Scalability of mode-locked thin-disk oscillators: issues and scenarios of destabilization

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Recent progress of the high-energy ultrafast pulse oscillators brings many new options for high-field physics experiments [1]. The combination of high pulse energy with high pulse repetition rate is especially an important target. Recently, the pulse energies of up to 26 µJ in multipass geometry [2] and average power of 141W have been achieved directly from a thin disk mode-locked oscillator [3]. There exists a simple rule, which describes the pulse energy scaling in the anomalous dispersion regime: \(E \propto \beta A_{eff} / n_2\) (\(\beta\) is the net-group delay dispersion (GDD), \(A_{eff}\) is the average mode area in a resonator, \(n_2\) is the net-self phase modulation (SPM) coefficient) [4]. This rule suggests three main roads providing the energy scaling: i) GDD scaling, ii) mode area scaling, and iii) SPM suppression (e.g. by resonator purification). In practice, there are some obstacles for such direct scaling: cavity purification substantially complicates a system; GDD growth troubles the mode-locking self-starting ability and increases pulse duration; proportional growth of mode size at a disk and SESAM is hardly realizable due to the stability zone shrinking and not perfect quality of a SESAM, etc. In this work we report, for the first time to our knowledge, a mode-locked Yb:YAG thin-disk oscillator operating at 40 MHz repetition rate with the average power scaling ranging from 57 W to 100 W with roundtrip dispersion of -21000 fs². The air-filled resonator provides the Gaussian mode of 2.6 mm in diameter at the disk and 1.4-1.8 mm at a SESAM. The typical spectra corresponding to five different power levels are shown in Fig. 1 (left graph). It was found, that very weak satellites follow the pulse closely (few picoseconds). Simultaneously, the power growth changes the SESAM kinetics and its relaxation time increases, fluence is exceeding more than 55 times the 30 µJ/cm² saturation fluence of the SESAM. As a result, the weak cw-component appears behind the pulse (narrow spikes in left graph of Fig. 1). The main destabilization scenario was found to be chaotic-like Q-switch mode-locking with strong multipulsing.

Fig. 1. Left graph: Output spectra at different power levels. Right graph: Numerical evolution of the peak power in the Q-switch mode-locking regime. Insert shows intensity on the resonator period.

To analyze the destabilization scenario inherent the regime under consideration, we have performed the full-scale numerical simulations taking into account the real gain dynamics over resonator period. It has been found, that, as it takes place in the experiment, the mode-locking start and broad range of solitonic operation is possible due to strong hysteresis of a laser. That means, that the unstable mode-locking (e.g. multipulsing) appears at higher power levels and the stabilization results from adiabatic power decrease. The main scenario of destabilization has been found to be irregular Q-switching against the background of the soliton pattern formation (right graph in Fig. 1). The last means that the picosecond satellites appear both nearby (few picoseconds) the main pulse and far (nanoseconds) from it. Strong interaction of the pulses together with the contribution from a gain dynamics results in the irregular Q-switching.

In conclusion, we have demonstrated a Yb:YAG thin-disk oscillator with power ranging from 57 W to 100 W with optical to optical efficiency of 40%. This concept shows fiesability of usage of the oversaturated SESAM (i.e. at the increased relaxation time) for power scaling in soliton mode locking.

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References