High-power and high-efficiency frequency-doubled fundamental-mode thin-disk laser

Tom Dietrich*, Stefan Piehler, Martin Rumpel, Thomas Graf and Marwan Abdou Ahmed

Institut für Strahlwerkzeuge (IFSW), University of Stuttgart, Pfaffenwaldring 43, 70569 Stuttgart, Germany

**tom.dietrich@ifsw.uni-stuttgart.de*

Abstract: A highly efficient grating mirror for intra-cavity wavelength and polarization stabilization in a frequency-doubled Yb:YAG thin-disk laser enables up to 403 W of output power at an unprecedented efficiency of 40.7% in close-to fundamental-mode operation.

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1. Introduction

Driven by the increasing demand for copper components, e.g. in electromobility, renewable energy and battery technology, reliable deep penetration welding processes of copper have been of increasing interest in the last few years. Being insensitive against back-reflections from the workpiece, high brightness cw thin-disk lasers have become the ideal tool for welding of highly-reflecting materials, allowing for welding speeds of several meters per minute at welding depths of some millimeters, guaranteeing stable and reproducible process results.

Due to its very low absorption in the near infrared regime ($<$ 5% at room temperature) and the high thermal conductivity of 390 $W/(mK)$, copper is still a challenging material when it comes to laser welding, as very low feed rates are required resulting in many spatters and melt ejections, which lead to an inhomogeneous seam surface and defects in the weld seam. This problem can be circumvented for instance by using laser radiation in the green regime, as with about 40% at room temperature, the absorption for this wavelength regime is significantly higher in copper [1], so that at this point, a high-power, high-brightness green laser source could lead to a new level of high quality and high reliability copper welding technology. Whereas for pulsed systems, high average powers have been demonstrated in the green regime both for intra-cavity [2] (1,8 kW average output power, pulse duration between 100 ns and 300 ns) and extra-cavity frequency doubling [3] (820 W average output power at 70% efficiency), efficient high-power fundamental-mode cw operation using intra-cavity frequency conversion is still limited by losses and thermal lensing issues induced by the additional intra-cavity elements needed for wavelength and polarization stabilization such as etalons and thin-film polarizers. The highest output power demonstrated to date is 255 W with an optical efficiency of 30% [4] and 470 W in multimode operation [5]. In the present contribution, we use a highly efficient grating mirror for intra-cavity wavelength and polarization stabilization, enabling the extraction of 403 W of green radiation in fundamental-mode at an efficiency exceeding 40%.

2. High-power frequency-doubled fundamental-mode Yb:YAG thin-disk laser in cw operation

For stable and efficient phase-matching conditions, a well-defined linear polarization state as well as narrow spectral bandwidth operation is necessary to achieve efficient second harmonic generation. In current systems, the polarization state is fixed by using Brewster windows or thin-film polarizers, whereas the frequency-selection and narrowing is achieved by using one or multiple etalons inside the cavity [5]. As each of these elements generates additional losses, overall efficiency is limited by the higher round-trip cavity losses. Furthermore, each of these elements can suffer from thermal lensing and hence limits resonator stability.

In our approach, the functions of wavelength and polarization selection are combined in a highly efficient grating mirror operating in Littrow configuration and replacing one of the cavity end mirrors. A detailed description of this device can be found in [6]. For our laser experiments, a 130 μm thick, 15 mm diameter, 10 at.% Yb:YAG disk with a radius of curvature of 3.85 m, mounted on a diamond heat sink was pumped with a pump spot diameter of 5.5 mm. By pumping at the zero-phonon-line of Yb:YAG at 969 nm, heat generation can be reduced in comparison to standard 940 nm pumping.

In the laser experiments, a W-shaped resonator according to fig. 1 was used. This resonator was first optimized for fundamental-mode operation at 1030 nm by replacing the concave HR end mirror by an output coupling mirror with

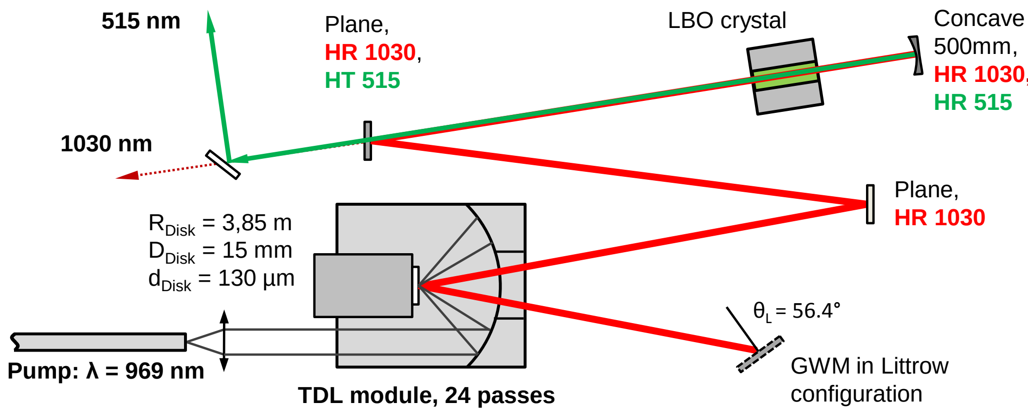
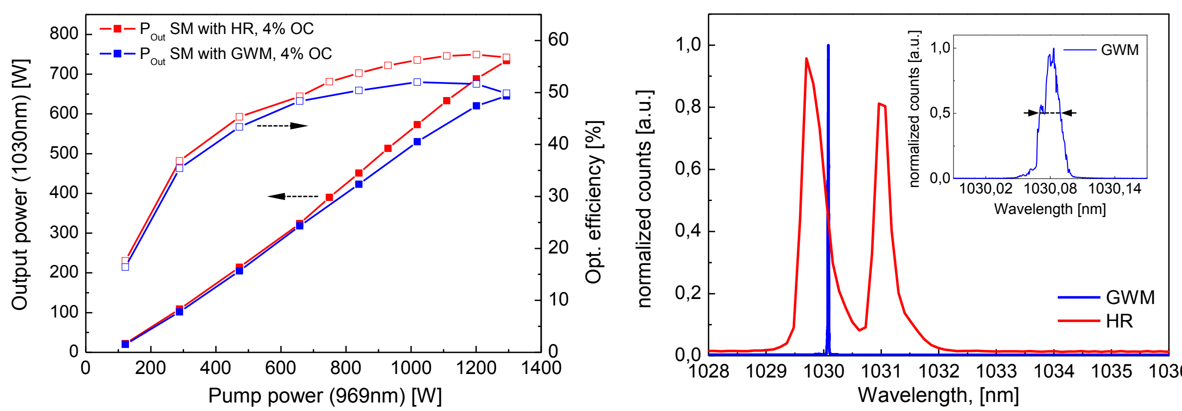


