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Original
Measurement techniques for the evaluation of photodarkening in bers for high-power lasers / Olivero M.; Boetti N.; Braglia A.; Neri A.; Lousteau J.;Milanese D.;Perrone G.. - STAMPA. - 7914(2011), pp. 79142-U1-79142-U6. ((Intervento presentato al convegno SPIE Photonics West 2011 tenutosi a San francisco (USA) nel January 22-27, 2011 [10.1117/12876276].

Publisher:
SPIE -The International Society for Optical Engineering

Published
DOI:10.1117/12876276

Measurement Techniques for the Evaluation of Photodarkening in Fibers for High Power Lasers

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ABSTRACT

A setup for core-pumping of Yb-doped optical fibers has been developed to induce photodarkening and benchmark their suitability as a long-life active medium in high power fiber lasers for industrial applications. The measurements setup, its reliability and preliminary tests on PD affected and PD free fibers are here presented. Repeatability of measurements has also been carried out.

Keywords: Fiber Lasers, Photodarkening, Active Fiber Characterization

1. INTRODUCTION

Fiber lasers (FL) are nowadays considered a disruptive technology in many industrial applications such as materials processing as well as in several other fields, ranging from biophotonics to spectroscopy and, more in general, fundamental research[1]. Borrowing most of the features from the low power world of information and communications technology, these lasers have been developed to meet the most challenging applications at higher power regimes. High power FL can be considered as a class of solid state lasers that features three main advantages: easier thermal management due to the geometry of the fiber, inherent high quality output beam and higher wall-plug efficiency than traditional CO_2 and solid state lasers. Among others, Ytterbium (Yb) doped silica optical fibers have been considered as the best candidates for realization of high power FL with emission around 1μm, mainly because of the high efficiency of Yb^{3+}:$^2F_{5/2} \rightarrow {}^2F_{7/2}$ transition, which does not suffer from unwanted parasitic processes and features less heat burden than that of fibers doped with Neodimium (Nd)[2].

Yb-doped silicate fibers, however, suffer from photodarkening (PD). This is a detrimental phenomenon that appears as a reduction in laser performance caused by an increase in active fiber propagation loss during laser operation[3]. In state-of-the-art high quality fibers, this phenomenon usually occurs after several hundreds to thousands of hours of operation at the laser full power; nevertheless, it poses a severe limitation for the wide spread of fiber lasers in industrial applications since in those cases the expected stability of the laser power in time is at least an order of magnitude higher.

The exact mechanism underlying the increase in propagation loss is still controversial, but it is certainly related to the density of inversion of the Yb^{3+} ions. Anyway, the macroscopic manifestation of PD is the increased loss in the active fiber and, as a consequence, a reduction of the available power at the output of the FL cavity. An extensive study of PD effect has been carried out since 2005, and a pinpoint investigation was performed by Koponen, Soderlund *et al.*[3-5]. These studies, investigating the photo-chemical mechanisms of PD, pointed out the need of isothermal conditions for reliable measurements and experimented ways to reverse this phenomenon by UV irradiation[6]. From a measurement viewpoint, the work of Koponen set a milestone in PD measurement in that he proved that the PD induced loss at 633nm can be used as a reliable test mark since it is ~71 times higher than that induced at the wavelength of interest of 1.1μm[3].

Since most of high power laser use double-clad active fibers, in literature, most of PD experiments have been performed by cladding pumping: high power/low brightness pump diodes have been used to pump the active fiber through the inner cladding, thus simulating the real operation of the fiber in a laser/amplifier configuration. This technique is easier to implement, stable and it ensures a uniform cross-sectional inversion. However, given the large diameter of the inner cladding, it requires high pump powers to achieve a relevant power density in the core; furthermore, since the fiber

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absorption in cladding-pumping configuration is in the order of 2-8 dB/m, it requires long fiber spans (meters) and this pose limitations in the realization of several tests, both in research and in industry, considering the high cost of commercial active fibers.

On the contrary, core pumping is advantageous because:

1) It requires very short samples, with associated cost reduction.
2) The test can run at low power (in the hundreds of mW range), with little demand of safety infrastructures.

To the authors best knowledge, there are few publications on PD in which experiments were carried out by core pumping, such as[3,7]. Further, there are no indications about the setup stability and the overall measurement uncertainty of PD.

The aim of this work is to explore core pumping of active, rare earth-doped fibers as a technique to induce PD and investigate its dynamics. The focus is set on the development of a reliable setup capable of yielding reproducible measurements and exploitable in fundamental research, to improve fiber compositions and fabrication, as well as in industry for pre-compliance tests of fiber batches that are going to be used in fiber laser arrangements.

