Optical loss mechanisms in femtosecond laser-written point-by-point fibre Bragg gratings

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Abstract: Fibre Bragg gratings inscribed with the point-by-point method using a Ti-sapphire femtosecond laser operating at 800 nm are shown to display strong increasing attenuation towards shorter wavelengths with a large and spectrally sharp recovery observed below 400 nm. The origin of this loss is shown to be Mie scattering, and the sharp recovery in the transmission results from wavelength dependent scattering within the numerical aperture of the core. The permanent losses from these Type II gratings have implications for high temperature sensors and fibre lasers.

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References and links
1. Introduction

Type II fibre Bragg gratings (FBGs), i.e., those that are written above the damage threshold of glass, have been written using high intensity UV-lasers [1, 2], as well as more recently, by femtosecond lasers [3-5]. Both processes operate above the so-called damage threshold of the glass [6, 7], which for point-by-point (PbP) femtosecond laser written gratings is ~0.15 μJ for a ~120 fs pulse duration, as determined through microscope and annealing studies. This leads to structural changes that can withstand temperatures approaching 1000 °C [8]. The importance of the underlying processes has meant extensive applications within a number of fields demanding superior temperature performance as well as long-term stability, including sensors, lasers, laser written waveguide channels and other components [9-12]. For example, we recently reported the use of femtosecond gratings for a high power fibre laser operating in excess of 100 W [13].

Short wavelength attenuation, i.e., attenuation stretching from the visible into the NIR is associated with all forms of grating writing, but the origins of the losses and the solutions to mitigate the losses are different for different types of gratings. For Type I gratings, written well below the damage threshold of the glass by excitation through defect absorptions, the losses are associated with photo-induced colour centres that can be annealed out at moderate temperatures [14, 15]. On the other hand, for Type II gratings, written above the damage threshold of the glass through bond breaking below the glass band edge [9], the losses are due to diffractive Mie scattering [16], which can only be remedied by addressing the overlap integral between the grating and the incident mode by changing grating size and morphology [17]. A limited study of short wavelength attenuation induced by femtosecond gratings [18] and recent studies of these gratings employed in core pumped fibre lasers [19] indicate that the differences in confinement of the induced changes compared to long pulse UV Type II gratings give rise to significant differences in attenuation, either from scattering and/or defect absorption.

This paper reports on the observation of significant short wavelength attenuation associated with PbP written femtosecond Bragg gratings written in the high intensity Type II damage regime. To address both sensor and fibre laser applications, the studies are carried out for both Ge-doped as well as Yb/Al/Ge codoped (henceforth referred to as Yb-codoped) fibres. Moderate temperature annealing procedures are carried out to separate the contributions arising from scattering and photo-induced colour centres. A simulation is carried out to qualitatively confirm the origins of scattering.

2. Experiments and results

The fibres used in the experiments were fabricated by modified chemical vapour deposition (MCVD) and their properties summarised in Table 1. To fabricate the gratings, the fibre was mounted on a high-precision air bearing translation stage, the outer polymer cladding was stripped and femtosecond pulses were focused into the core using a 0.8 NA, 20x oil immersion objective lens. The pulses, which were generated by a regeneratively amplified
Ti:sapphire laser operating at 800 nm, had ~120 fs pulse duration, a 1 kHz repetition rate and pulse energies between 160 and 300 nJ (the so-called “Type II-IR” regime). The gratings were 50 mm long and written in the 20th order for 1.55 \( \mu \)m light (\( \Lambda_{\text{period}} = 10.7 \mu \)m). The scattering and absorption losses were grating period independent so a higher order period was used to remove coupling to cladding modes at shorter wavelengths, which can obscure the study of the losses associated directly with the structural changes. Optical micrographs of the gratings from top and side perspectives are presented in Fig. 1 showing that the changes are confined to well-defined cylinders across the core.

Table 1. Optical fibres used in the experiments.

<table>
<thead>
<tr>
<th>Fibre</th>
<th>NA</th>
<th>( \Phi ) core/( \Phi ) fibre [( \mu )m]</th>
<th>Dopants</th>
<th>( n_{\text{eff}} ) @ 1.55( \mu )m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge</td>
<td>0.14</td>
<td>8.2/125</td>
<td>Ge</td>
<td>1.44738</td>
</tr>
<tr>
<td>Yb</td>
<td>0.15</td>
<td>7/122</td>
<td>Yb (1.18%wt), Al, Ge</td>
<td>1.44991</td>
</tr>
</tbody>
</table>

