Photodarkening and photobleaching of an ytterbium-doped silica double-clad LMA fiber

I. Manek-Hönninger, J. Boullet

CELIA-PALA (UMR 5107 Université Bordeaux I – CNRS – CEA), Université Bordeaux 1, 351 cours de la Libération, F-33405 Talence, France
manek@celia.u-bordeaux1.fr

T. Cardinal and F. Guillen

ICMCB-CNRS, (UMR 9048), Université Bordeaux I, 87 av. A. Schweitzer, F-33608 Pessac, France

S. Ermeneux

PALA-Alphanov, Bât A11, 351 cours de la libération, F-33405 Talence, France

M. Podgorski, R. Bello Doua, F. Salin

EOLITE, 6 allée du doyen George Brus, F-33600 Pessac, France

Abstract: We studied the temporal evolution of the photodarkening effect in an Yb-doped silica LMA fiber. The absorption spectra exhibit an increase in absorption in the visible and in the near infrared spectral range when the fiber is exposed to pump light around 980 nm. We show the influence of the photodarkening on the cw lasing properties of the fiber, and demonstrate photobleaching of the same fiber by exposure to UV light at 355 nm. The corresponding absorption spectra and lasing performances are shown and are entirely comparable to those of a new fiber.

OCIS codes: (140.3510) Lasers, fiber; (060.2290) Fiber materials

References and links

1. R. Paschotta, J. Nilsson, A. C. Tropper, and D. C. Hanna, "Ytterbium-doped fiber amplifiers," IEEE J. Quantum Electron. **33**, 1049 (1997).
2. C.-H. Liu, B. Ehlers, F. Doerfel, S. Heinemann, A. Carter, K. Tankala, J. Farroni, and A. Galvanauskas, "810 W continuous-wave and single-transverse-mode fibre laser using 20 µm core Yb-doped double-clad fibre, " Electron. Lett. **40**, 1471-1472 (2004).
3. J. Nilsson, J. K. Sahu, Y. Jeong, W. A. Clarkson, R. Selvas, A. B. Grudinin, and S.-U. Alam, "High-power fiber lasers: new developments," Proc. SPIE **4974**, 50-59 (2003).
4. Y. Jeong, J. K. Sahu, M. Laroche, W. A. Clarcson, K. Furusawa, D. J. Richardson, J. Nilsson, "120-W Q-switched cladding-pumped Yb-doped fibre laser," CLEO Europe-EQEC 2003, Munich, Germany
5. J. Limpert, N. Deguil-Robin, S. Petit, I. Manek-Hönninger, F. Salin, P. Rigail, C. Hönninger and E. Mottay, "High power Q-switched Yb-doped photonic crystal fiber laser producing sub-10 ns pulses," Appl. Phys. B **81**, 19 (2005)
6. J. Limpert, N. Deguil-Robin, I. Manek-Hönninger, F. Salin, F. Röser, A. Liem, T. Schreiber, S. Nolte, H. Zellmer, A. Tünnermann, J. Broeng, A. Petersson, and C. Jakobsen, "High-power rod-type photonic crystal fiber laser," Opt. Express **13**, 1055-1058 (2005).
7. G. R. Atkins and A. L. G. Carter, "Photodarkening in Tb3+-doped phosphosilicate and germanosilicate optical fibers," Opt. Lett. **19**, 951 (1994).
8. P. Laperle, A. Chandonnet, and R. Vallée, "Photoinduced absorption in thulium-doped ZBLAN fibers," Opt. Lett. **20**, 2484 (1995).
9. J. J. Koponen, M. J. Söderlund, H. J. Hoffman, and S. K. T. Tammela, "Measuring photodarkening from single-mode ytterbium doped silica fibers," Opt. Express **14**, 11539-11544 (2006).
10. T. Kitabayashi, M. Ikeda, M. Nakai, T. Sakai, K.Himeno, and K. Ohashi, "Population inversion factor dependence of photodarkening of Yb-doped fibers and its suppression by highly aluminum doping," OFC 2005, paper OThC5.

