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# Inversion behavior in core- and cladding-pumped Yb-doped fiber photodarkening measurements

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Yb-doped fibers are widely used in applications requiring high average output powers and high power pulse amplification. Photodarkening of the Yb-doped silicate glass core potentially limits the lifetime or efficiency of such fiber devices. In many studies of photodarkening, two principal methods of controllably inducing an inversion are used, namely, cladding pumping and core pumping of the sample. We present simulation results describing the key differences in the inversion profiles of samples of different physical parameters in these two cases, and we discuss the problems and possibilities that arise in benchmarking fibers of various physical parameters. Based on the simulation and experimental work, we propose guidelines for photodarkening benchmarking measurements and show examples of measurements made within and outside of the guidelines. © 2008 Optical Society of America

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## 1. Introduction

Ytterbium (Yb)-doped fiber lasers and amplifiers have become an attractive option for many applications ranging from materials processing to frequency conversion to visible or ultraviolet wavelengths. The interest in silica based glass fibers doped with Yb arises from the low quantum defect that enables high efficiency, and a wide body of literature exists on the use of Yb fibers in amplifiers and lasers. The high optical efficiency in conjunction with double cladding (DC) fiber structure to convert large quantities of pump radiation to high brightness signal have pushed Yb-doped sources from research demonstrations to commercially available laser devices [1–7]. On the other hand, higher concentrations or pump intensities have in some cases been known to induce deleterious effects, such as photodarkening (PD), that manifests as a broad spectral attenuation in the Yb-doped core of the fiber [8]. In the work toward fiber with increased PD resistance, the PD as a material property needs further study, and preferably quantitative or qualitative measurement methods.

In our earlier work we have introduced two methods of comparing, benchmarking, and studying of Yb-doped fibers, namely, the core pumping method [8] and the cladding pumping method [9]. This work describes in detail the differences of the two methods and discusses their limitations and possibilities in characterizing fibers for PD.

Although good progress has been made in further understanding the PD process in silica glass, the mechanism(s) involved in PD are under discussion, and several hypotheses have been suggested for the principal underlying process. In a recent experiment, Yoo *et al.* [10] induced PD in both Yb-doped and Ge-doped glass, and observed a strong absorption band at 220 nm that was attributed to oxygen deficiency centers (for example, Yb—Yb or Yb—Si bonds) that could act as PD precursors, leading to color centers. A clustering related process was also proposed by Guzman Chávez *et al.* [11], in which  $\text{Yb}^{3+} - \text{Yb}^{3+}$  pairs (or even more complicated clusters) would lead to the formation of color centers or other structural defects. In a different set of experiments, Engholm *et al.* [12] observed an absorption band at 230 nm. However, the absorption was attributed to a charge transfer band involving the Yb ion, implying the possibility of

inducing a change of  $\text{Yb}^{3+}$  to  $\text{Yb}^{2+}$  and vice versa, creating free electrons or holes that could act as precursors for PD. Several different methods of fully or partially reversing the PD have been demonstrated. The different methods included temperature annealing [13], exposure to UV and visible light [11,14], and oxygen loading [10]. More recently, PD has also been shown to bleach by the pump power itself [15].

## 2. Photodarkening Measurement Methods

PD measurements can be realized either by measuring the properties of a small sample of the doped fiber of interest or by creating a full fiber laser or amplifier system, where the total efficiency and output power are measured as a function of time. A fast, quantitative, and repeatable method is preferred for benchmarking or studying different Yb-doped fibers. To achieve these objectives, the inversion of the investigated samples needs to be well controlled. Inducing a controlled inversion is easier with short sample lengths, as shown below. The different PD benchmarking and studying methods that aim to induce a repeatable and controllable inversion to the fiber sample can roughly be categorized to two dissimilar cases, namely, core-pumping [8,11,16] and cladding-pumping [9,15,17] methods. Both methods are based on the observation that the excited state population density is the main parameter affecting the rate of PD [18].

