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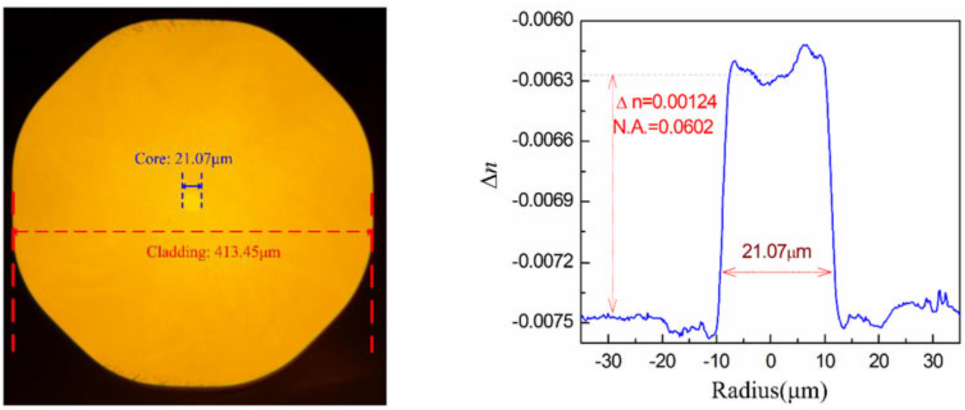

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Fiber Design and Fabrication of Yb/Ce Codoped Aluminosilicate Laser Fiber With High Laser Stability

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Abstract: By a chelate precursor doping technique, we designed and fabricated an ytterbium/cerium codoped aluminosilicate fiber for noticeable suppression of photodarkening and demonstrated its laser performance. Cerium/ytterbium ions ratio of 0.5 was specially designed to mitigate photodarkening. Aluminum/fluorine ions ratio of 1 was devised to keep low numerical aperture of fiber core. The measurements showed the fiber core was homogeneously doped with ~0.12 mol% Yb_2O_3, ~0.05 mol% Ce_2O_3, ~0.5 mol% Al_2O_3, and ~0.2 mol% SiF_4, respectively. Tested in a master oscillator power amplifier system, the fiber presented 1930 W laser output power with optical-to-optical efficiency of 79.2%. Stabilized at 1850 W for over 500 min, the output power presented a relatively small power degradation of <1.04%, directly justifying a strong photodarkening resistance. These results demonstrated that ytterbium/cerium codoped aluminosilicate fiber with appropriate concentration ratios of dopants could be an ideal choice for 2 kW-level commercial high power laser applications.

Index Terms: Fiber design and fabrication, lasers, fiber, fiber optics amplifiers and oscillators.

1. Introduction

Thanks to the substantial improvement of fiber performance, the application scope of high power lasers has been extended to various fields such as industrial processing, medical application and military defense [1]–[4]. One of the main requirements for high power fiber lasers is their superior stability at high powers. In other word, the large interest in this research field is, mainly driven by the industry, looking for reliable fiber lasers with tens of thousands of hours of operation with low maintenance and low operation cost [5]. Therefore, photodarkening (PD) phenomenon has gradually become a notable constraint and an important parameter to consider in long-term operation fiber lasers [2], [6], [7].

Currently, a number of different paths to ions co-doping have been presented and incorporated successfully into active fibers to reduce optical loss in the core and consequential the level of PD in ytterbium (Yb)-doped fiber lasers [8]. The most challenge is to dope high-level rare-earth (RE) ions into fiber core while still minimize background losses and PD effect. Chelate precursor doping technology (CPDT) has proven its controllable dopant flow and deposition speed, good symmetrical distribution and uniformity when doped a great deal of REs into fiber core and versatile refractive index profiles (RIPs) of large core diameter preforms. These merits give it the potential to fabricate multi-kW-level laser fibers [9], [10].

