Watts-level, short all-fiber laser at 1.5 μm with a large core and diffraction-limited output via intracavity spatial-mode filtering

Alexander Polynkin, Pavel Polynkin, Axel Schülzgen, Masud Mansuripur, and N. Peyghambarian

Optical Sciences Center, University of Arizona, 1630 East University Boulevard, Tucson, Arizona 85721

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We report over 2 W of single spatial-mode output power at 1.5 μm from an 8-cm-long, large-core phosphate fiber laser. The fiber has a numerical aperture of $\simeq$0.17 and a 25-μm-wide core, heavily doped with 1% Er^{+3} and 8% Yb^{+3}. The laser utilizes a scalable evanescent-field-based pumping scheme and can be pumped by as many as eight individual multimode pigtailed diode laser sources at a wavelength of 975 nm. Nearly diffraction-limited laser output with a beam quality factor $M^2 \simeq 1.1$ is achieved by use of a simple intracavity all-fiber spatial-mode filter. Both spectrally broadband and narrowband operation of the laser are demonstrated.

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Realization of an all-fiber cw single-frequency fiber laser with output power in the several-watt range is a goal of current laser research. Such a source will be useful in a variety of applications, including nonlinear frequency conversion and development of an extremely high-power laser source by coherently combining the outputs of several seeded fiber amplifiers.[1] Although hundreds of watts of output power from a fiber laser was reported recently by several groups,[2–4] such lasers employ 10–100-m-long Fabry–Perot fiber cavities, and therefore it is virtually impossible to force them into single-frequency operation. To that end, the cavity length has to be decreased to a few centimeters at most, but then the pump absorption in the active medium would decrease in proportion. Fibers made from low-melting-temperature glasses have a unique advantage compared with their silica counterparts, because such glasses can accept at least an order of magnitude higher concentration of dopant ions than silica.[5] Not surprisingly, at present the most powerful commercially available single-frequency fiber laser utilizes low-melting-temperature phosphate glass fiber as a host for the active ions[6]; with a 2-cm-long cavity, the laser is core pumped by a single-mode pigtailed laser diode. The output power reaches 200 mW and is limited by the available pump power.

In pushing the single-frequency fiber laser output into the several-watt range, two considerations are noted: the pumping scheme has to allow for low-brightness, multimode laser diode source(s) that can provide abundant pump power, and the doped core of the active fiber has to be large enough to facilitate rapid pump absorption. Still the laser has to emit spatially single-mode output, otherwise the phase shifts between several oscillating (spatial) modes will cause frequency drift of the laser output and longitudinal mode hops.

Several methods of achieving spatially single-mode operation of a large-core fiber laser have been reported. One approach is to design the fiber so that it remains single mode despite its large core size, which can be done either by tight control of the index step between the core and cladding[4,7,8] or by use of microstructured fibers.[9–11] Another approach is to use a multimode active fiber but to introduce a discriminating mechanism between the fiber modes so that only the fundamental mode is allowed to lase. This can be done either in a distributed way, i.e., by coiling the fiber,[4,12] or locally.[13,14] In particular, in Ref. 13 Alvarez-Chavez *et al.* reported using a short tapered section in a several-meters-long multimode fiber cavity, resulting in improvement of the beam quality factor from $M^2 \sim 3.5$ to $M^2 \sim 1.4$. The method presented in Ref. 14 relies on different expansion rates for the fiber modes in free space, and a nearly perfect diffraction-limited output laser beam with $M^2 \sim 1.1$ was reported. However, since it is not an all-fiber design there are potential stability issues associated with this approach.

In this Letter we report a simple yet effective way to discriminate between different spatial modes of a fiber laser by use of a short single-mode fiber section inside the laser cavity. Using this method, we forced an 8-cm-long multimode active fiber to oscillate in the fundamental spatial mode, with an almost perfect diffraction-limited output beam ($M^2 \sim 1.1$). The maximum optical power output exceeded 2 W. The laser utilizes a scalable side-pumping scheme, allowing the laser to be pumped by several multimode laser diodes. The total cavity length of the laser was 12–15 cm, depending on the feedback element used. We believe that the reported work is an important step toward realization of an all-fiber single-mode and single-frequency laser source with output power in the several-watt range.

