Influence of Blanket Postexposure on the Thermal Stability of the Spectral Characteristics of Gratings Written in a Telecommunication Fiber Using Light at 193 nm

Qinglin Wang, Arif Hidayat, Pierre Niay, and Marc Douay

***Abstract*—Bragg gratings have been written in a nonhydrogenated Corning's SMF28 telecommunication fiber using ultraviolet (UV) pulses at a high power density from an ArF laser. Some of these gratings were uniformly exposed with light at 193 nm. The isothermal accelerated aging method was used to characterize the thermal decays of both pristine and postexposed grating spectral characteristics. UV postprocessing led to an increase in the stability of the Bragg grating reflectivity meanwhile the shifts in the Bragg wavelengths of the postexposed gratings proved to be higher than those of untreated gratings. It is shown that the isothermal decays of the refractive index modulation cannot be used to predict the annealing induced irreversible shifts in the Bragg wavelengths. Our observations are discussed within the frame of the current theoretical descriptions of the links that may exist between the writing and the thermal stability of Bragg gratings.**

***Index Terms*—Bragg gratings, decay analysis of gratings, fiber gratings, optical communication, reliability, thermal reliability.**

I. Introduction

FIBER Bragg gratings (FBGs) are currently used for numerous applications such as spectral filtering, fabrication of fiber lasers or hybrid semiconductor-fiber lasers, fiber amplifier gain flattening, compensation of group velocity dispersion or fabrication of fiber sensors. The many applications of fiber grating technology are reviewed in recent papers or books [1]–[4]. Most applications require a long grating lifetime. For example, in dense wavelength-division-multiplexing (DWDM) optical communication systems, the grating spectral characteristics should be kept working to agreed specifications for 25 years in the temperature range $-40\ ^{\circ}\mathrm{C} < \theta < 80\ ^{\circ}\mathrm{C}$. Accordingly, the thermal stability of germano-silicate fiber grating reflectivity has been extensively studied through isothermal or isochronal annealing experiments ([5]–[15]). For analyzing and predicting the decay in the grating reflectivity, it is usually assumed that the grating inscription populates a broad distribution of thermodynamically unstable traps, those with a low activation energy decaying faster than those with a high one. The theory also postulates that the ultraviolet (UV)-induced change in refractive index is proportional to the population of traps. Provided that the decay only originates in one first-order thermally activated reaction, it can be shown that there exists a boundary for the activation energy (namely, the demarcation energy E_d) above which the traps remain filled [5], [16]. Assuming further that the distribution is temperature independent, one can show that the change in the refractive index after heating the grating at a temperature T for a time t only depends on $E_d = k_B T \ell n(k_o t)$ (k_B is the Boltzman constant and k_o is a parameter) [5] [16]. Starting from these hypotheses and assuming that the distribution of traps is a bell-shaped function of the activation energy, Erdogan *et al.* have shown that the decay in the change of refractive index is characterized by a "power law" function of time [5]. This behavior proved to be consistent with that measured for the refractive index modulation of nonhydrogenated fiber gratings. Furthermore, Erdogan's approach gives a coherent rationale of the thermal method usually carried out for stabilizing the spectral characteristics (i.e., heating the grating at a high temperature for a short time before using it at a lower temperature). Recently, Salik *et al.* have proposed an alternative method for stabilizing the strength of fiber grating without temperature annealing [17]. Briefly, the method consists in exposing the fiber to uniform light either before, during or after the grating inscription. Salik *et al.*have demonstrated the efficiency of the method for gratings fabricated in nonhydrogenated germano-silicate fibers by means of near UV light at 334 nm (or at 244 nm) [17]. Photosensitivity at 330 nm is triggered off by the excitation of the GODC triplet state through a one-photon absorption from the ground state [18]. Salik *et al.* could observe a strong enhancement in the thermal stability of the treated grating refractive index modulation when compared to that of pristine gratings. These authors have explained this observation by assuming that there exists a link between the writing conditions (namely, the rate

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of transformation of the defects being responsible for the photosensitivity) and the thermal stability of the resulting fiber grating: the longer the exposure time ; the higher the stability of the change in the refractive index. A first objective of the present paper is to show that the above-mentioned stabilization method is also efficient for gratings written in a standard fiber using pulsed exposure at 193 nm, i.e.: a photosensitive process which involves a two-photon absorption and makes it possible to increase the writing efficiency in a standard fiber without sensitization [19]. A second aim of the paper is to show that the postexposure stabilization method increases the thermal stability of the grating reflectivity at the expense of that of the Bragg wavelength. The results are discussed within the frame of the current theoretical approaches for predicting grating stability.

