Chaotic regime in chirped-pulse mid-IR oscillators

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Abstract: We present experimental investigation of the chaotic mode-locking operation regime in two novel chirped-pulsed Cr:ZnS and Cr:ZnSe mid-IR lasers. The long-term stable regime is caused by the nonlinear interaction of dispersive wave with the pulse.

1. Introduction

Mode-locked oscillators operating in the normal ($\beta_2 > 0$) dispersion regime have established themselves as versatile sources of energy scalable chirped picosecond pulses, which can be further compressed to about hundred femtosecond duration. The main interest in implementing such sources is the possibility to generate high-energy pulses directly from the oscillator, avoiding complex and costly amplifier schemes. These chirped-pulse oscillators (CPO, ANDi) operate in the dissipative soliton regime, which is more involved than a soliton-like compensation of self-phase modulation by anomalous dispersion as in conventional femtosecond lasers. A minimum set of parameters that are required for the CPO regime to exist includes additionally a spectral bandwidth filter and a saturable absorber [1, 2]. On top of that, the higher-order dispersion should be accounted for, as it is often unavoidable in a broadband system. As a result, the CPOs are described by a quite complicated stability diagram in a multi-parameter space; on practice one can often encounter increased amplitude or spectral noise, period multiplication and chaotic behaviour [3-5]. It is important therefore to establish the physical mechanisms, properties, and find simple practical rules to help recognising such regimes.

In this paper, we describe and characterize the observed chaotic regime in the Cr:ZnS and Cr:ZnSe lasers [6, 7] and confirm our physical model with the numerical simulations. We demonstrate that the origin of chaotic mode-locking in a solid-state oscillator results from a parametric resonance with dispersive wave, having different signature and mechanism than observed in the fiber lasers [5].

2. Experiment and simulation

The chaotic regime has been realized experimentally with a Kerr-Lens mode-locked Cr:ZnS and Cr:ZnSe lasers (Fig. 1). The third-order dispersion originated from the active medium itself, the YAG compensator, and from the mirrors. Switching form the regular chirped to chaotic regime was reliably controlled by either increasing the intracavity pulse power or decreasing β_2 by YAG wedge translation.

In the chaotic regime, the largest modulation could be observed on second harmonic signal and on the central wavelength, which were, however, practically uncorrelated (Fig. 2). The spectra were recorded by a FTIR device with 11 kHz detector bandwidth and were smooth and reproducible, so that even the weak narrow-band features resulting from the intracavity water vapor absorption [8] could be reliably recorded (Fig. 3a). Switching from regular to chaotic regime could be initiated both, dispersion change, as illustrated in Fig. 3, and by increasing the pump power. It is worth noting that the pulse energy did not show fluctuate significantly in the chaotic regime.

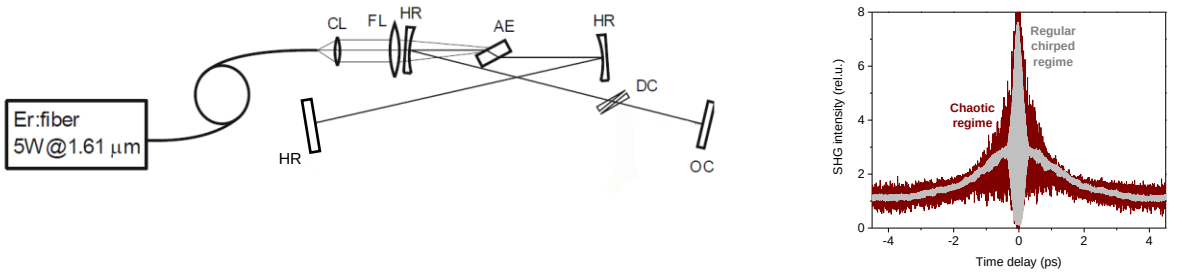

Figure 1. Schematic of the femtosecond graphene-mode-locked Cr:ZnS laser and typical autocorrelation signals in regular and chaotic regimes. CL – collimating lens, FL-focusing lens, HR – high reflector mirror, AE – Cr:ZnS active element, DC – dispersion compensation, OC – output coupler.

