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Pump Power Depreciation by Photodarkening in Ytterbium-doped Fibers and Amplifiers

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Abstract—In this paper, pump power depreciation due to photodarkening effects in an ytterbium doped fiber (YDF) is investigated. Photodarkening is monitored by measuring the transmitted power at visible and pump wavelengths simultaneously, which renders direct quantitative measurement of pump power reduction rather than excess background loss. Our observation of substantial reduction in the pump power and the shortened fluorescence decay time in the photodarkened fibre indicates that the photodarkening influences pump efficiency. The effect of the photodarkening in a device level is also investigated by observing the performance of the YDF amplifier implementing the same YDF. The pump power depreciation of this fiber amplifier is quantitatively investigated by numerical simulation. The results suggest that operating at a saturated regime helps to subdue the photodarkening, with explanation in terms of population inversion density provided. The level of power depreciation is calculated to be 15 ~ 30%, which matches our experimental observation

Index Terms — Optical fiber amplifiers, Optical fibers, Ytterbium.

I. INTRODUCTION

Fiber lasers and amplifiers are efficient, powerful, and compact devices providing optical output for various applications. In active gain medium of fiber lasers and amplifiers, rare earth elements are frequently used as dopants in a glass fiber. Compared to other rare earth elements, ytterbium provides larger gain bandwidth, and efficient energy transition with small quantum defect [1]. Hence, ytterbium doped fiber (YDF) lasers and amplifiers are interesting for material processing [2], military applications [3], medical [4] and nonlinear wavelength conversion [5]. All these applications require long operational lifetimes.

One of the key challenges in long-term reliability of high power YDF lasers and amplifiers is how to minimize the

photodarkening effect in its active gain medium. This phenomenon has been observed in directly pumped silica fibers with various rare-earth dopants [6-8]. For YDF, this phenomenon has been investigated under different probing wavelengths [9-11]. Existence of the photodarkening is usually observed as transmitted power decrease over time at a probing wavelength around 633 nm. Temporal change in the power is expressed by a stretched exponential function [9, 12]. The physical process of the photodarkening is viewed as the formation of color centers in the glass host [13]. These color centers have absorption peak below the visible wavelengths, but its absorption curve extends to Yb-band around 1.1 μm [14]. Hence, the formation of color centers in glass hosts attenuates both pump and signal power, and reduces the efficiency of YDF based devices. It is found that this effect is related to the population inversion factor [15]. Reduced photodarkening in YDF has been reported [15-18], while photodarkening is usually interpreted as addition loss in YDF.

In order to better understand the effect of the photodarkening, this paper presents the observation and investigation on photodarkening effect occurring on YDF as well as YDF amplifier. We observe the influence of the photodarkening at pump wavelength together with the conventional visible wavelength to envisage the direct impact of photodarkening on Yb-band. Our results suggest that photodarkening is not a simple excess background loss, but should be interpreted together with pumping efficiency for the power decay in both YDF and YDF amplifier.

II. PHOTODARKENING MEASUREMENT IN YDF

The first quantitative experimental observation of pump power depreciation attribute to the photodarkening, to the best of our knowledge, has been presented here. We examine photodarkening in an YDF by monitoring transmitted power of probe at 633 nm and pump at 977 nm. Thus, our experimental setup in Fig. 1 allows for an observation of a pump power change which has a direct impact to the performance of the YDF based devices. The YDF is pumped by a fiber-coupled and Bragg grating (FBG) stabilized 977 nm laser diode. The output end of the pump fiber is spliced to the YDF under test and the throughput pump power from the YDF is measured in a power meter. A He-Ne laser at 633 nm is coupled to the YDF through a chopper as a probe beam and co-propagated with pump. A lock-in amplifier and fiber couplers are used to

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separate the pump and probe beams for individual power measurement.

