

Yb³⁺-doped double-clad phosphate fiber for 976 nm single-frequency laser amplifiers

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Abstract: Highly ytterbium (Yb³⁺)-doped double-clad phosphate fiber was fabricated for the investigation of power scaling of a 976 nm single-frequency laser. Over 3 W single-frequency laser output power was obtained with gain fibers shorter than 10 cm. Our experimental results show that Yb³⁺-doped phosphate fiber is a promising gain medium for 976 nm laser amplifiers.

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1. Introduction

Single-frequency laser sources have attracted considerable attention since they have a wide range of applications, including coherent beam combining, high resolution sensing, optical frequency domain reflectometry, coherent LIDAR systems, optical parametric oscillators, gravitation-wave detection, and nonlinear frequency conversion [1–3]. Compared to other laser platforms, fiber lasers have the advantages of high power scalability, high beam quality, high heat dissipation capability, compactness, low manufacture and maintenance cost. Various single-frequency fiber lasers and amplifiers operating at different wavelengths have been developed for many applications mentioned above. In recent years, high power single-frequency fiber laser sources at 976 nm have garnered great interest because they can be used as low-noise pump sources for core-pumped ytterbium (Yb^{3+})- or erbium (Er^{3+})-doped lasers

and amplifiers [4] and nonlinear frequency converters to generate coherent visible and UV radiation [5–8].

Light emission at 976 nm results from the zero-line transition from the lowest level of the $^2F_{5/2}$ manifold to the lowest level of the ground $^2F_{7/2}$ manifold of Yb^{3+} ions which can be excited by absorbing pump light at 915 nm. Nearly 100-W output power has already been achieved with Yb^{3+} -doped rod-type photonic crystal fiber lasers [9, 10]. However, their output spectra are too broad for use in applications where narrow-linewidth lasers are required. Therefore, it is still of great interest to investigate single-frequency Yb^{3+} -doped fiber lasers and amplifiers to understand the power scaling of narrow-linewidth lasers at 976 nm. Single-frequency laser light at 976 nm can be generated with distributed feedback (DFB) diode lasers [11, 12] and short cavity distributed Bragg reflector (DBR) Yb^{3+} -doped fiber lasers [13, 14]. However, their output powers are on the order of several hundreds of milliwatts. Fiber amplifiers have to be employed to increase the output power so as to reach the requirements for many practical applications. In the last decade, several 9xx nm Yb^{3+} -doped silica fiber amplifiers were demonstrated. In 2004, D. Soh et al. demonstrated ring-doped jacked air-clad Yb^{3+} -doped fiber laser amplifiers at 977 nm and 978 nm with output powers of 4.3 W and 2.7 W, respectively [6, 15]. In 2010, J. Bouillet et al. developed a millijoule-class pulsed fiber laser system operating at 977 nm based on a Q-switched fiber oscillator and an ultra-large core photonic crystal fiber amplifier. An average power of 78 W was obtained in the pulsed regime [16]. However, all of these Yb^{3+} -doped silica fiber amplifiers were not demonstrated with single-frequency seed lasers. Furthermore, these complex fiber structures require special handling, making it hard to develop all-fiber compact laser systems.

So far, all of the watt-level 9xx nm Yb^{3+} -doped fiber amplifiers have been developed based on silica host glass fibers. Due to poor solubility, silica glass exhibits deleterious effects of ion clustering, which can result in concentration quenching [17] and photodarkening [18], consequently impairing the efficiency and long-term performance of silica fiber lasers. Compared to silica, phosphate glass has much higher solubility for rare-earth ions and thus much lower ion clustering. Concentration quenching was not observed in Yb^{3+} -doped phosphate glass with a concentration even as high as 18.9 wt% [19]. On the other hand, photodarkening in a phosphate fiber is also much less than in a silica fiber. It was found that Yb^{3+} -doped phosphate fibers with concentrations 6 times greater than the most photodarkening-resistant silica fibers have comparable resistance to photodarkening [20]. Thus, highly Yb^{3+} -doped phosphate fibers are promising gain media for high power laser at 976 nm.

