Characterisation of silicon fibre Bragg gratings in the near-infrared for strain and temperature sensing

A. Theodosiou, M. Fokine, S. Song, T. Hawkins, J. Ballato, U. J. Gibson and K. Kalli

This letter describes fibre Bragg grating inscription in crystalline silicon-core fibre using visible light femtosecond laser pulses. The femtosecond pulses at 517 nm propagate through the transparent silica glass cladding and are fully absorbed by the silicon core generating locally high temperatures and stress fields in forming the grating periods. The silicon-FBGs were characterised in reflection, calibrated for the first time as strain and temperature sensors and compared with that of FBGs inscribed in common silica fibres.

Introduction: Crystalline semiconductor fibres constitute a new class of optical fibres. Interest in semiconductor core optical fibres stems from their transparency, which can extend to the far-infrared, as well as their high optical nonlinearity, thermal conductivity, and damage threshold [1]. In previous work, the Authors demonstrated the restructuring of the crystalline semiconducting core using infrared and visible laser sources. Also reported was the first fibre Bragg grating inscription into a silicon-core fibre using a femtosecond laser [2]–[4]. Of the semiconductors realized in glass-clad optical fibre form, silicon is arguably the most important given its compatibility with current electronic chip technology. The ability to couple to optical fibres is a critical requirement for optical interconnects that can combine optical and electronic functionalities. The material differences between silica optical fibre and on-chip silicon devices limit continued advances in high-speed computing. Having silicon core fibres and demonstrating the incorporation of key optical components in said fibre is extremely important, as now two issues are being addressed, i) material differences and ii) the capability to incorporate optical filters for off-chip wavelength division multiplexing (WDM) devices.

This letter presents the characterisation of silicon-fibre Bragg grating over the temperature range from 30 ^{o}C to 55 ^{o}C and with axial strain applied. The results, in comparison with conventional silica fibre-based counterparts are shown to be quite different.

Femtosecond laser inscription: The inscription setup used for this work consists a femtosecond laser (femtoREGEN HighQ) operating at a wavelength of 517 nm with a 220 fs pulse duration, long working distance lens (Mitotoyo) x50 and an air-bearing translation stage for high precision movement [4], [5]. The silicon-fibre sample was fixed on a glass slide and mounted on the high precision stage while the laser beam was focused from above using a third mechanical stage. The pulse energies for the sample was set at 100 nJ as measured at the exit of the laser system and the repetition rate set at 5 kHz using a pulse selector.

The silicon fibre employed had a 12 μm core diameter and a glass cladding with total diameter of 125 μm. As shown previously [2] this femtosecond laser at 517 nm with pulse duration 217 fs, has a penetration depth into the silicon core of only about 0.9 μm, which is approximately 12 times smaller than the core diameter. However, for the particular laser wavelength and pulse duration, the silicon core is rapidly heated at extremely high temperatures (10^4 - 10^5) inducing large pressure fields across the core. During the inscription process, strong plasma generation in the region of the Si was observed as the laser swept across the core; this is consistent with the notion of extremely high temperatures in the regions of high fluence. The laser beam was swept transversely across the core at a velocity of 50 μm/s, resulting in a mean exposure of 100 pulses/μm. The fibre was displaced by a controlled step and this motion was repeated to define a periodic modulation along the fibre length. This resulted in the fabrication of a Bragg grating, which was probed in longitudinal reflection through the silicon core.

The periodic modulation of the core region occurred every ~1.82 μm, corresponding to an 8th order grating, where it was determined that a silicon refractive index of 3.4408 would result in a grating close to a wavelength of 1565 nm. From the recovered spectra, the refractive index of the guided modes was estimated to be ~3.44, which is close to the expected value. The refractive index would decrease slightly due to the overlap between the grating mode and the core/cladding. Due to the large core diameter and launch conditions, it is possible to excite a number of modes. That said, it also is possible to excite the fundamental as the primary sampled mode. Figure 1 provides the spectrum for a 2000-period FBG with a target reflectivity at 1565 nm where the reflected line-width is ~0.9 nm. In addition to the expected grating reflectivity, the effects of significant stress resulting from the grating fabrication are observed as are quasi-periodic stress relief in the glass cladding and variations in the stress-induced birefringence.

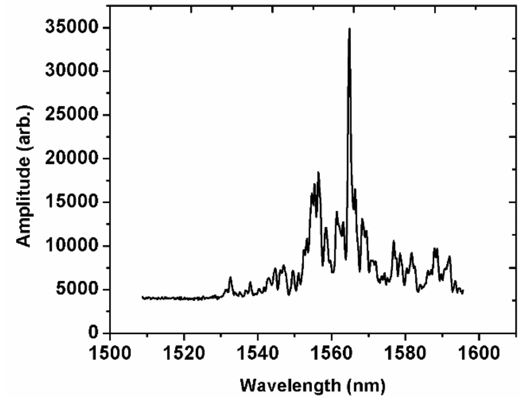

Fig. 1 *Reflection spectrum of the fibre Bragg grating inscribed in a silicon core fibre.*

Strain and Temperature Characterisation: The silicon grating was connected to an SMF-28 pigtail using the butt-coupling method and UV-glue. This was done to establish a stable coupling between the fibres and to be compatible with the optical equipment. A broadband light source (Thorlabs ASE730) with operating wavelength range from 1520 – 1600 nm was connected to a circulator and the grating was illuminated. The reflection spectrum of the grating was then recovered using a commercial Bragg spectrometer (IBSEN IMON HS).