Fig. 1. Schematic of measurement setup

The length of the YDF is fixed at ~ 1 cm to avoid building the undesired amplified spontaneous emission (ASE). We did not observe any ASE buildup in optical spectrum analyzer. This short length also helps to create uniform Yb population inversion throughout the fiber. The YDF has Al:Yb as a core dopant in silica host material. The core and cladding diameters are measured as 8 and 125 μm , respectively. Its core numerical aperture (NA) is 0.15 and Yb concentration is approximately $1 \times 10^{26} \text{ m}^{-3}$. Fig. 2 shows the temporal change of transmission of probe and pump beams when 42% of Yb ions are populated by pumping at 977 nm. The transmission data are fitted by an exponential growth curve [19]:

$$10 \log_{10} \left(\frac{1}{T} \right) = \alpha_{eq} \left(1 - \exp \left(- \left(\frac{t}{\tau} \right)^\beta \right) \right) \quad (1)$$

where T is transmission, α_{eq} is saturated loss, β is stretch parameter, and τ^{-1} is characteristic rate constant. Since the saturated loss is mainly contributed by photodarkening, it is used to indicate power loss level of photodarkening. The fitted parameters are listed in table I.

following an exponential curve which is a typical characteristic of photodarkening, and induces a loss of 640 dB/m. The pump throughput power at 977 nm also creates similar profile over the time with a saturated loss of 66 dB/m. The saturated output power drop amounts to about 17% of the initial power. Thus, our results indicate that about 17% of pump power is wasted due to photodarkening at the given experimental condition. This amount of pump power reduction is critical to device performance. We do not observe any significant change in the probe power after stopping the pump, which agrees with [10].

The transmitted spectrum is measured before and after the irradiation in the same fiber used in Fig. 1, and the difference of transmission spectra is represented in Fig. 3. Interestingly, as shown in Fig. 3, the measured loss at 633 nm is consistent with the temporal measurement while the loss at 977 nm marks a significantly lower value than temporal measurement. The results are summarized in Table I. It is noted that the transmitted power spectrum can only show an induced background loss after the photodarkening, whereas the temporal measurement directly reveals the reduction of pump power associated with the photodarkening. The larger temporal pump power loss than what observed from the spectral measurement indicates that the pump power is not only utilized to excite Yb ions, but also to create or energy transfer to defect centers accounting for the photodarkening [21, 22].

Fig. 2. Change of transmission, $\log_{10}(1/T)$, at probe and pump wavelength during 977 nm irradiation. Experimental data (symbols) are fitted by stretched

TABLE I

FITTED PARAMETER OF STRETCHED EXPONENTIAL FORM

	633 nm	977 nm		633 nm	977 nm
Temporal measurement			Spectral measurement		
α_{eq} [dB/m]	640	66	Excess loss [dB/m]	637	40
β	0.57	0.77			
τ^{-1} [1/min]	0.08	0.10			

As shown in Fig.2, the power at 633 nm quickly decays

Fig. 3. Spectral excess loss created by photodarkening measured in the same fiber in figure 2

The lost pump power is hypothesized to migrate to the existing defect centers in which case it can cause radiative lifetime shortening through concentration quenching, *i.e.* energy from excited Yb^{3+} ion migrates to the defect centers. Differentiating from our hypothesis, in [23], the Yb^{3+} to Yb^{2+} process is proposed to be the cause of the pump power depreciation. More investigations are required to find out the utility of the lost pump power. The fluorescence decay at $\sim 1 \mu\text{m}$ is measured from side of the fiber before and after the pumping and the results are compared in Fig. 4. The fluorescence decay observed here is comparable with the one recently reported in [22].

Fig. 4. Fluorescence power decay before and after irradiation. Experimental data (symbols) are fitted by exponential decay curve (lines)

There is clear reduction of the I/e fluorescence lifetime in the photodarkened fiber which is determined by fitting to an expression of single exponential decay. The lifetime shortens by $\sim 12\%$ from ~ 830 μsec to ~ 730 μsec after the photodarkening. As the lifetime linearly scales to laser efficiency [24], lasers operating at 46% of inversion level will carry $\sim 12\%$ performance degradation over time. In addition to the observed pump power reduction in Fig. 2, this can significantly hamper the device performances. Thus, our results suggest that the photodarkening is not a mere increase of background loss, but it should be interpreted with reduced pumping efficiency as well.

III. PHOTODARKENING IN YDF AMPLIFIER

To further investigate the pump power depreciation due to the photodarkening in a device level, the performance of YDF amplifier utilizing the same YDF in section II has been observed, and pump power depreciation in this YDF has been verified by simulation quantitatively. The population inversion density of YDF calculated by simulation has also been presented here. In experiment, a 20 cm long YDF used in Fig. 1 is spliced between two wavelength division multiplexing (WDM) couplers and a counter pumping configuration is arranged. The fiber is core pumped at pump power of 185 mW. Seed input powers are set to 20 mW and 2.5 mW to operate the YDF amplifier in saturated and unsaturated condition, respectively. The signal wavelength is varied to 1063 and 1079 nm which are the most common wavelengths achieved from YDF amplifiers. The output signal power is recorded with time to observe the photodarkening. In Fig. 5, the temporal trends of output signal powers are illustrated. Scale is adjusted to permit comparison of the curves. The actual readings of output power are summarized in table II.

