Stretched-Pulse Solitons in Driven Fiber Resonators

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Abstract: Stable broadband solitons are observed in a driven nonlinear resonator consisting of fibers with opposite signs of dispersion. Corresponding numerical simulations reveal periodic temporal stretching of the pulse, characteristic of stretched-pulse solitons in mode-locked lasers.
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1. Introduction

Micro-resonator-based optical frequency combs are well-suited for applications such as timekeeping, spectroscopy, metrology, and coherent communications. A broadband frequency comb can be generated in a cavity driven by a continuous-wave (CW) laser through parametric four-wave mixing gain and self-organization processes. In particular, solitons generated in these cavities through the balance of group-velocity dispersion (GVD) and Kerr nonlinearity enable ideal broadband and fully coherent frequency combs [1].

The nonlinear dynamics of driven cavities was studied previously in fiber cavities, and recently, stable solitons have been observed in these systems as well [2]. Highly desirable sources are developed based on related solitons in fiber lasers, which suggests that driven fiber cavities may also generate useful pulses in a versatile new platform for short-pulse applications.

In mode-locked fiber lasers, broadband solitons are generated in cavities with alternating segments of fiber with opposite signs of dispersion [3]. Operation with total dispersion close to zero enables short pulses and the periodic stretching and compressing of the pulses resulting from these short durations reduces the average intra-cavity pulse peak power. This 'stretched-pulse' regime has been predicted in a dispersion-mapped micro-resonator cavity [4], but no experiments have been reported. In fiber cavities, while solitons have been observed in cavities with a dispersion map [5], broadband stretched-pulse operation has not been observed. Here we report on numerical and experimental observations of broadband stretched-pulse solitons from a driven fiber resonator.

2. Theory

Driven cavity solitons form through the stable balance of nonlinearity and dispersion. In addition, cavity losses are compensated with a CW laser that is appropriately frequency detuned from the resonance of the cavity. A numerical model is developed incorporating these effects with the damped and detuned nonlinear Schrödinger equation. The numerical resonator consists of one segment of anomalous dispersion fiber and another segment of normal dispersion fiber. A CW drive and the fiber component losses are incorporated as lumped elements after the fiber sections. The wave equation is solved using a standard split-step Fourier transform propagation algorithm. For a given cavity dispersion map, the drive power and frequency detuning determine the behavior of the solutions.

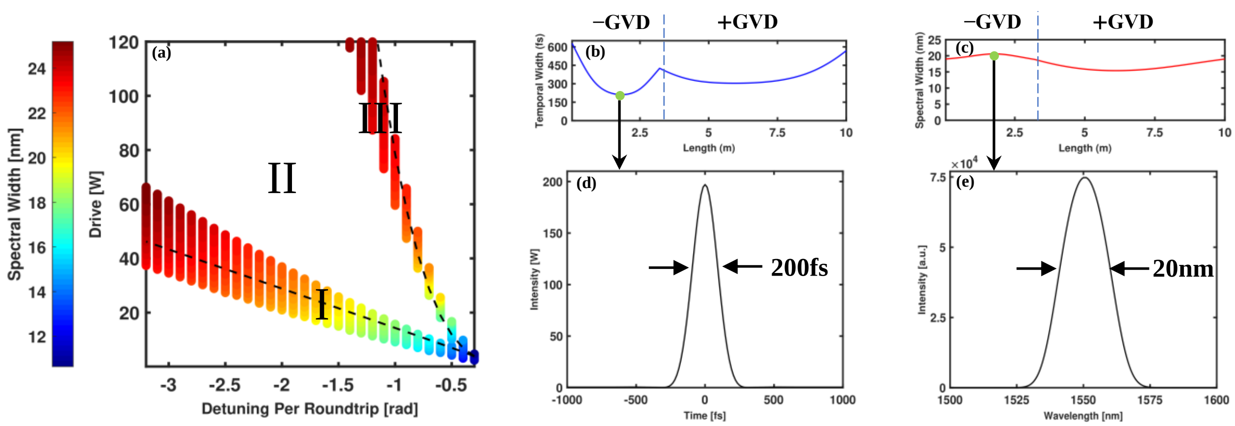

Fig. 1. (a) Stable solutions from numerical simulations with varying drive power and detuning for a fiber cavity with a total length of 10 m and net GVD of -8000 fs^2. Important regions are indicated with Roman numerals. (b) Temporal and (c) spectral width evolution in the cavity with drive power of 15 W and detuning of -1.5 rad, and (d) temporal and (e) spectral intensity profile of the shortest pulse in the cavity.

