Yb-Doped Aluminophosphosilicate Laser Fiber

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***Abstract*—By using modified chemical vapor deposition system combined with chelate precursor doping technique, we report on the fabrication and characterization of Yb-doped aluminophosphosilicate (Al_2O_3-P_2O_5-SiO_2) laser fiber. Based on a master oscillator power amplifier laser setup and pumped directly by 976 nm laser diodes, 3.1 kW laser at ∼1064 nm was achieved with a slope efficiency of 78.4%. Benefiting from codoped Al and P, the laser output power showed no evidence of roll-over. The linear fitting of the output power versus the pump power shows the potentiality for further power scaling. The results indicate that chelate precursor doping technique is a competitive method for rare-earth-ion-doped fiber preform fabrication, and aluminophosphosilicate host material has potentiality to develop multi-kW level laser fibers.**

***Index Terms*—Fiber design and fabrication, fiber laser.**

I. Introduction

YTTERBIUM (Yb)-doped silica fiber lasers attract more and more attention due to high efficiency and good beam quality benefiting mainly from great advances in fiber design and fabrication technologies [1]–[4]. However, fiber laser is subjected to nonlinear effects including stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), self-phase modulation (SPM), cross-phase modulation (XPM), and four wavelength mixing (FWM) generating in an active fiber core under high power operation at kilowatt (kW) level [5], [6]. The threshold for nonlinear effect can be raised by reducing active fiber length and/or increasing effective mode area [5]–[7]. In addition, high power laser fibers should also overcome photodarkening (PD) effect for long term stability of laser operation. Aiming for high power operation at ∼1 μm wavelength, it's essential to obtain high efficient Yb-doped large-mode-area (LMA) fiber [8]. However, to fabricate qualified Yb-doped LMA silica fiber and preform based on traditional modified chemical vapor deposition (MCVD) system is still a big challenge due to lack of appropriate rare-earth (RE) ions doping technique [9].

Currently, solution doping technique (SDT) is still the most-widely used RE-doping method but was found to be with low doping concentration, poor repeatability and homogeneity, and limited core size [9]. Alternatively, as a rapidly-developed RE-doping method, chelate precursor doping technique (CPDT) [8]–[16] is characterized by instant incorporation and reaction for RE precursors like $Yb(thd)_3$/$Al(acac)_3$ and normal MCVD gases such as $SiCl_4$/$GeCl_4$/$POCl_3$, which has shown obvious advantages over SDT as to avoiding RE-clustering to get homogeneous element distribution, increasing doping concentration to reduce fiber length, preventing solvent contamination to decrease background loss, and enlarging fiber preform core size up to 2∼5 mm in diameter [8]–[13].

By using CPDT, Yb-doped aluminosilicate (Al_2O_3-SiO_2, Yb-AS) fibers were recently fabricated and reported with a slope efficiency over 75% [4], [8], [9], and the maximum laser power was over 3.5 kW [14]. However, Yb-AS fibers are easily subjected to heavy PD phenomenon, limiting its applications [17], [18]. To suppress PD in Yb-AS fiber, it's recommended to codope with Ce_2O_3 or P_2O_5 [5], [14], [18]–[21]. For a practically vanishing PD, the concentration of Ce has to be about 70% of that of the Yb concentration [5]. Unfortunately, Ce_2O_3 is refractive index-increasing, thus it becomes difficult to realize low numerical aperture (N.A.) for Ce-doped Yb-AS fiber core, resulting in degradation of laser beam quality. Acting as glass former, P_2O_5 is strongly proposed to be introduced into host materials and form Yb-doped aluminophosphosilicate (Al_2O_3-P_2O_5-SiO_2, Yb-APS) fiber which has been intensely investigated recently for high power fiber laser [5], [18]–[21]. In addition, simultaneous integration of Al_2O_3 and P_2O_5 is capable of improving solubility of RE ions in silica matrix and reducing refractive index, highly desirable for small N.A. of fiber core which is essential for good laser beam quality [21]–[25]. However, P_2O_5 is well-known for low melting temperature m_p of 340 °C and sublimation point m_s of 360 °C making itself very difficult to sustain or survive during MCVD process at high temperature of 1600∼2300 °C. Further, the sublimation process of P_2O_5 will take most of the doped REs and Al away from the fiber preform core. Therefore, to make high quality Yb-APS fiber preform with adequate Yb ions concentration and high content of P_2O_5 is extremely difficult with traditional MCVD system and normal RE-doping methods. Aiming to develop stable high power laser fibers, technological breakthrough is required for the fabrication of Yb-APS fiber.

