Femtosecond laser writing of fibre Bragg gratings in large diameter air-clad optical fibre

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Fibre Bragg gratings were written in large diameter (~300-400 μm) air-clad optical fibre using an amplified Ti:Sapphire femtosecond laser (800 nm, 100 fs, 0.3 μJ/pulse) with the point-by-point method. Utilising multiphoton absorption, we induced modifications in the core of the air-clad fibre. By focusing the femtosecond laser close to the diffraction limit with a 20x air immersion microscope objective lens, the glass modification region is of the order of 1 μm in the fibre, which has a 5 μm core diameter. A technique to avoid the scattering effect of the large air-silica index contrast, on the femtosecond radiation, was implemented. Grating rejection strengths of 20 dB were achieved with an accompanying insertion loss of 3-4 dB at 1085 nm.

Introduction

Construction of narrow linewidth, high power fibre lasers generally requires replacement of external bulk mirrors with narrow bandwidth fibre Bragg gratings (FBGs). Ideally, the FBGs would be written directly into the active material; however, limitations in the UV photosensitivity of the active material restrict this approach using standard grating writing techniques. Therefore, a more common method is to attach, via fusion splicing, the FBGs contained in photosensitive optical fibre where the manufacturing is less complicated. However, fusion splicing can introduce fragility, hot spots at the splice, mode mismatch between photosensitive and active fibres, and temporal photodarkening of the photosensitive optical fibres. Recently we demonstrated FBGs written in the active core of large diameter air-clad Yb3+ doped fibre for high power lasers. Sufficient germanium defect centres were present to enable single UV photon absorption. Unfortunately, the inclusion of germanium is not always desirable in rare earth doped fibres particularly co-doped fibres such as Er3+/Yb3+.

Materials that have single photon absorption outside normal laser wavelengths, for example silica glass, require the use of multiphoton absorption to initiate material modification. The intensity required for material modification depends on the wavelength used. The volume of material affected is related to the intensity and the pulse duration. Exciplex and excimer UV lasers, operating on the nanosecond time scale, modify volume dimensions larger than the beam dimensions as the local relaxation time is shorter than the pulse duration causing thermal energy to spread through the material. Alternatively, femtosecond pulse durations do not cause this effect as the time is commensurate with the excitation time. When using a near infrared (NIR) femtosecond laser, multiphoton absorption can lead to the modification occurring with dimensions less than the wavelength or diffraction limit. In practice focusing with NIR light (e.g. 800 nm) results in material modification dimensions ~500-600 nm. Different wavelengths have been used for multiphoton Bragg grating writing, including two UV photons (193 nm) or five to six NIR (800 nm).

There are two predominant techniques used for the fabrication of FBGs: (a) direct writing with a transmission phase mask, or (b) point-by-point (PbP) writing. The direct method uses the interference pattern created by the phase mask to induce material modification and create all grating fringes simultaneously. The PbP method uses a high intensity, short laser pulse to modify the material one grating fringe at a time. Reli-
ence on interference for the direct method means the spatial coherence of the writing laser influences the quality of interference, and hence the quality of the material modification. Low spatial coherence sources, such as exciplex ArF UV (coherence length ~200 μm) lasers require the fibre core to be positioned in close proximity to the phase mask for maximum fringe visibility. Increased fibre dimensions results in a reduction in fringe contrast as the core and phase mask separation distance increases. The PbP method does not require the stringent coherence issues related to the direct writing method; however, it does require a high intensity, small spot size beam. Focusing the writing laser is required to: (a) increase the intensity to induce material modification; and (b) reduce the dimensions of the laser for single fringe fabrication. Limitations of the fringe size stem from the minimum dimensions obtainable with the focused spot leading to second or third order FBGs when writing gratings with Bragg wavelengths of 800–1600 nm.

The obstacle for air-clad fibres is scattering and the refraction of the writing laser from the air cladding, reducing the effectiveness of the multiphoton absorption. Previous work\(^3\) was not significantly affected by these issues since the writing method was single photon (no intensity threshold) and the grating growth was cumulative. An intensity threshold and the effect of scattering, both reduce the effective intensity for multiphoton absorption, which requires an even greater intensity, not usually possible for high exponent processes (5–6 photons). Filling the air cladding with a material with a similar index to silica at the wavelength of interest can reduce this issue, as demonstrated by Sorenson et al.\(^4\) who reduced the scattering from air holes in a photonic crystal fibre through the introduction of organic liquids. A similar approach is used for this report to not only reduce the scattering from the air cladding, but also allow visual confirmation that the focused laser spot is interacting with the core of the fibre. This resulted in gratings being successfully written directly into the active core of the fibre with a femtosecond laser and PbP writing system.

**Air-clad fibre preparation**

Fabrication of the air-clad fibre was done using the stack and draw technique. A modified chemical vapour deposition (MCVD) preform was encircled by a single layer of capillary tubes and stacked inside a containment tube. The air-clad preform was then drawn into fibre with particular attention to prevent hole collapse whilst minimising the thickness of the silica bridges, which has previously been reduced down to -100 nm.\(^5\) Figure 1 shows an SEM image of the fibre cross section, which has an outer diameter of 270 μm. The active core contained ~3 wt% Yb\(^{3+}\), ~15 wt% Al and ~5 wt% Ge and had an NA of 0.18.