#78464 - $15.00 USD Received 22 December 2006; revised 29 January 2007; accepted 29 January 2007

11. A. V. Kir'yanov, Y. O. Barmenkov, I. L. Martinez, A. S. Kurkov, and E. M. Dianov, "Cooperative luminescence and absorption in Ytterbium-doped silica fiber and the fiber nonlinear transmission coefficient at λ=980 nm with a regard to the Ytterbium ion-pairs' effect," Opt. Express **14**, 3981-3992 (2006).
12. R. Paschotta and A. C. Tropper, "Cooperative luminescence and absorption in Ytterbium-doped silica fiber and the fiber nonlinear transmission coefficient at λ=980 nm with a regard to the Ytterbium ion-pairs' effect: Comment," Opt. Express **14**, 6981-6982 (2006).
13. A. V. Kir'yanov and Y. O. Barmenkov, "Cooperative luminescence and absorption in Ytterbium-doped silica fiber and the fiber nonlinear transmission coefficient at λ = 980 nm with a regard to the Ytterbium ion-pairs' effect: Reply," Opt. Express **14**, 6983-6985 (2006).
14. E. J. Friebele and M. E. Gingerich, "Photobleaching effects in optical fiber waveguides," Appl. Opt. **20**, 3448- (1981), http://www.opticsinfobase.org/abstract.cfm?URI=ao-20-19-3448.
15. C. A. Millar, S. R. Mallinson, B. J. Ainslie, and S. P. Craig, "Photochromic behaviour of thullium-doped silica optical fibers," Elect. Lett. **24**, 590-591 (1988).
16. G. R. Atkins, A. L. G. Carter, and F. Oullette, "Photo-induced darkening and bleaching in terbium (III)-doped optical fibers," Proc. SPIE **2289**, 117-124 (1994).

1. Introduction

Yb-doped fibers are very often used for fiber lasers and amplifiers [1]. Double-clad rare-earth doped fibers find today many applications in continuous wave as well as in pulsed laser systems [2, 3]. In the recent years, big progress has been made, for example in the generation of high peak power pulses in Q-switched operation [4, 5]. When generating such pulses new challenges appear in the experiments as the active ion concentrations become higher and fiber lengths are getting shorter [6]. Photodarkening turned out to be one of the limiting factors in the output and reliability of high peak power fiber lasers as the laser output power decreases gradually when the photodarkening occurs. The phenomenon has been investigated for other rare-earth doped fibers such as Terbium and Thulium doped fibers [7, 8], and recently has shown up as well for Yb-doped fibers [9, 10].

We demonstrate for the first time the temporal evolution of the photodarkening process in an Yb-doped silica large-mode-area (LMA) fiber as well as photobleaching of the same fiber. Moreover, we show the influence of the photodarkening and photobleaching on the lasing properties when this fiber is used in a cw laser oscillator.

2. Temporal evolution of the photodarkening

The fiber used in this experiment is a commercially available microstructured LMA double-clad Yb-doped silica fiber. The inner active core has a diameter of 22 µm, whereas the pump cladding has a diameter of 265 µm. In order to study the temporal behavior of the photodarkening effect in this fiber we measured the absorption spectra of the fiber after a variable exposure time to pumping light of 45 W pump power near the absorption peak wavelength of 980 nm delivered from a fiber-coupled diode laser. The spectra were taken by injecting a fiber-coupled white-light source (OH-2000-BAL MICROPACK) containing a deuterium and a halogen lamp, where the deuterium lamp can be switched off independently. The transmission spectra of the white light were recorded by a spectrometer (SPECTRA PRO 500I). We introduced a red filter cutting wavelengths exceeding 600 nm while recording the spectra in the IR domain in order to avoid replica effects caused by second order diffraction of the grating of the absorption signal in the visible range of the spectrum. We applied the cut-back method for all absorption measurements to ensure that there was no influence from the injection alignment.

Figure 1 shows the absorption spectra of a new fiber (red line), and of the same fiber after different exposure times (7, 15 and 100 minutes) to 45 W of pump light at 976 nm. One clearly sees the dramatic increase of the absorption in the visible range with increasing pump light exposure (photodarkening) which is continuing to longer wavelengths up to 1100 nm. These changes in the absorption spectra might be the signature of the formation of color centers. From the spectra at different states of photodarkening one can see that the absorption at the lasing wavelength of 1030 nm increases. Even though the increase is much weaker in

#78464 - $15.00 USD Received 22 December 2006; revised 29 January 2007; accepted 29 January 2007

the infrared part of the spectrum than in the visible (note the logarithmic scale), there is a crucial influence on the lasing properties as we will show below.

