Grating Writing Through the Polyimide Fibre Coating with Femtosecond IR Radiation and a Phase Mask

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Abstract

Fibre Bragg gratings were written through the polyimide coating of commercial high NA fibres with ultrafast 800 nm radiation. Index modulations =2X10^{-4} remain after 140 hours at 360°C.

Introduction

Fibre Bragg grating (FBG) sensors are versatile sensing elements that can monitor both temperature and strain [1]. They offer a number of advantages such as quasi-distributed measurements along a single fibre, wavelength encoded output, immunity from electromagnetic interference and a large temperature range of operation compared to traditional electronic systems. For downhole monitoring applications in the oil and gas industry, FBG sensors are written into optical fibres coated with thermally stable polyimide (> 300 °C). Typically, FBGs are fabricated by side exposure of the fibre to UV laser light either using a two-beam holographic technique or a zero-order-nulled phase mask [2]. Prior to exposure, the protective polyimide fibre coating needs to be removed as it strongly absorbs UV light [3]. Polyimide is resistant to chemical attack so fibre stripping is only achieved by submerging the fibre in hot sulphuric acid. The fibre is then recoated after the FBG inscription [4]. Not only are the coating removal and replacement processes time-consuming, the mechanical integrity of the fibre is reduced [5]. Direct FBG sensor inscription through the polyimide coating is therefore desirable from a manufacturing and applications perspective.

Recently, FBG inscription through the standard acrylate coating of a fibre was reported using femtosecond (fs) infrared (IR) radiation and either the point-by-point method [6] or a phase mask [7]. When using the phase mask approach, FBG index modulations (Δn) of 3.5×10^{-4} were produced having fibre strengths at 85% of their pristine value. For this Δn, the *SMF-28* fibre was photosensitized by H_2-loading, which reduces the fs IR radiation threshold intensity for FBG writing in Ge-doped fibre [8].

In this paper, we present FBG inscription results through the polyimide coating of high numerical aperture (NA), high Ge-doped core concentration, single mode optical fibres that have been photosensitised using the H_2-loading process.

Experiment

The fibre used in this work is the commercially available *OFS ClearLite CL-POLY-1310-21* fibre, which has an NA of 0.21, a nominal core diameter of 4.6 μm and a mode field diameter of 5.8 μm at 1550 nm. The polyimide based *PYROCOAT* fibre coating has a thickness of 15 μm. The FBGs were made in *OFS* fibres that were pristine and H_2-loaded (23 °C and 2400 psi for 120 hours). Exposures were made using 125 fs auto correlated pulses of 800 nm IR radiation from a Ti:sapphire amplifier at a repetition rate of 100 Hz. An f = 12 mm focal length cylindrical lens was used to focus the 6.4 mm diameter IR beam through the phase mask and coating into the fibre core. The fibres were placed ~ 750 μm behind the 1.07 μm pitched phase mask, resulting in a two-beam interference pattern at the fibre core [9]. For a uniform core exposure, the focused beam was scanned perpendicular to the fibre axis ± 10 μm about the fibre core every 20 seconds. With this focusing geometry, pulse energies >180 μJ resulted in damage to the polymer coating. Transmission spectra were obtained using an Er^+ fibre white light source and an optical spectrum analyser.

For FBG performance at higher temperatures, long-term stability tests were performed in a Lindberg tube furnace. Gratings were loosely placed so that no external stresses were applied to the grating. The experiments were performed in ambient air and the heating rate was limited to 10 °C min−1. A swept tuneable laser system was used to continually measure the grating spectral responses.

Results and Discussion

For unloaded *OFS* fibre, the maximum FBG reflectivity achievable was 1%. A reflection spectrum of the device is shown in Fig. 1a). The Bragg resonance of the FBG, λ_B, is 1555.24 nm, which corresponds to an effective core mode index n_{eff} = 1.452. Similar FBGs written in *Corning SMF-28* result in a n_{eff} = 1.447, implying that there is a higher Ge-dopant concentration in the high NA fibre. The transmission spectrum of a FBG written in H_2-loaded *OFS* fibre with pulse energies of 180 μJ is presented in Fig. 1b). The total exposure time for the hydrogen loaded grating inscription was 5 minutes, after which no further grating growth was observed. For both the loaded and unloaded *OFS* fibre, the induced index change for the gratings occurred in a low intensity