In this study, Yb-APS fiber preform was fabricated with traditional MCVD system combined with CPDT. Yb-APS fiber with 30 μm-core and 400 μm-cladding (30/400) was drawn. Fiber laser performances were demonstrated on a master oscillator power-amplifier (MOPA) laser system. 3.1 kW laser output power at 1064 nm was achieved with a slope efficiency of 78.4%, indicating the capacity of Yb-APS and CPDT towards multi-kW fiber laser development.

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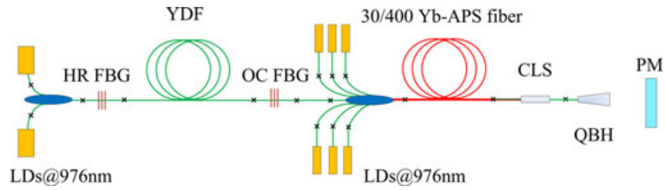


Fig. 1. Schematic diagram of MOPA laser set-up.

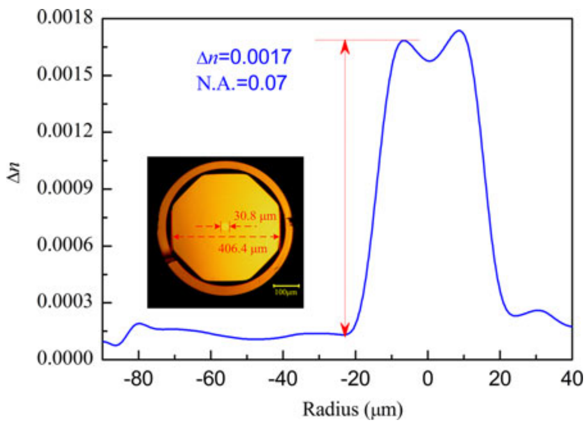


Fig. 2. Cross section and RIP of the 30/400 Yb-APS laser fiber.

II. Experimental Details

A. Preform and Fiber Fabrication

Schematic diagrams of CPDT and MCVD used for preform fabrication were described in detail by our group [8], [11]. The substrate tube used in the present study was an F-300 silica tube with a length of 500 mm to keep uniform longitudinal temperature distribution during RE doping process. In order to obtain a lower collapse temperature without sacrificing collapsing efficiency, substrate tube with a diameter of 24/28 mm was chosen. To get RE-doped core, the carrying gas He flow and temperature of precursor container were maintained at $Yb(thd)_3$-200 sccm/185 °C, $AlCl_3$-50 sccm/135 °C, $POCl_3$-20 sccm/35 °C and $SiCl_4$-100 sccm/35 °C respectively. Finally the tube was collapsed into Yb-APS fiber preform with a 2.5 mm-core in diameter. After jacketed with suitable clad tube, the fiber preform was grinded into octagonal shape to improve coupling efficiency of pump light into fiber core. Ultimately, the shaped preform was drawn into 30/400 Yb-APS fiber. The fiber sample was then cleaved and polished for optical characterization and elemental measurement. Refractive index profile (RIP) of the fiber was measured by the refracted near field method [19]. Attenuation spectrum of the drawn fiber was measured by the cut-back method [8], [9], [11]. Elemental distribution was measured by an electron probe micro-analyzer (EPMA).

