Liekki White Paper
Photodarkening: Understanding and Mitigating

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Photodarkening of rare-earth doped glass is a known problem with many rare-earth doped fibers. In fiber laser and amplifier applications the reliability and the cost of the product depends on the stability and efficiency of the fiber over time. This paper concentrates on the photodarkening of Yb doped fibers induced by signal and pump wavelength photons. Key results regarding photodarkening are presented, and methods to correlate the measured excess loss values are discussed. The Liekki Direct Nanoparticle Deposition process offers clear advantages over traditional processes in mitigating photodarkening because of low dopant ion clustering, tight process control and high repeatability.

Introduction

Photodarkening has been reported for many rare-earth doped glasses, such as thulium, praseodymium, cerium, and europium [Broer-93]. At the moment ytterbium (Yb) doped silica fibers are being developed for high power lasing and amplifier applications. A key concern for these applications is reliability. Photodarkening of the Yb doped fiber leads to degradation of power conversion efficiency, resulting in decrease of the signal output power that may be compensated only with additional pump power. This paper gives an overview of what photodarkening is, its probable cause and how it can be mitigated using Liekki Direct Nanoparticle Deposition (DND) process for manufacturing doped fibers.

Photodarkening

In this paper the term photodarkening is used to describe irreversible, permanent damage to the doped silica fiber which causes excess loss over a broad wavelength range. Photodarkening is caused by the pump and signal photons, which distinguishes the phenomenon from for example radiation darkening and photosensitivity. The excess loss is pronounced at visible wavelengths, but has a significant tail up to infrared wavelengths, as seen in Figure 1. Light induced polymer coating damage, which also leads to excess losses, is not considered as photodarkening.

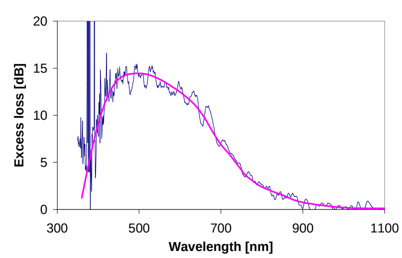

Figure 1. Example of photodarkening induced excess loss in Yb doped silica fiber. The loss is centered at visible wavelengths, but has a significant tail up to near IR wavelengths.

The cause of photodarkening is permanent damage of the silica structure the fiber consists of. Such damage can be caused by for example an energetic photon (photoionization), created by multiphoton absorption of signal and pump photons. For doped silica glass the band gap is on the order of 5.2eV [Glebov-02], which is small compared to the 9eV band gap of silica crystal [Ma-89]. The band gap energy of doped silica suggests that approximately four 1 micron wavelength region photons are needed to reach the energy level required to bridge the band gap. Impurities, co-dopants, and in-homogeneities of the glass influence the energy level structure of the fiber creating staircase type of energy levels. Also the energy migration between nearby Yb ions and such locations is possible. Impurities and co-dopants can be for example other rare-earth ions, B, Al, F, and Fe. A well known harmful in-homogeneity of doped fibers is the clustering of dopant ions, which greatly enhances the energy migration among the ions in the cluster.

Photodarkening takes place in the rare-earth doped core of the fiber. The signal wavelength suffers the photodarkening induced excess loss depending on the fiber geometry. In both core pumped and double cladding (DC) fibers the pump suffers photodarkening induced excess loss depending only on the total pump absorption. In a DC fiber the induced excess loss to the signal can be reduced with a shorter fiber. A shorter application length can be achieved by increasing the pump absorption either by increasing the core/cladding area ratio or by increasing the core Yb doping. However, the increase in doping must be made without increasing clustering.

Mitigating photodarkening

The causes for photodarkening are rare-earth ion impurities, co-dopants, and in-homogeneities of the glass. Thereby photodarkening can be mitigated by having ultra pure raw materials, a glass composition engineered for low photodarkening, and a uniform and reproducible doped glass structure. The doping process must also be such that ion clustering is avoided. In order to compare photodarkening between fibers, photodarkening has to be measured in a reliable and repeatable way.

Measuring photodarkening

The goal of photodarkening measurement is to age the fiber much faster than in normal applications. Since the effect of photodarkening is pronounced on the visible wavelengths, we have chosen the (HeNe) 633nm as our excess loss reference wavelength. In our tests we have measured the spectrum of the fiber before and after an exposure to high intensity pump light, Figure 2. The small signal absorption lengths of the samples have been kept constant at 140dB@976nm in order to have a constant number of dopant ions in the samples. A comparison of excess loss between Liekki DND fiber and MCVD fiber of similar Yb concentration is seen in Figure 3, which shows that photodarkening in DND fiber can be up to 50 times better than photodarkening in a similar commercial fiber manufactured by MCVD. Photodarkening is quick and easy to measure at visible wavelengths even from short fiber samples. Measurements illustrated in Figure 4 show the correlation between 633nm and signal wavelength excess loss. The dependence is

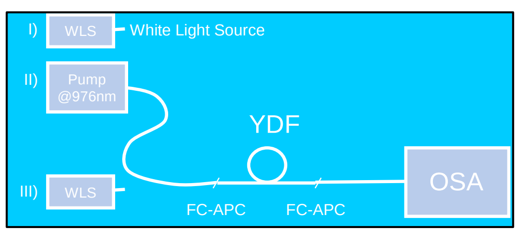

Figure 2. Measuring photodarkening from single-mode fibers consists of two transmission measurements separated by 30min of ageing with 300mW@976nm. This brightness compares to pumping a 25µm/250µm DC fiber with 1.2kW of pump power.

linear, which suggests that the spectral shape of the color center is constant, and the signal wavelength excess loss can be derived from the 633nm measurement result.

