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Qualitative photoluminescence study of defect activation in telecommunication fibers and Bragg gratings in hydrogen-loaded fibers

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ABSTRACT

Despite the relevance of glass fibers and integrated optical circuits for an increasing number of cutting-edge applications ranging from telecommunication to sensing and quantum photonics, the knowledge about their structural and chemical properties is still in its infancy. Optical spectroscopy techniques are challenged due to the intrinsically low cross-sections for inelastic processes. Our approach is to detect these properties along the core, extending the interaction to the fiber length. We report on in-situ temperature-dependent photoluminescence (PL) measurements in transmission geometry of a) pristine optical glass fibers (standard commercial telecom grade and different types of photosensitive fibers) and b) type I fiber Bragg grating (FBG) in hydrogen-loaded fibers of the same type. A laser with 473 nm wavelength and TEM 00 mode is coupled to an optical spectrometer through different fibers. The fibers are thermally cycled between room temperature and 950° Celsius. As a first observation, we detect a clearly visible red emission from the uncoated fibers at the location of the fiber Bragg grating. Fitting the luminescence spectra with a single Gaussian and monitoring the intensity as a function of temperature reveals an irreversible, thermally activated degradation of the luminescence associated to the fiber Bragg gratings. A closer inspection of pristine glass fibers without FBG revealed a faint, yet thermally stable luminescence with similar spectral characteristics. Analyzing qualitative data for two consecutive heating cycles confirmed two distinct activation energies. This may be due to several reasons such as different defects at the basis of this emission or different structural or chemical environments for the same defect. Further experiment will be carried out in the future to investigate the main reason of two distinct activation energies.

1. Introduction

Optical fiber sensors currently receive a surge of interest thanks to their efficiency and accuracy enhancement as demanded in many harsh environment applications like turbines, reactors, oil & gas industry etc. [1,2]. Fiber-based sensors are adopted for an ever increasing number of applications related to temperature and strain sensing [3,4] constantly replacing electrical sensors (e.g., thermocouple, piezoresistive gauges). The key advantages of fiber Bragg gratings (FBG) and scattering based fiber sensors are their small size, immunity to EM-fields and their capability for multiplexing [5,6]. FBGs consists of a periodic modulation of the refractive index along the glass fiber's axis that reflects a specific wavelength, λ_B under the Bragg condition: $\lambda_B = 2n_{eff}\Lambda$, where Λ and n_{eff} are grating period, and effective refractive index of light inside the fiber. This modulation is commonly achieved by UV exposure through a phase mask, referred as type-I FBG, which can only operate in principle up to 300 °C as it exhibits a strong decay above this temperature. For higher temperatures, so-called femtosecond gratings and regenerated fiber Bragg gratings (RFBGs) are suitable candidates [7–10]. RFBGs are high-temperature-annealed, stable index modulation with similar spectral features as a type-I grating. They however face severe challenges regarding the loss and only partial recovery of reflectivity [10,11]. So far, the mechanism remains barely understood despite emerging theories (e.g., chemical composition model, stress relaxation, densification etc.) [10,12,13] that aim at underpinning the status quo of the underlying regeneration dynamics. Still in their infancy, these models lack experimental quantification of key model parameters for validation. The most promising route towards a microscopic understanding is the quantitative correlation of macroscopic observations such as the regeneration and the refractive index contrast

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with microscopic features including point defects, extended defects and strain. Most of the related processes are thermally activated so that the identification of activation energies might pave the way for the correlation of macroscopic and microscopic effects [11]. Point defects are often observable by photoluminescence while extended defects and strain provide unique vibrational signatures as detectable by Raman or infrared spectroscopy.

Spectroscopic techniques are well suited in a single instrument platform for a simultaneous characterization of both the vibrational properties of low-energy phonons [11,14] in the spectral range below 1500 cm^{-1} and electronic properties in the spectral range of e.g. hydrogen-bonds (i.e. larger than typically 2000 cm^{-1}) in optical glass fiber. The aim here is, however, not to discuss the low wavenumber Raman bands associated to molecular vibrational frequencies, but to derive the striking features of temperature dependence of luminescence characteristics. Our interest therefore is principally to elucidate oxygen defect and hydrogen-induced PL of a glass fiber dependence on a) Ge-content and b) with prior hydrogen-treated grating under annealing between ambient and 950 °C.

The broad PL lines in silicate and germanosilicate glass corresponding to oxygen deficiency centers (ODCs) [15], non-bridging oxygen hole centers (NBOHCs) [16–18], and hydrogen-induced Ge-H defect [19] are well known. These PL bands that are detected in the visible range indeed results from allowed transitions of localized energy levels. The very first attempt to ex-situ PL measurements of RFBGs was undertaken by our group, where cross-sectional Raman mapping was implemented to monitor the PL from such defect centers inside core and outer cladding parts of FBG. These PL spectra provide details of the related defect emitters produced inside the fiber core during FBG inscription [18]. These results complement the annealing characteristics of red PL emission (650 nm) of hydrogen-loaded fibers in the study of Goutaland et al. [19]. A study on the influence of deuterium on FBG luminescence in a different fiber type was recently conducted by our group where we observed the decay of red PL emission from RFBG after annealing at 775 °C [10]. Therefore, in the present study, our investigation focuses on photoluminescence centers located in the core and at the core-cladding interface, thus the entire mode volumes to interact with the electromagnetic wave.

