Photodarkening in ytterbium-doped silica fibers

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ABSTRACT

Ytterbium-doped fibers are widely used in applications requiring short fiber amplifiers for high peak power pulse amplification. One of the key challenges posed on the performance and reliability of such amplifiers is mitigating photodarkening of the active fiber. Photodarkening manifests itself as a temporal increase in broadband absorption centered at visible wavelengths, and varies on how the active fiber has been manufactured. The tail of the photodarkening absorption extends to the 1µm region, thus in some cases seriously degrading the fiber efficiency over time. Accurate measurement methods for characterization of photodarkening must be developed in order to better understand its causes and create techniques to eliminate it so as to secure widespread commercialization of reliable Yb-doped fibers. This paper presents a simple method to characterize photodarkening in both single-mode and double clad Yb-doped fibers. A short length of fiber is pumped using high brightness source in order to achieve high and uniform inversion. The high inversion speeds up the formation of the color centers to the high degradation level, thus reducing the analyzing time from weeks to few of hours. With this method, photodarkening can be measured even from relatively short fibers by monitoring loss at visible wavelengths, where the degradation is greatest. We have analyzed the repeatability of the measurement method against the pumping conditions and fiber sample properties. The impact of photodarkening in different applications is discussed. We present the results of recent optimization of Liekki Yb1200 product family and also compare these with some other commercially available fibers.

Keywords: photodarkening, photoionization, rare-earth doped fibers, ytterbium, double cladding

1. INTRODUCTION

Fibers with double cladding structure are widely studied for laser and amplifier applications because of their ability to convert low brightness pump power into high brightness signal power, and their high surface to volume ratio that helps to minimize the detrimental thermal effects in high power applications [1, 2]. Ytterbium doped fiber lasers and amplifiers operating at the 1.0-1.1µm wavelength region are interesting for materials processing, military applications, and nonlinear wavelength conversion. Photodarkening has been reported for many rare-earth doped silica fibers, such as Tm^{3+}, Ce^{3+}, Pr^{3+}, and Eu^{2+} [3], and it has also been shown to exist in Yb^{3+} doped silica fibers [4]. In our earlier work ways to mitigate photodarkening in single-mode Yb-doped fibers were presented [4]. The underlying physical process for photodarkening is the formation of color centers in the silica glass host [5]. The color centers are permanent damage, and their spectra are formed at the visible wavelengths, but the tail of the broad absorption spectrum is significant up to the 1.1µm wavelength region. The color centers absorb both the pump and the signal light, thus reducing the power conversion efficiency of the fiber, and can generate excess heat to the fiber. The reduced power conversion efficiency leads to reduced output power, which can at least partially be compensated by increasing the pump power. The increased pump power, however, either decreases the reliability of the system or leads to a higher application cost. If the power is compensated by using the pump with higher current, the pump lifetime is reduced. More reliability can be had by using extra pumps in the system. Photodarkening is caused by the signal and pump photons in the silica fiber, and is thereby distinguishable from other detrimental effects such as polymer coating damage, or radiation damage from high-energy particles.

2. MEASURING PHOTODARKENING

At the moment there is no established way of measuring photodarkening. Previous attempt has been done by using a probe wavelength or by measuring the spectral properties of the fiber [3, 6]. The goal of this work has been to come up with a methodology of accelerated aging, namely photodarkening, of the doped fiber that is an application independent

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worst case test. Since photodarkening is more pronounced at the visible wavelengths, we have chosen 633nm as the reference probe wavelength for our measurements. In some of our tests we have measured the spectral properties of the Yb doped fibers (YDF) before and after the exposure to high intensity pump light. The tests are carried out in both single-mode fibers (SMF) and large mode area (LMA) double clad multimode fibers. The amount of work on single-mode fibers is more evident because of the faster access of such fibers.