The measurement technique we proposed for benchmarking single-mode Yb-doped fibers relies on saturating the inversion of the fiber to a flat and repeatable level across the sample by core pumping the sample with a high-irradiance, single-mode, fiber-coupled pump [8]. With this technique, PD can be measured with either a monochromatic or a white-light source coupled into the core of the fiber. As the area of the fiber core increases, the inversion becomes harder to saturate using a single-mode pump diode, and other means of inducing the flat and repeatable inversion level in the fiber sample must be introduced. Such means include cladding pumping of a short fiber sample, but the typical pump irradiance is several orders of magnitude lower than with core pumping, and the inversion is thus difficult to saturate, making inversion dependent on the incident pump power [9]. Both of these methods are illustrated in Fig. 1. In the simplest form, the PD measurement consists of measuring the transmission of the sample fiber before and after exposure to pump light, either by measuring a probe signal with a powermeter or a white-light source with an optical spectrum analyzer. During PD of the sample, care should be taken to ensure that the sample is not lasing, as any lasing significantly decreases the inversion level. Signal light feedback should be prevented by, for example, using angled fiber ends. Care should also be taken not to influence the measurement by using a powerful probe laser, as many reports indicate that the PD process can be influenced by illumination by many different wavelengths [11,14,15]. Potential probe laser influ-

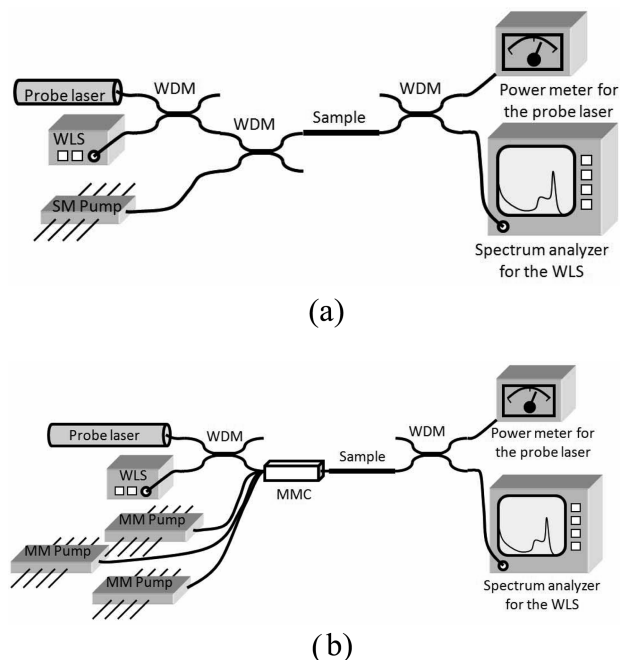


Fig. 1. (a) Core-pumping method for benchmarking. Single-mode pump laser diode is coupled to the sample fiber using a wavelength division multiplexer (WDM). Either a probe laser, for example, He-Ne, or a white-light source (WLS) can be used to measure the transmission of the sample before, after, or during PD using the powermeter or the spectrum analyzer, respectively. Sample can be, for example, fusion spliced to the setup from each end. (b) Cladding-pumping method uses a multimode combiner (MMC, for example, a 6 + 1 to 1 tapered fiber device) to couple light from multimode laser diodes to the sample fiber. The probe laser or other light source can be coupled to the core of the sample fiber by using a multimode combiner equipped with a signal fiber. Pump propagates in the cladding of the sample fiber.

ence can be decreased or eliminated, for example, by using very low intensities together with a sensitive receiver or by illuminating (and measuring) the sample only at some time interval.