II. Experimental Details and Results

First, a series of nearly identical 20-mm-long gratings has been fabricated within samples of a standard fiber (Corning's SMF28 fiber with 1.4 at % of germanium in its core). To this end, the fibers were exposed through a phase-mask to light at 193 nm from a pulsed ArF laser (characteristics of the mask purchased from QPS SA: pitch=1061 nm, diffraction efficiency $<$2% in the zero order, $>$38% in the $+1$ and -1 order). The mean UV fluence per pulse at the fiber core was 120 mJ/cm^2 with a frequency rate of 10 Hz. The growth of the gratings was stopped after $\cong$13 000 pulses at a time when the reflectivity was $R \cong 0.8.$, which corresponds to a refractive index modulation ($\Delta n_{\rm mod}$) of $\cong 5.3\,10^{-5}$. Interestingly, one can note that, at this time, the fiber photosensitivity was not saturated since this figure is lower, by at least an order of magnitude, than the saturated modulation which can be obtained in the SMF28 fiber once the exposure to 193 nm light is performed at a high fluence per pulse (typically $\Delta n_{\rm mod} \cong 10^{-3}$ after exposure of the fiber to 36 000 pulses at 650 mJ/cm^2 [19]). At the end of the exposure with the fringe pattern, the shift in the Bragg wavelength reached 0.063 nm, which corresponds to an increase in the core mean refractive index ($\Delta n_{\rm mean}$) by $\cong 1.3\,10^{-4}$.Then, some of the gratings were uniformly exposed with light from the ArF laser using the same frequency rate and power density as those used for the grating inscription. Due to the unavailability of the ovens devoted to the annealing experiments just after the grating inscriptions, the gratings were then stored at room temperature and pressure for one month. Finally, each grating was heated in a tubular furnace at a constant temperature ($T = 383 \pm 1$ K, or 453 ± 1 K or 523 ± 1 K) for a period of $\cong$350 h. To this end, the portion of the fiber within which the grating had been written was quickly translated up to the furnace. The origin of annealing time was arbitrarily taken at the moment when the grating was put at the center of the furnace. During annealing, the fibers were kept straight and still in order to reduce possible Bragg wavelength shift due to changes in fiber stress or position within the oven. In the course of writing, postexposing or annealing the gratings, transmission (and) reflection grating first-order spectra were periodically recorded by means of a monofrequency tunable infrared laser (TUNICS from Photonetics SA) and an optical power-meter (RIFOCS corporation 575L). To improve the accuracy of the Bragg wavelength measurement, the wavelength of the mono-frequency tunable laser was periodically calibrated to within an accuracy better than 1 pm with the help of a wavemeter (WA 1500 from Burleigh inc.). The data were computerized and stored in a PC. The experiments were carried out twice to check the reproducibility of the measurement. The accuracy of the reflectivity (R) determination is estimated to be better than 0.01. The UV-induced Bragg wavelength shifts were obtained as the differences between the Bragg wavelength after N pulses of UV light and those at the early times of the inscriptions (i.e., after $\cong 1300$ pulses of light from the fringe pattern when R $\cong 0.03$). To separate the temperature-induced reversible shifts in the Bragg wavelength from the annealing-induced irreversible ones, we proceeded as follows. Firstly, immediately before annealing, grating spectra were recorded at 23 °C to determine a reference Bragg wavelength ($\lambda_{\rm ref}$). Right at the end of the annealing, the Bragg wavelength ($\lambda_{\rm end}$) of the grating was measured. Then, the temperature of the oven was reduced down to room temperature (23 °C) and, at this time, the new Bragg wavelength ($\lambda_{\rm annealing}$) was measured. The difference ($\lambda_{\rm end} - \lambda_{\rm annealing}$) corresponds to the temperature-induced reversible shift, whereas ($\lambda_{\rm annealing} - \lambda_{\rm ref}$) is the annealing-reduced irreversible total shift. Thus, we were in position to correct the Bragg wavelength measured during annealing from the temperature-induced reversible shift. The absolute accuracy of the Bragg wavelength measurement is estimated to be better than 0.005 nm. Fig. 1 shows typical evolutions of the grating reflectivity and Bragg wavelength as a function of the number of UV pulses. It shows that the uniform postexposure led to a significant decrease in the grating reflectivity and to a further increase in the Bragg wavelength shift (the shift after blanket exposure $=$ 0.272 nm, which corresponds to an increase in the core mean refractive index by $\cong 3.9\,10^{-4}$). It is noteworthy that the FWHM linewidths of the gratings before and after postexposure were 0.060 nm and 0.061 nm (theoretical linewidths $= 0.06$ nm). Figs. 2 and 3, respectively, show the evolutions of the normalized integrated coupling constants (ICCs)