The experimental setup is shown schematically in Fig. 1. An 8-cm-long active fiber is made from phosphate glass. It has a 125-μm cladding and a 25-μm step-index core that is codoped with 1% Er^{+3} and 8% Yb^{+3}. The numerical aperture (NA) of the fiber is $\sim$0.17, thus the fiber core supports multiple modes at a peak laser wavelength of $\sim$1535 nm. The active fiber is pumped with a scalable pumping scheme based on evanescent-field coupling of pump light at 975 nm from multiple pump delivery fibers into the active fiber. This pumping method is similar to the schemes used in the high-power, long lasers reported

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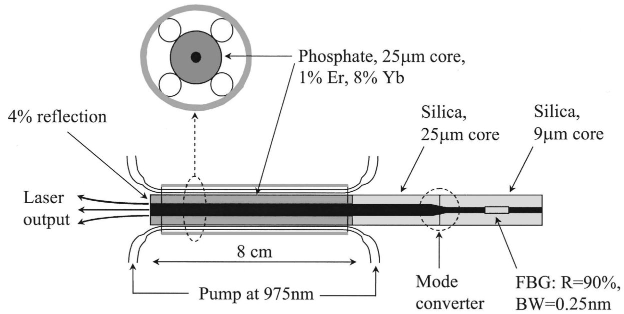

Fig. 1. Experimental setup. Inset, cross section of the fiber bundle. FBG, fiber Bragg grating; BW, bandwidth.

in Refs. 2 and 3 but is tailored to facilitate rapid penetration of the pump light into the active fiber over a short distance. In brief, the active fiber is surrounded by several coreless pump delivery fibers made from fused silica, all with an outer diameter of 50 μm. The fiber pigtails from the pump diode sources are nonadiabatically tapered and spliced to the delivery fibers. The tapering increases the NA of the pump light inside the delivery fibers and enhances the coupling between the delivery fibers and the active fiber. The fiber bundle is held together with a heat-shrink tube made from a low-index polymer, such that the index step between the tube and the delivery fibers is sufficient to prevent the pump light from leaking into the polymer. In the laser reported here, four pump delivery fibers are used, providing inputs for eight independent pump sources. A detailed description of the pumping scheme can be found in Ref. 15.

The intracavity spatial-mode filtering takes place in a short piece of a single-mode silica fiber (Corning SMF-28). The single-mode section of the resonator is linked with multimode active fiber by a different piece of silica fiber, with the core diameter and the NA closely matching those of the active fiber. The last two are fusion spliced together with an estimated splice loss for the fundamental mode of ~5%. To achieve a low-loss fundamental mode conversion between the single-mode and multimode sections of the laser cavity, both 25-μm-core silica fiber and SMF-28 fiber were adiabatically tapered to an outer dimension of ~80 μm, at which the field diameters of the fundamental mode in the two fibers become equal. Then the fibers were cleaved at the taper waist and fusion spliced together, as shown in Fig. 2. Also shown is a plot of the calculated diameter of the fundamental mode in the two fibers as a function of the cladding diameter. The total length of the mode converter was ~1.5 cm, and the converter was completely covered with an index-matching gel. The double-pass loss in the converter measured with broadband light at 1.5 μm launched from the single-mode side and reflected back was 0.7 dB.

For narrowband operation the laser cavity was formed by a fiber Bragg grating written on the single-mode fiber on one side and by ordinary Fresnel reflection from the cleaved end of the phosphate fiber on the other side. The grating had a 3-dB bandwidth of 0.25 nm centered at 1535 nm with a peak reflectivity of 90%. Using optical heterodyning of the laser output with a tunable, stable single-frequency laser (Agilent 81682A), we found that the fiber laser oscillated at a number of longitudinal modes (~10) that were separated by 630 MHz. This mode separation corresponds to the total laser cavity length of ~15 cm. By tuning the wavelength of the reference laser, we found that the total emission bandwidth of the fiber laser was ~6 GHz (~0.05 nm).

To determine the power penalty associated with the spatial-mode filtering as well as that associated with the spectral filtering by the Bragg grating, we fabricated two additional lasers with a design identical to that shown in Fig. 1, except that in one the grating was replaced by a 100%-reflective broadband dielectric mirror deposited on the cleaved single-mode fiber end of the resonator and in the other there was no mode filter and the broadband mirror was deposited on a cleaved 25-μm-core silica fiber. In the latter case the splice between the active phosphate fiber and the 25-μm-core silica fiber was still present. With broadband mirror feedback both lasers had a wide emission bandwidth of ~20 nm. In Fig. 3 the output power at 1.5 μm for lasers with different feedback elements is shown as a function of the combined pump power. Over the whole operation range, the wavelength of the pump was maintained at 975 nm, the peak small-signal absorption value for the doped glass. Of the three lasers, the one without the spatial-mode filter and with the broadband mirror has the highest optical-to-optical slope of 15.5%. The output power in this case remains a linear function of the pump power through the operating range and reaches 3.2 W. Right above threshold, the laser with the intracavity filter and the broadband mirror on the SMF-28 end has a slope of 13%, and the one with the fiber Bragg grating has a slope of 11%. At ~1.3 W, the output power in both cases with the spatial-mode filtering starts rolling off. We performed multiple runs with each laser to confirm that the curves in Fig. 3 were