Simulations run over a parameter grid defined by the drive power and frequency detuning reveal stable solutions in two characteristic branches (Fig. 1(a)). Well-behaved soliton solutions are found in regions I and III, and more complicated solutions exist in region II, including noisy and breathing solitons, in addition to continuous-wave solutions. A representative solution from region I, depicted in Fig. 1(b-e), exhibits stable Gaussian pulses. The pulse duration stretches and compresses twice in the cavity, as with stretched-pulse solitons in dispersion-managed mode-locked lasers (Fig. 1(b)) [3,4]. The pulse in this 10-m cavity has a full-width at half-maximum duration of 200 fs at its minimum dechirped duration in the cavity (Fig. 1(d-e)). The spectral width of the pulses depends on the drive power and detuning, in addition to the cavity length and total group-velocity dispersion.

3. Experimental results

An experiment was designed with parameters guided by the numerical simulations. The experimental setup consists of a fiber cavity, drive, and diagnostics (Fig. 2(a)). The ring cavity is comprised of one segment of standard single mode optical fiber with anomalous dispersion and another segment of dispersion-shifted optical fiber with normal dispersion. The cavity incorporates an optical fiber isolator to ensure unidirectional operation and to prevent stimulated Brillouin scattering. The frequency of the CW drive is locked with respect to the cavity resonance frequency with a feedback control circuit PID that changes the laser frequency given the output CW power as an error signal. Changes in the frequency set-point correspond to changes in the frequency detuning parameter. The effective drive power is enhanced by intensity modulating the CW power into ns pulses before amplification [6]. Residual drive light is filtered from the output coupled light with a fiber Bragg grating filter before the solitons are analyzed with time and frequency domain diagnostics.

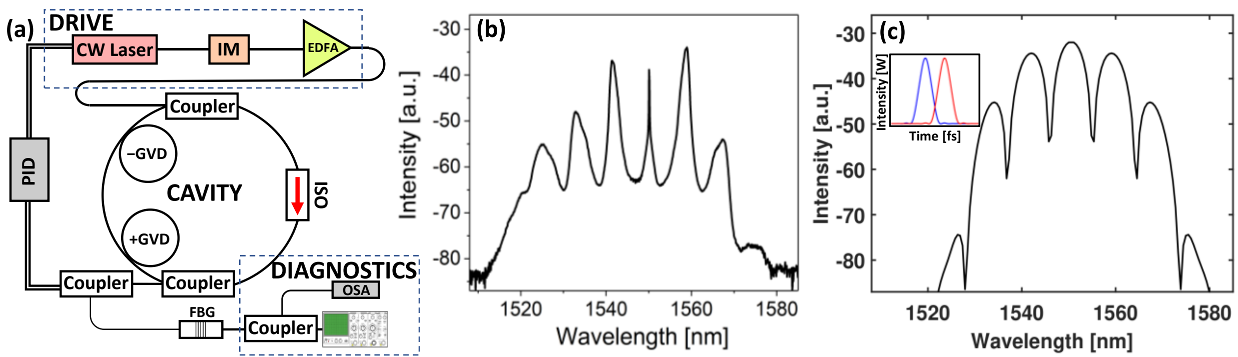

Fig. 2. (a) Experimental schematic, (b) experimental broadband output optical spectrum, and (c) simulated spectral interference pattern corresponding to the closely separated stretched-pulse soliton temporal intensity profile inset.

The net dispersion is reduced from large net anomalous toward net zero dispersion by introducing an increasing length of normal dispersion fiber. Stable solutions are observed in each cavity, with the spectral bandwidth broadening as the net dispersion approaches zero. The broadest spectral bandwidth observed in initial investigations corresponds to a pulse with 200-fs duration (Fig. 2(b)). With this short pulse duration, the pulses are expected to breathe by more than a factor of two in the cavity. Without specific control of the temporal initial conditions in the cavity, multiple pulses will arise in driven optical cavities [2]. The periodic structure observed on the spectrum is characteristic of such multiple pulses in the cavity with a small temporal separation. The simulated pulses are illustrated with a comparable temporal separation for comparison (Fig. 2(c)), with agreement to the experimental results given a 900-fs temporal separation (9nm spectral separation). With the addition of a pulse addressing beam, a single stretched-pulse soliton should be observable, as in the numerical simulations.

In summary, broadband stretched-pulse solitons are observed in a dispersion-mapped fiber cavity driven by a continuous-wave laser, in agreement with numerical simulations. Broadband soliton generation from driven fiber cavities may be a valuable new resource for short-pulse applications.

3. References

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