20 nJ 200 fs all-fiber highly chirped dissipative soliton oscillator

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The dissipative solitons (DS) generated in fiber oscillators with mode-locking mechanism based on nonlinear polarization evolution in a single-mode fiber exhibit stability and energy limits at the cavity lengthening. We demonstrate an alternative approach that enables us to increase the cavity length of the DS oscillator up to 30 m, namely, by the use of a long section of polarization-maintaining (PM) fiber in an all-fiber cavity configuration. We have also identified the next limit of energy scaling related to the onset of Raman conversion of the DS spectrum. The maximum energy of the stable highly chirped DS realized with a 5.5 μm core PM fiber, amounts to ~20 nJ in ~200 fs pulses after a grating compressor. As a next step, energy scaling by means of a fiber core enlargement is discussed.

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It has been shown in the last decade that chirped pulses generated in a cavity with normal dispersion offer higher energy than transform-limited soliton pulses generated in fiber oscillators with anomalous net dispersion [1]. The most powerful fiber sources, Yb-doped fiber lasers (YDFLs), operate at ~1 μm where conventional single-mode fibers (SMFs) and fiber components have normal dispersion. An all-normal dispersion (ANDi) YDFL was first demonstrated [2] with the following key parameters: several nJ pulse energy and a mode-locking mechanism via a nonlinear polarization evolution (NPE) effect arising at propagation of an elliptically polarized pulse in SMF. ANDi lasers usually employ spectral filtering of a frequency-chirped pulse to achieve their self-consistent evolution at high nonlinear phase shifts. The resulting stable linearly chirped pulses can be described as dissipative soliton (DS) solutions of the generalized Ginzburg–Landau equation [3,4].

Scaling of the pulse energy in the ANDi scheme is possible by increasing its cavity length or mode-field diameter of the fiber. The most successful attempt of the YDFL cavity lengthening [5] resulted in the generation of <200 fs dechirped pulses with energy increased to ~20 nJ at 12.5 MHz repetition rate (with 6 μm core fiber and free-space optics). Note that an even lower rate (2.3 MHz) has been demonstrated recently for Er-doped fiber lasers [6]. The tendency of the laser toward multipulsing at high pulse energies was interpreted by the authors as a result of overdriving the NPE [5]. Therefore, they tried another option, namely, intracavity large-mode-area (LMA) photonic crystal fiber resulted in the generation of 140 nJ pulses dechirped to 115 fs at an 84 MHz repetition rate [7]. Despite their simple configuration, most NPE-based schemes of ANDi lasers [3,5,7] utilize free-space polarization optics at the expense of environmental stability. All-fiber NPE-based Yb oscillator delivering 1.8 nJ 179 fs dechirped pulses at 33 MHz repetition rate was demonstrated in Schultz *et al.* [8]. The same group later developed an all-fiber Yb laser with higher (3.6 nJ) pulse energy [9]. Certain results are related to the implementation of polarization-maintaining (PM) fibers in combination with the mode-locking mechanisms other than NPE, like saturable absorber mirror [10,11]. The pulse energies realized in these schemes are lower and dechirped pulses are longer.

Here we report on the realization of an all-fiber Yb oscillator scheme combining short SMF and long PM fibers. This scheme provides environmentally stable generation of highly chirped DS pulses with energy scaling via cavity lengthening. This idea is based on the results of our previous study of highly chirped DSs in fiber oscillators [12,13]. It has been shown that in normal-dispersion NPE-based schemes, the frequency chirp and DS energy grow nearly linearly with the cavity length. The linear scaling is valid only up to some limit after which the DS stability is broken. The reason for the stability break is shown to be an excessive nonlinear rotation of the polarization ellipse in a long SMF [13]. Therefore, in Kharenko *et al.* [13], we proposed a combined cavity consisting of a short SMF part (for NPE mode locking) and a long PM fiber part (for generation of highly chirped DS pulses). The experimental realization of such an SMF-PM all-fiber oscillator together with results on its output parameters and scaling limitations are presented below.

