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Letter

Harmonic dissipative soliton resonance square pulses in an anomalous dispersion passively mode-locked fiber ring laser

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Abstract

We demonstrate the generation of dissipative soliton resonance square pulses from a co-doped Er:Yb double-clad fiber ring laser operating in an all anomalous dispersion regime. The obtained pulses have a repetition rate of 672 kHz and a pulse energy of 409 nJ. By carefully adjusting the polarization controllers while increasing the pump power, the square pulse can split into a series of identical equally spaced smaller square pulses up to the 13th harmonic of the fundamental repetition frequency. The average output energy of the square pulses follows a scaling law versus the harmonic order.

Keywords: fiber laser, harmonic mode-locking, mode-locked laser, dissipative soliton resonance

(Some figures may appear in colour only in the online journal)

Introduction

Passive mode-locking remains the most prominent technique used in generating all kinds of pulses from ultrashort to ultra-wide pulses [1] since it promotes the self-starting mode-locking states. In the last decade, the development of passively mode-locked ultrafast fiber lasers and their potential in multi-disciplinary fields [2, 3] has aroused great interest in exploring different architectures leading to a variety of novel operational modes. Among these modes, the generation of high energy nanosecond pulses has been widely studied [4–8]. However, achieving high energetic pulses from fiber lasers is relatively difficult since it is limited by factors like multi-pulsing instabilities [9, 10] that usually occur with high pump power.

In passively mode-locked fiber lasers operating in the anomalous dispersion regime, the pulse energy is limited by the area theorem as a function of the pulse shape [11], whereas in the normal dispersion regime, it is the nonlinear losses and the finite gain that tend to quantize and limit the energy [12]. To bypass these restrictions, different optical pulse shaping methods have been investigated. It was shown that parabolic shaped pulses allow the achievement of higher energies than solitons, however, wave-breaking would occur at moderate pump powers [13]. In 2008, a theoretical study predicting the generation of high energy pulses from mode-locked lasers was developed [14]. Based on a solution of the complex cubic-quintic Ginzburg–Landau equation, it stated that the pulse energy operating under dissipative soliton resonance (DSR) regime can increase indefinitely with a specific set of normalized parameters while its peak power remains stable. This breakthrough in the generation of high energy pulses led to a deeper investigation of the dissipative soliton resonance dynamics [9]. In the DSR region, the generation of square pulses has been demonstrated regardless of the sign of the dispersion. Thus, DSR square pulses were experimentally documented in the anomalous dispersion regime [15–22] and the normal dispersion regime [23, 24]. It has been experimentally proven that the high nonlinearity and cavity

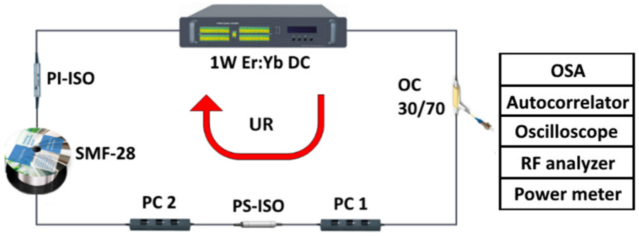

Figure 1. Experimental setup of the fiber ring cavity. PI-ISO—polarization insensitive isolator, PS-ISO—polarization sensitive isolator, OC—30% output coupler, Er:Yb DC—1 W co-doped Er:Yb double-clad amplifier, OSA—optical spectrum analyzer, PC—polarization controller, UR—unidirectional ring, SMF-28—250 m single mode fiber coil.

length play a major role in widening the pulse [17, 25]. It is worth noting that these square pulses were reported to have no internal fine structures within the square profile packet, and therefore they maintain the pulse coherence. Recently, a different type of square pulse has been demonstrated [26, 27] operating in the noise-like regime and exhibiting characteristics close to the DSR square pulses except they lack temporal coherence revealed by a coherence peak in the autocorrelation trace. These pulses' energy and width can be tuned continuously by increasing the pump power in high nonlinear cavities till wave-breaking occurs and pulses break. It has also been demonstrated that by carefully modifying the birefringence in the cavity while having noise-like square pulses, the laser can operate in a higher order of harmonics [27].

