

Photodarkening: measure, characterization, and figure of merit

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Investigation of photodarkening in ytterbium-doped fibers produces a standard for accurate measurement and a figure of merit for comparing performance.

Fiber lasers and laser amplifiers at $1\mu\text{m}$ wavelength are already a fundamental tool for materials processing. Their reliability and efficiency allow precise and cost-effective welding, cutting, trepanning (drilling), and engraving as well as micromachining or more exotic applications such as material forming (i.e., shaping) of 3D prototypes. The next generation of fiber-laser applications will include cost-efficient production of solar cells by 13nm lithography. However, such technology will require higher-power lasers and potentially ever-greater levels of doping with ytterbium (Yb), which is the most efficient active ion in the $1\mu\text{m}$ -wavelength region.

The availability of Yb-doped fiber for high-power lasers and fiber amplifiers at $1\mu\text{m}$ depends on overcoming several constraints that range from heat dissipation to available pump power. For some applications, however, the major bottleneck is the limit in the Yb doping level due to photodarkening (PD).¹ This effect causes propagation losses when the active fiber is pumped, and it has also been reported for fibers doped with other rare-earth elements, such as thulium.² The origin of PD is still unclear, but there is evidence of generation of a strong absorption band in the UV with a tail leading to loss at both pump and signal wavelengths for Yb-doped devices.³ A complicating factor for manufacturers is that the best host for these devices—aluminum (Al)-silicate glass—is more susceptible to PD. Alternative hosts such as phosphosilicate glass and cesium-doped glass reduce PD.^{3,4} However, altering the glass composition changes its properties: constraints on the achievable refractive index affect the numerical aperture, and the use of softer glass hosts may complicate the thermal management of

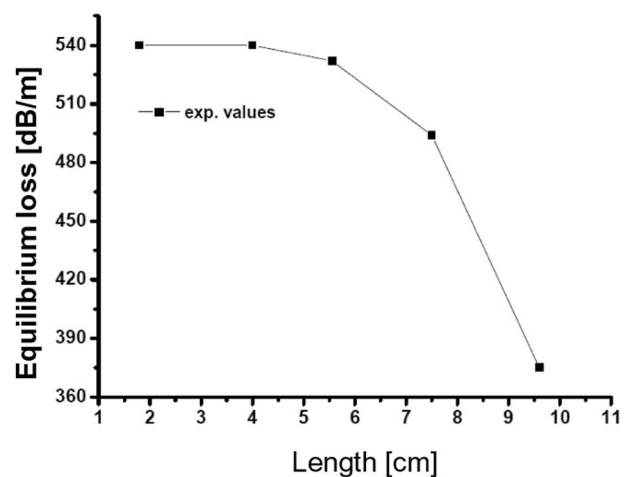


Figure 1. Equilibrium losses estimated by testing different fiber lengths. Non-uniform excitation for fiber longer than 4cm resulted in underestimation of equilibrium loss. The pump wavelength was at 976nm. exp: Experimental.

heat dissipation for high-power lasers. Thus, alternative glass hosts may not be suitable for all applications. In 2008, the European Commission funded a major fiber laser project known as LIFT.⁵ One of the key goals of this project is to understand PD and to devise a way of measuring and evaluating it. Here, we present and review our progress in PD characterization.

We first investigated the setup conditions required to provide a reliable number for characterizing PD in a specific fiber. Photodarkening is usually fitted to three parameters: losses at the final equilibrium state α_{eq} , time constant τ , and stretching factor β .⁶ We found that maintaining a uniform number of excited Yb ions (inversion) along the fiber under test is mandatory to avoid underestimating the final loss (see Figure 1).

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Uniform inversion also prevents miscalculating the time constant.⁶ We fabricated a large set of fibers with similar geometries to compare PD-induced losses over a large Yb concentration range up to 1.8wt% in Al-silicate and over 2% with phosphosilicate fibers. Figure 2 shows an example of equilibrium loss for different Al-silicate fibers. Each fiber has a different doping level but the same degree of inversion of Yb ions equal to 46%.

In Figure 2, the dashed line shows the resolution of our instrumentation. We also tested other types of glasses. In particular, under similar excitation conditions, we observed no measurable PD losses in phosphosilicate fibers. Consequently, we conclude the PD in such fibers is at least one order of magnitude less than in Al-silicate fiber. We also observed that time evolution is self-similar (see Figure 3). In other words, if we divide the PD loss by the equilibrium value, and the time scale by the time constant, all the curves overlap. This result may enable prediction of losses for fibers with different concentrations based on measurement of a similar fiber.