$$\eta \left(\eta = \frac{\tanh^{-1}\left(\sqrt{R(t,T)}\right)}{\tanh^{-1}\left(\sqrt{R(0,\,296{\rm K})}\right)} = {\rm ICC} \right)$$

where $R(0,\,296{\rm K})$ and $R(t,T)$ are respectively the initial grating reflectivity and that after annealing at T for a time t) and those of the Bragg wavelength shifts. The empty and full symbols are for postexposed and pristine gratings, respectively. In fact, η measures the evolution of the refractive index modulation as a function of annealing time, provided that the fraction of the optical power carried in the fiber core is constant for the time of the measurement. As the core mean refractive index irreversibly decreases with annealing time, one can suspect that this hypothesis is here non valid. However, the annealing-induced irreversible shift in the Bragg wavelength proved to be lower than -0.05 nm. Consequently, the confinement factor can be assumed to remain constant to within 1%. Annealing the gratings at 250 °C for 350 h led to a reduction of the grating

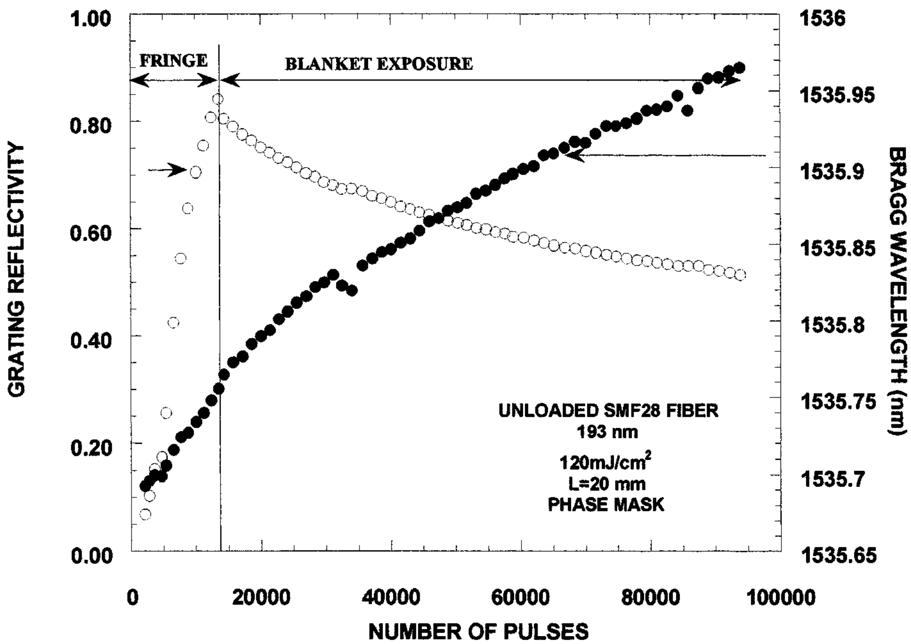

Fig. 1. Growth of the grating reflectivity and shift in the Bragg wavelength in the course of the exposure of the SMF 28 fiber to light at 193 nm. Empty symbols are for the reflectivity and full symbols are for the Bragg wavelength (nm).

