APPLIED PHYSICS LETTERS **88**, 161106 (2006)

Ultracompact cladding-pumped 35-mm-short fiber laser with 4.7-W single-mode output power

L. Li,[a] A. Schülzgen, V. L. Temyanko, M. M. Morrell, and S. Sabet
College of Optical Sciences, University of Arizona, Tucson, Arizona 85721

H. Li and J. V. Moloney
Arizona Center for Mathematical Sciences, University of Arizona, Tucson, Arizona 85721

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

(Received 31 January 2006; accepted 4 March 2006; published online 17 April 2006)

We report on ultracompact cladding-pumped fiber lasers, fabricated from single-mode phosphate glass microstructured optical fibers, with several watts of cw output at 1.5 μm. A maximum cw output power of 4.7 W has been achieved from a fiber laser that is only 35 mm in length, corresponding to a yield of 1.34 W/cm of active microstructured fiber. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2196053]

Compact high-power fiber lasers at 1.5 μm, with watt-level cw output power generated from a few centimeters of active fibers, have attracted substantial research interests recently.[1–3] These devices are essential elements for integrated photonics and excellent candidates for high-power single-frequency (SF) laser source.[4–6] Watt-level cw output powers have been achieved with active fibers 10 cm or shorter, with reported power yield of 1.33 W/cm from a multimode step index fiber (SIF) laser and 0.56 W/cm from a single-mode (SM) SIF laser, both are 7 cm in length.[2] However, 7 cm is still too long for linear-cavity SF laser, and the fiber needs to be further shortened to 50 mm or less so that the free spectral range can match the bandwidth of narrow band fiber Bragg gratings.

The output power of SM fiber laser is mainly limited by the small core size due to SM cutoff requirement, and the 13-μm-diameter core of the previous SM-SIF laser[2] is already considered large compared with those of most commercial SM fibers ($\leqslant$8 μm). Since the doping concentration of active ions can only be increased until the detrimental ion clustering effect takes place, the other option is to increase the core size while maintain SM guidance. Recently developed microstructured optical fiber (MOF) has been demonstrated for SM guidance with mode area much larger than that achievable by SIF[7,8] and therefore provides an ideal solution to expand the active SM core area for both the Yb^{3+}-doped[9] and $Er^{3+}-Yb^{3+}$-codoped fiber lasers.[10,11]

In this letter, ultracompact high-power SM fiber lasers, of lengths no more than 50 mm, have been constructed with heavily doped phosphate MOFs and optimized cavity designs. Over 5 W cw output power has been obtained from a 50-mm-short MOF laser. The SM output power per length has been greatly improved to 1.34 W/cm from a 35-mm-short fiber laser, which more than doubles the previously reported 0.56 W/cm from a SM-SIF laser.[2] These results clearly demonstrate the advantage of the MOF design over the conventional SIF in improving the device compactness as well as compressing the active fiber length sufficiently short for SF laser operation.

The phosphate MOF used to construct the fiber laser was drawn at the College of Optical Sciences and is shown as the inset of Fig. 1. The MOF has an outer diameter of 125 μm, a pitch (Λ, center-to-center spacing of neighboring air holes) of 9 μm, and a doped central area of $\sim$430 μm^2 corresponding to an equivalent core diameter of 23 μm. This MOF has four rings of air holes surrounding the core, and the air hole diameter (d_{AH}) varies under different fiber drawing temperatures. The index of the core glass is depressed by an amount of $\Delta n = n_{core} - n_{cladding} = -17\times10^{-4}$ to achieve SM guidance.[12,13] When d_{AH}/Λ reaches 0.4, the MOF guides only one spatial mode 1.5 μm and the measured M^2 value of this mode is $\sim$1.2. The deviation from the ideal value of 1.0 of a diffraction-limited beam is because the fundamental mode pattern of the MOF differs from the Gaussian mode.[13]

The MOF core is doped with 1.5 wt. % Er^{3+} and 8.0 wt. % Yb^{3+}. Figure 1 shows the absorption of highly multimode 975 nm pump light coupled into the MOF cladding. Less than 10% of the pump light is transmitted through the first 5 cm of the active MOF, indicating that sufficient absorption can be achieved within a very short length. In addition, output couplers (OCs) with 100% reflectivity at 975 nm were used to recycle the unabsorbed pump and further improve the laser efficiency. Another challenge to operate the very short heavily $Er^{3+}-Yb^{3+}$-codoped MOF laser is to efficiently remove the generated heat, which is a consequence of strong pump absorption within a very small volume.[14] We clamped the MOF inside a U-shaped silicon

