A comparison of the spectral properties of high temperature annealed long period gratings inscribed by fs laser, UV and fusion-arc

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ABTRACT

Long period gratings have been inscribed in standard single mode fibre using a fs laser system, a fusion arc and a UV laser and a comparative study carried out of their thermal behaviour. The fs laser induced gratings can survive temperatures in excess of 800 ºC, however the inscription process can induce considerable birefringence within the device. Annealing studies have been carried out showing that below 600 ºC, all three grating types show a blue shift in their room temperature resonance wavelengths following cyclic heating, while above 600 ºC, the UV and arc induced LPGs exhibit a red shift, with the fs LPG showing an even stronger blue shift. High temperature annealing is also shown to considerably reduce the birefringence induced by the fs inscription process.

1. INTRODUCTION

Long period gratings are currently the subject of considerable research interest due to their potential applications as filters and as sensing devices, responsive to strain, temperature, bending and refractive index. Compared to the more mature fibre Bragg grating sensors, LPGs have more complex spectra, usually with broader spectral features. On the other hand they are intrinsically sensitive to bending and refractive index, which FBGs are not. Perhaps more importantly, the fibre design and choice of grating period can have a considerable influence over the sensitivity to the various parameters, for example allowing the creation of a bend sensor with minimal temperature cross-sensitivity. This control is not possible with FBG sensors.

Most research has concerned LPGs inscribed using UV light, though recently devices have been reported that have been fabricated using electric arcs[1], CO_2 lasers[2] and fs lasers[3]. In this study we concentrate on an investigation of the fs technology and compare the resulting devices with gratings fabricated using UV and the electric arc. The use of a fs laser is attractive as it offers a potential route to LPGs that can be used at high temperature, and the gratings can be made without stripping the coating – something not possible with all the other approaches.

2. THE FABRICATION OF THE LPGs

A series of LPGs with the same period of 350µm was recorded, the length of LPGs being varied to obtain maximum strength attenuation bands. Three different fabrication techniques were used with the standard, single mode fibre (Corning SMF-28) which had core and cladding radii of 3.5µm and 62.5µm, respectively. The first technique was UV laser inscription using the "Point-by-Point" technique[4], which is based upon the photo-bleaching of germanium oxide colour centres[5] and is still being studied by several research groups. Secondly, the fusion-arc method was used, which creates LPGs by structurally damaging the fibre[1]. This technique was implemented by using the electric arc generated by a fibre fusion splicer. The fibre is pulled in a controlled manner between the electrodes of the splicer and at equally spaced intervals the fibre is subjected to the splicer's electrical arc, in this case with a period of 350µm. Thirdly, the refractive index changes to create the LPG were induced by a NIR femtosecond laser (800nm Spitfire/Evolution, titanium sapphire system, Spectra-Physics Lasers).

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The femtosecond laser radiation was focused at a predetermined point near the core with a ×100 (NA=0.55) microscope objective, while the fibre was moved in a direction parallel to the fibre axis. The translation speed was varied from $30\mu ms^{-1}$ to $100\mu ms^{-1}$, with the pulse energy varying from 0.25μJ to 0.5μJ. Neglecting the effect of the curved fibre surface and any self-focusing, the beam width was estimated to be 1.9 μm while along the axis of the beam the Rayleigh length was 3.6μm. The femtosecond laser system produced a 1 kHz train of 150 fs pulses at 800 nm, see figure 1; other details of the experimental set-up can be found elsewhere[3].

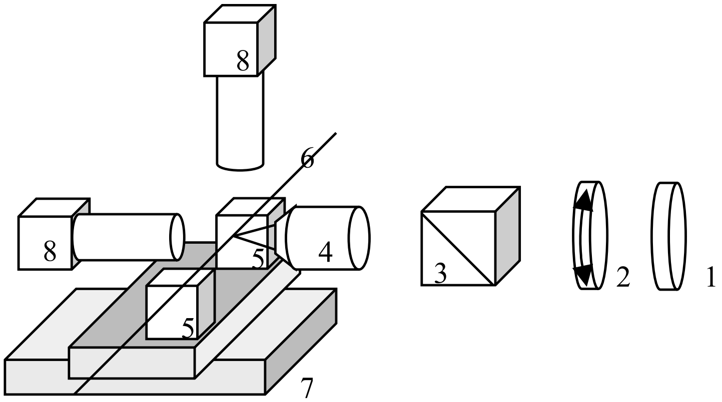

Figure 1: Optical layout of inscription scheme. The light passes a shutter (1), a half-wave plate (2), Glan prism (3), x100 long working distance microscopic objective (4), and is then focused in the fibre core (6). Two alignment 3D translation stages are mounted on top of the high precision computer controlled 2D-stage (7). We use two CCD-cameras (8) with optical zooming system for alignment and on-line monitoring of the inscription process.