Not only being relatively easy to fabricate, Yb/aluminum (Al)-doped silicate fibers have also high absorption and emission cross sections, good mechanical and thermal properties. However, they showed serious PD phenomenon at kW-level or above. In this regard, two of the most common methods are co-doping P_2O_5 or Ce_2O_3 as glass modifier. Yb/cerium (Ce) co-doped aluminosilicate (Yb/Ce-AS) binary fibers have relatively high laser induced damage threshold and controllable homogeneous refractive index profile (RIP), i.e., free from center ‘dip’ caused by evaporation of phosphorus (P), compared with Yb-doped aluminophosphosilicate (Yb-APS) ternary fibers. Moreover, incorporation of Ce ions can lead to the coexistence of redox couple of Ce^{3+}/Ce^{4+} in Yb-doped fiber, reduce the occurrence of $Yb^{3+} \rightarrow Yb^{2+}$ and therefore decrease the incidence of formation of color center due to valence changes, resulting in a strongly improved PD resistance in Yb/Al co-doped fiber without altering the beneficial optical and physical properties of Al co-doped materials [5]. Nevertheless, excessive Ce co-doping in Yb-AS fiber would bring less advantage to lower core numerical aperture (NA) due to its refractive index contribution, increase fluorescence intensity and lifetime of Yb ions, and reduce the thermal load owing to the interaction with excited Yb ions [11], [12]. Thus, Ce concentration must be maintained at a suitable value to effectively suppress PD while avoiding large thermal load.

Yb/Ce-AS fiber has been currently utilized to obtain multi-kW fiber lasers [13], but hardly proven its performance of PD resistance. Radiated by multi-kW-level pump light, Yb/Ce-AS fiber would generate more frequent Yb^{3+} excitation and therefore more hole- and electron-related color center. In this case, Ce doping seems to be difficult enough to achieve complete inhibition of PD [11]. Photodarkening-resistant of Yb/Ce-AS fiber has been demonstrated at $\sim$1 kW for 100 hours in [14]. However, no one has publicly demonstrated Ce ions to effectively suppress PD of Yb/Ce-AS fiber radiated by multi-kW pump light. Recently, nufern-20/400-9M fiber as a new product was proposed by Nufern Company and fully investigated by our research group [15]. With a MOPA configuration and pumped by 2.23 kW 976 nm laser diodes, the fiber obtained 1.83 kW laser output with a slope efficiency of 81.7%. Up the power level, the laser spectrum with unwanted peaks was found originating from nonlinear (NL) effects such as four-wave mixing (FWM) and stimulated raman scattering (SRS).

By optimizing chelate precursor doping technique, we fabricated a 20/400 μm Yb/Ce-AS fiber with noticeable suppression of PD and avoidance of some NL-related peaks. Directly forward-pumped by 976 nm laser diodes, 12 m-long Yb/Ce-AS fiber presented 1.93 kW laser output at 1079.61 nm with slope efficiency of 79.2%. Long-term running of more than 500 minutes at $\sim$1.85 kW showed power degradation less than 1.04%.

2. Experimental Details

2.1 Fiber Design and Calculation

The refractive index Δn of the fiber core is determined by REs content and concentration of the co-dopants:

$$\Delta \mathrm{n} = \sum_i c_{m,i} \delta n_{m,i} \quad (1)$$

where *i* denotes the particular rare earth dopant or co-dopant material, its concentration (mol%) and its molar refractive index change [16]. For suppressing PD effect, the molar ratio of Ce/Yb ions was set to be $\sim$0.5, regarded as a suitable ratio while avoiding large thermal load in Yb/Ce-AS laser fiber [11]. Additionally, negative index materials SiF_4 was introduced to neutralize the high molar refractivity change for Yb_2O_3, Ce_2O_3, Al_2O_3 doping and set to be approximately equal with the concentration Al ions to keep the low N.A. of fiber core. Considering the element volatilization, the molar concentration of Yb_2O_3, Ce_2O_3, Al_2O_3 and SiF_4 was designed to be 0.16 mol%, 0.08 mol%, 0.7 mol% and 0.35 mol%, respectively. According to Ref. [17], [18], per molar Yb_2O_3, Ce_2O_3, Al_2O_3, and SiF_4 can produce 67×10^{-4}, 67×10^{-4}, 23×10^{-4} and $(-50) \times 10^{-4}$ refractive index increments, respectively. Hence,

$$\Delta n \cdot 10^4 = 67C_{Yb2O3} + 67C_{Ce2O3} + 23C_{Al2O3} - 50C_{SiF4} \quad (2)$$

Consequentially, substituting the design value into the formula (2), refractive index Δn is obtained to be 0.001468, corresponding to N.A. of 0.065 (i.e., N.A. of commercial fiber by Nufern Company).

