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Generation of 8-nJ pulses from a dissipative-soliton fiber laser with a nonlinear optical loop mirror

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Abstract

Theoretical and experimental investigations of the behavior of normal-dispersion fiber lasers with nonlinear-optical loop mirrors are presented. The use of a loop mirror causes the laser to generate relatively long, flat-topped pulses. The pulse energy can be high, but the pulse duration is limited to greater than 300 fs. Experimentally, 8-nJ pulses that can be dechirped to 340 fs duration are obtained. The laser is a step toward an all-fiber, environmentally-stable design.

Passively mode-locked fiber lasers have been developed with significant progress in the last two decades [1–4]. Due to their compactness, alignment-free operation, and improving performance, fiber lasers have become a good alternative to solid-state lasers. Different operation regimes were explored to increase the achievable pulse energy. The normal-dispersion regime [3–4] attracts researchers as it favors large pulse energy, compared to the anomalous dispersion regime [1] and dispersion-managed techniques [2]. The pulse shaping is based on amplitude modulation that arises from spectral filtering. Chirped pulses with picosecond duration are generated, and then dechirped outside the laser.

A saturable absorber is generally needed to start the pulse-shaping from noise. Either physical or artificial saturable absorbers can be employed. The former include semiconductor saturable-absorber mirrors, e.g., while the latter include nonlinear polarization rotation, e.g. Kharenko et al. recently achieved 20-nJ and 200-fs dissipative solitons with an all-fiber laser based on nonlinear polarization evolution (NPE) [5]. Fiber-format absorbers that are potentially compatible with polarization-maintaining (PM) fiber are desired for integrated and maximally-stable instruments. Kieu et al. reported a saturable absorber based on carbon nanotubes wrapped around a tapered fiber [6], but long-term stability has been problematic in 1- μ m lasers. Among artificial saturable absorbers, the nonlinear optical loop mirror (NOLM) [7] is promising as it requires only a low-cost fiber coupler and moderate fiber segments, and can be implemented in PM format.

A NOLM relies on nonlinear interference of the fields that counter-propagate, so the intensity of the NOLM output is determined by the product of loop length, peak power, and splitting ratio. A variant of the NOLM is the nonlinear amplifying loop mirror (NALM) [8],

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which has an amplifier asymmetrically located in the loop. Consequently the loop length can be greatly reduced, at a price of increased cost and complexity.

The use of a NOLM or NALM with normal-dispersion lasers has been investigated [9–12]. A normal-dispersion Yb-doped fiber laser with a NALM made of a 60:40 splitter was implemented in PM fiber [10]. The laser is impervious to the environment, but the pulse energy is only 0.3 nJ. Numerical simulation suggests that pulse energies of tens of nanojoules should be achieved in normal-dispersion fiber lasers that employ a NOLM or NALM [11]. Very recently, 10 nJ and 240 fs pulses were achieved with a NALM [12]. It is important to understand if loop mirrors fundamentally limit the pulse energy or duration.

In this paper we report numerical and experimental investigations of a dissipative-soliton laser with a NOLM. We find that NOLMs tend to restrict the laser to the generation of flat-top dissipative solitons [13, 14]. The pulse energy can be fairly high, but the pulse duration is longer than desired. Experimentally, a Yb fiber laser with a NOLM generates 8-nJ pulses that can be dechirped to 340 fs duration.

The design of a NOLM involves several competing issues. Generally, the longer the loop length, the smaller the peak power required to reach the first transmission maximum. However, for fiber lasers operated in the normal-dispersion regime, shorter fiber length (i.e., smaller dispersion) allows broader bandwidths and higher pulse energies [15]. A short loop length is preferred for ultrashort pulse generation. For fixed loop length the largest modulation depth occurs for α closest to 50, where the coupling ratio is $\alpha : (100 - \alpha)$, but the highest peak power is required to reach the first maximum [7]. This is the approach taken in prior lasers with NOLMs [9–11]. Smaller peak power is required to reach the first maximum in a NOLM biased further from equal splitting, but less modulation depth is obtained. Self-starting of mode locking is generally required for practical applications. To reduce the threshold requirement for self-starting while maintaining adequate modulation depth, we chose an 80:20 coupler. Compared to the commonly-used 50:50 coupler, an 80:20 coupler produces a much-steeper increase in transmission at low intensity, while it maintains adequate modulation depth. The former is required for self-starting operation, and the latter is required for effective suppression of the background. With birefringent fiber, a polarization controller (PC) is generally inserted in the loop to control the linear phase shift that allows biasing the curve for increased transmission near zero power [11].

To determine if a fiber laser with a NOLM can support pulse energies around 10 nJ, numerical simulations were performed for the cavity indicated in Fig. 1 and the experimental parameters given below. Without the NOLM, the cavity is a typical normal-dispersion fiber laser [4]. Pulse propagation in the fiber is described by the nonlinear Schrödinger equation. In brief, the light field is divided when it goes through the NOLM coupler. The fields propagate individually along their respective directions before they are recombined in the NOLM coupler. The splitting ratio is applied again for the output of the NOLM. Starting from a weak Gaussian pulse, a typical stable solution is shown in Fig. 2. The temporal profile of the pulse in the cavity is characteristic of so-called flat-top dissipative solitons [13, 14]. The pulse in the cavity is nearly static, with duration 15 ps and 7.5-nm bandwidth. The transform-limited pulse duration is 230 fs, but the pulse can only be

dechirped to 320 fs with a linear dispersive delay. The deviation from transform limit is another feature of flat-top solitons. The 11-nJ pulse energy is limited by the gain saturation energy, which is determined by the pump power. The pulse energy and duration increase with pump power. However, the dechirped pulse duration is roughly maintained. Pulse energies up to 13 nJ are stable in simulations. The simulations indicate that a NOLM exerts significant influence on the pulse evolution, and seriously impedes the generation of dissipative solitons with characteristic cat-ear spectra [15], which yield the most-attractive combination of high energy and short pulse duration.

