Annealing of arc-induced gratings at high temperatures

G. Rego

Long period gratings arc-induced in different types of fibre were annealed at 1000°C for 24 h. During the annealing, the spectrum of the gratings written in Ge-doped fibres shifted towards longer wavelengths whereas an opposite shift was observed for gratings written in Ge-free fibres. A discussion on the mechanisms responsible for that behaviour is presented.

Introduction: In recent years, optical-fibre-based sensors have become a market of increasing demand, since owing to their intrinsic properties they offer clear advantages over the conventional ones. It is irrefutable that high-temperature sensors are of great importance and, since the appearance of UV-induced fibre Bragg gratings, much effort has been put forward from the scientific community in order to increase their high-temperature resistance. The electric arc technique is among the few techniques able to produce gratings that can withstand temperatures of the order of 1000°C. In past years, the subject of arc-induced gratings and their applications was intensively investigated, namely, long period fibre gratings (LPFGs) were inscribed in different types of fibre, their temperature behaviour was investigated up to 1200°C and distinct behaviour was observed for Ge-doped and Ge-free fibres [1]. It was also demonstrated that arc-induced gratings can withstand temperatures of 1200°C for short periods. Annealing experiments in the temperature range 900–1100°C, concerning gratings arc-induced in the SMF-28 fibre, were also conducted for a few hours [2]. In this Letter, we present results on the effect of annealing on gratings arc-induced in Ge-doped and Ge-free fibres at 1000°C for 24 h.

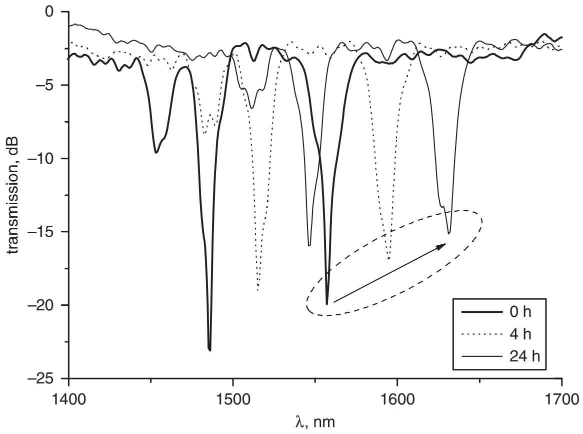

Fig. 1 *Evolution of spectra of one grating written in SMF28 fibre during annealing at 1000°C*

Experimental results: LPFGs were arc-induced in Ge-doped fibres namely, SMF-28 (3 mol%) and dispersion shifted (12 mol%) fibres from Corning and in a standard fibre (6 mol%) from Siecor, and also in Ge-free fibres: a pure-silica-core fibre with an F-doped inner cladding from Oxford Electronics and an N-doped fibre produced by SPCVD at FORC-GPI in Moscow [1–3]. Gratings were placed inside a tubular oven (a weight of 2.2 g was used to prevent bending) and were heated gradually in steps of 100°C up to 1000°C (the temperature T_a at which they were annealed for 24 h). Figs. 1 and 2 show the evolution of the transmission spectrum of the grating inscribed, respectively, in the SMF-28 fibre and in the N-doped fibre, during the annealing at 1000°C. As can be seen for the former, besides the displacement of the resonance wavelengths there is also some decrease of the grating strength. Considering that the mechanism responsible for the grating formation is the core shift due to temperature gradients [4] it is expected that the coupling strength should increase as a result of the dominant structural relaxation. Therefore, in this case all resonances were overcoupled. In [5] it can be seen that the strength of some resonances increases whereas others decrease during annealing. Regarding the N-doped fibre, the overcoupled resonances shift towards lower wavelengths and their strength also decreases. It can also be seen that the latter spectrum exhibits some degradation, more pronounced for higher order cladding modes, which may reflect the fact that the cladding comprises several silica tubes with periodic stresses that relax during annealing, leading to some modulation of the cladding's refractive index [3].

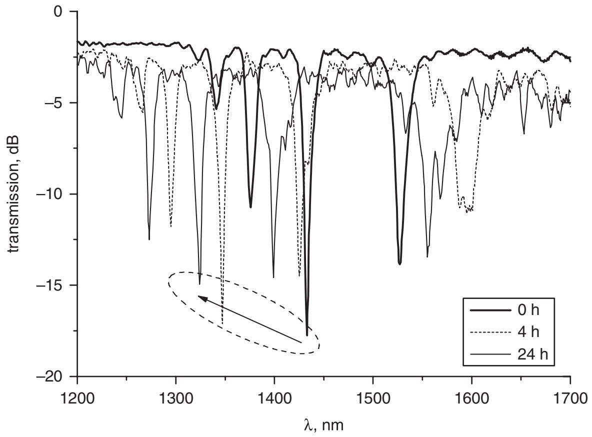

Fig. 2 *Evolution of spectra of one grating written in nitrogen-doped fibre during annealing at 1000°C*

Fig. 3 shows the displacement of the LP_{13} cladding mode belonging to gratings written in different fibres (for the SiO_2-core fibre the resonance monitored was the LP_{12}) during annealing at 1000°C. As seen, whereas for gratings arc-induced in Ge-doped fibres the resonances moves towards longer wavelengths, the resonances of gratings written in Ge-free fibres shift in the opposite direction. During annealing at those conditions, residual and viscoelastic stress relaxation, structural relaxations (changes in the fictive temperature, T_F) and dopant diffusion may occur. The timescales for the occurrence of these mechanisms ranges from a few minutes to several days.

