High-efficiency ytterbium-free erbium-doped all-glass double cladding silicate glass fiber for resonantly-pumped fiber lasers

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A highly efficient ytterbium-free erbium-doped silicate glass fiber has been developed for high-power fiber laser applications at an eye-safe wavelength near 1.55 μm. Our preliminary experiments show that high laser efficiency can be obtained from a relatively short length of the gain fiber when resonantly pumped at 1535 nm in both core- and cladding-pumping configurations. With a core-pumping configuration as high as 75%, optical-to-optical efficiency and 4 W output power were obtained at 1560 nm from a 1 m long gain fiber. When using a cladding-pumping configuration, approximately 13 W output power with 67.7% slope efficiency was demonstrated from a piece of 2 m long fiber. The lengths of silicate-based gain fiber are much shorter than their silica-based counterparts used in other experiments, which is significantly important for high-power narrow-band and/or pulsed laser applications.

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1. Introduction

High-power fiber lasers operating at an eye-safe wavelength near 1.55 μm are very useful for a variety of military and civil applications, such as remote sensing, material processing, and free space optical communications due to their unique features of retina-safe and low attenuation in the atmosphere [1,2]. To date, the highest laser power at 1.55 μm was limited at ~300 W [3], which was obtained from an erbium/ytterbium (Er/Yb) co-doped fiber laser pumped by laser diodes at 9XX nm. Comparing to the well-established multi-kilowatt Yb doped fiber lasers near 1 μm [4], power scaling of an eye-safe fiber laser at 1.55 μm is still quite limited. It is even worse than power scalability of another kind of popular eye-safe fiber lasers at longer wavelengths, i.e., Tm- or Ho-doped fiber lasers near 2 μm. However, the eye-safe wavelength in the 1.55 μm band is still more preferable for some applications in the atmosphere, because the 2 μm band is overlapped with some strong absorption features of water in the atmosphere.

With the current fiber laser design for the 1.55 μm band, i.e., Er/Yb co-doped gain fiber pumped by well-established 9XX nm laser diodes, the power scaling limitation is fundamental. Because of a large quantum defect from 9XX nm pumping wavelength to 1.55 μm laser wavelength, the highest slope efficiency of an Er/Yb-doped fiber laser is below 50% [5], much lower than that of an Yb-doped fiber laser (>80%). As a result, a lot more heat is generated in an Er/Yb-doped fiber laser than in its 1 μm counterpart at a same power level. Heat issues are always one of the most important limits for laser power scaling at very high power level. More importantly, those Yb ions

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co-doped in Er/Yb-doped fibers even don't allow for very high-power laser operation at 1.55 μm, because of Yb-ion emission or even the onset of parasitic lasing at 1 μm in Er/Yb-doped fiber lasers as pump power is high.

A new design has been proposed to eliminate the aforementioned fundamental limitation, which is a Yb-free Er-doped fiber laser pumped resonantly (so it is called resonant pumping, in-band pumping, or tandem pumping). After removing the fundamental limitation, Er-doped fiber lasers should have the potential for similar power scalability as multi-kilowatts Yb-doped fiber systems.

This new design has attracted great interest in recent years [6–9]. Recent experiments have demonstrated ~85% slope efficiency (with respect to absorbed pump power) in a core-pumped Yb-free single mode Er fiber laser [6], and 69% slope efficiency in a cladding-pumped laser [9], respectively. In these preliminary demonstrations, very long pieces of gain fiber have to be used (12 m for core pumping configuration and 15 m for cladding pumping configuration), due to their low doping concentration (thereby low pumping absorption) in those Er-doped silica glass fibers used in the experiments. The use of such a long piece of gain fiber could raise another concern about its power scalability, i.e., optical nonlinear effects in the gain fiber (such as Brillouin or Raman scattering), especially for laser operation with narrow-band or pulsed output. Therefore, it is necessary to develop new glass fibers that enable high doping concentration of Er ions in order to achieve high-power resonantly-pumped Er-doped fiber lasers by using a relatively short piece of gain fiber.

In this paper, we report our development progress on a new type of heavily-doped Er-doped fiber (Yb-free) for high-power scaling applications at 1.55 μm. The details about the glass/fiber design and fabrication are described in the following section. A preliminary experiment was done with the new fiber, exhibiting high efficiencies in a resonantly-pumped fiber amplifier under both core and cladding pumping configurations.

