Low photodarkening single cladding ytterbium fibre amplifier

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ABSTRACT

A single cladding ytterbium doped fibre amplifier pumped at 980 nm that exhibits negligible amount of photodarkening over a long period of time is demonstrated. The output power as a function of time decreased by a very small factor compared to standard single mode ytterbium fibres. To achieve this photodarkening resistant amplifier, a special ytterbium doped fibre has been developed. Codoping with aluminium or other rare-earth such as erbium is shown to decrease the multi-excitation of ytterbium clusters and thus lower photodarkening. Photodarkening was characterized by comparing the amount of excess loss created by core pumping single cladding fibres at high intensity at 980 nm. Photodarkening was found to be directly proportional to the excitation of the ytterbium ions by comparing different pumping scheme and pump wavelength. Core pumping of a single cladding ytterbium doped fibre amplifier at 980 nm represents the worst case scenario for photodarkening. Engineering ytterbium fibres for low photodarkening is therefore critical in pulsed amplification where short length of fibre with high doping level is required as demonstrated with 6 µm core ytterbium fibre amplifier pumped in the core or in the cladding. Photodarkening was correlated to clustering from cooperative luminescence measurement at 500 nm produced by ytterbium clusters that would emit UV radiation under strong pumping.

Keywords: photodarkening, ytterbium, fibre amplifier, co-doping, clustering

1. INTRODUCTION

Fibre lasers, with their high efficiency, good beam quality, large heat dissipation and robustness have a significant advantage over traditional gas or crystal based lasers. For example, with an ytterbium doped fibre, optical efficiency higher than 80% is reached with respect to pump power. Furthermore, ytterbium can be pumped with a large spectral range from 900 to 1000 nm and presents a simple energy level diagram which decreases significantly undesired effects such as upconversion or clustering. Increase in pump brightness and the use of double cladding fibre in the last years allowed power scaling of ytterbium fibre laser for various applications. Continuous wavelength (CW) fibre lasers have reached the kW level with diffraction limited beam[1,2] and pulsed fibre amplifier can demonstrate mJ output energy with nanosecond pulses and excellent beam quality[3,4].

This power scaling brought new constraints to the fibre itself. One is that double cladding fibres need a high ytterbium doping level to maintain a good pump absorption because the overlap between the pump power and ytterbium ions is very low, typically below a few percents. This requirement was not present in low power single cladding ytterbium fibre because only a few meters of doped fibre is necessary with doping level around $1x10^{25}$ ions/m^3. However with high power double cladding ytterbium fibre, doping level greater than $1x10^{26}$ ions/m^3 is often required to avoid using long lengths of fibre which increase non-linear effects and decrease optical conversion efficiency.

As doping requirement increases for ytterbium fibre, photodarkening effect starts to appear and yield to an increase in background loss of the fibre over time which decreases the output power. Because it is important that the output power remains stable over the lifetime of the fibre laser, understanding this effect and finding ways to eliminate it or make it negligible is of paramount importance.

In this paper, the effects of photodarkening in ytterbium doped fibre and the basic underlying principles are firstly discussed. Then the origin of this phenomenon and how it can be reduced are explained. Finally, the impacts of photodarkening in different applications and how it can be mitigated are presented, where an ytterbium amplifier with core and cladding pumping showing none or negligible photodarkening are demonstrated, core pumping representing the worst case scenario for this phenomenon to occur.

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2. EFFECTS OF PHOTODARKENING

2.1 Signature of photodarkening

Photodarkening is a phenomenon that induces a permanent increase in core background loss of the doped fibre. It has been observed in silica fibre doped with different rare-earth such as thulium, europium, praseodymium and cerium[5,6,7] and, to the best of our knowledge, the first experimental evidence of this phenomenon in ytterbium doped silica fibre was first described in the literature in the mid 90's[8]. Figure 1 shows a typical signature of background loss in an ytterbium fibre after photodarkening occurred. When light propagates in the core, such as pumping the fibre, an induced background loss appeared in the visible region with its peak located around 450 nm. This background loss affects the efficiency of ytterbium fibre laser because it has a significant tail in the near-infrared region at wavelength from 900 to 1100 nm, where the pump and signal propagate. Hence, throughout this paper, photodarkening refers to this increase in background loss in the core.

