Annealing of UV-induced fiber gratings written in Ge-doped fibers: investigation of dose and strain effects

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Abstract: Effects of UV-dose and fiber strain on annealing properties of fiber gratings written in Ge-doped fibers have been experimentally investigated. It was found that tensile stress in the fiber core strongly changes the grating decay curve. A new band in the distribution of the activation energy of the grating thermal decay with a center at 2.9 eV has been observed.

OCIS codes: (060.2270) Fiber characterization, (060.2400) Fiber properties

1. Introduction

The goal of most studies of thermal stability of photoinduced fiber gratings is to reveal mechanisms of induced index change and to get quantitative information about the grating aging which could be used for prediction of the grating lifetime. As a rule the aging curve model of the induced index annealing which was proposed in [1] is applied to derive the distribution g(E) of the activation energy of the temperature activated processes responsible for the grating decay. Typically step isochronal or isothermal annealing techniques are used to perform accelerated aging of fiber gratings [2]. A new continuous anneal method suggested in [3] allows one to simplify the decay measurements and to measure the aging curve carefully in a wide energy range.

2. Results and discussion

We applied the technique described in [3] for measuring the decay properties of gratings written in unloaded Ge-doped fibers (fiber A - 14 mol.%, fiber B - 24.5 mol.%) with different experimental conditions. The fibers were fabricated by MCVD technique and had no other co-dopants in the core and cladding regions. The gratings for annealing were prepared with cw 244-nm radiation ($I \approx 50$ W/cm^2) in a Lloyd interferometer scheme and had length of about 5 mm. Measured values of the index modulation amplitude and the mean index change were close to each other indicating a high contrast value of the interference pattern. The gratings were placed in the center of a 30-cm-long tube furnace which temperature regime was controlled by a computer. Linear heating scans in temperature range 300 ÷ 1400 K were performed with three speeds of 0.05, 0.25 and 1.25 K/sec in order to obtain the value of attempt frequency ν_0 and the resulting aging curve (see [3] for details).

To measure the effect of UV-dose on the grating decay, similar four-grating chains have been prepared. Gratings in each chain were written with certain UV-doses. They were placed spatially close to each other (about 1 mm between the neighboring gratings) in order to minimize the possible difference of the grating temperatures caused by the temperature gradients along the furnace axis. Grating resonance wavelengths were slightly different and covered a small spectral interval (~10 nm) that allowed us to measure the decay curves of all the gratings in one temperature scan. Grating transmission spectra were recorded once per each 3 K. As a result each annealing curve consisted of about 300 ÷ 400 points of the grating reflection coefficients and the Bragg wavelengths that were derived from the measured spectra. This procedure allowed us to measure the grating decay curve with a high accuracy necessary to clarify details of the grating annealing behavior.

Fig.1 presents the temperature-induced decay of the index modulation amplitude and the Bragg wavelength displacement that were obtained at 0.05 K/sec heating speed for one of the grating chains. It is seen that the wavelength shift is approximately equal for all the gratings, which confirms that there was no difference between the

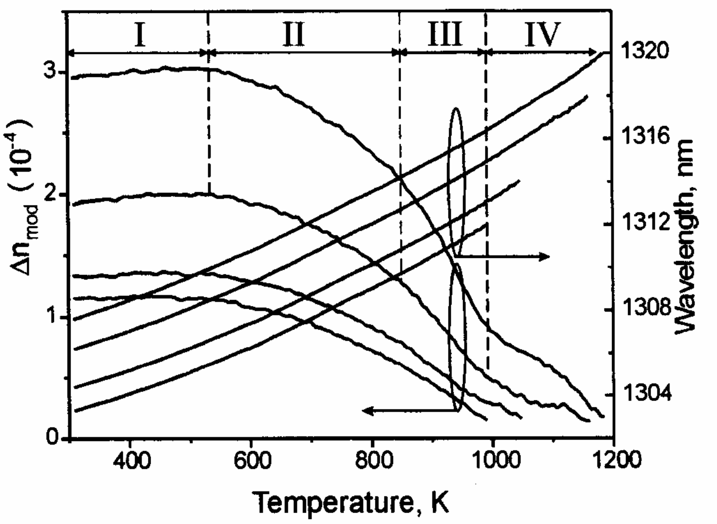

Fig.1. Dependencies of the index modulation amplitude and the resonance wavelengths on the temperature at 0.05 K/sec heating speed. The curves shown bottom-up correspond to the gratings written in fiber A with doses 1.1, 2.2, 6.5, 22 kJ/cm^2, respectively.