## 3. Simulated Inversion in Core- and Cladding-Pumping Measurements

To decrease the time required for each benchmarking measurement, the inversion in the fiber sample should be maximized during the measurement in order to rapidly induce PD. On the other hand, the inversion level needs to be reproducible between measurements and samples. Inversion of a fiber sample is defined by the pump brightness, the sample properties, and the pump wavelength, and the most convenient way of deriving a relatively accurate inversion profile of the fiber is by simulation. The results presented here were calculated using commercially available fiber simulation software Liekki Application Designer v4.0. For simulating fiber types of different compositions, the absorption and emission cross-section data need to be accurate for each fiber type. The results shown here are based on cross sectional data from aluminosilicate fibers (Fig. 2). The used cross sectional data were shown

to fit experimental data well by Farrow *et al.* [19]. The other typical simulation parameters used were Yb ion density of  $1.2 \times 10^{26} \text{ m}^{-3}$  and an excited state lifetime of 0.85 ms. The amplified spontaneous emission (ASE) values were calculated for 101 wavelengths between 1000 and 1100 nm, and the inversion was calculated in 100 points along the fiber sample, regardless of simulated fiber length.

In the simulator the core propagating pump (and ASE) transverse intensity profile is calculated based on the given refractive index profile [20,21]. The pump absorption is derived through the rate equations of the active fiber (taking into account the concentration of ions and cross section data), and the overlap of the core propagating pump mode and the doped region of the core is taken into account. The cladding propagating pump is assumed to homogeneously fill the cladding and core. The inversion is calculated both in the radial direction and the longitudinal direction of the fiber, assuming cylindrical symmetry. The rate equation model was described in more detail by Rebolledo *et al.* [22]. The inversion values shown later are typically the average values of the total volume of each fiber sample. The inversion is defined to be flat, when the standard deviation of the inversion data is  $<1\%$ . This definition is based on what is readily attainable using both the core-pumping and the cladding-pumping methods, and ensures that the sample volume represents well the behavior at the nominal (average) inversion fraction level. In the case of a flat inversion, also the radial dimension is typically flat, although pump and ASE distribution in the core affect the inversion profile.

#### A. Inversion in Core-Pumped Samples

The inversion profile of a core-pumped sample was simulated as a function of pump power, sample length, Yb ion concentration, and pump wavelength for a  $4 \mu\text{m}$  core diameter fiber. The average inversion over the whole sample and the standard deviation of the inversion were calculated from the simulated inversion profiles. Each longitudinal inversion point is the average of the radial inversion, and in cases where the inversion is defined to be flat (i.e.,  $<1\%$  standard deviation over the length of the sample)

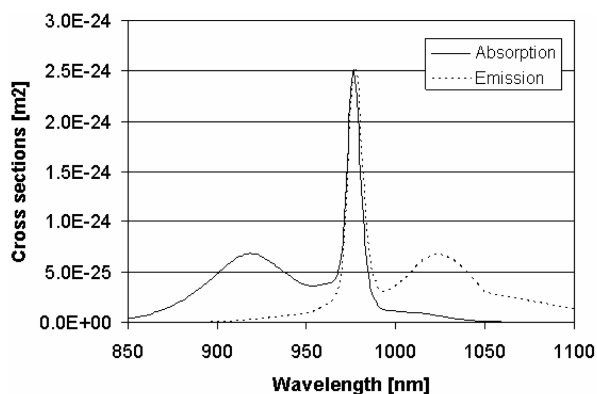


Fig. 2. Absorption and emission cross sections used in the simulations. Based on measurements made from aluminosilicate fibers.

also the radial inversion profile was confirmed to be flat. Figure 3 illustrates how the inversion of a 10 cm core-pumped sample saturates with increasing pump power at two different pump wavelengths. The inversion level of a fiber changes very little with increased pump power when the inversion is flat. Due to the short sample length and the high brightness of the pump, the ASE contribution to the inversion is small. A general view of the influence of pump wavelength is shown in Fig. 4, where each point represents the average inversion of a particular sample length irradiated with 250 mW of pump light. As shown, the saturation level of inversion is mainly defined by the ratio of the absorption and emission cross sections at the pump wavelength. The longer samples at 920 nm show a decreased average inversion. The pump power used was not high enough to saturate the inversion in those data points, and the inversion profile of the said points is not flat.

