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Improved Setup and Procedure for Benchmarking of Photodarkening in Ytterbium Doped Silica Fibers

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Abstract. This paper presents a new setup and a corresponding procedure for the accurate measurement of photodarkening in ytterbium doped fibers. The core-pumping scheme enables the use of short samples and a low pump power and the automation of the measurement permits long-term tests for an effective benchmarking of fibers with low photo-degradation. Exploiting temperature-controlled components and coherent detection, this arrangement allows the measurement of transmission drops below 2% over hundreds of hours. For the first time, a long-term photodarkening experiment (up to 450 hours) has been carried out and correlated to the drop in output power experienced by a laser using the same type of fiber, demonstrating that the system can be employed in pre-compliance testing of active fibers prior to their use in a laser configuration.

Keywords: Fiber lasers, Photodarkening, Photochromism, Power lasers, Ytterbium

PACS: 42.81.Cn, 42.55.Wd, 42.70.Hj

1. Introduction

Fiber lasers (FL) have been, in recent years, an enabling technology for many industrial applications. Thanks to the outstanding power level achieved [1], their unique thermal management properties due to the large surface-to-volume ratio of the fiber, and the inherent ability to steer the laser beam, FL are expected to substitute traditional diode-pumped solid-state (DPSS) lasers in a number of applications. Among several implementations, FL based on Ytterbium (Yb) doped fibers appear to be particularly attractive because of their high quantum efficiency at 1μm. The latter is an interesting wavelength in some applications such as metal cutting, where it has proved to be more effective and time-saving than the well-known 10.6μm delivered by CO_2 lasers [2].

However, Yb-doped silicate fibers for high power FL are known to suffer from photodarkening (PD)[3]. This is a detrimental phenomenon that appears as a reduction of the laser performance caused by an increment in the active fiber propagation loss after medium to long-term laser operation. The photochromic damage can be permanent or, in some cases, bleachable by irradiation from UV light, thermal treatment etc.

The PD phenomenon has been broadly investigated over the past few years. The first comprehensive work by Koponen *et al* [3] used a basic setup in which a pump laser excited a short sample and a He-Ne laser was used to probe the photo-induced loss. The key point of that work was the demonstration of the 600 nm source as a better probe for PD, since the fiber exhibits ~70 times higher loss at that wavelength than that at 1μm. Furthermore, it was inferred that a 50% population inversion (achievable by pulsed FL only) was a constraint for accelerated PD. A further confirmation of this hypothesis came in a subsequent publication [4], in which core- and cladding-pumping were compared; it was proved that PD depends on the inversion rate, highlighting the importance of avoiding spurious lasing in order to allow the growth of the population in the excited states. Theoretical investigations of the PD phenomenon were proposed in [5], where a cladding pumping scheme was employed to prove that the PD rate can be parameterized as a function of the excited Yb concentration and of a parameter, the so-called “PD propensity”, which describes the behavior of a particular glass composition. Finally, a single mechanism of color center formation was proposed as the main source of PD. The work also pointed out the importance of performing PD measurements under uniform population inversion and emphasized the large time required to record the PD decay curve in the case of low inversion (i.e. low pump power density).

Remarkable efforts have also been devoted to the minimization of the PD. These have mainly consisted in engineering the host glass from which Yb doped fibers are drawn. Cerium co-doping [6] and use of phosphorous instead of Aluminum [7] in silicate glass are main examples of such investigations. Other areas of research have included a study of Thulium impurities in the Yb precursor as a cause of PD [8], which has been subsequently controverted [9], and a detailed analysis of color centers and defects related to the increased absorption has recently been presented [10].

All the above mentioned publications share common features regarding the experimental observation of PD:

1) cladding pumping is preferred to core pumping because it guarantees a uniform transverse excitation, resulting in enhanced reproducibility of the results;
2) however, cladding pumping requires higher powers, from 3 to 11 W, compared to core pumping;
3) the length of the samples usually spans from 10 to 50 cm in the case of cladding pumping;
4) PD induced loss ranges from ~5 to tens of dB, i.e. the transmission at visible wavelengths drops to ~40% or more;
5) measurement times are between a few minutes to ~1500 minutes (except in [10], where it goes up to ~50 hours),

and any concern about the measurement accuracy and stability over time does not appear to be presented.