B. Laser Experiment

Continuous-wave (CW) laser performances of our home-made 30/400 Yb-APS fiber were conducted on a MOPA system as shown in Fig. 1. In the oscillator stage, the pump source was composed of two 200 W laser diodes (LDs, 976 nm), and the pump light was launched into a segment of 18-m-long

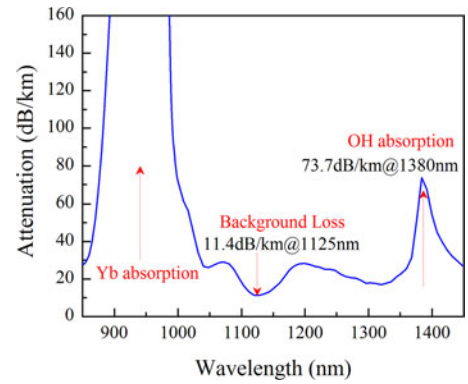


Fig. 3. Attenuation spectrum of the drawn 30/400 Yb-APS laser fiber.

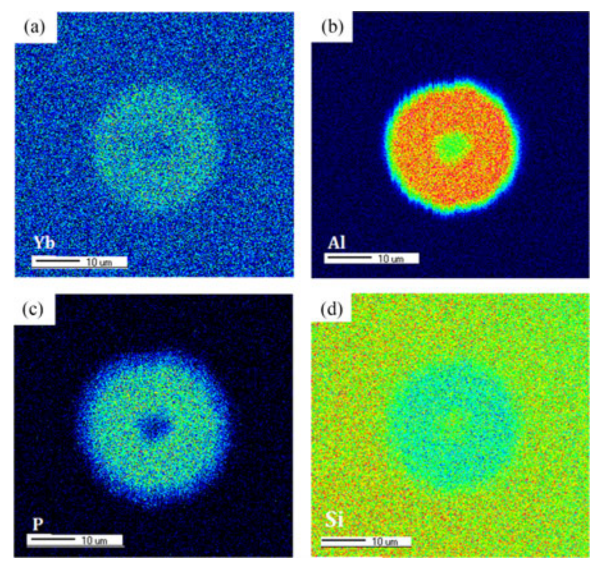


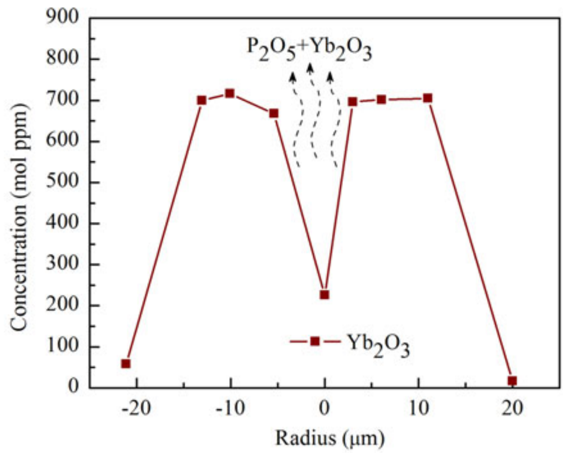
Fig. 4. Elemental distribution in the fiber core: (a) Yb; (b) Al; (c) P; (d) Si.

commercial Yb-doped fiber (YDF-20/400-M) through a 2 × 1 fiber combiner. The seed laser cavity was completed by two fiber Bragg gratings (FBG) with reflection rates of 99% and 10%, respectively. The amplifier stage was constructed by 6-m-long home-made Yb-APS fiber which was deployed with a coiling diameter of 35 cm on an aluminum cooling plate. Pump source for the amplification stage was supplied with 42 LDs (976 nm). Rated power of each LD was 95 W. These LDs were combined through six (7 × 1) type combiners and then further combined through a (6 + 1) × 1 fiber combiner to introduce 650∼665 W pump power from each port and get 3.6 kW pump power input in all. In order to remove residual pump light and high-mode cladding light, a home-made cladding light stripper (CLS) was fixed between the Yb-APS fiber and the quartz block holder (QBH) used as collimator for laser output. Laser power was then measured by a power meter (PM).

