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Nonlinear-Mirror Modelocked Thin-Disk Laser Delivering 21 W Average Power with 324-fs Pulses

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Abstract: We present the first nonlinear-mirror modelocked thin-disk laser. We achieve 21 W of average power at 324 fs of pulse duration, which is an order-of-magnitude shorter than previously demonstrated with this technique in bulk lasers.

OCIS codes: (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers; (190.7110) Ultrafast nonlinear optics

1. Introduction

Ultrashort-pulsed sources with high peak and average power are important for many industrial and scientific applications. Reaching the required performance directly from a laser oscillator, without an amplification system, offers a compelling route to reducing system complexity and improving reliability. Thin-disk lasers (TDLs) currently offer the highest performance of any modelocked laser oscillator technology in terms of average power and excellent beam quality. Modelocked with semiconductor saturable absorber mirrors (SESAMs), Yb:YAG TDLs achieved 275 W of average power with 583-fs pulses and 80 uJ of pulse energy with 1.07-ps pulses [1]. Pushing the pulse durations to significantly shorter values at high output power, however, becomes challenging due to two-photon absorption and comparatively long recovery times. Alternatively, Kerr-lens modelocking (KLM) based on Yb:YAG resulted in 270 W of average power with 330-fs pulses [2] and 155 W with 140-fs pulses [3]. However, KLM relies on cavity designs close to their stability edge, which introduces additional challenges in alignment sensitivity and stability.

Here, we present the first TDL modelocked by the frequency-doubling nonlinear-mirror (FD-NLM) modelocking technique [4, 5]. In this proof-of-principle result we achieve 21 W of average power with 324-fs pulses and, in another configuration, 28 W with 600-fs pulses from an Yb:YAG TDL. Compared to prior results of FD-NLM modelocking in bulk lasers [6-8], we decrease the achieved pulse durations by an order of magnitude (Fig. 1c). We demonstrate good agreement of our experimental results with a newly developed numerical simulation of the process and outline the path towards further power scaling.

The FD-NLM process is ideally suited for high-power short-pulsed TDL operation as it provides an easily scalable modulation depth and, in analogy to SESAM modelocking, does not require operation close to the cavity stability edge. Additionally, the FD-NLM technique features a high damage threshold and involves negligible thermal load, which avoids heat-removal challenges. Furthermore, this approach allows for straightforward power scaling via an increase of the spot size on the nonlinear crystal.

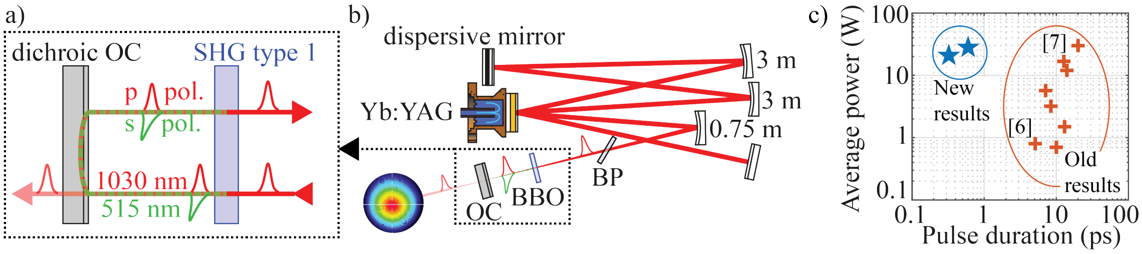

Fig. 1 a) schematic of the frequency-doubling nonlinear-mirror modelocking (FD-NLM) technique (OC – output coupler, SHG – second-harmonic generation) b) sketch of the cavity design (BP – Brewster plate) c) Our thin-disk laser results decrease the achieved pulse durations with the FD-NLM technique by an order of magnitude to sub-350 fs, at output powers approaching 30 W.

The FD-NLM modelocking technique combines an intracavity nonlinear crystal and a dichroic output-coupling (OC) mirror to result in an intensity-dependent reflectivity (Fig 1a). During the first pass of the fundamental through the nonlinear crystal, part of it converts to the second harmonic (SH). The fundamental is partially reflected by the OC while the SH is totally reflected. During the returning pass through the nonlinear crystal, the reverse process, degenerate optical parametric amplification (OPA), converts the SH back to the fundamental. Adjusting the distance between the nonlinear crystal and the OC mirror allows for tuning the phase offset between the fundamental and the SH and optimizing the OPA process. Overall, this modelocking process results in a lower OC transmission rate for high peak intensity light due to the higher efficiency of the nonlinear process. Effectively, it acts as a saturable loss, which enables modelocking.