We made several measurements using a standard setup.⁶ We combined the probe radiation at 633nm and the pump radiation at 976nm using a custom-designed wavelength division multiplexer (WDM). The output of the WDM was spliced to the fiber under test. We monitored the time evolution of the probe beam exiting the fiber using a high-resolution optical spectrum analyzer. The main outcomes, based on the existing literature and our own investigations, can be summarized as follows. PD losses scale with the number of inverted Yb ions at fixed concentration⁸ and with the square of the doping level⁶ (see Figure 2). PD shows self-similar effects,^{6,7} and the time evolution scales with a power (between three and four) of the number of excited ions.^{6,8}

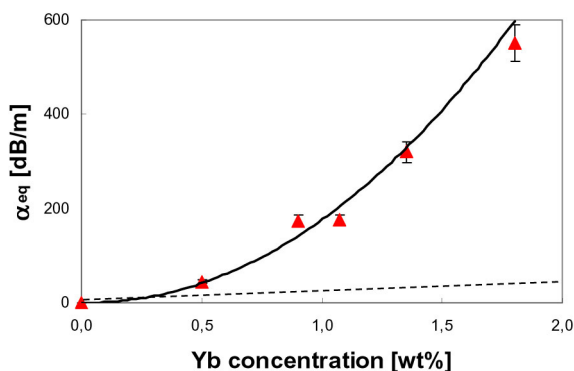


Figure 2. Equilibrium losses for fiber with different doping levels. Inversion is the same for all fibers. The fitted power law is 2.08. The dashed line represents the minimum detectable photodarkening loss using our setup. α_{eq} : Final equilibrium state. Yb: Ytterbium. (Adapted from Taccheo et al.⁶)

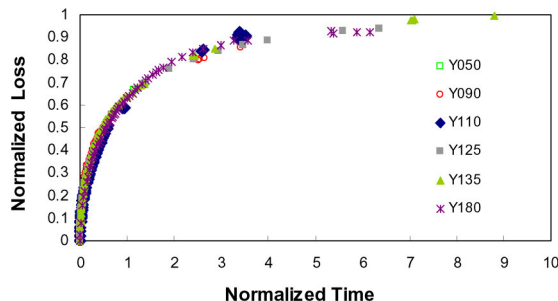


Figure 3. Normalized evolution of photodarkening losses to the equilibrium value and time to the time constant. The three digits in the fiber name indicate the Yb doping level in wt%.⁷

Finally, phosphosilicate fiber exhibits very low PD, between one and two orders of magnitude below Al-silicate fibers.⁵ Note that the fiber under test must show uniform inversion. Single-mode fibers should preferably be tested under 976nm pumping to clamp the inversion all along the fiber.

The self-similarity of curves shown in Figure 3 suggests that only two fitting parameters are needed to describe fiber behavior.⁶ However, to compare the PD performance of two fibers, we propose introducing a figure of merit (FOM). This figure of merit should take into account the saturation loss at the pump as well as at the signal wavelength. Both effects depend on the induced extra loss times the fiber length. In addition, the gain provided by a given length of fiber should also be considered. An increase in the Yb concentration reduces the length of fiber in a linear fashion and, in some cases, minimizes some of the length-dependent undesirable nonlinear effects, such as Raman or pulse broadening. A comprehensive FOM should therefore consider the drawback of high Yb concentration (PD loss) and the benefit (shorter fiber):

$$PD_{FOM} = (\alpha_{eq} L)^2 L \approx \frac{\alpha_{eq}^2}{N_{Yb}^3},$$

where we assume that required length, L , would be proportional to the inverse of Yb concentration N_{Yb} . Because saturation loss scales as the square of Yb concentration (see Figure 2), the FOM increases linearly with the doping level. Note that, as defined, the lower the value of the FOM, the better the fiber performance in terms of PD. The time scale of the PD process is a second issue. To describe the time evolution, we use the time parameter. For example, a time interval equal to five times the time scale constant would guarantee that 90% of the final loss value is reached (see Figure 3).

In conclusion, we reported an extensive investigation of PD in Yb-doped fiber. Although the actual mechanism of PD is still unknown, we devised a reliable setup to test the PD properties of different types of fibers. We also proposed an FOM to compare the PD performance of active fibers. These developments lead to a PD loss-related number in manufacturers' fiber specification sheets. We are currently working to improve the resolution of our setup by a factor of three for core pumping and a factor of 12 for cladding-pumped fibers.

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Stefano Taccheo received his PhD in nuclear engineering (1989). He joined the Politecnico di Milano as a researcher in 1990 and was made an associate professor in 2004. In 2007, he joined Swansea University as an associate professor and head of the Laser Group. He was a visiting researcher at CSEL, Turin, Italy (1990), the Optoelectronics Research Centre, Southampton, UK (1997), and Lucent Bell-Labs, Crawford Hill, NJ (1999). He is also an industrial consultant on fiber and fiber devices.

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