Focusing on features 4) and 5), the works presented have reported on phenomena that are fairly easy to measure, with low-demanding stability of the measurement and very few concerns about the interpretation of the result.

On the other hand, the PD has been drastically reduced in current commercial production and, for state-of-the-art fibers, the photo-induced loss is limited to few % and usually occurs after hundreds to thousands of hours with the laser at full operational power. Such a low induced loss cannot be detected by simply pumping a short span of fiber and monitoring its variation in transmission because the environmental perturbations (thermal effects, mechanical drifts etc.) are as large as tens of %. Nevertheless, the drop of efficiency of the fiber in a laser cavity poses a severe limitation for the widespread deployment of FL in several applications, since the desired stability of the emitted power is required to be at least ±5% for thousands of hours.

From an industrial viewpoint it would be convenient to define a pre-compliance procedure to predict the PD behavior, and thus the fiber lifetime, by testing a short sample of the fiber that will be used to manufacture the laser. This work addresses the problem and focuses on the reliability of the photo-induced degradation measurement by proposing a highly stable setup based on core-pumping and a procedure that can detect PD loss induced over hundreds of hours, with high accuracy and reproducibility. The system is expected to become a useful tool for benchmarking commercial fibers as well as new prototypes without the need for long, hence costly, samples or manpower-consuming measurements.

2. Advanced core-pumping scheme

The choice of investigating the core-pumping arrangement relies on the reduced sample length and reduced pump power required to track a significant loss. The burden of maintaining a sufficient inversion and obtaining high reliability and reproducibility of the measurement is then placed on the setup complexity and measurement procedure.

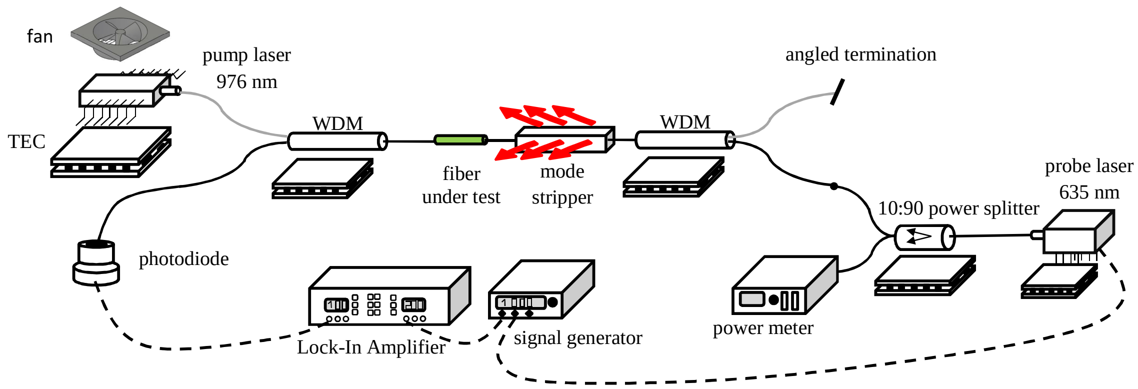

Figure 1 Setup for long-term testing of photodarkenable ytterbium doped fibers. Gray and black connections represent optical path made through fibers, whereas dashed lines point out electrical connections. All instruments are computer-controlled via GPIB (not shown).

