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Gratings in Large Diameter Air-clad Optical Fibre using a Femtosecond Laser

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Abstract: Fibre Bragg gratings were written in large diameter (~300µm) air-clad optical fibre using an amplified femtosecond Ti:sapphire laser with a point-by-point method.

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1. Introduction

Femtosecond laser grating writing is one approach to writing high temperature stable gratings for laser applications that involve large laser intensities. To fabricate FBGs using a femtosecond laser, two main techniques exist: (a) direct writing with a transmission phase mask, or (b) point-by-point (PbP). The phase mask method [1], uses the interference pattern created by the phase mask to induce material modification. The PbP method [2], uses a spherically focused high intensity, short laser pulse to modify the material. Reliance on interference in the phase mask method means the spatial coherence of the writing laser greatly influences the quality of interference, and hence the quality of the material modification. In the PbP method the laser beam is focused into the fibre core where it becomes possible to create sub-wavelength sized features due to the multiphoton absorption of light into the dielectric medium. Bonds are broken, analogous to so-called damage gratings [3], but the changes are localised by rapid cooling of the excitation. Using an IR femtosecond laser (λ_{Laser} = 800nm) the diffraction limit using such a laser, despite the high exponent absorption, means that for gratings with $\lambda_{Bragg} \sim 1$ µm it is necessary to fabricate second and third order gratings.

The difficulty when using a femtosecond laser for writing PbP gratings in air-clad fibres is the scattering and refraction affects that the air cladding induces on the writing laser light. These effects reduce the effectiveness of the multiphoton absorption process that leads to refractive index modification. Previous work using cylindrically focused UV laser beams and a phase mask [4] was not significantly affected by these issues since the writing method used a single photon process (no intensity threshold) and grating growth was cumulative. In the PbP method the requirements to exceed an intensity threshold and the effect of scattering both reduce the effective intensity for multiphoton absorption which therefore 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 the grating writing laser can reduce this issue as has been demonstrated by Sørenson *et al* to reduce the scattering of air holes in a photonic crystal fibre through the introduction of organic liquids [5].

2. Air-clad Fibre Preparation

Fabrication of the air-clad fibre was done using the stack and draw technique. An initial MCVD preform was stacked with surrounding capillary tubes 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 to <1µm [6]. Figure 1 displays a SEM image of the fibre cross section with an outer diameter of 270 µm. The NA = 0.18 and the active core contains ~3 wt% Yb^{3+}, ~15 wt% Al and ~5 wt% Ge.

Decreasing the index contrast of the air holes was achieved by inserting index matching liquid (N_D=1.4587) into the holes. The fibre was inserted inside a needle on the end of a syringe and super glued to eliminate leakage when the liquid is pumped in. Sufficient pressure was necessary to overcome the viscosity of the fluid. To permit a number of FBGs to be written in the fibre, the entire fibre length was filled with liquid. In practice, for laser applications, the FBG would be inscribed at the end or ends of the fibre. Thus the liquid would only be required to be inserted a short distance making it easier to remove with heat under vacuum.

To allow real time characterisation of the FBG writing, 125 µm diameter pigtail fibres were custom fusion spliced onto the ~270 µm diameter air-clad fibre. Core alignment and coupling was performed using a helium-neon laser and monitoring the near field image. A complication that required more stringent fusing conditions was the presence of the index matching liquid within the holes.

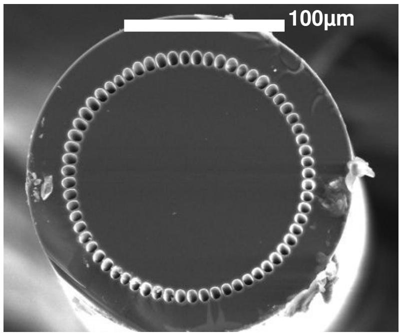

Figure 1. SEM image of the air-clad fibres cross section.

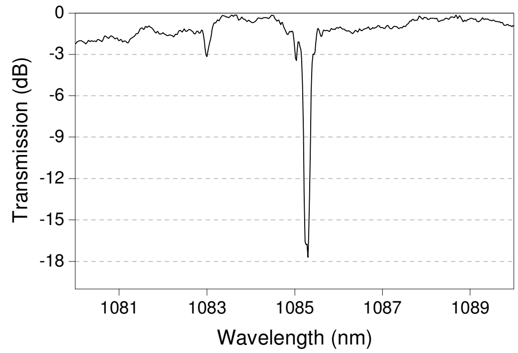

Figure 2. Transmission spectrum of the 2nd order FBG.

