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Hydrogen loading in tin-phosphosilicate fibres: a method to achieve enhanced thermal stability in fibre-Bragg-grating based devices

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Abstract: Enhanced photosensitivity has been observed in hydrogen-loaded tin-phosphosilicate fibres by using a 248 nm excimer laser. Isothermal measurements up to 860 K demonstrated significant advantages over fibre gratings written in conventional H-loaded fibres. Gratings written in this fibre require a considerably shorter post-fabrication thermal annealing in order to satisfy the stability requirements of telecom components.

Key Words: Gratings, Thermal stability, Materials, Photosensitivity.

1. INTRODUCTION

Devices based on fibre Bragg gratings require high photosensitivity and extremely small tolerance on the optical properties over a long time scale in order to be assembled in reliable WDM components. High photosensitivity in standard telecom optical fibres is achieved with the so-called hydrogen (or deuterium) loading process, which can increase the photosensitivity by more than two orders of magnitude [1]. Since its first use in germanosilicate fibres, hydrogen loading has been successfully applied to many silicate fibres [2], including phosphorus, aluminium or cerium doped or codoped fibres. No improvement has been observed when the dopant is nitrogen [3]. It has to be remarked that high photosensitivity at 248 nm has been observed in phosphorus-doped silica fibres only when gratings were written in heated fibres [4]. A weak effect has been observed in unheated H-loaded phosphosilicate fibres when exposed to the KrF laser [5]. A drawback of all the gratings written in hydrogen-loaded fibres is the extremely poor temperature stability. In fact in most fibres the photo-induced refractive index change starts to be erased at 100 ^{0}C in one hour. Tin doping has been shown to be a powerful method to achieve high photosensitivity [6]. Moreover, the enhanced stability of gratings written in tin-silicate fibres does not require post-fabrication annealing to satisfy the requirements of telecom components [7].

In this paper we study the effect of hydrogen loading on tin-doped fibres, with particular stress on the excellent thermal stability.

2. HYDROGEN LOADING

The tin-codoped phosphosilicate fibre used in the experiments was fabricated by modified chemical vapour deposition (MCVD). $SnCl_4$ was the precursor used to introduce Sn in the optical fibre preform. The fibre external diameter, numerical aperture and cut-off were d=110μm, NA~0.14 and λ_c~1.42 μm respectively. The fibre was placed in a hydrogen-loading cell at 165 bars and 25 ^{0}C for 14 days. The photosensitivity of samples taken from the vessel was tested by writing gratings at ~1.55μm with a "Lambda Physik" line-narrowed KrF-laser (mod. EMG150) and a phase-mask. The exposure time, laser repetition rate and pulse fluence were t_{exp}=30 minutes, RR=20 Hz and I_p~300 mJ/cm^2 respectively. In order to let the hydrogen outdiffuse, the fibre samples were left at room temperature for a period of 7-14 days before being spliced to a fibre-coupled diode. Spectra were collected using an optical spectrum analyser. Figure 1 compares the reflectivity spectrum of the grating written both in the hydrogen-loaded and in the pristine fibres.

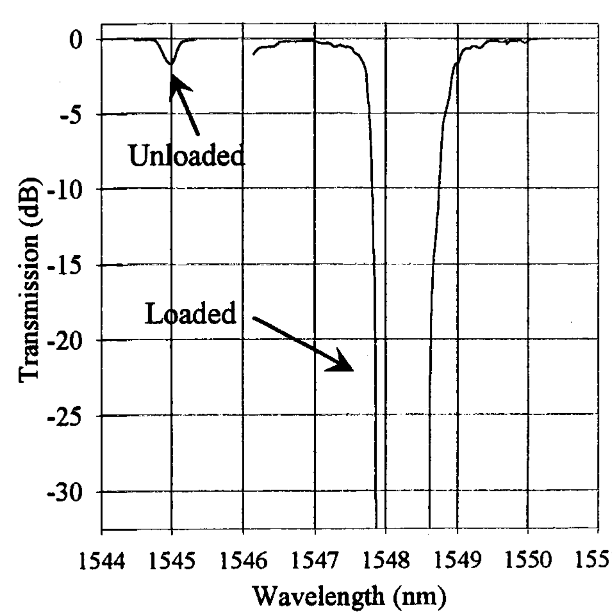

Fig. 1: Transmission spectra of gratings written in loaded and unloaded tin-phosphosilicate fibres. Grating length, exposure time, laser repetition rate and pulse fluence are L=2mm, t_{exp}=30 minutes, RR=20 Hz and I_p~0.3 J/cm^2 respectively. The loading process was carried out leaving the fibre in the hydrogen-loading cell at 165 bars and 25 ^{0}C for 14 days.

