

Fiber Bragg gratings with enhanced thermal stability

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Abstract

Gratings written in tin-doped silica fibers by using a 248 nm excimer laser exhibit extremely high thermal stability. Isothermal measurements up to 1100 K demonstrate significant advantages over conventional fiber gratings. Extrapolations from experimental data indicated that gratings operating at 500 K for ten years will retain more than 99 % of the initial strength.

Some Bragg grating devices require extremely small tolerance on the optical properties over a long time scale to assemble reliable wavelength division multiplexing (WDM) components. Other applications, such as sensors, are required to survive high temperatures. Therefore thermal stability of gratings and their lifetime forecast has received much attention in the last 7 years¹⁻⁷. New materials⁸⁻¹¹ and post-fabrication treatments¹²⁻¹⁴ have been proposed to achieve enhanced thermal stability in optical fibers. Tin-phosphosilicate⁸ and tin-germanosilicate⁹ fibers are low-loss in the third telecom window at 1.55 μm (40 and 2dB/km, respectively) and exhibit high photosensitivity, but they have high numerical aperture (NA)($\text{NA}>0.2$)⁸, thus poor compatibility with telecom fibers. Oxynitride fibers are not photosensitive to 248 nm excimer laser radiation and require shorter wavelength lasers¹⁰. Post-fabrication techniques require the fibers to be hydrogen loaded¹²⁻¹⁴; this is time-consuming and induces high-loss at 1.55 μm . Ultraviolet (UV) sensitization can be optimized to reduce the induced loss but still requires the fiber to be hydrogen-loaded¹⁵. Compared to Boron-codoping and Hydrogen-loading, the use of SnO_2 keeps the absorption at 1.55 μm low, is less time consuming and potentially cheaper. In particular, if tin is used as the only dopant, fibers with telecom compatible NA can be fabricated^{16,17}. Bragg grating sensors written in tin-silicate (SS) fibers can have large-scale multiplexing and remote interrogation.

In this paper, the temperature stability of gratings written in SS fibers is evaluated by using the isothermal method¹.

If the grating reflectivity (R) is recorded as a function of time t and the refractive index modulation (Δn_{mod}) is evaluated from R at the Bragg wavelength (λ_B) and the grating length (L) using the relation $R(\lambda_B) = \frac{\pi}{\lambda_B} \Delta n_{mod} L$, it is possible to measure the grating decay with the normalized integrated coupling constant (η), defined as the ratio $\frac{\Delta n_{mod}(t)}{\Delta n_{mod}(0)}$ between Δn_{mod} at time t and its initial value $\Delta n_{mod}(0)$. The time dependence of η is well approximated by a power-law dependence¹:

$$\eta = \frac{\Delta n_{mod}}{\Delta n_{mod}(0)} = \frac{1}{1 + Bt^\epsilon} \quad (1)$$

where the temperature-dependent coefficients B and ϵ can be easily expressed as $B = B_0 e^{-bT}$ and $\epsilon = \frac{T}{T_0}$ (B_0 , b and T_0 are constants).

The power law has been used to explain the observed temperature dependence with defect dynamics^{1,3}. In this model the refractive index change is induced by electrons that are excited to the conduction band by UV radiation and are then trapped in a continuous distribution of energy states situated within the band gap^{1,4}. In other words, the induced refractive index change at time t seems to be strictly proportional to the total number of electrons $N(t)$ trapped ($\Delta n_{mod}(t) = \alpha N(t)$). Thermal erasure is the process of emptying the traps; the depopulation is ruled by statistical processes and is supposed to follow an exponential-law relation¹. The detrapping rate is enhanced at high temperatures and is time dependent. It is possible to define an aging parameter (called demarcation energy $E_d(T,t) = k_B T \ln(\nu_0 t)$) that includes both time and temperature (k_B is the Boltzmann constant, ν_0 the characteristic frequency of the electron in the trap). The demarcation energy increases with time to take into account the electrons that moved to the conduction band.

