SAND2009-0433C

Combined photodarkening and thermal bleaching measurement of an ytterbium-doped fiber

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ABSTRACT

A combined photodarkening and thermal bleaching measurement of a large-mode-area (LMA) ytterbium-doped fiber (YDF) is presented. Photodarkened YDF sample is recovered to pre-photodarkened state by thermal bleaching. As a result, this approach enables repeated measurements with the same sample and therefore eliminates uncertainties related to changing of the sample (such as sample length and splice losses). Additionally, our approach potentially improves the accuracy and repeatability of the photodarkening rate measurement, and also allows automation of the measurement procedure.

Keywords: Photodarkening, ytterbium, doped fiber, double cladding, thermal bleaching

1. INTRODUCTION

In high power applications, ytterbium-doped fiber has become the most used rare-earth ion because of the favorable characteristics providing excellent efficiency (e.g. beam quality or thermal management). However, photodarkening has emerged as a potential threat to the lifetime of Yb-fiber lasers [1]. Photodarkening refers to the temporal increase in the transmission losses of a doped glass which, in the case of Yb-doped fiber devices, results in a decrease of the efficiency and lifetime limit. Spectrally, this loss is centered in the visual band wavelengths but it has a tail that extends up to the pump and signal region (0.9-1.1μm in an Yb-doped fiber laser). Photodarkening effect has been attributed to the formation of color centers [2-5]. Previous works suggest they may be originated by Yb-associated oxygen deficiency centers [4] or formation of Yb^{2+} ions in the glass matrix from Yb^{3+} [5,6]. Studies about the temporal and spectral characterizations of the PD evolution have been carried out, attributing the rate of photodarkening to the number of Yb-excited ions. Spatially uniform and tunable inversion level in Yb-doped DC fibers resulted in a well-repeatable approach to characterize the initial PD rate and quantitatively compare PD properties of various fibers. Initial rate has been shown to follow modified exponential time dependence. Both bi-exponential and stretched exponential functions, defined mainly by a time scaling mechanism (rate constant τ^{-1}), were used as a fitting functions to the initial decay. It was reported that the measured rate constant τ^{-1} is related to the density of excited Yb ions by power-law dependence with an exponent of approximately 3.5 [3]. This suggests on average 3 to 4 closely located excited Yb ions create a color center. Other publications report that the number of Yb ions involved is 6 [Shubin] or 7 [Joona applied optics 2008]. A recent publication suggests that the discrepancy in the number of Yb ions involved in the process may be partly caused by uncertainties in the PD rate fitting procedure such as the resolved measurement time [9].

Determination of the ion-dependence in form of log(inversion) vs. log ($1/\tau$) requires detailed knowledge of various active fiber parameters and that these parameters remain invariable during the characterization process. A new sample is typically spliced in for each measurement, resulting in changes of the sample length, splice losses and potentially also the active fiber properties (for example due to longitudinal variations in the doping homogeneity or geometrical variations). Therefore, invariability of the measurement conditions cannot be guaranteed, and the derived ion-dependence results are subject to significant uncertainty. This uncertainty could be eliminated if all the measurements were done on one, undisturbed sample.

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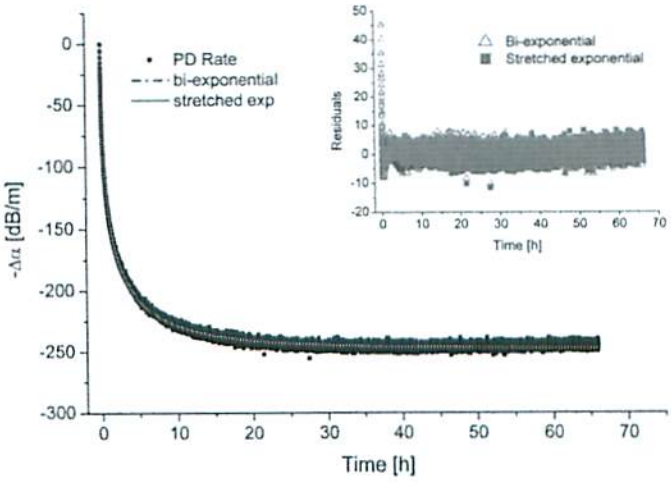

Fig. 2. Absorption coefficient change - in negative sign - as a function of time (in hours). Solid lines represent the stretched exponential (red) and bi-exponential fit (black) to the data. Inset: Residuals represent the difference between measured absorption in negative sign and the corresponding fit value at a specific time. Stretched exponential improves the fitting mainly in the first fast decay.