3. Fibre Bragg Grating Writing

The grating fringes were written with a Hurricane Ti:Sapphire femtosecond laser operating at 800 nm (120 fs, 1 kHz). Grating writing focal intensity was calculated to be ~$2\text{x}10^{14}$ W.cm^{-2} (pulse energy 0.21 µJ) and the beam was focused into the core of the fibre with a 20X oil-immersion microscope objective creating a spot size ~1 µm at the $1/e^2$ intensity. Positioning the fibre was done using a computer controlled 3-axis stage system. This permitted 3-dimensional positioning of the fibre by defining the start and stop positions with micrometer precision. The grating was 5 mm in length and characterised with an optical spectrum analyser (res. = 0.01 nm). From the transmission spectrum (Figure 2) the grating had a Bragg wavelength at $\lambda_B = 1085$ nm ($\Delta\lambda = 0.22$ nm) and a rejection ~16 dB. Feature sizes less than the beam size, ~1 µm, are created presumably because the 5-photon absorption process inherently localises the intensity. The effective index of the fundamental mode was determined to be 1.4555.

For the intensities used in this report, the grating periods are formed from permanent material modification, arguably related to the index change associated with damage gratings. These damage regions are formed by filament-like structures [7], which are on the order of 0.6 µm wide and 5 µm in length. Figure 3 shows preliminary images of the filamentary regions. Comparing these dimensions to that 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 have birefringence, often beneficial in fibre lasers. In Figure 2 the dip to the shorter wavelength side of the main Bragg resonance is consistent with a higher order mode.

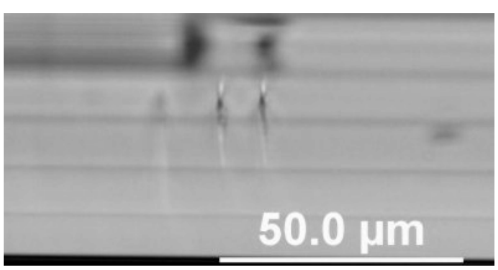

Figure 3. Optical micrograph of typical filament damage regions from the femtosecond laser. Horizontal lines are effects from the air-clad holes.

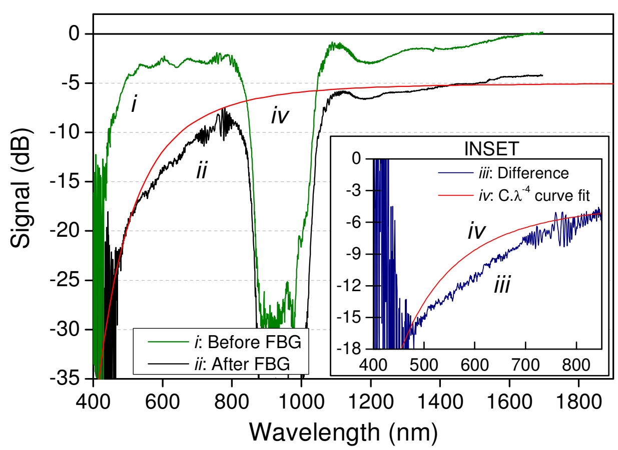

Figure 4. Transmission spectra before and after writing FBG showing short wavelength attenuation in the visible and NIR. Background transmission has been subtracted. The large attenuation between 805 and 1070nm is Yb^{3+} absorption. INSET: Transmission loss of fibre with FBG after subtracting fibre without FBG.

As the polymer coating has low attenuation at 800 nm, gratings were also written through the coating. This is advantageous as the removal process of the polymer, unless carried out using sophisticated methods, will degrade the surface of the fibre. However, the working distance of the present objective lens limits fibre dimensions and can exclude large diameter fibres. This issue is also relevant when using exciplex or excimer UV lasers, inherently having short coherence length, to write gratings with the phase mask method.

4. Short Wavelength Attenuation

Post writing analysis displayed visible scattering at the FBG region when using a helium-neon laser to align the cores. Short wavelength loss extending into the region where laser operation is desired is displayed in Figure 4. The short wavelength attenuation is similar to photodarkening [8], associated with defect generation in doped fibres. Straightforward electronic defect absorption seems unlikely since it was not possible to fit Gaussian or Lorentzian peaks to the spectra without great difficulty. Rather, a λ^{-4} fit indicates Rayleigh scattering is a contributing source.

The variation from the λ^{-4} fit is indicative of scattering from the grating region interface as well as possible inhomogeneities within these regions commensurate with the Rayleigh dimensions. Both spectra were adjusted to remove a 3dB butt coupling loss. There is a 3-4dB insertion loss for the 1085nm FBG in the near IR, although we believe this can be reduced significantly by creating weaker local index change and more grating periods.

5. Conclusion

A femtosecond laser in conjunction with the point-by-point method was used to write fibre Bragg gratings in air-clad optical fibre with a diameter ~300 μm. Low distortion and scattering of the writing laser 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 since it is a rapid method which exploits the structural change associated with bond breaking the glass through multiphoton excitation in to the band edge. The PbP method enables any desired Bragg wavelength to be chosen and depending on the dimensions of the fibre and the working distance of the objective, writing through the polymer coating. A point of interest is the observed short wavelength attenuation which stretches into the region where laser operation is desired.

6. Acknowledgement

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7. References

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