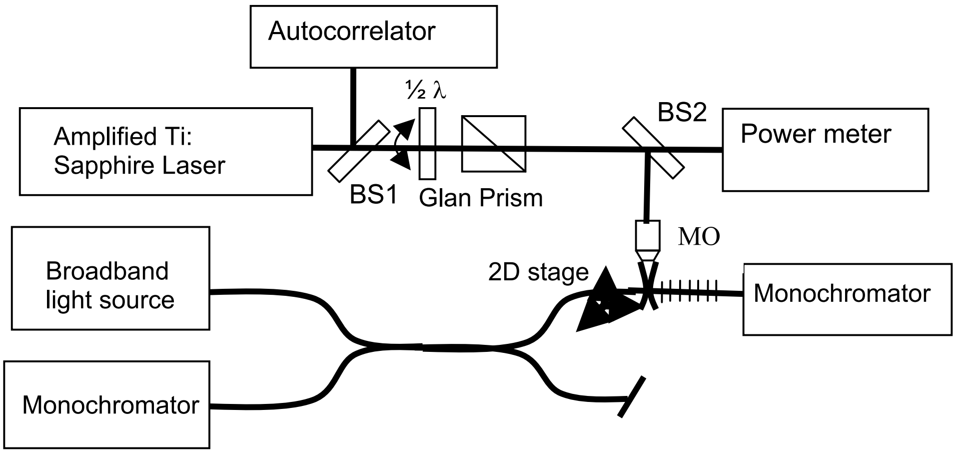

Figure 3.4: Experimental set-up for femtosecond inscription of FBG using a point by point technique. MO stands for microscopic objective, ½λ for half-wave plate and BS for beam splitter.

The beam was focused into the fibre core by a X100 microscopic objective. Pulse energy was approximately 0.5µJ, corresponding to peak intensities in the order of 10^{14}W/cm^2. The grating lengths were ranged between 15mm and 35mm. Standard telecommunication fibres (SMF) was used; no photosensitisation procedure was carried out prior to the exposure. The fibre was placed on a high-precision, two-coordinate translation stage. The stage moved at a constant speed along the fibre axis, translating the fibre with respect to the focal point of the beam. Each laser pulse produced a grating pitch in the fibre core. Therefore, the grating period was set by changing the ratio of the translation speed to the pulse repetition rate. All the gratings used for this experiment were of second order gratings for a resonant wavelength of 1550nm, this means a grating pitch of 1.07µm.

A broadband light source was coupled into the fibre and used as reference to monitor the inscription in real time. Reflection and transmission spectra were captured using two optical spectrum analysers. After the inscription, the gratings were characterised using a high-performance analyser with a resolution of 5pm.

3. EXPERIMENT AND RESULTS

3.1 Thermally induced wavelength shift

A grating under varying thermal conditions will present a shift in its resonant wavelength which follows equation 1; this shift comes as a result of the thermal expansion or contraction of the material and therefore the change in the pitch of the grating inscribed[6]. This is a property of the material of the fibre rather than the grating itself and therefore the behaviour of UV inscribed gratings and femtosecond inscribed grating is not expected to vary significantly.

$$\frac{1}{\lambda_B}\frac{\delta\lambda_B}{\delta T} = 6.67x10^{-6} \quad {}^{o}C^{-1} \qquad (1)$$

where λ_B is the resonant wavelength and T is the temperature. Since the wavelength shift is primarily dependent on the material properties, the shift for a femtosecond inscribed grating should follow this relationship, leading to an approximate 10pm/ºC shift. This was study using an environmental chamber. The results are shown in figure 2.