Fig. 1. Schematic diagram of the thin-disk laser setup. The W-resonator consists of the Yb:YAG disk, the grating mirror and three additional mirrors.

4% of transmission. The experiments were conducted in both cases i.e. with HR and with the GWM. With the GWM, an output power of 620 W (lin. polarized) with an optical efficiency of 51.6% could be extracted at 1030 nm, whereas up to 730 W (unpolarized) with an optical efficiency of 58% was achieved with the HR mirror. In fig. 2(a), the power and efficiency characteristics of the IR-resonator with the GWM are compared to that with a standard HR mirror.



(a) (b)

Fig. 2. (a): Comparison of power characteristic of the IR-resonator with HR as well as grating end mirror. (b): Longitudinal spectrum with and without grating mirror.

At maximum power, the beam quality was measured to be $M_x^2 = 1.3$ and $M_y^2 = 1.2$. The spectral bandwidth $\Delta\lambda$ was measured to be 20 pm FWHM at a central wavelength of 1030.07 nm with the GWM in place, showing the efficient wavelength selection when compared to $\Delta\lambda$ = 2 nm FWHM measured with a HR end mirror. The measured spectra of the emitted laser beams for both resonators are shown in fig. 2(b).
Subsequently, for intra-cavity second-harmonic generation, a (15x4x4) mm^3 lithiumtriborate (LBO) crystal cut for type I phase-matching at $50°C$ was introduced in the cavity. For high conversion efficiency, the cavity was designed for a beam diameter at the crystal's position of about 460 μm, being almost constant within the intended power range. With this setup, up to 403 W near fundamental-mode green laser radiation could be generated with a high green-to-pump power efficiency (P_{515nm}/P_{969nm}) of 40.7% (see fig. 3). At maximum output power the residual IR power was measured to be 2 W leading to the conclusion that the infrared power content in the measurement is negligibly small. Whereas at 403 W the beam quality was measured to be $M_x^2 = 1.3$ and $M_y^2 = 1.7$ due to thermal effects inside the LBO crystal, the beam quality in both axes was measured to be $M^2 < 1.3$ for output powers of up to about 300 W.

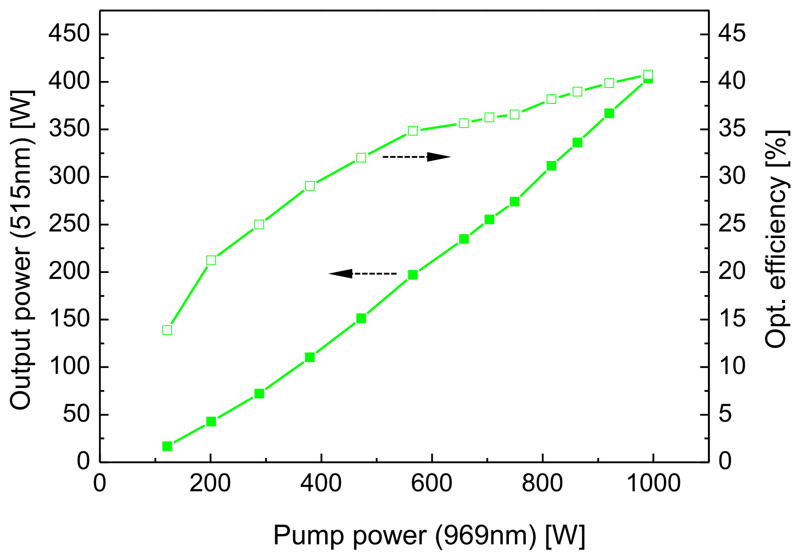


Fig. 3. Output power characteristic and optical efficiency of second harmonic frequency generation.

3. Conclusion

In summary, we have demonstrated a close-to fundamental-mode operation of an intra-cavity frequency-doubled green thin-disk laser at an output power of 403 W with an unrivalled optical efficiency of 40.7%. A beam quality factor of $M_x^2 = 1.3$ and $M_y^2 = 1.7$ was demonstrated so far. As the total efficiency was still increasing at this point, we believe that both output power and beam quality can be further improved. Recent results of the ongoing experiments will be presented at the conference.

4. Acknowledgements

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