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Enhanced thermal stability of gratings written in H-loaded tin-phosphosilicate optical fibers

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Abstract

Enhanced photosensitivity has been observed in hydrogen-loaded tin-phosphosilicate fibers by using a 248 nm excimer laser. Isothermal measurements up to 860 K demonstrate significant advantages over fiber gratings written in conventional H-loaded fibres.

Hydrogen loading has been shown to be a powerful sensitising method to achieve high photosensitivity in germanosilicate fibres[1,2]. While the unloaded standard telecom optical fibres show small induced refractive index changes when exposed to UV radiation, hydrogen (or deuterium) loading can enhance photosensitive response by up to more than two orders of magnitude. Hydrogen loading has been tested on silicate fibres doped with other elements than germanium. While in phosphorus[3,4], aluminium[5] or cerium[6] doped or codoped fibres it induces or enhances photosensitivity, no improvements have been observed when the dopant is nitrogen[7]. High photosensitivity in phosphorus-doped silica fibres is enhanced by hydrogen-sensitisation only when the gratings are written by using a 193 nm excimer laser[8] or by heating the fibre during the exposure with the 248 nm laser[9]. A weak effect has been observed in unheated H-loaded phosphosilicate fibres when exposed to the KrF laser[10]. A common feature of all the gratings written in hydrogen-sensitised fibres is the extremely poor temperature stability. In fact in most fibres the photoinduced refractive index change starts to be erased at 100 ^{0}C in one hour.

In this paper the results on photosensitivity of hydrogen-loaded tin-doped fibres are presented, with particular stress on the excellent thermal stability.

The fibre used in the experiments was a tin codoped phosphosilicate fibre produced via modified chemical vapour deposition (MCVD). Sn was introduced in the optical fibre preform bubbling nitrogen in $SnCl_4$ bubbler heated up to 40 ^{0}C. The fibre external diameter, numerical aperture and cut-off were d=110 μm, NA$\sim$0.14 and $\lambda_c \sim 1.42$ μm respectively. The fibre was placed in a hydrogen loading cell at 165 bars and 25 ^{0}C. The photosensitivity of samples taken from the vessel was tested by writing gratings at $\sim 1.55 \mu$m with a 248 nm KrF excimer laser and a phase-mask.

Gratings were written by exposing the loaded fibre for 30 minutes to a KrF excimer laser delivering pulses at 20 Hz and $I_p \sim 300$ mJ/cm^2. 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 analyzer. The inset of figure 1 compares the reflectivity spectra of the grating written in the fibre hydrogen-loaded for 14 days to the grating fabricated in the as-produced fibre. Similarly to what has previously been observed in fibres doped with Ge, Al and Ce, hydrogenation enhances photosensitivity to UV laser radiation in the Sn-doped phosphosilicate fibre. The induced refractive index modulation (Δn_{mod}) was evaluated from the reflectivity R by using

$$R = \frac{1}{1 + \frac{1}{\kappa^2 L^2 sinc^2(\gamma L)}}. \tag{1}$$

where L is the grating length, $\kappa = \frac{\pi}{\lambda}\Delta n_{mod}$ the "ac" coupling constant, λ the wavelength, $\gamma = \sqrt{\kappa^2 - (\sigma + \delta)^2}$ the propagation constant inside the grating, $\sigma = \frac{2\pi}{\lambda}\Delta n_{ave}$ the "dc" coupling constant, $\delta = \beta - \frac{\pi}{\Lambda}$ the detuning, β the propagation constant in vacuum and Δn_{ave} the induced average refractive index change. In the unloaded fibres Δn_{mod} was estimated to be $\sim 1.3 \cdot 10^{-4}$, in the fibre loaded for 14 days $\sim 1.4 \cdot 10^{-3}$. Figure 1 shows the Δn_{mod} growth in the fibres. The fit curves for the unloaded and loaded fibres are $\Delta n_{mod} = 1.097 \cdot 10^{-4} \cdot (1 - e^{-0.0679 \cdot t})$ and $\Delta n_{mod} = 1.109 \cdot 10^{-3} \cdot (1 - e^{-0.0782 \cdot t})$ respectively. While the absolute value differ by an order of magnitude, the time constant of the process does not show any significant modification.

The dependence of Δn_{mod} on hydrogen loading time was studied by taking out fibre segments from the hydrogen loading vessel over a period of 15 days and testing photosensitivity. All the gratings have been written by exposing the fibre samples to KrF laser pulses at 20 Hz and $I_p \sim 300$ mJ/cm^2 for 30 minutes. Figure 2 shows the dependence of Δn_{mod} on the hydrogen loading time.