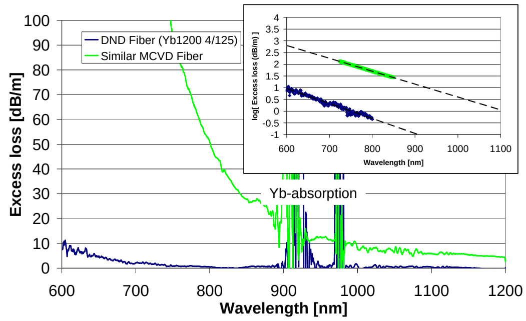

Figure 3. Photodarkening spectra of DND fiber in comparison to similar fiber manufactured with MCVD. Inset is in log scale.

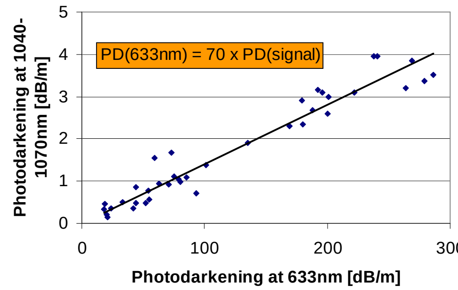

Figure 4. Correlation between photodarkening induced excess loss at 633nm and signal wavelength (at 1040-1070nm) is linear for a given glass composition.

The measurement of excess loss at a given wavelength gives a well-defined benchmark for fiber comparison. It also represents a worst-case scenario, as the pump intensity and inversion in the fiber is high. In real applications the key figure of merit is the signal output power decay over time, which should be as small as possible. The signal output decay of two Liekki Yb1200 fiber lasers are shown in Figure 5 and Figure 6. Both lasers show a decay of <8% within 74h of pumping. However, most of photodarkening occurs during the first 40 hours.

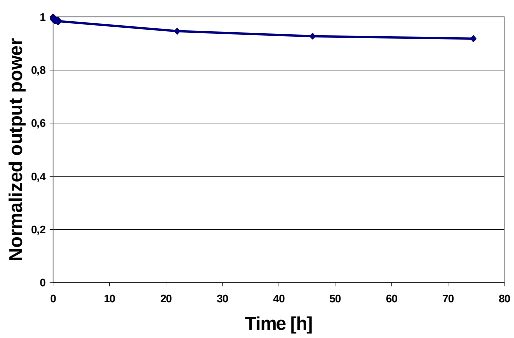

Figure 5. Signal output decay curve for SMF laser with Yb1200-4/125 fiber. Output signal decays 8% within 75h. Pumped with 200mW, 976nm.

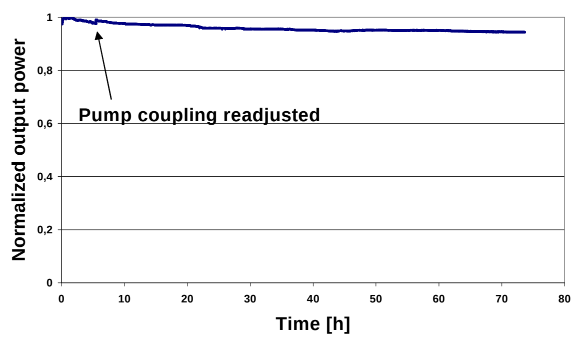

Figure 6. Signal output decay curve for LMA fiber laser with Yb1200-30/250DC fiber. Output signal decays 6% within 74h. Pumped with 24W, 914nm.

The DND process

The DND process has several advantages that help making fibers with low photodarkening [Liekki-05]. In particular, the one step doping, the use of nanoparticle deposition, and the ability to control the doping make it possible to create a fiber composition that is highly doped yet resists photodarkening. Due to technical constraints, processes based on MCVD use gases or high vapor pressure liquids as starting materials. Pure RE-dopants such as ytterbium are only available in low vapor pressure form. Previously they have most conveniently been inserted to the glass matrix for example by a solution doping post-process. In comparison to MCVD, the DND process uses liquid raw materials with both high and low vapor pressures, which means that the glass formation and doping are done in a single step. The deposition of doped nanometer scale particles leads to better glass uniformity, and minimizes the clustering of doped ions. The ability to use both high and low vapor pressure starting materials also means that a large selection of dopant materials are available. The low amount of clustering in a DND fiber can be seen from the long excited state lifetime of a highly Yb-doped silica fiber, as a shorter excited state lifetime can be attributed to increased clustering [Burshtein-00]. Clustering of dopant ions not only decreases the power conversion efficiency of the fiber, but also enhances the energy migration between dopant ions, thereby increasing the chance of photodarkening. Reproducibility and repeatability are key issues for any industrial manufacturing process. The DND made fibers also show excellent batch to batch photodarkening uniformity, as can be seen from Figure 7.