Firstly, the transmission spectra of the three different fabricated LPGs were observed along with the polarisation dependence of the transmission spectra. Figure 2 shows a schematic of the arrangement used for this study. The light output from a broadband source was polarised and then a polarisation controller was to change the polarisation of the light illuminating the LPGs.

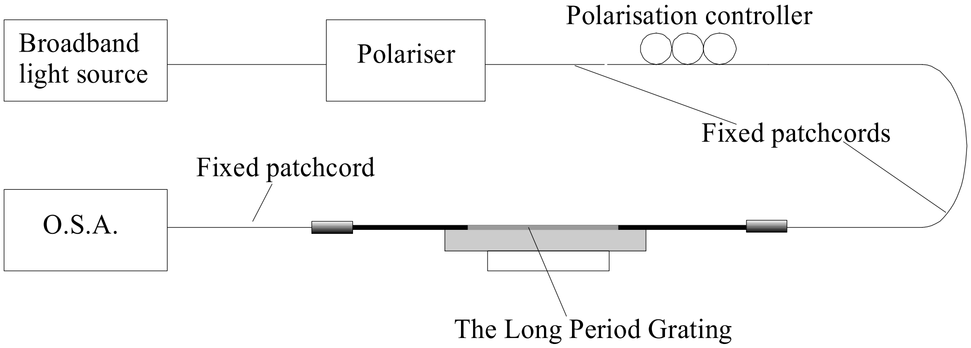

Figure 2: A schematic of the apparatus used to investigate the transmission spectra and polarisation dependence of the LPGs

It was noted that, in general, the overall strength and transmission profile of the attenuation bands of the LPGs varied most with the fs laser inscription technique compared to the other two techniques being used. Secondly, the observed polarisation dependence varied greatly for the fs LPGs ranging from 1nm to 46nm, with the arc induced LPGs having typically a 0.3nm variation, approximately the same as that for the UV LPGs. Three typical transmission spectra are shown in figure 3.

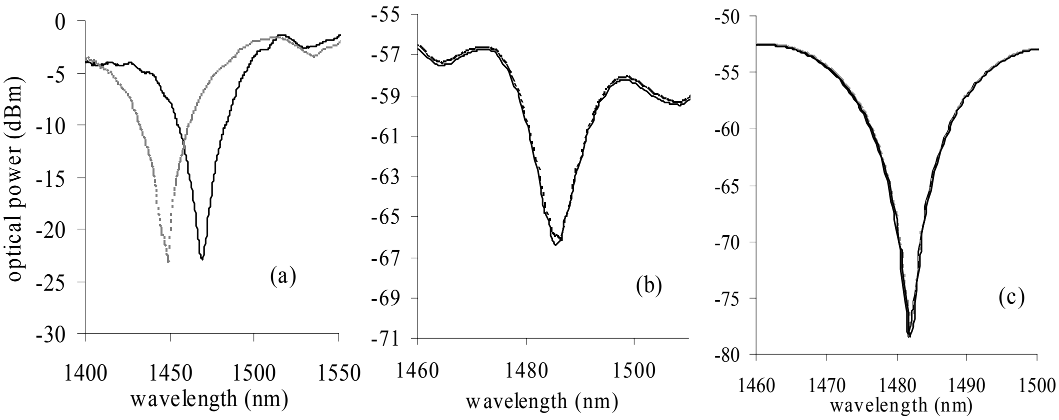

Figure 3: Typical transmission spectra of gratings with polarisation dependence: (a) Femtosecond laser LPG, period 350μm, inscription power 0.31μJoules, length 1.7cm; (b) UV LPG, period 350μm, inscription power 85mW, length 4.2cm and (c) Fusion-Arc LPG, period 350μm, length 1.4cm.

In the case of the LPGs produced with the fs laser, the polarisation dependence appears to be linked to some degree with the inscription power of the femtosecond laser. Note that the precise nature of the change in the refractive index in the core is not fully understood at the present and is the subject of much research. In the case of the LPGs produced in this work, it is observed that the index modification wanders somewhat within the core of the fibre itself (an alignment problem) which will complicate the polarisation properties of these LPGs. See figure 4 for some typical transmission spectra, illustrating the range of variation observed.