grating temperatures. The annealing curve of index modulation is different for different irradiation doses and has more complicated structure than that observed in most published papers [1-3]. To analyze this curve we roughly divided it on four parts displayed in fig.1. In part I we see a slight increase of the modulation amplitude which is due to reversible index changes, usually observed in unloaded Ge-doped fibers [4]. In parts II and III the gratings are annealed with a progressively increasing decay rate. As will be shown below these two regions correspond to annealing of two different bands in g(E) distribution. Part IV which observed at T > 1000 K is characterized by noticeable decrease of the decay rate which is followed by the final disappearance of the grating. The nature of the mechanism responsible for the index decay in part IV is not clear, nevertheless as it follows from fig.1 the contribution of this mechanism to the induced index change increases with UV-exposure. We suppose that this part of the aging curve is related with annealing of a photo-elastic stress grating formed in the fiber core during the grating fabrication and having an opposite index sign with respect to the basic grating [5]. In this high temperature region, viscosity of doped glass of the fiber core becomes small enough to promote stress relaxation leading to erasure of the stress grating. Several experimental evidences reported below support stress related mechanism of region IV.

We performed annealing of the grating chains with three heating speeds mentioned above and found that the best coincidence of the annealing curves measured for different speeds can be achieved at $\nu_0 = 10^{13}$ Hz. This value is in a good agreement with that given in [3]. A set of normalized aging curves obtained for several UV-doses is presented in fig.2. It was found that the shape of energy distribution g(E) depends on exposure dose strongly. In addition variations in part IV do not follow the aging curve model and hinder the calculation of g(E) in all energy range we covered. Nevertheless this distribution below the region of stress relaxation (E < 3.2 eV) can be fitted well with a sum of two gaussian bands (insert in fig.3) centered at 2.3±0.1 eV (FWHM - 0.9±0.2 eV) and 2.9±0.1 eV (FWHM - 0.5±0.15 eV). Only small variations of the band parameters within the stated accuracy have been observed for all the gratings. Similar aging curves having all the regions pointed in fig.1 have been obtained for annealing of photo-induced long-period gratings written in fiber A. This fact shows no sensitivity of the grating annealing properties to the period of index modulation and to temperature induced changes is silica cladding. Relative intensity of the energy bands depends strongly on irradiation dose. According to our results the amplitude of the band at 2.3 eV is saturated at a dose level of about 10 kJ/cm^2 whereas the amplitude of 2.9-eV band grows slower and has no saturation in the dose range we tested (D ≤ 100 kJ/cm^2). This means that the formation of the second band takes place with a smaller rate coefficient or as a result of a cascade process in which the first band is an intermediate. The amplification of the second band with dose explains improved thermal stability of the gratings written with higher doses (fig.2). It should be noted that the relative intensity of the bands depends also on type and wavelength of UV radiation.

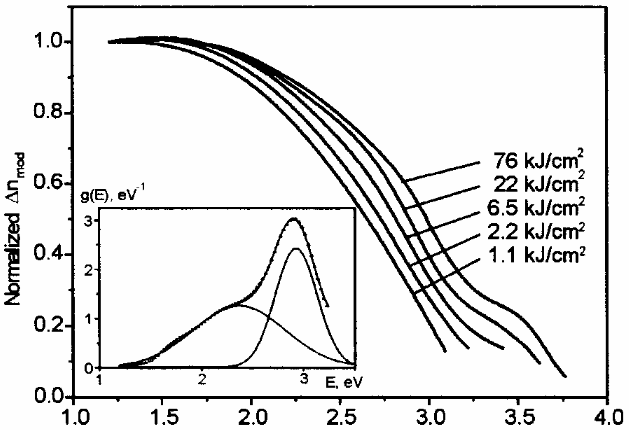

Fig.2. Dependencies of normalized index modulation amplitude on the demarcation energy obtained for the type I gratings written in fiber A with different irradiation doses.

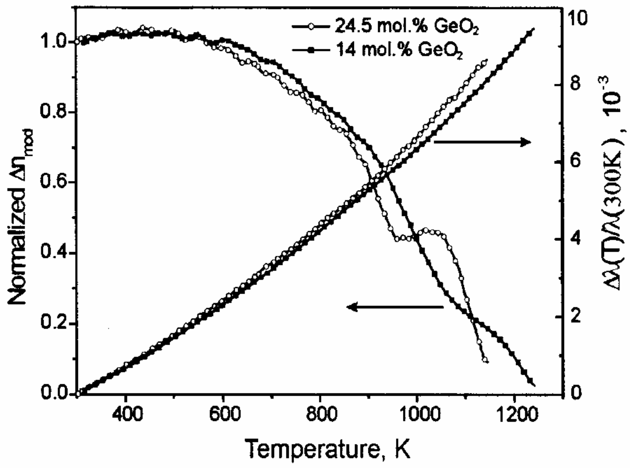

Fig.3. Normalized index modulation and relative Bragg wavelength change versus temperature measured in fibers A and B.