In order to measure the strain response of the silicon-FBG, the grating was secured using UV glue between two manual stages and steps from ~900 με to ~2800 με axial strain were applied along the grating. The grating response to the axial strain was found to be ~0.23 pm/με, as is shown in Fig. 2. Compared with silica-FBG counter parts the sensitivity is reduced by a factor of 3.1.

According to Lorentz-Lorenz equation, the elasto-optic coefficients of silica and silicon are 0.007873 and 0.764132, respectively based on,

$$P_{12} = \frac{(n^2-1)(n^2-2)}{3n^4}, \quad (1)$$

where n is the refractive index of core (at a wavelength of ??). A simplified form describing the Bragg wavelength due to the strain is given below [6],

$$\Delta\lambda(\varepsilon) = (1-p_{12})\varepsilon\ , \quad (2)$$

where the p_{12} is the transverse photo-elastic coefficient and ε is the applied strain. Solving Eqn. (2) using the proper material coefficients, the corresponding wavelength shift for the silica and silicon FBGs for 1 mε, is 0.992127 and 0.235868, respectively, a factor of 4 difference, which is close to the experimental results.

In order to measure the temperature response of the grating, the sample was placed inside a climate chamber. The wavelength shift of the Bragg grating with temperature is shown in Fig. 3, and the temperature response was found to be 76.64 pm/^{o}C. Compared to a conventional glass fibre [7], the silicon grating is approximately ~7.6 times more sensitive.

The thermo-optic and thermal expansion coefficients of silica fibre at 30 ^{o}C are ~8 x 10^{-3} [8] and 0.5 x 10^{-6} [9], respectively, whereas, for silicon, the corresponding values are 90 x10^{-3} [10] and 3 x 10^{-6} [11]. The wavelength shift of the Bragg grating when subjected to temperature

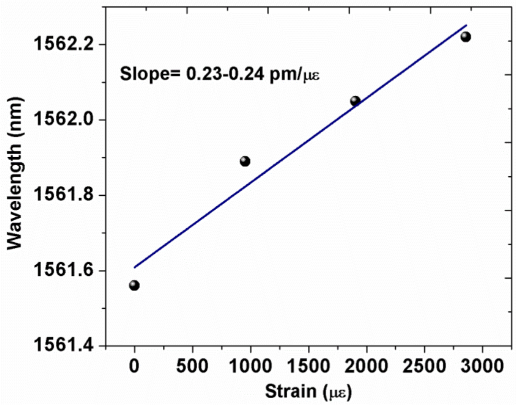

Fig. 2 *Wavelength shift of the Bragg grating inscribed in a silicon-core fibre with axial strain applied to the fibre.*

excursions is given by,

$$\Delta\lambda = (a_n + a_\Lambda)\Delta T \ , \quad (3)$$

where a_n is the thermo-optic coefficient, a_Λ is the thermal expansion coefficient, and ΔT is the temperature difference. Solving Eqn. (3) yields a temperature sensitivity for the silicon grating that is ~11 times higher than for a silica fibre, close to the measured results. Some differences may be expected for the following reasons. Firstly, the thermal expansion of the cladding (silica) glass is 6 times less than for silicon. However, this effect should be insignificant to these measurements since the thermo-optic coefficient dominates. Secondly, the literature values of the thermo-optic coefficients in the two materials (Si core and silica clad) assumes that the light traverses the pure materials. However, in practice the light at 1550 nm experiences both the core and cladding materials, which would act to reduce the thermo-optic response of the fibre structure.

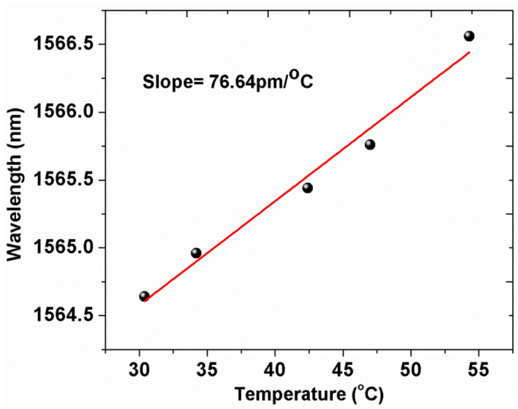

Fig. 3 *The wavelength shift of the silicon-core Bragg grating for temperature variation range 30 ^{0}C to 55 ^{0}C.*

Conclusion: Demonstrated here was the stress and thermal response of first FBG in silicon-core fibres written by stressing the silicon fibre core, using a visible femtosecond laser. The period of the stress modification zones was accurately controlled utilising an 8th-order fibre Bragg grating operating at 1565 nm. The strain sensitivity of the silicon grating was found to be ~4 times less than for silica fibres, whereas the temperature sensitivity was ~11 times higher. The experimental results were evaluated by comparing the thermal (thermo-optic and thermal expansion) and elasto-optic coefficients of the core / clad phases.

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