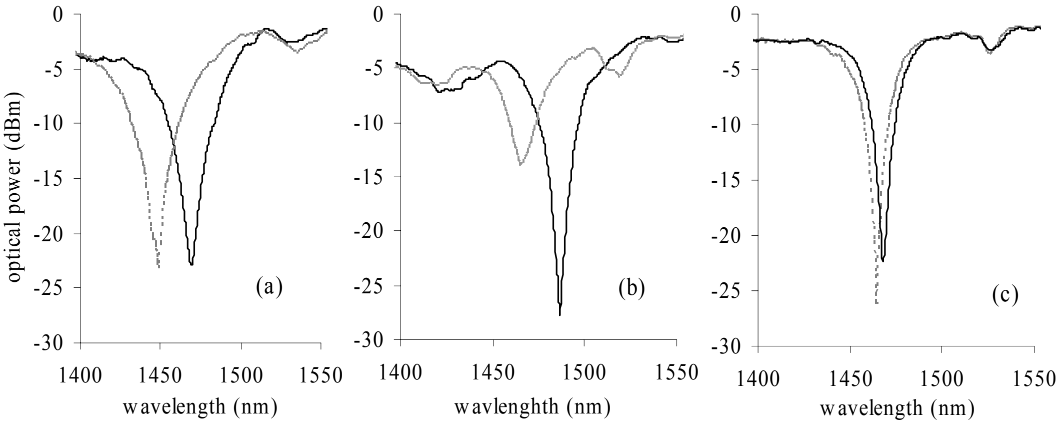

Figure 4: Three typical spectra showing the variation of polarisation dependence of LPGs inscribed by fs laser. The LPG inscription conditions are (a) 0.31μJoules, 100μms^{-1}, length 1.7cm, (b) 0.34μJoules 100μms^{-1}, length 1.5cm and (c) 0.31μJoules 70μms^{-1}, length 3.8cm.

It was also observed that the transmission profiles and the central wavelength of the attenuation bands of some of the fs laser induced LPGs changed over a period of 6 weeks at room temperature. The amount of wavelength shift varied from 0 to 41nm red shift and smaller blue wavelength shifts of up to 1nm; an example is shown in figure 5. The two solid curves were obtained by adjusting the polarisation of the incident light to obtain the strongest attenuation bands; the grey curves correspond to the orthogonal polarisation states. The dependence of birefringence on inscription pulse energy can be seen in figure 6. It may be seen that there is a loose correlation between pulse energy and birefringence; this is being studied at present.

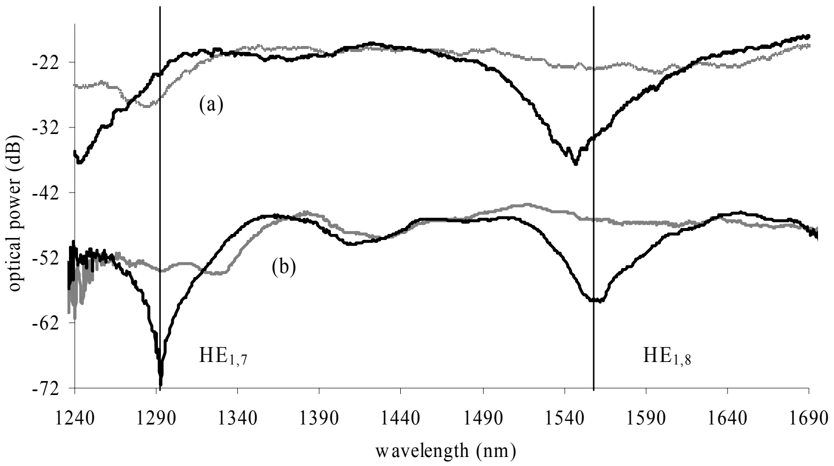

Figure 5: An example of the change in the spectral characteristics of the fs laser induced LPGs: (a) transmission spectra taken just after inscription and (b) transmission taken after 6 weeks at room temperature.