The basic design of the DS all-fiber laser is depicted in Fig. 1. The NPE part of the cavity with optimal length L_1 ~1.5 m consists of non-PM SMFs: passive fiber

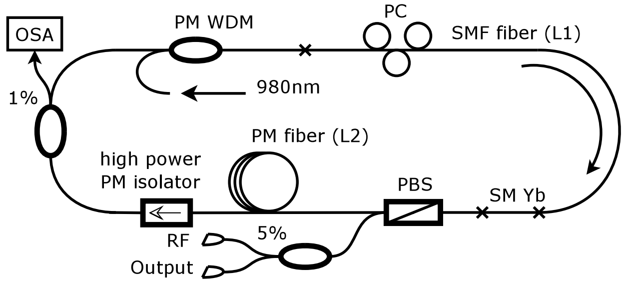

Fig. 1. Experimental setup of an all-fiber highly chirped DS fiber oscillator.

(Nufern 1060-XP) and a 15 cm piece of active Yb-doped fiber (CorActive Yb-17-05) with 900 dB/m absorption at 976 nm. A polarization controller (PC) and a polarization beam splitter (PBS) set before and after the SMF part provide NPE-driven self-amplitude modulation. The DS part consists of only PM fiber components: long section ($L2 = 5$–25 m) of passive PM fiber (Nufern PM980-XP), a PM isolator, a 1% PM splitter, and a PM WDM coupler for pumping active fiber by a single-mode laser diode at 976 nm. The core diameter of the PM fiber used is $d \approx 5.5$ μm.

A linearly polarized pulse is equally affected in PM fiber by dispersion and self-phase modulation providing linear chirp [13]. We did not use additional spectral filters because Yb gain spectrum and transmission spectra of the fiber components naturally limit the bandwidth. The output fiber was appended by a 95:5 PM splitter for simultaneous measurements of power, radio-frequency (RF) beat spectra, and optical spectra. Both outputs of the PM splitter were protected by APC (angled physical contact) connectors.

At the normal cavity dispersion of ~0.023 ps^2/m, the laser generates stable highly chirped DS pulses with energy nearly linearly increasing with the cavity length, similar to the SMF scheme with free-space optics [13]. The main difference is that the lengthening in the combined SMF-PM scheme does not lead to the stability loss: the cavity length can be easily increased up to $L \sim 30$ m (~7 MHz repetition rate), about two times more than in Chong *et al.* [5]. Moreover, at $L \geq 30$ m, the DS regime remains stable but another limiting factor comes into play, namely, stimulated Raman scattering. In addition to the main DS peak (centered at 1010 nm), a Raman peak (centered at 1055 nm) appears in the generated spectrum (see Fig. 2). The Raman peak increases with the pump power and cavity length and becomes comparable to the DS peak. This effect limits DS maximum energy without deteriorating its stability: RF spectra measured at 7 MHz and 750 MHz remain narrow (~1 kHz) and of high-contrast (~60 dB) (see inset in Fig. 2).

The maximum pulse energy achieved is 23 nJ (>150 mW output power at 390 mW pumping), 17 nJ of which correspond to the DS. To the best of our knowledge, this value is about one order of magnitude higher than that in the previous all-fiber YDFL configurations [8,9], and comparable with the best results for SMF-based ANDi laser with bulk optics [5]. Notably, we use fibers of smaller diameters together with lower pump powers. To prove the key component that provides the result, we have replaced our PM fiber with a non-PM fiber, keeping the rest unchanged. The cavity length limit of 10 m (~20 MHz repetition rate) with the corresponding maximum pulse energy of ~2 nJ has been found to be comparable to the pulse energy demonstrated in an SMF all-fiber scheme [8,9]. This scheme tends to have problems of self-starting and multipulsing as the cavity becomes longer. In such a way we have identified that the combined all-fiber cavity consisting of SMF and PM fiber parts offers an opportunity of energy scaling via lengthening.

