20 W single-mode Yb^{3+}-doped phosphate fiber laser

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We report the demonstration of the first, to our knowledge, cladding-pumped continuous-wave Yb^{3+}-doped phosphate-glass fiber laser. Phosphate hosts are of interest because they can be much more heavily doped than silica, and because of the possibility that they may have a higher photodarkening threshold. In an 84.6 cm double-clad fiber doped with 12 wt. % of Yb_2O_3 and laser-diode pumped at 940 nm, nearly 20 W of single-mode 1.07 μm output power was generated with 60.2 W of absorbed pump power. The measured dependence of the output power on pump power is in excellent agreement with simulations. © 2006 Optical Society of America

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In the past few years, cw rare-earth-doped silica fibers have been exploited extensively to scale the power of fiber lasers sources to the kilowatt level.[1] High-brightness kilowatt-class single-frequency fiber laser sources are required in many applications, including coherent beam combining, advanced remote sensing, and coherent lidar systems. Power scaling of these sources is ultimately limited by two mechanisms. The first one is stimulated Brillouin scattering (SBS). The second one is photodarkening, which can limit the maximum achievable output power and/or induce output power degradation over time. The SBS limitation has been effectively pushed back by increasing the fiber core area and reducing the fiber length. However, single-mode fibers with core diameters greater than $\sim 45\ \mu$m need to be kept straight to avoid bending losses,[2] making them difficult to handle in practice and poorly suited for compact geometries. The second approach, shortening the fiber, requires increasing the rare-earth-ion concentration. Because of the low solubility of rare-earth oxides in silica, this concentration can be increased only so much [to $\sim 2.1\times 10^{20}/cm^3$ for Yb^{3+} (Ref. 3)] before the onset of upconversion processes between ions, which degrade the laser efficiency. Therefore, silica-based fibers can be shortened only to some degree, and other means of dealing with SBS must be found.

Phosphate glass offers a potential solution to these problems, because rare-earth oxides are considerably more soluble in this material than in silica. For example, Yb^{3+} phosphate-glass fibers can be doped with up at least to 2.12×10^{21} Yb^{3+}/cm^3 ($\sim$10 times as much as silica) and still exhibit no upconversion.[4] Since the theoretical SBS gain coefficient of phosphate glass is comparable with that of silica,[5] the maximum achievable output power of a single-frequency phosphate fiber source is expected to be $\sim$10 times higher than in a silica fiber source with a comparable geometry. In addition, photodarkening has recently emerged as a serious limiting factor in the long-term performance of kilowatt silica fiber lasers. The study of phosphate fibers as laser hosts is therefore important because it presents the opportunity to evaluate whether this material has a higher threshold for photodarkening than silica does.

To our knowledge, the first rare-earth-doped phosphate fiber lasers were built by Yamashita in 1989.[6] More recently, a 2.1 W cw double-clad Nd-doped phosphate fiber laser and the first (to our knowledge) pulsed double-clad Yb^{3+}-doped phosphate fiber laser were reported.[7] Compact single-frequency Er–Yb codoped phosphate fiber lasers and amplifiers have also been extensively studied.[8] A 975 nm Yb^{3+}-doped phosphate fiber laser was also recently demonstrated.[9] Thus far, however, the use of Yb^{3+}-doped phosphate fibers for power scaling at 1 μm has not been reported.

In this Letter, we report what we believe to be the first cw cladding-pumped Yb-doped phosphate fiber laser. Doped with 12 wt. % of Yb_2O_3 and pumped with 80 W at 940 nm, this large-mode-area fiber produced an output power of 19.6 W at 1.07 μm, which to our knowledge is also the highest power reported for any phosphate fiber laser.

The fiber preform was fabricated by the rod-in-tube technique. The core and cladding glasses have a high Al_2O_3 content ($\sim$5 mol. %) to ensure high mechanical strength and good chemical durability. Alkali ions (K^+, Na^+, Li^+), which are present in most commercial phosphate glasses, were also eliminated to further enhance the glass properties. A photograph of the cleaved fiber end is shown in Fig. 1. The fiber has a double-clad structure with a 355 μm circular outer cladding, a 240 μm circular inner cladding with a NA of 0.445, and a 10 μm circular core with a NA of 0.07 that is single mode at wavelengths above 914 nm. The outer cladding is made of phosphate glass and has thermal properties superior to the polymers widely used as outer cladding in silica fibers. To enhance pump absorption, the core was offset from the fiber center by 15 μm and an air hole was introduced

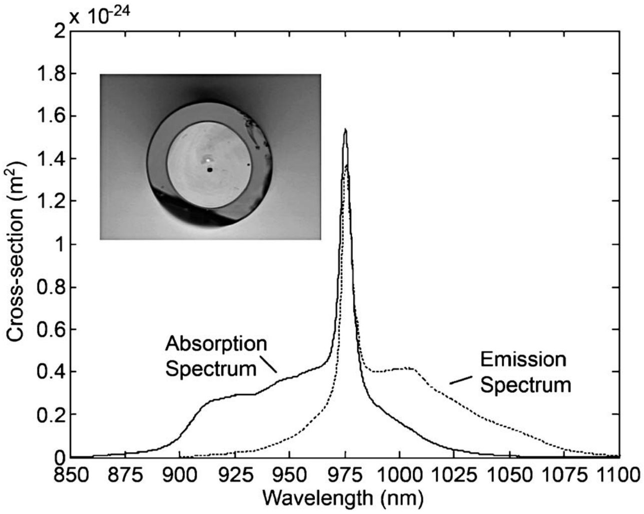

Fig. 1. Measured absorption and emission cross-section spectra of the Yb^{3+}-doped phosphate fiber. Inset, cleaved fiber end.