On the basis of experimental results, the following energy distribution of trap density has been proposed¹:

$$g_0(E) = \frac{N_0}{k_B T_0 \cdot \frac{e^{\frac{E-E_p}{k_B T}}}{\left[1 + e^{\frac{E-E_p}{k_B T}}\right]^2}} \quad (2)$$

where $g_0(E)$ is the energy density of states, $k_B T_0$ is related to the full width at half maximum (FWHM) ($\text{FWHM} \sim 3k_B T_0$) and $E_p = -k_B T_0 \ln(B_0)$ represents the peak of the distribution. If post-processing is not carried out³, the grating stability is uniquely determined as a function of E_p and T_0 . The higher and narrower the energy density of states (high E_p and low T_0), the higher the grating thermal stability.

In order to compare the thermal stability of gratings written in SS fibers, isochronal experiments were carried out. Gratings were written using a KrF excimer laser and a phase mask in four different fibers: SS, germanosilicate (GS), borogermanosilicate (BGS) and hydrogen loaded telecom (HLT). The SS, GS and BGS fibers were produced via modified

chemical-vapor deposition (MCVD). The numerical aperture (NA), cut-off wavelength (λ_c) and loss (α) of the fibers are given in table I. The SS fibre loss, evaluated using the cut-back method over 250 m, was $\alpha \sim 8$ dB/km at $1.55 \mu\text{m}$ and $\alpha \sim 16$ dB/km at $1.3 \mu\text{m}$. The water content (1 ppm) was estimated from the absorption at $1.38 \mu\text{m}$ of the second harmonic of the OH peak (~ 45 dB/km). Δn_{mod} was calculated from the $R(\lambda_B)$. The gratings were spliced together and placed in a furnace. The experimental set-up allowed in-situ measurements to be carried out. Light from a LED passed through a 50/50 coupler and reached the gratings in the furnace. The reflected light passed through the coupler and was then collected by an optical spectrum analyzer. A reference grating was placed outside the furnace and used to compensate for eventual output oscillations of the light source. An additional thermocouple was inserted in the furnace to have a better measurement of the furnace temperature. The grating temperature was increased at a rate of ~ 25 K/min and left at each temperature for 8 hours. The furnace temperature was then decreased and $R(\lambda_B)$ measured. The thermal cycle was subsequently repeated increasing the maximum temperature in steps of 100 K. Several cycles have been performed starting from 360 K.

The grating coupling constants η were evaluated from the reflection spectra and then plotted versus temperature. Figure 1 summarizes the measurements performed on all the fibers. Although the BGS and HLT fibers showed high photosensitivity, their thermal stability was very poor. From figure 1 the gratings are seen to be completely erased at 760 K ($\eta(760\text{K})=0$). In particular, the grating fabricated in the HLT fiber cannot even survive thermal treatment at 560 K. Gratings written in germanosilicate (GS) fibers (NA ~ 0.28 , $\lambda_c \sim 1250$ nm) show lower photosensitivity than those in BGS and HLT fibers but they have a slower decay. Nevertheless GS fiber gratings still showed a gradual decrease in reflectivity with increasing temperature and vanished after treatment at 960 K.

On the contrary, the grating fabricated in the SS fiber showed extremely high thermal stability and still maintained more than 20 % of the initial Δn_{mod} after the treatment at 1060 K ($\eta(1060\text{K}) > 0.2$). According to the "defects theory" the enhanced temperature stability indicates that the traps are very deep in energy and their distribution is narrow. Since Δn

is given by structural changes^{17,18}, it is possible to use the same mathematical formalism to describe the changed configuration if $g_0(E)$ is assumed to represent the energy distribution of the modified structure. The energy distribution of electronic traps in GS fiber has been evaluated previously from the isothermal method¹.

Three gratings were written at ~ 1543 nm using a 248 nm KrF excimer laser and a phase mask. Repetition rate, pulse duration, pulse fluence, grating length and exposure time were 20 Hz, 20 ns, $I_p \sim 0.1$ J/cm², $L=4$ mm and 40 minutes respectively. The reflectivity at the Bragg wavelength was $\sim 90\%$. Each grating was placed in the furnace at a different temperature and the transmission at the Bragg wavelength was continuously monitored. Figure 2 shows the time decay of the gratings for three different temperatures ($T=750, 920$ and 1100 K). It must be noted that reversible changes in the spectral characteristics of the fiber Bragg gratings have been observed when the temperature is changed¹⁹. In order to have a quantitative correct measurement, correction have to be adopted to compensate for the temperature-induced changes. This corrections have been shown to be non-negligible when the Ge-doping level is high or when the core contains B. The experiment reported in figure 1 has shown that no similar temperature-induced reversible changes have been observed in the refractive index of SS fibres. While at 750 K the grating undergoes just a small decay within 4 hours, at 1100 K a considerable decay is observed in the initial 10 minutes. A comparison with the measurements made on gratings written in GS fibers¹ shows that a similar decay occurs at $T=820$ K.

