Efficient yellow-light generation by frequency doubling a narrow-linewidth 1150 nm ytterbium fiber oscillator

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A linearly polarized, narrow-linewidth, diode-pumped, Yb-doped silica-fiber oscillator operating at 1150 nm was frequency doubled to produce 40 mW of 575 nm radiation. The oscillator generated 89 mW of cw linearly polarized output power and was tunable over 0.80 nm. The laser output was coupled to a periodically poled $LiNbO_3$ waveguide that converted 67% of the coupled power to the yellow. The system was fully integrated, with no free-space optics, and had an overall optical-to-optical efficiency of 7.0% with respect to the incident diode-laser pump power. © 2006 Optical Society of America

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There is a need for high-brightness yellow-light sources for applications in medicine and to generate laser guide stars for adaptive optics correction of large telescopes. The 573–580 nm band is very attractive for ophthalmology and dermatology applications.[1,2] Coherent yellow radiation is typically generated with inefficient and bulky dye or copper-vapor lasers. A diode-pumped, solid-state yellow source would be a preferable alternative. Yellow wavelengths, which are difficult to generate directly from solid-state gain media, have been obtained by pairing a diode-pumped oscillator with nonlinear optical systems.[3,4] Denman *et al.* reported 50 W of power at 589 nm through cavity-enhanced sum-frequency generation of two injection-locked, high-power, single-frequency Nd:YAG amplifier chains.[5] Sharma obtained 1.52 W of cw power at 590 nm by using a frequency-doubled, Raman-shifted, fiber based system.[6]

In this Letter, we report a new method for generating yellow radiation by directly frequency doubling a diode-pumped 1150 nm Yb-doped fiber laser in a periodically poled lithium niobate (PPLN) waveguide. This system is much simpler because it uses a single laser operating at a single wavelength with no cavity enhancement required. It has so far produced 40 mW of 575 nm radiation, which can easily be scaled in a master-oscillator power-amplifier configuration and bulk periodically poled nonlinear crystals. Furthermore, as it does not rely on fiber-stimulated Raman scattering, it can ultimately be used to produce yellow light with linewidths under that of stimulated Brillouin scattering (~100 MHz). Since this system contains no free-space optics, it can be made highly compact. To our knowledge, the only other mW-class yellow source produced through frequency doubling of a diode-pumped oscillator without additional nonlinear frequency steps is a Yb:YAB microchip laser system frequency doubled to 565 nm.[7] However, that system was limited to low output power (<1 mW) and suffered from low efficiency (<0.1%).

Yb-doped silica is an attractive gain medium for the 1 μm band because of its wide gain bandwidth and high quantum efficiency when it is pumped at 980 nm. Although its gain bandwidth stretches to 1200 nm,[8] it has been difficult to make fiber lasers and amplifiers at wavelengths greater than 1120 nm.[9] The challenges are the low-emission cross section at these wavelengths and gain competition from shorter wavelengths, especially in the 1030 nm region, where the gain is much higher. The second of these problems is exacerbated by the low cavity loss required for oscillation at longer wavelengths, which makes lasing at shorter wavelengths more likely. We overcame the first challenge by forming the fiber laser cavity with fiber Bragg gratings (FBGs) that have high reflectivity at 1150 nm [23 and 3.4 dB for the high reflector (HR) and the output coupler (OC), respectively]. Furthermore, these FBGs have extremely weak reflectivities in the 1030 nm region (<0.0005 dB), which helped to address the second challenge. To fully overcome the second challenge and prevent excessive amplified spontaneous emission (ASE) generation at 1030 nm, we inserted in the gain medium a section of fiber with a high Yb^{3+} concentration, which introduces a strong loss around 1030 nm due to ground-state absorption (GSA) of Yb^{3+} but not at 1150 nm, where GSA is considerably weaker.

To reduce the spurious scattering loss of the gain medium at 1150 nm, which would unduly reduce the laser efficiency or inhibit lasing altogether, the fiber should be as short as possible. For this reason it should have the highest doping concentration that does not exhibit photodarkening at the highest available pump power, since photodarkening in Yb-doped silica is known to extend to 1150 nm.[10] Given the low gain at 1150 nm, even a small amount of photodarkening (whose threshold is reduced with increasing dopant concentrations) produces enough excess loss to inhibit lasing. We observed photodarkening in some of our initial experiments: The output power at 1150 nm would decrease over tens of minutes until the photodarkening loss suppressed oscillation. We solved this problem through proper design of the gain medium, as described below.