2.2 Preform Fabrication Using MCVD With CPDT

The schematic diagrams of CPDT and modified chemical vapor deposition (MCVD) used for preform fabrication were described in detail by our research group [9], [10], [19], [20]. The precursor materials include (2,2,6,6-tetramethy1-3,5-heptanedonato)-yetterbium(Yb(tmhd)$_3$, precursor for Yb_2O_3), (2,2,6,6-tetramethy1-3,5-heptanedonato)-cerium(Ce(tmhd)$_3$, precursor for Ce_2O_3), $AlCl_3$, $SiCl_4$ and SiF_4 with high purity more than 5N (99.999%). The substrates were F-300 silica tubes with a short length of 500 mm to keep temperature uniform longitudinally and diameter of 24/28 mm to obtain a lower collapse temperature without sacrificing any collapsing efficiency. To form a reflection-mirror layer, cladding layers with composition of SiO_2 was deposited and directly sintered at 1950 °C. Volatized precursors (e.g., Yb(tmhd)$_3$, and Ce(tmhd)$_3$), O_2 gas and the MCVD gases (e.g., $SiCl_4$, and $AlCl_3$) were transported through three different lines and allowed to mix each other in the deposition zone. During soot deposition and collapsing processes, excess O_2 gas environment was kept to reduce possible precursors for PD. For the RE-doped core deposition, carrying gas He flow and temperature of precursor container were maintained at Yb(tmhd)$_3$-180 sccm/220 °C, Ce(tmhd)$_4$-100 sccm/220 °C, and $AlCl_3$-30 sccm/160 °C, respectively. Then, they were collapsed into Yb/Ce-AS 'mother' fiber preform with a 2∼3 mm core in diameter. After elongating the mother preform to a certain diameter and jacketing it with suitable silica tube to form a resulted preform with designed core/clad ratio, the fiber preform was milled to octagonal shape. Finally, it was drawn by a drawing tower into standard 20/400-Yb/Ce-AS fiber (i.e., core of 20 μm and clad of 400 μm in diameter).

2.3 Laser Performance With MOPA Configuration

For the purpose of investigating the continuous-wave (CW) laser performance of this Yb/Ce-AS fiber, an all-fiber master oscillator power amplifier (MOPA) configuration was constructed. The fiber oscillator comprises of two fiber Bragg gratings (FBGs) and home-made ultra-low NA fiber [21], and aggregate pump light at 976 nm through a fiber coupler. Via a commercial (6+1)×1 fiber combiner, four groups of 600 W 976 nm LDs were injected into the 12m-long Yb/Ce-AS fiber used as a gain medium for test. A home-made cladding power stripper (CPS) was spliced with the active fiber to remove residual pump and high-order modes signal light, ensuring the accuracy of slope efficiency calculation. The output laser was collimated by quartz block holder (QBH) and split by beam splitter for laser beam quality and output spectrum measurement.

3. Results and Discussion

3.1 Fiber Structure and RIP Distribution

Analyzed by refracted near field method, cross section and refractive index profile (RIP) of our home-made Yb/Ce-AS fiber was shown in Fig. 1. The fiber core diameter was 21.07 μm and the fiber cladding diameter (flat to flat) was 413.45 μm. The octagonal cladding with a N.A. of 0.46 was designed to enhance the pump absorption. The fiber core N.A. with respect to pump cladding was calculated to be 0.060, corresponding to the core-cladding refractive index difference of ∼0.00124, which was slightly less than design value, arising from element volatilization at high temperature deposition and inevitable gas flow disturbance and temperature vibration. It can be found there

