Linearly polarized, 3.35 W narrow-linewidth, 1150 nm fiber master oscillator power amplifier for frequency doubling to the yellow

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A high-power linearly polarized Yb-doped silica fiber master oscillator power amplifier at 1150 nm is reported. It produced 3.35 W cw and 2.33 W of average power in 1 μs pulses at a 100 kHz repetition rate, both with 8 pm linewidth. This is the first report, to the best of our knowledge, of a high-power Yb-doped fiber amplifier at a wavelength longer than 1135 nm. The pulsed output was frequency doubled in a bulk periodically poled near-stoichiometric $LiTaO_3$ chip to generate 976 mW of average power at 575 nm with an overall system optical-to-optical efficiency of 9.8% with respect to launched pump power. © 2007 Optical Society of America

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High-power yellow sources are needed for medical and scientific applications. Yellow sources at ~575 nm are used to treat skin tumors [1]. Single-frequency sources at 579 nm excite europium for quantum computing [2]. Correcting for aberrations with adaptive optics systems in large telescopes requires narrow-linewidth 589 nm radiation to excite the atmospheric sodium layer [3]. There has been considerable interest in the past decade to develop solid-state alternatives to the inefficient and complex dye and copper-vapor lasers that have been traditionally used for these applications. Since there is no known solid-state material that efficiently emits radiation directly at these wavelengths, the solutions investigated to date all utilize nonlinear frequency conversion. Sum frequency generation of two single-frequency (cw) Nd:YAG master oscillator power amplifiers (MOPAs) at 1064 and 1319 nm have produced 50 W at 589 nm [4]. However, this system is expensive and requires two tightly controlled infrared laser systems. To address these issues, the use of high-power fiber lasers has been recently investigated. For example, yellow sources based on frequency doubling Raman-shifted fiber lasers require only a single narrow-linewidth infrared laser. Such a system produced 3 W cw at 589 nm from 23 W at 1178 nm [5]. However, four-wave mixing (FWM) significantly broadened the Raman laser's linewidth at higher output powers.

A much simpler approach is direct frequency doubling of a single laser. Bismuth-doped fiber lasers at 1146 nm have been recently developed for this purpose [6]. However, the oscillator efficiency was low and the output was unpolarized. An alternative gain medium is Yb-doped silica. Since its gain stretches to 1200 nm, frequency doubling a narrow-linewidth Yb-doped fiber laser operating from 1140 to 1180 nm could generate yellow radiation with a single laser and a single nonlinear conversion step. This approach has produced 40 mW at 575 nm by frequency doubling an 1150 nm Yb-doped silica fiber oscillator [7]. A Yb-doped silica fiber laser with 1.9 W of polarized output at 1178 nm was also recently demonstrated [8]. Unfortunately, the high intracavity signal powers required to suppress amplified spontaneous emission (ASE) resulted in FWM-induced spectral broadening at higher output powers. A promising alternative to a high-power oscillator is a MOPA configuration. Fiber MOPAs have been shown to maintain the linewidth of the oscillator if the amplifier fiber length is short enough to prevent the onset of nonlinearities [9]. Another advantage is that the master oscillator can be amplitude modulated to obtain high peak powers if the power amplifier is saturated. The main difficulty in scaling the power of a Yb-doped fiber amplifier above 1130 nm is the presence of ASE at shorter wavelengths, which tends to overwhelm the comparatively small gain of the long-wavelength signal (ASE saturation).

This Letter demonstrates for the first time, to the best of our knowledge, that with a suitable combination of ASE management techniques, Yb-doped silica fiber can be a useful amplifier medium at long wavelengths. With several watts of output at 1150 nm, this is the first reported high-power (>100 mW) Yb-doped fiber MOPA operating above 1135 nm. Using this source, we demonstrate the highest average power in the yellow generated by direct frequency doubling of an infrared laser.

The schematic of our system is shown in Fig. 1. The oscillator was pumped with 1.2 W of pump power launched from 980 nm laser diodes. The cavity mirrors were formed by fiber Bragg gratings (FBGs) centered at 1150.3 nm. The FWHM linewidth of the output coupler (OC) FBG was 40 pm. The gain medium consisted of polarization-maintaining (PM) Yb-doped silica fiber sections with different levels of Yb doping to mitigate the appearance of photodarkening and minimize scattering losses while still providing sufficient ground-state absorption (GSA) to prevent the

