Ytterbium-Doped Low-NA P-Al-Silicate Large-Mode-Area Fiber for High Power Applications

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Abstract: We demonstrate an efficient, ytterbium-doped low-NA fiber with core glass containing high levels of Al_2O_3 and P_2O_5 in silica host that shows low-photodarkening and generated 175 W of continuous-wave output power with 80% laser efficiency.

OCIS codes: (060.3510) Lasers, Fiber; (060.2290) Fiber materials.

1. Introduction

The last decade has witnessed a remarkable growth in power scaling of fiber lasers and amplifiers. The CW output power of ytterbium (Yb) doped fiber lasers (YDFLs) have now reached several kilowatts [1]. High power fiber sources that maintain a good output beam quality are often realized using a large-mode-area (LMA) fiber (i.e., large core and low NA) to reduce optical intensity in the core whilst guiding only a small number of modes. This is combined with a high rare-earth (RE) ion concentration to reach sufficient pump absorption even in a cladding-pumped configuration. This reduces the fiber length and increases the threshold for undesirable nonlinear effects in the fiber. In order to allow a higher RE doping level into the silica matrix, the fiber core is usually co-doped with high concentration of Al_2O_3 (Al) or P_2O_5 (P) to prevent clustering of the RE ions. Yb-doped fiber (YDF) with high levels of Al and P also exhibits low photo-darkening (PD) [2]. PD is a detrimental effect which limits the long term performance of YDFL in many applications. Silica doped with Yb-ions and with either Al or P increases the refractive index, and so the core NA, significantly. This is undesirable for some LMA fiber approaches. Although a pedestal geometry can be used to ensure a low effective core NA, this is a significant fabrication challenge.

Lipatov et al. reported passive optical fiber with refractive index (RI) close to pure silica using a ternary glass system of Al_2O_3-P_2O_5-SiO_2 with an equimolar amount of Al and P [3]. The fiber preforms were fabricated by the modified chemical vapor deposition (MCVD) process adding $AlCl_3$ vapor to the reaction gas mixture during deposition, to maintain a precise control of the co-dopants. Recently, low PD in YDF with P/Al molar ratio of 1, fabricated using conventional MCVD and solution doping technique, was reported [2]. However, this report failed to demonstrate a low-NA YDF with step-like core RI profile, particularly for fiber containing equimolar amounts of P and Al. This makes it difficult to reach large mode areas in such fiber structures. In this work, we present an efficient Yb-doped LMA fiber by engineering the P and Al composition in the fiber. We observed a low PD in the fiber when tested under 965 irradiation at a Yb^{3+} excitation level of 35%. As a free running laser, the fiber exhibited a slope efficiency of 80% with respect to launched pump power.

2. Experiments and results

A series of preforms were fabricated by MCVD, by depositing a phosphosilicate soot and in-situ solution doping [4] them in an aqueous solution containing the Yb and Al precursors. Unlike conventional solution-doping, in-situ doping eliminates the need to remove and reassemble the glassware for soaking with RE ions and the Al co-dopant. We varied the Al strength in the solution and paid attention to maintaining all other fabrication parameters identical. Double-clad fibers were drawn to 200 µm inner cladding (D-shaped) with 15 µm core and coated with a low index polymer outer cladding. Fig. 1 shows the RI profile of an Yb-Al-P-silicate fiber that exhibited minimum index contrast between the core and silica cladding. The core NA was 0.07. It is worth mentioning that passive fiber with a similar levels of Al and P co-dopants, exhibited NA of less than 0.03. The small-signal cladding absorption at the pump wavelength of 975 nm was measured to 6.2 dB/m. The core glass composition was determined by an energy dispersive spectroscopy (EDS) as SiO_2 (85.44 mol%) – P_2O_5 (8.23 mol%) – Al_2O_3 (6 mol%) – Yb_2O_3 (0.33 mol%), so with a P/Al molar ratio of 1.37. The ytterbium excited-state lifetime was measured to 0.84 ms, which is closer to that of Yb in aluminosilicate than in phosphosilicate. Another fiber with a slightly higher P/Al molar ratio of ~ 1.97 and core glass composition of SiO_2 (90.04 mol%) – P_2O_5 (6.38 mol%) – Al_2O_3 (3.24 mol%) – Yb_2O_3 (0.34 mol%), showed a Yb lifetime of 1 ms, which lies between Yb-doped phosphosilicate and aluminosilicate. The NA in this fiber was 0.09. Thus, the NA, Yb lifetime, and absorption spectrum (not shown here) are sensitive to the variation of P/Al ratio in the fiber.

The PD in Yb-Al-P-silicate fiber was tested together with an in-house fabricated Yb-doped aluminosilicate fiber (NA ~ 0.15) with similar Yb concentration for comparison. A 400 mW, 965 nm fiber-coupled single-mode

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laser diode was used to core-pump the fibers under test using a WDM coupler. A He-Ne laser at 633 nm, used as a probe beam, was coupled into the fiber through the other arm of the WDM. We used ~ 1 cm of the fibers to suppress amplified spontaneous emission. The pump input power was maintained to provide ~35% of population excitation of Yb^{3+}. The temporal characteristics of the transmitted probe power are presented in Fig. 2. After fitting the measured results with a stretched exponential, we found that the saturated induced loss at 633 nm in Yb-Al-P-silicate fiber was less than 25 dB/m.