The scalability of the core-pumping method to larger core diameters is shown in Fig. 5, where the simulated pump power required for inversion saturation of a 10 cm sample is illustrated for two different pump wavelengths. The simulations were done using the typical parameters listed above. The pump power required to saturate a core-pumped sample increases as the core diameter increases, but the required irradiance is constant. This limits the core size of a practical benchmarking measurement to approximately  $9 \mu\text{m}$  (920 nm pump) and  $18 \mu\text{m}$  (976 nm pump) with 500 mW of coupled pump power. Practical limitations such as splice losses between dissimilar fibers and the availability of high brightness pumps further limit the core diameters, making the core-pumping method suitable mostly to single-mode and few-mode fibers up to 10 to  $15 \mu\text{m}$  diameter when using the 976 nm pump wavelength.

A key parameter regarding a benchmarking measurement is the length of the fiber sample. The irradiance requirements presented above are based on the absorption and emission cross sections shown in Fig. 2 and the typical Yb ion concentration of  $1.2 \times 10^{26} \text{ m}^{-3}$ . The same irradiance requirement can be

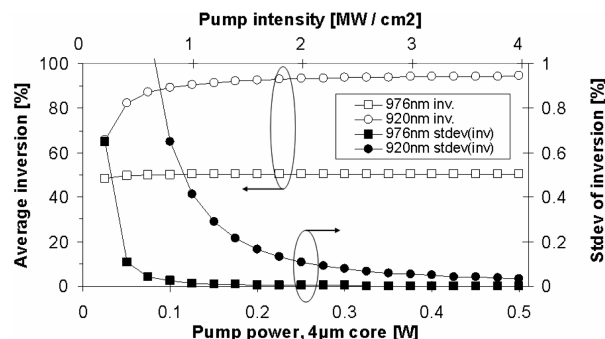


Fig. 3. Average inversion and standard deviation of the inversion versus pump power for a core-pumped, Yb-doped fiber. The inversion of the sample saturates, i.e., additional pump power no longer significantly increases the inversion. The saturated inversion level is mainly defined by the ratio of absorption and emission cross sections.

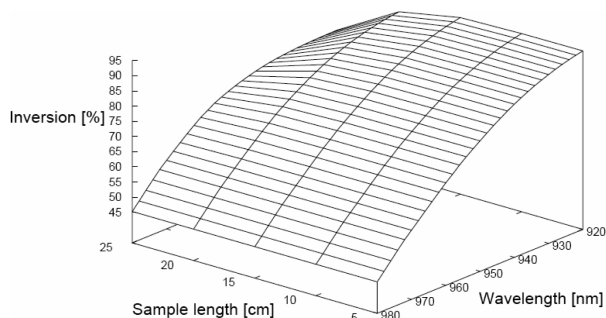


Fig. 4. Simulated average inversion of a  $4\text{ }\mu\text{m}$  core diameter fiber samples core pumped with 250 mW of pump power. Each data point represents a fiber sample of certain length. Inversion is the average over the volume of the sample. The average inversion of a sample is mainly defined by the ratio of absorption/emission cross sections. The inversion of each sample is flat excluding the points at the 920 nm long sample's corner, where the average inversion is seen to decrease.

used for fiber samples where the number of ions is kept constant, i.e., higher concentration samples need to be shorter and lower concentration samples can (but do not necessarily have to) be made longer. Shorter sample lengths may also be required when, for example, studying spectral regions of high absorption such as the shape of the visible photodarkened spectra or the Yb ion absorption peak [11].

#### B. Inversion in Cladding-Pumped Samples

To achieve a flat inversion in  $>10\text{ }\mu\text{m}$  core diameter fibers, a different approach of inducing the inversion is required. Cladding pumping using multimode pump diodes, as shown in Fig. 1(b), fulfills the requirement. Figure 6 shows the calculated average level and standard deviation of the inversion over fiber samples with a  $20\text{ }\mu\text{m}$  core diameter and a  $400\text{ }\mu\text{m}$  cladding diameter with varied pump power. The results indicate that a flat ( $<1\%$  standard deviation) inversion is achieved over the whole range of pump power, but the average inversion achieved depends on the pump irradiance. The operational regime is far from the ir-

