Generation of watt-level single-longitudinal-mode output from cladding-pumped short fiber lasers

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We generate as much as 1.6 W of continuous-wave 1550 nm single-longitudinal-mode output from a cladding pumped Er–Yb codoped phosphate fiber laser. This power is to our knowledge among the highest in single-longitudinal-mode fiber lasers. The narrowband fiber Bragg grating output coupler is demonstrated to be an effective element for providing the single-longitudinal-mode selection. © 2005 Optical Society of America

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Generation of high-power narrow-linewidth coherent radiation near 1550 nm from a compact fiber laser source is of great interest because of its applications in telecommunications, interferometers, and sensing instruments. Since the first demonstration of single-longitudinal-mode fiber lasers,[1] many successful single-frequency operations with fiber lengths of a few centimeters and powers in the megawatt range were reported by several groups of scientists.[2–6] Because of the lack of powerful single-mode pump diodes and small core sizes, these core-pumped single-frequency fiber lasers are not yet able to generate watt-level powers. Although the use of multistage amplifiers can boost the single-frequency output power to the several-hundred-watt level,[7] it is still a challenging task to obtain watt-level single-frequency output, which can preserve a high signal-to-noise ratio, directly from fiber oscillators. Recently we demonstrated the generation of multiwatt output directly from cladding-pumped short fiber lasers without using bandwidth-limiting elements.[8,9] We used a narrowband fiber Bragg grating (FBG) as the output coupler of the fiber laser with a 5.5 cm long active fiber and successfully generated as much as 1.6 W of single-longitudinal-mode output.

One of the key elements of a single-longitudinal-mode fiber laser is a single-mode Er–Yb doped phosphate fiber. Heavily Er–Yb codoped phosphate glass fibers have been successfully used in high-gain short-length amplifiers and lasers, as reported previously in Refs. 8–10. Compared with other common host materials, e.g., silica glass, phosphate glass has higher solubility of rare-earth ions and low clustering effects, which allow the ion doping level to be increased without significantly enhancing the detrimental fluorescence-quenching process. In addition, phosphate glass has bigger phonon energy, leading to a shorter lifetime of the erbium $^4I_{13/2}$ state, and thus has a higher transfer rate of energy from Yb to Er ions. The glasses of our single-frequency fiber lasers were provided by NP Photonics, Inc. The diameters of the cladding and the core were 125 ± 2 and 13.5 ± 0.5 μm, respectively. The core was centered in the circular-shaped cladding to facilitate fusion splicing with the narrowband FBG. The numerical aperture of the core was ~0.08, thus supporting only the fundamental transverse modes at the lasing wavelength of 1550 nm. The core was 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 Er and Yb doping levels in an attempt to increase pump absorption and energy transfer from Yb to Er ions.

Figure 1 is a schematic of the single-longitudinal-mode fiber laser. The 976 nm diode pump light is delivered through a multimode fiber with a 100 μm core diameter and a numerical aperture of 0.22. The pump delivery fiber is butt-coupled to the doped phosphate laser fiber. The phosphate fiber was put into a low-index glass tube that had an inner hole diameter of 135 μm and was cooled by external circulating water. The numerical aperture of the phosphate fiber cladding region was therefore larger than 0.3, securing the pump confinement in the cladding. The output end of the pump delivery fiber was coated with a dielectric mirror with reflectivities $R_1(\lambda_s)>98\%$ at the signal wavelength ($\lambda_s=1550$ nm) and $R_1(\lambda_p)<5\%$ at the pump wavelength ($\lambda_p=976$ nm). This fiber coating, prepared by the authors' research group, provides high signal reflection and allows injection of pump light into the laser cavity. The output end of the doped phosphate fiber was fusion spliced to a narrowband fiber Bragg grating, which was also fabricated by our research group. We used the typical phase-mask UV-illumination method to fabricate the FBG. The photosensitive FBG fiber, provided by Nufern, had cladding and core sizes of 125 and 15 μm, respectively. The FWHM bandwidth of the FBG was 0.04 nm, and the peak signal reflectivity

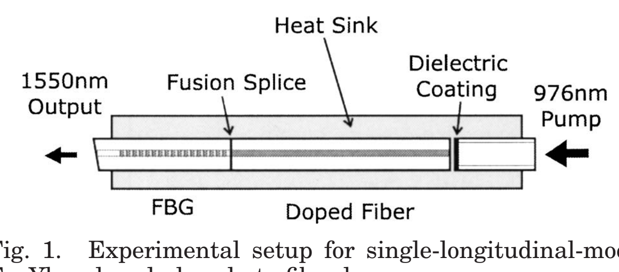

Fig. 1. Experimental setup for single-longitudinal-mode Er–Yb codoped phosphate fiber lasers.