2. Yb-free Er-Doped All-Glass Double Cladding Silicate Fiber

One of the critical challenging issues in realizing high-power resonantly-pumped Yb-free Er-doped fiber laser is to develop heavily Er-doped glass fiber with high pump absorption and high quantum conversion efficiency. In general, a high Er-doped silica glass will easily form the so-called Er ion-clusters and produces detrimentally cooperative up-conversion, resulting in a lower quantum conversion efficiency. Phosphate glasses can release high Er concentrations [10–12], but its propagation loss is very high at ~10 dB/m preventing it from high power scaling [13–15]. Although a short length (tens of centimeters) of phosphate glass fiber is able to provide sufficient high gain for power scaling in a fiber amplifier, due to its high gain per unit length (several dB/cm), heat dissipation becomes a big issue while power scaling at a very high level (>100 W) in such a short gain fiber, not to mention its low glass transition temperature. Fortunately, silicate glass, multi-component glass with SiO_2 as the glass network former, also exhibits excellent solubility for rare-earth oxides. The glass network modifiers, such as sodium ions, potassium ions, barium ions, and calcium ions break the well-defined glass network of silica, which produces a large amount of sites for rare-earth ions. We thus intend to develop silicate glass compositions with high Er concentrations [16].

We use a standard rod-in-tube fiber drawing technique to fabricate all-glass double cladding Yb-free Er-doped silicate glass fibers in house. A silicate glass with 1 wt. % of Er_2O_3 doping concentration was used to form core glass, and other two undoped silicate glasses were used as inner cladding and outer cladding glasses. The core glass rod was first drilled from the Er-doped silicate glass and its barrel was then high-surface-quality polished. Two cladding glass tubes were done similarly. For better performance, it is good to keep the inside diameter of the inner cladding tube, diameter of the core glass, outside diameter of the inner cladding tube, and inside diameter of the outer cladding tube matching correspondingly. Note that all the fabrication process of fiber preform and fiber drawing were carried out at AdValue Photonics Inc. Table 1 lists the parameters of the newly developed fiber. The double-cladding large-mode-area fiber has 1 wt. % erbium doping concentration with 26, 125, and 148 μm diameters for the fiber core, inner glass cladding, and outer glass cladding, respectively. The propagation loss was measured to be 0.7 dB/m at 1.3 μm using a standard cut-back measurement technique.

3. Laser Characteristics of the Er Fiber

For resonantly pumped Er-doped fiber lasers, the pumping wavelength can be in a wide wavelength range from 1.47 to 1.53 μm, which eventually can be provided by multimode long-wavelength InGaAsP/InP diodes (14XX–15XX nm) for direct diode pumping. Currently, however, commercial long-wavelength InGaAsP/InP diodes have relatively low brightness. Therefore, here we use fiber lasers at a wavelength near 1535 nm as the resonant pumping sources to characterize our newly developed Er-doped fiber. Also in the preliminary experiment described here, only forward pumping configuration was used to test the gain fiber in a fiber amplifier by seeding a low-power continuous wave laser.

Table 1. Parameters of Er-doped All-Glass Double Cladding Fiber

Core Diameter	Core NA	Inner Cladding Diameter	Inner Cladding NA	Fiber Diameter
26 μm	0.067	125 μm	0.488	148 μm

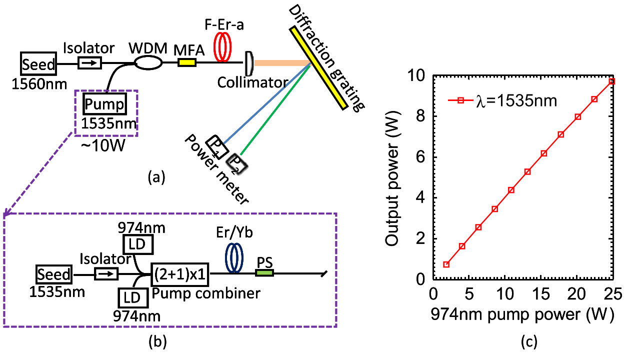

Fig. 1. (a) Experimental setup for a resonantly core-pumped fiber amplifier with 1 m long Yb-free Er-doped silicate glass fiber. (b) 10 W fiber source at 1535 nm was used as a pump source, and (c) its output characteristics. MFA, mode field adapter; PS, pump stripper.

A. Core Pumping

Figure 1(a) shows the schematic diagram for a core-pumping experimental setup. It consists of a single-mode fiber seed laser with 0.5 W output power at 1560 nm, and a single-mode fiber source at 1535 nm that was used as a pump source for resonantly core-pumped Er-doped fiber amplifier. The 1535 nm fiber source was built by using off-the-shelf components, including a piece of commercial Er/Yb-codoped fiber and fiber-coupled 9xx nm pump diodes, as shown in Fig. 1(b). Figure 1(c) shows output power available from the 1535 nm fiber source, which exhibited approximate 40% slope efficiency with respect to launched pump power at 9xx nm.

