Short cladding-pumped Er/Yb phosphate fiber laser with 1.5 W output power

L. Li,[a)] M. Morrell, T. Qiu, V. L. Temyanko, and A. Schülzgen
Optical Sciences Center, University of Arizona, Tucson, Arizona 85721

A. Mafi, D. Kouznetsov, and J. V. Moloney
Arizona Center for Mathematical Sciences, University of Arizona, Tucson, Arizona 85721

T. Luo and S. Jiang
NP Photonics Inc., UA Science & Technology Park, Tucson, Arizona 85747

N. Peyghambarian
Optical Sciences Center, University of Arizona, Tucson, Arizona 85721

(Received 29 January 2004; accepted 28 July 2004)

We report experimental results on a high-power, cladding-pumped, heavily Er/Yb co-doped phosphate fiber laser of very short length. Up to 1.5 W cw laser power was obtained from an 11-cm-long multimode-core active fiber with optimized input and output couplers, when pumped by a 15 W diode laser at 975 nm. The fiber laser was demonstrated at 1535 nm with a linewidth <1.2 nm, and a good beam quality of $M^2<3$. © *2004 American Institute of Physics*.
[DOI: 10.1063/1.1798394]

In recent years cladding-pumped rare-earth doped fiber lasers have had great success in producing high power and high brightness laser beams when pumped by multimode low brightness semiconductor laser diodes.[1] While Yb or Nd doped fiber lasers are able to deliver 1 kW cw power at 1.0–1.1 μm,[2,3] fiber lasers operating at eye-safe wavelengths ~1.5 μm are also making rapid progress, with a recent report of 103 W multimode cw power in literature[4] and 150 W single-mode cw power available in commercial catalogue.[5] One popular choice for the cladding-pumped 1.5 μm fiber laser is the Er/Yb co-doped fiber laser (EYDFL). In EYDFL, excited Er ions provide the emission at 1.5 μm, while Yb ions are added to both increase the pump absorption and improve the solubility of Er in the host glass. This configuration is especially useful for pumping with commercially available high power 975 nm semiconductor laser diodes since Yb has almost one order of magnitude larger absorption than Er at this wavelength and the absorbed pump energy can be efficiently transferred to Er. As for the host glass served in EYDFL, phosphate glass has been well known as an excellent candidate.[6,7] It not only has higher solubility for rare-earth ions without quenching, but also has a larger phonon energy resulting in a more efficient energy transfer from Yb to Er compared to other host glasses.[8] Heavily Er/Yb co-doped phosphate glass fibers have been successfully developed as high gain short-length amplifiers in our lab,[9] and the EYDFL reported in this letter was fabricated by the same rod-in-tube technique.

Regardless of the operating wavelength, cladding-pumped fiber lasers share the common property of being quite long in size. Active fibers as long as several tens of meters are usual and 1 to 2 m of active fibers are considered as compact size. The long length is required because of the rather low pump absorption coefficient in the cladding-pumping scheme. Theoretically, the absorption rate is determined by two main factors: the doping level of the absorbing ions and the ratio of the doped core area to the pump-confining undoped cladding area, which is typically much smaller than 0.01. Even for EYDFL with greatly enhanced pump absorption due to Yb, active fiber lengths in excess of 1 m were used to reach watt-level cw outputs.[10] In a recent report on an EYDFL only several centimeters long, the single-mode output power was limited to about 200 mW and it was core-pumped by a single-mode source.[11] The power scaling limitation of fiber lasers is ultimately set by nonlinear effects such as stimulated Raman and Brillouin scatterings, whose threshold power levels are inversely proportional to the fiber lengths in the first-order approximation.[12] Thus fiber lasers as short as several centimeters have the advantage of maximally suppressing these nonlinear scatterings. Other advantages include possible single frequency operation, less material cost, and extremely compact size. To produce a cladding-pumped watt-level cw output fiber laser while reducing the active fiber length to a few centimeters, high doping concentration, large core area, and optimized cavity reflectivity are essential.