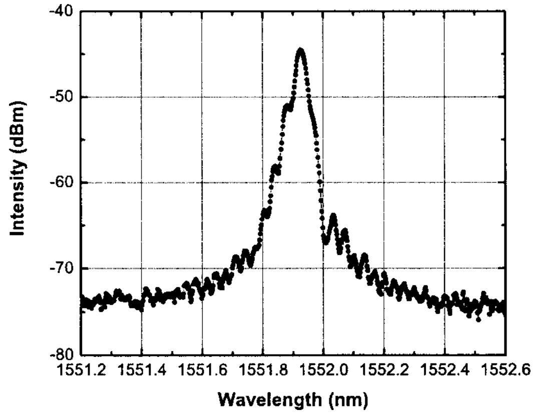

Fig. 2. Reflection spectrum of the FBG used in the single-longitudinal-mode fiber laser. The peak reflectivity is 35%, and the FWHM bandwidth is 0.04 nm.

was $R_2(\lambda_s)=35\%$. The length of the FBG was ~2.5 cm. A reflection spectrum of a broadband source from the FBG is shown in Fig. 2.

Figure 3 shows the dependence of the laser output power on the launched pump power for two lasers with active fiber lengths of 4.0 cm and 5.5 cm. Each of these lasers generates single-longitudinal-mode output with a high optical signal-to-noise ratio (Fig. 4). The threshold power for the 5.5 cm fiber laser is 390 mW; that of the 4.0 cm fiber laser is 280 mW. The 4.0 cm fiber laser had a stronger rollover at high pump powers than that of the 5.5 cm fiber laser. For the 5.5 cm fiber laser, a maximum signal power of 1.6 W was obtained at 37 W launched pump power, which is the maximum power available from the pump laser. The pumped power absorbed by Er and Yb ions at 37 W launched pump power was estimated from modeling to be 6.0 W. A slope efficiency of ~5% was achieved at pump powers smaller than 25 W. Compared with our previous results for the single-transverse-mode fiber laser,[8] which generated 4 W of power from a 7 cm long active fiber with an initial slope efficiency of 20%, there is a significant decrease of slope efficiency, which is due to several factors in the laser design. First, our current single-longitudinal-mode fiber laser uses a centered-core fiber geometry that reduces the pump absorption compared with that produced by an off-centered-core fiber geometry. Second, the shorter length of the active fiber will certainly decrease the efficiency of pump absorption. Third, the FBG output coupler used in the single-longitudinal-mode fiber laser does not provide high reflection for the pump, which also significantly reduces the pump absorption. And, last, the fusion splice between the FBG and the active fiber has extra losses because of mode mismatch owing to the different sizes of the cores and to differences in glass indices. We believe that, by using an off-centered active fiber, adding pump feedback at the output FBG, improving the quality of the fusion splice, and mode matching the FBG and active fiber, we could obtain higher slope efficiencies (>10%) in the cladding-pumped single-longitudinal-mode fiber lasers.

To have a better understanding of the single-longitudinal-mode fiber laser, we also made simulations to describe the slope efficiency of the laser. The solid curve in Fig. 3 is the result of such an effort for the 5.5 cm fiber laser. All the material parameters, such as absorption and emission cross sections, the energy-transfer rates, and scattering losses, are the same as those used in our research described previously.[8,11] However, a smaller pump filling factor was used because the centered-core fiber geometry should have a smaller pump absorption than that of the off-centered-core fiber. An additional coupling loss of 15% was introduced to take into account the mode-mismatch and fusion splice losses. In this way we are able to describe the laser slope efficiency with our existing model.

