Optics Communications 284 (2011) 5774–5780

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Optical properties of Yb^{+3}-doped fibers and fiber lasers at high temperature

S.W. Moore [a,*], T. Barnett [a], T.A. Reichardt [a], R.L. Farrow [b]

[a] Sandia National Laboratories, P. O. Box 969, MS 9056, Livermore, CA 94551, USA
[b] JDSU,430 North McCarthy Boulevard, Milpitas, CA 95035, USA

ARTICLE INFO

Article history:
Received 12 July 2011
Received in revised form 24 August 2011
Accepted 26 August 2011
Available online 12 September 2011

Keywords:
Spectroscopy
Lasers
Emission

ABSTRACT

Recent advances in power scaling of Yb^{+3}-doped fiber lasers to the kilowatt level suggest a need to examine the performance of Yb^{+3}-doped silica at temperatures well above ambient. We report experimental results for the absorption coefficient, emission cross-section, fluorescence lifetime, and slope efficiency of a Yb^{3+}-doped large mode area (LMA) silica fiber for temperatures spanning 23 °C–977 °C. To the best of our knowledge these are the highest temperatures to date for which these optical properties have been measured. We find a sharp reduction in the energy storing capability and lasing performance of Yb^{+3}:SiO_2 above 500 °C that coincides with the onset of non-radiative transitions in the excited state manifold (thermal quenching). As the temperature increases from room temperature to 977 °C, absorption in the 1020–1120 nm operating band increases monotonically, concurrent with a reduction in absorption at the 920-nm and 977-nm pumping bands. Conversely, the spectral weight of the emission cross-section shifts from transitions above 1010 nm to those below, with the exception of the 977-nm emission band.

1. Introduction

Advances in cladding-pumped, kilowatt-class, Yb-doped fiber laser systems have surged in recent years as these devices have proven especially suitable for material processing. The large surface area-to-volume ratio, small quantum defect (975-nm pumping vs. 1064- to 1100-nm lasing), and high slope efficiency of commercially available Yb-doped silica fiber reduces thermal management and operating costs while allowing for very high wall-plug efficiencies. Still, despite the intrinsic advantages in thermal management offered by fibers, a significant rise in core temperature is expected for fiber lasers and amplifiers operating at the 1–5 kW level. The operating temperature of standard Yb-doped silica fiber is limited by the protective acrylate/fluoroacrylate coating, which begins to degrade and eventually fails below 200 °C. Studies to date concerning the optical properties and performance of rare-earth doped glass oxide and crystal laser and amplifier systems have been conducted at or below this temperature [1–6]. However, to further reduce the cost of thermal management or, alternatively, to operate fiber lasers and amplifiers in high temperature environments by using cladding materials that can withstand higher temperatures such as polyimide, then it is important to evaluate the optical properties and performance of Yb^{+3}-doped silica at temperatures exceeding 200 °C.

In this paper we report the temperature dependence of the radiative lifetime, emission cross-section, absorption coefficient, and slope efficiency of Yb^{+3}-doped (2.4×10^{20}ions/m^3) large mode area (LMA) fiber from 23 °C to 977 °C. We find that absorption in the 1020–1120 nm operating regime increases rapidly while absorption at the 920-nm and 977-nm pump bands decreases steadily with increasing temperature. For temperatures exceeding 500 °C, a sharp reduction in amplifier performance at 1064 nm is observed that coincides with an abrupt drop in fluorescence lifetime associated with thermally activated non-radiative losses (thermal quenching). As the temperature is increased from ambient to 977 °C, we observe a redistribution in the spectral weight of the emission cross-section from transitions in the 1020–1120 nm operating regime to transitions below 1010 nm. Interestingly, most of the spectral weight is transferred from transitions near the peak of the gain, 1020–1040 nm, while the emission cross-section at longer wavelengths is nearly independent of temperature.