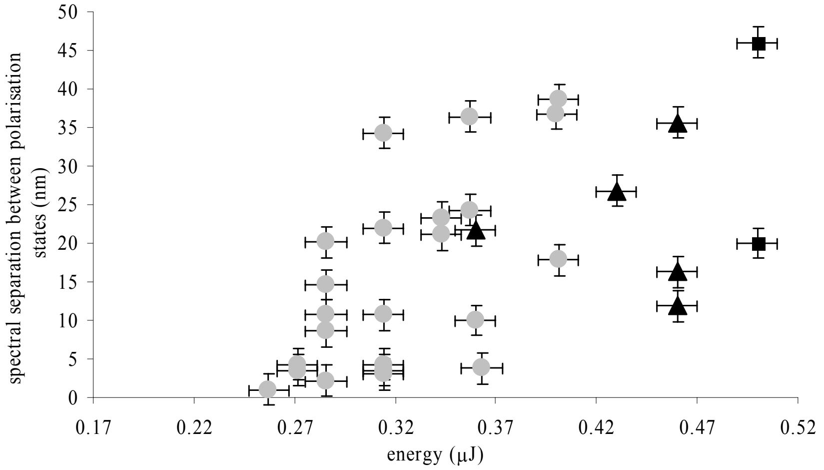

Figure 6: The variation of birefringence of the fs laser induced LPGs as a function of inscription energies used. Also indicated is the overall shift in the attenuation bands observed over several weeks at room temperature: ● is negligible/small red wavelength shifts (~0nm to 2nm), ▲ red wavelength shifts (~3nm to 40nm), ■ small blue wavelength shifts (~0nm to 2nm).

3. COMPARATIVE STUDY OF HIGH TEMPERATURE ANNEALING OF LPGS

One of each of the differently fabricated LPGs were placed in a furnace at the same time alongside a fs laser inscribed fibre Bragg gratings (FBG), for comparison. The optical arrangement to interrogate the LPG's transmission spectra and polarisation dependence at various temperatures is shown in figure 2 with the optical spectrum analyser (OSA) having an accuracy of 0.05 nm; a second OSA was used to interrogate the FBG with an accuracy of 0.03 nm. The gratings were raised in a period of approximately 5 minutes to set temperatures ranging from 100 to 850^{o}C in intervals of 50^{o}C, at which temperatures they were held for 10 minutes before being brought down to room temperature over a period of up to 2 hours, with measurements being taken after each change. Figure 7 shows sample measurements of the central wavelength of the attenuation bands made at each of the elevated temperatures. Figure 8 shows another fs laser induced LPG which shows somewhat different spectral behaviour with temperature. Figure 9 shows the shift in the room-temperature spectral location of an attenuation band following each heating cycle. Figure 10 shows the true temperature sensitivity obtained by taking into account the thermal hysteresis effect shown in figure 9.

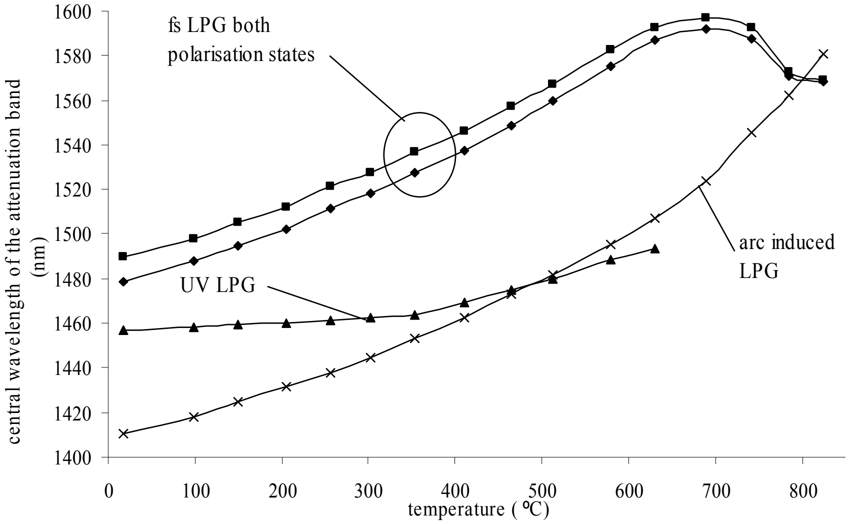

Figure 7: The shift in the same attenuation band of three different types of LPG as a function of temperature. Femtosecond laser LPG: period 350μm, inscription pulse energy 0.28 μJ, length 3.3cm. UV LPG: period 350μm, inscription power 85mW, length 4.2cm. Fusion-Arc LPG: period 350μm, length 1.4cm.