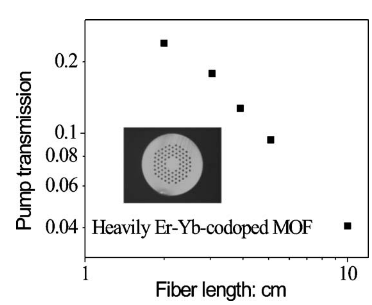

FIG. 1. Pump absorption of the heavily doped cladding-pumped MOF in log-log scale. Inset: photo of the large-mode-area active MOF.

[a]Electronic mail: lli@email.arizona.edu

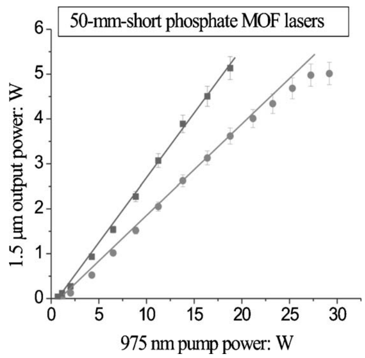

FIG. 2. Performances of two 50-mm-short MOF lasers. Squares: with external OC; dots: without OC; and solid lines: linear fits.

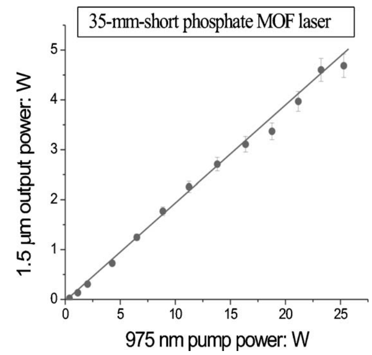

FIG. 3. Signal vs pump plot of a 35-mm-short MOF laser. Dots: experimental data; solid line: linear fit.

groove, which was attached to a thermoelectric cooler, to allow for efficient heat removal.

The fiber laser is constructed by a piece of MOF, with both ends cleaved and a pair of dielectric mirrors. The pump is delivered by a butt-coupled multimode fiber whose facet is coated with a dielectric mirror (transparent at the pump wavelength of 975 nm and highly reflective at the signal wavelength of 1535 nm). The other end of the MOF is butted against a bulk OC that has high reflectivity at 975 nm and various reflectivities at 1535 nm, which has been optimized to maximize output power for MOF lasers of various lengths.

Two MOF lasers, both 50 mm in length, were first fabricated. One had the bare cleaved facet as the output end and the other used an OC ($R_{1535\ \mathrm{nm}}=54\%$). Figure 2 shows the signal versus pump power plot of the two MOF lasers and it is clearly seen that the OC improves the laser efficiency significantly by at least 30%. The lasing threshold was less than 700 mW and a maximum output of 5.1 W was obtained for the MOF laser with OC. The lasing wavelength was centered at 1535 nm and the bandwidth was ~2 nm. It is noticeable that the output power of the 50-mm-short MOF laser starts to saturate at ~5 W output level, as seen from the MOF laser without OC. The output of the MOF laser with OC actually dropped below the maximum at higher pump level because of irreversible thermal damage and is not plotted in the figure. We believe that two reasons are responsible for this saturation behavior at high pump levels. First, the pump absorption coefficient saturates with increasing pump power.[14] Second, the so-called energy transfer "bottleneck" effect, which happens when the pump replenishes the Yb^{3+} excited state faster than the forward energy transfer rate from Yb^{3+} to Er^{3+} ions at very high pump level, sets a limit on the output power.[15] Both mechanisms are directly related to the number of active ions in the cavity as well as the forward energy transfer rate. By either increasing the active ion density or enhancing the energy transfer rate, the saturation behavior can be alleviated.

To further shorten the active fiber length, an OC with optimal reflectivity ($R_{1535\ \mathrm{nm}}=63\%$) was chosen for a MOF only 35 mm short. This MOF laser had a maximum 4.7 W cw output power at 21 W of pump. The lasing threshold was less than 400 mW and the slope efficiency was 20% with respect to the launched pump power. The signal versus pump power plot is shown in Fig. 3. The output saturation is also observed. This ultracompact MOF laser has a yield of 1.34 W/cm and it provides a realistic chance for a multiwatt linear-cavity SF fiber laser with its very short length of 35 mm.

