Fibre Bragg Gratings Written in Pure Silica Photonic Crystal Fibres with Ultraviolet Femtosecond Laser Pulses

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Abstract

We report the fabrication of fibre Bragg gratings in pure silica photonic crystal fibres using UV femtosecond laser radiation at 267 nm. Gratings have been fabricated with up to 10 dB transmission loss and an average index change of $\Delta n > 4\times10^{-4}$.

Introduction:

Photonic crystal fibres (PCFs), optical fibres with a periodic array of air holes in the cladding, comprise an exciting new class of waveguide with unique modal, dispersive and nonlinear properties. Guidance in these fibres is mediated by the index contrast between the silica core and low effective index holey cladding. They have been used as a platform for demonstrating new optical propagation phenomena and for creating tunable fibre devices. The ability to write fibre Bragg gratings (FBGs) in PCFs immediately suggests a broad range of new research to be conducted in these fibres. FBGs can be used as a diagnostic tool to experimentally probe the modal properties of a fibre or to locally modify the waveguide dispersion. They may also be used in the creation of novel fibre devices, where the PCF geometry may provide enhanced functionality over conventional step index fibres.

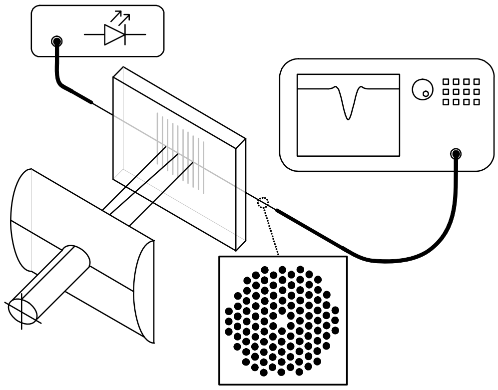

Fig.1. Experimental setup. The inset is a schematic diagram of the transverse structure of the PCF fibre.

One of the strengths of all-silica PCFs is that they are single material fibres, which makes the manufacturing process somewhat simpler. Current FBG technology as developed in step index fibres over the past 25 years relies on photosensitivity of core dopants (usually Ge). This photosensitivity can be enhanced by hydrogen loading the fibre. FBGs in doped fibres can be written via a single photon process at 242-248 nm using KrF excimer (248 nm) or frequency-doubled argon-ion (244 nm) lasers. Undoped silica is not photosensitive at 244 nm, so alternate grating writing processes are required for PCFs. The index of silica can be modified using high-power nanosecond pulsed ArF and F_2 lasers at 193 nm and 156 nm [1,2] where exposure at 193 nm excites a two-photon absorption (TPA) process. Here the photosensitivity is caused by both defect formation and volume compaction [3]. Hydrogen loading does not appear to be of any benefit in enhancing the volume compaction process [2]. Recently FBGs have been written in pure-silica core fibres with femtosecond pulses at 267 nm [4]. In that report, hydrogen loading did enhance the photosensitivity, possibly by modification of the band edge of the silica. However, there is evidence of a defect-based photosensitivity pathway after hydrogenation in bulk silica [5] and this may point to a photorefractive component to the photosensitivity in undoped silica when excited at 267 nm.

To our knowledge there are only two previous reports of FBGs fabricated in PCFs. Eggleton *et al.* [6] wrote Bragg and long period gratings in a special PCF fabricated with a Ge-doped core, using a pulsed laser at 242 nm. More recently Groothoff *et al.* [7] wrote FBGs in all-silica PCFs using TPA of nanosecond excimer laser pulses at 193 nm, where index changes of up to 2×10^{-4} were achieved. In this paper we report the first demonstration of FBG inscription in an all-silica PCF using a 267 nm femtosecond laser. Our gratings are written in a hydrogenated microstructured fibre under moderate fluences using a near-field phase mask technique. We describe the spectral and annealing properties of our samples.

Experiment:

Figure 1 schematically shows our writing scheme, based on a near-field phase mask method. 120 fs pulses at 267 nm are generated at a repetition rate of 1 kHz by frequency tripling the output from a Ti:sapphire regenerative amplifier. The s-polarized beam has a diameter of 4 mm and is focused into a line along the fibre through a cylindrical lens of focal length 104 mm. The fibre is placed in close proximity (60 μm behind) a phase mask with a pitch of 1061.89 nm. The phase mask we use is designed for 248 nm and less than 1 % of the beam is diffracted into the 0th order. The average power in each of the ±1st orders is 8 mW. The peak intensity at focus is approximately 2.5×10^{11} W/cm^2, not sufficient to damage the phase mask; for this reason we do not believe we are in the regime of type II damage gratings as reported with 800 nm femtosecond writing pulses [8].

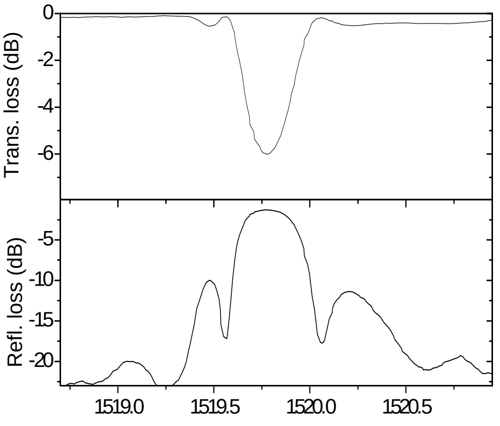

Fig.2. transmission spectrum (top) and reflection spectrum (bottom) of FBG written with femtosecond UV laser.