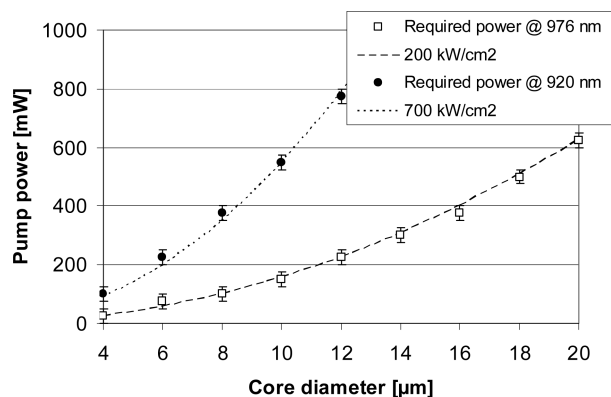


Fig. 5. Pump powers required to saturate a 10 cm sample by core pumping to different core diameters. The error ranges represent the uncertainty due to the pump power step between each simulated data point. The dashed irradiance lines are fit to the simulation results.

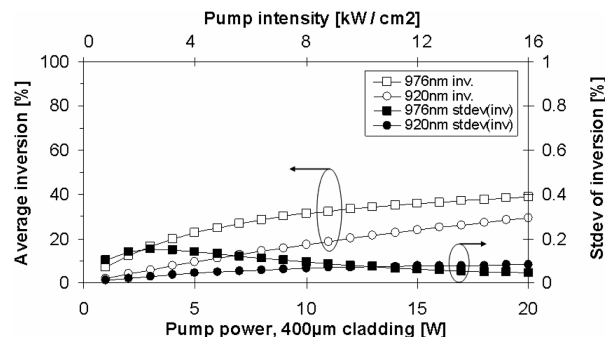


Fig. 6. Average inversion and standard deviation of the inversion versus pump power for a cladding-pumped, Yb-doped fiber with a  $20\text{ }\mu\text{m}$  core diameter and  $400\text{ }\mu\text{m}$  cladding diameter. The inversion does not have a practical threshold level after which the inversion is saturated, but rather the inversion is tunable and very flat over a range of pump power. The inversion level is mainly defined by the absorption cross section and the pump power.

radiance thresholds for inversion saturation;  $200\text{ kW/cm}^2$  for a  $400\text{ }\mu\text{m}$  diameter fiber translates to approximately 250 W of pump power, which is feasible but hardly practical for a benchmarking measurement. The pump wavelength dependence of a low irradiance cladding-pumped sample was studied by simulating the inversion profile of a fiber sample over a range of pump wavelengths and fiber lengths (Fig. 7). The inversion shown is the average inversion of the fiber sample of a certain length, i.e., the graph does not quantify the flatness of the inversion profiles. However, the inversion in the samples was flat within the shown wavelengths and sample lengths. The pump power was 5 W, and the core and cladding diameters were  $20\text{ }\mu\text{m}$  and  $400\text{ }\mu\text{m}$ , respectively. Due to the low irradiance of the pump light, the average inversion is defined mainly by the absorption cross section. In order to induce a comparable inversion between different fiber samples, one needs to have a repeatable pump wavelength and coupled pump power to the samples.

#### 4. Experimental Results

Some key differences of the two measurement methods are experimentally demonstrated to show the

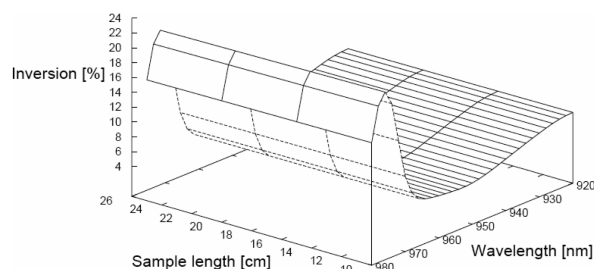


Fig. 7. Simulated average inversion of a  $20\text{ }\mu\text{m}$  core diameter sample cladding pumped to  $400\text{ }\mu\text{m}$  cladding with 5 W of pump power. Each data point represents a fiber sample of certain length. Inversion is the average over the volume of the sample. The inversion of cladding pumped samples is mainly defined by the absorption cross section, as the irradiance of the pump is more than an order of magnitude lower than in typical core-pumping case.



