Generation of 9.3-W Multimode and 4-W Single-Mode Output From 7-cm Short Fiber Lasers

T. Qiu, L. Li, A. Schülzgen, V. L. Temyanko, T. Luo, S. Jiang, A. Mafi, J. V. Moloney, and N. Peyghambarian

***Abstract*—We generate 9.3-W continuous-wave 1535-nm multimode output from a 7.0-cm short-length Er–Yb codoped phosphate fiber laser. A slope efficiency of 29% is obtained at pump powers below 27 W. Very high output power per unit fiber length of 1.33 W/cm is achieved. From another 7.1-cm Er–Yb codoped fiber laser, 4.0-W single-transverse-mode output with $M^2 \approx 1.1$ is generated.**

***Index Terms*—Continuous-wave lasers, erbium (Er), optical fiber lasers, optical glass, ytterbium (Yb).**

I. Introduction

GENERATION of high-power narrow linewidth coherent radiation around 1550 nm from a compact fiber laser source is of great interest because of its applications in telecommunications, interferometers, sensing, and medical instruments. Compared to long-length fiber lasers, short-length fiber lasers have advantages of extremely compact sizes for device integration, reduced nonlinear optical effects for high-power continuous wave or pulsed output, and potentially single-longitudinal-mode operation due to increased longitudinal mode separation. Successful single-frequency operations were reported by several groups with fiber lengths of a few centimeters and powers in the milliwatt range [1], [2]. Increasing the output power of the short-length fiber laser to watt-level is desirable for many applications. However, this constitutes a considerable challenge for a fiber laser with a length of only several centimeters. One of the biggest challenges is to achieve efficient absorption of the multimode pump light generated from high-power diode bars within such a short piece of fiber using the cladding pumping scheme. High doping levels of active ions are needed to increase the absorption of the pump, but this could cause detrimental effects such as Er^{3+} ion clustering in the gain medium. Careful optimization of the ion doping level and host material is required to minimize these detrimental effects.

In this work, we demonstrate the generation of high powers from two 7-cm short-length Er–Yb-doped phosphate fiber lasers. In Section II, the 9.3-W multimode fiber laser with $M^2 < 3.5$ is described. The power generated per unit fiber length of this laser reaches 1.33 W/cm, which to our knowledge is the highest among all single-core fiber lasers [3]. Section III presents the single-mode fiber laser which generates up to 4.0 W of power with $M^2 \approx 1.1$. The output power per unit fiber length of this laser is 0.56 W/cm, representing a record among single-mode Er- and Er–Yb-doped fiber lasers.

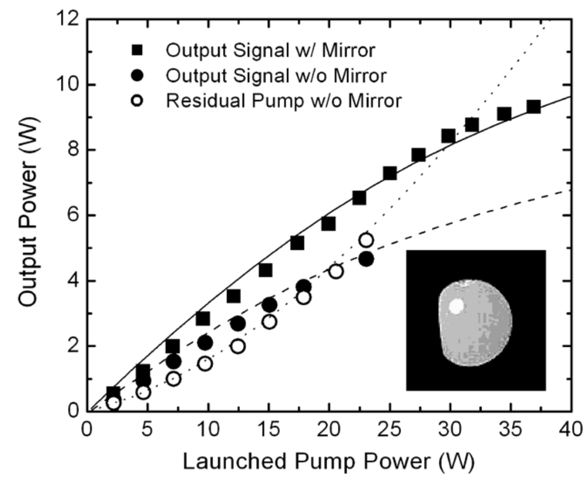

Fig. 1. Measured (symbols) and calculated (lines) output signal powers and residual pump powers of the 7.0-cm multimode fiber laser. Filled squares and solid line are for the 1535-nm signal from the laser using an $R_2(\lambda_s) \approx 30\%$ output mirror. Filled circles and dashed line are for the 1535-nm signal from the laser without an output mirror. Empty circles and dotted line are for the residual 976-nm pump light that exits the laser in the absence of an output mirror. Inset is a picture of the D-shaped fiber end facet of this laser.

II. Multimode 9.3-W Fiber Laser

Heavily Er- and Er–Yb-codoped phosphate glass fibers have been successfully used in high-gain short-length amplifiers previously reported from our group [4], [5]. The phosphate glass has high solubility of rare-earth ions and low clustering effects, which allows us to increase the ion doping level without significantly enhancing the detrimental fluorescence quenching process. The glasses and preforms of our fiber lasers were provided by NP Photonics Inc., and the fibers were drawn in house. The fiber has a D-shape clad and an off-center core (see inset of Fig. 1). This fiber geometry helps to achieve the so-called "chaotic propagation" of the pump [6] which improves the pump absorption. The diameters of the clad (circular part) and core are 130 ± 2 μm and 20 ± 1 μm, respectively. The numerical aperture of the core is about 0.17, thus supporting several transverse modes at the lasing wavelength of 1535 nm. The core is uniformly doped with 1.1×10^{26} ions/m^3 of Er^{3+} and 8.6×10^{26} ions/m^3 of Yb^{3+} ions. We used high erbium

Manuscript received May 7, 2004; revised July 19, 2004. This work was supported by Air Force Office of Scientific Research through MRI Program F49620-02-1-0380.