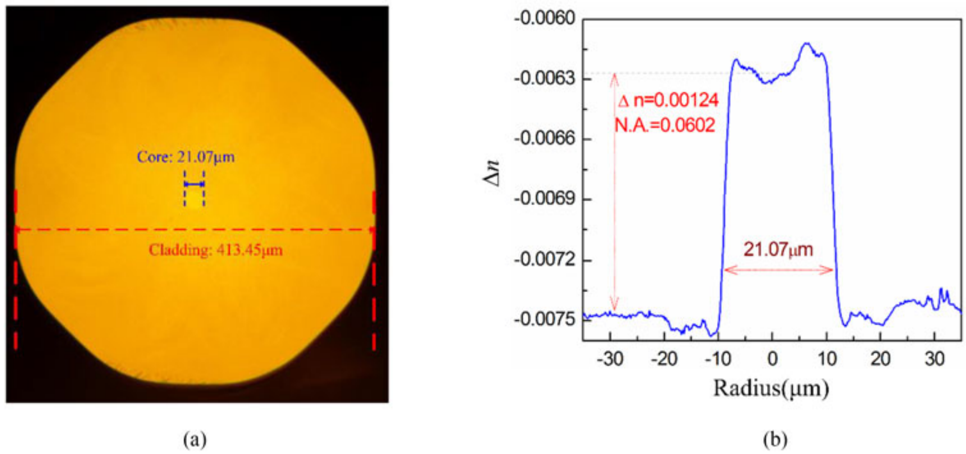

Fig. 1. (a) Cross section and (b) RIP of 20/400-Yb/Ce-AS fiber.

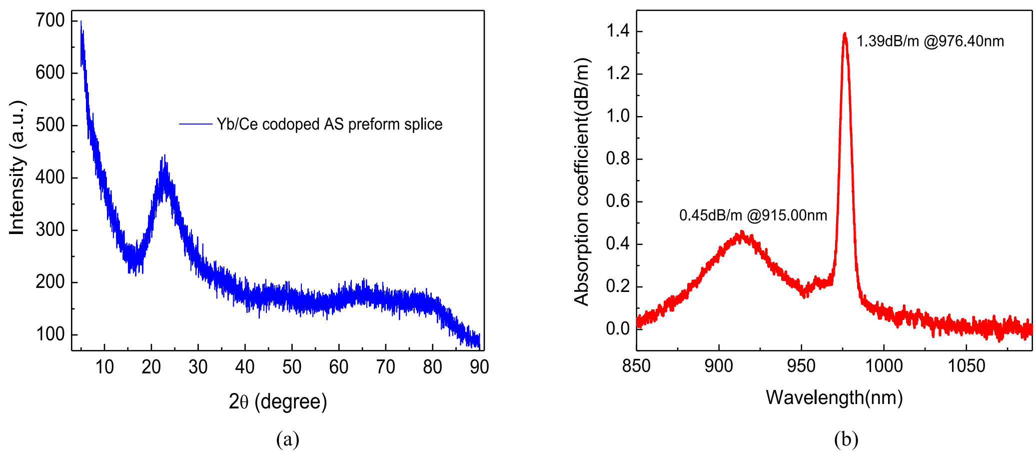

Fig. 2. (a) XRD spectrum of the Yb/Ce-AS preform specimen. (b) NIR-absorption spectrum of 20/400-Yb/Ce-AS fiber.

were no apparent variations or fluctuations in the fiber core, indicating excellent refractive index homogeneity. The well-known ‘central dip’ was not found in the fiber core, which is significantly important for high-power fiber lasers aiming to achieve good beam quality.

Fig. 2(a) depicted the measured x-ray diffraction (XRD) pattern from a polished slice with 2∼3 mm thickness. A diffractometer was employed to analyze the X-ray diffraction (XRD) diagrams of the sample using a CuK_α (1.5406 Å) X-ray source operated at 40 kV and 40 mA. Diffractograms are recorded in the 5°–90° 2θ range, which collected Bragg reflections from the planes parallel to the substrate surface. It is a direct evidence that this preform is fully amorphous without narrow diffraction peaks. With the cut-back method, the absorption spectrum was measured by a broadband source and shown in Fig. 2(b). The near infrared (NIR) absorption coefficients α was tested to be 0.45 dB/m at 915 nm and 1.39 dB/m at 976 nm respectively so as to estimate the optimal length for fiber laser use.