behavior of samples under different conditions. Core-pumped measurements using a setup as shown in Fig. 1(a) were done to long fiber samples using a core propagating probe laser operating at 633 nm. The aluminosilicate fiber samples with an Yb concentration of approximately  $2 \times 10^{26} \text{ m}^{-3}$  were exposed to different pump powers at 974 nm wavelength. The measurement results are shown in Fig. 8, and the simulated inversion profiles are as inset. During the relatively short exposure to pump light, all samples exhibit a different PD rate and degree of PD. The reason can be seen from the simulated inversion profiles: as pump power is increased, a longer piece of Yb fiber is exposed to high inversion, causing an increase in the measured total PD signal.

The simulation results suggest using a short fiber sample length in order to induce a comparable PD rate and degree of PD between samples. Measurement results from shorter fiber lengths with approximately  $1.2 \times 10^{26} \text{ m}^{-3}$  Yb concentration are shown in Fig. 9 for several pump powers at 974 nm wavelength. The inversion profiles of the samples are shown as inset; however, due to overlapping data points, only one profile can clearly be seen. The probe transmission of samples exposed to different pump intensities are the same within experimental error between the different samples. This is attributed to the identical inversion profiles shown in the inset, regardless of the coupled pump irradiance.

PD measurements with the cladding-pumping method were done using a setup as described in Fig. 1(b). The core propagating probe diode operated at  $795 \pm 10 \text{ nm}$  (coupled power  $68 \mu\text{W}$ ), and the cladding coupled pump wavelength was  $976 \pm 2 \text{ nm}$  (coupled power 8 W). The results are shown in Fig. 10, where the normalized transmission of the probe light per unit length is shown as a function of time. The simulated inversion profiles of the different sample lengths are illustrated in the inset. The fiber core diameter was  $30 \mu\text{m}$ , the octagonal cladding flat-to-

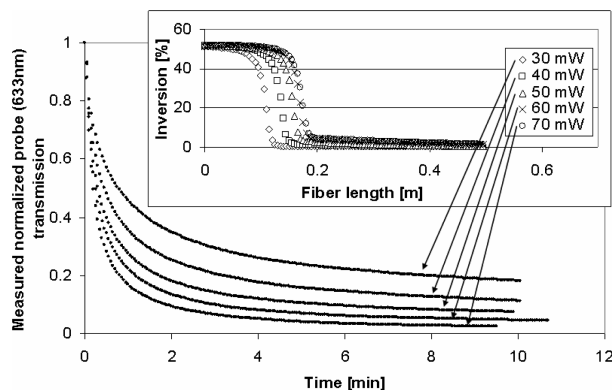


Fig. 8. Measured normalized probe transmission in a core pumped setup with varying pump powers. The pump wavelength was 974 nm, and the probe wavelength was 633 nm. The sample length is too long to achieve inversion saturation, and the rate and degree of PD after the observed time period are dependent on the pump power. Inset: simulated inversion profiles for each pump power at 974 nm.

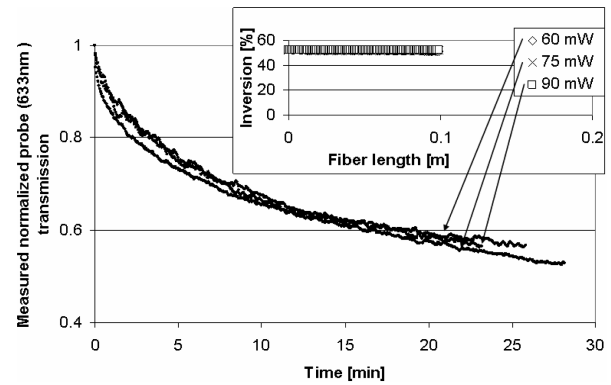


Fig. 9. Measured normalized probe transmission in a core-pumped setup with varying pump powers. The pump wavelength was 974 nm, and the probe wavelength was 633 nm. The inversion is saturated, and the degree of PD and the rate of PD are not dependent on the applied pump power after the observed time period. Inset: simulated inversion profiles for each pump power at 974 nm (data points overlap).