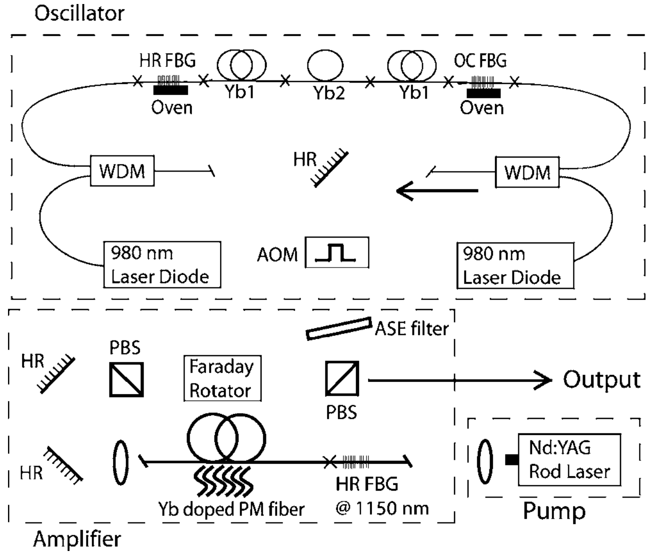

Fig. 1. Experimental setup for 1150 nm MOPA with dotted boxes illustrating the oscillator, amplifier and pump sections for clarity. Yb1, silica fiber with moderate Yb doping; Yb2, silica fiber with high Yb doping; WDM, wavelength division multiplexer; PBS, polarizing beam splitter; ×, splice.

appearance of parasitic lasing at shorter wavelengths [7]. To obtain single-polarization operation, the OC FBG was spliced at 90° to the gain fiber. This oscillator produced 212 mW, with a polarization extinction ratio of 21 dB and a FWHM linewidth of 8 ± 2 pm, measured with a high-resolution optical spectrum analyzer (OSA). The oscillator has operated for over 200 h without exhibiting any signs of photodarkening.

Amplification of the low-gain wavelength emitted by this oscillator in a fiber amplifier gain medium was challenging due to ASE saturation. We took several steps to circumvent this problem. The first step was to increase the seed power to allow the signal to saturate the amplifier. In initial experiments with an 89 mW oscillator output, our first amplifier, which consisted of a double-clad fiber pumped by a 20 W 975 nm laser diode, amplified the seed to 311 mW before the onset of ASE saturation [10]. Compared with this earlier design, the 212 mW oscillator described in the previous paragraph represents a 2.4-fold increase in seed power. In the second step, we carefully chose the amplifier gain medium to maximize the gain cross section at 1150 nm. Since the emission cross section of Yb^{3+} extends to longer wavelengths in aluminosilicates than in phosphosilicates [11], we used a single-mode aluminosilicate PM fiber with a high photodarkening threshold and low scattering losses. In the third step, we double passed the signal through the fiber amplifier by using a narrowband high-reflector FBG centered at 1150 nm (see Fig. 1). Thus, the ASE was only amplified in a single pass, as opposed to two passes for the signal. In the fourth step, we heated the gain fiber to increase the GSA experienced by the ASE.

The final step was to pump the amplifier at a wavelength considerably longer than the 1030 nm ASE gain peak. Since the absorption of Yb-doped silica is weak at these wavelengths, the amplifier was core pumped to increase pump absorption. Heating the fiber also greatly enhanced pump absorption. First-order calculations using gain-fiber characteristics and available signal power indicated that 1057 nm was the ideal pump wavelength. It would be straightforward to build a 1057 nm double-clad Yb-doped silica fiber laser and splice its output port to the amplifier for efficient pumping. However, to demonstrate proof of principle more expediently, we chose to pump the fiber amplifier with one of the high-power 1064 nm Nd:YAG rod lasers available in our laboratory.

For pulsed amplification, the 1150 nm output was modulated into 1 μs pulses using an acousto-optic modulator (AOM). For cw amplification, the AOM acted as a static deflector. The AOM output was filtered to suppress ASE and then transmitted through a pair of polarizing beam splitters and a Faraday rotator. These optics served both as an optical isolator and as a polarization multiplexer for the amplified 1150 nm signal. We were able to couple into the 18 m amplifier fiber a maximum of 8.8 W of pump power and 125 mW of signal power.

As the amplifier fiber temperature was increased, the pump absorption was enhanced and the cw amplifier output power increased accordingly. The output power curves for the amplifier measured at several temperatures are shown in Fig. 2. The maximum output power of 3.35 W was obtained when the fiber was at 110°C. Less than 4% of the output power was in the ASE. Further increases in temperature caused a reduction in output power, presumably because the pump was already completely absorbed, and the higher temperatures increased GSA at 1150 nm. In a separate test, the gain fiber transmission at 1319 nm and 130°C was found to exhibit no signs of degradation over several hours, indicating that the fiber can be operated at 110°C without risk of damage. At 110°C, the source had a measured slope efficiency of 37% with respect to launched pump power and showed no signs of rollover.

