Thermal properties of fiber Bragg gratings inscribed point-by-point by an infrared femtosecond laser

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Direct, point-by-point inscription of fiber Bragg gratings by infrared femtosecond laser had been recently reported. Response of these gratings to annealing at temperatures in range 500^{o}C to 1050^{o}C is studied for the first time. Gratings inscribed by infrared femtosecond lasers were thermally stable at temperatures up to 900^{o}C, representing a significant improvement in comparison with the "common", UV-inscribed, gratings. Annealing at temperatures up to 700^{o}C increased grating reflectivity.

OCIS codes: (350.2770) Gratings; (320.2250) Femtosecond phenomena

Introduction: Direct laser writing of fibre gratings by a focused femtosecond laser has been demonstrated, including directly written long period gratings [1], fiber Bragg gratings (FBG) produced using special phase-masks [2], and FBGs produced by a femtosecond UV laser using standard phase mask [3].

Recently, we reported a method for direct writing of FBG using point-by-point irradiation by an infrared femtosecond laser [4]. This method requires neither phase masks nor photosensitised fibers and hence offers a remarkable technological flexibility with a processing time of less than 60 second.per FBG. High quality, strong gratings were produced using this method in commercial, non-photosensitive fibers.

Growing interest in femtosecond laser inscription is based, among other factors, on the fact that the physical mechanism of this process is essentially different to that of

UV inscription. As a result, the physical properties of the femto-inscribed structures and devices are different to those of the UV-produced equivalents.

The refractive index change in femtosecond inscribed gratings is believed to be initiated by formation of localized plasma in the bulk of the material causing densification of the latter. The process involves highly nonlinear photo-ionization, thus requiring high intensity of light and it only occurs in a tightly focused laser beam. Previous reports indicate that; contrary to UV inscription, femto-inscription does not depend strongly on formation of defects [5]. As a result, the decay of defects caused by thermal annealing is likely to be insignificant in the femto-inscribed structures. Hence, femtosecond inscription should produce structures with improved thermal robustness compared to UV-written structures.

High thermal stability of the femto-inscribed structures has been observed recently in the FBGs produced by using a special, high-order phase mask [2]. In this paper, we present a study of thermal properties of FBGs produced using direct, point-by point inscription. These devices present smaller modified areas and higher refractive index contrast than gratings inscribed with a femtosecond laser and phase-mask. We established that these FBG are stable up to a temperature of 900^{o}C. Annealing at temperatures up to 700^{o}C actually increased the grating reflectivity, indicating the relaxation of strains induced during inscription in the vicinity of the modified region.

Experiment. Experimental setup and inscription procedure were similar to those used in our earlier study [3]. An amplified laser system, operating at a wavelength of 800nm, was used. The laser produced 150fs-long pulses at a repetition rate of 1 KHz. The beam was focused into the fiber core by a X100 microscopic objective. Standard fibre (SMF) was used; no photosensitization procedure was carried out prior to the exposure.

Pulse energy was set to approximately 0.5µJ corresponding to the peak intensities in the order of 10^{14}W/cm^2. The gratings were approximately 30mm long.

The pitch size in the gratings used in this work was 1.07µm, corresponding to the second order of the Bragg reflection at a wavelength of 1.55µm. Typical spectral characteristics of a femto-inscribed FBG are presented in figure 1, and are consistent with those reported previously [3].

Three similar samples of the femto-inscribed FBGs with reflectivity ranging from 80% to 90% were placed in an oven and annealed at constant 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-minute intervals was continued during the first 10 hours of the cooling process.

Three 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 three control samples were subjected to the procedures of annealing and measurement identical to the ones applied to the femto-inscribed samples as described above.

Results. Measured evolution of the grating reflection is presented in figure 2. Femtosecond inscribed gratings showed a significantly improved thermal stability compared to the hydrogenated, UV inscribed FBGs. The UV inscribed sampleexperienced a significant degradation at 500^{o}C and was rapidly erased at 700^{o}C, whilst the femto-inscribed FBG did not show any signs of rapid decay up to

1000°C. Comparison with the similar studies from literature shows that the thermal stability of the femto-inscribed FBGs is better than that of common Type I and Type IIA gratings and is similar to the stability of the Type II gratings, based on optical damage [4].

In all cases, we observed that the grating reflectivity after cooling down to room temperature was greater than that at the corresponding high temperature. This could be explained by relaxation of mechanical stress created in the outer regions of the modified area. Similar annealing behaviour has been previously observed femto-inscribed photonic crystals [6]. At lower temperature levels of 500°C and 700°C, this effect dominated in femto-inscribed gratings and the resulting reflectivity actually increased after the annealing-cooling cycle in those gratings.

Fig.3. shows the dynamics of grating spectra during the cooling down period. The measurements were taken after a 24 hour - annealing at 700°C. The measured spectral shift of 12.8pm/°C is in line with the values of 13pm/°C approximately, reported earlier for the UV-written FBGs [7].

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 4.

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 reflectivity was observed after the heating-cooling cycles at temperatures of 500°C and 700°C. The 900°C cycle produced a slight overall decrease 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%.

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 [2]. 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.

In conclusion, thermal annealing of 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°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.

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Figure captions:

Figure 1. Reflection and transmission spectra of a second order grating inscribed in standard telecommunication fiber.

Figure 2. Isothermal evolution of reflection of femto-inscribed and UV-inscribed gratings during a) 24-hour annealing and b) 10 hours of cooling down.

