Optics Letters

Highly efficient 400 W near-fundamental-mode green thin-disk laser

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Received 27 October 2015; revised 4 December 2015; accepted 4 December 2015; posted 7 December 2015 (Doc. ID 252537); published 22 December 2015

We report on the efficient generation of continuous-wave, high-brightness green laser radiation. Green lasers are particularly interesting for reliable and reproducible deep-penetration welding of copper or for pumping Ti:Sa oscillators. By intracavity second-harmonic generation in a thin-disk laser resonator designed for fundamental-mode operation, an output power of up to 403 W is demonstrated at a wavelength of 515 nm with almost diffraction-limited beam quality. The unprecedented optical efficiency of 40.7% of green output power with respect to the pump power of the thin-disk laser is enabled by the intracavity use of a highly efficient grating waveguide mirror, which combines the functions of wavelength stabilization and spectral narrowing, as well as polarization selection in a single element.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3580) Lasers, solid-state; (140.3515) Lasers, frequency doubled; (050.1950) Diffraction gratings.

http://dx.doi.org/10.1364/OL.41.000171

The emergence of e-mobility, as well as the large-scale development and installation of renewable energy sources, has driven the demand for reliable and durable high-power electric circuitry and battery technology. In this context, reliable, efficient, and reproducible deep penetration welding processes of copper have been of increasing interest in the last few years. Due to its unique material properties, however, reliable laser welding of copper is still a challenging task. Its high thermal conductivity impedes efficient localized heat deposition, while the very low absorptivity of copper in the near-infrared regime at room temperature of below 5%, along with the sudden increase of absorption at the melting point, makes the welding process very challenging to control and susceptible to variations in the surface conditions of the workpiece.

Both of these problems can be addressed by using high-power, high-brightness frequency-doubled solid-state laser sources emitting in the green wavelength range. At these wavelengths, the absorptivity of copper at room temperature amounts to 40% [1]. Together with the smaller focus diameters and, hence, higher intensities achievable by close to fundamental-mode continuous-wave laser beams, this potentially leads to continuous high-quality weld seams even at high feed rates [2]. Therefore, both reproducibility and quality of copper welding technology could be taken to a new level by using a high-power, high-brightness green laser source. Frequency-doubled thin-disk lasers [3] are well suited for the task of copper welding due to their insensitivity to back reflections from the workpiece and the potential for high output powers at good beam quality.

Apart from direct material processing applications, frequency-doubled high-power laser sources emitting in the green spectral range are very interesting pump sources for high-power Ti:Sa oscillators, as high-power laser diodes are not available in this wavelength regime. Frequency-doubled thin-disk lasers have been successfully used as pump sources in various high-power or high-energy Ti:Sa-based laser systems [4,5]. For the investigation of Ti:Sa laser oscillators which are based on the thin-disk laser concept, high-power green pump sources are a prerequisite to overcome the limited gain imposed by the very short crystal length [6].

So far, however, high average output powers in the visible spectral range have been demonstrated mainly for pulsed systems. By intracavity second-harmonic generation (SHG) of a Q-switched thin-disk laser emitting pulses with duration on the order of 100 ns, up to 1.8 kW of average output power, have been achieved [7]. Recently, extra-cavity frequency conversion has been demonstrated in the picosecond regime with up to 820 W of average output power and a very high SHG conversion efficiency of about 70% [8].

For continuous-wave operation, the highest output power at diffraction-limited beam quality reported so far was achieved by external frequency doubling of a 1 kW single-mode fiber laser, leading to 350 W of output power in the frequency-doubled output beam [9]. For high-power thin-disk lasers operating in continuous wave, the efficiency of intracavity frequency conversion is still limited by the losses and thermal lensing issues induced by additional intracavity elements needed to achieve stable phase-matching conditions. So far, up to 470 W of frequency-doubled output power was demonstrated in multimode operation [10] using conventional approaches for frequency and polarization control. By using a special grating-waveguide end mirror (GWM) in a highly multimode thin-disk laser resonator, up to 1 kW of frequency-doubled output power have recently been demonstrated in CW operation [11].

