# Noise and Stability in Giant-Chirp Oscillators Mode-Locked with a Nanotube-Based Saturable Absorber

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**Abstract:** We compare experimental results showing stable dissipative-soliton solutions exist in mode-locked lasers with ultra-large normal dispersion (as large as 21.5 $ps^2$), with both the analytic framework provided by Haus' master-equation and full numerical simulations.

**OCIS codes:** (140.4050) Mode-locked lasers; (140.3510) Lasers, fiber; (140.3560) Lasers, ring

## 1. Introduction

All-normal dispersion (ANDi) passively mode-locked fiber lasers, supporting dissipative solitons (DSs), have been widely studied since being proposed as a means of extracting energetic femtosecond and picosecond pulses directly from an all-fiber oscillator [1]. Recently, a new parameter regime has been explored in ultra-long, all-normal dispersion cavities [2-5], where the generated pulses carry a significant linear chirp [6]; such systems have become known as giant-chirp oscillators (GCOs). Noise-burst-like emission is a well known feature of normally dispersive lasers, mode-locked using nonlinear polarization evolution (NPE), because of pulse break-up due to polarization-dependent delay [7]. However, for applications requiring a coherent output, stable single-pulse generation is often favored. The fine temporal structure of pulses generated in an all-normal dispersion laser, mode-locked using NPE, was investigated in [8]. For the particular set of laser parameters, elongation of the laser cavity resulted in the generation of picosecond wave packets consisting of a quasi-stochastic train of femtosecond sub-pulses. Although low-coherence sources have many useful applications, such structures cannot be de-chirped to near-transform limited duration, and used as a source of high-energy femtosecond pulses [8].

Carbon nanotube-based saturable absorbers have emerged as a practical alternative to other passive mode-locking devices, such as semiconductor saturable absorber mirrors (SESAMs), and artificial saturable absorption mechanisms, such as NPE [9]. Recently, we reported an ultra-long ANDi fiber laser, with an ultra-large normal dispersion (cavity GVD of ~21.5 $ps^2$); mode-locked with a nanotube-based saturable absorber producing nanosecond duration pulses [5]. We characterised the nature of the pulse chirp in [6], where good agreement was found between the experimentally measured spectrogram and a theoretically generated spectrogram for the particular system parameters, based on the analytical mode-locking theory by Haus [10], in the framework of the master-equation.

Here we use a similar analysis, based on the master-equation mode-locking model, to investigate the regions of stability, and a full numerical simulation of the pulse evolution dynamics to explore the temporal pulse structure.

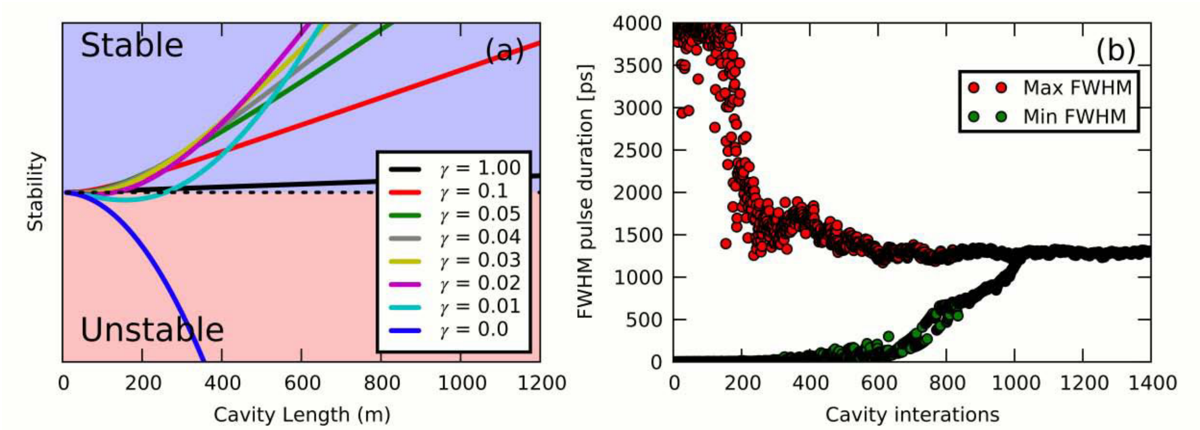


Figure 1. (a) stability regions for various values of saturation parameter γ according to the Haus master-equation. (b) convergence of numerical simulation to a single-pulse solution with a nanosecond envelope.

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**2. Results and Discussion**

In Fig. 1(a) we plot the stability criterion, based on Haus' analytic model, as a function of the resonator length for a family of curves with different values of the saturable absorption parameter γ, which is inversely proportional to the saturation intensity. It is clear that for a wide range of saturation intensities, GCO systems with very large dispersion are well within the stable regime.

Numerical simulations, based on the nonlinear Schrödinger equation, were also used to study the pulse evolution as a function of cavity round-trip time. Fig. 1(b) shows how the widest and smallest temporal intensity structures evolve from the extremes representing the initial cavity noise, to a converged and stable state after around 1000 cavity round-trips. The pulse envelope stabilizes first, as shown by the fact that the maximum full width at half maximum (max FWHM) converges to close to its final value after around 300 round trips. This envelope initially contains fine temporal structures, which clean up on each iteration until being totally eradicated after ~1000 round trips. These results are clearly exposed in Fig. 2, which shows the time-domain intensity evolution at each round trip position. The same clean and stable final pulse shape was retrieved from a range of initial noise conditions and always converged after ~1000 cavity round trips.

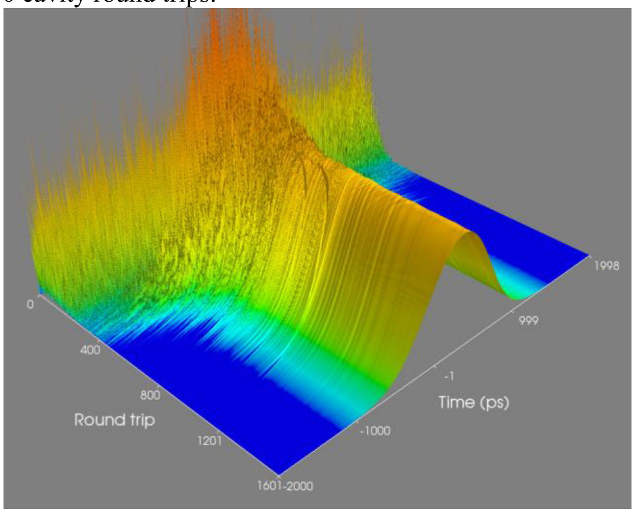


Figure 2. Numerical simulation of the evolution of a nanosecond pulse initiated from white-noise for the laser parameters described in [5, 6]. Femtosecond scale temporal fluctuations converge to a stable single-pulse solution with a nanosecond envelope.

In conclusion, we have shown that stable dissipative soliton solutions exist in mode-locked lasers with ultra-large, all-normal dispersion. Numerical simulations support experimental results of nanosecond pulses, carrying a significant linear chirp, with a clean temporal profile. The evolution of these giant-chirp solutions from white-noise, where femtosecond scale sub-pulses converge to a stable single-pulse with a nanosecond envelope, has been numerically simulated.

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