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Measuring photodarkening from single-mode ytterbium doped silica fibers

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Abstract: Photodarkening is recognized as a potentially important limiting factor on the lifetime and reliability of many Yb-doped fiber lasers and amplifiers. In particular, a photodarkening process attributed to the formation of photoinduced structural transformations can induce excess loss in the doped glass core of the fiber, resulting in reduced output power efficiency. Yet, quantifiable measurement techniques of this phenomenon have been scarce in the literature to date. Here we present a fast, simple and repeatable method to measure and compare the photodarkening rate caused by the formation of photoinduced structural transformations from Yb-doped single-mode fibers. The method relies on quantifying observations of transmission changes at visible wavelengths as an indicative measure of photodarkening at the signal wavelengths. Preliminary measurement results are presented supporting the utility of the technique for benchmarking the photodarkening behavior of different Yb-doped fibers.

OCIS codes: (060.2270) Fiber characterization; (060.2290) Fiber materials; (160.5690) Rare earth doped materials; (160.2750) Glass and other amorphous materials

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1. Introduction

Ytterbium (Yb) doped fiber lasers and amplifiers, both CW and pulsed, operating at the 1.0-1.1µm wavelength region are generating considerable interest for a large variety of applications including industrial (e.g., materials processing), military, biophotonic, and medical [1-5]. Many of these applications require carefully tailored laser output parameters and long operational lifetimes. However, as power output levels continue to increase and as fiber lasers and amplifiers become more commonly utilized as pulsed sources, user reports of a degradation mechanism - commonly referred to as photodarkening – have become more frequent. Photodarkening as a term has been ascribed to the temporal increase in the transmission losses of the doped glass. In applications, this can potentially translate into a continuous decrease in the output of a fiber laser system, which may or may not stabilize over time. Previously, performance degradations due to photodarkening have been reported for many rare-earth doped silica fibers, especially with dopants such as, Ce^{3+}, Eu^{2+}, Pr^{3+}, Tb^{3+} and Tm^{3+} [6-9], and similar effect has been observed in Yb^{3+} doped silica fibers as well [10].

In most cases, the underlying physical process for doped fiber degradation could be attributed to the formation of color centers or other photoinduced structural transformations in the silica glass host [11], to polymer coating damage, or to radiation damage from high-energy particles [12]. Among these processes, photodarkening by photoinduced structural transformations is commonly associated with defects, or permanent damage sites in the glass formed, typically, by photoionization. It is sometimes distinguished from the other mechanisms through center absorption at both signal and pump photons, resulting in broad absorption spectra that are most pronounced at the visible wavelength range, but with a significant absorption tail up to the 1.1µm wavelength region. While the mechanisms underlying the process are not fully known for Yb-doped glass, there are indications that it is associated with the composition and homogeneity of the active gain material matrix itself. This presents a fundamental issue in both fabrication and utilization of fibers in many laser applications, but especially those involving prolonged exposure to high pump intensity levels. In particular, absorption at both pump and the signal light can significantly reduce the overall power conversion efficiency of the fiber while further compounding any long term detrimental effects on the fiber laser system performance, lifetime and operational reliability. The efficiency reduction can, in turn, increase prime power requirements resulting in higher application costs, or it may, in certain severe cases even terminate lasing action altogether [13].

Presently, there is no standardized way of measuring photodarkening caused by photoinduced structural transformations. Previous work on photodarkening of doped fibers have been done by using a probe laser or by measuring the spectral properties of the fiber [6-7,14]. The goal of this work has been to devise a methodology of accelerated aging which could provide an application independent “worst case” test for benchmarking different types and characteristics of fibers, that is repeatable and simple enough to implement to make it practical in a commercial setting.

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2. 2. Measurement technique

The technique we use stems from a demonstrated linear correlation between changes in absorption at visible wavelengths, to absorption rate at signal wavelengths of interest (near 1.1 µm for Yb doped silica fibers), where absorption levels are much lower. Since transmission loss by the observed photoinduced structural transformations is more pronounced at visible wavelengths, signal acquired at visible wavelengths is significant and can therefore be measured quickly and accurately even from relatively short fibers with small photodarkening loss. Furthermore, by measuring the rate where it is near its highest, the method can be implemented easily using readily available light sources and detection systems.

The method, illustrated in Fig. 1, consists of measuring the transmission spectra of a white light source passed through the sample fiber before and after exposure to pump radiation, and deriving the photodarkening induced excess loss spectrum from the difference between the two. It should, however, be noted that the measurement method does not distinguish absorption losses from scattering losses, and photoinduced scattering can not therefore be ruled out as a potential degradation mechanism. To accelerate the measurement times, the fiber sample is preferably pumped at a wavelength proximate to the peak absorption under conditions of no lasing, allowing use of short sample lengths. For the measurements reported here, the HeNe laser wavelength of 633nm was selected as the reference wavelength for the spectral measurements. However, other sources may be utilized, including diodes, as long as they are sufficiently near the broad maxima of the photoinduced excess loss and are matched to detectors with good signal-to-noise ratio.