2.1. Measuring the spectral properties

Photodarkening has been measured from single-mode fibers by measuring the spectral properties of the fiber before and after illumination with pump light, Figure 1 [4]. For all samples the pump wavelength and power, and pumping time have been kept constant. For high throughput benchmarking purposes we have limited the pumping time to 30 minutes, despite of the saturation level of photodarkening has yet to be reached. The results can be used to compare the merit of different fibers, and to estimate the worst-case lifetime photodarkening of the fiber. The pump wavelength in our tests has been 974nm, and the pump power has been 300mW coupled to a single-mode fiber. The sample length has been derived from the small signal absorption level of the fiber, namely it has been 140dB small signal absorption at the peak absorption level of 976nm. This corresponds roughly to a fiber length of 10-15cm. The output ASE spectrum was measured while pumping the fiber to verify there is no lasing to decrease the inversion.

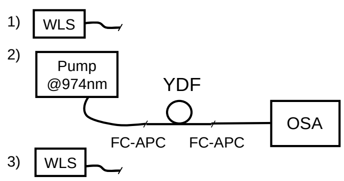

Figure 1. Setup for measuring photodarkening in single-mode fiber. 1) Transmission spectrum of YDF is measured with a white light source (WLS) and optical spectrum analyzer (OSA). 2) Sample is pumped with 974nm pump for 30 minutes. 3) Transmission is again measured after illumination.

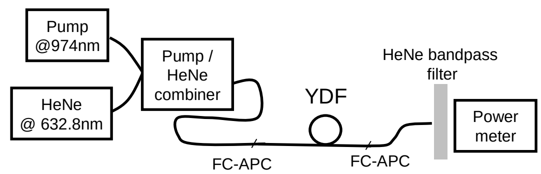

Figure 2. Setup for measuring photodarkening with a probe wavelength. Pump wavelength and HeNe are combined using a WDM, and coupled to the single-mode fiber. HeNe transmission is measured in real-time using the power meter.

A photodarkening measurement result is illustrated in Figure 3. The photodarkening induced excess loss is calculated from the difference of transmission spectra and the sample length. The measurement is noisy at the signal wavelength region, which is the most important part of the spectrum. After measuring a large number of different Yb-doped silica fibers, it can be seen from Figure 5 that the absorption at 633nm and at the signal wavelength has a linear correlation. The absorption at HeNe wavelength is approximately 70 times the absorption at the signal wavelength. This indicates that the shape of the induced excess loss spectrum is the same for a wide variety of Yb-doped silica fibers pumped at 974nm. The spectral shape of the color center has been the same with Liekki fibers as well as with the other commercially available fibers we have measured.

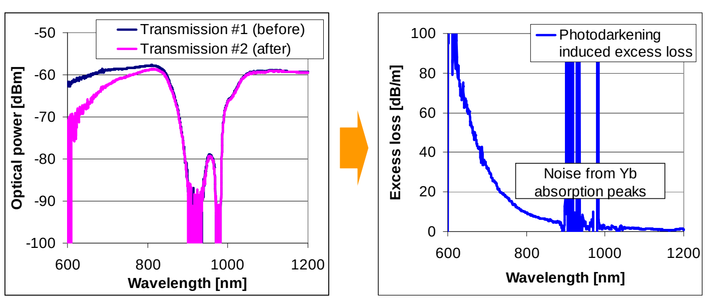

Figure 3. Calculating the excess loss from the measured transmission spectra. The photodarkening induced excess loss is calculated by reducing the before and after transmission spectra and by dividing with the length of the sample.

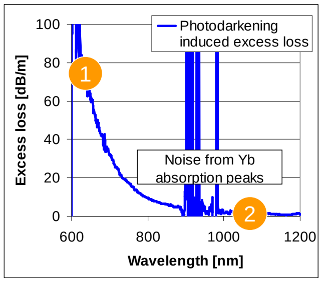

Figure 4. The excess loss is easy to measure at 633nm (1), but important to know at the signal wavelength (2).

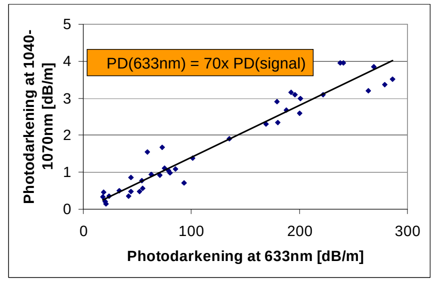

Figure 5. Photodarkening wavelength correlation. The photodarkening values have a linear correlation between the 633nm wavelength and the signal wavelength.