The advanced core-pumping setup for PD benchmarking of Yb-doped fibers is depicted in Fig. 1. A single-mode fiber-pigtailed pump laser at 976 nm, capable of delivering 600 mW, is spliced to a wavelength division multiplexer (WDM) designed to couple 976nm and 1064 nm to its double-cladding output fiber. The thermal management of the laser is performed by the use of a heat sink and a thermo-electrical cooler; the residual heat is drained by a fan and allows the laser being run close to its absolute maximum rating. The WDM output is spliced to the fiber under test and, thanks to the near match of the core diameters (samples with core 6 to 9 μm are acceptable) most of the pump can be absorbed within a few cm and can guarantee a high degree of inversion, in order to enhance the PD phenomenon; the residual pump is then routed out by a second WDM. The use of angled connectors all over the setup, as well as the special care in the splicing of all fiberized components, avoid lasing in the sample. Preventing the lasing of the fiber under test is crucial because even a weak signal at 1μm would quite likely cause catastrophic optical damage to the pump diode while also limiting the inversion level to a lower value than that potentially achievable. The PD-induced fiber loss is measured using a 635 nm fiber-coupled laser diode, whose signal counter-propagates with respect to the pump and is probed on the available port of the first WDM by a photodiode operating at visible wavelengths. This laser is thermally controlled too, and driven in constant current mode well above the threshold. A sinusoidal signal at 1 kHz overlaps the DC component of the driving current, in order to modulate the optical power of the probe for coherent detection through a Lock-In amplifier. Setting the probe in a counterpropagating configuration is beneficial because it prevents the photodiode, though mainly sensitive to visible wavelengths, to be influenced by the residual pump. The power of the probe is set to 0.5mW, according to [11], in order to avoid a partial bleaching which would hamper the measurement. However, this a precautionary setting, in that we performed measurements for tens of hours with probe levels above 2 mW and did not detect any bleaching phenomenon.

In order to enhance the sensitivity, a mode stripper along the path prevents guiding of cladding modes at 635 nm, which would otherwise produce fluctuations in the detected power. The power of the probe is also monitored at the beginning of the chain through a power splitter and a power meter, in order to compensate the reading of the photodiode for long-term drifts. It should be noted that the WDMs and the power splitter are temperature-controlled by thermo-electrical coolers (TEC) that should guarantee long-term thermal fluctuations below 10 mK, which matches the requirements inferred by previous investigations [12]. Actually, an effective thermal regulation of these components turns out to be very demanding because of the shape and poor thermal conductivity of their package. An accurate monitoring around these components, performed by thermistors, shows that the actual temperature varies ~3 K over 24 hours. The effect on the response of single components is undetectable, but the overall effect of temperature on the Lock-In signal can amount to a change of more than 15%, as depicted in Fig.2.

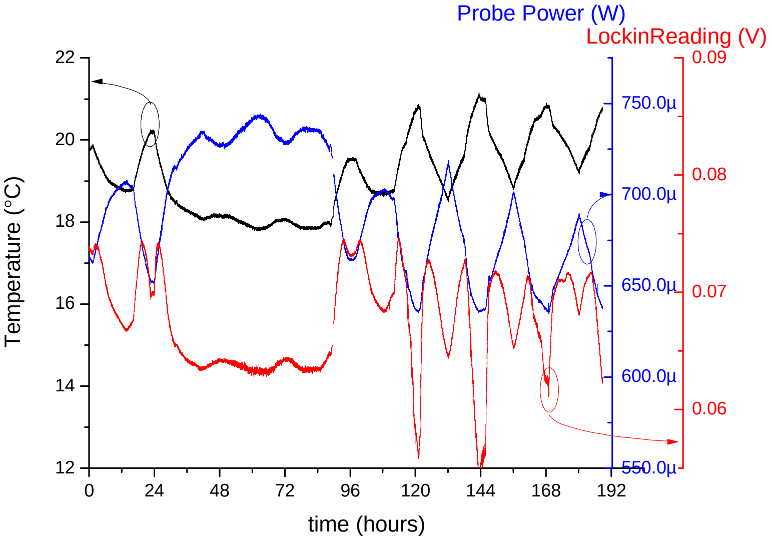

Figure 2 Environmental temperature measured on the PD bench, variation of the probe measured through a tap coupler and correspondent Lock-In reading. No active fiber is spliced into the setup. Notice that there is a good correlation between the three curves. The flat section of the curve corresponds to a sampling period in which the thermal regulation of the environment (i.e. the conditioning system of the room) was off.