Figure 1 shows a schematic of the experimental setup. The fiber oscillator consisted of polarization-

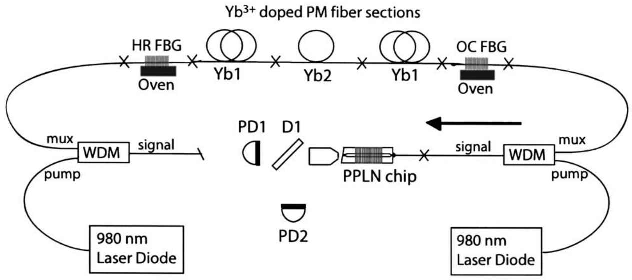

Fig. 1. Experimental setup for the generation of 575 nm laser light: Yb1, silica fiber with moderate Yb doping; Yb2, highly Yb doped silica fiber; WDMs, wavelength-division multiplexers; D1, 575–1150 dichroic beam splitter; PD1, photodetector with 1150 nm spike filter; PD2, photodetector with a 575 nm spike filter; x's splices; muxes, multiplexed ports.

maintaining (PM) Yb-doped fiber with a FBG written on PM fiber spliced at each end of the fiber. All fibers had core sizes and numerical apertures similar to those of Corning PM 980 fiber. The HR and OC gratings had FWHM linewidths of 0.35 and 0.09 nm, respectively. The fiber laser was pumped from both ends with two single-mode 977 nm fiber-pigtailed laser diodes. The power from each laser diode was coupled into the doped fiber through a wavelength-division multiplexer with 85% efficiency, allowing a total incident pump power on the two FBGs of 575 mW.

The gain medium consisted of three sections of fiber with different Yb concentrations. The fibers at each end, each 4 m in length, had relatively low doping levels and a small-signal pump absorption of 80 dB/m. The fiber between them was 2 m long and had a much higher Yb concentration: its small-signal pump absorption was 550 dB/m. The purpose of this highly doped fiber was to introduce sufficient GSA loss in the 1010–1040 nm range to suppress ASE in this range. Its high doping level enabled an overall reduction in length to be made, which reduced its passive propagation loss at 1150 nm. This length reduction has the additional benefit that future oscillators that incorporate extremely narrowband FBGs (or tunable filters) to produce emissions with linewidths of less than 300 MHz can achieve higher powers before they reach the stimulated Brillouin scattering threshold. In principle, it would be best to make the entire gain medium from the highly doped fiber. However, at high pump powers this fiber exhibited photodarkening. We used the moderately doped fibers on the ends to mitigate this effect by reducing the pump power coupled to the highly doped fiber. All fiber ends were cleaved at an angle to prevent parasitic oscillation.

To determine the optimum length of gain fiber for this laser, we developed a simulation code that models our oscillator output power. This code uses the Mueller matrix method to solve the standard coupled laser rate equations applied to a fiber.[11] Simulations showed that, for the pump powers and FBGs available, the optimal fiber length was 3.2 m if only the highly doped fiber was used. We placed a 3.2 m length of highly doped fiber in our laser and observed that the fiber photodarkened. We then reduced this length by ~30 cm and spliced to each end of this new fiber an equal length of moderately doped fiber such that the total small-signal absorption remained approximately the same. This new laser was then tested for photodarkening. This process was repeated until photodarkening was no longer observed. Further reduction of the length of the highly doped fiber resulted in reduced slope efficiencies.

The oscillator was first operated in an unpolarized configuration. A maximum output power of 121 mW was achieved, as shown in Fig. 2. A slope efficiency of 26.4% and an optical efficiency of 21% were measured with respect to the pump power incident on the FBGs. The laser was operated for tens of hours at this power with no sign of photodarkening. The measured threshold and slope efficiency agree well with simulation results (Fig. 2). The only fitting parameter in the simulation was the scattering loss of the Yb fiber at 1150 nm, which was determined to be 110 dB/km. All other parameters were obtained either from the fiber vendor (core size and Yb concentration) or from the literature[8] (Yb cross-section spectra and lifetime) or were measured (FBG spectra).

To achieve a linear output polarization, the polarization-dependent reflection spectrum of the FBGs, due to stress-induced birefringence of the PM fiber, was used. The OC was spliced at 90° to the gain fibers, while the HR was aligned with the gain fibers. The OC was thermally tuned until its fast-axis reflection peak wavelength matched the slow-axis reflection peak wavelength of the HR. This allowed only light polarized on the slow axis of the gain fiber to experience feedback and lase. This configuration yielded a maximum output power of 89 mW and a stable linear polarization state with an extinction ratio of 16 dB. A higher extinction ratio would be achievable with a narrower band HR. The slope and optical efficiencies were 20.4% and 15.5%, respectively.