In this letter, we present experimental results on a short cladding-pumped 1.5 μm EYDFL capable of delivering watt-level cw optical power. Enabling components consisted of optimized phosphate glass with high Er and Yb doping concentrations, a large active core, and appropriate choices of input coupler (IC) and output coupler (OC). We demonstrated 1.5 W output power from an active fiber only 11 cm long.

The glass former used for both the core and cladding glasses was P_2O_5. The core was heavily Er/Yb co-doped, and the core/cladding numerical aperture (N.A.) was adjusted to 0.17 at 1.5 μm by adding proper modifiers and stabilizers to both glasses. Preforms were provided by NP Photonics Inc. and the fibers were drawn at the Optical Sciences Center. The focus is on an active glass with 2 wt % Yb_2O_3 and 1 wt % Er_2O_3, which has the same Yb concentration but only one-third of the Er concentration compared with the previously reported short amplifiers.[9] Generally, our

[a)]Electronic mail: lli@optics.arizona.edu

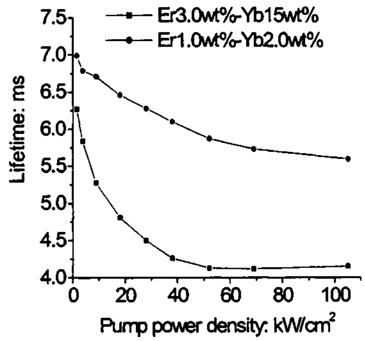

FIG. 1. Effect of cooperative upconversion on the lifetime of the Er upper lasing level in Er/Yb co-doped phosphate glass pumped at 975 nm. This process reduces the lifetime at high excitation levels and has an increasing effect at higher Er doping concentrations.

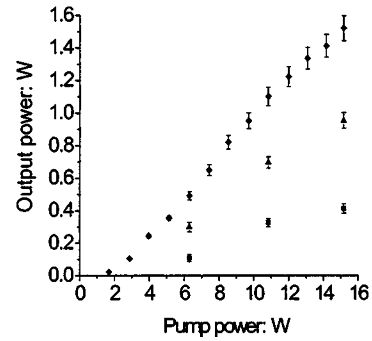

FIG. 2. Effect of the optimized IC and OC on the output for the 11-cm-long EYDFL. The squares represent the output from the laser cavity formed only by two cleaved fiber end faces without IC/OC; the triangles are with IC added only; the diamonds are with both IC and OC added.

phosphate glass allows for even higher Er doping levels. However, at very high doping levels the probability for cooperative upconversion of excited Er ions increases drastically. In order to characterize this detrimental effect, the decay of the intensity of the luminescence (Er energy levels, $^4I_{13/2}$ to $^4I_{15/2}$) was measured and fitted to an exponential to obtain the effective lifetime. The dependence of this lifetime on the pump power density is shown in Fig. 1. We see that the upconversion reduces the lifetime of the upper lasing level at high pump powers, which leads to a decrease of the laser efficiency. Figure 1 also shows that this effect is much more pronounced in the more heavily doped glass, and this is the reason why a higher Er doping level was not pursued for the laser as it was for the amplifier.

Choosing a fixed doping level of 1 wt % Er_2O_3 and increasing the Yb_2O_3 doping beyond 2 wt % might further improve the pump absorption and laser efficiency without significantly affecting the upper lasing level lifetime. However, more heat is generated in this case and at high pump levels the naturally-cooled free-running configuration is not sufficient to handle the excessive thermal load. As result of this effect, we have observed the breakdown of quite a few fiber lasers with the same Er but higher Yb concentrations. It thus requires specific heat removal arrangement to overcome the problem. This research area is being actively pursued in our lab and will be reported elsewhere.

The active fiber in the fabricated EYDFL had a 19 ± 1 μm diameter doped core, which was multimode at 1.5 μm, and a 125 ± 5 μm diameter circular-shaped undoped cladding. The core was placed offset the center of the cladding to increase the pump absorption. The active fiber had only a primary cladding and the air-cladding interface provided confinement to the pump light, which was directly launched into the cladding. The scattering loss coefficient of the multimode pump light was measured to be 0.015 cm^{-1}. Although the phosphate glass itself was not as loss-free as silicate glass, defects introduced during the fiber drawing process and the lack of an outer cladding contributed significantly to the loss. A lower index outer cladding to reduce the pump scattering loss will be applied in our future EYDFL.