Spectral transmission experiments

Normalised white light transmission spectra for gratings written with various pulse energies in both the Ge-doped and Yb-codoped fibre were taken in order to investigate the wavelength dependant losses as a function of pulse energy. A fibre-coupled, high brightness halogen light was used as the white light source. The fibres under test were cleaved to the same length (\( L \approx 25 \) cm) and SMF 28 fibre pigtails were spliced to the input and output ends. An optical spectrum analyser (OSA) was used to measure the transmission properties of the gratings (\( s-n \approx -35 \) dB, \( res = 5 \) nm, \( \Delta \lambda = 350-1750 \) nm). Figures 2(a) and 2(b) show the normalised transmission spectra for the Ge-doped and the Yb-codoped fibres respectively. Figure 2(a) and 2(b) show significant short wavelength attenuation stretching to the NIR with no observable cladding mode losses around 1500 nm. Maximum loss occurs in the region 380-400 nm, depending on pulse energy, below which a sharp rise in transmission is observed. The losses above 400 nm exhibit a strong dependence on the grating writing pulse energy, with greater losses for increasing pulse energies [bottom inset of Fig. 2(a)]. The transmission minimum around 380-400 nm shifts to longer wavelengths with increasing pulse energy. For the Yb-codoped fibre, this begins at ~400 nm with a similar, small shift towards longer wavelengths for increasing pulse energies [see top inset of Fig. 2(a)]. The reduced losses observed in the transmission spectrum between ~900-1000 nm in Fig. 2(b) are due to normalisation of the results to a slightly longer Yb\(^{3+}\)-doped fibre. To ensure that the increased transmission observed below 400 nm was not due to detection limitations of the optical spectrum analyser, a narrow line-width CW frequency tripled Nd:YAG laser emitting at 355 nm was coupled into the fibre and the signal measured with a UV power meter and the OSA. Within experimental error, the transmissivity was identical to the results obtained with the white light source and OSA. It should be noted that in the transmission spectrum of pristine...
SMF28 fibre, shown in the inset to Fig. 2(b), there is a narrow weak loss band (0.18 dB/250 mm) around 370 nm, the origins of which are currently unknown.

![Fig. 2. Normalised broad-band transmission spectra for femtosecond laser inscribed PbP FBGs written in (a) Ge-doped fibre and (b) 1.18 %wt Yb\textsuperscript{3+}-, Ge-, Al-doped fibre for various pulse energies as a function of wavelength (red = 160nJ, blue = 180nJ, green = 200nJ, yellow = 220nJ, pink = 260nJ and black = 300nJ) shown in same scale. Top inset in (a) shows the transmission (T) minimum wavelength (red = Ge, black = Yb) and the bottom inset shows the respective transmission losses, both as a function of pulse energy. Inset in (b) shows the transmission spectra of pristine Ge-doped fibre (SMF 28) for the normalised L = 25 cm.](image)

**Annealing experiments**

PbP gratings written with 160 and 300 nJ pulses for both the Ge-doped and Yb-codoped fibres were annealed at 300 and 400 °C for one hour consecutively, and the transmission spectra were taken before and after each step. The normalised change in transmission, $\Delta T$, is shown in Fig. 3(a)&(b) for the Ge-doped and Yb-codoped fibres respectively. Within experimental error, for the Ge-doped fibre, a slight decrease in transmission in the NIR for the 160 nJ grating after annealing at 300°C and for the 300 nJ grating after annealing at 400 °C is observed. For the Yb-doped fibre, no significant change in the transmission across the whole spectrum at any temperature can be seen. Overall, the results indicate no evidence of colour centre bleaching. The loss in transmission in the NIR for the Ge-doped fibre is attributed to increased scattering as a result of thermally-induced stress relaxations; the change in transmission from 1200 nm to 1070 nm is attributed to single mode cut-off.
For comparison, a typical example from an annealing study of a 193 nm written Type I grating (SMF28: 300 mJ/cm²/pulse, total 15kJ/cm²), which consists of photo induced colour centres, is shown in the inset of Fig. 3(b). In this case annealing reduced the amount of short wavelength attenuation by as much as 32 dB. From Fig. 3 it can be observed that this type of signal recovery does not occur in the IR written PbP FBGs.

To examine the nature of the scattering process, HeNe light (632.5nm) was launched into the fibre core containing a grating and the scattered light was captured by a screen placed parallel to the fibre. Scattering occurred over the entire length of the grating, so a small 1.5 mm section of the grating was apertured off to show the diffraction orders with greater clarity. Figure 4 shows a photograph of the screen. The angular distribution of these diffraction orders correspond to the diffraction angles that were calculated using the Bragg equation for diffraction [16]. Identical experiments using white light also produced spectrally dependent diffraction orders, thus confirming diffractive scattering as the dominant source for the losses in the visible wavelength region.

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Fig. 4. Photo of diffraction orders of 632.8 nm light emanating from a 20th order PbP FBG onto a screen parallel to the fibre.