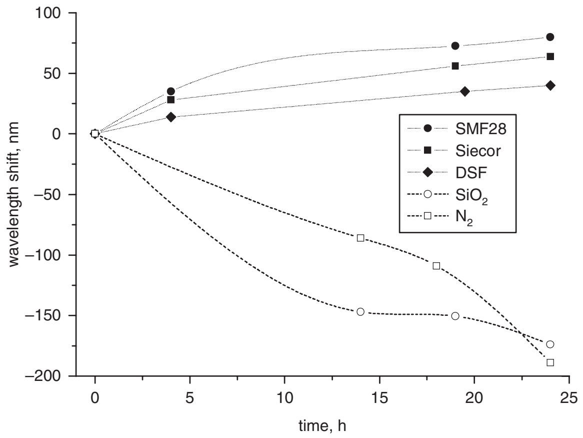

Fig. 3 *Time dependence of resonance wavelengths at 1000°C, for gratings written in different fibres*

In the case of Ge-doped fibres the dominant effect may be attributed to a decrease of the fictive temperature of the cladding. The refractive index of silica glass increases almost linearly with T_F up to about 1550°C [6, 7]. When the fibre is kept at T_a the glass structure starts to relax according to the relation $dT_F/dt = (T_F - T_a)/\tau$, where τ represents the structural relaxation time [8]. This means that, during annealing at a temperature lower than the initial fictive temperature of the glass, its structure relaxes and for each equilibrium state a new T_F can be assigned. If one waits long enough, for about 200 h at 1000°C, the new fictive temperature will approach the annealing temperature [8]. It is known that during fibre drawing the cladding cools more rapidly than the core, where T_F of the cladding is about 400°C above that of the core [9]. During annealing, the rate of change of T_F is higher for the cladding (larger temperature difference) and therefore the refractive index of the cladding reduces more than that of the core leading to a displacement of the resonances towards longer wavelengths. The contributions of stress relaxation [10] and Ge diffusion [11] that would cause a shift towards lower wavelengths are overcome by the change in T_F. Note that for the SMF-28 fibre the shift of the resonance wavelength would require a Δn induced of 1.5×10^{-4}, but this is about half the value achievable owing to the change of T_F in the core and cladding material [6, 7]. The larger shift obtained for the grating resonances written in the lowest Ge concentration fibre, may be related to its lower intrinsic stresses causing a smaller shift during annealing opposing that due to structural relaxation.

A similar reasoning can be applied to the pure-silica-core fibre. The dependence on T_F of the refractive index of pure silica is larger than for F-doped silica [7]. At the same time fluorine decreases the viscosity and affects the structural relaxation time. Moreover, $T_F - T_a$ is larger for the core, therefore, the refractive index of the core decreases more than that of the inner cladding leading to a shift of the resonances towards lower wavelengths. It should be noted that fluorine diffusion is negligible [12] and stress relaxation would cause a shift in the opposite direction. However, the change in the fictive temperature depends on stress: tensile stress enhances structural relaxation while compressive stress inhibits it [13]. For the Oxford fibre the core is less compressive than the inner cladding [2].

As far as the N-doped fibre is concerned, the observed shifted towards lower wavelengths requires a Δn induced during annealing of about 5×10^{-4}. In a previous work [3] where stress measurements and the refractive index profile (RIP) of this fibre were recorded before and after annealing at 1050°C for 30 min, it was observed that residual stress relaxation can account for about half that value, that viscoelastic stress may take place in the cladding and it is also possible that diffusion occurs. In fact, recently, nitrogen diffusion in silica glass was quantified and a large diffusion coefficient was obtained ($D = 1.3 \times 10^{-8} \exp(-1.48 \times 10^4/T)\ \mathrm{m}^2/\mathrm{s}$) [14], contradicting former knowledge on this subject [15]. It should be noted, however, that such high diffusion was not observed in the performed RIP of the fibre. Moreover, for the annealing conditions used, nitrogen would reach equilibrium across the whole fibre!

Conclusions: Results are presented on the effect of annealing (1000°C, 24 h) on the spectra of gratings written in Ge-doped and Ge-free fibres. It was observed that whilst the spectrum of gratings inscribed in the former fibres shifts towards longer wavelengths, gratings written in the latter fibres show an opposite shift. The behaviour was attributed to structural relaxations (changes in T_F) except for the N-doped fibre where other mechanisms, such as stress relaxation and diffusion, must prevail. Following the above results and to assess the possibility of implementing a high-temperature sensor based on arc-induced gratings the long-term behaviour (annealing time higher than 200 h) of an LPFG inscribed in the SMF-28 fibre needs to be investigated. Experiments are ongoing and results will be published elsewhere.

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G. Rego (*Escola Superior de Tecnologia e Gestão, IPVC, Av. do Atlântico, 4900-348 Viana do Castelo, Portugal, and Unidade de Optoelectrónica e Sistemas Electrónicos do INESC-Porto, Rua do Campo Alegre, 687, 4169-007 Porto, Portugal*)

E-mail: gmrego@fc.up.pt

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