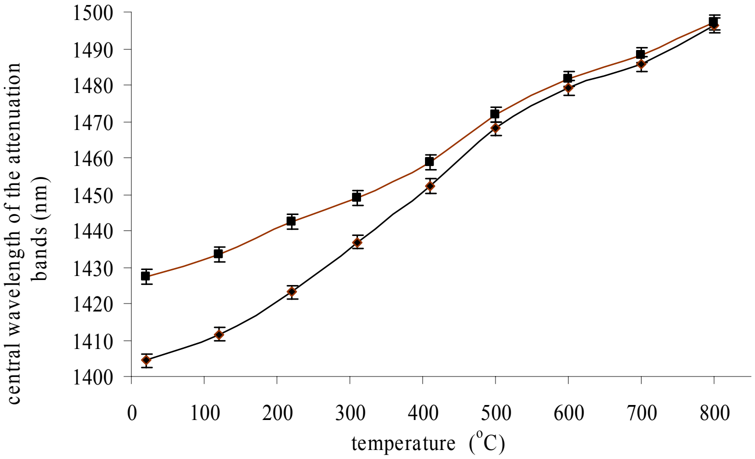

Figure 8: The temperature induced shift in the attenuation bands of the two polarisation eigenstates of a second fs laser inscribed LPG: period 350μm, inscription pulse energy 0.36μJoules, length 2.4cm.

Inspecting figures 7 and 9 it can be seen that there is an annealing or hysteresis effect occurring with the UV LPG at low temperatures, compared to the cases of the arc induced and fs LPGs. Comparing the two fs LPGs in figures 7 and 8 where the attenuation band is associated with the same cladding mode, the spectral sensitivity of the two gratings may be seen to differ somewhat. The fs LPG inscribed with 0.25μJ has an effective temperature sensitivity for both polarisation states of around +0.17 nm^{o}C^{-1} compared to the fs LPG inscribed with 0.36 μJ which shows sensitivities of +0.14nm^{o}C^{-1} and +0.09nm^{o}C^{-1} for the two states, which suggests that the inscription process itself is changing the local properties of the fibre where the LPG is written. It can also be seen that the birefringant behaviour of both fs LPGs are different; this is discussed later. Thirdly, it appears that at 500 to 600^{o}C both fs LPGs and the arc induced LPG spectral behaviour changes drastically, maybe due to thermal relaxation of quenched glass produced during the inscription; this is currently a topic undergoing study.

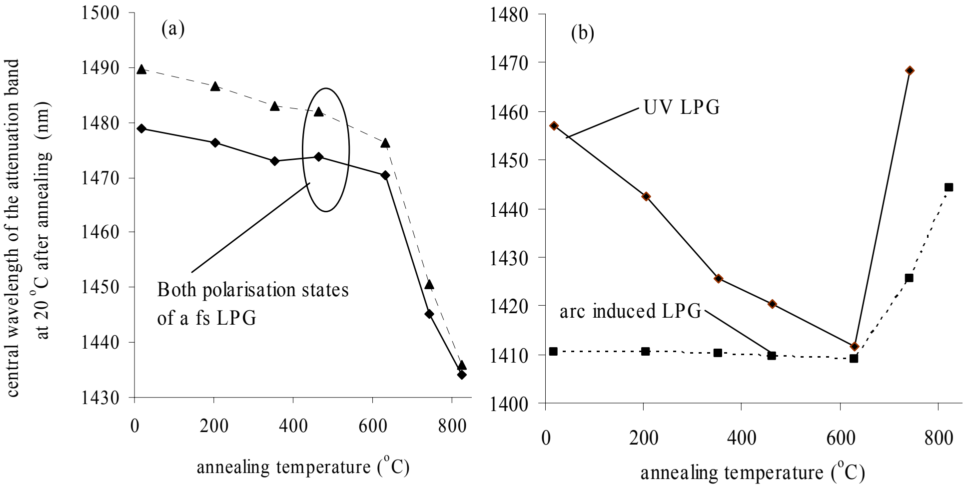

Figure 9. Shift in the position of an attenuation band at room temperature after annealing at the specified temperature. (a) fs laser induced LPG, (b) UV and Fusion-Arc induced LPGs.

The annealing curves of figure 9 show that up to a temperature of approximately 600°C all the LPGs produced blue wavelength shifts with the arc induced LPG having the smallest coefficient of -0.002nm°C^{-1} with the fs LPGs ranging from -0.013nm°C^{-1} to -0.034nm°C^{-1} and the UV LPG having the largest coefficient of -0.076nm°C^{-1}. After being heated to temperatures in excess of 600°C and then cooled, the fs LPGs produced larger blue shifts: typically –0.2nm°C^{-1}, compared to observed red wavelength shifts for the UV LPGs (+0.5nm°C^{-1}) and arc induced LPGs (+0.18nm°C^{-1}).