In the laser experiment setup, an 11-cm-long active fiber was inserted into a heavy-wall borosilicate capillary tubing with an inner diameter slightly larger than the size of the cladding. This tubing not only mechanically protected the fiber but also helped transfer the generated heat by direct contact. The two perpendicularly cleaved end faces of the active fiber were directly butted against two dielectric mirrors serving as IC and OC. The pump power was delivered through the core of a multimode fiber (AFS105/125Y, core diameter 105 μm, N.A. 0.22) directly butted against the other side of the IC. The output was collimated by an antireflection coated lens ($f=25.4$ mm) and filtered by a silicon wafer to block any residual pump. The signal was then sent to either a power meter or an optical spectrum analyzer. As the pump source, a semiconductor multi-emitter laser diode module (QPhotonics, L.L.C., model PUMA-980-20) was used that delivered up to 15 W cw power into the pump fiber. The central wavelength was stabilized around 975 nm by controlling the case temperature, and the linewidth was about 7 nm.

Our EYDFL was able to lase solely with the two cleaved fiber facets forming the cavity, and the output is shown in Fig. 2. However, in order to maximize the laser performance both the IC and OC had been optimized. All couplers were fabricated at the Optical Sciences Center by depositing alternating layers of SiO_2 and Ta_2O_5. To minimize the pump coupling loss, the IC was deposited on a thin glass substrate (thickness 150 μm). For optimized lasing, an IC with high reflectivity (99.9%) at 1.5 μm was fabricated which exhibited high transmission (94.7%) at 975 nm. Figure 2 shows that the sole addition of this IC doubled the output.

Clearly, any optimized OC should have 100% reflectivity at the pump wavelength in order to send any residual pump back into the fiber, which is close to the reflectance of the OC we used. The optimal signal wavelength reflectivity, however, depends on multiple factors such as pump power, fiber length, and scattering loss.[13] Applying the model from Ref. 14 we calculated the dependence of output power on this reflectivity and measured it with a series of couplers. The measured data and the theoretical curve are shown in Fig. 3. All measurements were performed with the optimized IC in place and at a launched pump power of 15 W. It was demonstrated that the output power was not very sensitive in the low reflectivity region with a relatively flat maximum around 10% reflectivity. Considering that the only assumption of the fiber laser parameters in the simulation was a signal scattering loss coefficient of 0.015 cm^{-1}, which was set equal to the measured pump scattering loss coefficient, the prediction and the measurement were in good agreement.

With the application of the optimized OC ($R_{1535\ nm}=11.1\%$, $R_{975\ nm}=99.6\%$), the output power of the EYDFL increased by another 50%, as shown earlier in Fig. 2. Thus,

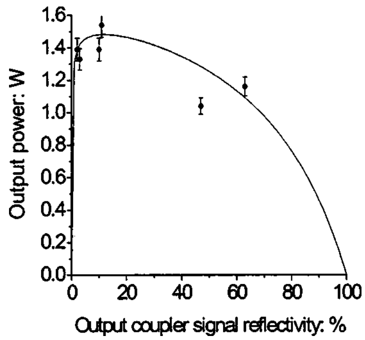

FIG. 3. Signal reflectivity optimization of the OC for the 11-cm-long EYDFL. Solid curve is the calculated output and the dots are the measured values. All the OCs had ~99% reflectivity at the pump wavelength (simulation assumed 100%).

