High peak-to-background-ratio solitons in a fiber laser with a detuned continuous-wave injected signal

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We generate a soliton comb with a 4 MHz repetition rate using a coherently driven active fiber resonator. The 790 fs solitons have a 90 W peak power and sit on a 3 mW continuous-wave background.

Temporal cavity solitons are sech-shaped optical dissipative structures that propagate indefinitely in passive Kerr resonators. They have been observed in fiber cavities 1, integrated resonators 2, 3 and free-space cavities 4. The output pulse train consists in an optical frequency comb which attracts interest in many fields. In particular, microresonator solitons allow for the generation of frequency combs with unprecedented characteristics and are being used for applications such as data transmission 5 or coherent ranging 6 to name a few. Conversely, the peak-to-background energy ratios of fiber cavity solitons are typically very low which makes it difficult to generate enough soliton power for applications. Amplifiers get saturated by the background as filtering it out is not trivial in long resonators. The limited peak-to-background ratio is due to the low finesse, which is mainly restricted by the insertion loss of the intracavity coupler(s) and isolator (to prevent stimulated Brillouin scattering). Yet, there are advantages to using a coherently driven fiber resonator for generating low-repetition-rate frequency combs, as compared to mode-locked lasers for example. The detuning of the injected signal is an important control parameter which can be used to tune the soliton peak power and duration. The tuning can be relatively fast, which opens the door to novel applications 6. Moreover, the timing jitter of driven solitons is very low (see 7 and references therein).

Several techniques to increase the peak-to-background ratio of solitons in fiber resonators have been implemented, including two cavity configurations 8 or more recently our demonstration of active cavity solitons 9 but the energy stored in the background is still orders of magnitude larger than that of the soliton. Synchronous driving 10 can also be used to suppress stimulated Brillouin scattering and increase the conversion efficiency but pulsed driving can add noise and requires more complex experimental designs 11. Here, by harnessing the cavity detuning in an active fiber cavity, we demonstrate the formation of tunable, high peak power solitons on a very low power continuous-wave background. When driving the cavity close to antiresonance, we obtain a peak-to-background ratio of $3 \times 10^4$ which is an 80-fold increase as compared to the state of the art. Our system is similar to a fiber laser with an injected signal. To the best of our knowledge, the signal detuning has never been exploited for soliton tuning, in particular peak-to-background ratio optimisation. Moreover, our cavity does not require any particular mode-locking scheme to ensure the stability of the pulse train 12.

The experimental set-up is shown in Fig. 1. The cavity is mostly made of standard single mode fiber $[L=47 \text{ m}, \beta_2=-23 \text{ ps}^2/\text{km}, \gamma=1.3 \text{ (W.km)}^{-1}]$ and a short amplification section composed of an erbium doped fiber ($\sim 30 \text{ cm}$) and two wave (de)multiplexers. The driving power is $P_d=100 \text{ mW}$ and the input coupler transmission is $\theta=10\%$. The active fiber is pumped with 2 W at 1480 nm. We define the effective loss $\Lambda_e$ as the difference between the intrinsic cavity loss and the gain. We operate the cavity in a regime of positive effective loss $\Lambda_e \approx 2\%$ (below the lasing threshold). In that regime, the intracavity field is well described by a driven-dissipative nonlinear Schrödinger equation (NLSE) which accounts for both intracavity propagation and the boundary conditions 9 12. In the limit of large cavity detunings (as compared to the linewidth), the driving and dissipation can be treated as perturbative terms 13 and first order NLSE solitons on a low power background are stable solutions. The peak power and duration of the soliton $[E(t)=\sqrt{P_0} \text{sech}(t/t_s)]$ depend on the cavity parameters including the cavity detuning, which is defined as $\delta_0=2k\pi-\varphi_0$ where $\varphi_0$ is the accumulated phase over one roundtrip at the driving frequency and $k$ is an integer. The soliton peak power is set by the condition that the soliton is on a mode of the cavity: $\gamma LP_0/(2-\delta_0)=0$ and the corresponding duration is $t_s=\sqrt{\beta_2 L}/(2\delta_0)$. Short solitons may be perturbed by higher order effects 14 15 but we show here that these scaling laws are good predictors of the soliton properties in a typical fiber loop. The background power is described by the Airy distribution of the cavity and can be minimised by working close to antiresonance: $P_b(\delta_0=\pi) \approx P_a/4$.