Current limitations of common approaches for intracavity frequency doubling are apparent when it comes to nearly diffraction-limited thin-disk lasers: the highest output power demonstrated to date is 255 W with an overall optical efficiency of 30% [12]. In the new approach reported in this Letter, we exploit the power capability of GWMs to scale the output of intracavity frequency-doubled continuous-wave thin-disk lasers with almost diffraction-limited beam quality. By the use of such a highly efficient grating mirror which combines the functions of wavelength stabilization, spectral narrowing and polarization selection in a single element, up to 403 W of output power at a wavelength of 515 nm with almost diffraction-limited beam-quality could be demonstrated at an unprecedented total optical efficiency of about 40% of frequency-doubled output power versus pump power incident to the disk laser. To the best of our knowledge, this is both the highest reported output power and the highest efficiency that has been reported so far for a near-fundamental mode frequency-doubled CW thin-disk laser.

For stable phase-matching conditions, the spectral width of the oscillating laser radiation has to be narrowed down sufficiently and stabilized to reliably match the spectral acceptance bandwidth of the nonlinear crystal. Furthermore, for critical phase matching, a stable and well-defined state of linear polarization has to be guaranteed. Usually, a set of one or multiple etalons is used for bandwidth narrowing and frequency stabilization, whereas thin-film polarizers or Brewster plates are used for polarization control [10]. Each of these additional elements inside the resonator increases the overall round-trip losses for a given cavity and, therefore, diminishes the overall efficiency. Furthermore, thermally induced distortions arising from these additional elements limit the resonator stability at increasing average powers, resulting in significant degradations of the beam quality and limitations of the usable power range. This is most pronounced in fundamental-mode operation.

In our approach, the functions of wavelength and polarization selection are combined in a single reflective diffractive element, reducing both round-trip losses and thermally induced distortions, compared to the use of transmissive intracavity elements. The highly efficient grating waveguide mirror (GWM) [13] is deployed as one of the cavity end mirrors. The GWM is operated in Littrow configuration, where the −1st diffraction order is fed back into the resonator. Since, due to the dispersion of the grating, the Littrow angle exhibits strong wavelength dependence, this feedback mechanism exerts a strong wavelength selectivity. Furthermore, being polarization selective by design, the use of the GWM leads to a pure linear polarization of the intracavity laser beam.

The resonator setup used for the experimental investigations is shown in Fig. 1. A 130 μm thick 10 at. % Yb:YAG disk provided by TRUMPF Laser GmbH with a diameter of 15 mm was mounted on a diamond heat sink and used throughout all of our experiments. The mounted disk had a radius of curvature of 3.58 m. The disk was pumped into the so-called zero-phonon line at a wavelength of 969 nm using spectrally stabilized laser diodes to reduce the thermal load in the laser crystal, compared to standard pumping around a wavelength of 940 nm [14]. The resonator was designed to provide about 70% of overlap between the fundamental mode and the pump spot with a diameter of 5.5 mm and, subsequently, was fine tuned to achieve close to diffraction-limited beam quality throughout the power range.

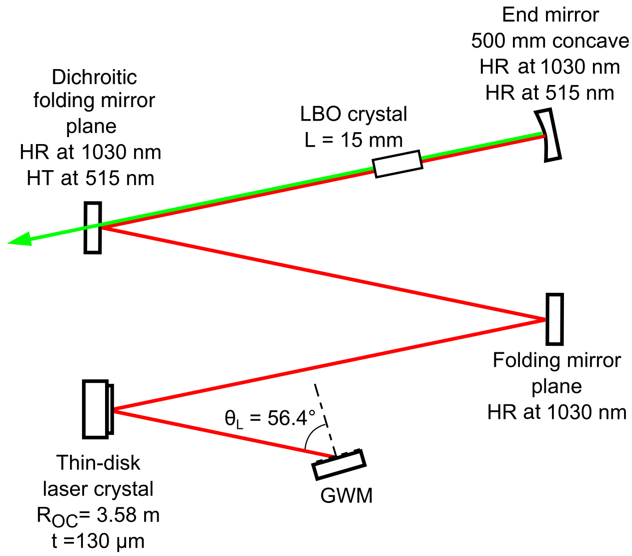

Fig. 1. Experimental setup.