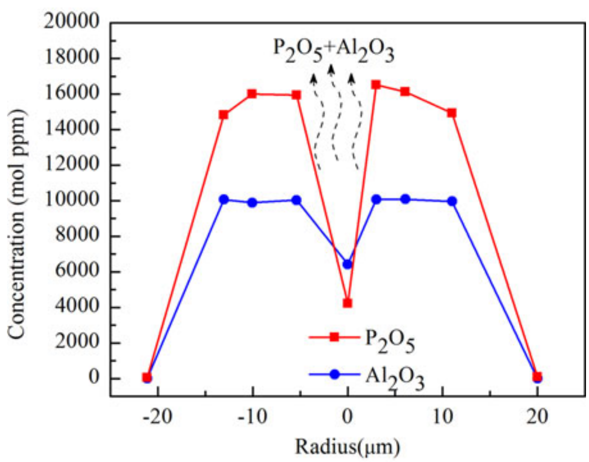
III. Results and Discussion

A. Refractive Index Profile and Attenuation Spectrum

Figure 2 shows the cross section picture and RIP of the Yb-APS fiber. The core diameter of the fiber was 30.8 μm while

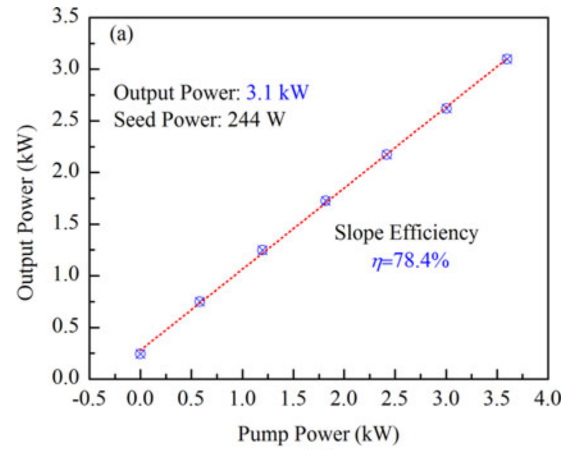


(a)

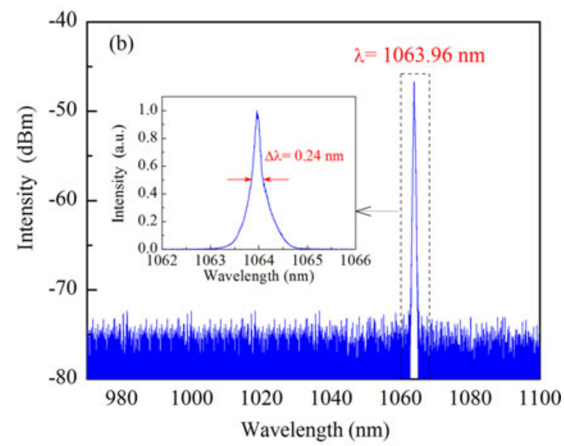


(b)

Fig. 5. Radial concentration profiles: (a) Yb_2O_3; (b) Al_2O_3 and P_2O_5.



(a)



(b)

Fig. 6. (a) Laser output power v.s. coupled pump power; (b) Spectrum of output laser at 3.1 kW (inset graph shows more clearly about the laser spectrum).

the cladding diameter (flat to flat) was 406.4 μm. The octagonal cladding with a N.A. of 0.46 was designed to enhance the pump absorption. As illustrated in Fig. 2, the refractive index difference Δn between fiber core and cladding was $\sim$0.0017 with a corresponding N.A. of 0.07.

The attenuation spectrum is presented in Fig. 3: 11.4 dB/km at 1125 nm to show low background loss and 73.7 dB/km at 1380 nm indicating low OH content.

B. Elemental Distribution

Elemental distribution of our home-made 30/400 Yb-APS fiber is illustrated in Fig. 4. Yb, Al, and P ions present lower dopant concentration in central region compared with outer core region, corresponding to a central RIP dip in the fiber core as shown in Fig. 2. The sublimation of P_2O_5 took away part of the doped Yb_2O_3 and Al_2O_3 during MCVD process. Based on this characteristic, it is possible to fabricate a special fiber with Flatten Modal Fiber design capable of enlarging the effective mode area as demonstrated by A. Ghatak *et al.* [26], and therefore beneficial to suppress nonlinear effects for high power laser operation [5]–[7].