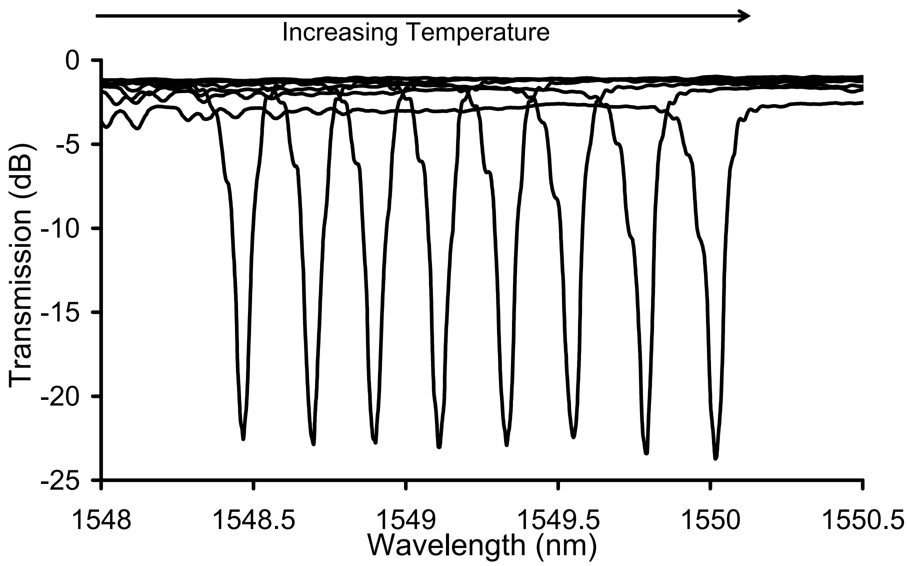

Figure 2: Variation in the grating transmission as function of the temperature with 20ºC increments, up to a maximum temperature of 180ºC.

The experiment in figure 2 lasted approximately 10 hours and the maximum temperature reached was 180ºC, it is worth noting that an equivalent experiment in a grating inscribed with UV light would result in a significant decay in the strength of the grating. In this case neither of the three gratings suffered any decay at the these temperatures.

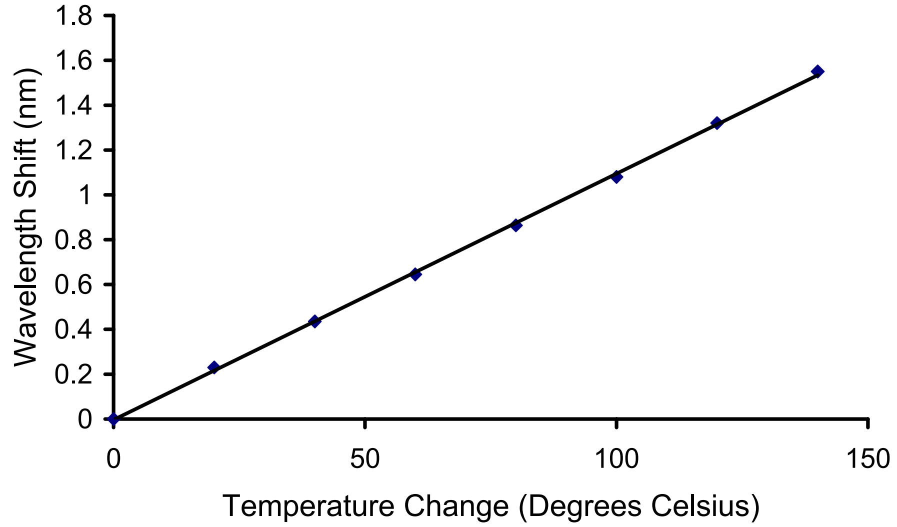

Figure 2: Wavelength shift against temperature in a fibre Bragg grating inscribed point by point by an infrared femtosecond laser

The result shown in figure 2 yields a temperature dependent shift of 11pm/ºC, in line with the shift predicted by equation 1. Three different gratings were studied simultaneously one of which had been annealed previously at high temperatures (600ºC), the three gratings observed similar wavelength shifts, no changes were observed in the spectral characteristics of the gratings.

3.2 Thermal decay of fibre Bragg gratings

In the initial experiment, three similar samples of the femto-inscribed FBGs with reflectivity ranging from 80% to 90% were placed in an oven and annealed at constant approximate temperatures of 500^{o}C, 700^{o}C and 1000^{o}C, respectively, for a period of 24 hours. The grating spectra were monitored every 30 minutes by an analyzer with a resolution of 5pm. After the annealing period, the oven was switched off and the gratings were allowed to cool down to room temperature. Monitoring of the grating spectra with the 30 minutes intervals was continued during the first 10 hours of the cooling process. The oven consisted of a tube furnace with capacity to heat up to 1200ºC the open ends of the tube gave rise to a significant gradient of tens of degrees across the tube. Although gratings were place at the centre of the tube, this gradient induced chirping in the grating due to the different thermal conditions across the grating.