Similarly to what has previously been observed in fibres doped with Ge, Al and Ce, hydrogenation enhances photosensitivity to UV laser radiation in the tin-doped phosphosilicate fibre. While in the unloaded fibre the maximum reflectivity was <2dB, in the H-loaded fibre it was > 35 dB. The induced refractive index modulation (Δn_{mod}) was evaluated by fitting the reflectivity curve $R(\lambda)$ with [8]:

$$R(\lambda)=\frac{1}{1+\frac{1}{\kappa^2L^2\mathrm{sinc}^2(\gamma L)}} \qquad (1)$$

where L is the grating length, $\kappa=\pi\cdot\Delta n_{mod}/\lambda$ the "ac" coupling constant, λ the wavelength, $\gamma=(\kappa^2-(\sigma+\delta)^2)^{1/2}$ the propagation constant inside the grating, $\sigma=2\pi/\lambda\cdot\Delta n_{ave}$ the "dc" coupling constant, $\delta=\beta-\pi/\Lambda$ the detuning, β the propagation constant in vacuum, Λ the grating pitch and Δn_{ave} the induced average refractive index change. Δn_{mod} was estimated to be $\sim1.4\cdot10^{-3}$ and $\sim1.3\cdot10^{-4}$ in the loaded and unloaded fibres.

Figure 2 compares the Δn_{mod} growth of gratings written in a fibre loaded for 3 days and in a pristine fibre.

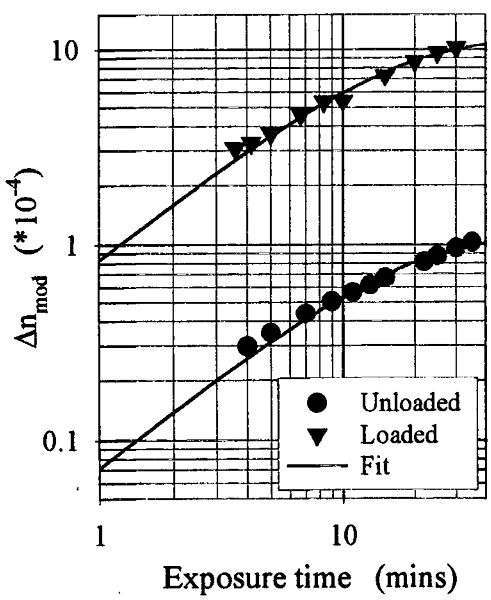

Fig. 2: Temporal evolution of Δn_{mod} in hydrogen-loaded (3 days at 165 bars and 25 ^{0}C) and pristine tin-phosphosilicate fibres.

The experimental data have been fitted with an exponential rising to the maximum:

$$\Delta n_{mod}=\Delta n_{sat}\cdot(1-e^{-t/\tau}) \qquad (2)$$

where Δn_{sat} is the asymptotic value of Δn_{mod} for long exposure times, τ is the time constant of the refractive index growth and t the exposure time. The fit parameters are reported in table 2. While Δn_{sat} differs by an order of magnitude, the τ does not show any significant modification.

	Δn_{sat}	τ (min)
Unloaded	$1.10\cdot10^{-4}$	14.7
Loaded	$1.11\cdot10^{-3}$	12.8

Tab. 1: Fit parameters for the data of fig. 2.

3. THERMAL STABILITY

The grating thermal stability was studied using the so-called master curve method [9]. It has been shown that this accelerating aging technique is a more general and preferable method as compared to the parallel power-law method for gratings written in hydrogen-loaded fibres [10]. In this approach the grating decay is recorded at different temperatures and all the data are combined to give a master curve from which it is possible to predict the grating reliability in different conditions. The aging parameter E_d (called demarcation energy) is defined as [9]:

$$E_d=k_BT\ln(\nu t) \qquad (3)$$

where k_B is the Boltzmann's constant and T the temperature. ν represents an attempt frequency and is determined during the data fit.