T. Qiu, L. Li, A. Schülzgen, V. L. Temyanko, and N. Peyghambarian are with Optical Sciences Center, The University of Arizona, Tucson, AZ 85721 USA (e-mail: tqiu@optics.arizona.edu).
T. Luo and S. Jiang are with NP Photonics Inc., UA Science and Technology Park, Tucson, AZ 85747 USA.
A. Mafi and J. V. Moloney are with Arizona Center for Mathematical Science, The University of Arizona, Tucson, AZ 85721 USA.

Digital Object Identifier 10.1109/LPT.2004.836352

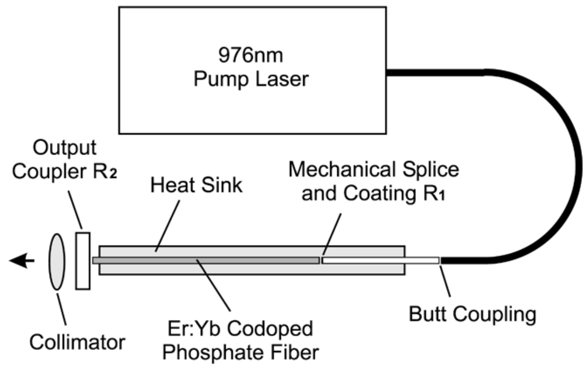

Fig. 2. Experimental setup of the short-length Er–Yb codoped phosphate fiber lasers.

and ytterbium doping levels in an attempt to optimize pump absorption and energy transfer from ytterbium to erbium ions.

The 976-nm diode pump light is delivered through a multimode fiber with 100-μm core diameter and a numerical aperature (NA) of 0.22. The pump delivery fiber is butt-coupled to a piece of undoped 105-μm core multimode silica fiber which in turn is mechanically spliced to the doped phosphate laser fiber (see Fig. 2). The phosphate fiber was put into a low index glass tube having an inner hole diameter of 135 μm and cooled by external circulating water. The NA of the phosphate fiber clad region is, therefore, larger than 0.3, securing the pump confinement in the D-shaped clad. The mechanically spliced end of the undoped silica fiber is coated with a dielectric mirror with reflectivity of $R_1(\lambda_s) > 98\%$ at signal the wavelength ($\lambda_s = 1535$ nm) and $R_1(\lambda_p) < 5\%$ at the pump wavelength ($\lambda_p = 976$ nm). This fiber coating, also prepared in house, provides high signal reflection and allows injection of pump light into the laser cavity. The total pump coupling loss through the butt-coupling, the dielectric coating, and the mechanical splice is about 10%–15%. The output end of the doped phosphate fiber is directly butted against a dielectric mirror. This output mirror has a high reflectivity $R_2(\lambda_p) > 96\%$ at the pump wavelength and a signal reflectivity of about $R_2(\lambda_s) = 30\%$.

The filled square symbols in Fig. 1 show the dependence of laser output power on the launched pump power. The threshold of the laser is about 100 mW of launched pump power. Weak power rollover was observed in Fig. 1 as pump power increases. A maximum signal power of 9.3 W was obtained at 37-W launched pump power which is the maximum available power from the pump laser. A slope efficiency of 29% was achieved at pump powers smaller than 27 W. Taking into account the coupling loss of the pump, the slope efficiency with respect to the coupled pumped power is estimated to be 34%. This slope efficiency is significantly higher than that previously obtained from a fiber laser doped with the same Er^{3+} concentration but lower Yb^{3+} concentrations (25% of the current Yb^{3+} doping level) [7]. As expected, with increasing Yb^{3+} concentration, both pump absorption and energy transfer from Yb^{3+} to Er^{3+} become more efficient [8]. The laser's free running output spectrum showed several peaks around 1535 nm with a total linewidth of 2 nm. Several transverse modes contributed to the laser output and the M^2 was measured to be smaller than 3.5.

To get more insights into the fiber laser loss mechanisms, the performance of the laser without the output mirror was also recorded. In this case, the 4% Fresnel reflection of the fiber end surface provides the signal feedback of the resonator, and the residual pump power was not reflected back into the laser cavity at the output. By subtracting the signal power from the total output power measured, the residual pump power exiting the laser output end was obtained. The signal power (filled circles) and residual pump power (empty circles) as a function of the launched pump power are shown in Fig. 1. At a launched pump power of 23 W, 4.7-W signal power was generated. Taking into account the 3.5-W pump coupling loss, 5.3 W of residual pump exiting the fiber end, and 2.2 W of measured pump scattering loss, the laser is estimated to have an efficiency of 39% with respect to the absorbed pump power. This value is very close to that (38%) obtained from a 1.4-m-long phosphosilicate fiber laser pumped at 980 nm [9], demonstrating that high efficiency is maintained in our heavily doped shorter fiber lasers.

