Point-by-Point Femtosecond Laser Inscription of Bragg Gratings In High NA (>0.4) Germania-Doped Optical Fibre

A. DONKO, M. NUÑEZ-VELAZQUEZ, P. BARUA, J. SAHU, M. BERESNA, & G. BRAMBILLA
Optoelectronics research centre, University of Southampton, Highfield Campus, Southampton, SO17 1BJ, UK
**a.l.donko@soton.ac.uk*

Abstract: Using point-by-point femtosecond laser inscription, a fibre Bragg grating (FBG) was written in a high NA germania-doped fibre. Thermal tests demonstrated that the FBG could withstand temperatures up to 800°C without significant effects on reflectivity.
OCIS codes: (060.3735) Fibre Bragg gratings; (320.2250) Femtosecond phenomena

1. Introduction

High concentration germania-doped fibres are of great interest due to their highly desirable non-linear properties [1]. However, taking advantage of these properties has been limited. Inscribing FBGs using classical UV based techniques into high concentration germanium fibres has been problematic due to their complex photosensitivity profile [2]. Several physical processes underpin the photosensitive phenomena and their dynamics can be extremely difficult to manage. Hydrogenation is often employed to enhance a material's photosensitivity at the expense of time and resources. Medvedkov et. al detailed the complex photosensitive profiles of pristine and hydrogenated 75% mol GeO_2 fibres when inscribing Bragg gratings [3].

The revolutionary discovery of femtosecond pulse interactions within transparent bulk glass by Davis et. al offered a new fabrication method for FBGs [4]. Fundamentally, multiphoton absorption and avalanche ionisation causes densification within the material. These processes hold very weak wavelength dependence and thus allow flexibility in the selection of writing wavelength. Infrared wavelengths transparent to the polymer coating can be employed [5]; this means coating removal is not necessary unlike in UV based techniques. Thus, by utilising different physical mechanisms, femtosecond writing does not encounter the same issues as photosensitive techniques allowing simpler fabrication of FBGs in high concentration germanium fibres.

This is the first display of good spectral quality FBGs inscribed within high NA (>0.4) germania-doped fibres. The gratings were inscribed using an IR femtosecond laser employing the point-by-point (PbP) technique. After fabrication, the gratings thermal stability was tested.

2. Experimental Methodology

A standard PbP femtosecond writing set up was assembled (figure 1). A Yb:KGW (Ytterbium-doped Potassium Gadolinium Tungstate) based femtosecond laser (PHAROS, Light Conversion Limited) for grating inscription. The laser had a repetition rate of 1 kHz and a pulse energy of 1.1 µJ. The laser emitted 1030 nm radiation, with a pulse duration of 206±5 fs. The beam was guided through a diffraction slit prior to focusing through a 0.65 NA objective lens. A dichroic mirror and CCD camera was placed directly above the objective enabling a computer to image the writing process. The fibre was secured to a computer controlled translation stage of precision 1±0.1 nm (Aerotech). Gratings were written by traversing the fibre beneath the objective and inscribing each refractive index modification individually. The FBG pitch was controlled by the synchronisation of fibre position with a pulse picker within the femtosecond system using a controller (Aerotech). The transmission spectrum of the gratings was monitored in-situ using a super continuum source (Fianium) and an optical spectrum analyser (OSA, Yokogawa). A 3 mm 3rd order grating was inscribed at a speed of 0.1 mm/s. After inscription of the grating its thermal stability was tested. Thermal tests were completed by removing the polymer coating and placing the grating within a 400mm tubular furnace. Temperatures were validated by an external thermocouple. Transmission spectra of the grating after isochronal periods were recorded using the supercontinuum source and OSA. The fibre was fabricated in house from an MCVD preform. Acrylate DSM-314 cured by photo-polymerisation coated the fibre. A multi-wavelength optical fibre analyser (IFA-100) was used to measure the fibre refractive index profile (figure 2). The core and cladding had diameters of 3.72 µm and 106 µm respectively.

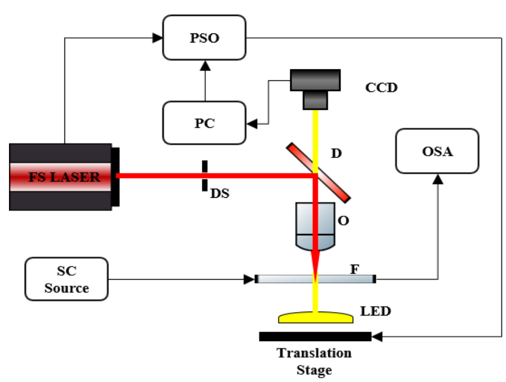

Figure 1 – Schematic diagram of femtosecond writing set up. **O**-Objective, **D**-Dichroic mirror, **F**-Fibre, **DS**-Diffraction slit, **PSO**-Synchronisation Controller, **LED** – Light Emitting Diode.