2. ALL-FIBER CORE-PUMPING SETUP

The idea behind the setup sketched in Fig.1 is to make a reliable, all-fiber, testbed for benchmarking different active fibers and foresee their PD-induced degradation when they are set in laser configuration.

Typical fiber lasers are pumped in the 915 nm – 940 nm range because in that region no strict control of the diode temperature, and thus emission wavelength, is required, although the absorption efficiency is quite low. In this work, to maximize the Yb-inversion, the pump diode used emits a 976 nm, which is close to the Yb absorption peak, and it is thermally stabilized through a Peltier cell.

Therefore, with reference to the scheme in Fig. 1, a pump laser emitting at 976 nm with maximum power of 600 mW delivered through a fiber with 6 µm diameter core is coupled into a wavelength-division-multiplexer (WDM) on the "pump" input (connection labeled "2"). The "signal" input is instead connected to an optical spectrum analyzer. The output of the WDM is spliced to the fiber under test using a standard fusion splicer for telecom. The splicing is performed by a core-alignment recipe in order to guarantee the maximum coupling. The active fiber is then spliced to a second WDM, whose outputs are left floating and connected to the Helium-Neon (HeNe) laser probe at 633 nm, respectively. The latter connection is made through a 99%-1% power splitter, in order to monitor the power fluctuation of the probe with a power meter. When possible, all fiber ends are angled-polished to reduce backreflections and avoid spurious lasing action (e.g. output "5"). Preventing lasing from the active fiber is crucial because it results in a higher population inversion to enhance the PD effect and it prevents damages of the pump laser. A second power meter can replace the spectrometer to monitor the total power at its input and avoid damages. The same instrument also behaves as a watchdog for the residual pump power entering the HeNe. Since the WDMs and all fiber connections are multimode at the probe wavelength, all components are spliced and fixed onto a metallic plate to reduce mode fluctuations due to vibrations and mechanical relaxations.

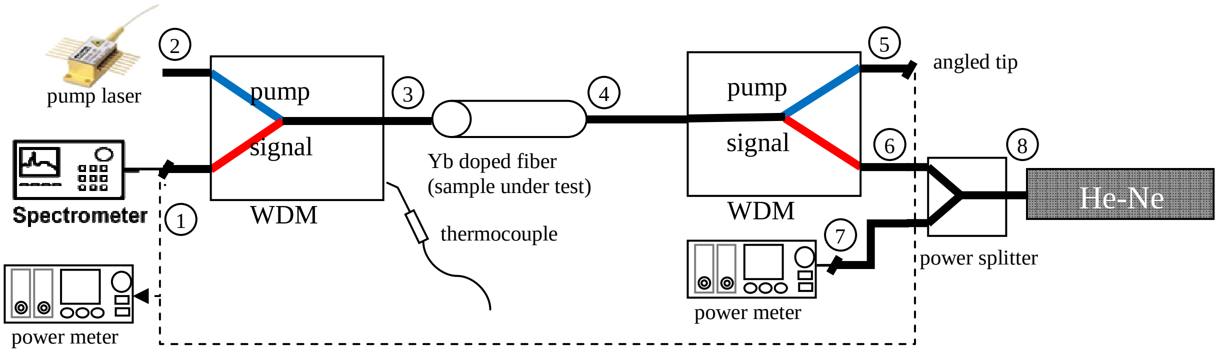

Figure 1. All-fiber core-pumping test bench for detection of PD in Yb doped fibers.

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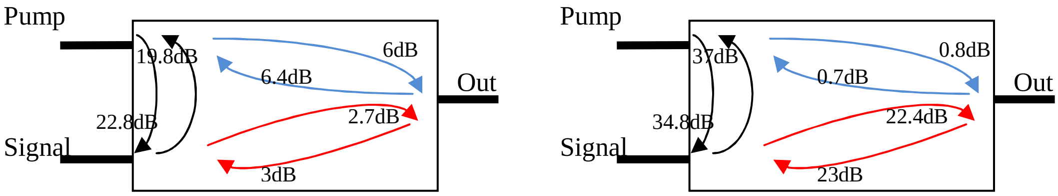
The optical response of the WDMs at 976 nm (pump) and 633 nm (probe) are summarized in Fig. 2. The low transmission experienced by the HeNe probe (≥ 6dB loss) sets a constraint on the sensitivity of the spectrometer but, on the other hand, allows a small amount of 633 nm radiation to enter the fiber under test hence avoiding to influence the measure[5]. The transmission of the pump, affected by a ~1.5dB attenuation plus extra losses due to splices, allows for a total pump power entering the fiber under test of 400 mW at the most. Since our tests are focused on single mode active fibers, with core diameters 6µm ÷10 µm, this corresponds to a power density of ~5 kW/mm^2, which is comparable with the levels achieved by high-power cladding pumping and should guarantee constant inversion over the sample length. The latter is chosen according to pump absorption of the fiber and ranges from 3 to 10 cm. The residual pump, together with the amplified spontaneous emission and spurious luminescence in the visible range, may still saturate the spectrometer input and corrupt the monitoring of the probe. In order to avoid saturation and to perform automatic, yet long-term measurements, all the devices are linked in a GPIB chain and computer-controlled through a Labview program, so that the pump is switched off at every reading of the power meters and spectrometer. The testbed is also provided with thermocouples to monitor the WDMs, which have been found to be very sensitive to temperature. While former experiments were performed at uncontrolled room temperature, the latest setup has been moved into a climatic chamber where the temperature and humidity are forced to 20°C and 35% respectively.