The photodiode used to detect the probe has a responsivity of 0.45A/W @ 635 nm, a dark current of 0.01 nA and a NEP of 3.1e-15 W/√Hz. These parameters set the limit to the minimum detectable signal of 50 nV, which is compliant to the lowest sensitivity of the Lock-In amplifier.

The Lock-In amplifier parameters are set according to the received signal [13] which, in turn, depends on the attenuation of the fiber under test and the total attenuation of the components along the chain. As an example, when the fiber under test is replaced by a dummy passive sample, hence producing the lowest possible attenuation along the path of the probe, the detected signal is ~70 mV and the scale on the Lock-In is set to 100 mV. It is worth noting that the detection range 1µV – 500 mV has the highest stability of 5 ppm/°C and all parameters (probe power, splices etc.) are optimized to have the Lock-In working in that range.

Because Yb doped fibers exhibit a core-pumping absorption ~100 times higher than that of cladding-pumping, the length of the fiber under test can be as small as a few cm In our experiments the sample length is chosen to be the minimum spliceable, i.e. 5 cm, thus limiting the waste of costly active fiber. In all cases considered, the inversion level has been simulated using a custom-made program based on rate equations in a three-levels model, and an inversion of ~50% has been calculated for the tested samples. This makes the measurements more reliable because a comparable inversion level is maintained in all experiments [4]. In order to enhance the stability of the inversion level, the sample under test is fastened on the metal optical bench acting as heatsink, though a more advanced control of the fiber core temperature shall be considered.

The optimized procedure to characterize an active fiber sample, developed by testing several commercial and custom fibers with different PD rates, consists of three steps:

1) the fiber under test is spliced between the mode stripper and the WDM; the Lock-In parameters (scale, time constant) are set according to the detected signal in order to obtain the lowest relative uncertainty and properly track any variation of the optical loss of the sample;
2) the PD experiment is started: with the pump OFF, a Labview program, which controls all instruments, begins recording the probe power, the temperature at several locations on the optical bench and the signal provided by the Lock-In; the data are collected for 24 hours. The curve Lock-In reading versus temperature is linearized and later used to correct the Lock-In reading;
3) the pump is turned ON and the Lock-In reading is recorded after compensation. The experiment can run for hundreds to thousands of hours and a drop of the Lock-In reading, after linear compensation, provides the information about the fiber degradation.

The Lock-In reading, compensated for temperature effects, normalized to its initial value and translated to 0, has been defined PD signature. The PD signature starts at level 0 and , as the photo-degradation occurs, it becomes negative. The drop indicates the reduction in the transmission of the probe through the sample with respect to its initial value, as sketched in Fig. 3. PD signature graphs from experimental data are going to be presented in sect. 3.

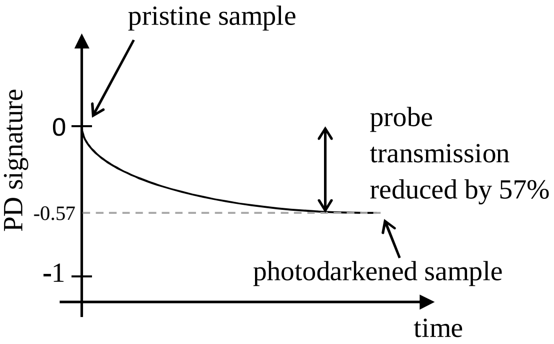

Figure 3 Example of PD signature graph.

3. Measurements and Results

The validation of the setup has been carried out on three mainstreams: i) the measurement of highly photodarkenable fibers and comparison of the result with that obtained using a simple core-pumping scheme as the one presented in [3], ii) the long-term characterization of the setup while the pump is OFF in order to assess the measurement uncertainty and finally, iii) the test of a low-PD fiber whose correspondent large mode area version was previously employed in a high power CW laser which exhibited a moderate level of photo-induced output power degradation.

