Highly-Chirped Solitons in Driven Resonators

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Abstract: Here we investigate driven fiber resonators with large net normal dispersion and a narrowband intracavity spectral filter. A range of stable solutions are observed, including the first experimental and numerical observations of highly-chirped solitons.

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1. Introduction

Micro-resonator-based optical frequency combs are ideal for applications such as timekeeping, spectroscopy, metrology, and coherent communications. In continuous-wave (CW) laser driven micro-resonators, frequency combs are generated through parametric four-wave mixing gain and self-organization processes. In particular, soliton formation through the balancing of anomalous group-velocity dispersion and Kerr nonlinearity enables ideal coherent frequency combs [1]. In addition to anomalous dispersion solitons, a variety of other stable solutions have been observed in different parameter regimes, such as switching waves, dark solitons, soliton crystals, and Turing patterns [2]. In general, the performance of the frequency comb is determined by the quality of these solutions.

In related mode-locked solid-state and fiber lasers, similar anomalous dispersion solitons enable commercially available tools that are used extensively for ultrashort-pulse applications. More recently, chirped pulses have been discovered in mode-locked lasers featuring normal group-velocity dispersion [3,4]. These highly-chirped pulses form through the balance of normal dispersion and nonlinearity as well as dissipative spectral filtering. While normal dispersion microresonators have been investigated [5], even in the case with effective spectral filtering [6], an analogous highly-chirped regime has not been observed in driven nonlinear optical cavities.

The nonlinear dynamics of driven cavities was first examined in fiber cavities, and recently, stable anomalous dispersion solitons have been observed [7], in addition to other patterns like switching-waves and Turing patterns. Fiber resonators represent an excellent platform to study chirped pulses because they allow for large powers and an array of pulse shaping tools. In particular, the spectral filter needed to stabilize chirped pulses in mode-locked lasers can be readily applied to fiber resonators. Here we examine highly-chirped solitons in large normal dispersion fiber optical cavities with an intracavity spectral filter.

2. Theory

We search for chirped pulses in driven fiber resonators with numerical simulations, using chirped-pulse mode-locked lasers for guidance. Simulations must account for dispersion, nonlinearity, and spectral filtering, in addition to loss and a frequency-detuned drive. The fiber sections are modeled with the damped and detuned nonlinear Schrödinger equation, and the spectral filtering, continuous-wave drive and additional losses are added as lumped elements after the fiber (Fig 1(a)). The pulse propagation in the fiber is evaluated with a split-step Fourier method and the field is propagated around the cavity until it converges to a steady-state.

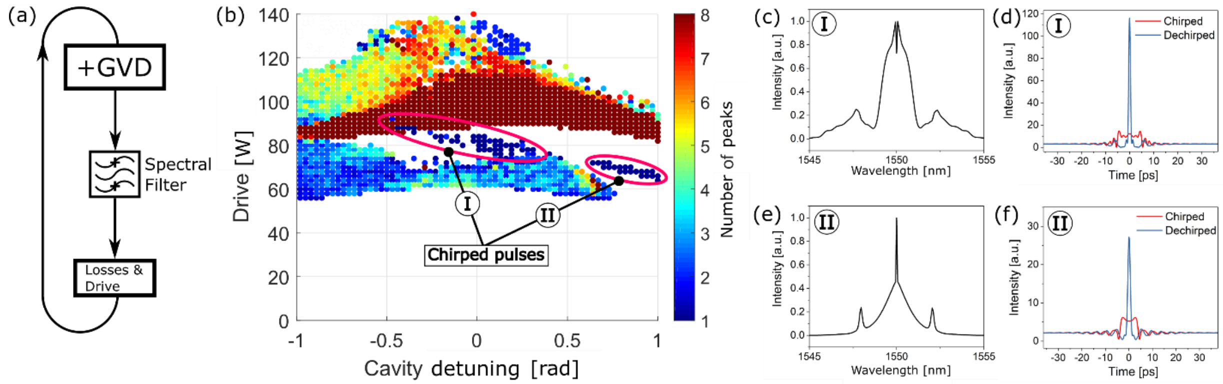

Fig. 1. Numerical simulation results from a (a) large normal dispersion fiber cavity (b) indicating the number of peaks of the converged temporal intensity profile vs. drive power and detuning with the (c) spectrum and (d) chirped/dechirped pulses from Region I and the (e) spectrum and (f) chirped/dechirped pulses from Region II.