The fit curve represent the H concentration C in the fibre core as estimated from Fick's laws of diffusion in cylindrical coordinates[11]. Assuming that the hydrogen is concentration constant over time at the optical fibre surface and equal to zero in the fibre at t=0, C can be expressed as a series of zero- (J_0) and first-order (J_1) Bessel functions[11]:

$$C(r) = 2C_{max}\left[1 - \sum_{n=1}^{\infty} \frac{1}{\chi_n} e^{-\left(\frac{\chi_n^2 t}{\tau}\right)} \frac{J_0\left(\chi_n \frac{2r}{d}\right)}{J_1(\chi_n)}\right], \tag{2}$$

where χ_n represents the n-th root of the equation $J_0(\chi_n)=0$, C_{max} the hydrogen solubility in silica, $\tau = d^2/4D$ the "time constant" of the diffusion process, D the diffusion constant and r the radial coordinate. The optimum fit was obtained for $\tau \sim$ 12.3 days and D$\sim$2.84$\cdot 10^{-11}$ cm^2/s.

The thermal stability of gratings written in hydrogen loaded fibres was studied by means of the master curve method[12]. In this accelerating aging 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 (also called demarcation energy E_d) is defined as E_d=k_BTln(νt), where k_B is the Boltzmann's constant, T the temperature and t the time. ν represents an attempt frequency and is determined during the data fit. In our experiment, four samples of fibre were hydrogen loaded for 6 days at 165 bars. Gratings were written as previously explained. The reflection spectra of the gratings, placed in the furnace, were measured in reflection by means of a white light source, a coupler and an optical spectrum analyzer. The time evolution of the normalized Δn_{mod} (defined as $\eta = \frac{\Delta n_{mod}}{\Delta n_{mod}(0)}$, where $\Delta n_{mod}(0)$ is the initial value of Δn_{mod}) is shown in figure 3 for four different temperatures. 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[12], in the same conditions the gratings written in the hydrogen-loaded phosphosilicate fibre had a change η $\sim$24%. The ν used to fit the data resulted to be 2.5$\cdot 10^{10}$ min^{-1}, considerable smaller than the value found for hydrogen-loaded germanosilicate fibres[13]. The master curve was at best approximated by the equation $\eta = (1 + e^{\frac{E_d - 1.65}{0.1258}})^{-1}$. From the curve it is possible to evaluate what is the thermal decay of a grating after 25 years at 80 ^{0}C: for E_d=1.23eV η=0.966, meaning that $\sim$3.4% of the original grating has been wiped away. As expected, the decay is considerable higher than the one observed in unloaded tin-doped fibres [14,15](<1%); nevertheless it is comparable or better than the values of degradation reported in literature for unloaded traditional fibres, such as germanosilicate[12] or borogermanosilicate fibres[16].

In summary, hydrogen loading enhances the photosensitivity of tin-doped phosphosilicate fibres. The photo-induced refractive index change of the gratings written in hydrogen-loaded fibres is one order of magnitude stronger than the gratings written in the unloaded fibres.

The dependence of fibre photosensitivity on loading time showed that saturation is reached after ~8 days at 25 ^{0}C and 165 bar pressure. 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. The excellent thermal behaviour can be explained by the small characteristic frequency ν of the photo-induced defects.