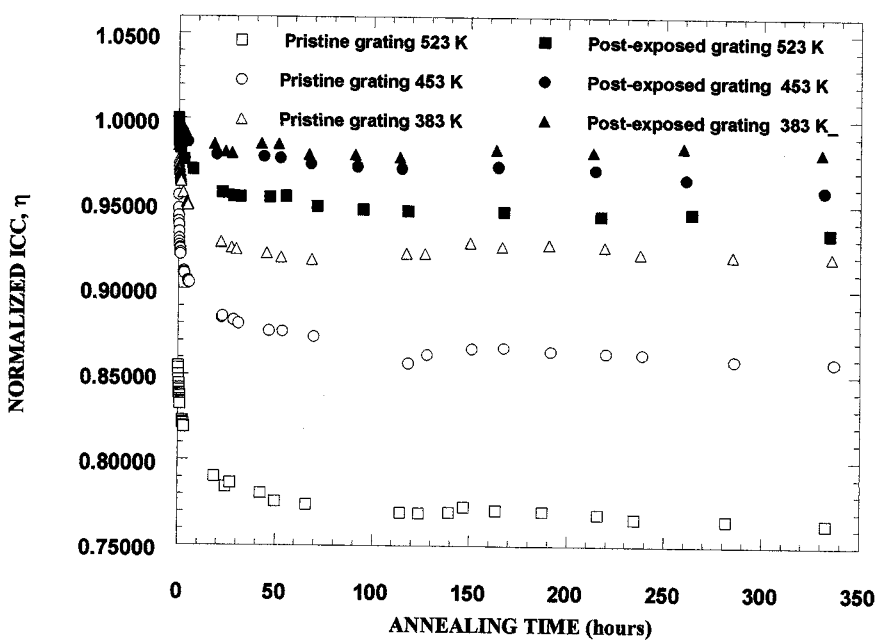

Fig. 2. Isothermal decays of the normalized integrated coupling constant (η) as a function of annealing time (hours). Full symbols are for postexposed gratings and empty symbols are for untreated gratings. Squares, circles and triangles correspond to temperatures at 523, 453, 383 K, respectively.

linewidths by a quantity <0.01 nm. Comparing the curves in empty and full symbols in Fig. 2, one can see, that, as in the case of CW exposure [17], uniform pulsed postexposure significantly increases the stability of the grating reflectivity. In contrast, the annealing-induced shifts in the Bragg wavelength of the postexposed gratings are higher than those of the pristine gratings. This result indicates that the improvement in the thermal stability of the grating reflectivity is made at the expense of that of the Bragg wavelength.

III. Discussion

Our experiments (or those by Salik *et al.*) deal with uniform gratings written in nonhydrogenated germano-silicate fibers at high writing intensity. These experiments, conclusively, demonstrate that the thermal stability of the grating spectral characteristics depends on the writing conditions.

Such a conclusion can be at first sight explained either through a modified form of the Erdogans approach in which

TABLE I
COMPARISON OF THE ANNEALING-INDUCED EXPERIMENTAL BRAGG WAVELENGTH (B.W.) SHIFTS TO THOSE CALCULATED USING THE DATA IN FIGS. 1 AND 2 [I.E.: THE TOTAL SHIFTS EXPERIENCED BY THE GRATING B.W. IN THE COURSE OF THE INSCRIPTION (FIG. 1) AND THE ISOTHERMAL DECAYS OF ICC IN FIG. 2]