Yb^{3+} -doped phosphate fibers have been successfully used to achieve single-frequency lasers at 976 nm. The first 976 nm single-frequency DBR fiber laser [13] was developed with a 2-cm 6 wt% Yb^{3+} -doped phosphate fiber. A 350 mW 976 nm core-pumped fiber amplifier was demonstrated with a gain fiber length of only 4 cm [21]. In order to further increase the 976 nm single-frequency laser output, cladding pumping with multimode diodes pumps has to be used because the available power of single-mode diode pump is limited to hundreds of milliwatts. In this paper, we report our experimental investigations into further power scaling of single-frequency lasers at 976 nm by using a Yb^{3+} -doped double-clad phosphate fiber.

2. Yb^{3+} -doped phosphate fiber

Phosphate glass, consisting of PO_4 tetrahedral units with three bridging oxygen atoms and one doubly bonded oxygen, has lower strength than silica glass [22]. Phosphate glass has a relatively low glass transition temperature 400–700 °C and is easy to synthesize with a variety of compositions. The addition of modifying alkali or alkaline earth cations can depolymerize the phosphate network by converting the $\text{P}=\text{O}$ bonds into bridging oxygens. Al_2O_3 can be incorporated into phosphate glass to ensure high mechanical strength and good chemical durability [19, 20, 24, 25]. Moreover, compared to silica glasses, the refractive indices of phosphate glasses can be easily adjusted [26], which is helpful for obtaining a much smaller

numerical aperture (NA) for the fiber core, enabling single mode operation with larger core size.

The phosphate glasses for fiber fabrication were manufactured with conventional glass melting method. Firstly, high purity raw materials were weighed and mixed. Then they were melted in a crucible at temperature of 1150 - 1500°C, depending on the glass compositions. The glass melt was bubbled with oxygen and stirred simultaneously to achieve high homogeneity. After dehydration and clarification, the melt was casted in a preheated metal mold. Finally, the glass was annealed in an oven at glass transition temperature and cooled slowly to room temperature at a rate of 0.5 °C/min. The phosphate fiber used in our experiment was manufactured at NP Photonics, by the rod-in-tube technique. As shown in Fig. 1(a), the Yb³⁺-doped double-clad phosphate fiber has a core diameter of 18-μm and numerical aperture (NA) of 0.04 that supports only the fundamental transverse mode at 976 nm. The inner circular cladding has a diameter of 135 μm and a NA of 0.45. The outer cladding is also made of phosphate glass and its diameter is 150 μm. The core was uniformly doped with $6.69 \times 10^{26} \text{ m}^{-3}$ (6 wt%) of Yb³⁺ ions.

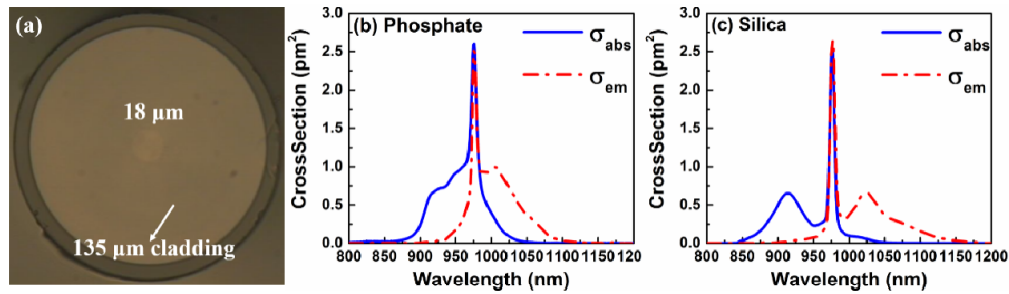


Fig. 1. (a) The end-face of the Yb³⁺-doped double-clad phosphate fiber; absorption and emission cross-sections of Yb³⁺ ions in (b) phosphate and (c) silica glasses [27].