Two UV inscribed FBGs were used as control samples. These were inscribed in hydrogenated fiber by using a 90mW beam from a CW laser operating at a wavelength of 244nm. After inscription, the FBGs were post-processed by annealing at 80^{o}C for 24 hours. The resultant reflectivity of control samples before the tests was in excess of 98%. The two control samples were subjected to the procedures of annealing and measurement identical to the ones applied to the femto-inscribed samples as described above. Measured evolution of reflection coefficients is presented in figure 3.

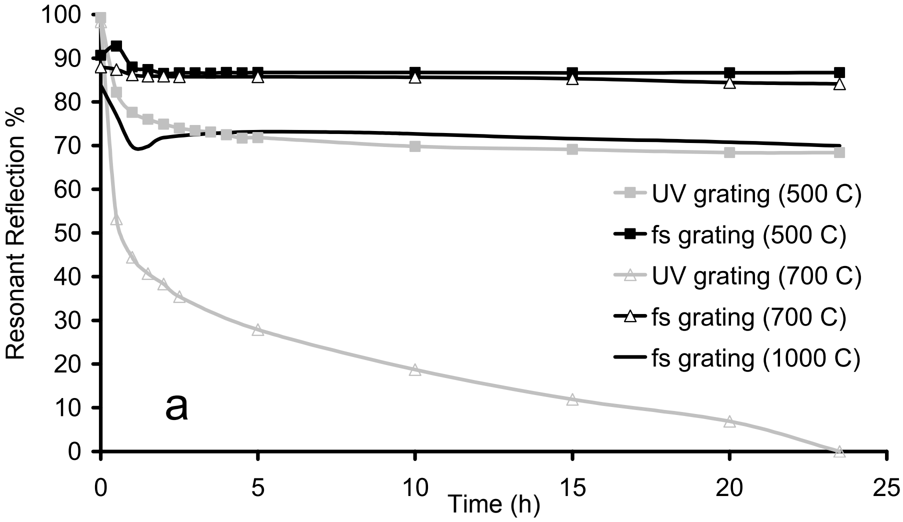

Figure 3: Isothermal evolution of reflection of femto-inscribed and UV-inscribed gratings during 24-hour annealing.

Femtosecond inscribed gratings presented significantly improved thermal stability compared to the hydrogenated UV inscribed FBG. UV inscribed grating suffered significant degradation at 500°C and was rapidly erased at 700°C; femtosecond inscribed gratings only presented significant decay at temperatures of 1000°C. Comparison with similar studies from literature shows that thermal stability of the femto-inscribed FBGs is significantly better than that of UV inscribed Type I and Type IIA gratings and is at least as stable as Type II damage gratings, based on optical damage [35, 4]. Furthermore the degradation observed in the grating at 1000ºC is likely to be an effect of degradation in the fibre rather than degradation of the grating itself.