Efficient single-pass frequency doubling in a bulk nonlinear periodically poled near-stoichiometric lithium tantalate (PPSLT) chip requires higher peak powers. By varying the signal power input into the

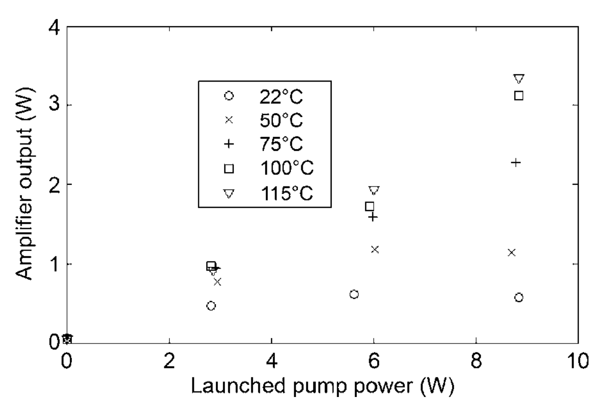

Fig. 2. Amplifier output power versus launched pump power at several amplifier gain fiber temperatures.

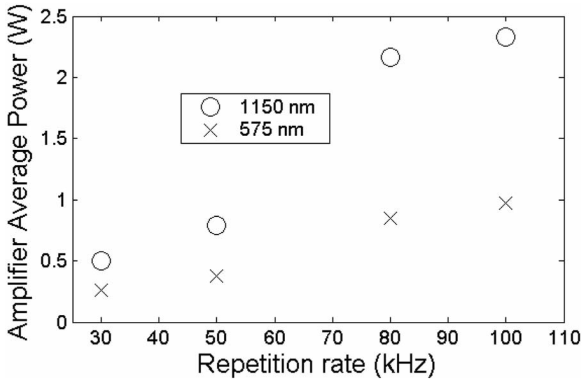

Fig. 3. Average power of 1150 nm and average power of 575 nm as a function of seed repetition rate.

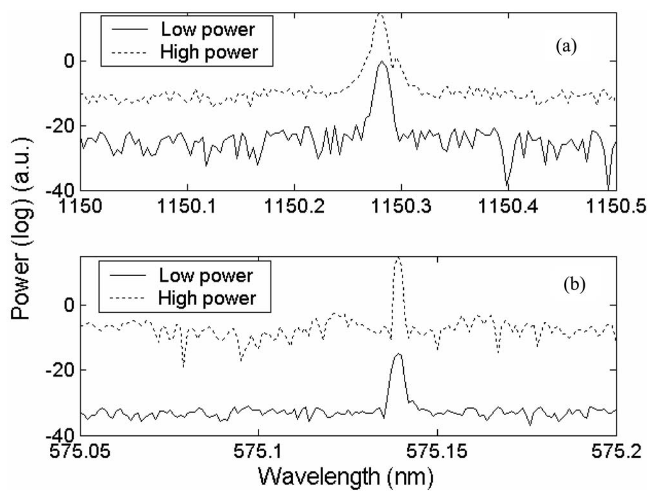

Fig. 4. Spectra of the (a) fundamental output of the amplifier at 1150 nm, and (b) frequency-doubled output at 575 nm of the PPSLT chip at low and high powers. For clarity, the curves for the high-power spectra are offset by 15 and 30 dB for the fundamental and second harmonic, respectively.

cw 1150 nm amplifier, we determined that the amplifier was well saturated. Therefore, to increase the frequency-doubling efficiency, the seed oscillator was amplitude modulated into 1 μs pulses. The average output power of this pulsed amplifier measured as a function of repetition rate is shown in Fig. 3. At 100 kHz, the amplifier produced 2.33 W of average power; the amplifier reduced the pulse width to ~490 ns to give a peak power of ~50 W. The amplifier output was frequency doubled in a 3 cm long anti-reflection-coated bulk PPSLT device. At low powers, the normalized efficiency of the device was measured to be ~0.53% $W^{-1}\,cm^{-1}$. A maximum average power of 976 mW was generated at 575 nm (see Fig. 3), corresponding to a peak power of ~20 W and a single-pass conversion efficiency of 42%. The overall optical-to-optical efficiency of this 575 nm system with respect to total launched pump power was 9.8%.

Figure 4(a) shows the output spectrum of the oscillator on a high-resolution (4 pm resolution at 1150 nm) as well as the output spectrum of the amplifier operating at the highest peak power. In spite of the reasonably high peak powers, no sign of FWM-induced broadening was observed, and the linewidth was unchanged after amplification. In addition, no sign of stimulated Raman scattering was observed. The narrow linewidth makes it possible to use a longer PPSLT chip (e.g, 5 cm), which would increase the 575 nm power more than 40%. The frequency-doubled output was also measured with 1 pm resolution at low and maximum output powers. The linewidth was unchanged at 2.5 ± 0.5 pm [see Fig. 4(b)].

In conclusion, we have reported a Yb-doped fiber MOPA that produces as much as 3.35 W of narrow-linewidth, polarized, cw power at 1150 nm. This is the highest power obtained directly from a Yb-doped silica source of any kind (laser or amplifier) at such a long wavelength. Under pulsed operation, nearly 1 W of 575 nm output was generated by single-pass frequency doubling in a bulk PPSLT nonlinear chip.

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