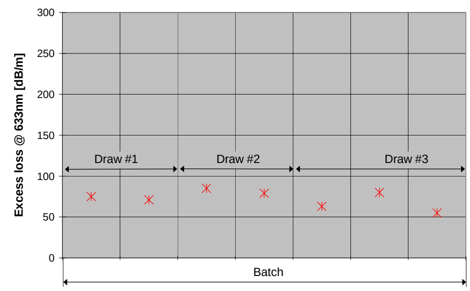

Figure 7. DND produces uniform fiber from preform to preform within a batch.

Strict process control

The strict control over the glass forming process gives the DND fibers a very homogenous glass matrix, and a highly controlled refractive index profile without any core burn-out, as is seen in Figure 8. In addition to glass homogeneity also the co-dopants and the glass composition influence photodarkening. DND allows controlled deposition of elements to facilitate the understanding and improvement of photodarkening. By using selected co-dopants - from the wide variety of starting materials available for the DND - the RE-doped core can be engineered to have lower photodarkening, illustrated in Figure 9. In addition, these results show that even very highly doped fiber can be made so that it resists photodarkening.

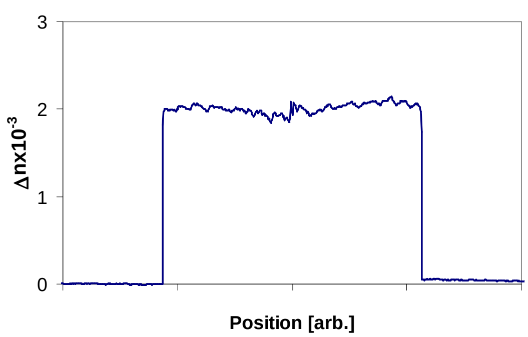

Figure 8. Example of refractive index profile measured from Yb doped DND preform.

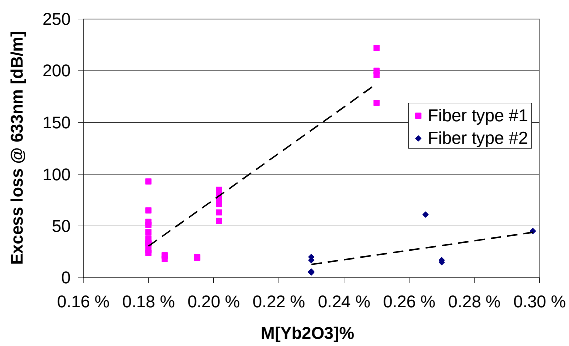

Figure 9. Photodarkening can be mitigated by controlling the doped glass composition.

Future work

Work on improving photodarkening resistance of Liekki fibers continues. An acceptable level of photodarkening must be defined, and a certain photodarkening behaviour must be specified for each fiber type. Additionally, the excess loss measured from fibers need to be correlated with key parameters such as power conversion efficiency. The plan to further improve Liekki Yb doped fiber photodarkening properties is illustrated in Figure 10.

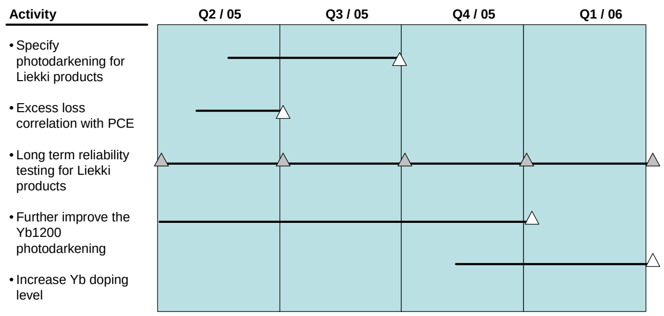

Figure 10. Plan to further improve the PD properties of Liekki fibers.

Conclusions

We have addressed the photodarkening problem concerning ytterbium doped silica fibers, and have illustrated a simple way to characterize photodarkening at visible wavelengths from short fiber samples. The excess loss due to photodarkening is the result of permanent damage to the glass the fiber consists of, which is caused by a multi-photon absorption process. The tail of the induced color centers extends to the signal and pump wavelengths, thereby decreasing the power conversion efficiency of the fiber. The Liekki DND process creates homogenous glass with little clustering, and gives a wide selection of raw materials to the preform making process. These are clear advantages towards solving the photodarkening problem of highly doped ytterbium silica fibers.

More work is needed to specify photodarkening for all Liekki products, and to correlate the excess loss to key fiber parameters such as power conversion efficiency. Further improvements to the Liekki Yb1200 fiber family are on the way.

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