The experimental set-up, data and subsequent analysis are divided into 5 sections. Section 2 gives a detailed description of the experimental set-up used to measure the absorption, emission, and slope efficiency as a function of temperature. In Section 3, the fluorescence lifetime is reported along with a description of the fitting routine used to determine the radiative lifetimes and energy separation of the individual Stark levels of the excited state manifold. Section 4 reports the temperature-dependent absorption coefficient and emission cross-section from 800 to 1200 nm. The saturated slope efficiency *vs*. temperature is presented in Section 5 followed by analysis and concluding remarks in Section 6.

2. Experimental set-up

Fig. 1 depicts the experimental set-up used to measure the emission and absorption cross-sections and slope efficiency of nLight

* Corresponding author.
E-mail address: seamoor@sandia.gov (S.W. Moore).

0030-4018/$ – see front matter
doi:10.1016/j.optcom.2011.08.064

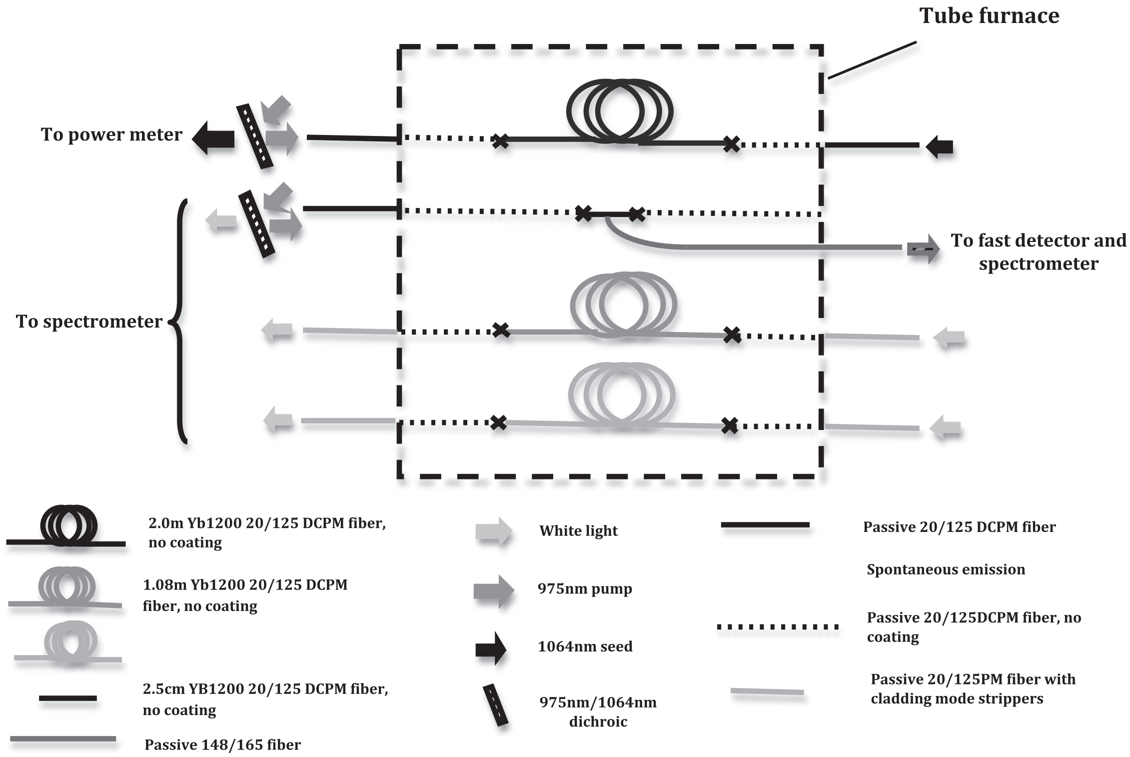

Fig. 1. Experimental set-up for absorption and emission cross-section, fluorescence lifetime, and slope efficiency measurements.