3.1. Characterization of a highly photodarkenable fiber

Fig. 4 shows the comparison between two PD measurements on two different samples of the same highly photodarkenable fiber, the first carried out by a simple core-pumping scheme without any compensation and a low power pumping diode (black dotted curve), and the second by the advanced setup (red solid curve). The fiber has a core diameter of 6 µm, a numerical aperture of 0.14 and a core-pumping absorption of 183 dB/m at 976 nm.

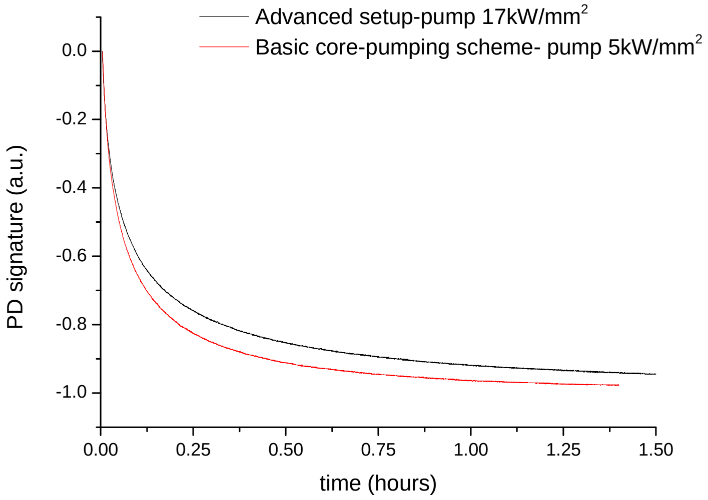

Figure 4 PD signature of a highly photodarkenable fiber, produced with a simple core pumping scheme at low power and with the advanced setup at high pump level.

The two dynamics (exhibiting a drop in transmission of almost 100%) nearly overlap, thus demonstrating that the inversion level is saturated [4] and exhibits good reproducibility . However, this is of little interest from a technological viewpoint, since current fibers used in FL are not reported to exhibit such a high degradation or bleaching phenomena. In this experiment, the complexity of the setup and measurement procedure have been proved to be suitable for characterization of fast PD dynamics. Although the PD is easily induced in this fiber even at low pump level, a high pump power is advantageous in most cases, since it makes the splicing of the fiber under test less demanding, i.e. a sufficient inversion level is achievable even if a lossy splicing occurs.

3.2. Long-term characterization and evaluation of measurement accuracy

Where commercial high performance fibers are concerned, the photo-degradation becomes undetectable by the basic core-pumping scheme because the power fluctuations of the probe, the uncertainty of the transmission measurement and the environmental fluctuations hide the photo-induced loss. We have performed several tests on our setup to figure out how these spurious effects alter the PD measurement.

Fig. 5 depicts the Lock-In reading as a function of the temperature variation over a week. The graph refers to a commercial Yb doped fiber (6 μm-core, NA 0.20, absorption 220 dB/m) spliced into the setup as in a PD benchmarking test, but in this case the pump is kept OFF to observe the environmental effects on the Lock-In reading.

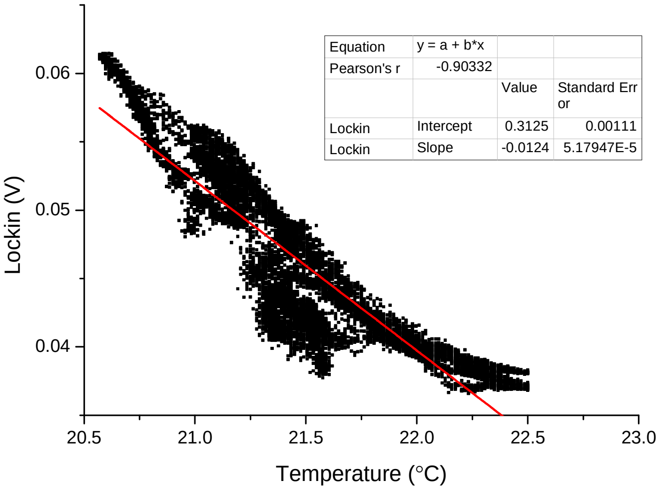

Figure 5 Lock-In reading vs Temperature. The scattered points are linearly fitted.