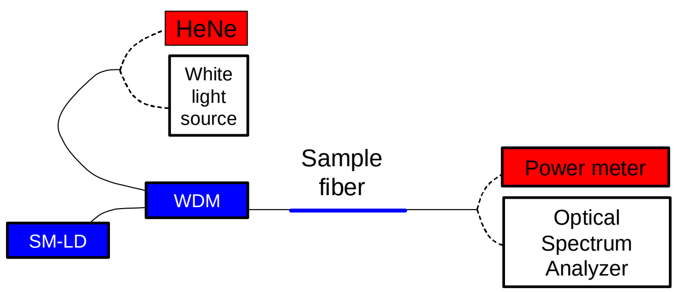

Fig. 1. Measurement methods for characterization of photodarkening. The induced excess loss spectrum can be calculated from the measured white light source transmission spectra of the sample before and after photodarkening by core pumping of a fiber sample. For single mode fibers, end-pumping by a single mode laser diode (SM-LD) pump is sufficient. Optionally the temporal behavior of the induced excess loss could be measured using a probe laser during the photodarkening of the fiber.

A set of measurements was carried out using Yb-doped fiber sample lengths corresponding to about 140dB of small signal absorption at the peak 976nm absorption wavelength. For typical aluminosilicate fibers with 800-1400dB/m peak pump absorption this length consists of about 10-15cm of doped fiber. In the preliminary set of measurements reported here, the photodarkening was induced by core pumping the sample with a single-mode pump laser tuned to 974nm for a fixed pump power of 300mW. These parameters, combined with a measurement time of about 30 minutes correspond, according to our simulations, to a flat 50% inversion throughout the sample, a rather high level for Yb ions. Generally, selection of the measurement time is an important factor in assuring data accuracy. It is selected by choosing an optimal tradeoff between the magnitude of the measured signal and the throughput time of the measurement. Thus, for the preliminary measurements described here, 30 minutes was determined to be sufficient to activate most of the defect sites in the sample fiber (the “photoinduced structural transformations”). Under these conditions additional pumping time provides diminishing returns in terms of the increased signal accuracy. By the same token, overly high pump power is neither necessary nor desirable, as this can result in crosstalk between the pump and the probe laser potentially reducing the

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accuracy of the excess photoinduced losses measured using a probe laser. This measurement method asssumes a dependence of the photodarkening rate on the level of inversion, an assumption borne out by our observations. Generally, for a given set of measurements, we found that it was important to keep the small signal absorption of the sample, pump wavelength, pump power and the photodarkening time all constant in order to provide readily repeatable, comparable results.

3. Measurement results

Two examples of measurement results are illustrated in Fig. 2, showing the photodarkening induced excess loss, as a function of wavelength. The loss is calculated from the difference of the before and after transmission spectra taking into account the sample length. As expected, the measured signal levels are much smaller at the 1.0-1.1μm region, whereas the noise levels are rather constant throughout the spectrum. Therefore the signal to noise ratio is considerably enhanced at visible wavelengths, especially when measuring samples with relatively low photodarkening levels. The inset in Fig. 2 shows the excess loss on a log scale, indicating a linear shape of the spectrum at wavelengths below the Yb ion absorption. This linearity could thus be used to extrapolate the photodarkening magnitude and rate from wavelengths that are within the dynamic range of the spectrum analyzer, set in this example, to the 633nm reference wavelength.

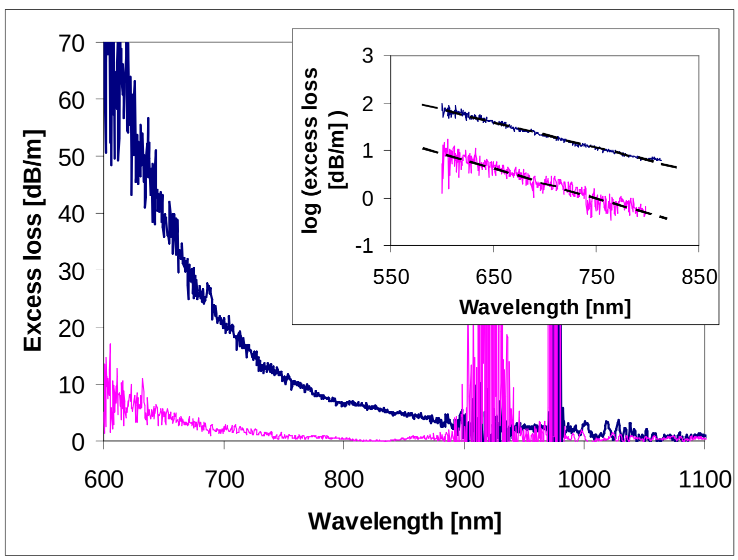

Fig. 2. Examples of measured spectral shape of the induced color center.