2.2. Measuring photodarkening using the 633nm probe laser

The temporal behavior of photodarkening of single-mode fibers has been measured using a setup illustrated in Figure 2. It is quite close to the spectral measurement setup, and the results can be verified using the spectral measurement method. The pump power was varied when using the probe wavelength, and an attenuator was used in order not to change the wavelength of the pump. The goal of these measurements was to get more information about the photodarkening phenomenon itself. A different rate of photodarkening has been observed for different applications, for example an ASE source has been seen to photodarken faster than a laser.

The expected temperature dependency of photodarkening was observed using the probe wavelength, however, the measurements shown were done within constant room temperature. The normalized HeNe probe transmission intensities could be fitted with a stretched-exponential function of the form [7,8]:

$$T(t) = A\exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right] + (1-A), \tag{1}$$

where T is the normalized transmission, (1-A) is the short term steady state transmission, τ is the characteristic time constant of the fit, and β is a dispersive parameter. The fitting of the curves was done using the least square method, and the same dispersive parameter could be used for the photodarkening of an ASE source and a laser.

2.3. Measuring photodarkening from LMA fibers

The photodarkening in LMA fibers was measured using the setup illustrated in Figure 6. The only difference to the single-mode setup is the coupling of pump to the fiber, and the cladding mode stripping before and after doped fiber. The pump brightness is lower, as the pump from 4µm core is coupled to for example a 20µm core with smaller NA. Typically a coupling and splicing loss of approximately 7% was achieved for the pump light, meaning that the coupled pump light to the doped LMA fiber core is approximately 280mW at the 974nm wavelength. The cladding modes were stripped by removing the polymer coating of the fiber for a length of approximately 5cm, and by applying a high index gel to the bare fiber. The results were measured using a spectrum analyzer, and a 30 minutes pumping time was used for each sample. The results measured from LMA fibers are spectrally very close to the result shown in Figure 3, however, at wavelengths over 1µm some modal beating was observed in the WLS measurement spectra. The cladding modes were stripped in order to make sure all pump light and light measured with the spectrum analyzer had propagated through the core, and not partially or fully in the cladding. The use of passive fibers in both ends of the active fiber makes the mode stripping and light coupling more convenient, since the sample size has been short.

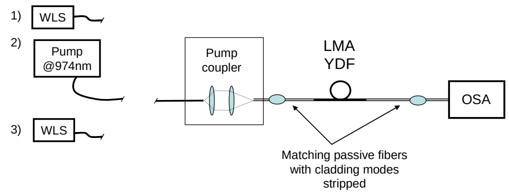

Figure 6. Measuring photodarkening from LMA fibers.

2.4. Pumping conditions in a photodarkening measurement

In order to achieve repeatable and fast photodarkening measurement it is beneficial to have a high and uniform inversion in the sample. The high inversion is presumed to increase the probability of energy transfer between rare-earth ions in the glass, thereby increasing the probability of creating color centers. This also implies that the temporal behavior of photodarkening is application dependent, namely a fiber used in an ASE source or an amplifier will degrade faster than the same fiber used in a laser cavity. The amount of possible color center sites in the glass is, however, an intrinsic material property and not related to the use of the fiber, but rather to the number of impurities and imperfections in the glass host. The uniformity of the inversion within a fiber sample makes the measurement more reproducible regarding to the sample length inaccuracy.

The brightness of the pump has been kept as high as possible in each measurement given the available equipment. The pump powers and corresponding cladding powers used in the different measurements are shown in Table 1. The corresponding cladding pump powers are calculated from the intensity of the light in the 4µm or the 20µm core. The shown cladding pump power is the corresponding cladding pump power level the rare earth ions experience, presuming a flat power distribution across the fiber and the core.

Table 1. Pump powers and corresponding intensities.