To understand the intrinsic loss mechanisms leading to the mismatch between the theoretically limited efficiency of $\lambda_p/\lambda_s = 63\%$ and the measured internal efficiency of 39%, numerical modeling of the laser using power-evolution and rate equations was performed. We found that the commonly used simplified rate equations, e.g., used in [10] and [11], were not able to explain our experimental results. Other loss channels such as the cumulative energy transfer process $Yb^{3+}(^2F_{5/2} \rightarrow {}^2F_{7/2}) \Rightarrow Er^{3+}(^4I_{13/2} \rightarrow {}^4F_{9/2})$ [8], [12], double energy transfer, and/or the clustering effects [13] have to be taken into account in order to provide reasonably good fits to the data. The model is able to fit the experimental results in Fig. 1 with a single set of reasonable parameters. It gives a fairly good description of both signal and residual pump power in the figure, including the weak saturation tendency of the pump absorption. We will present the details of the modeling in a separate paper.

III. Single-Mode 4-W Fiber Laser

To obtain a diffraction-limited beam from our short-length fiber laser, we designed a phosphate fiber with a numerical aperture of less than 0.08 and a core size of 13 ± 1 μm, which supports only the fundamental mode at 1535 nm. The core is placed off-center of the fiber to improve the pump absorption (see inset of Fig. 3). The circular clad diameter is about 125 μm. Both Er^{3+} and Yb^{3+} doping concentrations in the fiber core were the same as that of the multimode fiber laser described in Section II. This fiber laser setup was also similar to that of the multimode fiber laser shown in Fig. 2. The output mirror used here had a reflectivity of $R_2(\lambda_s = 1535$ nm$) \approx 30\%$ at the signal wavelength.

The filled square symbols in Fig. 3 show the output power of this 7.1-cm single-mode fiber laser as a function of the launched pump power. A maximum power of 4.0 W was obtained with $M^2 \approx 1.1$. To our knowledge, the power per unit fiber length of this laser (0.56 W/cm) is the highest among all single-mode Er- and Er–Yb-doped fiber lasers. The slope efficiency of the laser at low pump powers was about 20%, which is smaller than the multimode fiber laser due to less efficient pump absorption by

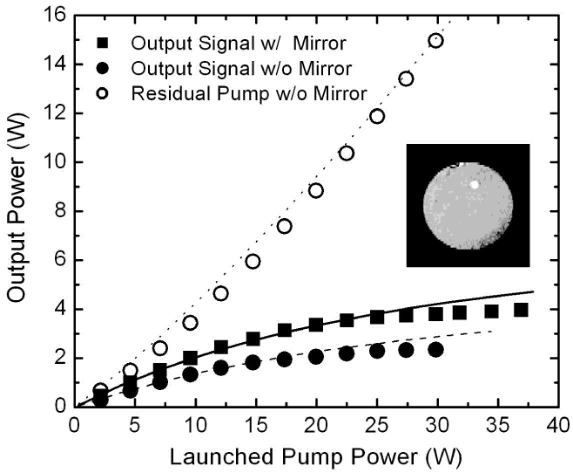

Fig. 3. Measured (symbols) and calculated (lines) output signal powers and residual pump powers of the 7.1-cm single-mode fiber laser. Filled squares and solid line are for the 1535-nm signal from the laser with an $R_2(\lambda_s) \approx 30\%$ output mirror. Filled circles and dashed line are for the 1535-nm signal from the laser without an output mirror. Empty circles and dotted line are for the residual 976-nm pump light that exits the laser in the absence of an output mirror. Inset is a picture of the fiber end facet of this laser.

the smaller core. However, the laser had a low threshold of about 70-mW pump power due to smaller core size. At high pump powers, the laser exhibited slightly stronger saturation behavior than the prediction of the model shown by the solid line in Fig. 3. This is due to the fact that, at 23-W launched pump power, the laser started to oscillate at 1030 nm as population inversion of the Yb^{3+} ions increased. The lasing at 1030 nm created an additional loss channel to the 1535-nm output which was omitted by the model to simplify the calculation.