The absorption and emission cross-sections of our Yb³⁺-doped phosphate glass were measured and shown in Fig. 1(b). The silica glass [27] exhibit different features as shown in Fig. 1(c); this is attributed to the differences between the phosphate and silica glass matrices. Both the absorption and emission peaks of the Yb³⁺-doped phosphate glass are located at 976 nm, while the corresponding values for silica glass are at 977 nm. As a consequence, the amplified spontaneous emission (ASE) of Yb³⁺-doped phosphate fiber and silica fiber are also different. Figure 2 shows the ASE spectra of a 24.5-cm long Yb³⁺-doped silica fiber (Nufern PM-YDF-5/130-VIII) and a 5-cm long Yb³⁺-doped phosphate fiber pumped with a single-mode 915 nm diode laser. To ensure that the silica fiber absorbs the same pump power as the phosphate fiber, a long piece silica fiber was cut so that the residual pump power equaled to that of phosphate fiber. Both of the launched pump powers were 150 mW and the residual pump powers were ~5.68 mW. The output spectrum of the silica fiber has a primary peak at 977.46 nm and a secondary maximum at 1027 nm. However, the phosphate fiber shows a primary peak at 975.96 nm and a secondary maximum at 1006.44 nm. All of these features indicate that Yb³⁺-doped phosphate fiber is more suitable than silica fiber for short-wavelength laser emission.

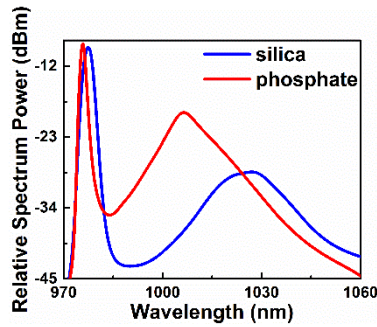


Fig. 2. ASE spectra of Yb^{3+} -doped silica and phosphate fibers (resolution: 0.1 nm).

3. Cladding-pumped single frequency fiber amplifiers

The 18- μm core Yb^{3+} -doped phosphate double-clad fiber was investigated for power scaling of the single-frequency laser at 976 nm using an experimental setup as depicted in Fig. 3. A 200 mW 976.9 nm single frequency DFB diode laser (LU0976M200, linewidth < 10 MHz) was used as the seed laser. A polarization maintaining (PM) fiber isolator and a 976/1030 nm PM wavelength-division multiplexing (WDM) were used to protect the seed laser by blocking the backward amplified spontaneous emission (ASE) and possible parasitic laser emission above 1 μm . The commercial isolator and WDM were fabricated with PM 980 fibers (5.5/125 μm , NA 0.13). The output end of the PM isolator was spliced to the signal port (PM 6/130 μm , NA 0.14) of the PM fiber combiner with a splice loss of 0.02 dB. Two fiber-coupled 915 nm multimode laser diodes were spliced to the pump ports (105/125 μm , NA 0.22) of the fiber combiner. The insertion losses of the PM fiber combiner are 0.7 dB for the 976 nm signal laser and 0.8 dB for the 915 nm pump laser, respectively. The maximum combined pump power was measured from the output port (PM 10/125 μm , NA 0.07) to be 70 W and the maximum signal power after the combiner was ~ 100 mW. The common port of the combiner was spliced to the Yb^{3+} -doped phosphate fiber directly using Vytran GPX3400. The splice loss is less than 0.5 dB. The output end of the gain fiber was angle cleaved ($\sim 8^\circ$) to eliminate the influence of Fresnel reflection.

The output spectrum was measured with an optical spectrum analyzer (Ando, AQ6317). A bandpass filter at 976 nm (± 10 nm) was located before the output end to remove the residual pump and 1030 nm ASE and the output powers were measured with a thermal power meter (Thorlabs, SC310C).