flat diameter was  $250 \mu\text{m}$ , and the Yb concentration in the core was approximately  $1.2 \times 10^{26} \text{ m}^{-3}$ . Samples with longer lengths have lower overall average inversion, and particularly the simulated inversion of the longest sample shows inversion depletion at the input and output ends of the fiber due to ASE. The results show different PD rates for each sample length. The results highlight that, in cladding pumping, the repeatability of the sample length also is of concern, and, to control the inversion in the samples, a short enough length should be chosen to not deplete part of the inversion by ASE.

## 5. Discussion

The principal differentiator of the core- and cladding-pumped methods is the pump brightness. The difference in the achieved inversion profiles is illustrated in Figs. 4 and 7, where the core-pumped saturated

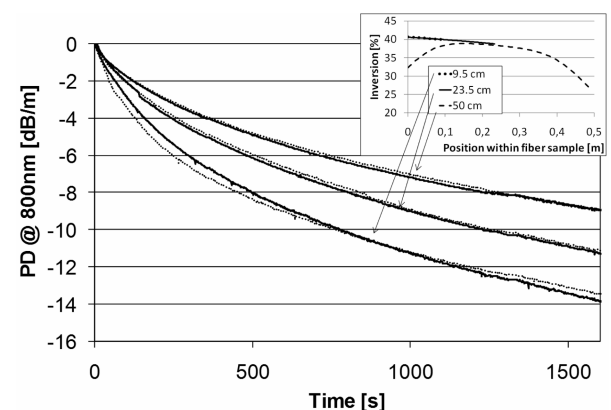


Fig. 10. Measured normalized probe transmission in cladding pumped samples with varying lengths. The pump wavelength was  $976 \pm 2 \text{ nm}$ , and the probe wavelength was  $795 \pm 10 \text{ nm}$ . To make signals comparable, they were normalized with the sample length. Two measurements were done for each length (shown as line, dotted line). Inset: simulated inversion profiles for each fiber length. The simulation data shows the depletion of inversion due to ASE at the input and output of the long sample fibers.

inversion is shown to follow the ratio of absorption/emission cross sections, whereas the cladding-pumped inversion mainly follows the absorption cross section shape. Therefore the highest core pumping inversion can be achieved by pumping at shorter wavelengths (e.g., 920 nm). In the typical cladding-pumped case, the pump brightness is lower, and higher inversion is attained at the 976 nm wavelength pump.

The core-pumping method using a single-mode, fiber-coupled, high-brightness diode relies on inversion saturation to achieve inversion flatness and repeatability between different samples. In the case of core pumping too long a fiber, the inversion profile is very flat in the beginning of the fiber, where the inversion is saturated. When the coupled pump power is insufficient to saturate the full length of the active fiber, the high core absorption leads to a sharp drop in the longitudinal inversion profile as the propagating pump irradiance is reduced. By increasing the coupled pump power, the longitudinal inversion profile may retain a similar shape, but the saturated portion of the fiber becomes increasingly longer. The effect becomes more evident with increasing core size, as is the case with large mode area (LMA) fibers. At some point the fiber sample can no longer be saturated using reasonable pump power, and the inversion over the fiber sample is no longer flat and repeatable. From the simulation results the threshold levels for core-pumping saturation using 920 nm and 976 nm pumping were approximately  $700 \text{ kW/cm}^2$  and  $200 \text{ kW/cm}^2$ , respectively. For a single-mode, fiber-coupled pump with 500 mW output power, the maximum core diameters feasible for inversion saturation using core pumping are approximately  $9 \mu\text{m}$  and  $17 \mu\text{m}$  for 920 nm and 976 nm pumping, respectively, suggesting that the preferred wavelength for core pumping experiments is near the 976 nm absorption band. In practical measurement setups one should operate further away from the calculated limits due to coupling losses to the sample fiber and uncertainties in the simulation results. Given the above, the sample lengths need to be limited from a few centimeters to a few tens of centimeters (depending on the Yb concentration) to ensure that the inversion within the sample is saturated.