We observe temperature-dependent decays of defects due to the presence of type I FBGs in hydrogen loaded fibers and compare them to the decay of luminescent defects in the as-received fibers. While the decay in the as-received fibers is reversible as a function of temperature to 950 °C, the luminescence decay associated to FBGs, even though occurring in exactly the same spectral range, has a considerably lower activation energy and is irreversible. Our observations correlate to thermal regeneration of FBGs with respect to both the irreversible nature of the first temperature cycle and the temperature onset for the observation of these changes.

2. Materials and methods

2.1. Optical fibers and FBG fabrication

We aim at providing the temperature dependent in situ PL investigation of a) telecom grade fibers (Siecor-SMF28), photosensitive fibers (Nufern-GF1B double-clad) with and without FBG, and b) a pristine fiber (Fibercore-PS1250/1500). FBG inscription is performed with a 248 nm KrF exciplex laser from Tui Laser (ExciStar S-200) and the phase mask technique (Λ= 1070.7 nm). For this, the hydrogen-loaded fiber ~50 cm (see Table 1 for grating inscription and fiber parameters) is mechanical uncoated in the midst of the fiber over a length of approximately 4 cm and a 15 mm-long uniform FBG is fabricated using a continuous scanning process with a moveable mirror.

Before measuring the fiber samples in the furnace, we stored the fibers for 4 weeks at room temperature to ensure that no molecular hydrogen is left in the fiber.

Table 1
Overview of fiber and summary of grating inscription parameters [20–23].

Parameter/Fiber	SMF28	GF1B	PS1250/1500
Manufacturer	Siecor	Nufern	Fibercore Ltd.
Core radius, μm	4.1	4.5	3.5–4.5
Cutoff wavelength, μm	1.26	1.26	1.26
N.A.	0.14	0.13	0.12
Core dopants (mol %):			
GeO_2	3.5	> 10	10
B_2O_3	No	No	20
P	No	Yes	No
F	No	2	No

Inscription parameter	Value
Output power (mW)	525
Repetition rate (Hz)	100
Voltage (V)	1300

Fiber types	**H-loading**
SMF28	26 days 23 °C 150 bar
GF1B	2 days 80 °C 110 bar

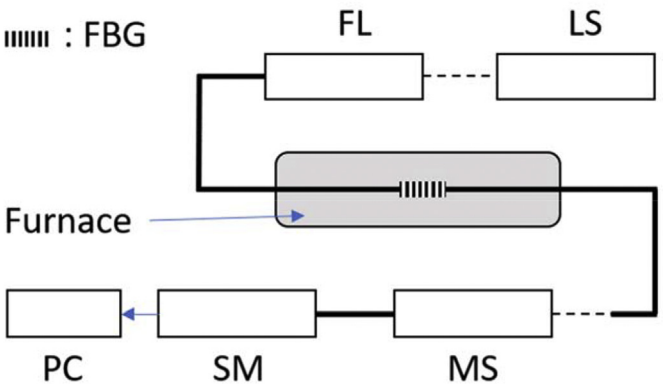

Fig. 1. Schematic set-up for the in situ PL characterization. Dashed and solid lines represent optical free path and optical fibers, respectively. LS denotes the laser system, FL stands for 'fiber launcher', MS for microscope, SM to the spectrometer. The personal computer (PC) serves for data acquisition and analysis.

2.2. PL setup and characterization

Fig. 1 sketches the experimental configuration starting with a 473 nm solid-state laser (Cobolt blue) that is launched into the fiber a fraction of which is heated in a furnace and the subsequent collection of Raman spectra and luminescence emission in a commercial laser scanning microscope attached to a spectrometer. The choice of a short excitation wavelength is to promote inelastic processes to be detected and analyzed as a function of temperature along the fiber. A more detailed description of the instrumentation and free space optics design can be found elsewhere [11].

The coupling unit provides an NA of 0.1 with micrometric alignment precision and sufficient thermal stability to neglect drift during the experiments. A volume fraction of the total fiber is inside the heating zone of two types of electric furnace: a) 75% of PS1250/1500 fiber in a muffle furnace (SNOL 8.2/1100 LHM01) and b) 0.5% of SMF28-FBG and GF1B-FBG in a tube furnace (GSL-1100X-UL) that has an internal K-type thermocouple to measure temperature with an accuracy of ± 1 K. The Raman and luminescence signals were collected by a × 100 microscope objective (0.9 NA) into a Raman optical probe