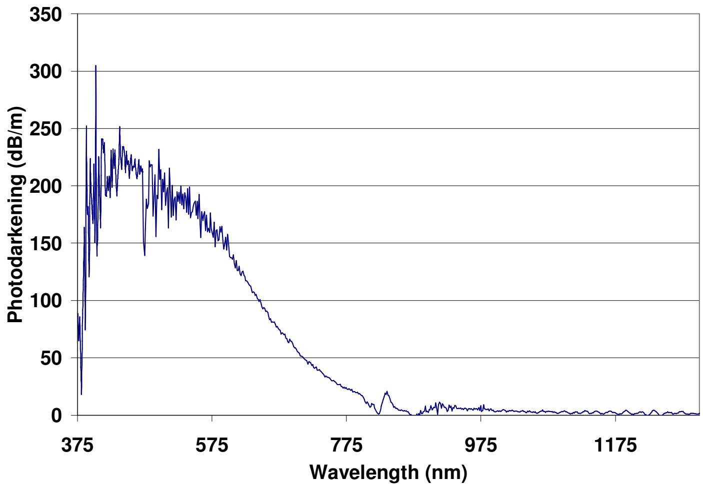

Figure 1. Typical signature of core background loss in an ytterbium doped induced by photodarkening

2.2. Inversion of the ytterbium ions

In order to photodarkening to happen, the ytterbium ions must be inverted by a pump source to cause the increase in background loss. Figure 2 shows a darkening comparison in a fibre that was core pumped with 100 mW of power from a diode at 977 nm and 500 mW from a fibre coupled Nd-YLF laser at 1047 nm. The highly doped ytterbium fibre used, not engineered for low photodarkening, had the following parameter: $2x10^{26}$ ions/m^3 ytterbium concentration, 3.5 µm core diameter, 0.17 numerical aperture. The background loss of the fibre is monitored before and after pumping and the increase in loss in dB/m is then measured by subtracting the two curves. Results are shown on Figure 2, where the focus is on the 1050 to 1100 nm region, the emission band normally used for ytterbium. The 977 nm pumping creates a significant increase in background loss while the 1047 nm produces no photodarkening at all even if the light intensity is five times lower in the 977 nm case. The 977 nm almost totally inverts the ytterbium fibre while the 1047 nm only inverts an average of about 2 % of the ions. Calculations of the theoretical inversion were performed using a standard rate equations model for rare-earth doped fibre amplifier or laser systems validated in previous works [14,15]. Therefore, this demonstrates that ytterbium ions must be significantly inverted for photodarkening to happen while an intense beam of light with wavelength around 1.0 ±0.1 µm does not necessarily cause photodarkening.

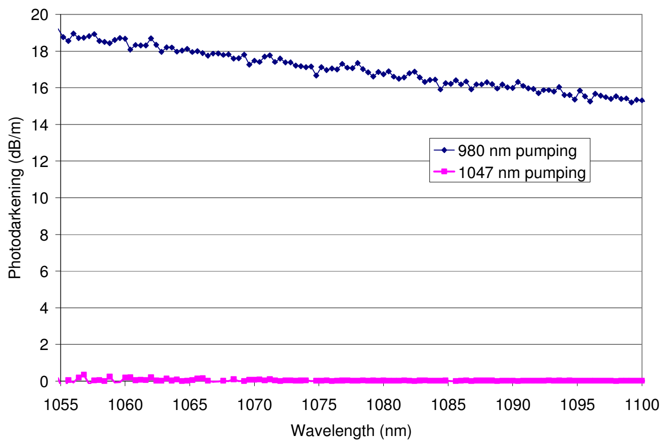

Figure 2. Photodarkening effect of an ytterbium fibre under different pump wavelength.

2.3 Time behavior of photodarkening

Photodarkening is an effect that occurs strongly at the beginning and then decreases to reach a stable value. This effect is shown on Figure 3, where a short sample of 5 centimeters of the ytterbium fibre described above is core pumped with 150 mW at 977 nm. The normalized transmitted output pump power at 977 nm was monitored as a function of time. The decrease in output power is directly correlated to the increase in background loss of the fibre. It can be clearly seen on Figure 3 that the decrease in output power occurs within the first minutes and then stabilizes.