		Corresponding cladding pump power for different fiber diameters		
Pump power / core diameter	Intensity [W/cm2]	125µm [W]	250µm [W]	400µm [W]
300mW / 4µm	2.4E+06	293	1172	3000
280mW / 20µm	8.9E+04	11	44	112

We have calculated the inversion in our fiber samples using Liekki Application Designer v3.0 modeling software. The pumping conditions have been analyzed for single-mode fiber (SMF) samples and for LMA samples, the core absorption has been presumed to be in the order of 1200dB/m at the 976nm peak absorption. Figure 7 illustrates the calculated inversion in SMF and LMA fibers, when 974nm single-mode pump with 280-300mW pump power is used. The figure shows that the inversion for SMF sample is very uniform, and at an average 53% level. The sample length we have used is 140dB of small signal absorption at pump wavelength, which corresponds to 10-15cm of fiber. Because of the uniformity of the inversion, small length inaccuracies do not contribute systematic measurement errors. For LMA fibers the average inversion is 45% for the 5cm fiber length. According to our simulations the single-mode fiber with 974nm pump will have approximately the same inversion level down to 100mW, after which the inversion of the fiber will drop starting from the end of the fiber.

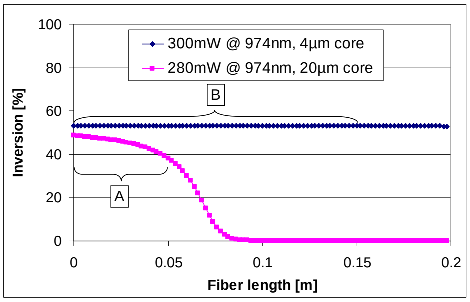

Figure 7. Inversion in a short fiber sample using 974nm pumping. The sample length of LMA fiber (A) has been chosen as 5cm, giving an average inversion of 45%. The sample length for single-mode fiber corresponds 10-15cm, giving an average inversion of 53%.

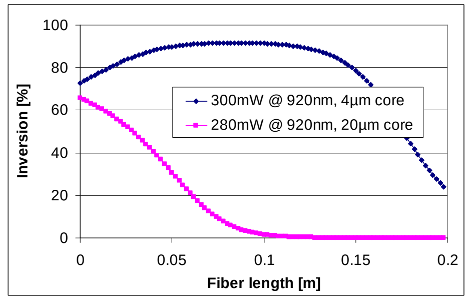

Figure 8. Inversion in a short fiber sample using 920nm pumping. The average inversion levels of the samples are further apart than with 974nm pumping. However, the average inversion is higher.

The inversion level of the fiber is derived from the pump wavelength and the emission and absorption cross sections. For 920nm pumping the inversion in the fiber sample is shown in Figure 8. The average inversion possible with this wavelength is higher, but the inversion is less uniform. Additionally, the difference between the inversion of the SMF and LMA samples of similar lengths than used with 974nm pumping is higher. The average inversion of 15cm SMF is 87%, and for 5cm LMA fiber 51%. The higher inversion level would, however, be beneficial in order to speed up the photodarkening. The use of higher energy pump photons could also influence the photodarkening process itself, for example by exciting a spectrally different color center.

3. PHOTODARKENING IN APPLICATIONS

The acceptable amount of photodarkening induced excess loss a fiber can have is proportional to the application length. The application length is influenced by variables such as the core dopant concentration, the used pump wavelength, the core cladding area ratio, and the application specific requirements for pump absorption. It is in our interest to know what the amount of photodarkening each application can tolerate without excess degradation of power conversion efficiency.

For DC fibers the application length can be defined by the cladding pump absorption of the fiber, for example 13dB pump absorption for an amplifier. For double clad fibers the cladding pump absorption is proportional to the core cladding area ratio, and the application length can be written as:

$$L_{A,\lambda} = \frac{\alpha_{tot}}{\alpha_{clad,\lambda}} = \frac{\alpha_{tot} C}{\alpha_{core,\lambda}(d_{core}^2 / d_{clad}^2)}, \tag{2}$$

where α_{tot} is the required pump absorption (dB), $\alpha_{clad,\lambda}$ is the cladding absorption (dB/m), C is the area correction factor if non-round shapes are used, $\alpha_{core,\lambda}$ (dB/m) is the core absorption, and d_{core} and d_{clad} are the core and cladding diameters (m).