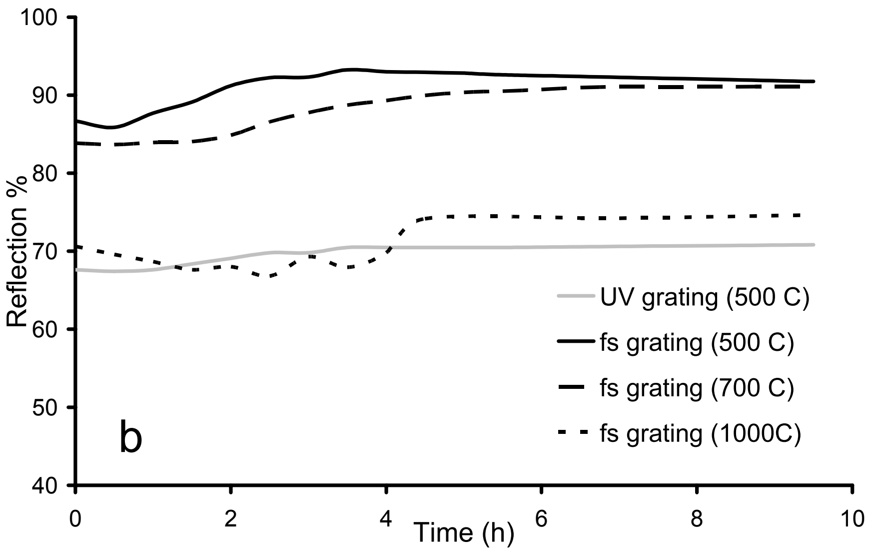

Figure 4: Isothermal evolution of reflection of femto-inscribed and UV-inscribed gratings during 10 hours of cooling down after 24 hours of thermal annealing.

In all cases, we observed that the grating reflectivity after cooling down to room temperature was greater than that at high temperature. This could be explained to be a result of the relaxation of mechanical stresses created in the outer regions of the modified area; similar type of annealing at high temperatures has been previously reported in the femtosecond inscription of photonic crystals[7]. At lower temperature levels of 500°C and 700°C, this effect in femto-inscribed gratings was stronger than the reflectivity decrease during the annealing. As a result, the resulting reflectivity actually increased after the annealing-cooling cycle in these gratings. Subsequent cycles at temperatures up to 600ºC did not affect the grating reflectivity further. Cycles at temperatures below 200ºC did not affect in any way the reflectivity of the gratings indicating that a threshold temperature at which the mechanical stresses are relaxed would be between 200ºC and 500º. The increase in the grating strength after a whole cycle annealing at temperatures of 500ºC and 700ºC is only observed in the first cycle. Subsequent cycles at the same temperature do not affect the reflectivity of the grating further.

The spectral evolution of the grating as it is cooling down to room temperature after 24 hours at temperatures of 700°C is shown in figure 3, the initial untreated spectra is also presented. The spectral shifts measured at 700ºC and 1000ºC were 8.5nm and of 13.72nm, this wavelength shifts do not agree with the wavelength shifts of 11pm/ºC expected from the experiment carried out in the highly accurate environmental chamber. Analysis of the furnace oven revealed that the thermostat readings had up to a 10% error in their readings and therefore the gratings were subjected to higher temperatures.

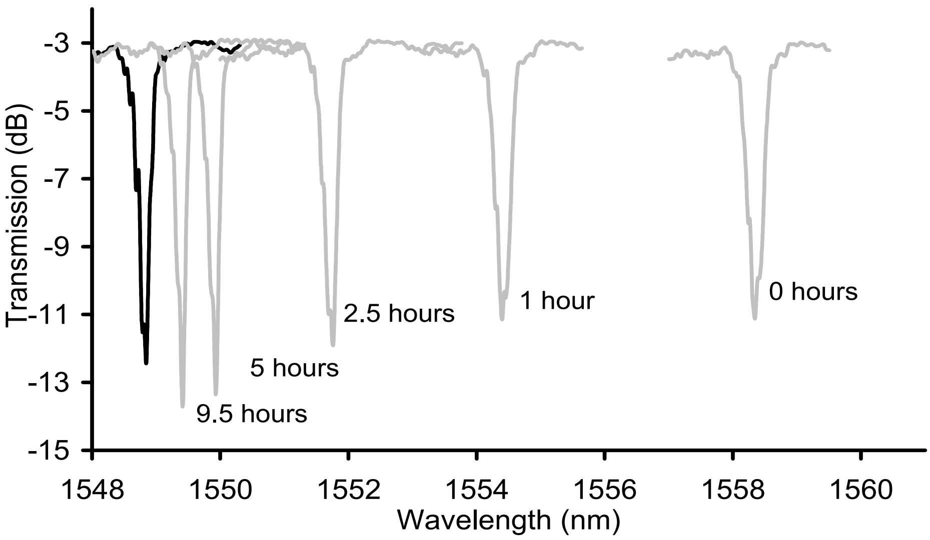

Figure 5: Spectral evolution of FBG as it is cooling down to room temperature after 24 hours at 700°C. Trace in black correspond to the pretreated FBG, it was shifted -1nm for clarity.