Similar to the multimode laser, we also measured the signal output and residual pump power of the 7.1-cm single-mode fiber laser when the output coupler was removed. Again, the 4% Fresnel reflection of the fiber end was used for the resonator feedback and pump light was not reflected back into the fiber. The results are shown in Fig. 3. Due to the smaller core size, we saw a large amount of pump power exiting the fiber without being absorbed. For example, at 20-W launched pump power, 9.1-W residual pump power exited the fiber end. Considering 2.1 W of generated signal power, 3.0-W pump coupling loss, and 2.4-W estimated pump scattering loss, we got 38% efficiency with respect to the absorbed pump power. This value is similar to that of the multimode fiber laser, indicating similar intrinsic loss mechanisms due to the fact that the same Er–Yb-doped phosphate glass has been used.

IV. Conclusion

Utilizing highly Er–Yb-doped phosphate fibers, we have demonstrated the generation of 9.3 W of power from a 7.0-cm short-length multimode fiber laser and 4.0 W from a 7.1-cm single-mode fiber laser. The generated power per unit fiber length reaches 1.33 and 0.56 W/cm, respectively. The slope efficiency of the multimode fiber laser relative to the launched pump power reached 29%, while the slope efficiency with respect to absorbed pump power was about 39% for both lasers. Theoretical modeling shows that the major intrinsic loss channel is related to the cumulative energy transfer process in the Er–Yb system.

Acknowledgment

The authors would like to thank E. Temyanko for coating of fibers and mirrors.

References

[1] C. Spiegelberg, J. Geng, Y. Hu, Y. Kaneda, J. Wang, W. Li, M. Brutsch, S. Hocde, M. Chen, J. Babico, K. Barry, W. Eaton, M. Blake, D. Eigen, I. Song, and S. Jiang, "Compact 100 mW fiber laser with 2 kHz linewidth," in *Proc. Optical Fiber Communication (OFC 2003)*, Atlanta, GA, 2003, Postdeadline Paper PD-45.

[2] W. H. Loh, B. N. Samson, L. Dong, G. J. Cowle, and K. Hsu, "High performance single frequency fiber grating-based erbium: Ytterbium-codoped fiber lasers," *J. Lightwave Technol.*, vol. 16, pp. 114–118, Jan. 1998.

[3] Y. Jeong, J. K. Sahu, D. N. Payne, and J. Nilsson, "Ytterbium-doped large-core fiber laser with 1 kW of continuous-wave output power," *Electron. Lett.*, vol. 40, pp. 470–472, Apr. 2004.

[4] B. Huang, S. Jiang, T. Luo, J. Watson, S. Honkanen, Y. Hu, F. Smektala, J. Lucas, and N. Peyghambarian, "Performance of high-concentration Er^{3+} doped phosphate fiber amplifiers," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 197–199, Mar. 2001.

[5] Y. Hu, S. Jiang, T. Luo, K. Seneschal, M. Morrel, F. Smektala, S. Honkanen, J. Lucas, and N. Peyghambarian, "Performance of high-concentration Er^{3+}-Yb^{3+} codoped phosphate fiber amplifiers," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 657–659, July 2001.

[6] P. Leproux, S. Février, V. Doya, P. Roy, and D. Pagnoux, "Modeling and optimization of double-clad fiber amplifiers using chaotic propagation of the pump," *Opt. Fiber Technol.*, vol. 6, pp. 324–339, 2001.

[7] L. Li, M. Morrell, T. Qiu, V. L. Temyanko, A. Schülzgen, A. Mafi, D. Kouznetsov, J. V. Moloney, T. Luo, S. Jiang, and N. Peyghambarian, "Short cladding-pumped Er/Yb phosphate fiber laser with 1.5-W output power," *Appl. Phys. Lett.*, vol. 85, pp. 2721–2723, Sept. 2004.

[8] 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. Amer. B*, vol. 17, pp. 833–839, May 2000.

[9] J. Nilsson, S. Alam, J. A. Alvarez-Chavez, P. W. Turner, W. A. Clarkson, and A. B. Grudinin, "High-power and tunable operation of erbium-ytterbium co-doped cladding-pumped fiber lasers," *IEEE J. Quantum Electron.*, vol. 39, pp. 987–994, Aug. 2003.

[10] G. C. Valley, "Modeling cladding-pumped Er/Yb fiber amplifiers," *Opt. Fiber Tech.*, vol. 7, pp. 21–44, 2001.

[11] E. Yahel and A. Hardy, "Modeling high-power Er^{3+}-Yb^{3+} codoped fiber lasers," *J. Lightwave Technol.*, vol. 21, pp. 2044–2052, Sept. 2003.

[12] V. P. Gapontsev, S. M. Matitsin, A. A. Isneev, and V. B. Kravchenko, "Erbium glass lasers and their applications," *Opt. Laser Technol.*, pp. 189–196, Aug. 1982.

[13] E. Maurice, G. Monnom, B. Dussardier, and D. B. Ostrowsky, "Clustering effects on double energy transfer in heavily ytterbium-erbium-codoped silica fibers," *J. Opt. Soc. Amer. B*, vol. 13, pp. 693–701, Apr. 1996.