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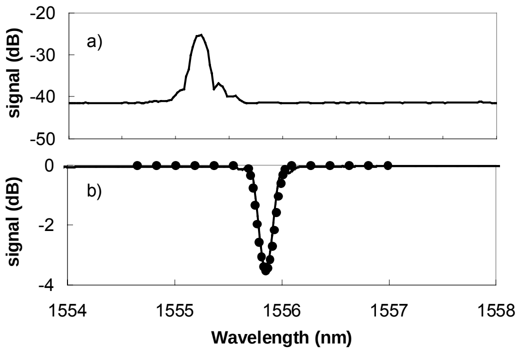

Figure 1: a) Reflection spectrum of an FBG written through the polyimide jacket of the OFS fibre without H_2-loading; b) Transmission spectrum of an FBG written through the polyimide jacket of H_2-loaded OFS fibre. Modelled spectrum shown with black dots.

regime that is likely associated with defect formation/material compaction (Type I-IR). For SMF-28 fibre, the Type I-IR induced index change has been shown to be a 5-photon process [10]. Using the Rouard method [11], the transmission spectrum of the grating was modelled assuming a Gaussian index profile 6.4 mm in length and a 5-photon process. The modelled response shown as the dotted line in Fig. 1b) corresponds to a $\Delta n = 4.8 \times 10^{-4}$. For the unloaded case, the reflectivity of 1% corresponds to a $\Delta n = 3 \times 10^{-5}$.

Observation of the exposed polymer jacket under an optical microscope revealed some damage to the jacket surface after the 5-minute exposure. The ablation threshold for polyimide decreases with the number of incident fs IR laser pulses [12]. It is likely that the initial fs IR laser pulses induce 'incubation sites' in the polyimide coating that eventually reduces the transmission of the IR radiation through the jacket thus limiting the Δn growth.

Isochronal annealing studies were performed on the FBGs at elevated temperatures to determine their thermal stability. The reduction of Δn with temperature is shown in Fig. 2 for a FBG with an initial Δn of 3.6×10^{-4}. A portion of the Δn rapidly anneals out at 200 °C but the remaining Δn is relatively stable with increasing temperature up to 400 °C. After 16 hours at 400 °C, the grating had a Δn of 2×10^{-4} with no visible erasure. Since the rated temperature of the fibre coating is 300 °C, it is likely that the FBG reflectivity will remain stable within the operating temperature of the coating. When the fibre temperature was increased in 100 °C increments and annealed for 1 hour, FBG erasure was observed with complete grating erasure occurring at 800 °C. In a separate experiment, another device was annealed at 360 °C for 140 hours after being pre-annealed at 75 °C for 36 hours in order to out-gas any remaining

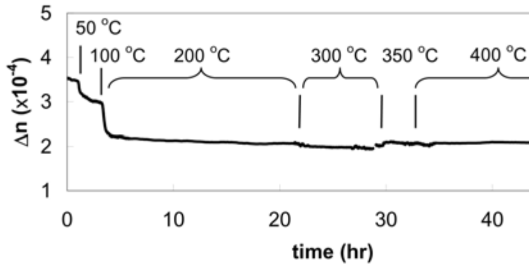

Figure 2: Isochronal annealing study of a FBG in the polyimide coated OFS fibre.

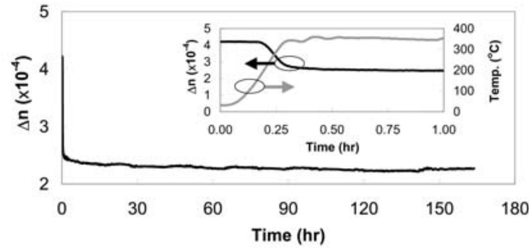

Figure 3: Long term annealing study at 360 °C of a FBG in OFS fibre. Inset is an expanded view of the initial annealing with Δn and temperature denoted by black and grey traces respectively.

hydrogen (see Fig. 3). After 140 hours, a Δn » 2.2 $\times 10^{-4}$ remained.

Conclusions

Fibre Bragg gratings have been inscribed directly through the polyimide polymer coating of commerically available high NA optical fibres with femtosecond 800 nm IR radiation and a phase mask. Index modulations up to 3.6×10^{-4} were achieved with hydrogen loaded fibre. After an initial decrease, index modulations of 2×10^{-4} remained after annealing for 6 days at 360 °C.

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