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Thermal decay analysis of fiber Bragg gratings at different temperature annealing rates using demarcation energy approximation

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In this study the thermal degradation of gratings inscribed in three types of fiber namely, PS 1250/1500, SM 1500 and zero water peak single mode fiber is demonstrated. A comparative investigation is carried out on the aging characteristics of the gratings at three different temperature ramping rates of 3 °C/min, 6 °C/min and 9 °C/min. During the thermal annealing treatment, a significant enhancement in the grating reflectivity is observed for PS 1250/1500 fiber from ~1.2 eV until 1.4 eV which indicates a thermal induced reversible effect. Higher temperature ramping rates lead to a higher regeneration temperature. In addition, the investigation also reflects that regardless of the temperature ramping rate the thermal decay behavior of a specific fiber can be successfully characterized when represented in a demarcation energy domain. Moreover, this technique can be accommodated when predicting the thermal decay characteristics of a specific fiber.

1. Introduction

Fiber Bragg gratings (FBGs) are considered as key components in the fabrication of optical devices due to their immense technological advancements and are routinely being used in the telecommunications and sensing industries. Optical fiber sensors employing these Bragg gratings have been beneficial in numerous applications, particularly in temperature and strain measurements [1]. The understanding of the thermal decay behavior of FBGs is crucial in determining the effective functionality of them when conducting such measurements. Therefore, many studies have shown keen interests in analyzing the thermal decay characteristics and predicting the lifetime of FBGs.

Erdogan et al. proposed a model based on a power law function of time along with a master aging curve approach to describe the rapid thermal decay followed by a subsequent slow thermal decay at particular temperatures [2]. The thermally induced decay of standard FBGs usually consists of an exponential behavior. Several research studies have demonstrated that an extension of the temperature measurement range to approximately 300–400 °C can be achieved through accelerated aging at specific temperature and time conditions [2–4]. Dong et al. reported a complex grating decay at elevated temperatures based on a three energy level model where the stability of both positive and negative index gratings were studied at elevated temperatures [5]. Furthermore, Razafimahatratra et al. and Hidayat et al. reported temperature induced reversible and irreversible changes in grating reflectivity where the processing and type of the grating were considered to be responsible for these changes [6,7]. A thermal induced reversible effect deviating from the general thermal decay behavior was observed in hydrogen loaded photosensitive Germanium/Boron co doped fiber as well. When analyzed with respect to the demarcation energy domain, a similar trend was observed in the accelerated aging characteristics during both continuous and stepwise annealing procedures [8]. Over the last two decades a significant contribution has been made in extending the temperature range of FBG based sensors by introducing numerous types of gratings namely, type II [9], type IIa [10], chemical composition gratings (CCGs) [11] and regenerated fiber Bragg gratings (RFBG) [12]. In the recent years, researchers all across the world have contributed tremendously in the investigation of regenerated fiber Bragg gratings suitable for temperature sensing using various types of fiber [13,14]. Even though, most grating regeneration studies mainly focus on hydrogen loaded fiber, some research studies have indicated the possibility of grating regeneration in the absence of hydrogen [15,16].

In this study, we present a comparative investigation of the thermal decay characteristics of three different types of fiber namely, PS 1250/1500, SM 1500 and OFS zero water peak fiber (ZWPF) at three different temperature annealing rates. Furthermore, the article focuses on the evolution of the accelerated aging

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curves during the thermal annealing procedures based on the normalized integrated coupling coefficients (NICC) represented with respect to the demarcation energy (E_d). Regeneration and decay characteristics of the gratings are also explored and analyzed.

2. Experimental procedure

PS 1250/1500, SM 1500 and OFS zero water peak fiber (ZWPF) were initially hydrogenated at 2000 psi pressure for 12 days prior to the FBG inscription process. Afterwards, 10 mm long gratings were inscribed on each type of these hydrogenated optical fiber using 193 nm ArF excimer laser irradiated phasemask technique. During the inscription process, the UV beam size was adjusted using a beam expander, and the grating length was controlled and maintained at 10 mm using an adjustable vertical slit. The gratings were then placed inside an oven at 80 °C for 24 h in order to remove the residual H_2 and subsequently left at room temperature for 14 days. These gratings were then divided into three batches based on the ramping rate they were assigned to be subjected to. Afterwards, the gratings were inserted into a tube furnace one at a time and the annealing procedure was carried out on all three batches of gratings by heating them at increasing temperatures for a fixed ramping rate until the point where the gratings regenerate and completely extinguish. Three different continuous ramping rates of 3 °C/min, 6 °C/min and 9 °C/min were used for each batch. An inbuilt program in the furnace was used to maintain the annealing rate during the thermal annealing process. The transmission spectra of the gratings were monitored and recorded using an optical spectrum analyzer (OSA) controlled by a LabVIEW program via a NI GPIB interface. The thermal decay behavior of each grating was represented in terms of the normalized integrated coupling coefficient (*NICC*), η, since *ICC* is directly proportional to the UV-induced refractive index change and can be used to model the grating strength.

$$ICC = \tanh^{-1}\left(\sqrt{1 - T_{\min}}\right) \quad (1)$$

where T_{min} denotes the transmission minimum of the FBG at the Bragg wavelength (λ_B). Therefore, the *NICC* values (η) can be computed as

$$NICC = \frac{\tanh^{-1}\left(\sqrt{R_{t,T}}\right)}{\tanh^{-1}\left(\sqrt{R_{0,T_0}}\right)} \quad (2)$$

where $R_{t,T}$ represent the reflectivity after an annealing time t at an annealing temperature T and $R_{0,T0}$ the initial reflectivity at room temperature.

