60-W green output by frequency doubling of a polarized Yb-doped fiber laser

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The frequency doubling of a 110-W linearly polarized diffraction-limited Yb-doped fiber oscillator power amplifier (FOPA) has generated 60-W near-diffraction-limited linearly polarized green output. The FOPA produces as much as 2.4 kW of peak power and less than 20-pm linewidth at a 10-MHz repetition rate and 5-ns pulse duration without the onset of nonlinear effects. With two lithium triborate crystals at noncritical phase matching, a maximum of 54.5% doubling efficiency has been demonstrated. The overall electrical efficiency to the green portion of the spectrum is 10%. © 2005 Optical Society of America

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High average power, high brightness, linearly polarized green lasers are of great interest for scientific, industrial, medical, and defense applications. Green lasers that produce several hundred watts of power have been demonstrated that are based on Q-switched diode-pumped solid-state lasers, but their beam quality is at least 10 times diffraction limited owing to thermal lensing effects in the diode-pumped solid-state lasers. Yb-doped fiber lasers have demonstrated diffraction-limited beam quality at powers of kilowatts, as the beam quality is determined by the fiber structure instead of by thermal lensing effects as in diode-pumped solid-state lasers. Combining the high efficiency, compact size, and high brightness of fiber lasers with second-harmonic generation (SHG) is an attractive alternative that will facilitate many applications.

There has been success in generating high-power green lasers by use of the SHG of fiber laser sources. Usually KTP or periodically poled KTP (PPKTP) is used, because these nonlinear crystals require relatively low pulse energies or average powers for efficient conversion. A 6-W average power green laser was demonstrated by use of the combination of a laser-diode-seeded Yb fiber amplifier and quasi-phase-matched SHG in PPKTP. Unfortunately, the beam quality was not reported, and the efficiency rolled over at higher average power owing to local heating in the PPKTP crystal. Creation of color centers, or gray tracks, in KTP has also been reported for high-power cw and Q-switched lasers. Therefore, using PPKTP or KTP to achieve high conversion efficiency for cw or low-peak-power fiber lasers will face many obstacles, such as degradation in beam quality, power instability, and crystal damage.

In general, for efficient SHG, narrow linewidth and high peak power are desired. However, conventional Yb-doped high-power fiber laser oscillators usually operate with broad linewidths owing to the broad gain bandwidth and the nature of inhomogeneous broadening of the rare-earth-doped gain medium. For a conventional fiber laser oscillator without special linewidth control, the fiber laser’s linewidth can be as much as several tens of nanometers. In addition, high-power fiber lasers may also suffer from the onset of nonlinear effects, such as stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), four-wave mixing, and self-phase modulation, which will not only broaden laser linewidth but also affect laser stability.

In this Letter we report a 60-W, 10-MHz, linearly polarized green laser based on a frequency-doubled fiber laser. To produce narrow linewidth and high peak power we use a fiber oscillator power amplifier (FOPA) configuration. With an Yb-doped large-mode-area (LMA) fiber, the FOPA operating at a high repetition rate with a short pulse duration has generated as much as 2.4 kW of peak power without the onset of nonlinear effects. The diffraction-limited beam quality from the FOPA allows us to replace KTP or PPKTP with two LBO crystals to increase the interaction length to achieve efficient SHG without gray tracking problems.

The green laser based on frequency doubling of the FOPA consists of a cw fiber oscillator, an amplitude modulator, a fiber preamplifier, a fiber power amplifier, and a second-harmonic generator, as shown schematically in Fig. 1. The cw Yb-doped fiber oscillator with two fiber Bragg gratings generates a
The laser linewidth was measured to be less than 20 pm, and the measured linewidth is limited by the resolution of the optical spectrum analyzer. The cw laser light is then modulated by an amplitude modulator, which can vary the pulse duration and the repetition rate separately. The pulse duration of the seed source can be varied from hundreds of microseconds to nanoseconds, and the repetition rate can be varied from hundreds of kilohertz to hundreds of megahertz. The average output power after the modulator is determined by the modulation duty factor. At a 10-MHz repetition rate (100-ns repetition period) and 5-ns pulse duration, a duty factor of 0.05 produces approximately 1 mW of average signal power. The signal is then amplified by a single-mode Yb-doped fiber preamplifier. The maximum output power from the preamplifier is 200 mW, and the maximum gain is 23 dB. Fiber isolators are used between the fiber oscillator, the preamplifier, and the fiber power amplifier stages to protect each stage from backreflection, which can affect the performance of each stage. As the ratio of pulse duration to repetition period varies, the seed source provides a range of peak powers, and the preamplifier has reached a peak power of tens of watts without the onset of nonlinear effects.