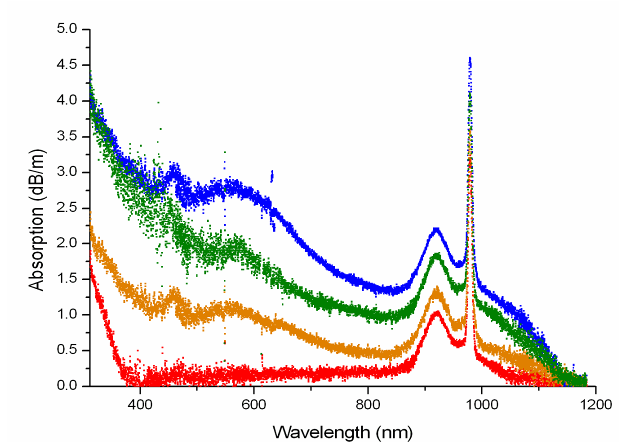

Fig. 1. Absorption spectra of a new Yb-doped LMA fiber (lower curve, red) and of the same fiber at different states of photodarkening at 7 min, 15 min and 100 min (upper curves, orange, green and blue) of pumping the fiber by light of 45 W at 976 nm.

In order to verify the absorption spectra we measured the transmission of an injected signal by the fiber at different states of photodarkening for two different wavelengths. The experimental setup is shown in Fig. 2. The fiber was photodarkened by the pumping light in exactly the same way as for the absorption spectra measurements. In counter propagation we injected a HeNe laser or a Nd:YAG laser and measured the transmission as a function of pumping time.

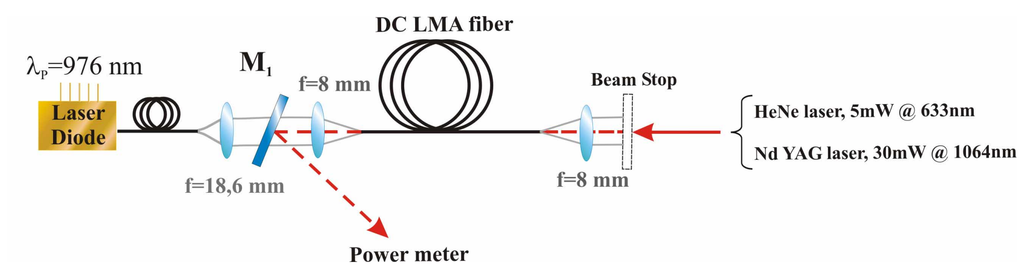

Fig. 2. Experimental setup for the transmission signal pump-probe experiment: M_1 is a dichroic mirror (T_{max} @ λ=980 nm and R_{max} @ λ=1.06 µm).

In Fig. 3 the transmission signals of a HeNe laser and a Nd:YAG laser as a function of exposure time to the pump light are depicted. The very strong decrease in transmission at the wavelength of 633 nm and the much weaker but still visible decrease at 1064 nm (saturation at about 4%) is in complete agreement with the increase in absorption in the visible and infrared spectral region as can be seen from Fig. 1 (see upper curves). The solid lines are exponential fits to the data, respectively, with a decay time constant of 10 minutes for 633 nm and of about 12 minutes for 1064 nm. For exposure times exceeding ≈40 minutes the photodarkening effect saturates, and thus the transmission loss at 633 nm and 1064 nm stays almost constant. This means that the photodarkening is an effect caused by the pump light and saturating after about an hour under our pumping conditions.

#78464 - $15.00 USD Received 22 December 2006; revised 29 January 2007; accepted 29 January 2007

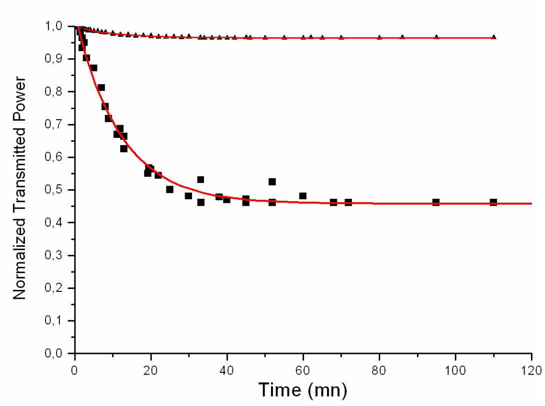

Fig. 3. Transmission of 633 nm and 1064 nm signals as a function of exposure time to pump light, the solid lines represents an exponential fit to the data.