The data are linearly fitted to extract the correction coefficient to be applied to the subsequent PD measurement. It can be observed that the Pearson's coefficient is ~-0.90, indicating a close statistical dependence between the two quantities.

Because of the periodic behavior of the temperature, the fitting of the data sampled over 24 hours produces nearly the same result as the overall fitting. This is shown in Fig. 6, in which the PD signatures calculated from data acquired in different days are compared. Although the absolute variation of the Lock-In signal over time is not perfectly reproducible, when applying the linear compensation retrieved from any 24h – monitoring, the result is the expected nearly flat curve. This is a demonstration that a linear compensation of the temperature variation obtained from a 24h sampling of the Lock-In reading produces a PD signature with an uncertainty of ±1% (standard deviation) and it is well suited to detecting power drops just above the uncertainty band. Thus, any long-term drop of more than 2% of the PD signature is considered as a photodarkening effect.

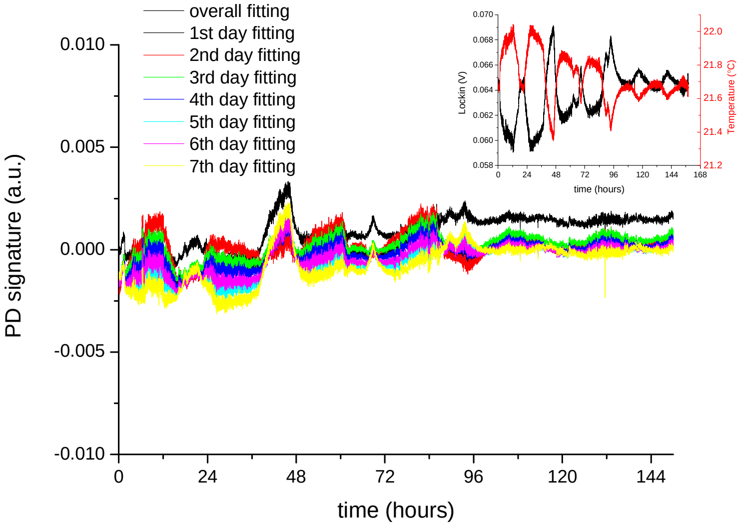

Figure 6 PD signature in the case of a dummy passive sample (the ideal trend should be a flat line centered at 0). The curves nearly overlap, regardless of the applied fitting. The inset shows the raw data of the temperature and the Lock-In reading.

3.3. Benchmarking of a low PD fiber

The final validation of the advanced PD setup and procedure consists of a benchmark of a fiber whose correspondent large mode area (LMA) version is used as the active medium in a high power CW laser (it is worth noting that this fiber was previously tested by simple core-pumping setup and did not exhibit remarkable PD). The fiber laser consists of a single fiber cavity made of a 20 µm-core Yb doped fiber and two fiber Bragg gratings, pumped so that it delivers 330W at 1.06 µm. This module, devised to become a commercial product as a part of a multi kW laser for industrial applications [14], has been run for 820 hours, experiencing a power drop of 17.8%. The same glass composition, drawn as a 6 µm-core fiber was cleaved and spliced into the advanced PD setup as a 5 cm sample and pumped for 450 hours. The reduced-core fiber has the following optical/spectroscopic properties: numerical aperture 0.15, core absorption ~260dB/m at 976 nm, The outcome of the experiment is presented in Fig. 7, where the PD signature is compared to the actual degradation of the laser performance. The PD signature is still heavily affected by environmental fluctuations. However the latter follow an exact 24-hour cycle and the mean photo-induced loss, retrievable by linear fitting, is ~30%.