Type of annealed gratings annealing temperature	Shifts in the B.W. (nm) calculated from the pristine grating ICC at the end of the annealing	Shifts in the B.W. (nm) calculated from the post-exposed grating ICC at the end of the annealing	Experimental B.W. shifts at the end of the annealing experiments (nm)
Pristine gratings UV-induced B.W. shift $\Delta\lambda_{Bragg}(0,296K) = 0.063$ nm			
383 K ± 1 K	- 0.005	- 0.001	- 0.012 ± 0.005
453 K ± 1 K	- 0.009	- 0.003	- 0.004 ± 0.005
523 K ±1 K	- 0.015	- 0.004	- 0.007 ± 0.005
Post-exposed gratings UV-induced B.W. shift $\Delta\lambda_{Bragg}(0,296K) = 0.28$ nm			
383 K ± 1 K	- 0.022	- 0.005	- 0.020 ± 0.005
453 K ± 1 K	- 0.040	- 0.012	- 0.030 ± 0.005
523 K ±1 K	- 0.066	- 0.018	- 0.050 ± 0.005

it is assumed, as suggested by Kannan *et al.* [12], that the temperature of the core region experiences a significant rise at the time of the grating inscription or the Various Reaction Pathway Approach (VAREPA) by Poumellec [16] in which the reversibility of the writing and erasing reactions is assumed. The two approaches differ by an important feature which leads to distinct behaviors for the contrast of the refractive index modulation (contrast $= \Delta n_{\rm mod}/\Delta n_{\rm mean}$). Indeed, the first approach is a nonlocal one as the rise in the temperature of the grating can be assumed to be constant over the length of the grating. Accordingly, the UV light-induced rise in the grating temperature leads to a bleaching of the traps with a low activation energy at the same rate everywhere along the grating. Thus, the distribution of sites before annealing depends on the mean UV power density and the exposure time, the longer the exposure time, the larger the truncation of the distribution of sites [see [12, Fig. 7(d)]) and consequently the higher the stability of the refractive index change. Thus, provided that the grating is uniform, the distribution of sites can be assumed to be the same everywhere along the grating length. Heating the grating to perform the annealing experiment keeps the contrast of the refractive index modulation constant, as the change in the refractive index only depends on E_d and not on the initial modulation. As a result from this approach, the decays in $\Delta n_{\rm mod}$ and $\Delta n_{\rm mean}$ follow the same temporal evolution. Thus the master aging curve used for predicting grating decay can be built by means of either the ICC or the Bragg wavelength shift data or, equivalently, the decay of $\Delta n_{\rm mean}$ can be predicted from that of $\Delta n_{\rm mod}$.

In contrast, the VAREPA approach is a local one. Indeed, it assumes that, as the writing time or (and) the writing power density are made to increase, the discontinuity of the degree of advancement of the writing reaction moves toward higher energy [16]. This means that the distribution of traps before annealing differs at the bright fringes from that at the dark fringes. Furthermore, by assuming the forward and backward reaction pathways are the same, B. Poumellec has shown that the decay rate for the change in refractive index $\Delta n(z,\, t,\, T)$ depends on the initial value of the index change ($\Delta n_i(z)$), the higher $\Delta n_i(z)$, the slower the decay rate. This means that the thermal stability of the refractive index at the bright fringes is higher than that at the dark fringes. Heating the grating not only triggers a decrease in the change of refractive index but also a rise in the contrast of the modulation. Now, let us assume that a master aging curve has been built from isothermal decays of ICC. Obviously this master curve cannot be used to predict the decays of the grating Bragg wavelength since the decays in $\Delta n_{\rm mean}$ is faster than that of $\Delta n_{\rm mod}$.