The photonic crystal fibres (PCF) used in this experiment are from Crystal Fibre (SC-5.0-1040). It has a core diameter of 4.9μm surrounded by 6 rings of cladding holes with a pitch of 3.2μm, hole size of 1.67μm. The diameter of holey region is 35μm and the outer cladding diameter is 125μm. Such PCFs are spliced to mode-matching high NA fibre pigtails, then hydrogenated at 18 MPa for one week prior to the grating inscription. The transmission spectrum is monitored during the inscription process. When UV light is incident on the PCF fibre, a complex diffraction pattern appears caused by the cladding holey region. We align the beam onto the core of the PCF by calculation of the mid-point of the intersection of the laser beam with the inner holey-cladding edges. This leads to some uncertainty as to overlap between the focused laser spot and the fibre core.

Figure 2 shows the transmission and reflection spectra of an FBG exposed for 60 minutes, with cumulative fluence of about 70 kJ/cm^2. This spectrum was recorded several days after the laser exposure, when the hydrogen had completely diffused out of the core. The peak amplitude is unchanged in this time. The main peak appears at a wavelength of 1519.8 nm, giving the core an effective index of 1.4312. Our modelling of this structure leads to an effective index of 1.4301, in fairly good agreement. Consistent with [7], we observe no cladding mode loss, due to the extended grating profile which prevents any coupling between the core and cladding modes. When polarized light is launched into the FBG no birefringence is observed in the grating response.

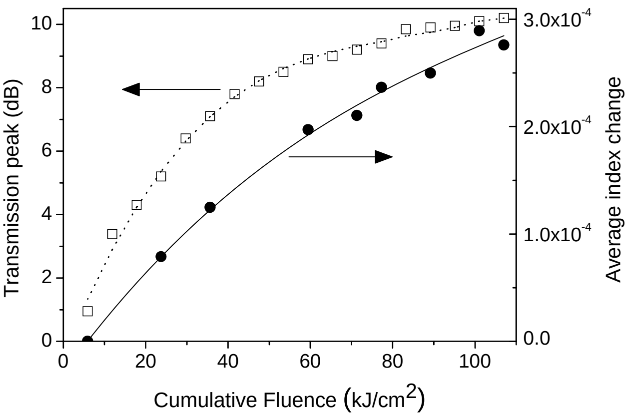

Fig.3. Grating strength increase and average index change with cumulative fluence during exposure.

The growth of a second deeper grating is monitored during the writing process. Figure 3 shows the increase in the peak transmission loss plotted against the cumulative fluence, as well as the change in the average refractive index calculated from the change in the Bragg wavelength during the writing process after the fibre was exposed for 90 minutes. The DC refractive index Δn_{eff} increases by around 4×10^{-4} during this time, while the AC component of the index change is approximately 1×10^{-4} (assuming perfect overlap between the laser focus and the fibre core). We attribute the relatively larger DC component to equipment instabilities during the long write time. The effective index during the writing process is 1.433, including the averaged index increase caused by the residual hydrogen in the core [9]. The grating growth appears to saturate at approximately 10-12 dB. This is consistent with the result in ref. [7], which may be due to a limit in the maximum index change in the compaction mechanism for photosensitivity in pure silica. However in our experiment there is an issue associated with the rate of leakage of hydrogen from the core into the air-filled holes and further experiments are underway to further test the limits in grating strength we can achieve.

We tried to write an FBG in PCF under the same exposure conditions but without hydrogen loading. In this case, after 60 minutes of exposure the grating formed had a strength of less than 0.2 dB. This is consistent with the requirement [4] for hydrogen loading in order to reach useful levels of photosensitivity in pure silica with 267 nm laser wavelengths.

A preliminary annealing study has been undertaken, to evaluate the stability of the gratings written with the femtosecond laser. We heated a grating in PCF in a controlled fashion between room temperature and 700 °C. At each setting the temperature was held constant for a period of 30 minutes prior to the grating strength being measured. We found that the refractive index monotonically decreased as a function of temperature, with a decay of 20% occurring at 400 °C. The observed decay curve differs somewhat from the results of [7] and may indicate that the grating written here has an origin related to defect formation as well as the compaction mechanism active in fused silica PCF in the 193 nm writing geometry [7].

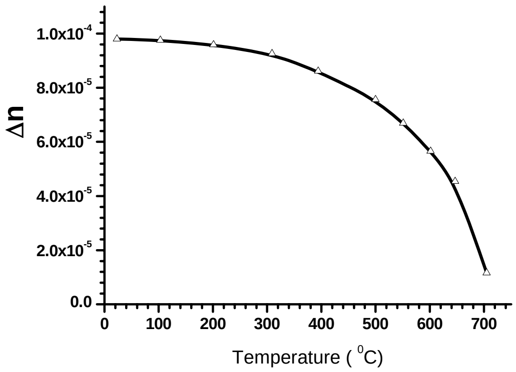

Fig.4. Refractive index change versus annealing temperature(30 minutes for each temperature)

Conclusion:

We have demonstrated the first femtosecond laser writing of FBGs in all-silica photonic crystal fibres. Writing FBGs in PCF opens up opportunities for the creation of novel fibre devices for functions such as channel dropping, tunable filters and channel monitoring. Furthermore, with grating formation in PCFs, we can envisage engineering the dispersion characteristics to offer additional flexibility over the designed PCF waveguide dispersion. Bragg grating solitons generated in such small core PCFs would open the way for a number of exciting experiments in nonlinear physics.

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