Decreasing the index contrast of the air holes was achieved by inserting an index matching liquid (Index Matching Fluid, York Technology Ltd, \(n_\text{f} = 1.4587\)) into the holes. The viscosity of the liquid meant that pressure was required to force it into the holes. To accomplish this, the fibre was inserted inside a needle, super glued to eliminate leakage and the liquid pressurised with a syringe. To permit a number of FBGs to be written in the fibre, the entire fibre length was filled with liquid. Normally the FBG would be situated at the end or ends of the fibre and the liquid would only be required a short distance inside the ends of the fibre, allowing easier removal of the liquid by heating under vacuum.

To allow real time characterisation of the FBG writing, pigtail fibres were fusion spliced onto the air-clad fibre. Custom fusion conditions were required due to the large diameter difference between the two fibres (125 μm for pigtails and -270 μm for air-clad). Rather than fusing the two fibres together after they momentarily melt, a low energy arc was used to soften the fibres and “tack” them together. This resulted in weak splices that required great care in handling. The index matched liquid in the holes further complicated the splicing. Core alignment was performed using a helium–neon laser and visually monitoring the transmitted intensity of the near field image to ensure core coupling rather than cladding coupling. The fusion process did result in minor core misalignments that decreased the quality of the “tack”.

**Fibre Bragg grating writing**

The PbP fringes were written with a Hurricane Ti:Sapphire femtosecond laser operating at 800 nm (100 fs, 1 kHz). To increase the intensity to \(2 \times 10^{14}\) W cm\(^{-2}\) (pulse energy 0.21 μJ) and reduce the beam dimensions, it was focused with a 20x oil immersion microscope objective creating a spot size ~1 μm. Positioning the fibre was achieved using a computer controlled 3-axis translation stage system. This permitted 3-dimen-
sional positioning of the fibre by defining the start and stop positions with μm precision. The second order FBG had a total length of 5 mm and a period of 746 nm producing a Bragg wavelength, \( \lambda_B = 1085 \) nm and -16 dB rejection measured on an optical spectrum analyser (resolution=0.01 nm). Feature sizes less than the beam size (~1 μm) are created because of the intensity threshold condition imposed by the 5-photon absorption process. The effective index of the fundamental mode was determined to be 1.4555 from the transmission spectra shown in Figure 2. The transmission dip at the shorter wavelength of 1083 nm (Figure 2) is due to a higher order mode.

The intensities used to write the FBGs in this report cause the grating fringes to form from permanent damage. The damage regions form filament-like structures that are of the order of 0.6 μm wide and 5 μm in length. Figure 3 shows images of the filament damage regions produced in the silica cladding by single laser pulses. The dimensions indicate that scattering should be expected. Comparing these dimensions to the size of the active core, the filament would extend across the core in the long direction but only cover ~1/5 of the core in the short direction. This would indicate that the grating would be birefringent, which can result in preferential lasing of the polarised lasing modes, often beneficial in fibre lasers.

Figure 3. Optical micrograph of typical filament damage regions in the bulk silica cladding from the femtosecond laser (horizontal lines are artefacts due to the air-clad holes)

Short wavelength attenuation

Analysis of the grating after writing using a helium–neon laser for core alignment, revealed visible scattering at the FBG region. Figure 4 shows the transmission spectra of the fibre with and without an FBG normalised by the transmission through SMF28. Short wavelength (<900 nm) loss is observable in the fibre with the FBG (Figure 4). The shape of the short wavelength attenuation bears close resemblance to that observed in UV photodarkened germanosilicate fibre, which is associated with defect generation. Poor fitting with Gaussian and Lorentzian expressions, which characterise the simple electronic transitions associated with most defects, of the short wavelength region of the spectra (400–800 nm) indicates that the attenuation is not related to defect absorption.

To verify that the attenuation originates from scattering, a curve proportional to \( \lambda^4 \) was fitted to the FBG broad wavelength transmission spectrum. The variation from the \( \lambda^4 \) fit is indicative of scattering from the damage region interface as well as possible inhomogeneities within these regions commensurate in size with those between Rayleigh and Mie dimensions. Both spectra were adjusted to remove a 3dB coupling loss. Evidently there is an additional 3–4 dB insertion loss at the 1085 nm Bragg wavelength. This could lead to limitations for devices using this structure. It is anticipated that the insertion loss can be reduced by further optimising the fringe dimensions and the size of the irradiated regions. The large attenuation between 805 nm and 1070 nm is attributed to absorption by the ytterbium ions.

Conclusion

A femtosecond laser in conjunction with the point-by-point writing method was used to write fibre Bragg gratings in air-clad optical fibre. Low distortion of the
800 nm writing laser and visual verification that the laser was interacting with the core was achieved by inserting index matching liquid into the holes, removing the large air–silica index contrast. High intensity femtosecond light is advantageous for writing FBGs because of the speed of fabrication. The PbP method enables any desired Bragg wavelength to be chosen. A point of interest is the observed short wavelength attenuation, associated with the damaged regions defining the grating fringes, which may interfere with the laser wavelengths. It is expected the short wavelength attenuation can be reduced with further refinement in the irradiation intensity, which will cause the attenuation to have an insignificant effect on the performance of the laser.

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References