Following the numerical results, the laser of Fig. 1 was built. All components consist of non-PM fiber. Two pump diodes with maximum powers of 600 and 750 mW, respectively, were used. A broadband 976/1030 nm wavelength division multiplexer (WDM) introduces the clockwise pump, while a narrowband WDM imports the counter-clockwise pump and at the same time functions as a filter with bandwidth of about 10 nm around 1030 nm. The Yb fiber (Yb501 from Coractive) is 65 cm long. An 80:20 fiber coupler is used, and the minimum length of the NOLM is 1.4 m. A 90% output coupler after the NOLM produces the output pulse. A polarization-insensitive isolator forces unidirectional propagation. The cavity length is 4.8 m. PCs in the loop and the cavity permit optimization of the cavity loss.

With appropriate settings of the PCs, self-starting mode-locking can be achieved when the total pump power is above 800 mW. Longer NOLMs allow self-starting at lower pump power. The NOLM was cut back to 1.4-m length, which is the minimum that provides self-starting operation. Figure 3 shows the details of the generated pulses at maximum pump power. The output power is 350 mW, which corresponds to a pulse energy of 8.4 nJ at 41 MHz repetition rate. The optical spectrum shows steep spectral edges (Fig. 3(a)), with a 3-dB bandwidth of 7.5 nm. The triangle-shaped autocorrelation trace is consistent with that expected for a flat-topped soliton [13, 14], and implies a pulse duration of about 18 ps. The pulse can be compressed to 340 fs (Fig. 3(c)) with a pair of gratings, which is about 1.5 times the transform-limited duration. All of the experimental measurements agree well with the simulations, and are also consistent with the analytic dissipative-soliton solution with offset-phase parameter $B > 1$ [14]. The radio-frequency spectrum (Fig. 3(d)) is limited by the noise floor of the analyzer, but still exhibits contrast near 80 dB, which indicates that there are only low-amplitude fluctuations. Single-pulse operation was confirmed by the combined measurement of an autocorrelator (scan range > 175 ps) and a high-speed sampling oscilloscope (30 GHz optical channel). Multiple pulses are not observed even at the highest available pump power. Once adjusted, the laser is stable for several days in the laboratory.

The results presented here imply that dissipative-soliton lasers can be constructed entirely with PM fiber. Environmentally-stable all-fiber lasers that can approximate the performance of dissipative-soliton lasers with nonlinear polarization rotation will be extremely attractive for applications. A common disadvantage of loop mirrors is the long length that can be required. We have shown that repetition rates of at least 40 MHz can be obtained, by optimizing the coupling ratio of the loop. NOLMs with other splitting ratios were also tested. For > 80 , it is difficult to achieve mode locking due to the small modulation depth. For $50 < \alpha < 80$, mode locking can be obtained but the operation is not self-starting unless a longer loop is used. Despite trying several different designs and combinations of cavity

parameters (e.g., different filter bandwidths), we have found that it is difficult to avoid the flat-top regime of dissipative-solitons when a loop mirror is used as the saturable absorber. This limits the pulse duration to greater than 250 – 300 fs, with some deviation from the transform limit. We attribute this behavior to the sinusoidal transmission curve of the NOLM. In contrast, dissipative soliton lasers with other saturable absorbers generate pulses shorter than 100 fs.

In principle, a shorter loop can be used if higher pump power is available. A shorter loop implies smaller cavity dispersion, and it will be interesting to see if dissipative solitons with $|B| \sim 1$ can be generated in a laser with a NOLM or NALM. This will be the subject of future work. Ding et al. have proposed combining two NPE segments to produce a transmission curve with desirable properties, such as enhanced pulse energy [16]. It will also be interesting to see if customizing the shape of the transmission characteristic of the loop mirror will allow generation of shorter pulses.

In conclusion, a study of the performance of a NOLM as the saturable absorber in normal-dispersion fiber lasers was presented. The NOLM does limit the pulse duration to >300 fs in simulation and experiment, and this may limit the opportunities for lasers similar to that described here. Although the pulses are longer than desired, this type of laser may still be attractive for some applications. One example would be seeding of high-energy fiber amplifiers, which typically generate ~ 300 -fs pulses [17]. The 8-nJ pulse energy achieved is limited by the available pump power and further scaling is possible. The laser is self-starting, and the construction is all-fiber. It should be possible to construct a similar laser with PM fiber for ultimate stability.

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Fig. 1. Schematic of the laser. WDM: wavelength division multiplexer; YDF: Ytterbium-doped fiber; I: polarization-insensitive isolator; PC: polarization controller.

Fig. 2.

(a) Optical spectrum and (b) pulse profile of a simulated pulse (dashed red line: output pulse; solid blue line: dechirped pulse).

Fig. 3.

(a) Optical spectrum and (b) autocorrelation trace; (c) dechirped pulse autocorrelation trace; (d) RF spectrum of the generated pulse.