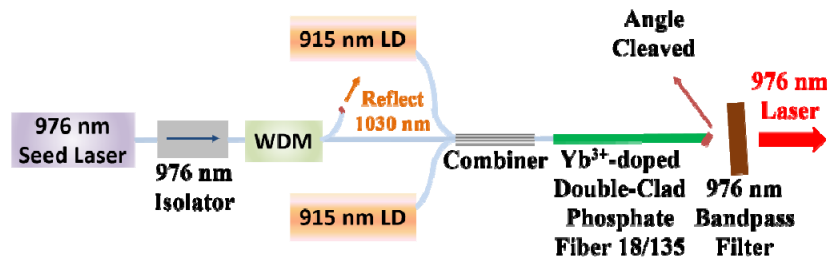


Fig. 3. Schematic of the 976 nm Yb^{3+} -doped double-clad phosphate fiber amplifier.

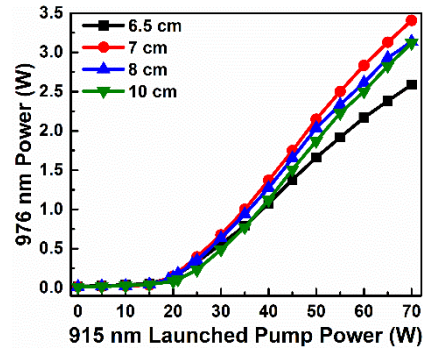


Fig. 4. 976 nm output power as a function of the launched pump power for the 6.5 cm, 7 cm, 8 cm and 10 cm Yb^{3+} -doped double-clad phosphate fiber amplifiers with 100 mW incident signal power.

In our experiment, 6.5 cm, 7 cm, 8 cm and 10 cm Yb^{3+} -doped phosphate fibers were tested. The output powers of these fiber amplifiers with an incident signal power of 100 mW were measured as shown in Fig. 4. The output powers of the 6.5 cm, 7 cm, 8 cm, and 10 cm fiber amplifiers are 2.58 W, 3.41 W, 3.14 W and 3.12 W respectively, at the maximum launched pump power of 70 W. The 7 cm fiber amplifier has the largest output power of 3.41 W with a slope efficiency of 6.8%, which is much lower than the core-pumped Yb^{3+} -doped phosphate fiber amplifier [28]. This is mainly due to the relatively low spatial overlap between the pump and the doped fiber core in the cladding pumping configuration.

The spectra of the 6.5 cm, 7 cm and 10 cm fiber amplifiers at different pump powers were measured and are shown in Fig. 5. It is found that the amplified spontaneous emission (ASE) peaks at around 1007 nm, which is shorter than the 1030 nm ASE peak of silica fiber amplifiers [29]. This is in a good agreement with the fluorescence output spectra shown in Fig. 2. The power of the ASE at long wavelengths increases with the increased gain fiber length while the optical SNR decreases with the increased gain fiber length. At the maximum pump power, the 6.5 cm fiber amplifier has the smallest ASE with a SNR of 34.2 dB. ~21.1 dB SNR was achieved for the 7 cm fiber amplifier, while the SNR becomes 18.9 dB when the fiber length is 10 cm. It should be noted that the SNRs were calculated by dividing the 976 nm laser power by the total ASE power. It is also clear that there is no ASE peak around 980 nm, which has always been observed in the 976 nm silica fiber amplifiers [29]. This is because the gain peak of Yb^{3+} -doped silica fiber is not at 976 nm as shown in Fig. 2. Hence a Yb^{3+} -doped phosphate fiber amplifier has larger SNR than a Yb^{3+} -doped silica fiber amplifier and can provide higher gain for the 976 nm single-frequency laser. This is another advantage of Yb^{3+} -phosphate fiber over Yb^{3+} -silica fiber for the 976 nm single-frequency laser amplifier.