The experimental cavity detuning is fixed by use of a frequency-shifted control signal 11. The solitons are generated by sending a single short pulse at 1535 nm 11. We excite the soliton at $\delta_0=0.5$ and then slowly scan the detuning so as to probe the soliton branch 9. Our results are shown in Fig. 1. We scan the detuning between 0.5 and 2.9 in steps of 0.015 rad (at an approximate rate of 0.03 rad/s). The 160 spectra are plotted

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Figure 1. a, Experimental setup. FS: frequency shifter. AOM: acousto-optic modulator. PBS: polarization beam splitter. PC: polarization controller. b, Experimental optical spectra of the solitons as a function of the detuning. The solid black line indicates the driving wavelength. The dashed white line is the soliton center wavelength. c, Two experimental spectra corresponding to different cavity detunings. The dashed lines correspond to the theoretical scaling law (as shown). d, Experimental and theoretical autocorrelation traces corresponding to the spectra shown in c. e-f, Portions of the experimental electrical spectrum showing beatnotes every free spectral range (FSR).

in Fig. 1b. Two examples, and their respective autocorrelation trace, are shown in Fig. 1d and compared to theory. The agreement is excellent, confirming the generation of sech-shaped pulses in the cavity. At \( \delta_0 = 2.7 \), the pulses are \( t_s = 450 \text{ fs} \) in duration (FWHM = 790 fs). The corresponding peak power is about 90 W, which is 30,000 times the measured background power (\( P_b \approx 3 \text{ mW} \)). We also show portions of the electrical comb corresponding to the pulse train obtained with \( \delta_0 = 2.7 \) (see Fig. 1e-f). The FWHM of the beatnotes are resolution limited within the bandwidth of our detection system. The experimental soliton duration and energy ratio (extracted from the spectra of Fig. 1b) are plotted as a function of detuning in Fig. 2 and compared to theory. The theoretical ratio is \( R = KP_s^2 t_s/(0.88P_b t_r) \) where \( t_r = 242 \text{ ns} \) is the roundtrip time. We introduced a free parameter (\( K = 1.3 \)) to account for the sub-\( t_r \) dynamics in the experiment. Gain, loss (each about 25%) and driving are localized in our cavity while they are distributed in the theoretical model. The evolution with the detuning of both the duration and the ratio are very well predicted by the scaling laws. These results highlight the importance of the cavity detuning parameter. Compared to measurements at \( \delta_0 = 0.5 \), the peak-to-background ratio is increased by a factor 50, and the soliton duration is decreased by a factor 2, when working close to anti-resonance. We stress that the ratio for \( \delta_0 = \pi \) is a local maximum. Higher ratios could be obtained by driving the cavity beyond the next longitudinal mode (\( \delta_0 > 2\pi \)) but the detuning range is limited by Raman induced instabilities in our experiment. The soliton center frequency gradually red-shifts when the detuning is increased (see Fig. 1b) and eventually loses its stability [15].

In conclusion, we generated a low repetition rate soliton comb with unprecedented peak-to-background ratio by harnessing the cavity detuning in a coherently driven fiber laser. The soliton is a robust attractor of the system and as such does not require a mode locking scheme [12]. Our system can be adapted to generate soliton combs with a wide range of repetition rates. There is in principle no upper limit on the period of the pulse train because the system operates below the lasing threshold, even in the absence of solitons. This is interesting for applications where highly dense frequency combs are required, such as THz spectroscopy [16]. Finally, we note that the same solitons, but without the continuous wave background, can be generated by driving the cavity through phase sensitive amplification [17].

Figure 2. Experimental and theoretical soliton duration and energy ratio as a function of the detuning.

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