3. Experimental results and discussion

Fig. 1 demonstrates the decay characteristics of PS 1250/1500, SM 1500 and ZWPF at three different annealing rates of 3 °C/min, 6 °C/min and 9 °C/min. In Fig. 1(a), a gradual decay is observed until 425 °C in PS 1250/1500 which follows the usual temperature decay behavior of a grating. However, subsequently an increase in the NICC is observed in the region of 425–550 °C depending on the respective ramping rate. This phenomenon referred to as the thermal induced reversible effect was observed in PS 1250/1500 gratings during both stepwise and continuous annealing procedures as well [8]. Afterwards, a rapid thermal decay can be observed until the grating completely vanishes, commencing the grating regeneration process. Nevertheless, when the annealing temperature is further increased the regenerated grating initiates its decaying process in the region of 900–950 °C. It is also noticed that gratings inscribed on PS 1250/1500 exhibit the lowest regeneration temperature among the three types of fibers examined. Presence of the

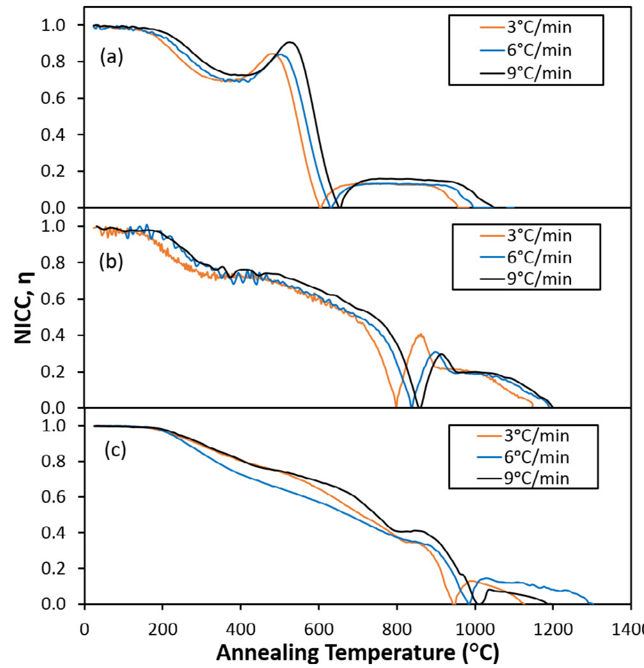

Fig. 1. Thermal decay characteristics of (a) PS 1250/1500 (b) SM 1500 and (c) ZWPF at temperature ramping rates of 3 °C/min, 6 °C/min and 9 °C/min.

boron dopant reduces the glass transition temperature of the fiber material which permits stress relaxation and rearrangement of the glass structure at a lower temperature [17]. A slight increase in the *NICC* in the region of ~350 °C is observed in SM 1500. However, it is less significant compared to the phenomenon noticed in Fig. 1(a). Regeneration characteristics in SM 1500 gratings are observed at 800 °C, 838 °C and 860 °C for temperature ramping rates of 3 °C/min, 6 °C/min and 9 °C/min respectively. When compared with PS 1250/1500 and OFS zero water peak fiber, SM 1500 exhibits the highest *NICC* during regeneration especially when the experiment is conducted at a ramping rate of 3 °C/min. The presence of the thermal induced reversible effect can be considered negligible in ZWPF although grating regeneration can still be clearly observed in 950–1015 °C range which subsequently decays to a complete zero with increasing temperature. Furthermore, according to Fig. 1 it is also noticed that with increasing annealing rate the temperature at which the grating regeneration occurs gradually increases. This condition is visible in the gratings inscribed in all three types of fiber. In addition, it is also found that hydrogen loading plays a vital role in enhancing the possibility of attaining high temperature regeneration [18].

The degree of aging of a particular grating at a given time (t) and temperature (T) is determined by demarcation energy, (E_d) also known as the aging parameter [2]. It can be expressed as

$$E_d = k_B T \ln(\upsilon t) \quad (3)$$

where k_B denotes the Boltzmann's constant and υ represents the frequency term which is obtained through the successful fitting of sets of data acquired at different temperatures by undergoing an iterative process. Fig. 2 illustrates the accelerated aging curves of the three types of fiber at three different temperature ramping rates. When plotted on an overlaid graph in the demarcation energy (E_d) domain, each type of grating namely, PS 1250/1500, SM 1500 and ZWPF indicate a common regeneration point regardless of the difference in the temperature ramping rate. For PS 1250/1500 this point occurs at ~1.46 eV and it is clearly noticed that a higher ramping rate results in a higher NICC of 0.16. In the case of SM 1500 and ZWPF, the regeneration point is generated at 1.57 and