Figure 3 shows the spectrum of the laser output at the highest power when the laser was operated at a center wavelength of 1150.1 nm. The ASE peak at

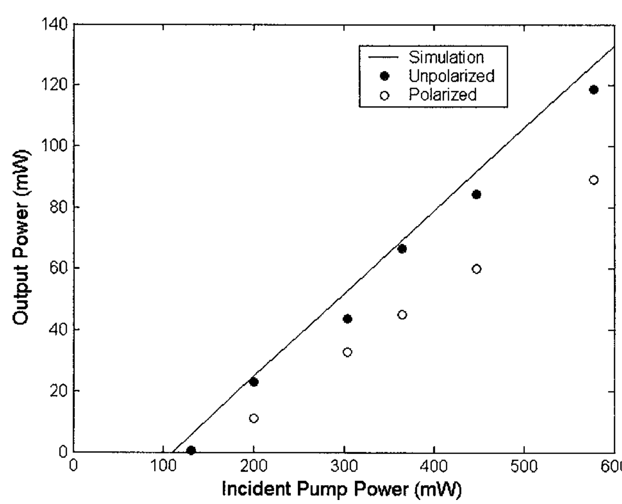

Fig. 2. Signal output power versus incident diode-pump power for a 1150 nm Yb:fiber oscillator for unpolarized and polarized cases. Simulation results are also shown.

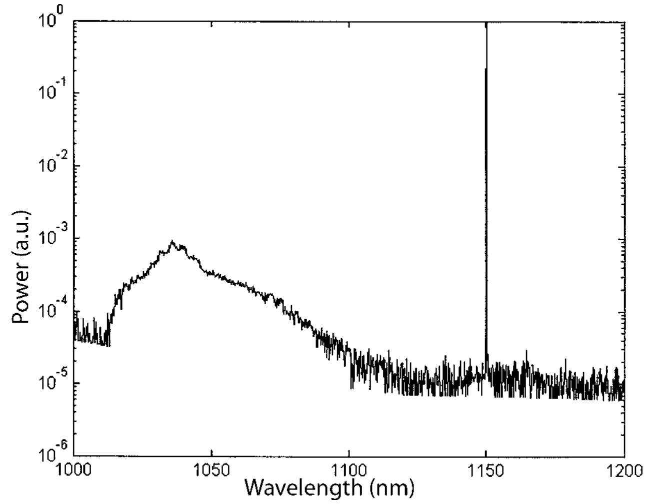

Fig. 3. Output spectrum of 1150 nm linearly polarized Yb:fiber oscillator as measured with an optical spectrum analyzer.

1030 nm was 30 dB below the signal level; and the in-band ASE, more than 45 dB below the signal level. It was determined independently, by measuring the laser power through a narrowband spike filter and integrating the power in the spectrum of Fig. 3, that more than 98% of the output power was in the 1150 nm laser line. The laser linewidth, inferred from measurement of the coherence length of the laser with a Michelson interferometer, was 40 ± 5 pm. Thermally tuning the two FBGs together tuned the laser wavelength by 0.80 nm, with the output power remaining constant to within 0.3 dB. The tuning range was limited by the operating temperature range of the FBGs.

To frequency double the output we used a fiber-pigtailed reverse-proton-exchanged PPLN waveguide. The normalized efficiency of a PPLN waveguide scales with L^2, where L is the length of the poled crystal, while its conversion bandwidth scales with L^{-1}. Consequently the laser linewidth must be less than the acceptance bandwidth of the nonlinear crystal to allow the use of long, uniform-period crystals for high conversion efficiency. We used a 5.2 cm long waveguide chip with a 3 cm periodically poled length and an estimated loss of 0.1 dB/cm at 1150 nm. The poled region had a FWHM conversion bandwidth of 96 pm. While the laser's narrow linewidth allows the use of longer poled regions, the temperature acceptance bandwidth for such a device would have been so narrow that maintaining the required temperature uniformity over the poled region's entire length would have been challenging.

The waveguide had a normalized efficiency[12] of $\sim 200\%$ W^{-1} cm^{-2} and a phase matching temperature of 115.6 °C. Since the chip was not antireflection coated, its output facet was angle polished to prevent optical feedback into the laser. The loss of the laser-to-chip pigtail was estimated at 1.5 dB, which resulted in ~65 mW of infrared power being coupled into the waveguide; improved adiabatic spot-size converters should significantly reduce this loss. At the highest pump power, 40 mW of 575 nm radiation was generated inside the waveguide. The optical-to-optical efficiency of the entire system with respect to incident diode-laser pump power was 7.0%. Signs of photorefraction were observed after several hours of operation, but this issue can be eliminated by replacing the crystal with either periodically poled stoichiometric $LiTaO_3$ (PPSLT) or periodically poled $Mg:LiNbO_3$, which are more resistant to photorefractive damage.[13,14]

In conclusion, we have reported what is to our knowledge the first linearly polarized, diode-pumped, Yb-doped fiber oscillator at a wavelength greater than 1135 nm with an output power greater than 10 mW. The fiber laser produced 89 mW of linearly polarized narrow-linewidth output at 1150 nm, which was frequency doubled to 40 mW at 575 nm in a PPLN waveguide. The system's output power and efficiency are almost 2 orders of magnitude greater than those of prior yellow sources produced by direct frequency doubling of a diode-pumped oscillator. In future experiments we plan to build an oscillator with a linewidth under 500 MHz and amplify it to an average power of 5 W. The amplified output will be frequency doubled by focusing into a damage-resistant PPSLT crystal to obtain several watts of yellow light.

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