We offer the following explanations for some of the features seen in figure 9. The phase matching condition for the central wavelength of a LPG's attenuation band is given approximately by[6]

$$\lambda_{res} \cong \left[\left(n_{eff}^{Co} - n_{eff}^{Cl}\right) + \Delta\overline{n}\right] \cdot \Lambda \qquad (1)$$

where n_{eff}^{Co} is the effective index of the core mode, and n_{eff}^{Cl} the effective index of the radial cladding mode, both indices being dependent on the core refractive index n_1, the cladding refractive index n_2 and the wavelength λ. The period of the LPG is Λ and $\Delta\overline{n}$ is the induced change in the core mode effective index due to the fabrication of the LPG, which may consist of various components depending upon the fabrication process used for inscription, e.g. photobleaching, stress optic effect, voids, densification or quenching.

The red wavelength shift for high temperature annealing of arc induced LPGs has been previously reported[7] and related to a rearrangement in the glass structure and plastic deformation of the fibre[8,9] as well as the relaxation of intrinsic stresses introduced during the fibre drawing process producing a contraction and densification of the fibre structure[10]. Whilst the mechanisms involved in UV inscription are still the subject of some research, it is generally accepted that UV written gratings have some component of structural change, which may affect the core and cladding, as well as photobleaching, which only affects the core. Furthermore, $\Delta\overline{n}$ is a positive quantity from both structural and photobleaching effects, thus increasing the effective index of the core mode (similar to the case of the arc induced LPGs) but the cladding also needs to be considered when there is a structural change. Therefore at temperatures below 600°C $\Delta\overline{n}$ is decreasing due to thermal erosion of the photobleaching and mechanical relaxation of the structural component thus producing a blue wavelength shift. At temperatures over 600°C we see a red wavelength shift, as discussed above.

The fs induced LPGs can be considered using equation 1 again (noting that for fs LPGs the core and cladding are both probably changed). The behaviour at low temperatures is similar to the arc and UV induced LPGs, but there are a couple of major differences in the components of $\Delta\overline{n}$. One contribution due to voids created in the material during inscription is negative while in addition thermally induced stress appears to play a major role, providing a positive contribution to $\Delta\bar{n}$. At temperatures over 600°C there are major reductions in the stress induced components while the negative contribution of the voids remains, generating a blue wavelength shift. Our study of these mechanisms is continuing.

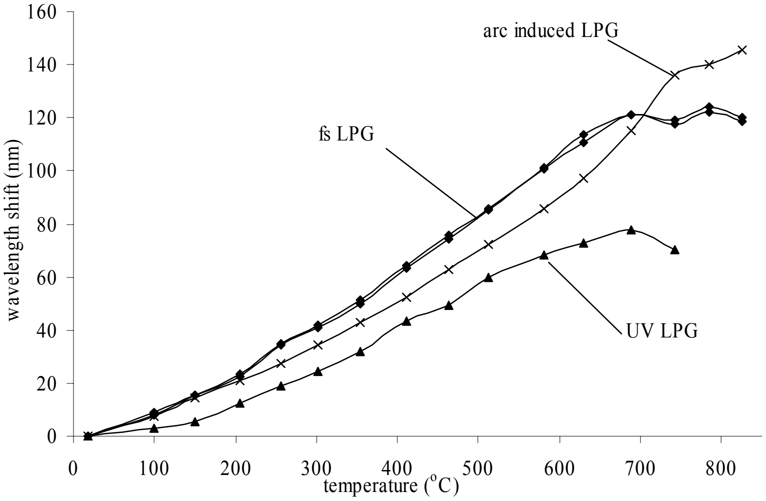

Figure 10: The spectral sensitivities of the three differently inscribed LPGs as a function of temperature, taking into account the annealing hysteresis illustrated in figure 9.