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REFERENCES

1. P.J. Lemaire, R.M. Atkins, V. Mizrahi and W.A. Reed, Electron. Lett. **29,** 1191 (1993).
2. H. Patrick, S.L. Gilbert, A. Lidgard and M.D. Gallagher, J. Appl. Phys. **78,** 2940 (1995).
3. B. Malo, J. Albert, F. Bilodeau, T. Kitagawa, D.C. Johnson, K. O. Hill, K. Hattori, Y. Hibino and S. Gujrathi, Appl. Phys. Lett. **65,** 394 (1994).
4. P.J. Lemaire, A.M. Vengsarkar, W.A. Reed and D.J. DiGiovanni, Appl. Phys. Lett. **66,** 2034 (1995).
5. T. Taunay, P. Bernage, G. Martinelli, M. Douay, P. Niay, J.F. Bayon and H. Poignant, Opt. Comm. **133,** 454 (1997).
6. T. Taunay, P. Bernage, M. Douay, W.X. Xie, G. Martinelli, P. Niay, J.F. Bayon, E. Delavaque and H. Poignant, JOSA B **14,** 912 (1997).
7. E.M. Dianov, K.M. Golant, R.R. Khrapko, A.S.Kurkov, B. Leconte, M. Douay, P. Bernage and P. Niay, Electron. Lett. **33,** 236 (1997).
8. B. Malo, J. Albert, F. Bilodeau, T. Kitagawa, D.C. Johnson, K. O. Hill, K. Hattori, Y. Hibino and S. Gujrathi, Appl. Phys. Lett. **65,** 394 (1994).
9. P.J. Lemaire, A.M. Vengsarkar, W.A. Reed and D.J. DiGiovanni, Appl. Phys. Lett. **66,** 2034 (1995).
10. Strasser, in Proceedings of *Optical Fibre Communication,* OSA Technical Digest Series (Optical Society of America, Washington DC, 1996), 81, paper TuO1.
11. M.E.Glicksman, "Diffusion in solids - Field theory, solid-state principles, and applications", John Wiley and Sons, (2000).
12. T. Erdogan, V. Mizrahi, P. J. Lemaire and D. Monroe, J. Appl. Phys. **76,** 73 (1994).

13. S. Kannan, J.Z.Y. Guo and P. Lemaire, J. Lightwave Tech. **15,** 1478 (1997).

14. G. Brambilla, and H. Rutt, Appl. Phys. Lett. **80,** 3259 (2002).

15. G. Brambilla and H. Rutt, in *Trends in Optics and Photonis (TOPS) Vol.70, Optical Fiber Communication Conference,* Technical Digest, Postconference edition (Optical Society of America, Washington DC, 2002), paper ThGG35, 660.