In the first step, the performance of the GWM was tested in the resonator without SHG. For this purpose, the LBO crystal provided by Cristal Laser was removed, and the concave end mirror was replaced by a concave output coupler with 4% of transmission. As shown by Fig. 2, in this setup the laser emitted 620 W of output power with an optical efficiency of 51.6%. When the GWM was replaced by a standard plane HR end mirror, the laser emitted up to 730 W of power in an unpolarized beam with an optical efficiency of 58%. The marginal drop in efficiency when using the GWM may be explained by its slightly lower reflectivity of >99.7%, along with losses due to thermally induced depolarization in the thin-disk laser crystal. In both cases, the beam quality at maximum output power was measured to be $M_x^2 < 1.3$ in the horizontal plane (drawing plane in Fig. 1) and $M_y^2 < 1.2$ in the vertical plane.

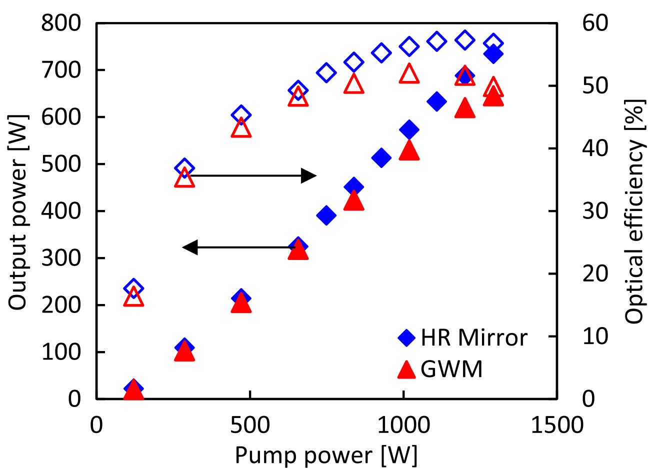

Fig. 2. Performance of the fundamental-mode laser without SHG, either with a standard HR mirror (diamonds) or the GWM (triangles) used as an end mirror.

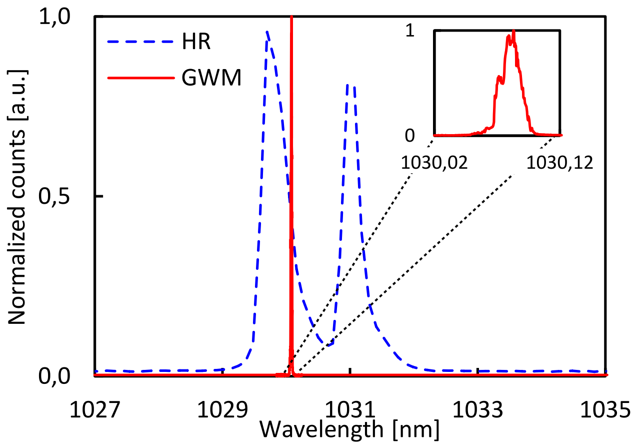

Fig. 3. Measured spectrum of the laser beam emitted from the laser without SHG, either with a standard HR mirror (dashed line) or the GWM (solid line) used as the end mirror. The measurements were taken at a pump power of 1 kW.

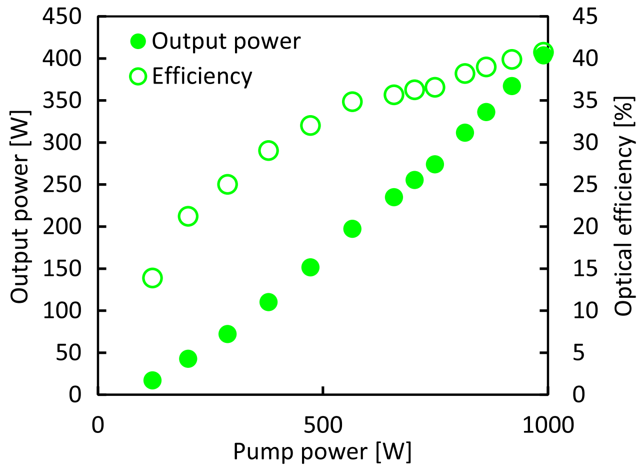

Fig. 4. Overall performance of the frequency-doubled laser.