The single-longitudinal-mode nature of the laser was tested through typical heterodyne detection of the beat signals between the fiber laser and a tunable local single-frequency diode laser. Figure 5 shows two examples of spectra recorded from an electrical spectrum analyzer (ESA). Because our fiber laser has no polarization discrimination elements in the cavity, laser output in most cases contains two polarization modes, as shown in the spectrum in Fig. 5(a). The two peaks, separated by ~25 MHz, correspond to the

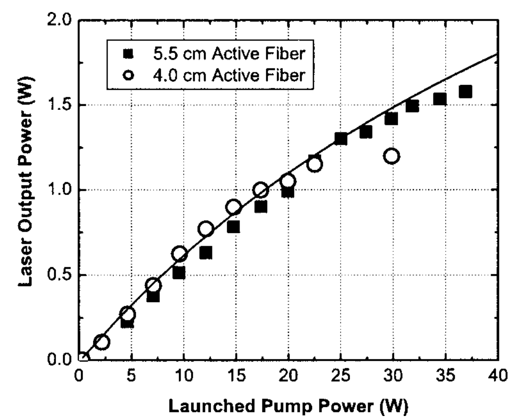

Fig. 3. Output powers at 1550 nm versus pump powers at 976 nm for fiber lasers with active fiber lengths of 5.5 and 4.0 cm.

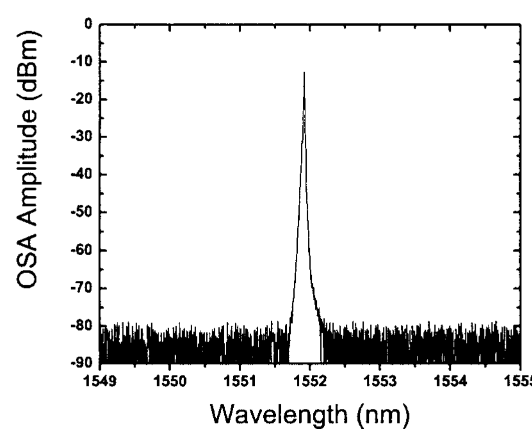

Fig. 4. Typical output spectrum of a single-longitudinal-mode fiber laser measured by an optical spectrum analyzer (OSA).

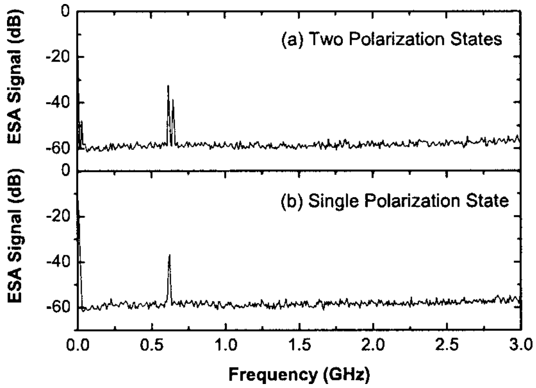

Fig. 5. ESA heterodyne signals for single-longitudinal-mode fiber lasers with two-polarization-mode and single-polarization-mode output.

two polarization states of the output. To obtain single-polarization output, we applied pressure on the FBG through a glass plate and caused the FBG to exhibit birefringence such that the two polarization modes will have a larger frequency separation. The narrowband FBG will thus provide enough discrimination to prevent one polarization state from lasing and keep the laser output at a linearly polarized state. A spectrum of such a single-polarization output is shown in Fig. 5(b).

Without any automatic feedback control, the 5.5 cm fiber laser can maintain its single-longitudinal-mode operation for a period of several minutes without mode hopping, once its cavity mode is tuned close to the center of the FBG reflection peak and thermally stabilized. Tuning can easily be accomplished by fine adjustment of the pump current, which changes the fiber temperature, leading to changes in laser cavity length and in the corresponding longitudinal-mode spacing. We determined from the ESA spectra that the frequency separation of the longitudinal modes is 1.47 GHz for the 5.5 cm active fiber laser; this corresponds to an effective cavity length of ~6.7 cm. The extra 1.2 cm cavity length comes from the FBG output coupler. We also tried using an active fiber length of 7 cm to see whether single-longitudinal-mode operation could be maintained. Unfortunately, this longer cavity length allows an additional longitudinal mode to oscillate, owing to reduced longitudinal-mode spacing.

In summary, we have demonstrated generation of as much as 1.6 W of single-longitudinal-mode output at 1550 nm from a short fiber laser, using a cladding-pumped scheme. Single-polarization output can be obtained by inclusion of birefringence in a fiber Bragg grating output coupler.

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