Energy scalability of mode-locked oscillators: comparative analysis

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Abstract: A theory of energy scalability of modelocked oscillators is developed. An oscillator is characterized by a two-dimensional master diagram and by a simple scaling rule, which justifies sub-mJ femtosecond pulses feasible directly from an oscillator.

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1. Introduction

Development of 1–100 μJ-level pico- and femtosecond mode-locked oscillators can provide the tools for direct experiments on light-matter interactions at the intensity levels approaching PW/cm², which are of interest for physics, chemistry, material science, medicine, and biology.

The energy-scalable oscillators can be divided into three main types: i) thin-disk mode-locked oscillators operating in both anomalous (ADR) [1] and normal (NDR) [2] dispersion regimes; ii) all-normal-dispersion (ANDi) fiber oscillators [3]; and iii) solid-state chirped-pulse oscillators (CPOs) operating in the NDR [4]. To date, the over-10 μJ fs-pulses have been obtained directly from the Yb:YAG thin-disk oscillators [5, 6], sub-1 μJ pulses from the Ti:Sa CPO [4], and over-100 nJ pulses from the ANDi fiber oscillator [7]. The existing approaches have been based on either approximations justified for the NDR [8] or extensive numerical simulations [9]. Nevertheless the issue of energy scalability is far from being exhausting.

Here we present a completely analytical approach to an issue of the femtosecond pulse energy scalability. The main result is that all types of the energy-scalable oscillators can be analyzed from a unified viewpoint. The most interesting properties of the presented model are its reduced parametrical space and the scaling rules. As a result of these properties, an energy-scalable oscillator can be described on basis of two-dimensional master diagram connecting the pulse energy with the universal laser parameter describing relative contribution of the dissipative and non-dissipative factors governing an oscillator dynamics.

2. Model

The approach is based on the variational model of a mode-locked oscillator and is validated by the numerical simulations of the thin-disk Yb:YAG oscillators operating in both AND and NDR. The underlying idea is that one can describe a time (t)-dependent field-envelope a(t) by the force-driven Euler-Lagrange equations [10]:

$$\frac{\partial}{\partial t} \int_{-\infty}^{\infty} L dt - \frac{d}{dz} \int_{-\infty}^{\infty} L dt = 2\Re \int_{-\infty}^{\infty} Q \frac{\partial a}{\partial T} dt,$$

where the Lagrangian L corresponds to the conservative factors defining the nonlinear Schrödinger equation, which are the self-phase modulation (SPM) with the inverse power γ, and the net-group-delay dispersion (GDD) with the dispersion coefficient β so that β < 0 is related to the NDR. The dissipative force affecting a field evolution is defined by:

$$Q \equiv i \left[ -\Sigma + \frac{\rho}{1 + \sigma} \int_{-\infty}^{\infty} |a|^2 dt \right] \left( 1 + \tau \frac{\partial^2}{\partial t^2} \right) + \frac{\mu \zeta |a|^2}{1 + \zeta |a|^2} a.$$
This corresponds to an oscillator with the net-loss coefficient $\Sigma$, and the low-signal gain coefficient $\rho$ saturable by a total field energy ($\sigma$ is the inverse gain saturation energy). The spectral dissipation is defined by the parabolic-like gain-band profile with the squared inverse gain bandwidth $\tau$. The self-amplitude modulation (SAM) with a modulation depth $\mu$ providing mode-locking corresponds to a semiconductor saturable absorber mirror (SESAM). The parameter $\zeta$ is the inverse saturation power of a SESAM. The arguments of the functional derivatives in Eq. (1) are: $f \equiv \{A, T, \psi, \phi\}$, where the values dependent on a propagation distance $z$ are: $A$ is the amplitude, $T$ is the pulse width, $\psi$ is the chirp, $\phi$ is the phase shift due to a slip of the carrier phase with respect to an envelope.

As a result, an oscillator operating in both ADR and NDR can be characterized by sole algebraic equation for the pulse amplitude $A$, which depends on only two parameters: $c \equiv \tau\Sigma\gamma/|\beta|\zeta$ and the energy $E$ normalized to $\zeta/\sqrt{\tau\Sigma}$.

