Strong asymmetric stresses arc-induced in pre-annealed nitrogen-doped fibres

G. Rego, F. Dürr, P.V.S. Marques and H.G. Limberger

Long-period gratings were written using arc discharges in pristine nitrogen doped fibres. Comparison of the resulting gratings spectra show that the resonant positions of gratings in fibres pre-annealed at 1050°C for 30 min are shifted towards shorter wavelengths and their coupling strength is considerably higher. The refractive index and residual stress profiles were measured before and after annealing, as well as the two-dimensional stress profiles inside the grating region. Arc discharges induce periodic and strong asymmetric stresses in the fibre core of the pre-annealed nitrogen doped fibre.

Introduction: Long-period gratings (LPGs) fabricated by electric arc techniques have revealed interesting properties that highlight their potential application in optical communications and sensing. In particular, it was shown that arc-induced gratings in Ge-free Al/Er co-doped fibres exhibit a linear peak shift for temperature changes up to 700°C [1] and that by changing the fabrication parameters it is possible to modify the temperature and strain sensitivities of gratings written in SMF-28 fibre [2]. Recently, the influence of the drawing tension as well as the external load applied during the arc discharges on coupling strength was investigated through analysis of two-dimensional stress profiles [3]. In this Letter, we analyse the effect of fibre pre-annealing on grating formation. The refractive index and residual stress profiles were measured before and after heat treatment. In addition, two-dimensional stress profiles were recorded after LPG inscription.

Experimental results: LPGs were arc-induced in a nitrogen doped fibre ($D_{core} = 6.0$ μm, $D_{clad.} = 126.0$ μm and $\lambda_{cut\text{-}off} \sim 1.1$ μm) using the setup described in [4]. The fibre, manufactured at FORC-GPI, Russia, was drawn with a tension of 195 g and a temperature of 1880°C. Several samples of this fibre were annealed in a tubular oven at 1050°C for 30 min. To prevent the building of new stresses during thermal treatment, heating and cooling rates were kept at ~5°C/min. A small weight of 2.2 g was suspended at one end of each fibre sample to keep it straight. After cooling to room temperature, LPGs were written in the pre-annealed fibre samples. For gratings inscription, fabrication parameters were set as follows: axial tension, 22.8 g; electric current, 9 mA; arc duration, 1 s, and a grating period of 400 μm. The spectra of the gratings written in the pristine and pre-annealed fibre are presented in Fig. 1. The coupling strength of the grating induced in the pre-annealed fibre is three to four times higher than that induced in the pristine one, despite the fact that only half the periods were used. Furthermore, the spectrum of the former also moved towards lower wavelengths and the shift increases with the order of the cladding modes ranging from 30 (HE_{12}) to 65 nm (HE_{16}).

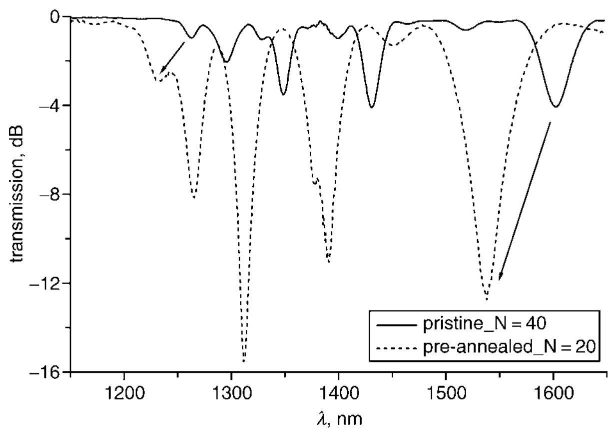

Fig. 1 *Spectra of gratings written in pristine and pre-annealed fibre*
Note, LPG written in pristine fibre is twice as long (40 × 400 μm = 16 mm)

The fibre's refractive index profile (RIP), before and after pre-annealing, was measured at room temperature (18°C) using a S14 refractive index profiler from Photon Kinetics. For calibration, an oil with a refractive index of 1.47 (25°C and 632.8 nm) was used. The accuracy of the measurements was $\sim 10^{-4}$. For a fibre drawn from the same preform with a tension of 125 g, the refractive index was found to be significantly higher in the cladding (Fig. 2). The thermal treatment induced an overall increase of fibre refractive index in both fibres. In particular, almost the same cladding refractive index is obtained. The cladding index of the fibre drawn at 195 g can thus be increased by about 1.5×10^{-3} by annealing.