Presuming a 10% loss of output power is acceptable within the lifetime of the fiber, for an amplifier with linear gain in the fiber we can approximate a total loss of 0.5dB / ½$L_{A,\lambda}$ at the signal wavelength. Similar calculations can be done for other loss parameter, shown in Figure 9. The figure shows the benefit of a short application length, which permits a higher photodarkening induced excess loss per unit length. Therefore it is beneficial to design the fibers to have high cladding absorption $\alpha_{clad,\lambda}$, or to have a high core absorption and a high core/clad area ratio. Compared to 915nm pumping, the pump wavelength of 976nm reduces the application length roughly by the factor of 4 because of the increased $\alpha_{core,\lambda}$. For example the 30/250DC fiber with 13dB pump absorption at 976nm pump wavelength gives an application length of 0.8m, assuming 1200dB/m core absorption and an area correction factor of 1.05 for an octagonal fiber.

In order to reduce application length, the core size should be maximized. The upper limit of core size is primarily set by the required beam quality, although for example launching conditions and the coiling of the fiber [9] influence the extracted beam quality. The lower limit of the cladding size can be seen to be limited partly by the availability of bright, high power, low cost fiber coupled pump sources. The primary goal for fiber manufacturers is to develop an Yb doped fiber with higher pump absorption and reduced photodarkening. The proprietary Direct Nanoparticle Deposition technology of Liekki provides several advantages in this regard.

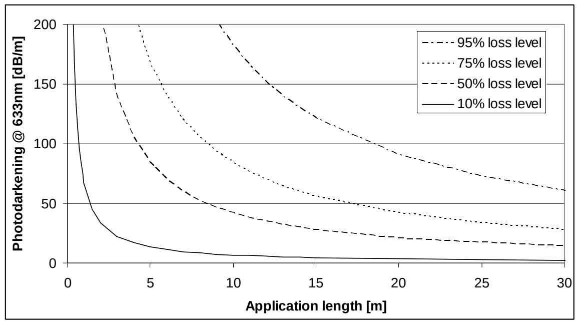

Figure 9. The acceptable worst-case photodarkening level for different application lengths was calculated based on 13dB pump absorption and an amplifier configuration.

4. RESULTS

4.1. Photodarkening of single-mode fibers

Photodarkening has been measured from several different types of fibers, as was already shown in Figure 5. The measurement method was used for feedback to systematically improve the glass composition of the fiber. There is a clear photodarkening dependence to the Yb concentration in the fiber, Figure 10. It is also shown that it's possible to increase the core absorption and core doping while simultaneously having lower photodarkening. A fiber manufacturing process with high throughput and high repeatability, such as the Liekki Direct Nanoparticle Deposition technology, is beneficial for the iterative work on material optimization. The excess loss spectra for two similar Yb-doped single-mode fibers are shown in Figure 11, where two commercially available fibers with the core absorption of approximately 1000dB/m are shown after the 30 minutes photodarkening test. The fiber samples are likely to have different glass compositions, and are also manufactured using different deposition technologies. The shape of the photodarkening spectrum is similar with both fibers, and the photodarkening results are >400dB/m and 6dB/m at 633nm, yelding >5.7dB/m and >0.09 dB/m at the signal wavelength.

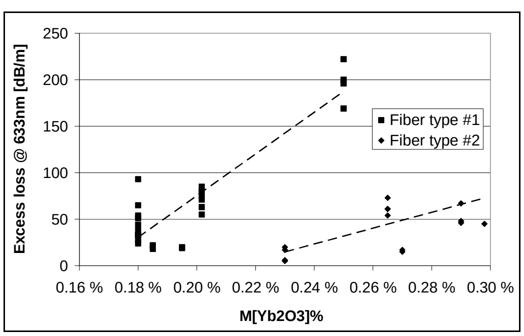

Figure 10. Photodarkening of different fiber types. Higher doping and higher core absorption can be had with lower photodarkening.

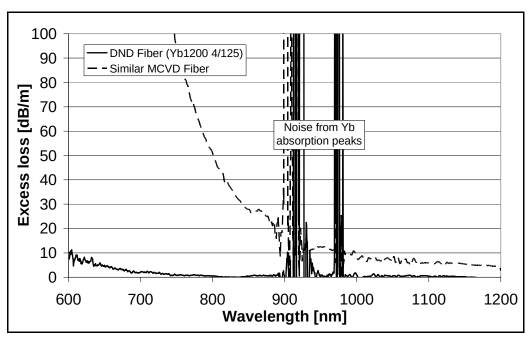

Figure 11. Photodarkening spectra of low photodarkening DND fiber and similar competitor's fiber.

