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# Photo- and radio-darkening in rare-earth-doped silica-based optical fibers

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**Abstract:** We study rare-earth-doped optical fibers under laser pumping and/or ionizing radiation conditions, and characterize the photo- and/or radio-darkening phenomena happening through processes depending on fiber composition and experimental conditions.

**OCIS codes:** (160.5690) Rare-earth-doped materials; (140.3510) Lasers, fiber; (160.2750) Glass and other amorphous materials; (060.2410) Fibers, erbium; (140.3615) Lasers, ytterbium; (300.1030) Absorption; (260.5210) Photoionization; (350.5610) Radiation; (190.7220); Upconversion.

## 1. Introduction

Rare-earth doped optical fibers (REDF) are one of the key components that allowed the development of numerous devices and systems. Ground and submarine telecommunications benefit from the erbium-doped fiber amplifier, whereas the laser industry benefit from ytterbium-, erbium- and, more recently, thulium-doped fibers (YDF, EDF and TDF, respectively), that emit around 1  $\mu\text{m}$ , 1.55  $\mu\text{m}$  and 1.9  $\mu\text{m}$ , respectively. Since the first deployment of EDF amplifiers, many new applications implementing REDF have been proposed, including amplifiers, laser sources and sensors, in many areas of application, like medicine, metrology, processing industry (laser cutting, marking, etc).

More recently, EDFs and YDFs have been thought to be employed in harsh environments (nuclear reactor, space communications, etc.). They are considered as solutions for deep-space optical telecommunications, they represent an attractive option to design high output power laser sources as needed for optical inter-satellite links (OISL) or remote sensing (LIDAR).

TDF are well known for laser emission around 1.9  $\mu\text{m}$ , mostly benefiting industry (cutting, welding) and medicine (surgery). Now, new applications for high-power REDF lasers are sought to operate at wavelengths not yet exploited, particularly those shorter than 0.85  $\mu\text{m}$ . TDF may be excited via near-infrared (NIR) pump-upconversion to allow emission along transitions spanning from 0.45 to 1.3  $\mu\text{m}$ . Early demonstrations at low power, using TDF made of so-called ‘soft glasses’ (such as ZBLAN) [1], serve as inspiration for future high power versions based on silica glass as a reliable, sturdy and low cost host [2].

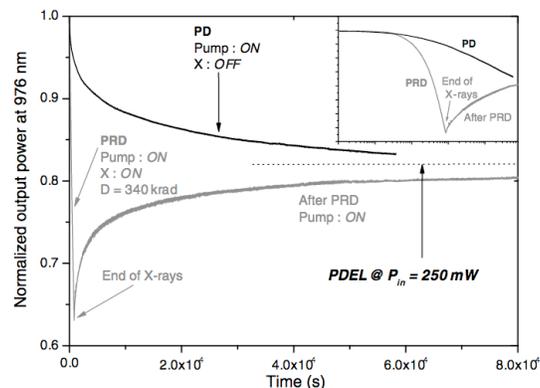


Figure 1 : Normalized output power at 976 nm in an alumino-silicate fiber sample for pure photodarkening (PD), and photo-radio-darkening (PRD) followed by photo-bleaching (PB). Pump input power is  $P_{in} = 250$  mW. Inset: same graphs in logarithmic scales to enlarge the PRD region. A same Photo-Darkening Equilibrium Level (PDEL), uniquely dependent on the pump power, is shown to be reached either from a lower degradation level (case of pure PD on the pristine sample) or a higher degradation level (X-irradiated sample). Figure from [3].

## 2. Photo- and Radio- Induced Attenuation in REDF.

When exposing silica-based REDF to either radiative environments or/and high-brightness pump beams, most often a strong and broad attenuation appears across the visible range and spanning up to the NIR. This excess loss causes pump attenuation (hence reducing the power available for population inversion and gain) and signal absorption. It is reported that fiber composition and experimental conditions influence the characteristics of both radiodarkening (or radiation-induced attenuation, RIA) and photodarkening (or photo-induced attenuation, PIA). It is now admitted that the creation of color centers (CC) are responsible for the PIA and RIA. Even if various hardening processes during the fabrication stage are known, the fundamental mechanisms behind the formation or healing of the CC remain unclear. As a consequence, high power YDF lasers benefit from some ‘tricks’ that minimize PIA and RIA in REDF, mostly obtained through phenomenologic investigations only. It is therefore necessary to investigate further the behavior of REDFs under harsh conditions and link it to basic and fundamental physical phenomena.