In the next experiment, the same femto-inscribed grating was annealed successively at increasing temperatures of 500°C, 700°C, 900°C, 1000°C and 1050°C. Annealing at each temperature lasted for 20 hours, after which the grating was allowed to cool down for 5 hours to room temperature before the next annealing cycle. The dynamics of the grating reflection during this exercise is shown in Figure 5.

Firstly, the grating reflection dropped during each heating period and subsequently increased during the cooling period, similarly to the behavior during the previous experiment as described above. Reflectivity decrease caused by annealing at lower temperatures was reversible. A certain increase in the reflectivity was observed after heating-cooling cycles at temperatures of 500°C and 700°C. The 900°C cycle produced a small overall reduction of reflectivity and, the 1000°C cycle caused a significant permanent degradation of the grating performance. Finally, annealing at a temperature of 1050°C practically erased the grating, rapidly and irreversibly reducing the reflection coefficient to a level below 20%.

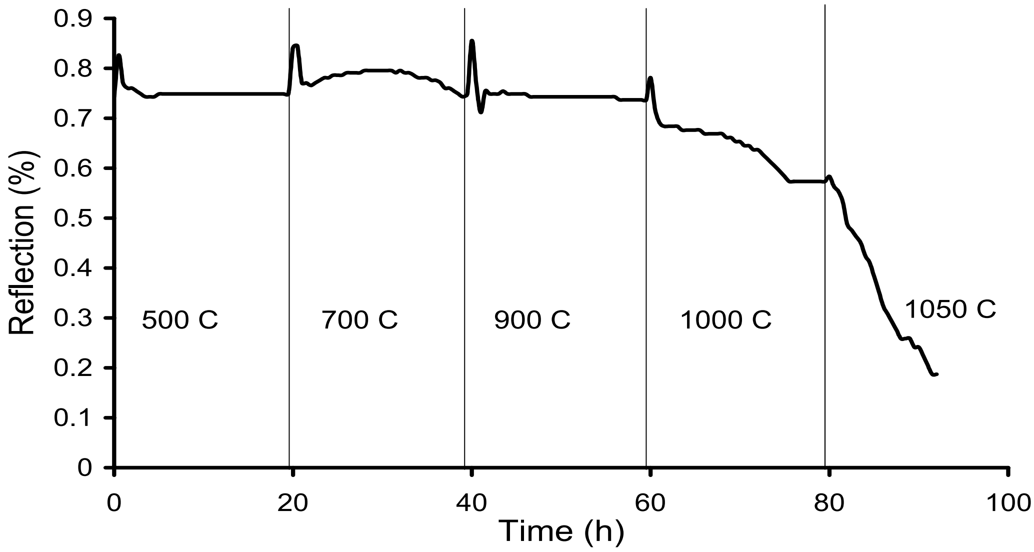

Figure 6: Thermal study of a femtosecond inscribed gratings. Reflection of FBG at Bragg wavelength during annealing at the set temperatures.

Overall, the results in this work are complementary to those reported in previous studies of the thermal behavior of the structures inscribed in glass by ultrafast lasers[8]. Thermal stability of the femto-inscribed grating is comparable to that of type II, UV-inscribed gratings formed by optical damage. No significant difference was established between the observed annealing behavior of the structures directly written by a tightly focused ultrafast laser beam and the reported earlier high-temperature tests of the gratings, produced with a phase mask by a defocused beam of a similar laser.

4. CONCLUSIONS

Thermal annealing fiber Bragg gratings, produced by direct, point-by-point femtosecond writing has been investigated for the first time. The gratings were formed in commercial fibers without any photosensitization. The gratings were thermally stable up to temperatures of the order of 1000^{o}C, showing a significant improvement compared to the conventional, UV inscribed FBGs. Dynamics of reflectivity during the annealing-cooling cycles indicates, in particular, that the strain in the material volume adjacent to the modified region is a significant factor affecting the grating performance. These gratings are therefore particularly suited for applications such as high temperature sensors, furthermore, the deterioration of the fibre takes place before the decay of the inscribed grating, it is therefore possible by an adequate choice of fibre to produce devices with an increased robustness to temperature.

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