15 μm from the center, across from the active core. These features break the circular symmetry of the inner cladding, which increases the number of pump modes overlapping with the core, and hence increases pump absorption. Although the fiber is unjacketed, our experience with these fibers shows that their mechanical strength is more than adequate for laboratory use. A fiber jacket or metal sheath should be employed for more rugged environments.

The core was uniformly doped with 1.42×10^{21} Yb^{3+}/cm^3 (12 wt. % Yb_2O_3). The lifetime of the Yb^{3+} ions was measured to be 1.2 ms. The fluorescence relaxation curve showed a single exponential, thus demonstrating negligible concentration quenching. The propagation loss of the fundamental mode at 1310 nm was measured to be 3 dB/m, which is much lower than the loss published for Er/Yb-doped phosphate fibers fabricated by a similar process.[8] We surmise that this loss is due mainly to defects introduced during the perform fabrication, as well as chemical impurities of Yb_2O_3. We are planning to confirm this hypothesis experimentally in the near future.

The performance of this phosphate fiber as a laser was modeled by using an advanced simulation code developed at Stanford University that is essentially identical to the model developed by Wagener *et al.*[10] Because the absorption and emission cross-section spectra of rare-earth ions typically depend critically on glass compositions, we measured the spectra in a Yb^{3+}-doped bulk phosphate sample with the same chemical composition as our fiber core. To avoid fluorescence reabsorption and distortion of the measured fluorescence spectrum, the sample was polished to a 400 μm thickness and pumped at 980 nm near one of its edges, and the emitted fluorescence was collected from the thin side. Figure 1 shows that the absorption and emission peaks are located at 975.2 and 975.8 nm, respectively.

The unsaturated pump absorption coefficient in the cladding, inferred from the absorption spectrum and the ratio of the core to cladding areas (assuming uniform pump excitation of the cladding), is 16.3 dB/m at 975 nm and 3.89 dB/m at 940 nm. The peak emission cross section shown in Fig. 1 (1.37×10^{-20} cm^2) was calculated by applying the McCumber method to the measured absorption spectrum. Although this method tends to overestimate the peak emission cross section in Er-doped silica,[11] it provides a good first-order calibration of the measured fluorescence spectrum. The value we obtained appears reasonable: it yields a ratio of absorption and emission peak emission cross sections of 1.11, which is close to the value reported for a Yb^{3+} -doped silica fiber.[12]

The experimental setup is shown in Fig. 2. It consisted of an 84.6 cm length of the Yb^{3+}-doped phosphate fiber placed in an optical cavity that was formed at one end by a high reflector (HR, reflectivity greater than 99% at 1064 nm) butt-coupled to one of the cleaved fiber ends and at the other end by the Fresnel reflection from the other cleaved fiber end, which acted as a 95% output coupler (OC). The fiber was cladding pumped with a fiber-coupled laser diode at 940 nm through a dichroic beam splitter placed on the OC side. The broadband reflection spectrum of the HR allowed 20% of the unabsorbed pump to be reflected back into the fiber.

Figure 3 shows the laser output power measured versus launched pump power. The threshold was ~2.3 W. The maximum output power was 19.6 W (limited by the available pump power) for 80 W of launched pump power, corresponding to 60.2 W of absorbed pump power (including pump power dissipated by fiber loss). The measured laser slope efficiency against launched pump power and absorbed pump power are 25.8% and 34.4%, respectively. Because the fiber was single moded, the output beam was of course in the fundamental mode. Most of the fiber length was resting on the optical table, with no active cooling. The fiber ends were clamped in Al mounts 1 in. (2.54 cm) in length, which served to passively drain heat from the end regions of the fiber. We observed power degradation when operating this laser at its maximum output power for more than 30 s. We did not observe this behavior when we were operating the laser in quasi-cw mode at 1% duty cycle. This demonstrates that some thermal management is required at an absorbed pump power of about 60 W in ~85 cm, or, taking into account the quantum defect of this laser (~940/1070≈87.9%), up to an average thermal loading of ~8.7 W/m or above. Significantly higher output powers will be achievable by reducing the fiber loss.

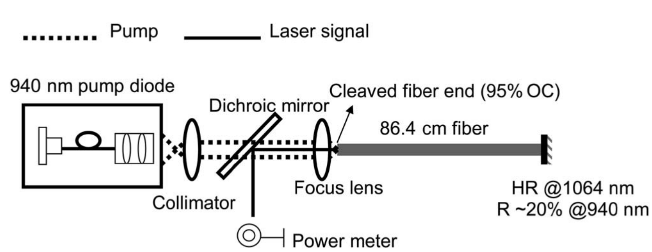

Fig. 2. Experimental Yb-doped double-clad phosphate fiber laser.