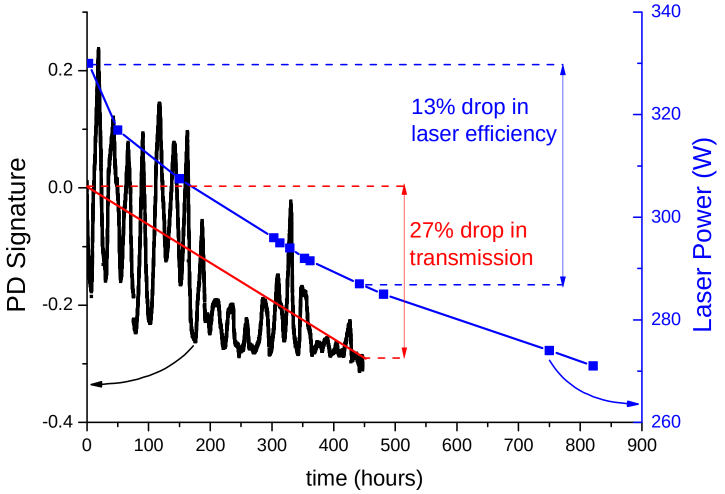

Figure 7 PD signature yielded by a 5 cm Yb doped fiber pumped for 450 hours. The correspondent large mode area fiber has been set up in a high power fiber laser configuration that ran for 820 hours and exhibited a PD –induced drop of efficiency ~13% in 450 hours.

If compared to the 13% drop in the laser efficiency, the attenuation at 635nm is not as enhanced as in previous investigations on PD [3]. However, it must be pointed out that the current study has been carried out on commercial fibers, which behave differently from the former manufactured-in-the-lab samples and might not follow the same trend (i.e. the loss at 635 nm is not 70 times higher than the loss at 1 µm). At present time there are no long-term PD investigations (i.e. >100 hours) on recently manufactured fibers, whereas the only available data come from fiber laser assemblers and that observe a general aging of their systems. Hence, in this case a quantitative correlation between the PD signature and the actual degradation of the laser system cannot be drawn. Nonetheless, the PD signature can be used as a marker of the laser aging rate.

The PD setup and procedure here presented do not allow an accelerated study of the PD resistance of the fiber under test, as pursued through other means (e.g. thermal enhancement [16] and UV radiation [17]), however they do provide some potentially important advantages, namely: 1) the test aims at producing a PD mechanism very similar to the one that will take place during the laser operation, 2) the relatively low power, automatic measurement and low cost of the setup would allow a straightforward replication of the setup so that a mass pre-compliance test of fiber batches could be run and 3) the know-how can be re-used to test other rare-earth doped fibers, provided the proper pump source replaces the 976 nm diode.

4. Conclusions

An advanced setup for accurately benchmarking the photodarkening of Yb doped fibers has been presented and discussed. This exploits fiber core pumping to limit the length of the sample under test to a few cm and the demand of pump power down to 600 mW . The fiber attenuation due to prolonged pumping is probed at 635 nm by a laser coupled, together with the counter-propagating pump, into the fiber under test by means of two thermally controlled wavelength division multiplexers. The signal from the probe, attenuated during propagation through the sample, is acquired by a photodiode and a Lock-In amplifier.

A procedure has been developed to evaluate a signature of the photo-induced loss in a reliable fashion, which consists in tracking the signal from the Lock-In for 24 hours while the pump is turned OFF and applying a linear compensation for thermal drifts. All the process is computer controlled and requires little human labor. For the first time, experiments in induced photodarkening have been carried out up to 450 hours, and it was possible to measure the photodarkening in commercial fibers that did not exhibit remarkable photodegradation and were declared “PD free”. A fiber, whose photodarkening was not detectable by simple techniques, has been benchmarked with the new measurement system and the result compared to the behavior of a high power fiber laser realized by the same fiber composition. The induced photodarkening exhibited a qualitatively similar dynamics and a level that could explain the drop in laser efficiency. This proves that the measurement system presented is suitable for pre-compliance testing of Yb doped fibers to be used in fiber laser cavities and it could be re-arranged to test different rare earth-doped fibers or be replicated for the parallel measurement of several samples.

Acknowledgements

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