Yb1200 20/125 DCPM [Yb-doped, 20-μm core, 0.07NA (numerical aperture), 125-μm clad, double clad, polarizing maintaining] fiber at high temperatures. Based on the cladding absorption at 920 nm (7 dB/m), the Yb^{+3} ion concentration is estimated to be 2.4×10^{20}ions/m^3. Spectral measurements performed simultaneously on passive 20/125 DCPM fiber subject to the same thermal conditions served as a reference for determining the absorption coefficient of the gain fiber. The jacketing of three gain fibers and one passive fiber were removed and the fibers were placed inside a tube furnace as depicted in Fig. 1. The gain fibers and passive fiber were 2.0 cm, 0.47 m, 2.3 m and 0.94 m in length, respectively. With the exception of the 2.2 cm Yb-doped strand, the fibers were coiled on a high temperature 6.7-cm diameter ceramic spool mounted to a sliding platform and centered in the middle of the furnace to minimize thermal gradients. Two sets of baffles were inserted at both ends of the tube furnace to further minimize thermal gradients and stabilize the temperature in the vicinity of the coiled fiber. Matching passive 20/125 DCPM (20 μm core, 0.07NA, 125-μm clad, double clad, polarizing maintaining) fibers were spliced to both ends of all the fibers to guide light into and out of the tube furnace. APC/FC connectors were mounted to the bare fiber ends to insure reproducibility when swapping the fibers between fiber-coupled instruments. As with the gain fibers, the acrylate/fluoroacrylate coatings were removed along all sections of the passive fiber pigtails resting inside the tube furnace. Finally, one end of a 0.22-NA silica clad passive fiber with a 148-μm diameter core was mounted in a fixture attached to the ceramic platform and butted against the side of the 2.2-cm gain fiber, while the other end was fed out of the tube furnace to collect the fluorescence spectrum and measure the radiative lifetimes.

Each fiber in Fig. 1 was used to measure different physical properties of the Yb-doped silica fiber as a function of temperature. The 2.2-cm Yb-doped silica fiber was pulse-pumped at 10 Hz with 5-ms, 3.5-W, 974-nm pulses from an Apollo F25-974 fiber-coupled diode bar to measure the radiative lifetimes. To measure the emission spectrum, the same gain fiber was pumped with 3.5 W of continuous wave (CW) power from the same fiber-coupled source. For both measurements, a fraction of the power emitted from the side of the fiber was captured by the 148-μm diameter core, passive fiber side-coupled to the gain fiber, and routed to either an InGaAs detector (Thorlabs PDA10CS), to measure the radiative lifetime, or to an optical spectrum analyzer (Ando AQ 6317), to measure the emission spectrum from 600 to 1300 nm. Using a short, 2.2-cm piece of fiber and capturing the emission from the side of the fiber minimized radiation trapping and ASE depletion of the inversion, which can alter the measured fluorescence lifetime. One end of the 0.47-m YB1200 20/125 DCPM fiber was illuminated with an Oriel 77501 white-light source to measure the (core) absorption spectrum, with the transmission of the 0.94-m passive fiber serving as the reference. Both fibers were mode stripped on at least one side to remove light propagating in the cladding. Finally, the 2.3 m YB1200 20/125 DCPM fiber was seeded with 1064-nm light from an IPG fiber laser and end-pumped in a counter-propagating configuration with the aid of a 975 nm/1064 nm dichroic optic to measure the slope efficiency.

3. Radiative lifetimes

The temperature dependence of the radiative lifetimes of YB1200 20/125DCPM is shown in Fig. 2. As observed by Newell et al. [1], the radiative lifetime decays approximately linearly with increasing temperature from room temperature to nearly 500 °C, at which point the decay rapidly accelerates due to thermal quenching of the excited state. The behavior below 500 °C can be best understood by examining the energy levels of Yb^{+3} in a silica host as shown in Fig. 3 [1,9,10]. The single electron energy level diagram of Yb^{+3}: silica is relatively simple, consisting of the $^2F_{5/2}$ (excited state) and $^2F_{7/2}$ (ground state) manifolds. The degeneracy of the manifolds is partially lifted by the silica host, which splits the lower manifold into four sublevels and the upper manifold into three, labeled *i*, *j*, *k*, *l*, and *a*, *b*, *c*, respectively. The radiative lifetime is inversely