Photodarkening rate in ytterbium doped silica fibers

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Photodarkening of Yb-doped silica fibers has been attributed to the formation of color centers in the rare-earth-doped glass[1], but the mechanism(s) behind this phenomenon are not fully understood. As a result, it is often difficult to predict how a particular fiber will perform under a given set of operating conditions. It is therefore desirable to develop a well-defined (and preferably simple) protocol for making photodarkening measurements that can be extrapolated to different fiber parameters, device configurations, and operating conditions, and perhaps provide insight into the physics of the photodarkening process.

While it is possible to make photodarkening measurements on a particular fiber device (for example, photo-darkening rate as a function of output power for a cw fiber laser), the physical insight that can be gained from such data is often limited, and quantitative extrapolation to other power levels or device configurations is difficult. The main problem is that as a single independent variable - such as output power - is varied, many other parameters vary in an uncontrolled and/or unknown manner, often over a wide dynamic range. Such parameters include the axial dependence of population inversion, temperature rise and signal intensity along the length of the fiber, among others.

One goal of the present study was to test the hypothesis that for a given fiber, the rate of photodarkening at a given temperature is determined by a single variable, the population inversion in the pumped fiber. In an effort to eliminate measurement artifacts and simplify data analysis, all measurements were carried out at constant temperature (in a water bath) and uniform inversion level along the length of the fiber (i.e., a short length of fiber, optically thin with respect to the pump light). Under these conditions, we recorded a series of decay curves for transmission as a function of time at different inversion levels. The typical length of Yb-doped double-clad fiber used in these experiments was ~10 cm. The pump wavelength was ~920 nm. To probe photodarkening we measured the transmittance of a HeNe (633 nm) laser through the fiber core as a function of time in a manner similar to our earlier work[2]. The population inversion at each pump power was calculated using the Liekki Application Designer (LAD) fiber simulation software. A thermal analysis indicated that the maximum temperature rise in the fiber core was 1-2°C at the highest level of inversion attained.

We found that the data for formation of color centers in the fibers undergoing photodarkening can be fit to either a simple bi-exponential kinetic function or stretched exponential fit. Note that neither of these fitting equations necessarily relate to the underlying mechanism(s) for photodarkening; in this preliminary analysis they are simply used to fit the data and derive a rate constant for photodarkening. The photodarkening rate was observed to have an approximately 7th-order dependence on the level of inversion, as shown in Figure 1. Although this experiment presents data from just two different fibers (corresponding to two different Yb doping levels), some preliminary conclusions can already be drawn.

1) The rate constant for photodarkening in these experiments can be parameterized in terms of single variable, the inversion level in the fiber. This result has important implications for comparison and extrapolation of photodarkening measurements among different fibers and operating conditions.
2) The rate constant for photodarkening appears to follow a simple power law, and is approximately proportional to $[Yb^*]^7$, where [Yb*] is the number density of Yb atoms in the excited state.
3) The simple functional dependence for the rate of photodarkening may be an indication of a single, well-defined mechanism for color-center formation.

4) This very high-order dependence on population inversion has significant implications for fiber devices. For example, if we assume the above 7th-order dependence, a fiber operating as a pulsed amplifier may photodarken up to 10^5-10^7 times faster than one used in a cw laser (even a cw laser operating at very high power), assuming average inversions of 40-50% and 5-10%, respectively. Figure 2 shows the relative photodarkening rate as a function of inversion and indicates typical operational regimes for different fiber device configurations.
5) These results demonstrate the importance of making photodarkening measurements under uniform population inversion; the 7^{th}-order dependence on inversion level makes quantitative analysis of a fiber with non-uniform inversion very difficult.
6) The time required to record the photodarkening decay curve can be inconveniently long (or impractical) if insufficient pump power is available to achieve a high enough level of inversion.

Further experiments should be undertaken to extend this study to a wide range of different fiber compositions and codopants, explore the temperature dependence of the photodarkening process, and attempt to analyze the underlying photochemical mechanism(s) for color center formation.

[1] L. B. Glebov, *Linear and Nonlinear Photoionization of Silicate Glasses*, Glass Science and Technology, Vol. 75, No. C2, 2002
[2] J. Koponen, M. Söderlund, S. Tammela, and H. Po, *Measuring photodarkening from Yb-doped fibers*, CLEO/Europe Conference '05, No. CP2-2-THU, 2005

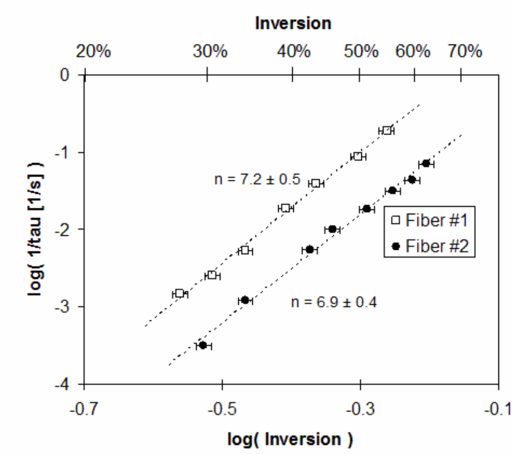

Figure 1. Measured photodarkening rate constant as a function of inversion. The slope of the log-log plot indicates a 7^{th} order power dependence.

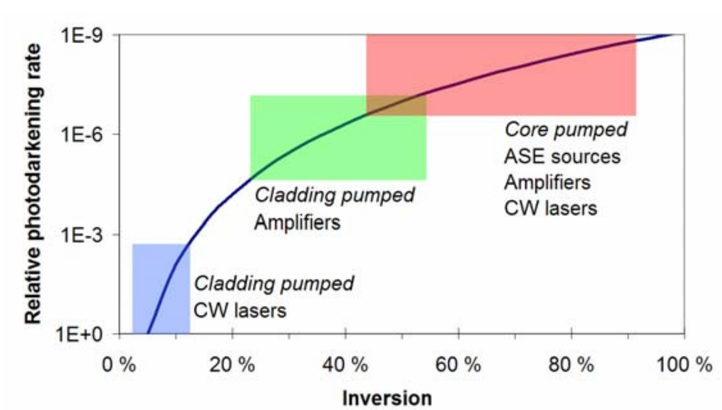

Figure 2. Normalized photodarkening rate as a function of inversion, assuming a 7th-order power law. Device application regions with different inversion levels are highlighted.