Figure 2 shows an example of photodarkening-induced absorption coefficient change ($\Delta\alpha$) measurement until saturation. The active fiber is exposed to a pump power of 16.4 W during 65 hours. Data is normalized to its initial absorption state and it is represented in negative sign. Photodarkening rate parameter(s) (τ^{-1}), which is used to compare the degradation velocity of different fibers, is obtained from two modified exponential fittings. The absorption coefficient change can be fit by a stretched exponential function,

$$-\Delta\alpha(t) = \alpha_0 \cdot \left[1 - \exp\left(-(t/\tau)^{\beta}\right)\right] \tag{1}$$

where the constant α_0 is the saturation parameter, τ is the time constant, and β is a parameter that range between 0 and 1 and is referred to as the stretching parameter. This equation is a common used empirical formula that describes the relaxation rates of many physical properties of complex systems such as polymers and glasses, and the fitting result is the same as a distribution of exponential decays. In characterization of photodarkening, particularly in PD rate measurements, Eq. 1 is mainly used to determine the rate constant (τ^{-1}) as a benchmarking method for photodarkening rate comparison. Table 1 summarizes the parameter values of equation 1 and the goodness of the least-squares fitting (R^2) in percentage.

Table 1.

Stretched exponential parameters	α_0	β	τ [s]	R^2 [%]
BB % inversion	-247.7	0.4818	5113	99.3

Acceptable fitting is also achieved by using a bi-exponential function,

$$-\Delta\alpha(t) = \alpha_0 + a_1 \cdot \exp\left(-t/\tau_1\right) + a_2 \cdot \exp\left(-t/\tau_2\right) \tag{2}$$

where the constant α_0 is again the saturation parameter, a_1 and a_2 are the amplitude constants and τ_1 and τ_2 are the PD time constants of the fast and slow exponential decays. Apparently, the fitting of the bi-exponential function is almost as good as the stretched exponential and R^2 values in tables 1 and 2 suggest that. However, inset graph of Fig. 2 shows

some important discrepancy at the beginning of the decay suggesting that a faster term may need to be considered. Table-2 summarizes the parameter values of the bi-exponential function.

Table 2.

Parameters bi-exponential	a_1	a_2	τ_1 [s]	τ_2 [s]	a_0	R^2 [%]
BB % inversion	105.3	95.53	2211	21430	-246	99.24

Saturation at 99% to the saturation level according to the fit, is achieved after 21.8 hours of pumping for the case of bi-exponential fitting and 31.4 hours for the case of the stretched exponential fitting.

3. THERMAL BLEACHING OF YTTERBIUM-DOPED FIBER

Bleaching of photodarkening in Yb-doped aluminosilicate fibers by thermal annealing of the sample has been reported in previous works. Shubin *et al.* [8] demonstrated recovery of the absorption coefficient at temperatures 400 C and up. However, the recovery of absorption was incomplete, although final room temperature absorption was not presented. In another work, where the fiber was heated by a tube furnace [10], complete recovery of sample transmission was achieved at approximately 500 C after cooling the fiber to room temperature. Spectral measurement confirmed complete recovery of the absorption within 450 – 1600 nm wavelength band. This result is interesting, because the potential advantage of being able to recover and work with one undisturbed sample through possibly a long sequence of measurements. This advantages applies not only to the kinetic data that can be measured (such a derivation of ion-dependence), but also to thermodynamic analysis (e.g. associated thermal binding energy) of the photodarkening effect.

In our work, a miniature oven (MHI Inc. model FibHeat200) was used to thermally recover the photodarkened sample. Due to its small dimensions, the oven could be attached to a micrometer translator, necessary for positioning carefully the active fiber inside its narrow groove. A thermocouple monitors the temperature by placing it inside the oven groove close to the active fiber. Additionally, this setup is placed on a movable stage controlled by a stepper motor that moves away the oven from the fiber.

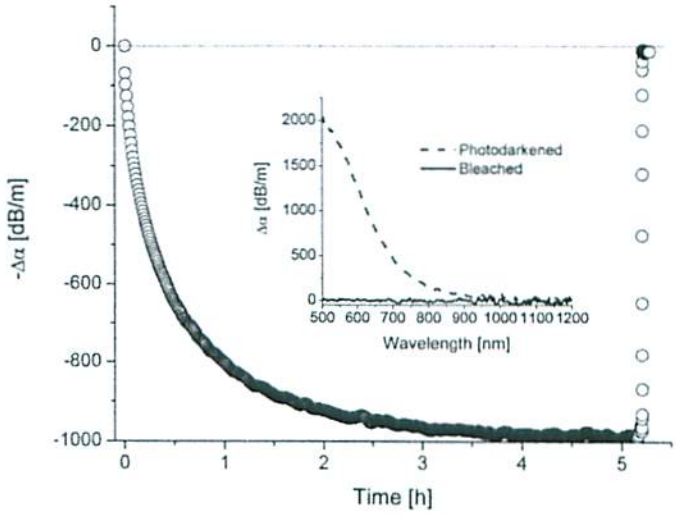

Fig. 3. Absorption coefficient as a function of time (in hours). PD rate (5.2 hours) and bleaching measurements are shown together. Inset graph shows spectrally the absorption coefficient of the photodarkened sample (dash line) and after the bleaching measurement (solid line).