Hence, a quick and repeatable way to measure the photodarkening level of an ytterbium fibre is to measure the increase in core background loss of a short sample that is strongly inverted under core pumping around 977 nm. This can be achieved with any fibre, whatever the core size or the ytterbium concentration, with lengths varying from a few centimeters to half a meter. The fibre length must be short enough such that several mW of pump power exit the fibre to ensure that the ions in the sample are thoroughly and equally inverted. Since photodarkening is also a function of time, an important point to ensure a repeatable comparison between fibres is to pump the fibre until the power reaches a stable output, which can take several hours in low photodarkening fibre. A similar measurement method for single-mode ytterbium fibre was also reported in the literature[16].

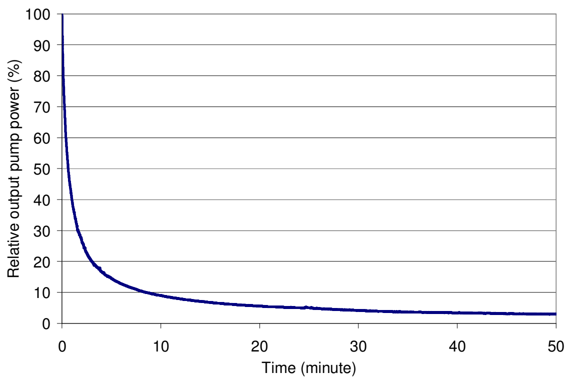

Figure 3. Typical temporal behavior of photodarkening effect in an ytterbium fibre showing the drop in transmitted output pump power as a function of time through a short ytterbium fibre sample core pumped at 977 nm.

3. PHOTODARKENING REDUCTION

3.1 Origin of photodarkening

Our investigations of photodarkening suggest that this phenomenon is related to a multi-excitation of ytterbium clusters emitting light in the UV region. Photodegradation of silica fibre under direct UV irradiation is well known where an increase in background loss under UV radiation occurs[9,10]. When strongly pumping ytterbium fibre with a pump at 977 nm, clusters of three or four ytterbium ions can emit radiation in the UV region. It was already demonstrated that clustering of ytterbium emits light around 500 nm through cooperative luminescence from the simultaneous de-excitation of two clustered ions[11]. Adding one or two ions to the same clusters, which can easily happen in highly doped ytterbium fibre, will further emit light in the UV region. An experiment was conducted to correlate emission at 500 nm, or clustering, with different ytterbium doped fibre as previously reported[11]. The side emission around 500 nm of 2 mm sample ytterbium was measured with an optical spectrum analyzer. The fibre was strongly pumped with 100 mW of power at 977 nm. An Ando AQ6315A optical spectrum analyzer was used because of its free space input and wavelength coverage down to 350 nm. The measurements were done several times and the fibre positioned carefully to ensure a repeatable measurement within all the fibres tested. Figure 4 shows results obtained for different CorActive's fibres tested: the Yb-13-05 and Yb-17-03, which are fibres not engineered for photodarkening with ytterbium concentration of $1x10^{26}$ and $2x10^{26}$ ions/m^3 respectively, and the Yb-19-06, a fibre with $2.5x10^{26}$ ions/m^3 engineered for low photodarkening. A large difference in emission at 500 nm between high and low photodarkening fibre can be seen right away on Figure 4 : an average difference of 5 dB is measured.

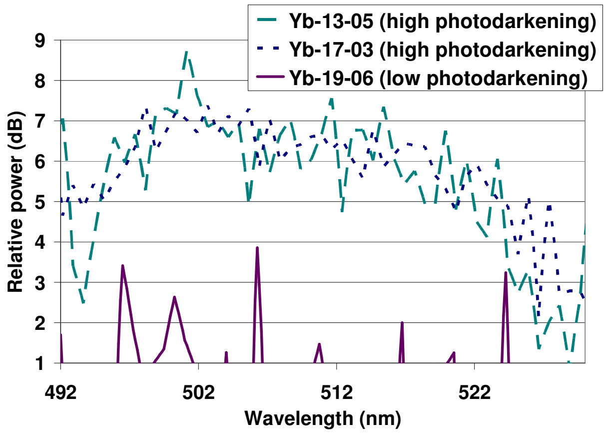

Figure 4. Cooperative luminescence around 500 nm of high and low photodarkening ytterbium fibre

A 10 cm sample of ytterbium fibre Yb-13-05 was exposed to UV radiation directly during a 30 minutes period and the increase in background loss was measured after the exposure. Another 10 cm sample of the same fibre was also core pumped with 100 mW of power at 977 nm. Figure 5 shows the resulting photodarkening of both samples. The same signature of photodarkening can be seen when inverting the fibre core with pump light or when irradiating it with UV radiation. Furthermore, the same time behavior (shown on Figure 3) is observed when irradiating the fibre with UV generation as when it is pumped at 977 nm. A rapid increase in background loss is observed at the beginning of the exposure followed by a stabilization period. This time behavior is also reported in the literature for UV irradiation[9].