4. BIREFRINGENCE AS A FUNCTION OF ANNEALING TEMPERATURE

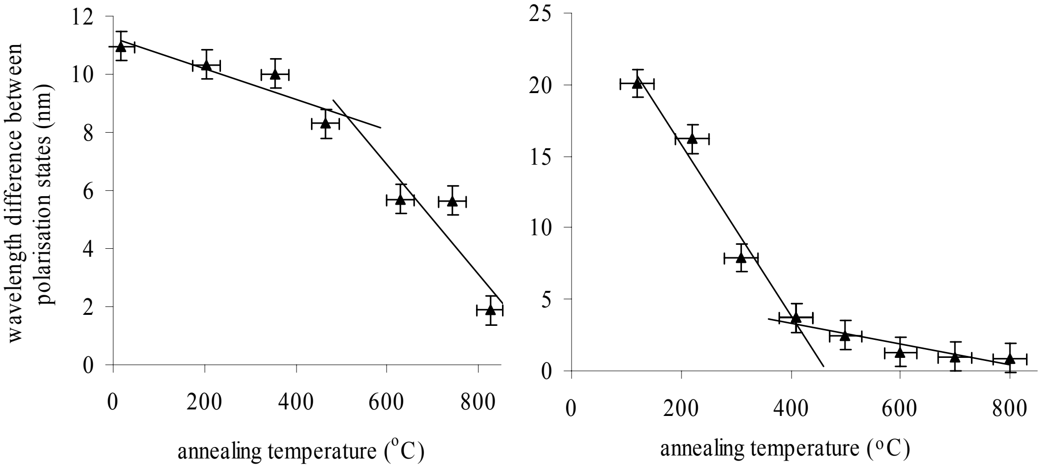

Figure 11: The wavelength separation between the orthogonal polarisation states of two fs LPGs inscribed using different pulse energies: 0.28 µJ (left) and 0.36 µJ (right). In both cases the plots show the wavelength separation measured at room temperature after cycling the device to the temperature indicated.

The birefringence of the all the LPGs was also investigated as a function of annealing temperature. As stated earlier, the polarisation dependence varied greatly for the fs LPGs, ranging from 1nm to 46nm. with the arc induced LPGs having typically a 0.3nm variation, approximately the same as the UV LPGs. The variation of the birefringence was negligible over the range of annealing temperatures for the arc induced and UV LPGs investigated. The fs LPGs showed a strong variation of birefringence with annealing temperature and the inscription energy used to produce the LPG. Two examples are shown in figure 11; the fs LPG with an inscription power of 0.28 µJ showed two distinct temperature regimes with a coefficient of -0.005nm°C^{-1} from room temperature to ~500°C and above this a dramatic increase in the rate of reduction of birefringence to -0.019nm^{o}C^{-1}. The second fs LPG, produced at an inscription power of 0.36 μJ, showed again two distinct temperature regimes with a coefficient of -0.060nm^{o}C^{-1} from room temperature to ~500^{o}C and above this a dramatic decrease in the rate of reduction of birefringence to -0.007nm^{o}C^{-1}.

5. HIGH TEMPERATURE ANNEALING OF FBG

During the previous temperature cycling experiments, fs laser inscribed Bragg gratings were also included in the oven for comparison. Figure 12 shows the wavelength as a function of temperature (analogous to Figures 7 and 8).

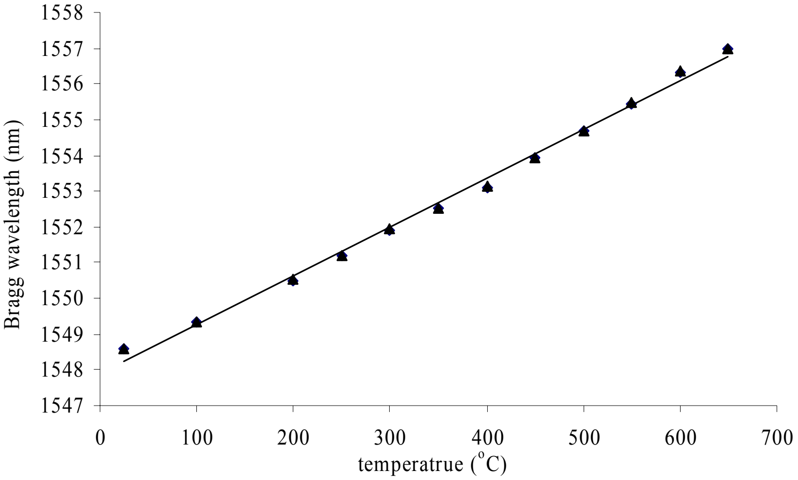

Figure 12: Temperature induced shift in the Bragg wavelength of a fs laser inscribed FBG. The straight line indicates a sensitivity of 14 pm ºC^{-1}.

Again, the central wavelength of the FBG was also measured at room temperature after the grating had been held at various annealing temperatures, see figure 13. There seems to be two distinct regimes, similar to the behaviour of the LPGs. At annealing temperatures below 400^{o}C and smaller effect is seen with a coefficient of -0.00007 nm^{o}C^{-1} while at temperatures above 400^{o}C the coefficient is much greater: -0.0004 nm^{o}C^{-1}, approximately an order of magnitude larger.