(a) (b)

Figure 2. Optical response of the WDM at (a) 633 nm and (b) 976 nm.

However, the spatial temperature uniformity of the climatic chamber is within ±2°C. This results in an unpredictable variation of the coupling coefficients of the two WDMs. Several tests on stability were performed to quantify the phenomenon and figure out the requirements for a long-term reliable test-bench. As an example, Fig. 3 reports the log of the HeNe power at connections “1” and “7” over ~20 hours. The test was performed by inserting a dummy i.e. a passive fiber that does not suffer photodarkening or other photoinduced modifications.

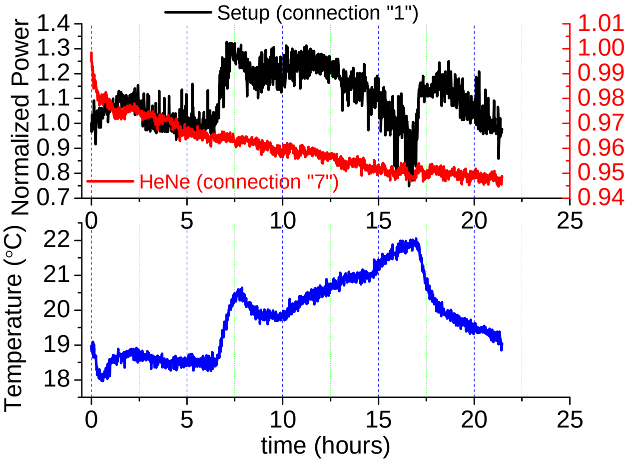


Figure 3. Log of the HeNe power at connection “7” (i.e. source fluctuation) and at connection “1” (i.e. WDM fluctuation), together with the actual temperature measured across one of the WDMs.

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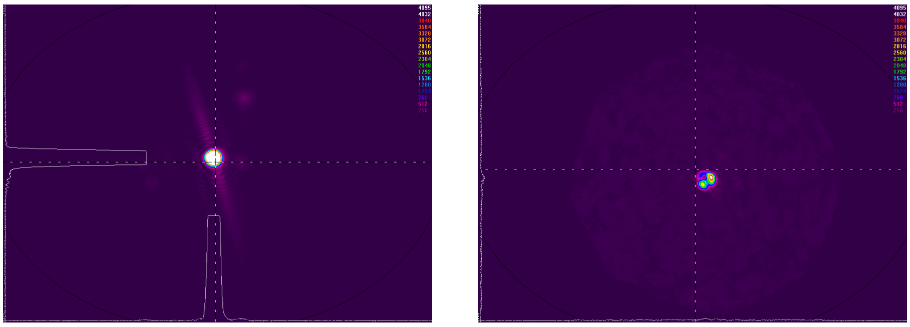
The fluctuation of the source is within 4%, whereas the WDMs increase the temperature dependence up to ±25% around the initial value. Furthermore, the WDMs behavior appear to be unpredictable, since both increment and decrement of the power at connection “7” are observed when the temperature increases. Therefore a tight control of the temperature across the WDMs is required. Since recent colloquiums on PD stated that most active fibers exhibit a 10% decrement when in laser configuration[8], a rough estimation of the stability constraint, for a 1% uncertainty on the HeNe reading through the setup, leads to a ±0.04°C. Commercial Thermoelectric Coolers (TEC) systems for laser stabilization guarantee a 24-hours stability better than ±0.01°C[9]. The setup is therefore being upgraded with two TEC for a precise stabilization of the WDMs response.