So far, the FD-NLM technique only modelocked bulk solid-state lasers with pulse durations in the multi-ps regime, high repetition-rates (~100 MHz), and, most of the time, only for few-W output powers (Fig. 1c). The resulting limited intracavity peak powers required using long nonlinear crystals as well as tight focusing geometries into the nonlinear medium. Due to this, the phase-matching bandwidths, and pulse durations, were strongly limited because of group velocity mismatch and spatial walk-off. High-power ultrafast TDLs overcome these problems as their high intracavity peak powers allow for driving the nonlinear process with short crystals, which results in larger bandwidths and a corresponding short response time of the saturable loss.

Our proof-of-principle demonstration of 21 W of average power with order-of-magnitude reduced pulse durations of 324-fs opens the door towards a new class of high-power short-pulsed modelocked thin-disk oscillators based on the FD-NLM technique.

2. Experimental setup and simulations

We present a schematic of the cavity layout used in our laser in Fig. 1b. The 230-μm thick, 5-at.% doped Yb:YAG disk was polished and coated by Dausinger + Giesen. It is mounted in a 24-pass head with a 2.1-mm diameter pump spot and pumped up to 160 W. In a double-pass configuration over our gain crystal without the nonlinear medium included, we achieve up to 30 W of output power with 33% optical-to-optical efficiency in continuous-wave single-mode operation ($M^2<1.1$). We custom designed our OC with 19.7% transmission at the fundamental wavelength (1030 nm) and high reflection at the SH (515 nm). To start the FD-NLM modelocking process, we insert a 0.5-mm-thick type-1 BBO crystal close to a cavity focus on our OC mirror (beam waist 185 μm). The crystal is cut for phase matching at 1030 nm with both faces anti-reflection coated for 1030 nm and 515 nm. We achieve the correct phase offset for high-efficiency OPA by tuning the spacing between the nonlinear crystal and the OC between 5 mm and 8 mm. Flat dispersion-compensating mirrors providing negative group delay dispersion are used in the cavity to balance the self-phase modulation (SPM) picked up in air, in the BBO crystal, and in the Brewster plate (BP), which we inserted for polarization control.

In the FD-NLM modelocking technique, the effective OC rate of the cavity changes with the efficiency of the nonlinear process, which is dependent on the peak intensity in the nonlinear crystal. Therefore, the higher the intensity of the light, the more we saturate our loss, i.e. the more we exploit our modulation depth. Additionally, for a given configuration, increasing the pump power decreases the effective transmission, which results in a non-linear relation between output power and pump power. Furthermore, by slightly varying the phase offset via the distance between BBO and OC, we can reduce the FD-NLM effect and thus optimize our cavity for operation at higher output powers or shorter pulses.

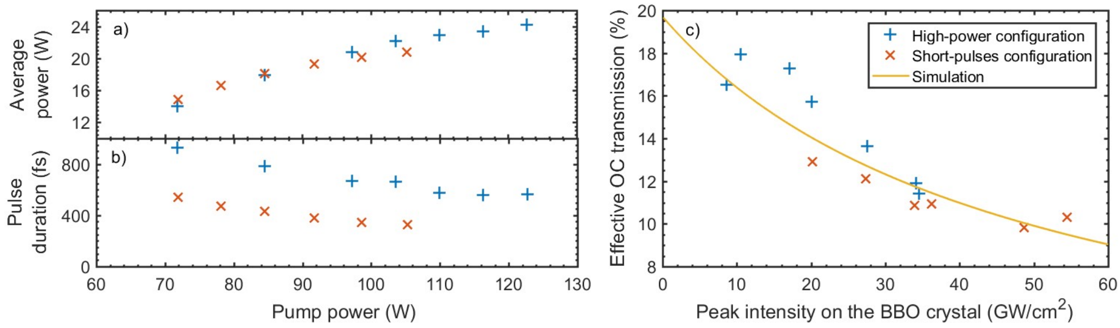

Fig. 2. a) and b) Characterization of pulse duration and average power versus the pump power. Blue ('high-power configuration') and orange ('short-pulses configuration') data points refer to experimental data for different phase offsets. c) Saturable loss effect of the nonlinear mirror, the solid line is the prediction of our simulation.