Figure 3. Spectral evolution of FBG during thecooling down periodafter annealing at 700^{o}C. Dotted line - Black trace shows the original spectrum before the annealing.

Figure 4. Dynamics of reflection in a femto-inscribed FBG during annealing at increasing temperatures.

Figure1.

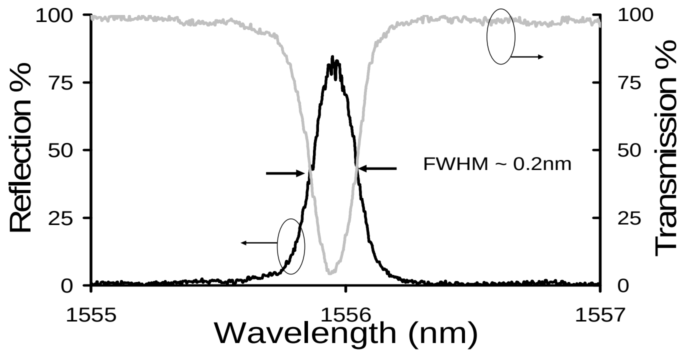

100
75
50
25
0
Reflection %
100
75
50
25
0
Transmission %
FWHM ~ 0.2nm
1555
1556
1557
Wavelength (nm)

Figure 2.

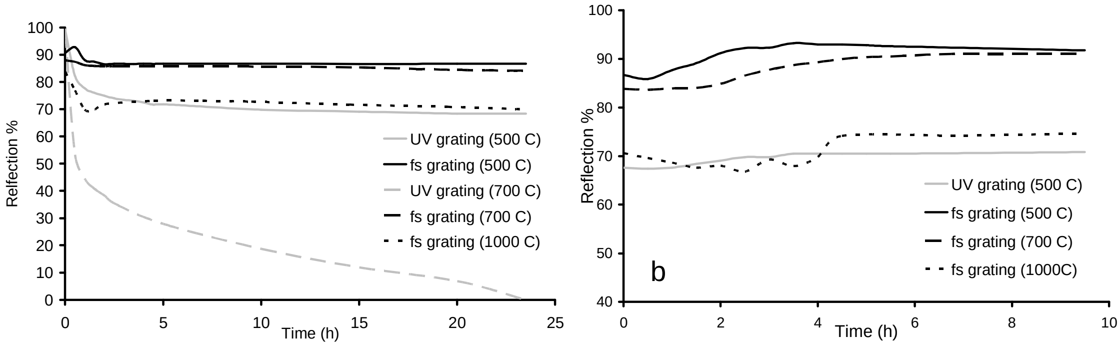

100
90
80
70
60
50
40
30
20
10
0
Relfection %
0
5
10
15
20
25
Time (h)
UV grating (500 C)
fs grating (500 C)
UV grating (700 C)
fs grating (700 C)
fs grating (1000 C)
100
90
80
70
60
50
40
Reflection %
0
2
4
6
8
10
Time (h)
b
UV grating (500 C)
fs grating (500 C)
fs grating (700 C)
fs grating (1000C)

Figure 3.

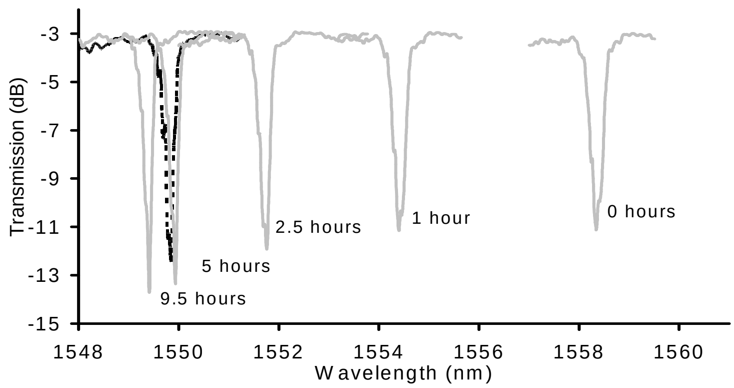
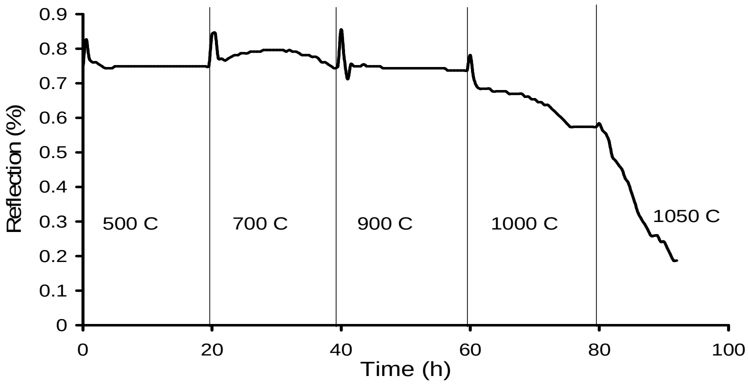

Transmission (dB)
-3
-5
-7
-9
-11
-13
-15
1548
1550
1552
1554
1556
1558
1560
Wavelength (nm)
0 hours
1 hour
2.5 hours
5 hours
9.5 hours

Figure 4.



0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Reflection (%)
500 C
700 C
900 C
1000 C
1050 C
0
20
40
60
80
100
Time (h)