A homemade wavelength division multiplexer (WDM) for 1535/1560 nm wavelength was used to combine the seed and the pump laser together. The gain fiber was our newly developed Yb-free Er-doped silicate glass fiber, which had a core diameter of 26 μm and 1 wt. % doping concentration. Before launching the two laser beams from single-mode fiber (Corning SMF-28) into the gain fiber, a mode field adapter was used to improve mode distribution of both pump and seed laser beam inside the core of the gain fiber in order to optimize pump absorption and laser efficiency.

We used a bulk diffraction grating to separate the amplified seed laser and residual pump coming out of the resonantly core-pumped fiber amplifier. Two power meters (P1 and P2) were used to record the power of two diffracted laser beams simultaneously. Since diffraction efficiency of the bulk diffraction grating is polarization dependent, we did calibration on it for each of the measurements for both the seed laser beam and the pump beam separately.

Figure 2 shows the results of the resonantly core-pumped fiber amplifier with 1 m long Er-doped silicate glass fiber. The input versus output curve in Fig. 2(a) deviates from a linear slope at low pump power. This deviation can be attributed to self-absorption in the end section of the gain fiber when pump power was low. As pump power increased, the gain fiber was fully excited throughout its length, and the self-absorption was significantly reduced. When the absorbed pump power was more than 2.4 W, the signal output power increases linearly with the absorbed pump power. We obtained 4 W output power at 1560 nm without any sign of power saturation in the pump power range available from the resonantly core-pumped Er-doped fiber amplifier. The slope efficiency, K’, is 74.8% with respect to the absorbed pump power.

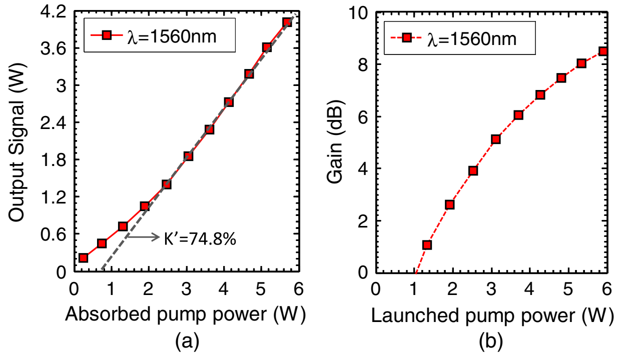

Fig. 2. (a) Laser output power and (b) gain from the resonantly core-pumped Er-doped fiber amplifier. The seed laser power was about 0.5 W.

Optical spectra of the laser output from resonantly core-pumped Er-doped fiber amplifier were measured by coupling the laser beam into a fiber-pigtailed optical spectrum analyzer. Figure 3(a) shows the laser spectrum directly coming from the amplifier. No significant amplified spontaneous emission (ASE) could be observed. Figure 3(b) shows the amplified signal beam after the residual pump was filtered out by the diffraction grating.

B. Cladding Pumping

We also used the same kind of Er-doped silicate glass fiber to investigate its performance in a resonantly cladding-pumped fiber amplifier. The experimental setup was shown in Fig. 4(a). Six identical fiber sources at 1535 nm (as described in the last section) were used as the resonant pump sources. Although these six pump sources had single-mode output beams, they were combined together by using a commercial $(6+1) \times 1$ pump combiner, replacing the homemade 1535/1560 nm WDM used in the core

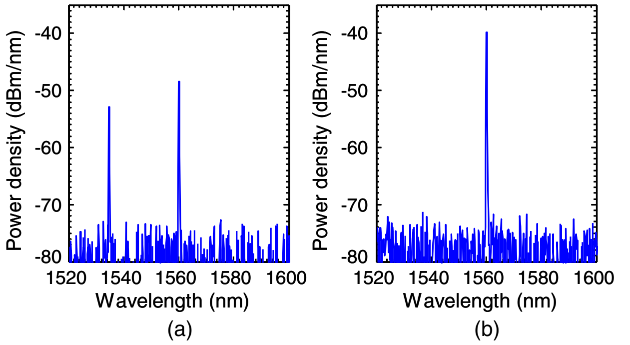

Fig. 3. Optical spectra of the laser output from the resonantly core-pumped Er-doped fiber amplifier (a) without a diffraction grating and (b) with a diffraction grating.