Long-term photodarkening tests of single-mode fibers are also underway. A fiber laser using Yb-doped single-mode fibers has been built, shown in Figure 12, and the measurement is on-going. The accumulated result is shown in Figure 13, where the stabilization of the output power of the laser can be seen. After the stabilization the output power of the laser has slightly increased, indicating some sort of self-annealing process within the fiber. The fiber has been kept in constant room temperature throughout the measurement, and the pump power is stabilized. The additional noise in the stabilized part of the result is a measurement artifact caused by the connecting and disconnecting of the laser output to the power meter.

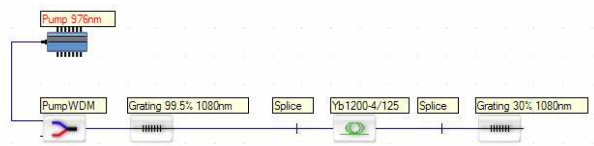

Figure 12. Measurement setup for long-term testing of single-mode fiber. 30% grating is the output of the system, which is connected to a power meter.

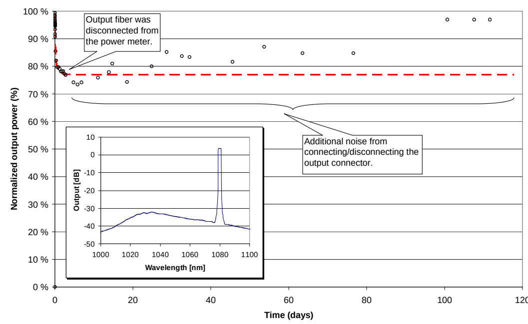

Figure 13. Long-term result of single-mode fiber photodarkening shows an initial performance drop of 25% in the output power, and rapid stabilization of the output power.

4.2. Initial rate of photodarkening

The temporal behavior of photodarkening was measured with the setup illustrated in Figure 2. The measurements were done using the pump wavelength of 974nm, and pump powers from 30 to 90mW. Two different measurement series were done: one with a long fiber sample length and total pump absorption to the sample and one with a short fiber sample and a constant pump absorption to the sample. Each measurement was made with a fresh non-photodarkened fiber, and the length of the samples were 0.5m and 0.1m for variable and constant inversion, respectively. All normalized probe transmissions were fitted with the stretched exponential function shown in Equation 1, and the dispersive parameter β value for all samples was 0.54, giving a good fit for all pump powers. The measured decay curves are shown in Figure 14 for the variable inversion case, and in Figure 15 for the constant inversion case. The inversion profiles for the corresponding cases were calculated with the Liekki Application Designer v3.0, and are shown in Figure 16.

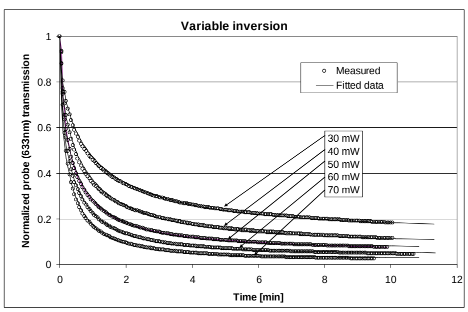

Figure 14. HeNe probe transmission through 0.5m SMF samples with different launched pump powers. All pump light was absorbed by the sample, and therefore the inversion of the fiber changed with every pump power. Normalized probe transmissions were fitted with the stretched exponential function.

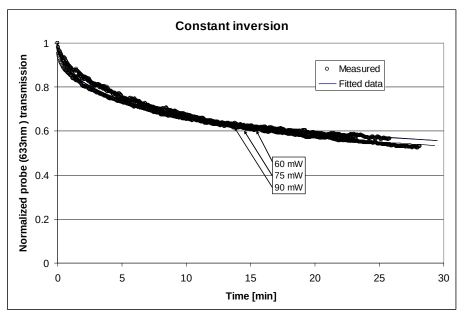

Figure 15. HeNe probe transmission through 0.1m SMF samples with different launched pump powers. Enough pump power was used to saturate the inversion in the fiber to approximately 50% level. Normalized probe transmissions were fitted with the stretched exponential function.

