Annealing effects in femtosecond laser-inscribed mid-infrared fibre Bragg gratings

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The demonstration of femtosecond (fs) laser-inscribed fibre gratings, in particular fibre Bragg gratings (FBGs), into fluoride fibers has enabled the development of alignment free, Watt-level all-fiber mid-infrared (mid-IR) laser systems by eliminating bulk optical elements and thus atmospheric absorption losses [1]. However, there has been no study to date that systematically investigates the spatial profile of the induced refractive index change within the core of the fluoride fiber and its annealing behaviour. Moreover, several reports show that both, the grating strength as well as the resonant wavelength, substantially change upon post-annealing of the fibre [2-4]

In this paper, we report on the use of micro-reflectivity measurements to investigate the influence of the repetition rate of the inscription laser on the induced refractive index profile within the optical fibre. We show that when going from a low repetition rate of 1 kHz to a high repetition rate of 50 kHz, the underlying physical mechanisms that lead to the formation of the grating planes change, resulting in a fundamentally different annealing behaviour.

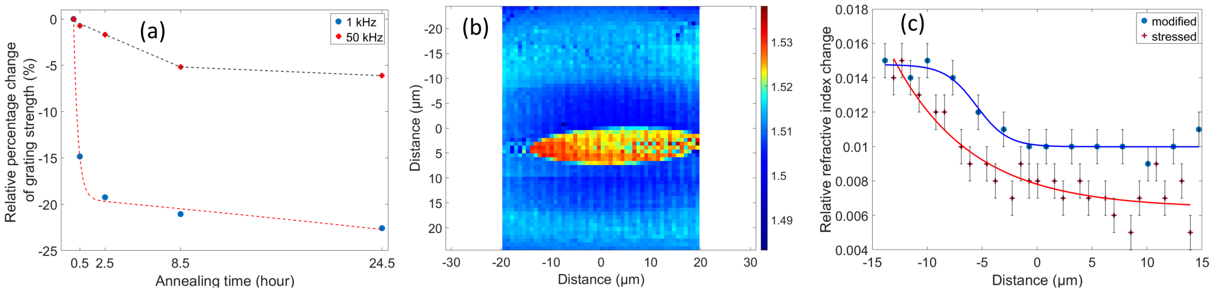

Fig. 1. (a) Relative percentage change of the grating strength (κ) values when annealed at 150°C for 24.5 hours (b) Micro-reflectivity image of the grating structures written at 1kHz (c) Line profile of the refractive index modification within the core

Line-by-line, non-damage (type-I) FBGs were inscribed into passive zirconium fluoride (ZBLAN) fibre using 190 fs laser pulses at 1030 nm center wavelength (Light Conversion, Pharos). Using a 40x dry objective with an NA of 0.6 and a fixed translation speed of 20μm/s, the pulse energy was varied from 100 nJ to 350 nJ. It was found that 300 nJ provides strong and smooth grating structures for repetition rates ranging from 1 kHz to 150 kHz. The highest grating strength of $\kappa = 448\ m^{-1}$ was obtained at 1 kHz repetition rate followed by $\kappa = 365\ m^{-1}$ for 50 kHz. However, as can be seen in Figure 1 (a), κ shows a small and linear decrease upon annealing at 150°C, whereas an exponential decrease in grating strength can be observed for 1 kHz grating, indicating gratings written at 50 kHz are much more thermally resilient.

In order to study the underlying physical mechanisms for this observed behaviour, micro-reflectivity scans were performed [5]. For this, the fibres were side-polished at an angle of 13° to expose 14 FBG planes, each at a different location across the core of the fibre. From the micro-reflectivity image of the FBG inscribed at 1 kHz (Figure 2 (b)) the induced refractive index change profile within the fibre can be extracted. The uncertainty of the measurement is on the order of 1×10^{-3} and the average induced refractive index change is measured to be $2.1\ \times 10^{-3}$. Figure 2 (c) shows a line profile of the fs-laser modified region and the stressed region in between the grating planes. A sigmoid fit is found to be the best fit for the modified region, whereas the stressed region follows an exponential profile, indicating that fundamentally different mechanisms are involved in the formation of these regions. To the best of our knowledge, these are the first direct measurements of the induced refractive index change profile in mid-infrared compatible fibers as well as the first systematic study of the influence of laser repetition rate on the thermal stability of inscribed gratings.

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