The generated DS pulses acquire large chirp because of their propagation in the long PM fiber. Their autocorrelation trace has a triangle shape (see inset in Fig. 3) that corresponds to the rectangular DS pulse of about 30 ps duration, in accordance with theoretical predictions [12,14]. The DS spectrum has fluctuations that make difficult its comparison with the DS resonance shape (e.g., see Grelu and Akhmediev [4]), but it definitely has steep edges with the corresponding ripples in the autocorrelation trace (Fig. 3) after the compressor. The output pulses were externally compressed down to ~200 fs (at a transform-limited pulse duration of 160 fs). The resulting compression factor is as high as ~150. We use a double-pass compressor consisting of a grating pair. It introduces a one-pass group delay dispersion $D = -0.64\ \text{ps}^2$. For the autocorrelation measurements (by Avesta AA-20DD) shown in Fig. 3, we separated the DS and Raman spectra by using blades inside the compressor, selecting 990–1030 nm part; otherwise, the dechirped pulses became longer with worsened quality of the autocorrelation trace (the contrast lower than 8∶1). The auto- and cross-correlation traces of the DS and the Raman pulse indicate different chirp, although they copropagate in the laser cavity and have similar

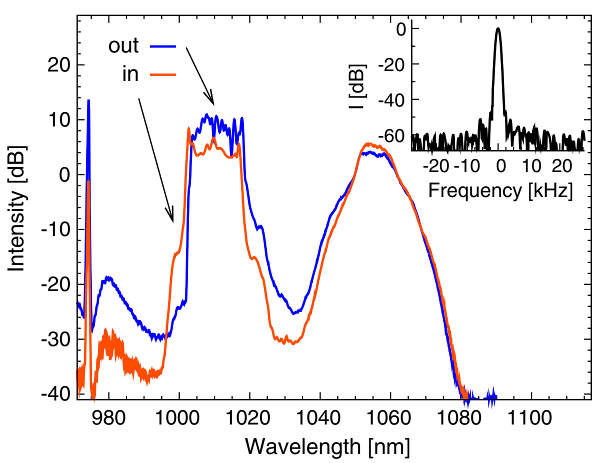

Fig. 2. (Color online) Measured optical spectra (in-inside the cavity at 1% port, out-out of the PM splitter) and RF spectrum at 750 MHz (inset) for 390 mW pumping and 30 m length.

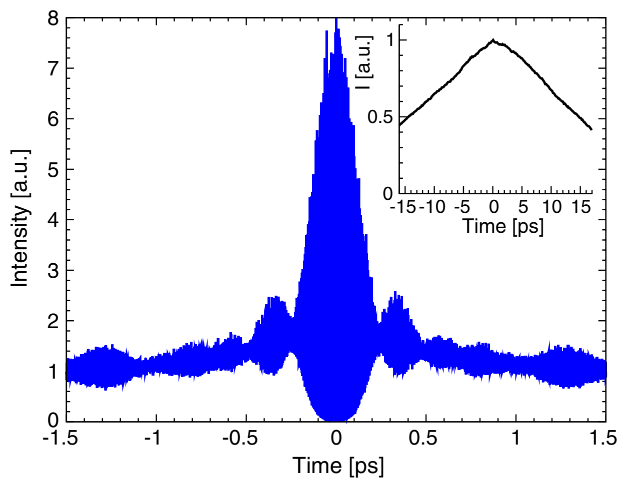

Fig. 3. (Color online) Autocorrelation traces for the dechirped and chirped (inset) DS output pulses at 390 mW pump power and 30 m cavity length.

durations, with a ≥15 ps shift between their centers. Having different parameters, the DS and Raman pulses should propagate at different velocities in passive fibers, and so-called runaway Raman solitons may be generated (e.g., see Akhmanov *et al.* [15]). On the other hand, interaction of the DS and Raman pulses in the laser cavity makes their average velocities equal, with partial overlap between them. This effect requires a detailed theoretical analysis. The appearance of the Raman component in a high-energy fiber laser was mentioned without details and discussion in Kobtsev *et al.* [16]. The Raman effect at the pulse chirping was also studied theoretically in Schadt and Jaskorzynska [17].