3. Results and discussion

Below we shall consider two main oscillator regimes: the ADR corresponding to generation of chirp-free pulses, and the NDR corresponding to generation of chirped pulses.

3.1. Anomalous dispersion regime

Fig. 1, a demonstrates an analytical master diagram for the ADR. The pulses are stable below the shown curves. One can see, that there are two main sectors in the diagram: i) sector of the almost constant $c$ ($c/\mu \approx 1$ here), where the pulse width decreases with the growing $E$; and ii) sector of the linearly decreasing $c$, where the pulse width is almost constant.

Scaling properties differ in these two sectors. The left sector corresponds to small energies (or/and small SAM, i.e. $\zeta$) or/and strong dissipation (large $\tau$ or/and $\Sigma$). This sector is perfectly energy scalable (i.e. $c$ does not depend on $E$) but by the cost of strong variation of the pulse width. The right sector corresponds to large energies (or/and large SAM, i.e. $\zeta$) or/and to weak dissipation (small $\tau$ or/and $\Sigma$). In this sector, $c$ decreases linearly with $E$, but the pulse width is minimum and remains almost constant. The scaling rule for dimensional energy in this sector is

$$cE_0\zeta/\sqrt{\tau\Sigma} \approx \ell,$$

where the $\ell$ grows almost linearly with the modulation depth parameter $\mu$. 

Fig. 1. Thresholds of the pulse stability in the ADR (a) and the NDR (b). Different curves correspond to (a): $\mu = 0.002$ (solid), 0.008 (dashed), and 0.016 (dotted); (b): $\mu = 0.5$ (solid), 0.02 (dashed), and 0.025 (dotted). The pulses are stable below the corresponding curves. Symbols demonstrate the operational points in the vicinity of stability threshold for the different oscillators (corresponding output energies are inscribed). The values of the $b \equiv \gamma/\zeta$-parameter are inscribed for the NDR. In (b): analytical thresholds from [8] are shown by curves (the pulse is stable below the curves). One corrected threshold from Eqs. (1,2) is shown by crosses (the pulse is stable in the direction of arrows subscribed by italics type).
The points corresponding to some oscillators operating in the vicinity of stability threshold are shown by symbols. The experimental estimations of parameters required for the formulation of Eqs. (1,2) have been found only for a few oscillators published. This fact defines our choice of the data presented in Fig. 1. The point corresponding to an airless thin-disk Yb:YAG oscillator has been obtained from the numerical simulations. One can see, that, despite a huge scatter of the parameters, the operational points are well-fitted by the master diagram. Fig. 1 demonstrates that the oscillators can operate within both sectors of diagram, although the right sector is more typical and provides better characteristics (higher energy and lower pulse width).

3.2. Normal dispersion regime

Fig. 1, b demonstrates an analytical master diagram for the NDR. The master diagram can be divided into three main regions: i) \( b = \gamma/\zeta \ll 1 \) corresponds to a thin-disk solid-state oscillator (dotted curve and crosses); ii) \( b > 1 \) corresponds to a ANDi fiber oscillator (solid curve); and iii) \( b < 1 \) corresponds to a broad-band solid-state CPO (dashed curve). The scaling rule for dimensional energy can be formulated as follows

\[
E \frac{\zeta c^2}{\gamma \sqrt{\tau \Sigma}} \approx \Upsilon.
\]

Here \( \Upsilon \) is the growing function of \( \mu \) slowly varying with \( c \). This rule covers all types of oscillators with \( |c| \ll 1 \) (the master diagram is two-dimensional in this limit, otherwise the diagram becomes three-dimensional, i.e. \( b \)-dependent). For solid-state oscillators, this scaling rule demonstrates a substantial reduction of dispersion in the NDR in comparison with that in the ADR. For the ANDi fiber oscillators, the scaling rule is almost perfect: fiber length scaling provides almost linear scaling of the pulse energy. For the solid-state oscillators the dispersion scaling is required: \( |\beta| \propto \sqrt{E} \).

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