In our experiment, gratings were written as previously explained in samples of fibre hydrogen loaded for 6 days at 165 bars. Real time spectra of the gratings placed in the furnace, were recorded by means of a white light source, a coupler and an optical spectrum analyser. The time evolution of the integrated coupling coefficient η (defined as $\eta=\Delta n_{mod}/\Delta n_{mod}(0)$, where $\Delta n_{mod}(0)$ is the initial value of Δn_{mod}) is shown in figure 3 for four different temperatures.

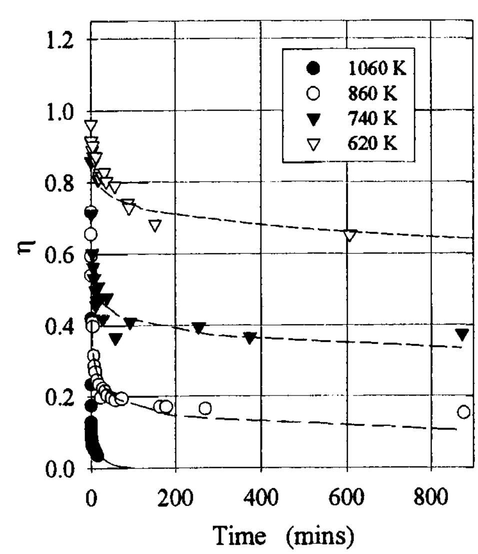

Fig. 3: Decay of the gratings written in H-loaded tin-phosphosilicate fibre for different furnace temperatures. The fibres were hydrogen-loaded at 165 bars and 25 ^{0}C for 6 days. Gratings were written by exposing the fibre for 30 mins at I_p=0.3J/cm^2.

It is worth stressing the enhanced thermal stability of these gratings. While gratings written in unloaded germanosilicate fibres had ~27% erased in 60 mins at 350 ^{0}C [9], in the same conditions the gratings written in the hydrogen-loaded tin-phosphosilicate fibre had a change η~24%. The experimental data were fitted using $\nu=2.5\cdot10^{10}$ min^{-1}, considerable smaller than the value found for hydrogen-loaded germanosilicate fibres [10]. The master curve was approximated by the equation $\eta=(1+e^{Ed-1.65)/0.1258})^{-1}$ small decays. From the curve it is possible to evaluate what is the thermal decay of a grating after 25 years at 80 ^{0}C (E_d=1.23eV): η=0.966, meaning that ~3.4% of the original grating has been wiped away. Table 2 compares the values obtained in this paper to the results published on the stability of gratings written in germanosilicate [9], in boro-germanosilicate [10] and in tin-silicate [7] fibres.

Fibre	$1-\eta$	Ref.
HL-SPS	0.034	This paper
GS	0.0782	[9]
BGS	0.138	[10]
SS	0.0014	[7]

Tab. 2: Estimation of the fraction of the initial grating erased after 25 years at 80 ^{0}C. HL-SPS, GS, BGS and SS represent hydrogen-loaded tin-phosphosilicate, germanosilicate, boro-germanosilicate and tin-silicate, respectively.

As expected, the decay is considerable higher than the one observed in unloaded tin-doped fibres (<1%); nevertheless it is better than the values of degradation reported in literature for unloaded traditional fibres.

4. CONCLUSIONS

In summary, hydrogen loading has been shown to enhance the photosensitivity of tin-doped phosphosilicate fibres. The photo-induced refractive index change of the gratings written in hydrogen-loaded fibres was one order of magnitude stronger than the gratings written in the unloaded fibres. The thermal stability of gratings written in hydrogen-loaded tin-phosphosilicate fibre has been tested with iso-thermal annealing and proved that >15 % of the initial photosensitivity survived a treatment at 860 K for 14 hours. An estimation of the grating fraction surviving 25 years at 80 ^{0}C shows that hydrogen loading of tin-codoped phosphosilicate fibres has a significant advantage over conventional fibres. Gratings written in this fibre require a less-severe post-fabrication thermal annealing in order to satisfy the stability requirements of telecom components.

The author is grateful to E. J. Tarbox and D.J. Richardson for their helpful discussions.

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