Another important issue arising from core pumping is to guarantee that pump power is efficiently coupled into the core. Care must be taken during the splicing of the sample under test with the output fiber of the WDM and custom splicing recipes might be required. The coupling into the core was verified by near field (NF) imaging of the samples under test, as depicted in Fig. 4b. The comparison with the NF of the WDM output (cf. Fig. Figure **4**a, intentionally saturated to better highlight the mode dimension) shows a good mode matching and the faint color in the inner cladding indicates a low amount of power out of the core.



(a) (b)

Figure 4. Near Field imaging of (a) the WDM output and (b) the output of the active fiber under test. Notice the little amount of power in the octagonal inner cladding.

3. PD MEASUREMENTS

A number of fiber samples from different manufactures were tested. The fibers were pumped at 976 nm for up to 1000 min and two of them showed a remarkable PD effect. The outcome of this experiment is summarized in Fig. 5.

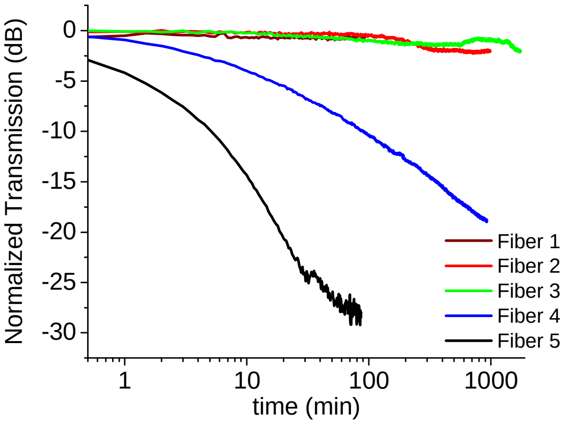


Figure 5. PD induced by core pumping of different fibers. Two samples out of 5 exhibit a remarkable PD effect. The log scales highlight the exponential decay of transmission, which is a common feature of photodarkenable fibers.

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Concerning fibers 1-3, there is not a notable decrement of transmission at 633 nm or at least it remains within the current uncertainty. Longer experiments shall be carried out once the behavior of the WDM will be accomplished. Notice the graph is plotted in log scales to better highlight the nearly exponential decay observed.

In order to quantify the reproducibility of the measurements, fiber #5 was selected for PD repeated tests. The reproducibility test aimed at detecting the effect of fiber positioning, tolerance in length, splicing, source alignment etc. Seven runs on pristine samples were conducted, as Figure 6 reports.

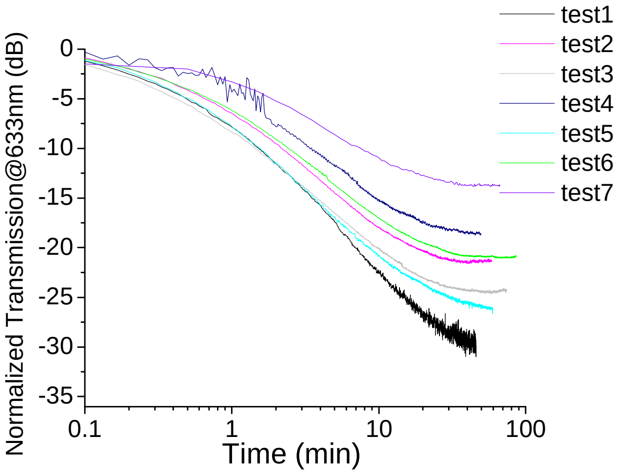
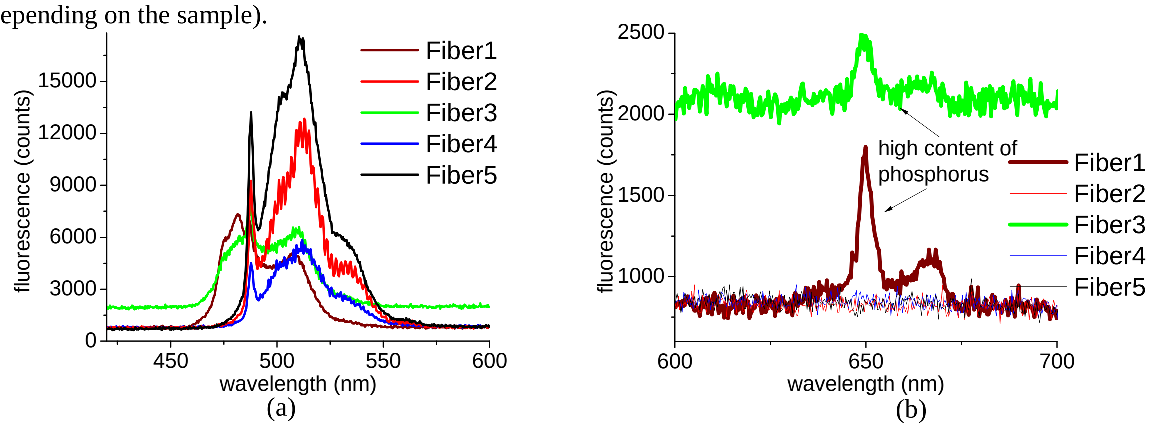


Figure 6. Repeatability test on fiber #5.