The data from measurements of 22 different glass compositions, with approximately two points per composition, are indicated in Fig. 3. As this figure clearly shows, the absorption at 633nm has a near linear correlation with that measured at the signal wavelength to within experimental error. From the slope, the absorption at the HeNe wavelength is seen to be about 71 times larger than the absorption at the signal wavelength. Furthermore, the limited spread of the data points indicates that the shape of the induced excess loss spectrum is quite similar for the wide variety of 974 nm pumped Yb-doped silica fibers used in the experiment. More surprisingly, in other measurements comparing fiber samples grown using Liekki's Direct Nanoparticle Deposition (DND) process and commercially available single mode fibers fabricated by conventional MCVD techniques, the spectral shape of the photodarkening spectrum was observed to be nearly identical, though the signal power degradation rates could be significantly different.

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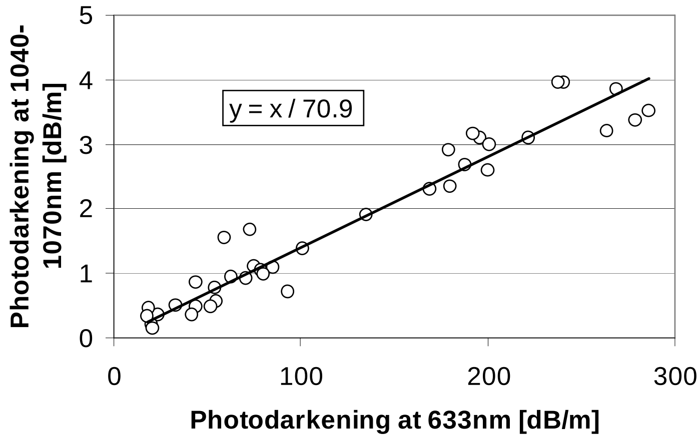

Fig. 3. Correlation between the excess loss at 633nm and at signal wavelength 1040-1070nm.

4. Conclusions

In summary, we found that measuring Yb-doped fibers under conditions of high, flat inversion could provide repeatable and comparable data even from very different types of single-mode silica fibers. It was also demonstrated that spectral information obtained from transmission measurements at visible wavelengths has the advantage of providing higher SNR's and therefore greater accuracy of the data points. It is noted that the over 50% constant inversion levels achieved in the samples used in our measurements generally correspond to the inversion levels typical of strongly pumped double clad pulsed amplifier fibers or single-mode ASE sources. This contrasts with standard double clad fibers used in CW lasers, where inversion levels of 10-20% are more typical, even for high power fiber systems of > 100 W outputs. Indeed, there have been sporadic reports and indications by users of fibers from various sources that fiber systems operated under conditions of high inversion (such as in pulsed, ultrafast and ASE applications) appear to photodarken faster than in applications involving lower inversion levels, such as CW lasers. The fact that, to date, significant photodarkening rates have not been reported with CW fiber laser systems correlates well with indications from our measurements. We therefore believe that the technique we described, based on transmission measurements under conditions of sufficiently high, near-constant fully repeatable inversion, can be useful in characterizing and benchmarking the expected photodarkening behavior of different fibers. This straightforward measurement approach can also be used to compare fibers of different composition or made by alternative manufacturing procedures, to therefore guide new designs and fabrication efforts aiming to improve the performance of doped fibers. Optionally, the white light transmission measurements utilized in our experiments can be augmented by using a probe laser during the photodarkening process to directly observe the temporal behavior of the induced excess loss. Such data could add further insight into the nature and behavior of the photodarkening process in various types of fibers.

It should be pointed out here, that the experimental demonstrations described in this brief paper were limited to those involving single mode, core pumped fibers. Measurements from these fibers were no doubt facilitated by saturation of the inversion, rendering the results relatively insensitive to pump levels beyond a certain magnitude. Such single mode fiber samples are however limited to relatively small cores of less than 14 µm for 976 nm pumping and less than 7 µm for 920 nm pumping. Ongoing work utilizing cladding pumping of large mode area fibers has since confirmed the validity and utility of the measurement techniques, and these results will be summarized elsewhere.

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Further work is also needed to study the parameters that affect the photodarkening rate in order to understand better the effect of photodarkening in different applications and with alternative glass compositions. In particular, the technique described so far should not be construed as an approach to quantifying photodarkening susceptibility of different types of fiber compositions. Rather, it is to be understood that the measurements of excess loss that are the subject of this work are most useful in comparing those fibers that display spectrally broad and relatively large levels of photodarkening behavior, most pronounced around the visible portion of the spectrum. And whereas the assumption that absorption at visible wavelengths is indicative of photodarkening behavior at longer wavelengths may not apply to all photodarkening phenomena, it does appear to be a common characteristic of a large class of Yb-doped silicate fibers, especially when used under high inversion conditions.

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