The starting rate of photoinduced excess loss phenomena such as photodarkening is proportional to the number of photons involved in the process [3, 10]. A decay rate $\tau_{1/e}$ was extracted from each probe measurement, where the intensity I(t= $\tau_{1/e}$) corresponded to value of (1-A)+A/e intensity value, where (1-A) is the steady state transmission value of the fit. The inverse of the decay rates are plotted as a function of launched pump power in Figure 15. The slope of the data is calculated in log-log scale in order to get an indication of the amount of photons needed for each photodarkening event. The slope of the variable inversion case is 1.3±0.2, and the slope of the constant inversion case is zero within experimental error. The slope of the variable inversion case indicates that the photodarkening process would be similar to a one-photon process. This is unlikely, as the photoionization threshold for doped silica fibers is >5.2eV [5], and the pump photon energy is 1.27eV, roughly 4 times less than the threshold. The slope for constant inversion case is practically zero, indicating no correlation between the pump intensity and the photodarkening, as long as the inversion is practically constant. It can therefore be argued, that the photodarkening process in Yb-doped silica fibers is not a nonlinear process, but rather a stepwise process requiring the energy of multiple photons for the formation of each color center. The energy required for the photoionization is stored in excited Yb ions, and the probability of the formation of a color center increases with inversion.

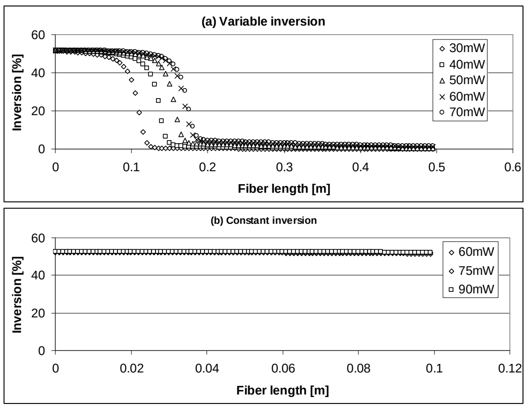

Figure 16. The calculated inversions for different decay measurements. (a) Variable inversion case with 0.5m fiber length. (b) Constant inversion case with 0.1m fiber length.

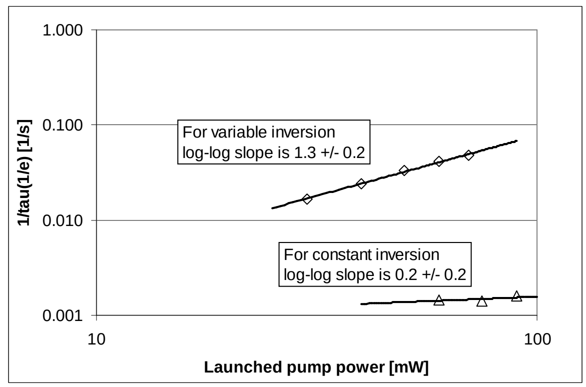

Figure 17. Photodarkening decay time constants as functions of launched pump power.

The effect of inversion to the initial rate of photodarkening was experimentally studied by using the same fiber type as an ASE source with higher inversion, and as a laser with lower inversion. The inversion profile shape of the ASE source is similar to the graphs seen in Figure 16 (b), and the inversion profile of the laser resembles the shape seen in Figure 16 (a). The photodarkening of the ASE source was measured with the probe wavelength, and the photodarkening of the laser was measured from the signal output power. Both of these decay rate measurements had a good stretched exponential fit using the β=0.54 parameter, and the fit for the laser is seen in Figure 13 as a dashed line. The time constants of the fits, however, were very far apart. The characteristic time constant τ for an ASE source was 370s, and for the laser 12960s. In order to better understand the photodarkening phenomenon in Yb doped fibers, a more rigorous investigation of the correlation between the inversion and the initial photodarkening rate is required.

4.3. Photodarkening of LMA fibers

A small number of LMA fibers were measured with the setup shown in Figure 6. The same 5cm sample length was used for all fibers for photodarkening measurement, and from longer samples the cladding absorption of each fiber were measured as well. The core absorption was calculated from the cladding absorption result. Commercially available fibers were used for reference, and two different Liekki fibers, namely an older reference and a more recent fiber are shown. The results are shown in Figure 18. In order to compare the fibers, the photodarkening result for the application length was calculated for each fiber. These results are shown in Figure 19. It should be noted that the photodarkening levels represent the worst-case lifetime scenarios of photodarkening, and typical applications are known to degrade much less than the graph suggests. In a typical application the inversion of the fiber is not as high as in the photodarkening measurement, and the effects of signal photons in the photodarkening process are not yet fully explored.