In the case of cladding pumping the longitudinal inversion profile as a function of input pump power is quite different from the core-pumping method. Even with small input pump powers the inversion tends to be very flat throughout the fiber, and by increasing the pump power the inversion increases evenly throughout the short sample, as shown in Fig. 6. The inversion across the length (and in the radial direction) is relatively uniform. The cladding-pumped sample length is limited by the onset of ASE in the fiber, as the ASE suppresses the inversion in both the input and output ends of the fiber. The onset of ASE limits the practical length of cladding-pumped samples to a few tens of centimeters. In the cladding pumping case the inversion at the end part of the sample de-

creases due to reduced pump irradiance. If one wishes to compare samples at similar inversion levels, the pump absorption of different Yb fiber samples should be kept constant in order to induce a similar inversion profile between the fibers, or one should further flatten the inversion profile by using a two-directional pumping scheme. Another approach is to keep the excited Yb ion density constant, as suggested before [9]. To keep the excited state density constant between samples of different core/cladding dimensions, one potentially needs to tune both the coupled pump power and the wavelength.

To reliably determine the inversion level of a cladding-pumped sample, both the pump wavelength and the coupled pump power must be known. In addition to knowing well the experimental parameters, the material parameters used in the simulation need to be accurate in order to obtain reliable inversion results. If the glass composition is changed considerably, for example, by introducing or changing the amounts of Al, P, B, or Ge doping in the glass, the absorption and emission cross section data need to be updated. Accurate determination of both absorption and emission cross sections and their error ranges to ensure the accuracy of the simulated inversion is under way and will be the subject of a later report.

## 6. Conclusions

The benchmarking of PD from different types of fiber samples is feasible by inducing a flat, known, and repeatable inversion to the sample volume. In order to induce the PD to the sample in a short amount of time, the inversion level within the sample should preferably be high. The simulation results illustrated that, depending on fiber type, this can be achieved both by core pumping (single-mode fibers, cores typically smaller than  $10 \mu\text{m}$ ) and by cladding pumping (LMA fibers). The four principal conclusions are the following:

- The critical parameter defining the inversion of a sample in the core-pumping method is the pump wavelength. Pump irradiance and sample length have lesser effects when working in the inversion saturation regime. The pump wavelength can easily be stabilized, for example, by using grating stabilized sources.
- As discussed above, the core-pumping method required inversion saturation. To decrease the pump power required for the inversion saturation, the use of 976 nm pump wavelength region is preferred. The coupled pump power should be well above the simulated minimum irradiance due to simulation uncertainty, possible coupling losses, and PD induced pump losses during the measurement.
- The cladding-pumping method has multiple critical parameters: pump wavelength, pump power, and sample length all have a significant effect on the level and profile of the induced inversion. The pump wavelength induced inversion uncertainty can be minimized by using a pump wavelength away from

976 nm. The pump power induced inversion uncertainty can be decreased by increasing the pump power. The sample length induced inversion uncertainty can be decreased by decreasing the sample length.

– The main sample length limitation in the core pumped case is the available pump power. In the case of cladding pumped setup the main sample length limitation is the onset of ASE, which in turn reduces the inversion at the ends of the sample.

The harmful measurement artifacts of using too long fiber samples were demonstrated with both core- and cladding-pumping methods. When properly applied as a benchmarking measurement, the core-pumping method is more repeatable, as the pump wavelength is the principal parameter in defining the inversion level of the sample. The cladding-pumping method, however, is more suitable for LMA fibers and advanced studies of the PD phenomenon, such as the rate of PD at different levels of inversion. In such work, care needs to be taken to validate the simulated inversion levels. The simulation parameters need to be quantified through experiments, and the simulation model needs to be demonstrated to fit the experimental data. Documentation of the methodology and results of such work are under way and will be the subject of a later publication.

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