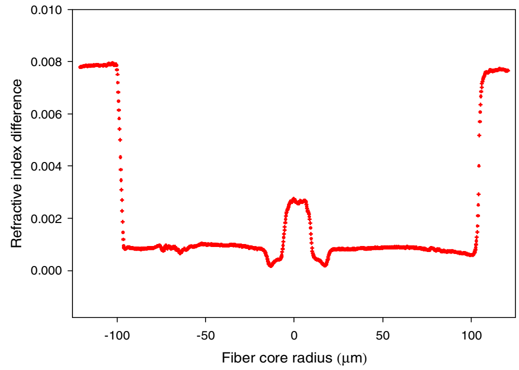

Fig. 1. Refractive index profile of Fiber A.
(outer diameter 200 μm, core diameter 16 μm and NA ~ 0.07)

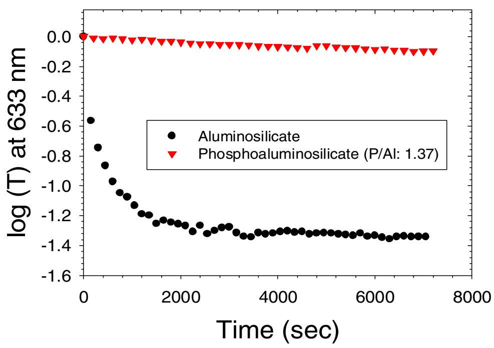

Fig. 2. Output power decrease under 975 nm irradiation (Inversion ~ 35%)

For laser experiment, an end-pumped 3 m long fiber was tested in a 4% - 4% linear laser cavity. The fiber inner cladding diameter was chosen as 400 μm to enable an efficient pump launch from the high-power diodes. The laser output characteristics is shown in Fig. 3, together with the output spectrum. The output reached 175 W with 220 W of absorbed pump power. The slope efficiency was 80% with the laser emission centered at 1070 nm. The beam quality factor (M^2), measured in a 200/15 μm clad/core fiber, was found to be 1.07.

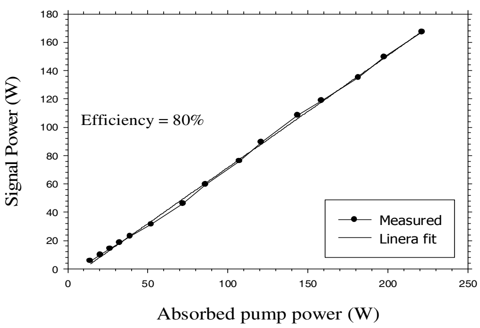

Fig. 3a. Fiber laser output power *vs.* absorbed pump power. Fiber outer diameter 400 μm and core diameter 35 μm.

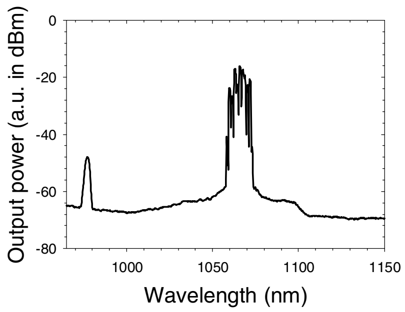

Fig. 3b. Laser spectrum at maximum output power. (OSA resolution 1 nm.)

3. Conclusions

We have successfully manufactured a 0.07 NA, Yb-doped fiber by co-doping the core with P and Al. The NA in the fiber is found to be very sensitive to the ratio of P/Al. The fiber exhibited low PD induced loss compared to the Yb-doped aluminosilicate fiber. Output power of 175 W (limited by the pump power) with 80% laser efficiency was demonstrated. Work is in progress to reduce the fiber core NA further by optimizing the co-dopants and the results of this work will be presented.

4. References

[1] D. Gapontsev, “6 kW CW single-mode ytterbium fiber lasers in All-fiber format,’’ Solid state and diode laser technologies review, Albuquerque, 2008.
[2] S. Jetschke, S. Unger, A. Schwuchow, M. Leich, and J. Kirchhof, “Efficient Yb laser fibers with low photodarkening by optimizing of the core composition,” Opt. Express **16**, 15540-15545 (2008).
[3] D. S. Lipatov, M. V. Yashkov, A. N. Guryanov, M. E. Likhachev, K. V. Zotov, and M. M. Bubnov, ‘Optical properties of highly Al2O3 and P2O5 doped silica hosts for large mode area fiber lasers and applications’’ in Proc. ECOC 2007, Vol. 5, P020.
[4] A. S. Webb, A. J. Boyland, R. J. Standish, S Yoo, J. K. Sahu, D. N. Payne, “MCVD in-situ solution doping process for the fabrication of complex design large core rare-earth doped fibers” submitted to J. Non-Cryst. Solids.