For LMA fibers the long-term photodarkening testing is needed to verify the results given by the fast benchmarking measurement. This applies to lasing configurations, as well as amplifier systems.

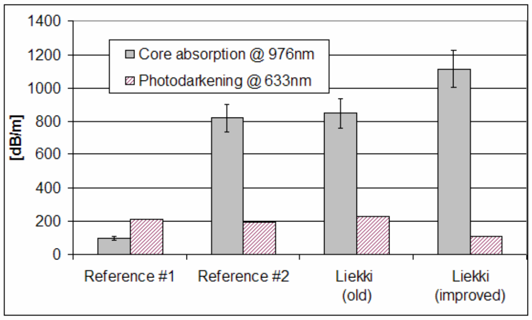

Figure 18. Photodarkening of LMA fibers compared. The PD at 633nm is comparable between reference fibers and Liekki fiber #1. A higher doped Liekki #2 fiber has the lowest photodarkening.

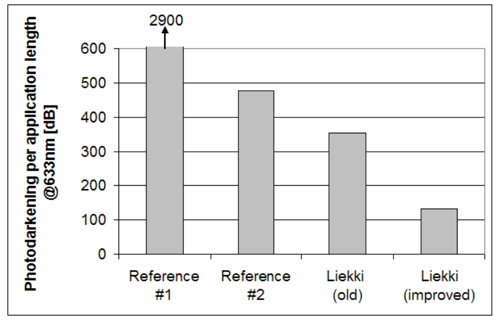

Figure 19. Photodarkening at application length. The application length for each fiber was calculated presuming 13dB pump cladding absorption, 976nm pump, and 200µm cladding diameter.

5. CONCLUSIONS

A measurement method for benchmarking both single-mode and large mode area multimode Yb-doped silica fibers was described. A uniform inversion level close to 50% is generated in both cases, thereby making the measurement repeatable from one sample to another. The visible wavelengths are used to measure photodarkening in order to have a higher measured signal, thereby making the measurement easier. In Yb-doped silica fibers the spectral shape of the induced color center has been the same for Liekki fibers and for the competitors' fibers we have measured, making it possible to estimate the effect of photodarkening on signal and pump wavelengths.

The measurement method has been used to benchmark doped silica fibers and to improve the fiber manufacturing process. The photodarkening performance can be improved by different glass compositions, and the work to develop highly-doped ultra-low photodarkening fibers is underway. In the long-term testing of single-mode fiber a self-annealing phenomenon has been observed, but the full implications of the result are yet not known. The possible effects of high brightness signal to the photodarkening of the fiber needs further studying.

The photodarkening rate measurements using a probe wavelength indicated that the inversion of the fiber is proportional to the initial photodarkening rate. The energy of roughly four pump photons are needed to overcome the photoionization threshold of doped silica glass. The energy levels of the Yb ion alone can not explain the existence of the photoionization capable energy level. Thus, there needs to be an energy transfer mechanism from excited Yb ions to other sinks or impurities causing the photoionization. This also suggests that the clustering of rare-earth ions causes photodarkening in a fiber because of the enhanced energy transfer between neighboring ions or impurities in the cluster. Therefore a fiber manufacturing process that gives homogeneous high doping with low clustering such as the Direct Nanoparticle Deposition technology is very beneficial.

The effect of photodarkening was illustrated as a function of application length, showing the benefit of higher core absorption and fiber geometries that increase cladding absorption. Further work will include the long-term testing of large more area double clad fibers in order to verify their photodarkening measurement results. Also the correlation between photodarkening and power conversion efficiency or amplifier saturation power need more research.

ACKNOWLEDGMENTS

The authors would like to acknowledge Dr. Jeff Koplow and Dr. Dahv Kliner (Sandia National Laboratories, Livermore, CA) for invaluable discussions and co-operation regarding photodarkening, and Heidi Parpala for her photodarkening measurement work.

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