Let us estimate a threshold pulse energy for the Raman conversion. In the Raman process, an amplification of the wavelength-shifted Stokes wave from the noise level is induced by the DS pulse field. Therefore, the Stokes wave starts propagating together with the DS pulse and its power grows exponentially with the coefficient $g_R P_0$, where P_0 is the DS power and g_R is the Raman gain coefficient normalized on the mode field area. Because the DS and Stokes pulses have different group velocities (v_0 and v_R, correspondingly) because of dispersion, the Stokes pulse "overpasses" the pump pulse (DS soliton) of duration $T \approx 30$ ps after propagation of critical distance $L_C = T/\delta v^{-1} \sim 20$ m, where $\delta v^{-1} = v_0^{-1} - v_R^{-1} \approx 1.5$ ps/m. Outside the interaction region, DS power tends to zero and the Stokes radiation starts to attenuate. Therefore, the maximum Stokes power is shifted relative to the main DS pulse. We can estimate the maximum peak power of the Stokes pulse as $P_R = P_{\text{noise}} \exp(g_R P_0 L_C)$. Evaluation of the noise power that takes into account about a four-orders-of-magnitude difference between the pulse duration and the roundtrip time, resulting in $P_{\text{noise}} \sim 10^{-8} P_0$, leads to the ratio for the peak powers and thereby to the following ratio of the Raman and DS pulse energies:

$$\frac{\varepsilon_R}{\varepsilon} \propto \frac{P_R}{P_0} \approx \exp\left(\frac{g_R P_0 T}{\delta v^{-1}} - 18\right). \tag{1}$$

The Raman-component energy, ε_R, becomes comparable with the energy of the DS pulse, $\varepsilon = P_0 T$, at critical intracavity energy estimated as $\varepsilon_{cr} \approx 18\delta v^{-1}/g_R$. This estimate corresponds to ~15 nJ for our 5.5 μm fiber with the Raman gain coefficient $g_R \sim 2\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$. Note that critical output energy in the experiment is about two times higher than the intracavity one (see the "in" and "out" spectra in Fig. 3).

The smaller the core diameter, the lower the critical intracavity energy at which Raman scattering becomes significant. Therefore, to push further the scaling of the all-fiber dissipative-soliton laser, one should combine our approach with LMA fibers [7]. The Raman effect in this case will be suppressed because of the lower coefficient g_R. In such a combined SMF-PM all-fiber configuration with a 25 μm core LMA, the estimation above gives $\varepsilon_{cr} \sim 0.5$ μJ. As additional steps in the direction of the energy upscaling, one can increase the dispersion parameter δv^{-1} and add a selective filter to introduce high losses for the Raman component, thus extending the range of Raman-free operation.

Although the Raman scattering is a parasitic effect in the problem of femtosecond fiber lasers energy scaling, the effect is very interesting for the fundamental physics and should be studied elsewhere. It will be especially interesting to study in detail the features of the generated Stokes radiation and its interaction with the DS, which will help to answer the question why such a strong Raman scattering does not deteriorate the soliton. In general, the developed DS fiber oscillator is easily self-starting and not sensitive to disturbances, having stable and reproducible parameters at daily operation.

In conclusion, we have realized and studied an all-fiber oscillator that combines non-PM and PM cavity parts and provides environmentally stable generation of highly chirped (chirp parameter >150) DSs. The pulses of ~20 nJ have been generated at a repetition rate of ~7 MHz. After external grating compressor, they were dechirped to ~200 fs. We found that in the present configuration, the Raman scattering becomes the main factor limiting the pulse energy. Further energy upscaling is shown to be possible using long PM LMA fibers.

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