Note that photodarkening on this time scale was provoked by pumping the fiber with excitation light around 976 nm without lasing and not in continuous wave laser configuration where we saw no photodarkening effect even after several hours of cw laser operation. This confirms the hypothesis that the photodarkening depends on the population inversion as reported in reference 10. Moreover, one has to notice that during pumping cooperative luminescence was observed in the visible indicating the presence of Yb^{3+}-Yb^{3+} pairs [11-13]. The relatively high Yb^{3+}-concentration in the fiber causes short distances between the active ions which lead probably to Yb^{3+} clustering that favors cooperative processes.

3. Influence of the photodarkening on the lasing characteristics

In order to study the influence of the photodarkening on the laser properties a laser oscillator was built up using a 1 m long piece of the Yb-doped silica fiber that was pumped through a dichroic mirror (M_1) by a fiber-coupled laser diode (Φ=400µm, NA=0.22). The cavity was formed by a high reflecting end mirror M_2 and by the cleaved end of the fiber that served as output coupler. Figure 4 shows the experimental setup of the fiber laser. M_3 is a dichroic mirror (T_{max} @ λ=1.06 µm and R_{max} @ λ=980 nm) that served to eliminate the residual pump light.

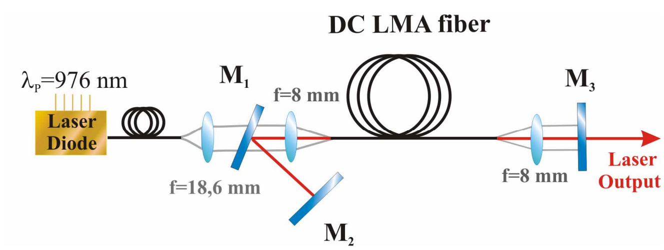

Fig. 4. Experimental setup of the LMA fiber laser. M_1 is a dichroic mirror (T_{max} @ λ=980 nm and R_{max} @ λ=1.06 µm for i=22.5°), M_2 is a high reflecting mirror at λ=1.06 µm, and M_3 is a dichroic mirror (T_{max} @ λ=1.06 µm and R_{max} @ λ=980 nm) that served to eliminate the residual pump light.

As in the previous experiment, fast photodarkening is obtained by exposure to 45 W of pump power at 976 nm while suppressing laser oscillation by blocking the mirror M_2. However, residual lasing was observed by the Fresnel reflections on the fiber ends. The residual lasing output was less than 900 mW. After a period of pumping, we unblocked mirror M_2 and quickly measured the output power versus pump power. In Fig. 5 the measured slope

#78464 - $15.00 USD Received 22 December 2006; revised 29 January 2007; accepted 29 January 2007

efficiency of the cw fiber laser oscillator is plotted as a function of absorbed pump power for different states of photodarkening. The data correspond to a new fiber (red squares), to 16 minutes (orange squares), 64 minutes (green triangles) and 155 minutes (blue circles) of photodarkening, respectively. The black solid line is a linear fit to the data of the output characteristics using a new fiber.

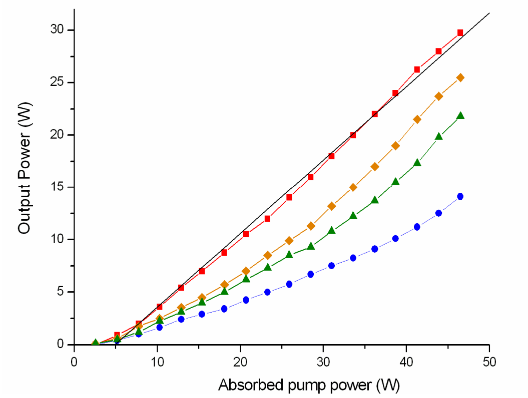

Fig. 5. Output characteristics of the fiber laser for different states of photodarkening: new fiber (red squares and linear fit to the data as a black solid line), 16 min (orange squares), 64 min (green triangles), and 155 min of photodarkening (blue circles).