3. Discussion

The transmission losses for wavelengths longer than 400 nm are consistent with the expectations from a grating written with a process that exceeds the damage threshold of glass [16]. The observed recovery in the transmission for wavelengths <400 nm can be explained if the strong wavelength dependency of the longitudinal angular Mie scattering crosssection is
taken into consideration. From scattering theory, light incident on particles of the order of the wavelength and larger is predominantly back-scattered within a small solid angle, $\Omega$, whereas light incident on particles significantly smaller than the wavelength scatter less, but into a much larger $\Omega$ [20]. It is expected, therefore, that short wavelength light (i.e., $\lambda < 400$ nm) is scattered from the refractive index modulations into solid angles that are within the NA of the fibre and continue to be guided. The micrographs in Fig. 1 indicate that the maximum diameter of the tubular refractive index modulations is, $\varnothing \sim 1.8 \mu m$, which is comparable to the relevant wavelengths.

The wavelength dependency of the Mie scattering cross-section within an optical fibre core was simulated using the ScatLab dedicated Mie-scattering software, which largely relies on methods and approximations described in [20]. To a first approximation the cylindrical regions formed by irradiation were described as spheres of the same diameter. The longitudinal angular scattering cross-section of a single spherical scatterer was normalised to the modal diameter of the fibre ($w = 8.6 \mu m$ FWHM). In order to estimate the index change in practice, we wrote a second order grating using identical methods as those described above. Assuming a moderate index change for a mid-range energy (220nJ) written second order grating in SMF28, the refractive index modulation ($\Delta n_{\text{mod}}$) was estimated using coupled mode theory with a square step index profile. The calculated value was $\Delta n_{\text{mod}} \approx 0.01$ using $\Delta n_{\text{mod}} = \tanh^{-1}(R_0)\sqrt{\eta L \pi}$, where the reflectivity, $R = 17$ dB, the overlap integral, $\eta \approx 0.22$, the Bragg wavelength, $\lambda_B = 1580$ nm and grating length $L = 21.6$ mm. The critical angle for total internal reflection of the core of the fibre $\varphi_{\text{crit}} = 4.8^\circ$ (SMF28: $\Delta n_{\text{core-clad}} = 0.36\%$, $n_{\text{eff}} @ 1300$ nm = 1.4677, $\varphi_{\text{crit}} = 90-\sin^{-1}(n_{\text{clad}}/n_{\text{core}})$). The results are shown in Fig. 5. Those in black represent the normalised transmission of unscattered light whilst the results in red show the sum of the unscattered light and the scattered light with $\alpha < \varphi_{\text{crit}}$ (guided by the NA of the fibre). The characteristic spectral shape of the latter results is in qualitative agreement with the experimental results and the minimum transmission loss across 4 700 periods at the scattering maximum of $\sim 0.0017$ dB/grating (not considering resonances) would be $\sim 8$ dB, which is in quantitative agreement with measured results. It also stands to reason that the higher NA of the Yb$^{3+}$-codoped fibre will have a larger $\varphi_{\text{crit}}$, thus resulting in a shift in the transmission minimum to longer wavelengths, which is observed in Fig. 2. The limitation in our single sphere-based simulation means that properties such as multimode propagation, multiple reflections within the higher order Bragg grating, and polarisation sensitive scattering from the actual cylindrical shaped scatterers will change some of the profile features, but despite these limitations, the qualitative spectral features observed overall will remain the same.

The results of the transmission measurements in Fig. 2 show that the Yb-codoped fibre has significantly more induced attenuation than the Ge-doped fibre; however, Bragg gratings in the Yb-codoped fibre have been measured to be stronger, so the losses are similar for a given strength Bragg grating.
Our simulations indicate that the diffractive losses can be reduced significantly, perhaps by as much as three orders of magnitude, by producing larger and transversely flatter gratings. This result concurs with standard grating theory [17]. The use of an astigmatic lens with a lower NA in the transverse direction compared with the longitudinal direction [11] may facilitate the required grating shape; however, the femtosecond laser will need to produce greater pulse energy. If the current focusing geometry is retained to write FBGs for fibre lasers, issues such as core pumping need consideration since the pump light will be scattered substantially [19].

4. Conclusion
We have shown that PbP gratings inscribed with 800 nm femtosecond laser pulses in the Type-II regime exhibit strong and permanent attenuation at short wavelengths. We attribute the losses to diffractive scattering because photo-induced colour centre formation was not a significant feature in this type of grating. The transmission for wavelengths longer than 400 nm showed strong similarities with previous reports of UV written Type II damage gratings, and the femtosecond-written grating formation process therefore falls under the same classification. The losses may be reduced by controlling the size and morphology of the gratings with respect to the wavelength of operation. The transmission rise we measure at \( \lambda < 400 \) nm relates to scattering into a solid angle within the critical angle for propagation. Overall, the periodic structures analysed in this investigation give rise to large scattering losses at short wavelengths because of the large number of interfaces present.