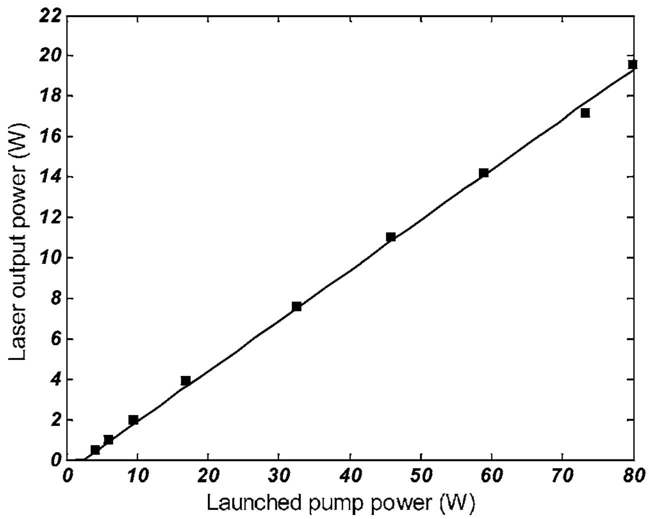

Fig. 3. Measured 1.07 μm laser power generated by the 86.4 cm phosphate fiber laser as a function of the launched pump power at 940 nm. Solid line, theoretical prediction; squares, experimental data points.

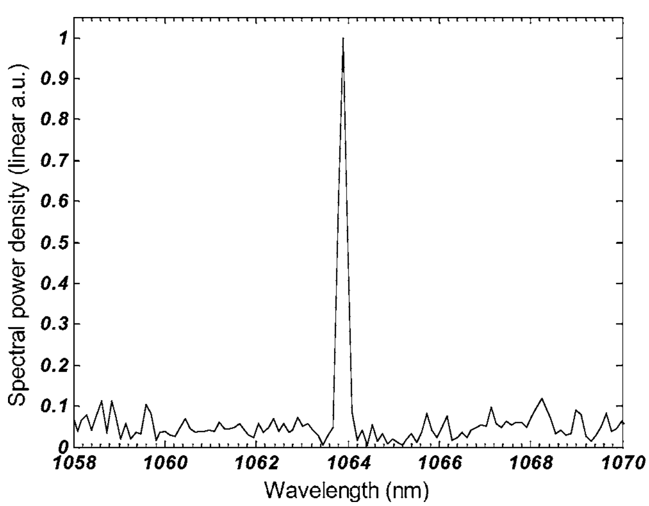

Fig. 4. Measured fiber laser spectrum at an output power of 10.4 W.

The theoretical curve plotted in Fig. 3 agrees very well with the measured output power curve. The simulation curve was calculated by using the measured values of the fiber parameters, in particular the fiber loss at the pump and signal wavelengths and the cross-section spectra, and by making the single assumption that the pump power was uniformly distributed across the highly multimoded inner cladding. The slopes agree to within ~1% and the thresholds to ~10%. A perfect agreement could be obtained for the threshold (with negligible change to the slope) by either increasing the peak emission cross section by 10% or by tightening the pump intensity distribution by 10%, which is within the uncertainty in our knowledge of these two quantities.[11]

The slope efficiency of our laser is primarily limited by the fairly high loss of the fiber. When the laser was operated at 19.6 W, about half of the 60.2 W absorbed by the fiber were lost to propagation loss. Our simulations predict that reducing the passive fiber propagation loss to 0.3 dB/m through improved fabrication will approximately double the slope efficiency. Even with the current 3 dB/m propagation loss, a slope efficiency against launched pump power as high as 55% should be attainable by pumping at 975 nm (instead of 940 nm), utilizing a shorter fiber (since absorption at 975 nm is stronger), and using an HR mirror that is highly reflecting at the pump wavelength. Pumping at 975 nm will also reduce thermal loading and allow higher output power without active cooling.

The output spectrum of the fiber laser at an output power of 10.4 W is shown in Fig. 4. This spectrum was measured with an optical spectrum analyzer with a 0.1 nm resolution and an integration time of 116 ms. The measured FWHM linewidth is 0.25 nm. However, the laser's center wavelength was observed to drift between 1064 and 1073 nm. A silica fiber Bragg grating, which can be spliced to the gain fiber with a low insertion loss, can stabilize the center wavelength and narrow the linewidth.

In conclusion, a 19.6 W single-mode 1.07 μm laser constructed with an 86.4 cm, cladding-pumped, Yb^{3+}-doped phosphate fiber has been demonstrated. To the best of our knowledge, this is both the first report of a cladding-pumped cw Yb^{3+}-doped fiber laser and the highest output power reported for a phosphate fiber laser. Simulation results are in excellent agreement with the experimentally measured laser output power curve.

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