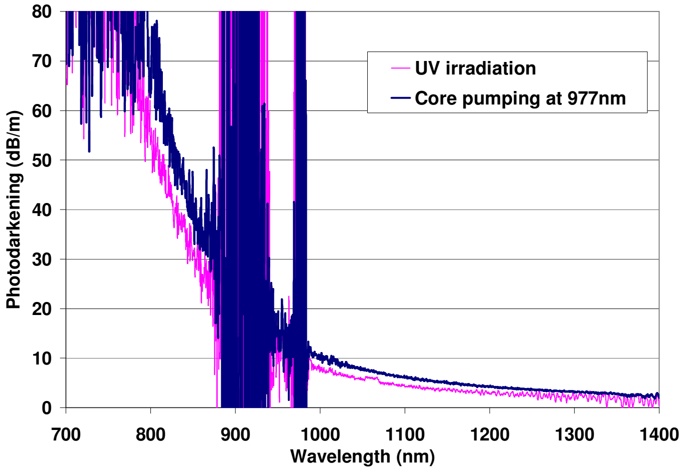

Figure 5. Photodarkening signature of ytterbium fibre under UV irradiation and core pumping at 977 nm

Another important aspect of photodarkening is that it is directly related to the concentration of ytterbium ions as shown on Figure 6, where photodarkening at 1100 nm is shown of short sample of 5 µm core diameter fibre core pumped with 200 mW of pump power at 977 nm. This also seems to correlate with the presence of clusters since clustering increases with respect to the concentration of dopants. An ytterbium concentration around $5x10^{25}$ ions/m^3 represents a threshold value where photodarkening becomes significant and where fibres must be carefully engineered to avoid photodarkening.

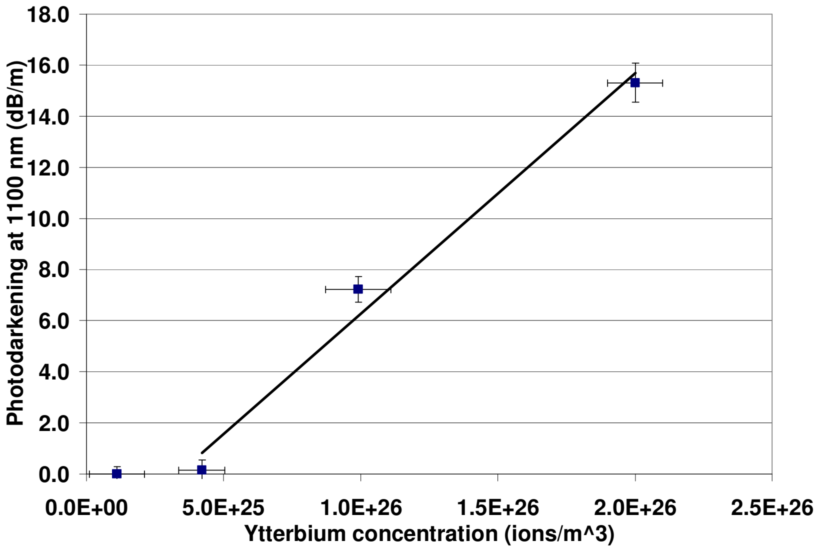

Figure 6. Increase in background loss at 1100 nm created by photodarkening as a function of the ytterbium concentration.

3.2 Photodarkening reduction

Photodarkening has been reduced by applying solutions that diminishes clustering. Using aluminum as a co-dopant is well known to reduce clustering in erbium doped fibre[12,13]. The same solution can be applied with ytterbium to reduce clustering and thus photodarkening. Figure 7 shows the photodarkening of two similar fibres, one codoped with germanium and the other with aluminum: a large difference can readily be seen between the two fibres. It is important to note that the presence of germanium does not contribute to photodarkening since germanium free ytterbium fibre also photodarkens.