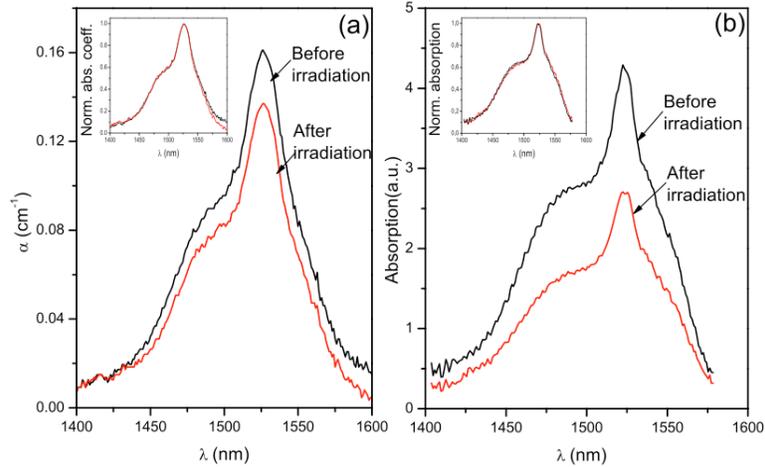


Figure 2 : (a) Near-infrared absorption of pre- and post-irradiated Al:Er-doped preform. (b) Same in a commercial Liekki Er-80 fiber. Insets show the normalized data. The difference of attenuation is interpreted as a direct effect of the ionic reduction of Er<sup>3+</sup> ions during the irradiation. Figure from [4].

Our group has recently engaged into the systematic study of photodarkening and radiodarkening in REDF, under various dynamical experimental conditions. Thanks to the in-house fabrication of all samples, almost comprehensive series of compositions are characterized. Some commercially available REDF are also characterized. Both RIA and PIA may be simultaneously investigated, in EDF and YDF. The interplay between both phenomena lead to some equilibrium state depending on pump power, dose (D) and dose rate (D<sup>2</sup>) (figure 1) [3]. It is interesting that this interplay is observed even in a radio-hardened commercial fiber. In EDF, the ionic reduction of Er<sup>3+</sup> has also been observed, as a contribution to the loss of available erbium population for inversion (figure 2). [4].

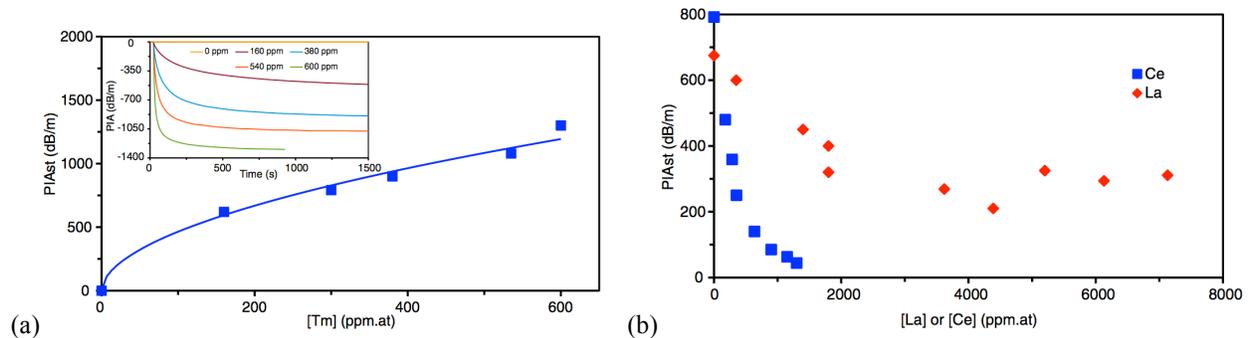


Figure 3 : (a): Steady-state PIA (PIAst) versus thulium concentration in aluminum-thulium-codoped series, recorded at 550 nm. Pump power: 1 W. Sample length : 2 cm. Squares, experimental data; solid line, power-law fit with exponent = 0.5 . (Inset): Corresponding temporal curves, vs thulium concentration. (b) : Steady-state PIA (PIAst) versus cerium concentration in the Ce-Al-Tm series (blue) and versus lanthanum concentration in the La-Al-Tm series (red), recorded at 550 nm. Pump power: 1 W. Sample length : 2 cm. Squares: experimental data. Figure from [5].

Thulium ion, under NIR pumping (1.07  $\mu\text{m}$ ) is an interesting system to study PIA : it has been recently proposed that the emission of UV photons, as a consequence of multi-step upconversion and non-radiative energy transfers among  $\text{Tm}^{3+}$ -ions, was the cause of the creation of CC. Thorough studies of PIA as a function of thulium concentration, additive codopants concentrations (cerium and lanthanum) and pump power have allowed to propose original interpretations and models (figure 3) [5].

Details of the sample preparation, experiments, results and discussion of the interpretations will be given during the conference. It is foreseen that these studies will contribute to the global understanding of the fundamental reasons governing the creation or healing of the CC, and to the design of new applications for REDF.

### 3. References

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