for this fiber laser the cavity optimization resulted in tripling the output compared with that from the cleaved-facet-only cavity. The linear dependence of output power upon the launched pump power was well maintained up to the highest pump and the overall optical-to-optical conversion efficiency was 10%. Considering the pump coupling loss (estimated to be >20%) and pump scattering loss (~30% for a round trip in the cavity), the output slope efficiency was ~20% against the absorbed pump power. The pump coupling loss was estimated from the cutback measurement result, an 85% pump coupling efficiency obtained without IC (the pump fiber butt-coupled without index matching fluid, which cannot be applied when pumped over watt-level), and the loss included two air-glass Fresnel reflections together with the mode sizes mismatching. With an IC (94.7% transmission at the pump wavelength) inserted, the pump coupling efficiency was ~80% at the best. We think the actual coupling loss was even higher considering the finite thickness of the IC. In order to reduce this thickness and eliminate one air–glass reflection, we are currently working on directly depositing the dielectric coatings onto the fiber facets.

The EYDFL output was not single frequency and the spectrum was centered at 1535 nm with a linewidth <1.2 nm, when measured at 1.5 W output power. However, applying a proper fiber Bragg grating as the OC can dramatically narrow the linewidth and it is now under investigation in our lab. The spatial beam quality was measured using a real-time beam profiler BeamMAP (DataRay Inc.). The M^2 value was measured to be 2.75 at the highest output power, indicating good beam quality with few transverse modes. The M^2 value was stable in the whole output range from 20 mW to 1.5 W, even though no specific heat removal arrangement was applied. Single transverse mode operation at high output power remains a future challenge.

In summary, this letter demonstrated a cladding-pumped EYDFL of very short length that delivered watt-level cw output power at 1.5 μm. We optimized the IC and OC that tripled the output, and demonstrated 1.5 W optical power with a slope efficiency of 10% against the launched pump power. Future efforts include direct coating of the fiber facets to enhance the pump coupling efficiency, application of fiber Bragg grating to narrow the output spectrum, and specific heat removal arrangement to enable operation with even higher doping level to further reduce the active fiber length.

The authors would like to thank Elena Temyanko for making all the dielectric mirrors for the experiment. This work is supported by the Air Force Office of Scientific Research through MRI Program No. F49620-02-1-0380.

[1]L. Zenteno, J. Lightwave Technol. **11**, 1435 (1993).
[2]Y. Jeong, J. K. Sahu, D. N. Payne, and J. Nilsson, Electron. Lett. **40**, 470 (2004).
[3]K. Ueda, H. Sekiguchi, and H. Kan, Conference of Lasers and Electro-Optics, 2002 (CLEO '02), Technical Digest Vol. 2, CPDC4-1 2002.
[4]J. K. Sahu, Y. Jeong, D. J. Richardson, and J. Nilsson, Opt. Commun. **227**, 159 (2003).
[5]Product catalogue of IPG Photonics (2003). [online:www.ipgphotonics.com].
[6]E. Snitzer, R. F. Woodcock, and J. Segre, IEEE J. Quantum Electron. **4**, 360 (1968).
[7]M. J. Myers, J. D. Myers, R. Wu, and D. Rhonehouse, Optical Fiber Communication Conference and Exhibit, 2001 (OFC 2001), Vol. 3, WDD22-1.
[8]S. Jiang, M. J. Myers, and N. Peyghambarian, J. Non-Cryst. Solids **239**, 143 (1998).
[9]Y. Hu, S. Jiang, T. Luo, K. Seneschal, M. Morrel, F. Smektala, S. Honkanen, J. Lucas, and N. Peyghambarian, IEEE Photonics Technol. Lett. **13**, 657 (2001).
[10]P. K. Cheo and G. G. King, IEEE Photonics Technol. Lett. **13**, 188 (2001).
[11]C. Spiegelberg, J. Geng, Y. Hu, Y. Kaneda, S. Jiang, and N. Peyghambarian, J. Lightwave Technol. **22**, 57 (2004).
[12]G. P. Agrawal, in *Fiber-Optic Communication Systems*, 2nd ed. (Wiley, New York, 1997), p. 61.
[13]I. Kelson and A. Hardy, J. Lightwave Technol. **17**, 891 (1999).
[14]M. Karasek, IEEE J. Quantum Electron. **33**, 1699 (1997).