Codoping the fibre with other rare earths such as erbium, shown on Figure 7, also contributes to reduce photodarkening. In the presence of erbium, clusters of ytterbium will preferably transfer their energy to the erbium ions rather than emitting UV radiation with a neighbor ytterbium ion. The right amount of co-doping must be aimed when using another rare-earth not to decrease the efficiency of the fibre. All fibres were prepared using a modified chemical vapor deposition (MCVD) process with a solution doping technique. This process allows to manufacture highly doped ytterbium fibre exhibiting no significant photodarkening.

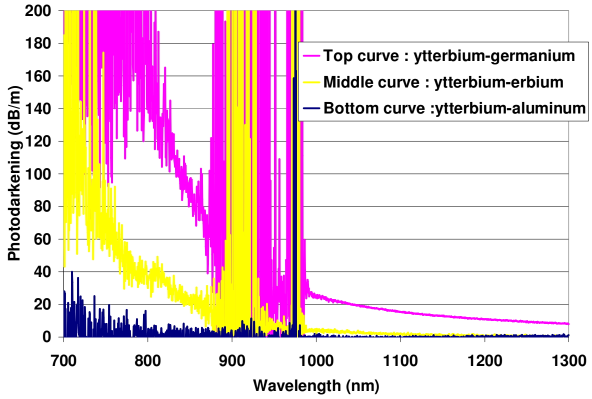

Figure 7. Difference in photodarkening of different ytterbium fibre depending of their co-dopants.

4. PHOTODARKENING AND APPLICATIONS

To investigate the importance of considering photodarkening in applications, two different experiments were conducted with the same double cladding ytterbium fibre, having a core/cladding diameter of 6um/125um and an ytterbium concentration around 1×10^{26} ions/m^3. This fibre was not engineered for low photodarkening.

1) Firstly a 20 W output power laser was built by injecting in the cladding 30 W of pump power at 915 nm using a multimode pump combiner. The fibre length was 15 meters and Fibre Bragg Gratings (FBG) at 1064 nm of 99.9% and 5% reflection were used.

2) Secondly, a 60 mW output power single cladding amplifier was built by injecting in the core a 5 mW signal power at 1064 nm and 200 mW of pump power at 977 nm using a 1064nm/977nm multiplexer. Isolators at the input and output were used to avoid lasing effect and a length of 20 centimeters of fibre was used.

The normalized output power as a function of time is shown on Figure 8-a. The single cladding amplifier shows a rapid decrease of output power whereas the double cladding fibre laser has a stable output. This behavior was expected since when pumping the cladding, the inversion of ytterbium ions is way lower than when pumping directly the core. Figure 8-b shows the theoretical difference in ytterbium inversion along the fibre length between the core pumped amplifier and the cladding pumped laser. The core pumped amplifier inverts more than 90% of the ions while the cladding pumped laser inverts less than 1% because of the small overlap of the pump light with the core. This results correlates with the results of section 2.2, where a pump wavelength of 977 nm inverts a lot the ytterbium ions and creates photodarkening while 1047 nm pumping does not invert much the fibre and does not create loss. The graph on Figure 8-b focuses on the first 20 cm of fibre length because the fibre of the core pumped amplifier is short, but the level of the inversion of the cladding pumped fibre laser is barely the same over all its fibre length. All the calculations of theoretical inversion were done using the same model mentioned in section 2.2.

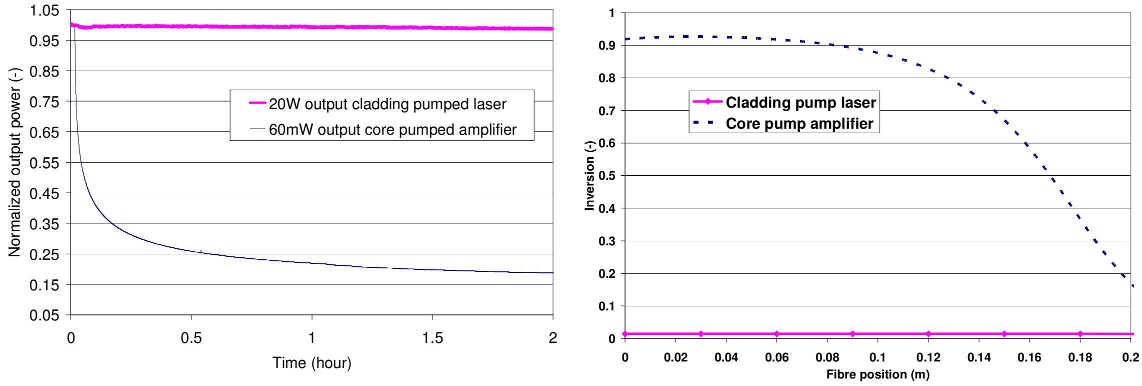

Figure 8. (a) Measured temporal degradation and (b) theoretical ytterbium inversion of the same ytterbium fibre used in two different applications: cladding pumped fibre laser and core pumped amplifier