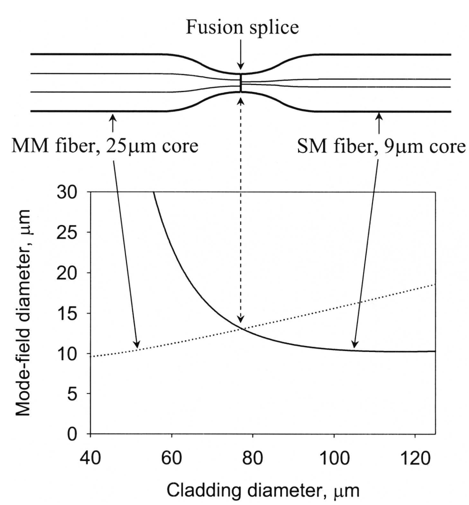

Fig. 2. Schematic of the spatial-mode converter. The graph shows the calculated mode-field diameter of the fundamental mode in the two fibers. MM, multimode; SM, single-mode.

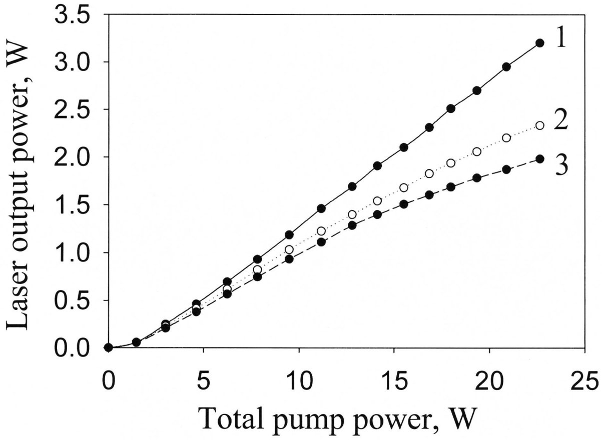

Fig. 3. Output power of the laser with different feedback: 1, without a spatial-mode filter and with a broadband mirror on the multimode fiber end; 2, with a mode filter and a broadband mirror on the single-mode fiber end; 3, with a mode filter and a narrowband fiber Bragg grating at the single-mode fiber end.

repeatable. Thus, roll-off is not related to permanent damage to the active fiber or to other laser components but may result from transversely varying gain saturation in the doped fiber core.[16] The roll-off can still be of thermal origin, and we are currently investigating this issue further. Note that, at the same output power from the lasers with and without spatial-mode filtering, the maximum power density inside the active fiber core is different by a factor of $2(d_{\text{core}}/d_{\text{mode}})^2 \simeq 3.5$ (d_{core} is the core diameter, and d_{mode} is the mode-field diameter of the fundamental fiber mode).

The M^2 parameter of the three lasers was measured at the multimode fiber side by use of a beam profiler (BeamMap, Dataray). We estimated the measurement accuracy at ± 0.02. M^2 of the laser without mode filtering grew from ~2.5 at just above threshold to ~3.5 at the highest power level. For both broadband and narrowband lasers with mode filtering, the beam quality factor was stable at each particular value of the pump power but varied from 1.05 to 1.12 when the pump power was changed. The dependence of M^2 on pump power was random. We believe that this variation resulted from thermally induced phase changes between the fundamental fiber mode and the residual high-order mode content of the laser beam. From the data we estimate that this higher-order mode content carried less than 5% of the total laser power.

Note that, if the intracavity spatial-mode filtering described here is applied to an active fiber with even larger core, we expect the output from such laser to have somewhat less than perfect beam quality, as the coupling between different spatial modes in the active fiber rapidly grows with increasing fiber core size.[17] The quantitative limitations of the reported approach are still to be determined.

Finally, we emphasize that at this point our laser is not short enough to make single-frequency operation straightforward. However, various approaches of frequency selection in fiber lasers that have been successful in producing single-frequency output from ~10-cm-long low-power fiber lasers[18–20] can be applied to our laser, making it a promising candidate for a high-power, single-mode, single-frequency fiber laser source.

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