Figure 3 shows an example of combined photodarkening and thermal bleaching measurement. PD rate measurement used XX W of pump power, corresponding to XX% inversion, during 5.2 hours. Afterwards, a bleaching measurement

was carried out at constant temperature of 600 C. Sample shows recovery to within 1.5% of its pristine condition after cooling at room temperature. However, rate measurements describe only the phenomena dynamics in a spectrally narrow region (580-620 nm). Consequently, transmission spectrum of a broad region is also measured before and after thermal exposure. The WLS is this time neither filtered nor modulated and detector number 1 (see Fig. 1) is replaced by an optical spectrum analyzer. Inset graph in figure 3 shows the derived absorption coefficient (dB/m) as a function of wavelength showing that the sample is completely recovered.

However, one cycle of photodarkening and bleaching does not guarantee that the sample remains undisturbed by the thermal annealing procedure, i.e. the photodarkening behavior (time constant, saturation level) are not affected in any way. This is studied in the next section.

4. PHOTODARKENING RATE MEASUREMENT USING REPEATEDLY BLEACHED YTTERBIUM-DOPED FIBER

In the experiments we conducted, repeated measurements of 6 PD rate/bleaching cycles were next carried out. Measurements are done under the same condition of pump power (roughly 16.4 W) neglecting pump source drift and temperature changes. The sample was every time bleached until maximum reduction of absorption and cooled down to room temperature before the next PD rate measurement. Before we started the measurement cycle, heat-treatment is applied to the sample as in the case of the thermal bleaching explained in section 3. This procedure aims at recovering the fiber from an initial state of photodarkening that might be caused in the manufacturing process. However, no changes in the absorption coefficient were appreciated.

For comparison, all PD rates are fitted using both stretched and bi-exponential fitting. To summarize the results, table 3 and 4 show average values and standard deviation of the parameters described above in equations (1) and (2). The standard deviation is also presented in percentage normalized to the average value of each parameter. For consistency the same measurement time of 21.5 hours is used for all data.

Table 3.

Parameters stretched exponential	a_0	β	τ [s]	R^2 [%]
AVERAGE (6 samples)	-262.65	0.468	7901.17	99.78
STDEV	5.36	0.008	1182.93	0.02
+/- [%]	2.0	1.8	15.0	0.02

Table 4.

Parameters bi-exponential	a_1	a_2	τ_1 [s]	τ_2 [s]	a_0	R^2 [%]
AVERAGE (6 samples)	94.94	118.80	2010.00	19878.33	-248.98	99.63
STDEV	2.30	5.46	165.95	1281.23	4.14	0.02
+/- [%]	2.4	4.6	8.3	6.4	1.7	0.02

Figure 4 shows the evolution of τ and τ_1. Error bars represent the standard deviation for each parameter. For the bi-exponential fitting, Fig. 4 represents only the fast PD time constant τ_1; nevertheless, τ_2 appeared to vary following the same trend. In the first PD rate both fittings show that the time constant is considerable lower than in the consecutive cycles. This trend has been observed also in previous measurements though a well-founded explanation is still unknown.

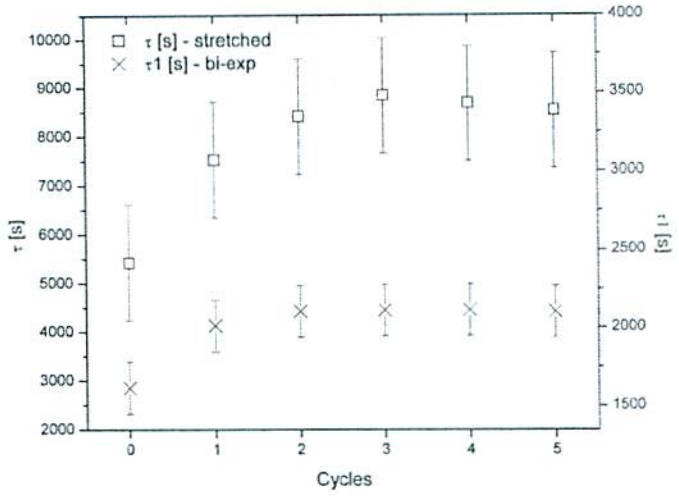

Fig. 4. The time constant of the stretched exponential fitting (squares) and the fast time constant of the bi-exponential fitting (crosses) as a function of the cycle. The error bars represent the standard deviation.

5. DISCUSSION

6. CONCLUSIONS

A combined photodarkening and thermal bleaching measurement was described. Yd-doped fiber is recovered to its pristine state by heat-treatment allowing measuring the PD rate multiple times over the same sample. PD rate measurements are mainly used as a benchmarking method for photodarkening rate comparison. However, the demonstrated connection between the PD rate and the population inversion makes necessary to establish a well-defined and repeatable measurement method. By our approach, uncertainties related to changing of the sample are eliminated and it potentially improves the accuracy and repeatability of the photodarkening rate measurements. On the same direction, WLS drift is compensated

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