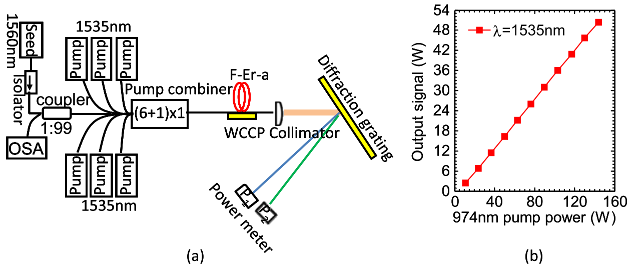

Fig. 4. (a) Experimental setup for a resonantly cladding-pumped fiber amplifier with 2 m long Yb-free Er-doped silicate glass fiber. (b) Total pump power at 1535 nm available for the fiber amplifier. WCCP, water-cooling controlled copper plate; OSA, optical spectrum analyzer.

pumped configuration. The cladding-pumped fiber amplifier was resonantly pumped at 1535 nm with an available maximum pump power at 50.3 W [see Fig. 4(b)] and with a seeding power of about 1 W at 1560 nm. The double-cladding gain fiber had a length of 2 m, which was coiled and glued on a water-cooled copper plate.

Figure 5 shows laser output power from the cladding-pumped fiber amplifier. Obviously, the output power was linear in the whole pump-power range, as compared to the core-pumped result [see Fig. 2(a)], with a slope efficiency of 67.7%. This difference can be explained by the fact that cladding pump-power distribution was more uniform than core pump-power distribution. Some measurement points were deviated away from the linear slope, which could be explained by pump-power variation during the measurements. The maximum output power was about ~13 W.

Figure 6 shows backward and forward optical spectra from the resonantly cladding-pumped fiber amplifier pumped at 50 W at 1535 nm. In addition to the pump beam and the signal beam, ASE can be seen only in backward spectra.

C. Discussion

We have preliminarily demonstrated high laser efficiency of our newly developed, heavily Er-doped silicate glass fibers in the two different pump configurations in a fiber amplifier. It should be noted, however, that the gain fiber lengths used in the experiments were optimized for high efficiency, not for high output power. In fact, nearly 50% pump power was not absorbed by the gain fibers in both pump configurations. Our experiments showed that the laser output power (and the pump absorption as well) could be further increased when increasing the length of gain fibers by a certain percentage, but at the expense of a slight reduction in the laser slope efficiency with respect to the absorbed pump power. The non-negligible propagation loss (~0.7 dB/m) of the gain fiber should be responsible for the efficiency reduction with an increased fiber length. Future improvement in our fiber fabrication process can further reduce the fiber propagation loss. This will allow us to use longer lengths of gain fibers for higher pump absorption and higher overall laser efficiency. Since the doping concentration of our Er-doped silicate glass fiber is 1–2 orders of magnitude higher than its commercial silica counterparts, it is assured that the optimal fiber length of the gain fiber can be the same order of magnitude shorter than those commercial silica doped fibers.

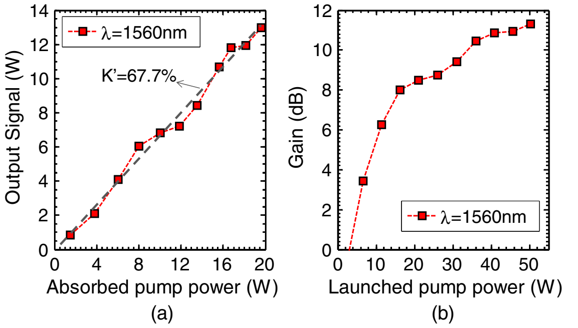

Fig. 5. (a) Laser output power and (b) gain from the resonantly cladding-pumped Er-doped fiber amplifier. The seed laser power was about 1 W.

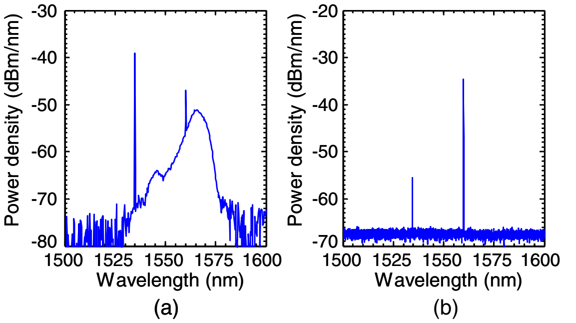

Fig. 6. Typical optical spectra of the laser output from with the resonantly cladding-pumped Er-doped fiber amplifier with (a) backward output and (b) forward output.