If the fibre was used as a cladding pumped amplifier instead of laser, the average inversion would be around 2%, which is twice the value of the cladding pumped laser but still way below core pumping; therefore, the application impacts strongly the occurrence of photodarkening and core pumping represents the worst case for photodarkening to happen. The long term stability of core pumped amplifier was used to test CorActive ytterbium fibre engineered for low photodarkening in applications.

Fibre #	Product ID	Numerical aperture (-)	Core size (µm)	Ytterbium concentration (ions/m^3)	Equivalent 125 µm diameter cladding absorption at 915 nm (dB/m)	Engineered for low photodarkening
1	Yb-13-06-02	0.13	6	$1.25x10^{25}$	0.05	No
2	Yb-13-05	0.13	5	$1.0x10^{26}$	0.60	No
3	Yb-16-06	0.16	6	$0.85x10^{26}$	0.50	Yes
4	Yb-19-06	0.19	6.5	$2.5X10^{26}$	1.10	Yes

Table 1. Different parameter of tested ytterbium fibre in amplifier experiment.

Figure 9 shows the output power over time of different ytterbium fibres in core pumped amplifiers. The experimental conditions are the same as described at point 2 above in this section and fibre length was optimized for maximum output. Four different fibres are shown on the graph. These fibres all have core diameter around 6 µm and numerical aperture around 0.15; details on the fibre specifications are given in Table 1. All fibres show a initial output power around 65 mW. The small initial power difference simply comes from the core and numerical aperture variation that changes the overlap with the dopant and thus efficiency. On Figure 9, the doped fibre #1 Yb-13-06-02 shows no temporal degradation at all. This fibre was not engineered for low photodarkening but no degradation occurs because of its low doping level. In fact, 3.5 meters of fibre were required for the low doped Yb-13-06-02 compared to less than 0.5 m for the other fibres. Hence, such a fibre could not be used in cladding pumped application because the absorption at 915 nm would be less than 0.1 dB/m for a cladding diameter of 125 µm. Fibres #2 Yb-13-05 and fibre #3 Yb-16-06 have both a cladding absorption around 0.5 dB/m at 915 nm, which is of practical interest for cladding pumped amplifier. One is engineered for low photodarkening by co-doping with aluminum and the other not. A large difference in power degradation is seen between the two fibres. The last fibre #4 Yb-19-06 is a special engineered fibre with very high doping level. This fibre shows the smallest power degradation and is stable after 100 hours operation. The high doping level of fibre #4 made the fibre length 20 cm instead of 45 cm for fibre #3.

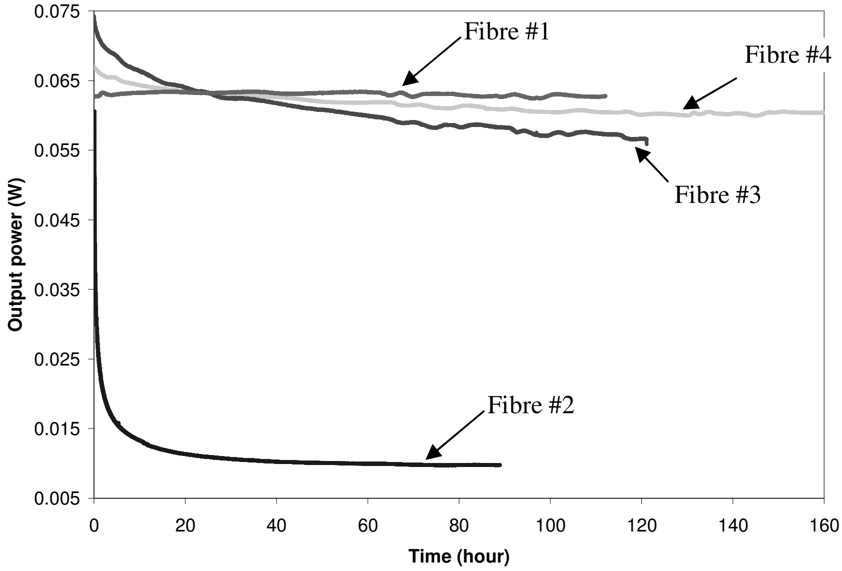

Figure 9. Output power over time of core pumped amplifier. Fibres are 6um/125um core/cladding with different cladding absorption at 915 nm: fibre #1 = 0.05 dB/m; fibre #2 and #3 ≈ 0.55 dB/m; fibre #4 = 1.1 dB/m