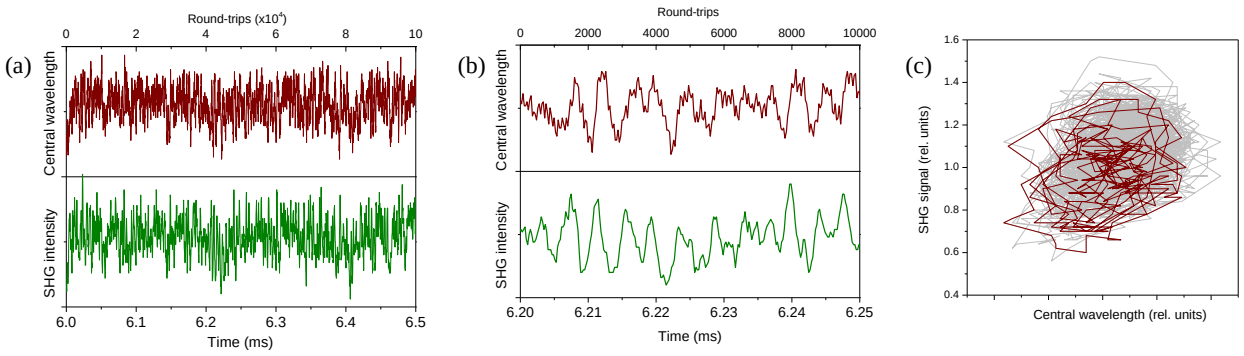

Figure 3. (a, b) Recorded HR mirror leak (grey, related to central wavelength) and second-harmonic intensity (red, related to pulse peak power) of the Cr:ZnSe CPO laser in chaotic regime on two time scales. (c) Parametric diagram corresponding to the signals on graphs (a, b), showing uncorrelated truly chaotic behaviour.

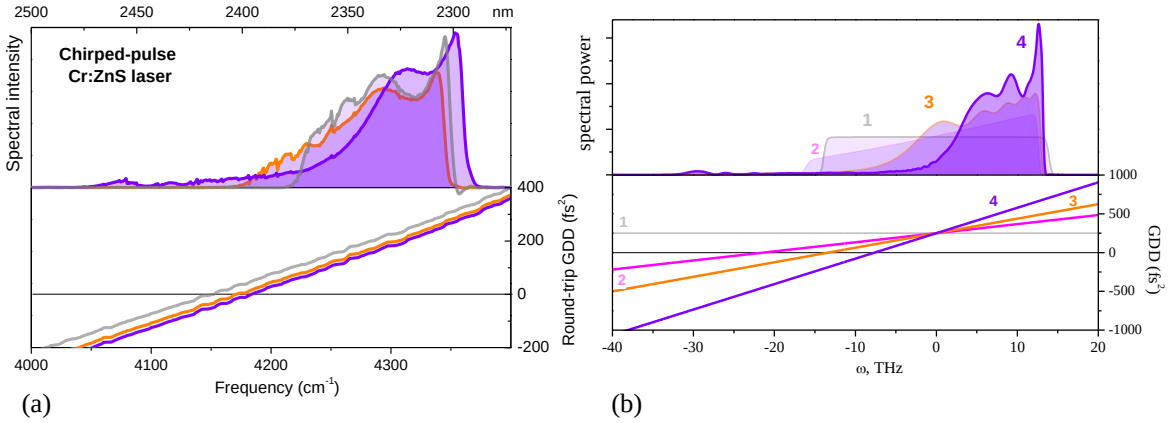

Figure 3. (a) Output spectrum and dispersion of a Kerr-lens modelocked Cr:ZnS laser. (b) Simulated spectra and corresponding dispersion curves for a mid-IR CPO with different values of the TOD.

In the numerical simulation, which followed the complex nonlinear cubic-quintic Ginzburg-Landau equation model [2], we were able to reproduce all experimental regimes, including switching between regular and chaotic regimes. The numerical model demonstrated that the pulse spectral shape, time-bandwidth product, pulse duration, and chirp do fluctuate without significant correlation on the time scale of 10–10^3 round-trips. Averaging by 10^4 round-trips (corresponds to the actual 11 kHz detector bandwidth) resulted in stable predictable spectra as shown in Fig. 3b. The model also allows recognizing the origin of the destabilization and chaotic behavior: as the zero-dispersion wavelength approaches the pulse spectrum, the corresponding dispersive wave merges with the pulse edge and becomes strongly amplified. This merger can be a result of either dispersion change, as illustrated in Fig. 3, or pulse power increase with associated spectrum broadening. Both mechanisms can be observed in the experiment and in the simulation. Since the dispersive wave now overlaps with the pulse both spectrally and in time, their interference results in modulation, both in spectral and time domain. Normaly, this should cause some kind of periodic perturbation, but strong nonlinear interaction in the active medium causes the chaotic regime. The results of simulation and measurements (Fig. 2c) confirm the uncorrelated, truly chaotic regime. From a practical point of view, the chaotic regime is stable on the long-term time scale and can be used even for such demanding aplications as high-resolution spectroscopy, however, it can be also easily recognized by a characteristic shape with a long tail, resembling the dispersive wave in a conventional soliton propagation (Fig. 3).

In summary, using the example of chirped-pulse mode-locked Cr:ZnS and Cr:ZnS lasers we have observed and established the nature of chaotic behaviour in solid-state chirped-pulse oscillators, which occur when the dispersive wave merges with the pulse. This occurs when the dispersion zero-crossing reaches the CPO spectrum edge due to

dispersion decrease or power increase. A simple to observe signature of this regime is the characteristic shape of the spectrum edge, resembling a dispersive wave. We also demonstrate that this regime exhibits high long-term stability and a predictable spectrum, making possible its use in such applications as high-resolution molecular spectroscopy.

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