3. Experimental Results

A single grating was inscribed at a Bragg wavelength λ_B ~ 1550 nm. At 1550 nm, the fibre has a normalised frequency V = 3.05. This indicates the fibre supports four modes: HE_{11}, TE_{01}, TM_{01} and HE_{21}. In the subsequent transmission spectra (figure 3) three transmission troughs are present, confirming the multimode nature of the fibre. The second and third reflections occur at λ_B ~ 1534 nm and 1536 nm with extinction ratios of 17.5 and 6 dB respectively. The main Bragg resonance had an extinction ratio of 25 dB. The inscription process induced an overall loss of 2.5 dB. The variance in power distribution between modes can be partialy attributed to the difference in core radius between the SMF patch cords and the germania-doped fibre, as well as off axis coupling between the SMF patch cords and the supercontinuum source.

The result differs from that predicted by coupled mode theory. From simulations, three resonances were expected at λ_B ~1526 nm, 1541.5 nm and 1557 nm corresponding to the LP_{11} – LP_{11} self-coupling, LP_{01} - LP_{11} cross coupling and LP_{01} - LP_{01} self-coupling, respectively. As most of the power launched in the fibre was in the fundamental mode, the LP_{11} - LP_{11} self-coupling is not observed in the spectra. Thus, only resonances corresponding to LP_{01} - LP_{11} cross coupling and LP_{01} - LP_{01} self-coupling are present. The presence of two transmission troughs located at λ_B ~1534 nm and 1536 nm has not been verified. The close proximity of the two shorter wavelength peaks suggests two possibilities: first, because of the large numerical aperture, the degeneracy commonly observed in the hybrid modes constituting the LP_{11} mode is partially removed, with the TE_{01} mode having a larger effective index than the TM_{01} and HE_{21} modes; secondly, the writing could have induced birefringence of the order of 10^{-4} between orthogonal polarisations. Further testing is required to determine the physical processes responsible for the splitting. Thermal testing results are displayed only for the fundamental mode of resonance λ_B ~ 1550 at 20 °C; the resonances of the higher modes were also seen to shift with a temperature increase in the same manner as the fundamental mode. Thermal testing revealed the FBG was erased at 800 °C and had an average sensitivity of 18.5 pm/°C (figure 4).

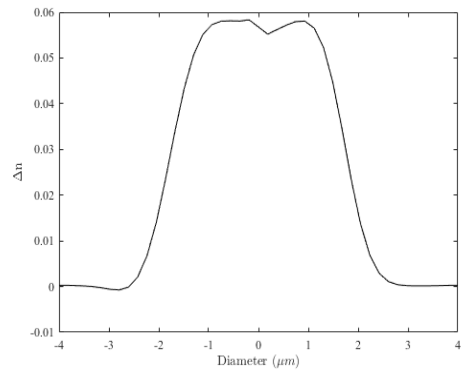

Figure 2 – Refractive index profile of the high concentration germanium fibre core with NA = 0.41.

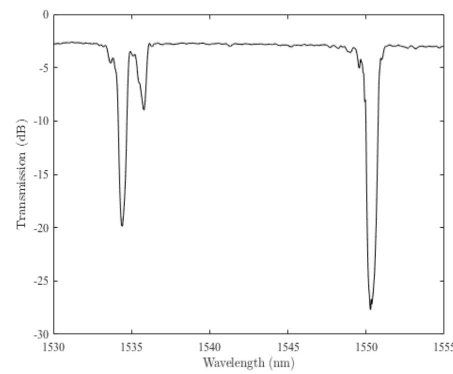

Figure 3 – Transmission spectra of the grating inscribed at λ_B ~ 1550 nm. Secondary resonances were observed at λ_B ~ 1534 nm and 1536 nm due to higher modes.

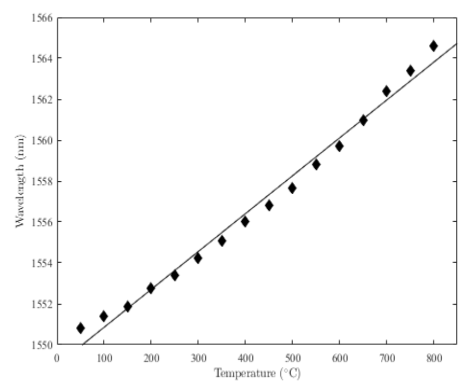

Figure 4 – Thermal testing results showing shift in the Bragg wavelength against temperature. Regression deduced a sensitivity of ~18.5 pm/°C.

4. Conclusions

A FBG was inscribed at λ_B ~ 1550 nm and additional resonances were observed from higher order modes. Further testing is required to determine the physical processes responsible for the separation of higher order resonances. Thermal testing demonstrated the FBG could withstand temperatures up to 800 °C before being erased. The fibre demonstrated a greater sensitivity than SMF-28 fibre and suggests it has the potential to be utilised as a temperature sensor. Furthermore, the successful inscription of a FBG in high concentration germania fibres offers foundations for further studies based on its non-linear properties; in particular for Raman laser applications where there are currently limitations in wavelength generation.

5. References

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