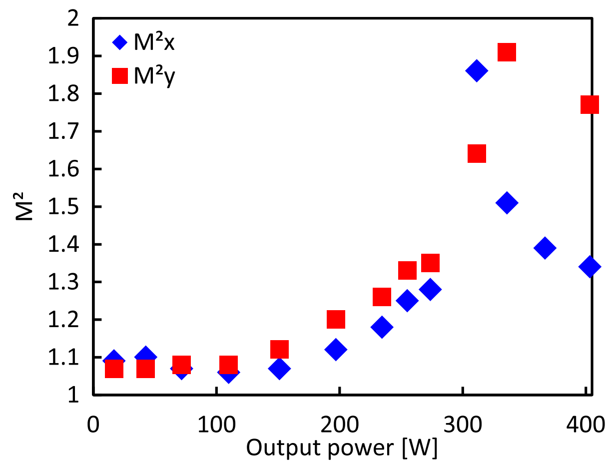

Fig. 5. Measured beam quality of the frequency-doubled output in the horizontal (diamonds) and vertical (squares) planes, respectively, as a function of the output power.

The comparison shows that the use of the GWM reduces the optical efficiency by moderate 6.4%, but with the significant advantage of a linearly polarized output in a substantially narrower and stable spectral bandwidth, as shown in Fig. 3. With the GWM used as an end mirror, the emitted spectral bandwidth was measured to be $\Delta\lambda \approx 20$ pm FWHM at a central wavelength of 1030.07 nm. In the setup with the standard HR end mirror, the spectral width was approximately 1.5 nm $< \Delta\lambda < 2$ nm FWHM which is two orders of magnitude wider.

After the confirmation of the stable spectral narrowing obtained by means of the GWM, the lithium–triborate (LBO) crystal was introduced for the resonator (now again in the setup shown in Fig. 1) for intracavity second-harmonic generation. The LBO crystal was cut for type I phase matching at a temperature of 50°C. The size of the crystal was 15 mm × 4 mm × 4 mm. To obtain an efficient conversion efficiency, the necessary high-power densities in the crystal were reached by designing the cavity for a beam diameter at the crystal's position of about 460 μm. Furthermore, the cavity was adapted with respect to an assumed maximum thermal lens in the thin-disk laser crystal of about $-0.02\ \mathrm{m}^{-1}$, as well as up to $0.5\ \mathrm{m}^{-1}$ in the LBO crystal, leading to an almost constant beam diameter both in the LBO and on the disk throughout the intended power range. The performance of the frequency-doubled laser is shown in Fig. 4.

Up to 403 W green laser radiation was generated at an unprecedented overall optical efficiency of 40.7% with respect to the pump power of the thin-disk laser. At a maximum pump power of 1 kW, the fundamental IR laser power leaking through the dichroitic folding mirror was measured to be less than 2 W and, hence, negligibly small. With the overall efficiency still increasing at this point, further power scaling of this system should be possible in principle.

However, as can be seen from Fig. 5, a slight degradation of beam quality was observed starting at around 300 W of output power. While the beam quality can be considered as diffraction limited up to an output power of 300 W ($M^2 < 1.35$), an increase of M^2 value was observed at higher powers, predominantly in the vertical plane. This effect is presumably due to a power-dependent thermally induced change of the critical phase-matching angle, so that either the crystal has to be slightly realigned at each power level, or the temperature of the crystal oven has to be adapted accordingly. By readjusting the crystal for maximum efficiency at output powers above 300 W, the beam quality could be slightly improved again for the higher output powers. However, due to the comparatively small aperture of the currently available crystal of 4 mm × 4 mm, the angular tuning range was too limited to allow for more significant optimizations. Therefore, we could not make use of the full 1.3 kW of pump power available. However, we are confident that by using larger crystals and an improved crystal oven, these limitations can be overcome, and the full pump power available can be exploited.

In summary, we have demonstrated an intracavity frequency-doubled thin-disk laser providing a green output power of up to 403 W with an unprecedented optical efficiency of 40.7% and close to diffraction-limited beam quality. This high performance was achieved by using efficient grating-waveguide mirrors for combined wavelength and polarization selection.

The onset of thermally induced effects in the LBO crystal observed at output powers exceeding 300 W indicate that the length of the LBO crystal should be optimized, and a better control of the crystal temperature will be required for further power scaling.

Funding. Seventh Framework Programme (FP7) (619177).

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