To check this point, we have compared the experimental shifts in the Bragg wavelength at the end of the annealing experiments to those calculated from the corresponding ICC values (comparison performed at a fixed value of E_d). To this end, we have assumed, for a while, that the decays in $\Delta n_{\rm mod}$ and in $\Delta n_{\rm mean}$ follow the same temporal evolution. Thus, we have assumed that $\eta(t,\, T) = (\Delta n_{mean}(t,\, T)/\Delta n_{mean}(0,\, 296\,{\rm K})) =$ ICC. Column 4 of Table I displays the experimental values of the pristine and post exposed grating Bragg wavelength shifts at the end of the annealing experiments (Fig. 3). The calculated shifts in the Bragg wavelength are given in columns 2 and 3 for the pristine and post exposed gratings respectively. To perform this calculus, we took the UV light-induced Bragg wavelength shift at the end of the exposures as the normalization factors [$\Delta n_{\rm mean}$(0, 296 K)]. Concerning the comparison of the Bragg wavelength of the pristine gratings, the differences between the calculated and experimental values are not really significant when taking into account of the experimental uncertainty. In contrast, with regard to the postexposed gratings, these differences become significant especially for the data corresponding to the annealing experiment at 523 K. This conclusively shows that the thermal stability of grating Bragg wavelength cannot be accurately predicted from a master curve built using the ICC $= \Delta n_{\rm mod}(t, T)/\Delta n_{\rm mod}$(0, 296 K) data. Obviously, to accurately predict the stability of the Bragg wavelength, one has to build a specially designed master curve by combining the Bragg wavelength decay data together. The fact that the experimental shifts in the Bragg wavelengths of the postexposed grating are lower than those predicted using the pristine grating ICC, means that the postexposure reduces the rate of thermal

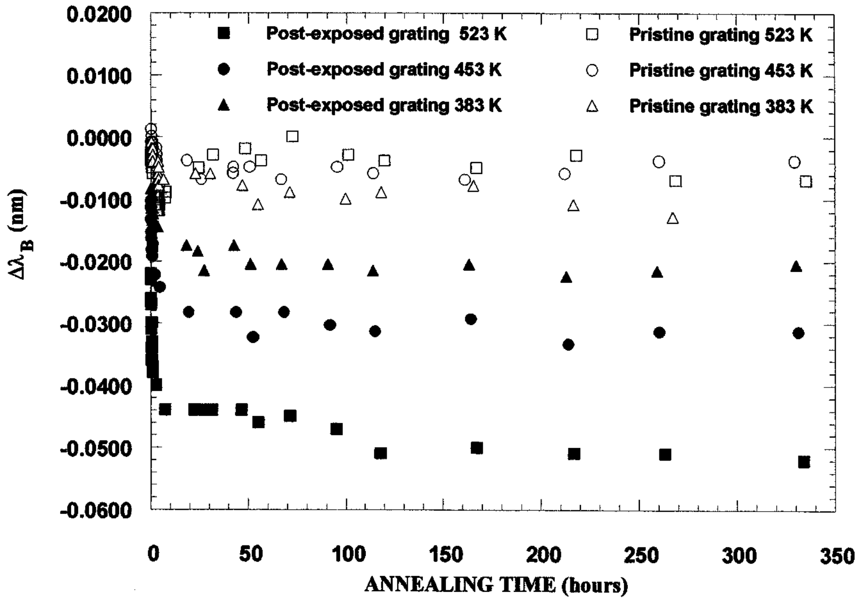

Fig. 3. Isothermal decays of the Bragg wavelength shifts as a function of annealing time (hours). Full symbols are for postexposed gratings and empty symbols are for untreated gratings. Squares, circles and triangles correspond to temperatures at 523, 453, and 383 K, respectively.