3.2 Rare-Earth Ions Distribution and Homogeneity

To further investigate the elemental distribution, the core compositions were characterized by electron probe micro analysis (EPMA) and presented in Fig. 3. It exhibits a homogenous distribution

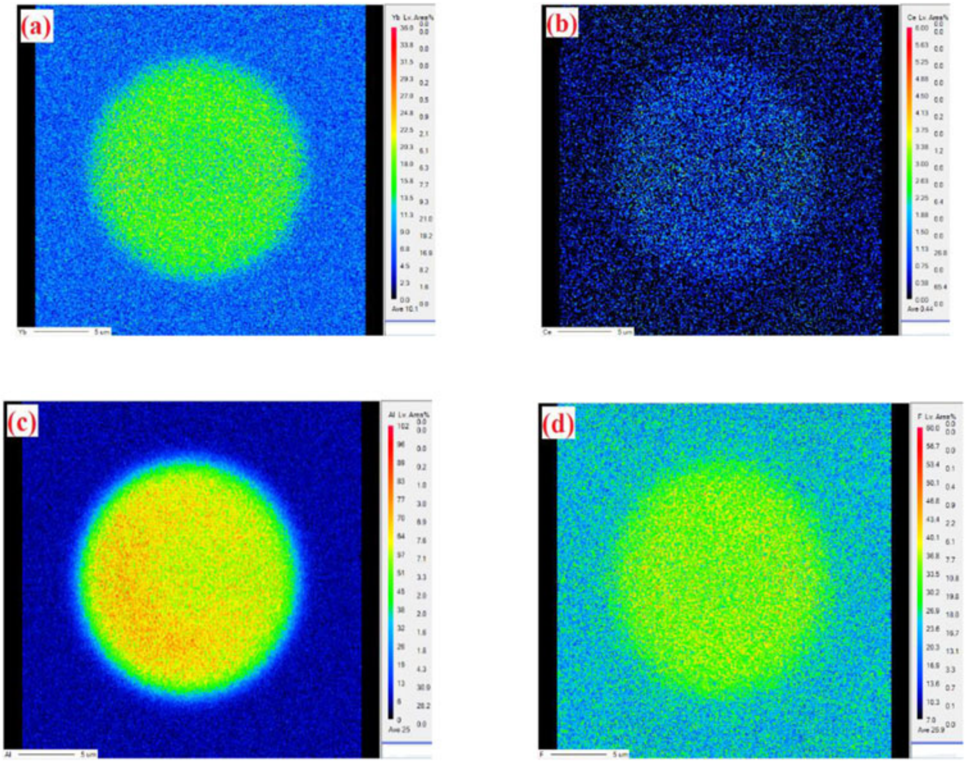

Fig. 3. EPMA area analysis of (a) Yb (b) Ce (c) Al and (d) F elements.

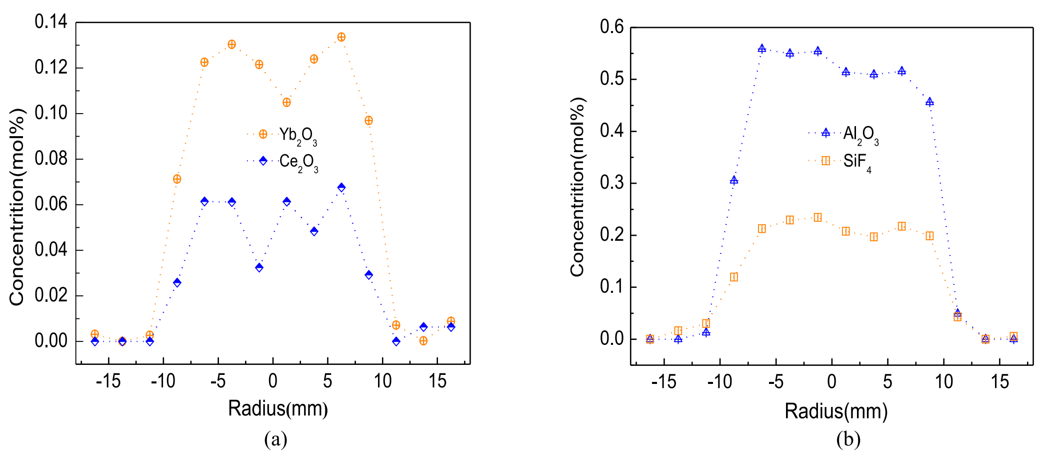

Fig. 4. Elemental analysis by EPMA: (a) radial concentration of Yb_2O_3 and Ce_2O_3. (b) radial concentration of Al_2O_3 and SiF_4.