4. Summary

In summary, a new Yb-free Er-doped silicate glass fiber was developed and characterized for high-power fiber laser application at 1.55 μm. The new multicomponent silicate glass composition enables us to achieve high-doping concentration of Er ions in the glass without detrimental clustering and quenching effects. The fiber exhibits high efficiency when resonantly pumped at 1.53 μm with a significant reduction of the length of gain fibers as compared to those previously reported experiments by using Yb-free Er-doped silica glass fibers as a gain fiber. More than 74% slope efficiency, with respect to the launched pump power, and 4 W laser-power output at 1560 nm were demonstrated in the core pumping configuration with 1 m long gain fiber. In the cladding pumping configuration with 2 m long gain fiber, the slope efficiency was greater than 67%, and the maximum output power was 13 W in the preliminary demonstration.

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References

1. V. Philippov, C. Codemard, Y. Jeong, C. Alegria, J. K. Sahu, J. Nilsson, and G. N. Pearson, "High-energy in-fiber pulse amplification for coherent lidar applications," Opt. Lett. **29**, 2590–2592 (2004).
2. S. D. Jackson and A. Lauto, "Diode-pumped fiber lasers: a new clinical tool?" Lasers Surg. Med. **30**, 184–190 (2002).
3. Y. Jeong, S. Yoo, C. A. Codemard, J. Nilsson, J. K. Sahu, D. N. Payne, R. Horley, P. W. Turner, L. Hickey, A. Harker, M. Lovelady, and A. Piper, "Erbium: ytterbium codoped large-core fiber laser with 297 W continuous-wave output power," IEEE J. Sel. Top. Quantum Electron. **13**, 573–579 (2007).
4. Y. Jeong, J. K. Sahu, D. N. Payne, and J. Nilsson, "Ytterbium-doped large-core fiber laser with 1.36 kW continuous-wave output power," Opt. Express **12**, 6088–6092 (2004).
5. D. Y. Shen, J. K. Sahu, and W. A. Clarkson, "Highly efficient Er,Yb-doped fiber laser with 188 W free-running and >100 W tunable output power," Opt. Express **13**, 4916–4921 (2005).
6. M. Dubinskii, J. Zhang, and V. Ter-Mikirtychev, "Record-efficient, resonantly-pumped, Er-doped single mode fibre amplifier," Electron. Lett. **45**, 400–401 (2009).
7. S. D. Setzler, M. P. Francis, Y. E. Young, J. R. Konves, and E. P. Chicklis, "Resonantly pumped eyesafe erbium lasers," IEEE J. Sel. Top. Quantum Electron. **11**, 645–657 (2005).
8. E.-L. Lim, S. Alam, and D. J. Richardson, "Optimizing the pumping configuration for the power scaling of in-band pumped erbium doped fiber amplifiers," Opt. Express **20**, 13886–13895 (2012).
9. J. Zhang, V. Fromzel, and M. Dubinskii, "Resonantly cladding-pumped Yb-free Er-doped LMA fiber laser with record high power and efficiency," Opt. Express **19**, 5574–5578 (2011).
10. S. Jiang, S. B. Mendes, G. Nunzi-Conti, A. Chavez-Pirson, Y. Kaneda, T. Luo, Q. Chen, S. Hocde, D. Nguyen, E. Wright, J. Wang, W. Tian, Y. Hu, T. Nikolajsen, and N. Peyghambarian, "Multi-mode pumped amplifier using a newly developed 8 cm long erbium-doped phosphate glass fiber," Opt. Eng. **42**, 2817–2820 (2003).
11. S. Jiang, T. Luo, B.-C. Hwang, F. Smekatala, K. Seneschal, J. Lucas, and N. Peyghambarian, "Er^{3+}-doped phosphate glasses for fiber amplifiers with high gain per unit length," J. Non-cryst. Solids **263–264**, 364–368 (2000).
12. B. Hwang, S. Jiang, T. Luo, J. Watson, G. Sorbello, and N. Peyghambarian, "Cooperative upconversion and energy transfer of new high Er^{3+}- and Yb^{3+}–Er^{3+}-doped phosphate glasses," J. Opt. Soc. Am. B **17**, 833–839 (2000).
13. S. Jiang and C. P. Spiegelberg, "Rare-earth doped phosphate-glass single-mode fiber lasers," U.S. Patent 6,816,514 (9 November, 2004).
14. S. Jiang, T. Luo, and K. Seneschal, "Alkali-metal-free phosphate glass with $dn/dT \approx 0$ for use in fiber amplifiers," U.S. Patent 6,836,356 (28 December, 2004).
15. S. Jiang, Y. Kaneda, C. Speigelberg, and T. Luo, "Single frequency narrow linewidth 1 micron fiber laser," U.S. Patent 6,982,997 (3 January, 2006).
16. S. Jiang and T. Luo, "Thulium and/or holmium doped silicate glasses for two micron lasers," U.S. Patent 8,121,154 (21 February 2012).