decay for the mean refractive index change. However, as the postexposure increases the change in the mean refractive index, the annealing-induced shifts in the Bragg wavelength remain high. It is noteworthy that the shifts in the Bragg wavelength calculated from the postexposed grating ICC are lower than the experimental Bragg wavelength shifts. We would like to suggest that this discrepancy provides a clue that the thermal stability of the change in refractive index locally increases with this change as it is assumed in the VAREPA approach [16]. However, an other explanation could be that different defect distributions are responsible for the mean index change and the modulation, the distribution for the mean index being less stable than that for the modulation. This hypothesis has already been suggested in [20] and [21]. Indeed, it has been demonstrated that the Ge(1) and Ge(2) defect centers mainly contribute to the uniform component of the index of Bragg gratings in germano-silicate fibers [20], [21], whereas the Ge(E') centers are responsible for a large part of the modulation [22]. It is well known that the thermal stability of Ge(1) and Ge(2) defect traps is significantly lower than that of Ge(E') [23]. However, we do not believe that the bleaching of the Ge(1) and Ge(2) centers can entirely account for the order of magnitude of the difference between the shifts at 523 K. Indeed, B. Leconte has measured the evolution of the UV-induced absorption ascribed to Ge(1) and Ge(2) centers in the course of exposure of a highly doped germano-silicate glass to light at 193 nm. He has estimated that the Kramers–Kronig contribution of this absorption to the mean refractive index is lower than 5×10^{-5} [21]. Moreover, Tsai and Friebele have shown that the UV-induced concentrations of Ge(1) and Ge(2) traps in a SMF28 fiber are lower by an order of magnitude to those in a highly doped fiber [22]. Consequently starting from the assumption that these figures are also valid in our experimental conditions, we can give a crude estimation for the contribution of the Ge(1) and Ge(2) traps to the mean refractive index $\cong 10^{-5}$. The difference between the two shifts at 523 K in columns 3 and 4 of Table I respectively correspond to a mean refractive index variation of $\cong 4.4 \times 10^{-5}$. Thus, this figure looks too high to be entirely explained through the thermal annealing of the Ge(1) and Ge(2) centers.

Now, from a practical point of view, the results displayed in Table I show that assuming the validity of the aging curve approach and building a master curve by combining together data obtained from isothermal decays of pristine grating ICC [5] [10] will overestimate the rates of decay for both the ICC and the Bragg wavelengths of the postexposed gratings. Thus, when predicting the reliability of postexposed gratings through this method, one only has to keep in mind that it leads to pessimistic estimations. However, it can easily be carried out as it only requires the recording of the evolution of the pristine grating reflectivity with annealing time and in fact reduces the difficulty that comes from an accurate measurement of the grating Bragg wavelength .We have used this method to firstly estimate how the storage of gratings at room temperature for one month could change the results of annealing and secondly to predict the Bragg wavelength shift for a postexposed grating kept at 80 °C for 25 years.To this purpose, we have built a master curve by plotting all the data displayed in empty symbols in Fig. 2 according to the aging parameter E_d [5]. The value of the parameter which optimizes the collapse of the three plots into one is $k_o \cong 1.7\,10^{14}$ Hz .Thus it can be concluded that storing the grating at 23 °C for 30 days yields an equivalent decay to that obtained at temperatures of 110 °C, 180 °C, or 250 °C for times respectively lower than 60, 0.2, or 0.03 s The changes in the grating spectral characteristics which result from these annealing conditions remain below the accuracy of our measurements. Now, keeping a grating at 80 °C for 25 years yields an equivalent decay to that obtained when the grating is kept at 110 °C for 140 days. Thus, Fig. 3 shows that the upper limit for the shift in the Bragg wavelength experienced by a postexposed grating kept in these conditions is about 0.02 nm. Obviously, such an aging-induced shift is acceptable for most applications, but must be taken into account in future DWDM systems when the projected space between channels can be lower than 0.2 nm.

IV. Conclusion

In conclusion, we have shown that UV postexposure of a grating to uniform light at 193 nm with a high power density leads to an increase in the thermal stability of the refractive index modulation. Uniform postexposure induces a strong rise in the fiber core mean refractive index at the grating place. Consequently, the annealing-induced shift experienced by the postexposed grating Bragg wavelength. proves to be larger than that for an untreated grating. However, it remains quite acceptable for most current applications of Bragg gratings. The rate of annealing-induced decrease in the mean refractive index looks larger than that of the index modulation. Consequently, long-term decay of the grating Bragg wavelength cannot be accurately predicted through a master aging curve approach using ICC data but in contrast one has to build a master curve from annealing-induced decays of Bragg wavelength. This difference between the rates of decay can be explained by assuming either that the annealing increases the contrast of the modulation or (and) that different defect distributions are responsible for the mean refractive index change and the modulation. A coherent rationale of the first hypothesis is formulated in the VAREPA approach [16], whereas the mean refractive index change ascribed to the UV-induced formation of Ge(1) and Ge(2) defects seems too low to account for our measurements.

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