We present two characterizations of output power and pulse duration versus pump power in Fig. 2. Here, by adjusting the phase matching, we adapted the loss saturation (Fig. 2c) and optimized one configuration for high power (blue crosses), and one for short pulse duration (red crosses). In the two cases presented in Fig. 2 we included a total round-trip cavity GDD of -5900 fs^2 from the mirror and obtained pulse durations down to 324 fs at 21 W of output power. Our shortest pulses are supported by an optical spectrum with a full-width at half maximum (FWHM) of 4.24 nm, which translates to transform-limited pulses of 262 fs. We ensured clean modelocking in all configurations by obtaining the optical spectrum, the autocorrelation trace, radio frequency spectra, and a sampling scope trace with a 45 GHz bandwidth photodiode to prove single-pulsed operation (see Fig. 3 for the 324-fs pulse data set). The measured spectrum could support even shorter pulses (transform-limited duration 262 fs). In a slightly different cavity configuration with GDD of -7000 fs^2 we measured 600-fs pulses and 28 W of output power at an optical-to-optical efficiency of 19%.

The maximum achievable output power is currently limited by the comparatively small pump spot size on our disk. We restricted the maximum pump power on our disk to 160 W, which approaches the safety pump intensity limit of 5 kW/cm^2. Increasing the spot size on the disk and simultaneously on the BBO would allow us to pump harder and thus scale up the average power to the 100-W regime, while still maintaining comparable modelocking parameters.

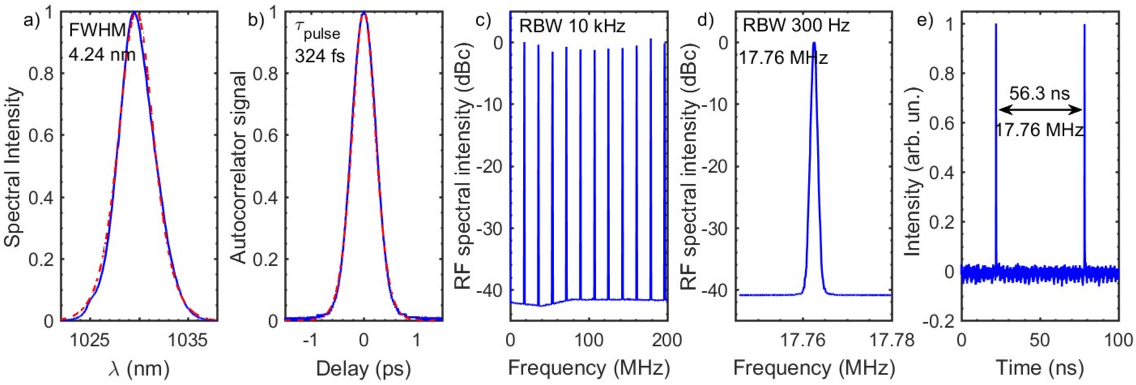

Fig. 3 Diagnostics for the configuration with the shortest pulses (324 fs, 21 W). (a) optical spectrum, (b) autocorrelation trace, (c) radio frequency (RF) trace showing the RF comb, and (d) RF trace showing the peak at the repetition rate (RBW = resolution bandwidth), (e) sampling scope trace. Data are in blue, the autocorrelation trace and the optical spectrum are fitted with a sech^2 (red dashed line).

We developed a simulation of the modelocking mechanism based on a plane-wave approximation of the two nonlinear processes involved [9], namely SHG and OPA. We accurately predict the effective OC rate as a function of the peak intensity on the BBO, see Fig. 2c for a comparison to our experimental data. Moreover, our simulation allows us to scan the effective OC rate as a function of the wavelength. In particular, optimizing the peak intensity on the BBO between 30 GW/cm^2 and 40 GW/cm^2 predicts a modulation depth larger than 5% and a modulation bandwidth of ~8 nm, which would allow for sub-200-fs pulses with Yb:YAG gain material. By applying broadband gain materials such as Yb:LuO or Yb:CALGO, even shorter pulses could be achieved.

3. Conclusion and outlook

We demonstrated the first FD-NLM modelocked TDL, obtaining pulse durations down to 324 fs and output powers up to 28 W, which are record values for this technique. Predictions from our newly developed simulations stand in good agreement with our experimental results. The FD-NLM technique is based on ultrafast nonlinear processes, provides easily scalable modulation depths, features low parasitic losses, and benefits from high intracavity peak powers. It is therefore ideally suited for thin-disk operation and is power scalable via an increase of the spot size on the nonlinear crystal. Based on our first experimental results and simulations, we expect this proof-of-principle demonstration to pave the way towards a new class of high-power short-pulsed modelocked thin-disk oscillators in the near future.

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