The slope efficiency decreases considerably when a photodarkened fiber has been used as active laser medium. In this experiment, we observe a further decrease of the laser output characteristics for pumping times exceeding one hour. We explain this behavior by the residual lasing on the fiber end faces which causes a reduction in population inversion compared to the case for pumping without lasing, and thus the photodarkening process was slowed down to a longer time scale than in the transmission signal pump-probe experiment. Moreover, the ratio between output power to absorbed pump power does not stay linear but shows a behavior that could be interpreted by an additional saturable loss within the cavity as it is the case by reabsorption at the lasing wavelength of 1030 nm. This is in excellent agreement with the evolution of the absorption spectra shown in Fig. 1 and the transmission signal of the Nd:YAG laser at 1064 nm as depicted in Fig. 3. Thermal effects could be excluded as a source of the nonlinear shape of the output characteristics as we verified the experimental results after switching off the pump diode for relatively long periods of one to two hours permitting the system to cool down.

4. Photobleaching of the Yb-doped silica LMA fiber

Photobleaching effects in optical fibers using cw sources have been reported for the first time in 1981 [14] in order to investigate the reduction in radiation damage by ions. In Thulium-doped fibers [15] and Terbium-doped fibers [16] photobleaching was successfully obtained using visible light to restore the fiber characteristics. We achieved photobleaching of the Yb-doped fiber by a short exposure time to UV light at 355 nm delivered by a frequency-tripled Nd:YVO_4 laser. We operated the laser at a power of 450 mW and at a repetition rate of 5 kHz, which corresponds to 90 µJ energy of UV light, and the exposure time was several minutes. Longer exposure times were studied but showed no supplementary effect.

After the photobleaching by UV light we recorded the absorption spectrum as for the new and the photodarkened fiber. The absorption spectrum gets almost back to the original one as can be seen from Fig. 6(a) where a comparison of the spectrum of a new fiber (upper graph, black line) and of the same photobleached fiber (lower graph, red line) is depicted.

We built up the same laser configuration as for the photodarkened fiber (see Fig. 4) in order to compare the lasing properties of the photobleached fiber to the ones of a new fiber.

#78464 - $15.00 USD Received 22 December 2006; revised 29 January 2007; accepted 29 January 2007

Note that the slope efficiency is the same for the laser using a new and a photobleached fiber [see Fig. 6(b)]. We tested the stability of the laser after photobleaching of the fiber, and we did not see any difference between a new and a photobleached fiber.

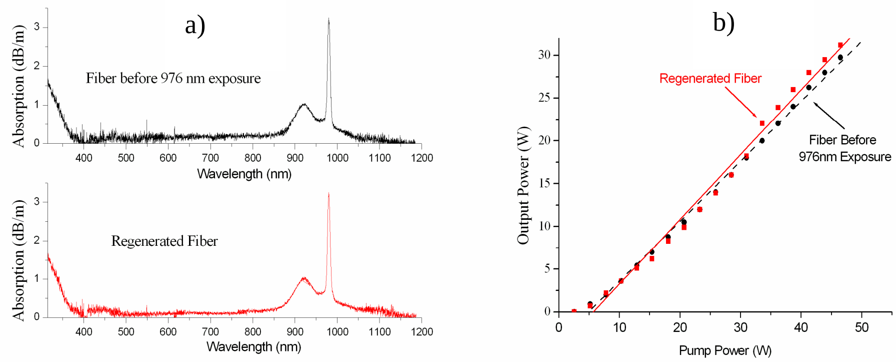

Fig. 6. (a). Absorption spectrum of a new (black line, upper graph) and a photobleached (red line, lower graph) fiber and (b). output characteristics of the cw LMA fiber laser oscillator using the same fiber, new (black circles) and photobleached (red squares).

Moreover, we tested the behaviour of the fiber after several consecutive cycles of photodarkening and photobleaching and obtained the same spectra and performances no matter whether the fiber was new or already photobleached. This confirms that both the photodarkening and photobleaching are reversible processes.

5. Conclusions

In conclusion, we investigated the temporal evolution of the photodarkening phenomenon in an Yb-doped double-clad silica fiber and demonstrate photobleaching by UV exposure of the same fiber. Moreover, the influence caused by the photodarkening on the lasing properties of this fiber is shown. By photobleaching the lasing characteristics can be fully restored. Our results in lasing operation are in total agreement with the interpretation of the white-light absorption spectra of the fiber and the transmission signals at 633 nm and 1064 nm, respectively. Correlation with cooperative luminescence and an inversion population effect could be shown.

Acknowledgment

This work is partially supported by the Fond Européen de Développement Economique Régional, the Conseil Régional d’Aquitaine and the Agence National de la Recherche.