16. S.R. Baker, H.N. Rourke, V. Baker and D. Goodchild, J. Lightwave Tech. **15,** 1470 (1997).

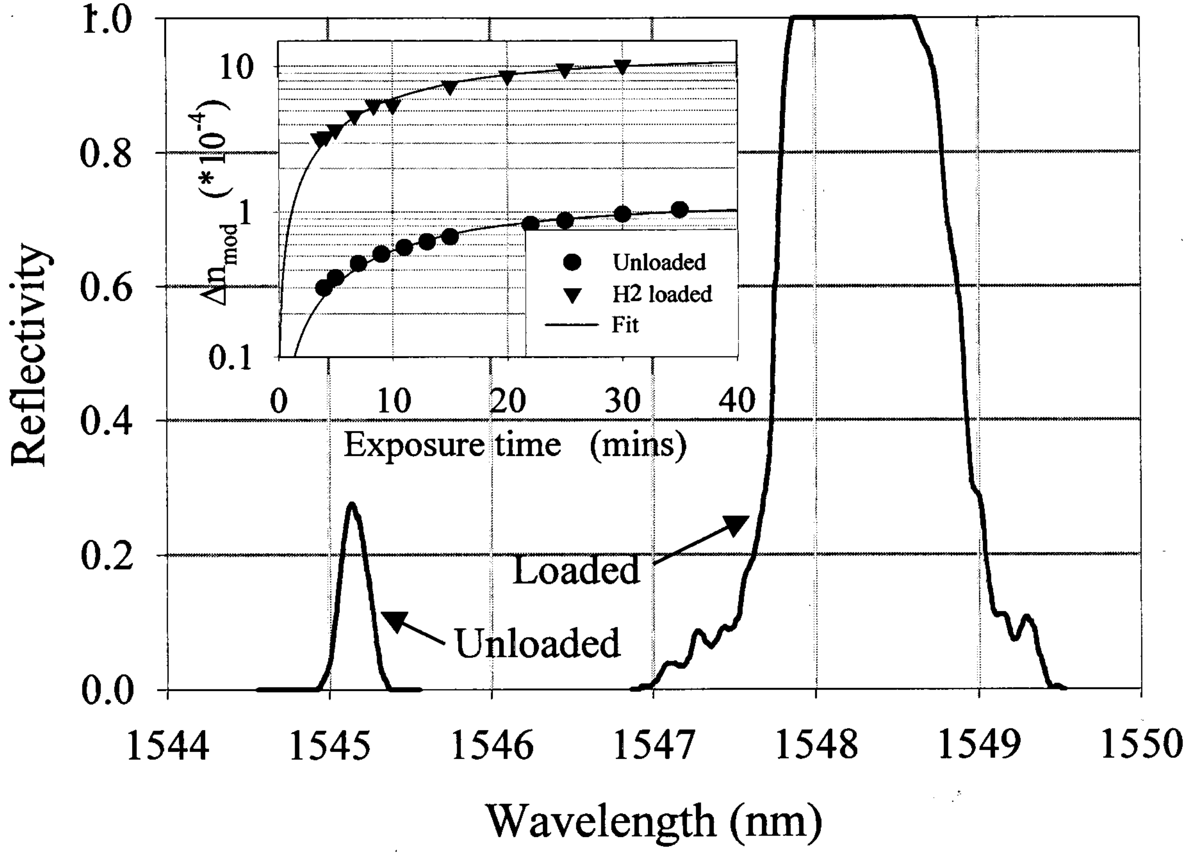
FIGURES

Fig. 1. Reflection spectra of gratings written in loaded and unloaded tin-phosphosilicate fibres. Grating length, exposure time, repetition rate and pulse fluence are L=2mm, t=30 minutes, RR=20 Hz and I_p ~300 mJ/cm^2 respectively. In the inset, temporal dependence of Δn_{mod} for loaded (3 days at 165 bars and 25 ^{0}C) and hydrogen-unloaded fibres.

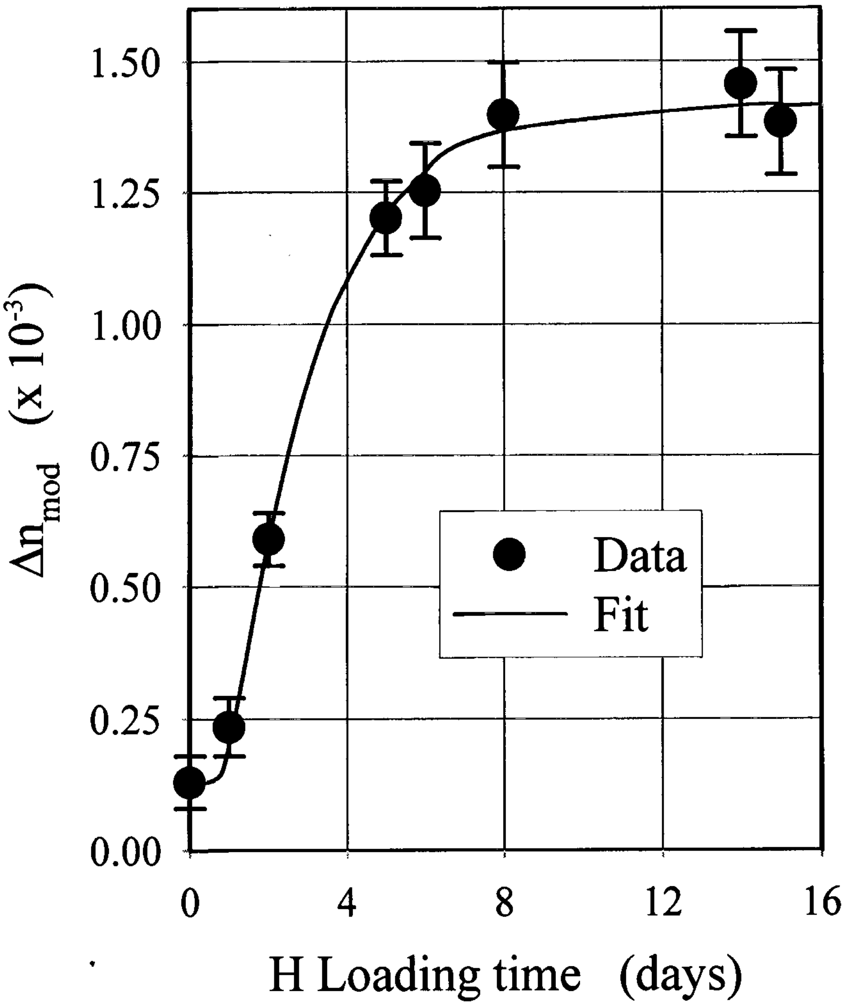
Fig. 2. Dependence of induced photosensitivity on H-loading time. Δn_{mod} represents the change in the refractive index modulation. The fit represents equation 2 for τ_H ~12.3 days and D~$2.84 \cdot 10^{-11}$ cm^2/s.

Fig. 3. Decay of the grating written in H-loaded tin-phosphosilicate fibre for different furnace temperatures. η represents the normalized refractive index modulation change.

Brambilla Fig. 1



Brambilla Fig. 2



Brambilla Fig. 3