The fiber power amplifier uses an Yb-doped polarization-maintaining double-clad LMA fiber with a fundamental mode-field diameter of 18 μm and a numerical aperture of 0.06. Compared with conventional single-mode double-clad fibers, the LMA fiber provides higher absorption and larger mode-field diameter, which thus reduce the fiber length and signal power intensities that are the key parameters for reducing the nonlinear effects. The fiber length of 10 m absorbs 98% of the pump power at 976 nm. The single-mode linearly polarized pulsed signal from the preamplifier is launched into the LMA core with a set of specially designed lenses that achieve mode matching between the single-mode fiber and the LMA fiber to selectively excite the fundamental mode. To achieve a maximum polarization-extinction ratio, the fiber’s stress-rod plane (or slow axis) is aligned parallel to the polarization of the seed light. The pump light is launched into the LMA fiber opposite the pump end, as shown in Fig. 1. The pump wavelength is set to the strongest absorption peak near 976 nm to shorten the fiber, thus minimizing possible nonlinear effects. The dielectric mirror for separating the pump light and the amplified signal provides >99% reflectance at 976 nm and <2% reflectance at 1080 nm. All lenses are antireflection coated for both pump and signal wavelengths to reduce undesirable backreflection. The maximum power from the fiber-coupled laser diode is 200 W, and the coupling efficiency between the laser diode and the fiber is estimated to be 85%.

At a 10-MHz repetition rate and a 5-ns pulse duration the fiber power amplifier produces as much as 120 W of output power, corresponding to a slope efficiency of 71% with respect to the launched power, as shown in Fig. 2. The polarization-extinction ratio is better than 95%. The beam quality, measured with a Model BeamScan-XYGEPREC beam scanner from Photon, Inc., is 1.1 times diffraction limited. No linewidth broadening beyond the 20-μm instrumental resolution or nonlinear effects have been observed, even at 120-W output power.

The efficiency of conversion to green output may be increased by reduction of the duty factor, which thereby increases the peak power. This may cause nonlinear effects in the fiber. Among fiber nonlinear effects, SBS has the lowest threshold for a narrow-linewidth system, but SBS can be prevented by a simple reduction of the pulse duration to well below 16 ns. Once the SBS is suppressed, the maximum peak power of the fiber power amplifier is limited by either SRS or material damage. For a 10-m-long fiber with a mode-field diameter of 18 μm, the SRS threshold can be estimated for a linearly polarized beam by use of Raman gain coefficient \( g_R = 1 \times 10^{-13} \) m/W and assuming a uniform signal distribution along the fiber length to be \( 16^4 A / g_R L = 4 \) kW. When the fiber power amplifier is end pumped, the nonuniform signal distribution along the fiber length will make the SRS threshold much higher than 4 kW. To be conservative, we used a 5-ns pulse duration and a 10-MHz repetition rate to enhance the peak power by a factor of 20. As a result, 2.4-kW peak power is generated from the fiber power amplifier at the maximum average power of 120 W.

Lithium triborate (LBO) is used as the frequency-doubling crystal even though it has a relatively low nonlinear coefficient compared with KTP and PPKTP. This is so because multikilowatt peak power is sufficient for a long LBO or multiple crystals to achieve high efficiency without suffering from gray tracking. As it is difficult to obtain a high-quality long crystal and increasing the number of crystals will affect system complexity and may also induce unwanted phase shifts, a system with dual long crystals was chosen. The two antireflective-coated LBO crystals are 25 mm long and cut for noncritical phase matching at the 1080-nm operating wavelength. Based on the manufacturer’s specifications and on the experiments, the two crystals have similar optical characteristics. Each of the crystals is mounted in a temperature-controlled oven with a crystal separation of 5 mm to

![Fig. 2. Output power of the fiber power amplifier versus launched pump power. Inset, measured \( M^2 \) for both || and \( \perp \) polarization at 110 W.](image-url)
Fig. 3. Dependence of the green signal on LBO temperature.

Fig. 4. Green output power versus fundamental power. Inset, measured $M^2$ of the green power for both $||$ and $\perp$ polarization at 50 W.

Keep the effective optical path as short as possible. The beam from the fiber power amplifier is focused by a 15-cm focal-length lens, and the beam waist is 56 $\mu$m ($1/e^2$) as measured by the high-resolution BeamScan beam scanner (resolution, $<4 \mu$m). Following the crystals, two dielectric filters are used to separate green and fundamental beams. The green signal was measured as a function of crystal temperature at low power and is shown in Fig. 3. The temperature tolerance for efficient phase matching is approximately 2°C (FWHM). The green output is shown versus fundamental power in Fig. 4. At 110-W fundamental power, as much as 60 W of green power is produced, corresponding to maximum conversion efficiency of 54.5%. The peak power of the fiber power amplifier at 110 W is estimated to be 2.2 kW. The beam quality of the green laser is 1.33 times diffraction limited. Although all crystal temperatures are optimized at low power, they provide efficient frequency doubling at 60 W of green output power with no temperature adjustment.

In our experiment the pulse duration is limited by the speed of the available modulator driver. The maximum modulation frequency of the modulator can be as much as 10 GHz; replacing the modulator driver can easily reduce the pulse duration to 500 ps and increase the pulse repetition rate to 100 MHz. With instruments of the same peak power and configuration, we expect to demonstrate similar performance.

In conclusion, we have demonstrated a highly efficient, near-diffraction-limited linearly polarized 60-W green laser based on the frequency doubling of a fiber laser. The overall electrical efficiency to green is 10%.

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