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

J. K. Sahu, S. Yoo, A. J. Boyland, A. Webb, C. Codemard, R. J. Standish, and J. Nilsson
Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, United Kingdom
jks@orc.soton.ac.uk

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.

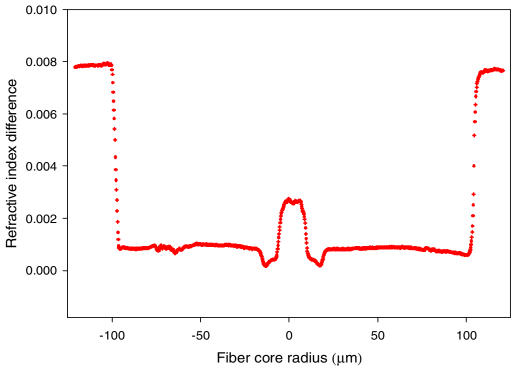

Fig. 1. Refractive index profile of Fiber A.
(outer diameter 200 μm, core diameter 16 μm and NA ~ 0.07)

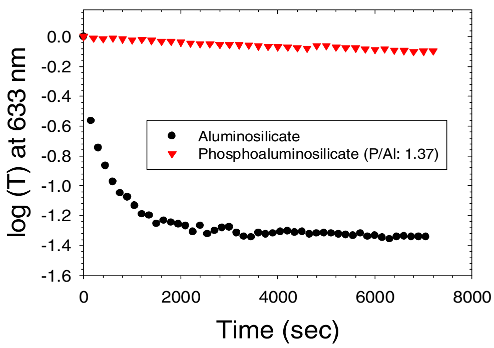

Fig. 2. Output power decrease under 975 nm irradiation (Inversion ~ 35%)

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.

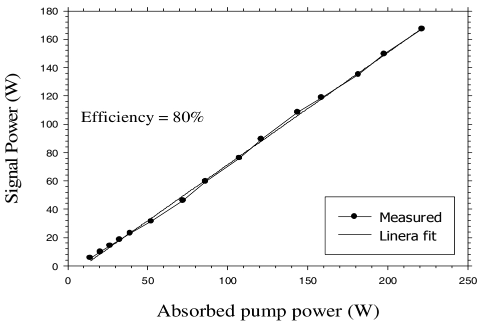

Fig. 3a. Fiber laser output power *vs.* absorbed pump power. Fiber outer diameter 400 μm and core diameter 35 μm.

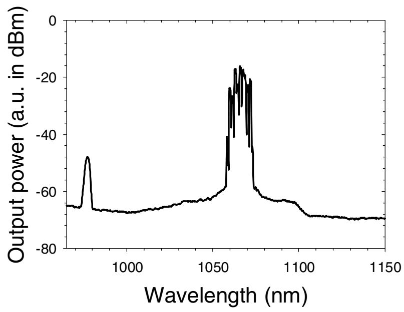

Fig. 3b. Laser spectrum at maximum output power. (OSA resolution 1 nm.)

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

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