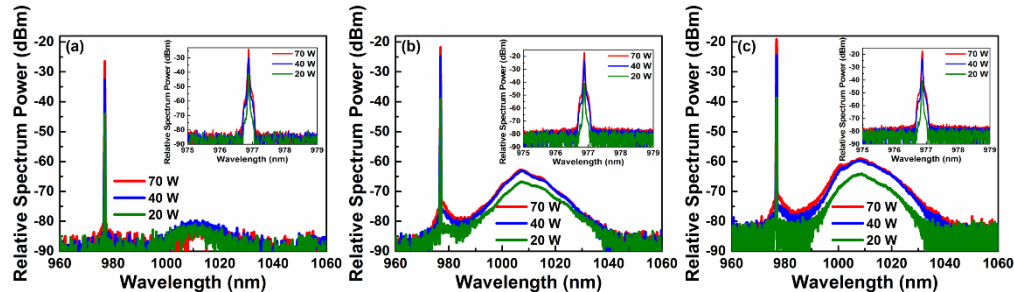


Fig. 5. Output spectra of the Yb^{3+} -doped double-clad phosphate fiber amplifiers at different launched pump powers for (a) 6.5 cm fiber; (b) 7 cm fiber; (c) 10 cm fiber (resolution: 0.1 nm), inset: spectra measured with 0.01 nm resolution.

The efficiency of the 976 nm Yb^{3+} -doped double-clad fiber amplifier is still much lower than that of a Yb^{3+} fiber amplifier operating above 1 μm . Since the 976 nm laser operates near the zero-line wavelength of Yb^{3+} , where the emission and absorption cross sections are equivalent, the quasi-three-level operation requires intense pump power for exciting 50% of the Yb^{3+} -ions to create gain. Moreover, the quasi-four-level operation of Yb^{3+} -doped fiber lasers above 1 μm is much more competitive, since the transparency population inversion is only 5%. Using a fiber with a smaller inner cladding and a larger core can help improve the efficiency. However, the core size cannot be too large for inducing multimode operation and the too small inner cladding will not be matched with that of the standard double-clad fibers. In order to overcome this problem, various techniques have been utilized to suppress the competitive laser at long wavelengths. So far, ring-doped fiber [30], jacked air-clad fiber [31, 32], rod-type photonic crystal fiber [9, 10], tapered fiber [33], depressed-clad hollow fiber [34], and spectral gain discrimination [35] have been demonstrated to achieve high power output around 980 nm. These special waveguide designs successfully realized in silica fibers should be able to be applied to phosphate fibers. Therefore, the efficiency of a 976 nm fiber amplifier will be significantly improved by using a Yb^{3+} -doped double-clad phosphate fiber with special waveguide designs.

On the other hand, the mode mismatch between the combiner output fiber and phosphate fiber increase the losses of the signal and pump powers. The new phosphate fiber with the suitable core and cladding sizes will be drawn in the future work. Furthermore, the reflection from the un-optimized splice between the silica fiber and the phosphate fiber enhance the ASE at long wavelength and limit further power scaling. Thus the future effort to improve the splicing quality between the silica fiber and the phosphate fiber can be helpful for increasing output power and SNR will also be better. Because the 976 nm laser transition strongly depends on the population inversion, optimizing the fiber doping level can further increase the efficiency of a 976 nm cladding pumped fiber amplifier.

4. Conclusion

Significant efforts on the power scaling of 976 nm Yb^{3+} -doped fiber lasers have been made in the last decade and 100-watt level laser output was successfully obtained. However, investigation on the power scaling of the 976 nm single-frequency laser using Yb^{3+} -doped fiber amplifiers has been lagging behind. In addition to other schemes of the power scaling, it is very meaningful to study the amplification of the 976 nm single-frequency laser with different fiber materials.

In this paper, Yb^{3+} -doped double-clad phosphate fiber was fabricated and used to investigate the power scaling of a 976 nm single-frequency fiber laser with cladding pumping. 3.41 W single-frequency output with an optical SNR of 21.1 dB was obtained from a 7 cm fiber amplifier. Our experiments have shown that Yb^{3+} -doped fiber is a promising gain medium for 976 nm single-frequency laser amplifiers. The output power and the efficiency of the 976 nm single-frequency laser fiber amplifier can be significantly improved by using a phosphate fiber with an optimal concentration, a small inner cladding, a large core, and a specific waveguide to suppress the long wavelength ASE.

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