of Yb, Ce, and F ions in the fiber core region, avoiding the possibility of the clustering effectively. Compared with other elements, Al element presented worse uniformity due to possibly improper gas flow and spinning speed during core deposition process. Dopant concentration of Yb_2O_3, Ce_2O_3, Al_2O_3 and SiF_4 was estimated to be 0.12 mol%, 0.05 mol%, 0.5 mol% and 0.2 mol%, respectively, lower than that of nufern-20/400-9M [15]. The molar ratio of Ce/Yb ions, as shown in Fig. 4(a), was controlled to be ∼0.5 in this work, regarded as a suitable ratio for suppressing PD phenomenon while avoiding large thermal load in Yb/Ce-AS laser fiber [11]. With molar ratio of Al^{3+}/F^{-} close to

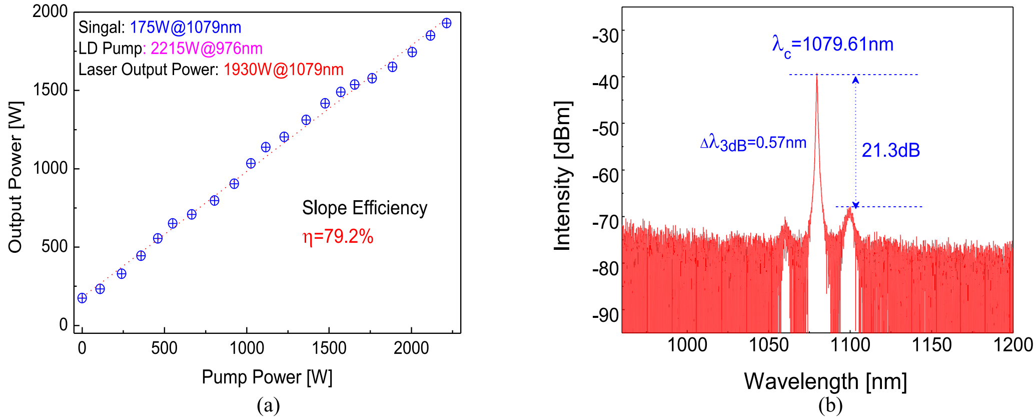

Fig. 5. (a) Laser output power v.s. input pump power. (b) output laser spectrum at 1930 W.

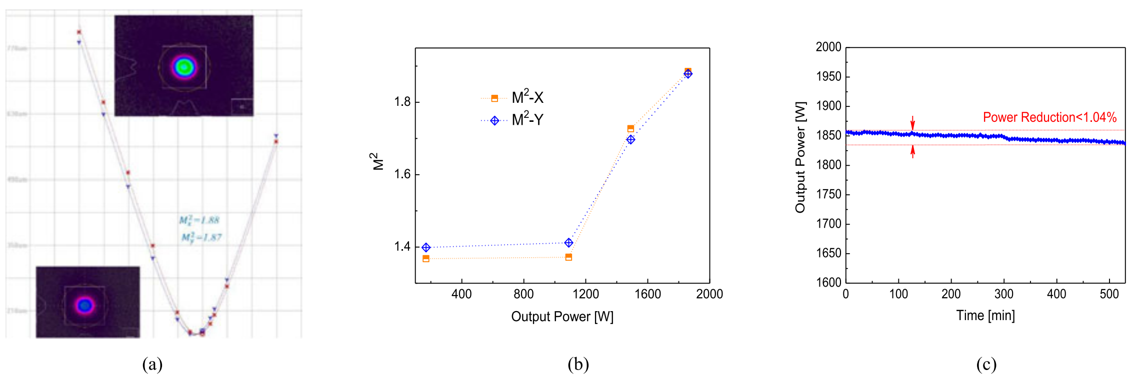

Fig. 6. (a) Laser beam quality at 1.85 kW; (b) Variation in beam quality as power increased and (c) Laser stability testing at 1.85 kW.