As shown in Fig. 5, the concentration of Yb_2O_3, Al_2O_3 and P_2O_5 was estimated to be 700 ppm, 10000 ppm and 16000 ppm in molar percent, respectively. Molar ratio of Al/Yb and P/Yb in our home-made Yb-APS fiber is over 10 and 15, thereby preventing Yb ions clustering and enhancing quantum efficiency of Yb ions as demonstrated by K. Arai *et al*. [27]. More importantly, co-doping with Al and P is designed to decrease refractive index difference to achieve small N.A. and simultaneously to effectively suppress PD effect as has been demonstrated in our previous work [18].

C. Laser Performance

CW laser performances are shown in Fig. 6. Pumped by a total power of 3.6 kW pump source at 976 nm, the maximum output laser power was 3.1 kW at 1064 nm, limited only by available pump power. The laser output power as a linear function of the input power was presented in Fig. 6(a). Linearly-fitted slope efficiency of the output laser power to pump power was about 78.4%, benefiting from low background loss of the fiber. Fig. 6(b) shows the spectrum of the laser output at 3.1 kW. As can be seen, the central wavelength of output laser is 1063.96 nm with full width at half maximum (FWHM) of 0.24 nm. Neither residual pump light of 976 nm nor SRS nonlinear component can be found in the spectrum. The narrow bandwidth and clean spectrum make the 30/400 Yb-APS fiber

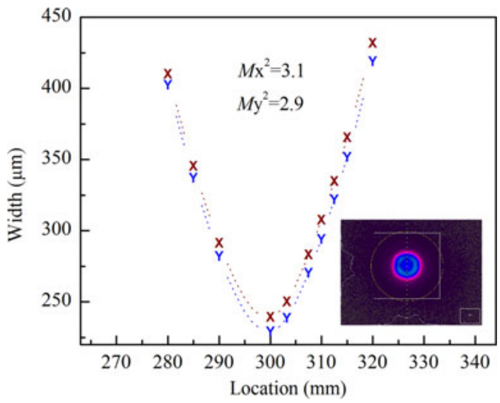


Fig. 7. Beam profile and M^2 data of output laser at 3.1 kW.

suitable for laser combining applications [28]. Besides, in the case of the maximum injected pump power, the Yb-APS fiber temperature was less than 30 °C when the laser system was cooled by 16 °C cooling water. According to the above results, it is believed that the output power can be further increased by integrating more pump power.

Beam profile at 3.1 kW laser output is illustrated in Fig. 7. The M^2 factor was ∼3.0. There was obvious degradation of laser beam compared with that (M^2∼1.2) of seed light from the oscillator, mainly induced by excitation of high-order modes in the 30 μm-core with 0.07-N.A., imperfection of the splicing points and mismatching of mode field diameter between the 30 μm-core active fiber and the 20 μm-core oscillator fiber. The beam quality can be further optimized by improving modal field adaption, splicing quality and reducing the active fiber core diameter and N.A.

IV. Conclusions

We have successfully fabricated Yb-doped aluminophosphosilicate laser fiber by applying chelate precursor doping technique in combination with modified chemical vapor deposition system. Controllable RIP and uniform dopants distribution were realized. Based on a MOPA system, laser output power of 3.1 kW was achieved with slope efficiency of 78.4% at around 1064 nm. There was no evidence of roll-over for laser output power, showing the potentiality for further power scaling. The results indicate that chelate precursor doping technique is a competitive method for rare-earth ion doped fiber preform fabrication, and aluminophosphosilicate host material is potential to develop multi-kW level laser fibers. The future work will be focused on how to achieve excellent beam quality $M^2 < 2$ for multi-kW level aluminophosphosilicate ternary glass fiber.

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