In all the cases, the signal output power is observed to reduce over the operating time and this tends to be more profound in the amplifiers operating in unsaturated regime. The saturated power is approximated at 26 mW calculated from $P_{\text{sat}} = \frac{Ah\nu_p}{(\sigma_{\text{abs}} + \sigma_{\text{em}})\tau_{\text{Yb}}}$ where A is effective area, $h\nu_p$ represents photon energy at signal wavelength, τ_{Yb} is fluorescence lifetime, σ_{abs} is absorption cross section, and σ_{em} is emission cross section. The values of these four parameters are $50 \mu\text{m}^2$, $1.87 \times 10^{-19} \text{J}$, $4.34 \times 10^{-13} \mu\text{m}^2$, $7.22 \times 10^{-15} \mu\text{m}^2$, 820 μs respectively,

which is obtained from our YDF.

Fig. 5. Output power drop during operation of YDF amplifier

The signal power drops $\sim 80\%$ in the amplifier operating in unsaturated regime and $\sim 65\%$ in saturated regime. Thus, our results propose that operating in saturated regime is favorable for long term reliability of the device.

TABLE II
CHANGE OF SIGNAL OUTPUT POWER DURING THE OPERATION

Signal wavelength / nm	Seed Input / mW	Signal Power / mW		Power Drop / %
		Initial	End	
1063	20	48.6	16	67
	2.6	14.7	2.9	81
1079	20	35.5	13.1	63
	2.4	10.4	2.3	78

The observation is believed to account for the different Yb inversion populations. A simulation program based on Optiwave commercial software is used to feature the performance and characteristics of the YDF amplifier. The photodarkening effect is considered by adding in excess background loss in our simulation program. The YDF is based on the solution of the rate and propagation equations [1, 25] of a two energy level system.

The population density of YDF is calculated with the same experimental parameters in Fig. 5, and the distribution of Yb ions along the fiber is shown in Fig. 6. Nearly half of the Yb ions are excited toward the pump end at 0.20 m in the figure while the excited level is quickly depopulated toward the other end, *i.e.* signal input end. As expected from the results in Fig. 5, under the saturated regime, the population inversion density is relatively low, which leads to a less photodarkening effect. While under unsaturated regime, the population inversion density is high, and this accelerates the output power decay. The calculated output signal power trend is in good agreement with the experimental results. On the other hand, there is no significant change in the distribution between the different wavelengths, which is consistent to the observation in Fig. 5.

We then, theoretically investigate if an increase of a background loss can explain the observed output power drop. The excess background loss at signal wavelength is estimated as ~ 10 dB/m from our experiments in Fig. 2 assuming that the background loss follows the typical ratio of ~ 70 [26]. We note that this estimated loss corresponds to 46% of the population

inversion over the entire fiber length, which is then overestimated for the amplifiers with inversion levels in Fig. 6. Nonetheless, it is found that the calculated output powers are higher than the experimental results by ~40%. We noticed that pumping efficiency needs to be adjusted to 70~85% of original value to be consistent with experimental result. In this way, the pump power depreciation observed in experiment is verified quantitatively by simulation.

Fig. 6. Excited Yb ion density, n_2 , along the YDF

IV. CONCLUSIONS

We have observed the pump power depreciation caused by photodarkening effect on Yb band. The temporal decay of the pump power is fitted by the stretched exponential function. The measurement result suggests that ~17% of the pump power vanishes during photodarkening when 46% population inversion is created in our YDF. In addition, the fluorescence life time is found to be reduced by ~12%, which can additionally impair the performance of YDF based devices. Hence, we conclude that the photodarkening effect is not a mere excess background loss, but necessary to be interpreted with pumping efficiency as well.

The YDF amplifier utilizing the same YDF is tested to measure the photodarkening in a device level. The observation of smaller signal power reduction when operated above saturated power than below saturated power is interpreted by different Yb population inversion density. In order to reach consistent theoretical results to experimental measurements, pump power needs to be adjusted in simulation. It is found that significant amount of pump power, 15~30%, are impaired by the photodarkening on top of the excess background loss, which matches with our experimental observation.

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