The curves are normalized to the transmission prior to PD. The initial dynamics of this highly photodarkenable fiber looks different as it does the transmission after PD. We speculate this might be due to slight differences in splicing of the samples, which lead to a different coupling of the pump power. However, by playing some fitting and statistics on the curves, it turns out that the transmission decay between 1÷10 min is well fitted by an exponential with time constant 0.22±0.02 min^{-1}. Measuring the temporal decay of the transmission for a given fiber with good accuracy might be useful in predicting the lifetime of such a fiber in a laser configuration, as required by industrial applications.

4. LUMINESCENCE SPECTRA OF PUMPED FIBERS

The Yb-doped optical fibers used for the photodarkening experiments were also tested in terms of luminescence induced by optical pumping at 976 nm. A fiber spectrometer was put at connection “4” of Fig. 1. The resolution of the spectrometer, dependent upon the fiber core diameter, was 2 nm and its sensitivity was tuned by changing the integration time in order to get the highest spectrum dynamics while avoiding saturation. The luminescence spectrum was recorded by pumping the fibers with the minimum power required to observe any emission in the visible range (usually ~20mW, depending on the sample).



(a) (b)

Figure 7. Luminescence spectrum of the characterized fibers (a) around 500 nm and (b) around 600 nm.

The aim of this analysis was to detect any possible occurrence of significant spectral features that could be correlated to the level of induced PD. Recently, thulium contamination has been recognized as a possible cause of increased PD [10],

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since it causes emission in the UV (~350 nm) and produces color centers in the glass matrix. The samples analyzed during this campaign did not exhibit emission in the UV (or at least the system was not capable of detecting any significant emission), nor they showed the spectral signature of Thulium in the range 450-550 nm (cf. Fig. Figure 7a). On the other hand, they displayed the typical luminescence spectrum of Yb^{3+} cooperative emission at 520 nm [10]. As observed in Fig. Figure 7b, only two of the characterized fibers exhibit a detectable emission at 650 nm. These are know, from the manufacturers, to have a significant content of phosphorus, which seems to mitigate the PD effect [11]. Accordingly, these fibers did not manifest a strong PD degradation, but a consistent correlation between the measured spectra and the PD behavior is still ongoing. These preliminary results appear to confirm that PD is related to more than one mechanism, and the research shall be focused in setting up a reliable system to measure the PD and possibly discriminate its several causes.

5. CONCLUSION

The possibility to benchmark photodarkening in Yb-doped optical fibers by core-pumping has been investigated through the realization of an all-fiber setup that features the long term monitoring of the transmission at 633 nm of short fiber samples. The setup includes a pump source, a HeNe laser and a power splitter to monitor its signal, two wavelength division multiplexers to mux/demux the pump, power meters and a spectrometer to monitor the pump signal and emission/fluorescence spectra. It also features the monitoring of temperature through thermocouples. The devices are computer controlled through a GPIB bus for long-term automatic measurements. The study has comprised a detailed investigation of the temperature influence on the measurement and has highlighted the requirement of a thermal stabilization of the wavelength division multiplexers within ±0.4°C. Efficient coupling into the core of the fibers under test has been accomplished by fusion splicing with core-alignment and later checked by near field imaging of the fiber end. Photodarkening tests have been performed on five fibers from different manufacturers and two of them exhibited a significant degradation of the transmission at 633 nm after long-term pumping at 976 nm. The most photodarkenable fiber has been used to perform reproducibility tests and it has been found that the transmission decay is reproducible with a standard deviation of $\pm 0.02\ \mathrm{min}^{-1}$, whereas transmission absolute values before/after photodarkening are quite variable, likely because of reproducibility issues on the splicing. A preliminary investigation on the fluorescence spectra of the tested fibers did not show a pattern that could be correlated to thulium contamination as a possible source of photodarkening, but it rather highlighted a significant emission at 650 nm for fibers that contained phosphorus and did not exhibit photo-induced degradation of their transmission.

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