In single cladding amplifier, switching from 20 cm to 45 cm with higher doping level might not impact much the application, but designing highly doped fibre with low photodarkening is important in pulsed double cladding amplifier application. High doping level is required to keep the fibre length short and limit non-linear effects while photodarkening must be avoided to ensure a long term stability. A pulsed double cladding pre-amplifier was designed to test this issue. A signal coming from a seed diode at 1070 nm is current modulated at 50 ns pulsewidth and 20 kHz repetition rate giving an average power of 2 mW. Fibre #2 and #4 described in table 1 above were used, but in double cladding version, which corresponds respectively to CorActive's Las-Yb-06-01 and Las-Yb-07-01 product ID respectively. The fibre is pumped in co-propagation with 1.5 W of pump power at 915 nm with a multimode combiner with a signal feedthrough. Fibre #2 with cladding absorption of 0.5 dB/m at 915 nm requires fibre length of 15 meters and thus creates Raman effect at 1130 nm because of the high peak power and propagation length. With a fibre with doping level of 1.1 dB/m, the fibre length was shortened to 7 meters and thus eliminating the non-linear effect. Figure 10-b show that even with higher doping level photodarkening was avoided and no long term degradation occurs.

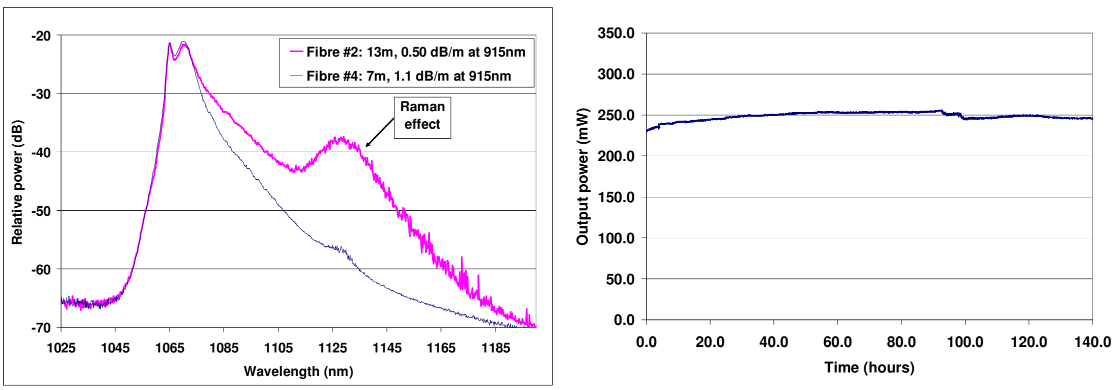

Figure 10. Output spectrum and temporal stability of pulsed pre-amplifier (50 ns, 20 kHz)

5. CONCLUSION

Spectral characteristics and time behavior of photodarkening in ytterbium fibre were investigated. Comparing pumping wavelength at 977 nm versus 1047 nm and comparing cladding pumping versus core pumping show that the inversion of the ytterbium ions is a critical parameter in the occurrence of photodarkening. Comparison of cooperative luminescence of high and low photodarkening fibre suggests that photodarkening is caused by ytterbium clusters that emit UV radiation. The dependence of photodarkening to ytterbium concentration also correlates with the generation of UV radiation by clusters. Similarities between the background loss signatures of ytterbium fibres irradiated directly by UV light and by pump light at 977 nm also support this assumption. Solutions to photodarkening were developed by co-doping the fibre with aluminum to prevent clustering. Codoping the fibres with other rare-earth also decreased the multi-excitation of ytterbium clusters. Low photodarkening fibres were tested in laser and amplifier application, where no significant degradation of output power was measured in core pumped amplifier, representing the worst case scenario for generation of photodarkening. Highly doped fibre engineered for low photodarkening allowed reduction of fibre length in cladding pumped amplifier without compromising the long term power stability of the system.

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