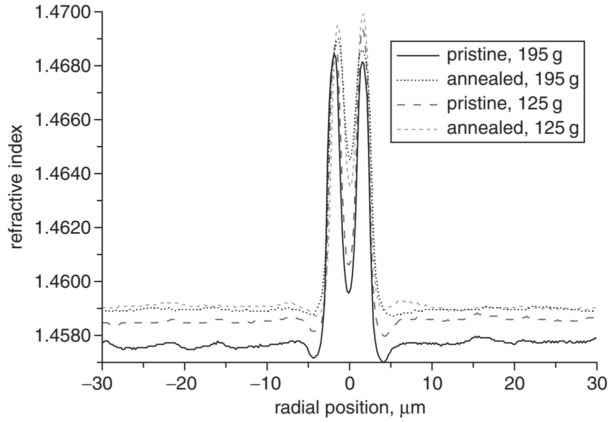

Fig. 2 *Refractive index profiles of fibres drawn with 125 and 195 g, before and after annealing*

The stress profiles of the pristine and heat treated fibre samples, determined as described in [3], were found to be azimuthally symmetric. Therefore, Fig. 3 shows only the one-dimensional stress profiles. For the pristine fibre, the core is under compressive stress (−55 MPa), whereas the surrounding silica tubes exhibit tensile stress up to a value of ~25 MPa. The annealing relaxes the drawing-induced stresses resulting from a mismatch in viscosity between core and cladding. The remaining tensile core stresses of about ~5 MPa result from the mismatch in thermal expansion coefficient between the core and the cladding.

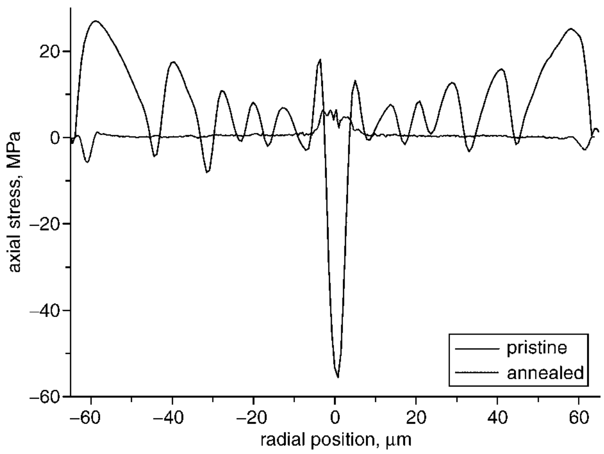

Fig. 3 *One-dimensional stress profiles of nitrogen doped fibre, before and after annealing*

Fig. 4 shows the two-dimensional stress profiles for a grating induced in the pristine and pre-annealed fibre, respectively. The profiles were recorded for two positions inside a grating period: midway between two discharges (space) and in the discharge region (mark). It is clearly seen that changes in the stress profiles are more pronounced for the pre-annealed fibre. In the core region, strong asymmetric stresses up to 150 MPa were induced by the arc discharge. In contrast, the stress profile of the cladding only exhibits small asymmetries (± 20 MPa). The increase in coupling strength shown in Fig. 1 might thus be due to periodic stress-induced index changes in the fibre core.

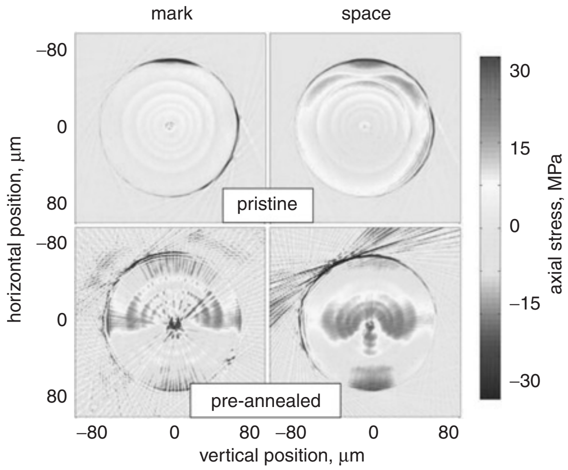

Fig. 4 *Two-dimensional stress profiles recorded inside two gratings induced in pristine and pre-annealed fibres, respectively*

Left column: profile shown directly at position of arc discharge; right column: gives profile just in middle of two discharges. Note, to keep a reasonable contrast in cladding region, scale limited to ±30 MPa, therefore core colour is saturated (150 MPa)

The cladding index changes related to stress changes (Fig. 3) by photoelasticity are one order of magnitude smaller than the index changes actually observed (Fig. 2). In contrast, the increase in cladding refractive index can be explained with the annealing of isotropic inelastic strains frozen into the fibre during its drawing process [5]. As the amount of inelastic strain increases with drawing tension, the annealing-induced index increase is higher for the fibre drawn with 195 g than for those with 125 g. The shift towards shorter wavelengths observed in Fig. 1 might thus be originated by a decrease of the core-cladding index difference due to inelastic strain relaxation.

Conclusion: Long-period gratings were arc-induced in nitrogen doped fibres after pre-annealing. A shift of gratings spectra towards shorter wavelengths and an increase of coupling strength was observed, when compared to the spectra of LPGs written in pristine fibres. The shift to shorter wavelengths might be explained by a reduction of the core-cladding index difference due to inelastic strain relaxation. The increase in coupling strength, in contrast, is attributed to large stress-induced index changes in the region of the arc discharge.

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