1:1, as depicted in Fig. 4(b), N.A. of 0.06 was obtained for matching with other components in the fiber system.

3.3 Laser Performance and Power Stability

Fig. 5(a) presented the output laser power as a function of the pump power. With a MOPA configuration and directly radiated by the total power of 2215 W pump source at 976 nm, a 12 m-long 20/400-Yb/Ce-AS fiber presented a maximum laser output power of 1.93 kW with a slope efficiency of 79.2%. The laser output spectrum was centered at 1079.61 nm with narrow 3 dB bandwidth $\Delta\lambda_{3dB}$ of 0.57 nm. Benefiting from short fiber in use, nonlinearity (e.g., SRS, FWM and self-phase modulation (SPM)) was well suppressed, and the suppression ratio was about ~21.3 dB. Compared with 2 kW-level laser spectrum generated from nufern-9M-20/400 commercial fiber [15], the spectrum studied here includes only two addition NL peaks centered at 1060 nm and 1100 nm, mainly caused by SPM or FWM. The suppression of NL effects can be attributed to less co-dopants content than that of nufern-9M-20/400 fiber. There are no SRS component and residual pump light in spectrum, indicating the output power can be further scaled when increasing pump power accordingly. As shown in Fig. 6(a), the laser beam quality was measured by a beam analyzer and the M^2 factor was measured to be 1.87 at 1.85 kW. The beam quality is much worse than the single-mode seed light whose M^2 factor should be ~1.1 [21]. The worsening of beam quality is mainly induced by the excitation and amplification of the high-order modes (HOMs) in the core. The HOMs were caused by the coiling of the active fiber and the imperfection of the splicing points. In addition to this, mode instability might be possible reason for beam quality degradation. To examine the TMI effect, Fig. 6(b) showed the factor M^2 as a function of output power. It important to note the M^2 factor suddenly increase markedly as the laser power is over 1.1 kW. In this case, TMI phenomena occurred into the fiber core. The threshold of MI for the co-pumping laser setup is estimated to ∼1.1 kW, lower than that (∼1.3 kW) of commercial 20/400 fiber [22]. To directly characterize PD effect of Yb/Ce-AS fiber, this MOPA laser setup was stabilized at 1.85 kW, i.e., radiated by 2.12 kW pump light, and then kept for more than 500 minutes. As depicted in Fig. 6(b), the output power presented a relative small power degradation of <1.04% from 1.85 kW to 1.83 kW. Therefore, the Ce/Yb ratio of ∼0.5 can maintain the PD-reducing capability and obviously avoid thermal issues during 2 kW-level pump radiation of over 500 minutes.

4. Conclusion

In conclusion, we reported on design, fabrication and laser performance of Yb-doped aluminosilicate laser fiber co-doped with Ce. By MCVD in combination with CPDT, 0.12 mol% Yb_2O_3 were uniformly dissolved into the fiber core plus with 0.05 mol% Ce_2O_3, 0.5mol% Al_2O_3 and 0.2 mol% SiF_4. Directly forward-pumped by 976 nm laser diodes, 12m-long 20/400-Yb/Ce-AS fiber presented 1.93 kW laser output at 1079.61 nm with slope efficiency of 79.2% and beam quality M^2 of 1.87. The spectrum with high nonlinearity suppression ratio of 19 dB and 3 dB bandwidth $\Delta\lambda_{3\,dB}$ of 0.57 nm was obtained. Thanks to Ce/Yb ratio of ∼0.5 to greatly improve photodarkening resistance, long-term running of over 500 minutes at ∼1.85 kW presented power degradation less than 1.1%. The results indicate that all-gas-phase chelate precursor doping technique is highly competitive for Yb/Ce-AS fiber fabrication towards high power laser, and Yb/Ce-AS fiber with Ce/Yb ratio of ∼0.5 is a promising gain medium as 2 kW-level industry fiber laser.

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