The first band which position and bandwidth well correspond to that observed in [2, 3] can be attributed to annealing of GeE' centers created in the fiber core by UV radiation. This assumption is confirmed by the results presented in [6] where it was shown that thermal stability of induced index and GeE' center concentration are similar. The observed rest of the index modulation after complete annealing of GeE' centers can be ascribed to the presence of more stable band at 2.9 eV observed in our experiments.

Fig.3 presents the comparison of the annealing characteristics obtained for type I Bragg gratings written in fibers A and B with a dose of ~20 kJ/cm^2. The core region of fiber B that has much higher germanium concentration is expected to be under higher tensile stress that is additionally amplified by UV irradiation. It occurred that the grating written in fiber B has slightly less thermal stability in parts II and III of the aging curve. At the same time much higher stress related contribution to the index modulation amplitude (part IV) has been observed.

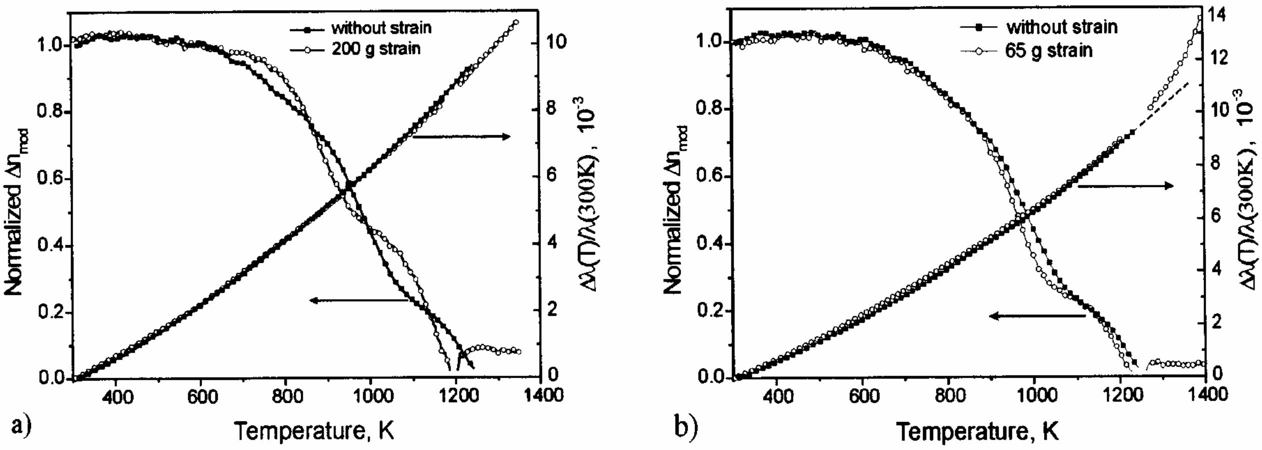

Fig.4. Normalized index modulation and relative wavelength change versus temperature for Bragg grating written in fiber A with UV-dose of about 20 kJ/cm^2; a) gratings written with and without strain; b) gratings annealed with and without strain

Fig.4 demonstrates the effect of external strain applied to the Bragg grating during both writing (fig.4a) and annealing (fig.4b) processes. In both figures region IV for the strained gratings appears at lower temperature comparing with that for the unstrained grating. Additionally, this region takes place at higher index modulation amplitude for the grating written with strain (fig4a). The amplification of this region is accompanied by a reasonable decrease of the index value related with 2.3-eV band which makes the strained grating more stable at temperatures below 850 K. Another new phenomenon which is clearly visible in fig.4 is a generation of a new high temperature grating phase after the complete grating erasure at temperature ~1200 K. This grating type is typically observed in hydrogen-loaded fibers [7] and we believe that our results are the first observation of such a grating in unloaded germanium doped fibers. In [7] this phenomenon was explained by hydrogen-assisted fluorine diffusion. Our fibers did not contain fluorine and were not H_2-loaded, therefore the appearance of this grating type in our experiments contradicts to the above-mentioned hypothesis. Additionally we observed that the strain applied to the fiber during fabrication (fig.4a) or anneal (fig.4b) of the grating gains the magnitude of this effect. It should be noted here that in this temperature range (above 1200 K) silica glass has inelastic deformations that manifest themselves in the accelerated displacement of the Bragg wavelength under the applied strain (fig.4b).

3. Conclusions

In conclusion we performed careful measurements of temperature induced decay of Bragg and long-period fiber gratings written in 14 mol.% and 24.5 mol.% Ge-doped fibers. Complex dynamics of grating annealing consisted of regions described by two bands (2.3 eV and 2.9 eV) in the activation energy distribution of the index decay and by temperature induced stress relaxation has been observed. Relative intensity of the band at 2.9 eV increases with UV-dose, which explains the enhanced thermal stability of gratings written with higher doses. The influence of both inherent stress and externally applied strain has been considered. Weak high temperature gratings arising in unloaded germanium doped fibers at the temperature above 1200 K have been revealed.

4. References

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