In summary, we report drastic improvement on short-length 1.5 μm SM fiber laser. Combining large-mode-area SM-MOF design with heavily doped phosphate glass, a cw output power of 5.1 W and a power yield of 1.34 W/cm have been achieved from ultracompact, 50-mm- and 35-mm-short MOF lasers, respectively.

The authors are grateful to S. Jiang and T. Luo of NP Photonics Inc. for providing the phosphate glasses and E. Temyanko and Y. Merzlyak for technical support. This work is supported by the Air Force Office of Scientific Research through a MRI Program No. F49620-02-1-0380, National Science Foundation Grant No. 0335101, and the state of Arizona TRIF Photonics Initiative.

[1]L. Li, M. M. Morrell, T. Qiu, V. L. Temyanko, A. Schülzgen, A. Mafi, D. Kouznetsov, J. V. Moloney, T. Luo, S. Jiang, and N. Peyghambarian, Appl. Phys. Lett. **85**, 2721 (2004).
[2]T. Qiu, L. Li, A. Schülzgen, V. L. Temyanko, T. Luo, S. Jiang, A. Mafi, J. V. Moloney, and N. Peyghambarian, IEEE Photonics Technol. Lett. **16**, 2592 (2004).
[3]J. Limpert, N. Deguil-Robin, I. Manek-Hönninger, F. Salin, F. Röser, A. Liem, T. Schreiber, S. Nolte, H. Zellmer, A. Tünnermann, J. Broeng, A. Petersson, and C. Jakobsen, Opt. Express **13**, 1055 (2005).
[4]N. Peyghambarian, T. Qiu, P. Polynkin, A. Schülzgen, L. Li, V. L. Temyanko, M. Mansuripur, and J. V. Moloney, Opt. Photonics News **12**, 41 (2004).
[5]C. Spiegelberg, J. Geng, Y. Hu, Y. Kaneda, S. Jiang, and N. Peyghambarian, J. Lightwave Technol. **22**, 57 (2004).
[6]T. Qiu, S. Suzuki, A. Schülzgen, L. Li, A. Polynkin, V. Temyanko, J. V. Moloney, and N. Peyghambarian, Opt. Lett. **30**, 2748 (2005).
[7]J. C. Knight, T. A. Birks, R. F. Cregan, P. St. J. Russell, and J.-P. de Sandro, Electron. Lett. **34**, 1347 (1998).
[8]N. A. Mortensen, M. D. Nielsen, J. R. Folkenberg, A. Petersson, and H. R. Simonsen, Opt. Lett. **28**, 393 (2003).
[9]J. Limpert, A. Liem, M. Reich, T. Schreiber, S. Nolte, H. Zellmer, A. Tünnermann, J. Broeng, A. Petersson, and C. Jakobsen, Opt. Express **12**, 1313 (2004).
[10]A. Shirakawa, J. Ota, M. Musha, K. Nakagawa, K. Ueda, J. R. Folkenberg, and J. Broeng, Opt. Express **13**, 1221 (2005).
[11]L. Li, A. Schülzgen, V. L. Temyanko, T. Qiu, M. M. Morrell, Q. Wang, A. Mafi, J. V. Moloney, and N. Peyghambarian, Opt. Lett. **30**, 1141 (2005).
[12]B. J. Mangan, J. Arriaga, T. A. Birks, J. C. Knight, and P. St. J. Russell, Opt. Lett. **26**, 1469 (2001).
[13]L. Li, A. Schülzgen, V. L. Temyanko, H. Li, S. Sabet, M. M. Morrell, A. Mafi, J. V. Moloney, and N. Peyghambarian, Opt. Lett. **30**, 3275 (2005).
[14]L. Li, H. Li, T. Qiu, V. L. Temyanko, M. M. Morrell, A. Schülzgen, A. Mafi, J. V. Moloney, and N. Peyghambarian, Opt. Express **13**, 3420 (2005).
[15]E. Yahel and A. Hardy, J. Lightwave Technol. **21**, 2044 (2003).