The experimental data of figure 2 were fitted by using equation 1. The coefficients B and ϵ for each temperature fit are given in table II.

Table III shows the coefficients T_0 , B_0 and b that best fit the values of B and ϵ reported in table II with the derived values of E_p and FWHM. Table III also reports the literature data on gratings fabricated in GS and BGS fibers. A comparison of E_p clearly shows that SS has by far the highest E_p and a relatively small FWHM. This implies that the fraction of electronic traps having low energy (below 1 eV) in the SS fiber is considerably smaller than in the other fibers. Figure 3 shows η as a function of the demarcation energy. The

experimental data are fitted by the solid line obtained from the parameters in table III.

Figure 4 presents the trap energy-distribution g_0 obtained by inserting the coefficients of table III in equation 2. Visual comparison shows a considerable difference in the fraction of traps at low energy. This implies an enormous improvement when very good stability is required over a long time. For example, at 500 K a change of 1 % occurs after 0.2 μ s and 5 ms in the BGS and GS fibers and after 11 years in the SS fiber. A post-fabrication grating anneal can also be carried out to empty the electronic traps at low energy and improve the grating stability even further.

Isochronal measurements showed that Bragg gratings written in tin-silicate fibers are more robust than those written in germanosilicate and boro-germanosilicate fibers. In particular, no significant degradation has been observed below 850 K over a few hours. Experiments carried out using the isothermal method explain the enhanced stability with a different energy distribution of the traps. In tin-doped silicate fibers the distribution peaks at higher energy and has a smaller FWHM with respect to the distribution in germanosilicate fibers. The nearly complete absence of traps at low energy implies a great difference in the erasure process. This exceptional temperature performance of the SS fiber makes it the most suitable candidate to improve the reliability of high-temperature grating-sensing applications and fiber Bragg-grating components for WDM systems.

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TABLES

Table I. Numerical aperture (NA), cut-off wavelength (λ_c) and loss (α) at 1.55 μm of the fibers used in the experiments. SS, GS, BGS and HLT represent tin-silicate, germanosilicate, boro-germanosilicate and hydrogen-loaded telecom fibers, respectively.

Fiber	NA	λ_c [μm]	α dB/km
SS	0.1	1.3	8
GS	0.28	1.2	5
BGS	0.12	1.4	~200
HLT	0.11	1.2	-

Table II. Summary of coefficients B and ϵ used in the equation 1 to fit the data presented in figure 2.

T [K]	B [min ⁻¹]	ϵ
750	0.0327	0.2409
920	0.2906	0.2427
1100	1.6302	0.2480

Table III. Comparison between thermal decay coefficients in tin-silicate (SS), germanosilicate (GS) and boro-germanosilicate (BGS) fibers.

	SS	GS ^a	BGS ^b
B	8.132×10^{-6}	1.86×10^{-3}	1.92×10^{-4}
b (K ⁻¹)	1.12×10^{-2}	7.64×10^{-3}	1.31×10^{-2}
T ₀ (K)	3.792×10^3	5.250×10^3	2.941×10^3
ν_0 (Hz)	4.64×10^{16}	1.9×10^{15}	5.40×10^{16}
E _p (eV)	3.7	2.8	2.1
FWHM (eV)	1.13	1.54	0.86

^aFrom¹

^bFrom⁵

FIGURES

Fig. 1. Dependence of grating decay on temperature T . η is the normalized integrated coupling constant. SS, GS, BGS and HLT represent the gratings written in tin-silicate, germanosilicate, boro-germanosilicate and hydrogen-loaded telecom fibers respectively.

Fig. 2. Time decay of gratings written in the SS fiber at different temperatures. η represents the integrated coupling constant. Solid lines are fits to the data obtained with equation 1.

Fig. 3. Dependence of normalized integrated coupling constant η on demarcation energy E_d . The solid line is the fit obtained with the parameters of table III.

Fig. 4. Energy distribution (equation 2) of the traps density of states ($g_0(E)$) in SS, GS¹ and BGS⁵ fibers.