Chirped pulses are observed with the appropriate combination of fiber dispersion and spectral filtering, as is the case with mode-locked lasers. For example, stable chirped pulses are observed at high drive powers with a cavity consisting of 50 m of dispersion-shifted fiber and a 4-nm spectral filter. However, to find chirped pulses with lower, more experimentally accessible drive powers, the total cavity length should be increased (by ~100m), while maintaining the same large net normal dispersion and the 4-nm spectral filter. This extended length reduces the drive threshold by increasing the nonlinearity, and enables larger quasi-CW pump powers when pulse pumping. A wide-range of stable solutions are observed as a function of drive and detuning (Fig 1(b)). In a representation of the solutions vs the number of intensity peaks, for example, periodic-structures can be identified in the red region, and dark solitons and switching waves in the low drive regions. The chirped pulses, identified by the localized dark blue regions in parameter-space, feature a long pulse on a continuous-wave background that can be compressed with the application of anomalous group-velocity dispersion (Fig. 1(c-f)). The compression factor of the dechirped pulse varies between solutions, with a factor of two difference between the solutions illustrated. The magnitude of dispersion required to dechirp the pulses is three times the normal dispersion in the cavity, suggesting that the positive chirp is the result of nonlinear processes, as it is for chirped pulses in mode-locked lasers.

3. Experimental results

Experiments are designed with parameters determined from numerical simulations. The experiment consists of the fiber cavity, a pulse-pumping setup, and pulse diagnostics (Fig. 2(a)). The pulse-pumping setup is comprised of a narrow-line fiber laser that is intensity modulated into a pulse train (10-ns pulses with the repetition rate of the fiber cavity) before high power amplification [8]. This enables ~80 W of quasi-CW pump power with a 2-W EDFA. Residual amplified spontaneous emission is removed with a fiber-Bragg-grating filter before the pump is coupled into the cavity. The frequency of the drive is locked to the cavity resonance with a PID control circuit and the locking frequency set-point gives experimental control over the detuning parameter. The large-net-normal dispersion fiber cavity includes a fiber-format super-Gaussian spectral filter with 4-nm bandwidth and a fiber isolator to ensure unidirectional operation. Chirped pulses are observed near the highest pump powers with specific settings of the pump polarization and detuning. The pulse spectrum features broad pedestal structure on the linear scale (Fig. 2(b)) and the pulse compresses to a clear minimum duration with an external grating-pair compressor (Fig. 2(c)). The pulse dechirps close to the transform-limited 1-ps duration. The magnitude of the pulse chirp is significant and corresponds to three times the total normal dispersion in the cavity, in excellent agreement with simulations.

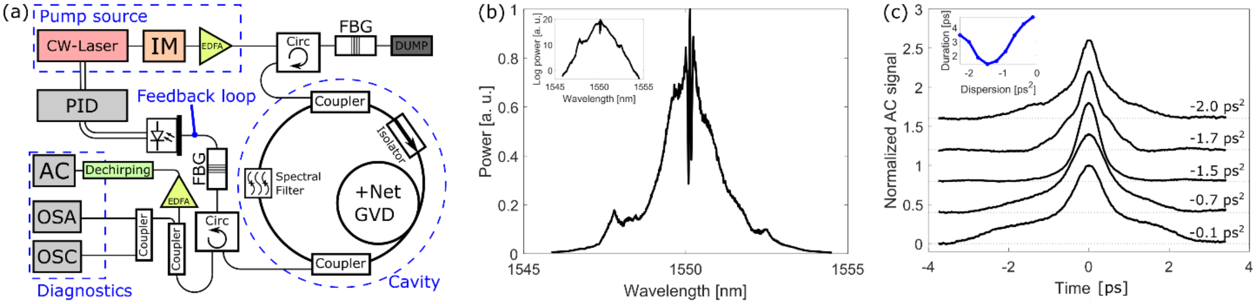

Fig. 2. (a) Experimental setup, (b) chirped-pulse output spectrum with log-scale inset, and corresponding autocorrelation measurements as a function of applied dispersion for dechirping. The extracted pulse duration variation is inset. OSA: optical spectrum analyzer; AC: autocorrelator; OSC: oscilloscope; FBG: fiber Bragg grating; IM: intensity modulator; and Circ: circulator.

In summary, we have observed highly-chirped pulses in a driven fiber resonator with large net-normal dispersion and a narrowband spectral filter. This system supports a wide range of stable optical patterns which may be attractive for frequency-comb and short-pulse applications

3. References

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