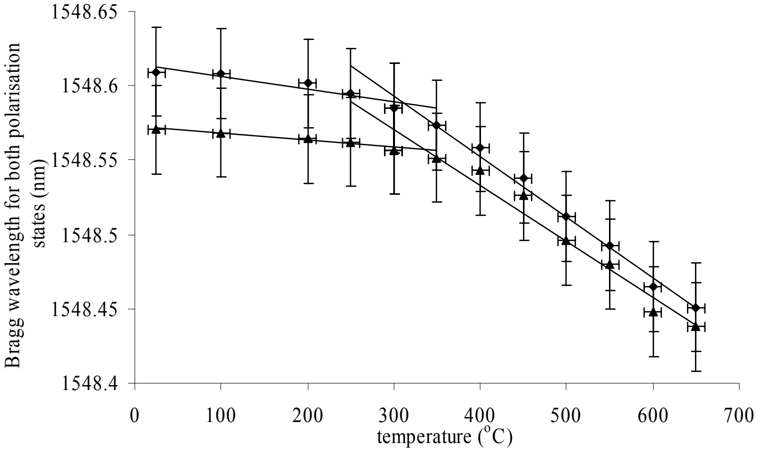

Figure 13: The spectral location hysteresis of the fs laser inscribed FBG after annealing to various temperatures and then cooling back to 20^{o}C, also showing the wavelength separation between the orthogonal polarisation states of the FBG.

6. CONCLUSIONS

Femtosecond laser induced gratings have a number of attractive features, such as high temperature survivability and the ability to be written without stripping the coating; however it is clear from the work reported here that their thermal behaviour is very complex, particularly in the case of LPGs, which are sensitive to differential effects between the core and cladding. Further work is needed on two fronts. Firstly it is necessary to obtain better control of alignment during the inscription process to improve the reproducibility of the grating properties. Secondly, more research needs to take place to unravel the various effects contributing to the annealing behaviour of these devices, to enable the generation of an annealing recipe that can be used for a given application, as is currently available for UV inscribed FBGs[11].

REFERENCES

[1] G. Rego, O. Okhotnikov, E. Dianov,and V. Sulimov, "High-Temperature Stability of Long-Period Fiber Gratings Produced Using an Electric Arc", *JOURNAL OF LIGHTWAVE TECHNOLOGY* **19**(10), pp. 1574 –1580, 2001

[2] D.D. Davies T.K. Gaylord, E.N. Glytsis, S.G. Kosinski, S.C. Mettler, A.M. Vengsarkar, Electron. Lett. 34 (1998) 302.

[3] A. Martinez, et al, "Point by point FBG inscription by a focused NIR femtosecond laser", OSA Conf.Proc. CLEO/IQEC and PhAST Washington, DC, 2004, CMY6

[4] L. Zhang, Y. Liu, L. Everall, J. Williams, and I. Bennion, "Design and realization of long-period grating devices in conventional and high birefringence fibers and their novel applications as fiber-optic load sensors," IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS 5(5), pp. 1373 – 1378, 1999.

[5] L. Dong, " Photoinduced absorption change in germanosilicate performs : evidence for the colour centre model of photosensitivity ", Appl. Opt. , vol34 , no18 , pp3436 , 1995

[6] T. Erdogan, "Fiber Grating Spectra", *JOURNAL OF LIGHTWAVE TECHNOLOGY* **, 15**(8), pp. 1277 –1294, 1997

[7] G. Rego, O. Okhotnikov, E. Dianov,and V. Sulimov, "High-Temperature Stability of Long-Period Fiber Gratings Produced Using an Electric Arc", JOURNAL OF LIGHTWAVE TECHNOLOGY 19(10), pp. 1574 –1580, 2001.

[8] R. Bruckner, "Properties and structures of vitreous silica. I," *J. Non- Cryst. Solids*, vol. 5, pp. 123–175, 1970

[9] W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, Introduction to Ceramics New York: Wiley, 1976, pp. 595–603, 704–766.

[10] H. Scholze Glass. Nature, Structure, and Properties New York Springer-Verlag, 1991, pp. 181–194

[11] T. Erdogan, V. Mizrahi, P.J. Lemaire, D. Monroe: "Decay of ultraviolet-induced fiber Bragg gratings", J. Appl. Phys., **76**(1), 73-80 (1994).