To the best of our knowledge, no harmonic mode-locking of square pulses has been demonstrated in the DSR regime. The aim of this letter is to address this point, thus demonstrating that multiple-pulsing also occurs in the DSR regime. More specifically, we experimentally demonstrate the transition from a single DSR square pulse into a series of harmonic DSR pulses up to the 13th harmonic from a double-clad Er:Yb co-doped fiber laser passively mode-locked through nonlinear polarization evolution.

Experimental setup

The experimental mode-locked laser setup shown in figure 1 is based on a simple all fiber ring cavity exploiting the nonlinear polarization evolution mechanism. It consists of a C-band double clad V-groove Er:Yb fiber amplifier from Keopsys capable of delivering up to 1.2 W of output power under 3 W of pump power. Inside the amplifier, several laser diodes operating at 980 nm pump a 5 m long double-clad fiber that has a second order dispersion of $-0.021\ \mathrm{ps^2\ m^{-1}}$.

The round-trip time of the cavity is 1.488 μs corresponding to a free spectral range of 672 kHz. A set of two polarization controllers (PC) is used with a high-power polarization sensitive isolator (PS-ISO) to form an artificial saturable absorber, thus leading to the self-start mode-locking of the fiber laser. A polarization-insensitive isolator (PI-ISO) is employed to improve the isolation ratio and the signal is extracted with a 30% output coupler. The output signal is detected using a high-speed photodetector (TIA-1200), and visualized with a fast oscilloscope (Tektronix TDS 6124C, 12 GHz, 40 GS $\mathrm{s^{-1}}$). Also, the output power is measured using an integrating sphere (Thorlabs S146C) connected to a digital monitor (Thorlabs PM-100D). The spectral properties are analyzed with an optical spectrum analyzer (Anritsu MS 9710C) and the fine temporal structures are measured with a range of $\pm$100 ps optical autocorrelator (Femtochrome FR-103 WS). An electronic spectrum analyzer (Rohde & Schwarz FSP Spectrum Analyzer 9 kHz to 13.6 GHz) is used to characterize the radio frequency (RF) spectrum of the laser. The slow-axis in the PS-ISO is rejected through a port which is connected to a high-power wattmeter (Coherent Molectron PM500AD). The laser can operate in different regimes by carefully adjusting the polarization controllers through the variation of both linear and nonlinear losses of the cavity.

The length of the cavity is specifically tailored to facilitate the coexistence of classical solitons and DSR square wave pulses. This is the main difference between this setup and the previous demonstrations by our group [18, 19]. In addition, the parameters for which harmonic mode-locked square pulses can exist are critical and we have spent a vast amount of time to find all the harmonic regimes. Let us stress that our detection apparatus allows us to reveal unambiguously the existence of short pulses within the square pulses which provides irrefutable proofs about the nature of the generated square pulse distribution.

Experimental results

Self-starting dissipative soliton resonance square pulses at the fundamental repetition rate are obtained with a threshold pump power of 400 mW. Figure 2(a) shows the optical spectrum trace of the generated pulses under 3 W of pump power. The resolution of the spectrum analyzer is 0.03 nm and the central wavelength is centered around 1566 nm with 3 nm spectral bandwidth at -3 dB.

In figure 2(b), the measured RF spectrum shows a signal to noise ratio around 60 dB at 672 kHz. The resolution bandwidth (RBW) of the spectrum analyzer is 100 Hz. The inset exhibits a characteristic modulation with a period of 3.71 MHz corresponding to the duration of the generated square pulses for 3 W. Figure 2(c) depicts the temporal trace of the generated pulses. The pulse has a square-shape with a duration of about 270 ns. To confirm the existence of this single square pulse and that we did not record the envelop of a bunch of short pulses, we verified the absence of a coherent peak in the autocorrelation spectrum as pointed out in figure 2(d). In addition, figure 2(d) represents the complete span of our autocorrelator which allows us to scan about $\pm$100 ps. Combined with the fast oscilloscope, this is sufficient to visualize any bunch of solitons and to verify that the pulse is solitary without any internal fine structure. Since the scanning range of the optical autocorrelator (200 ps) is very small compared to the pulse duration (hundreds of ns) we record only the very small central part of the whole autocorrelation spectrum. As a consequence, we observe a nearly flat signal instead of a

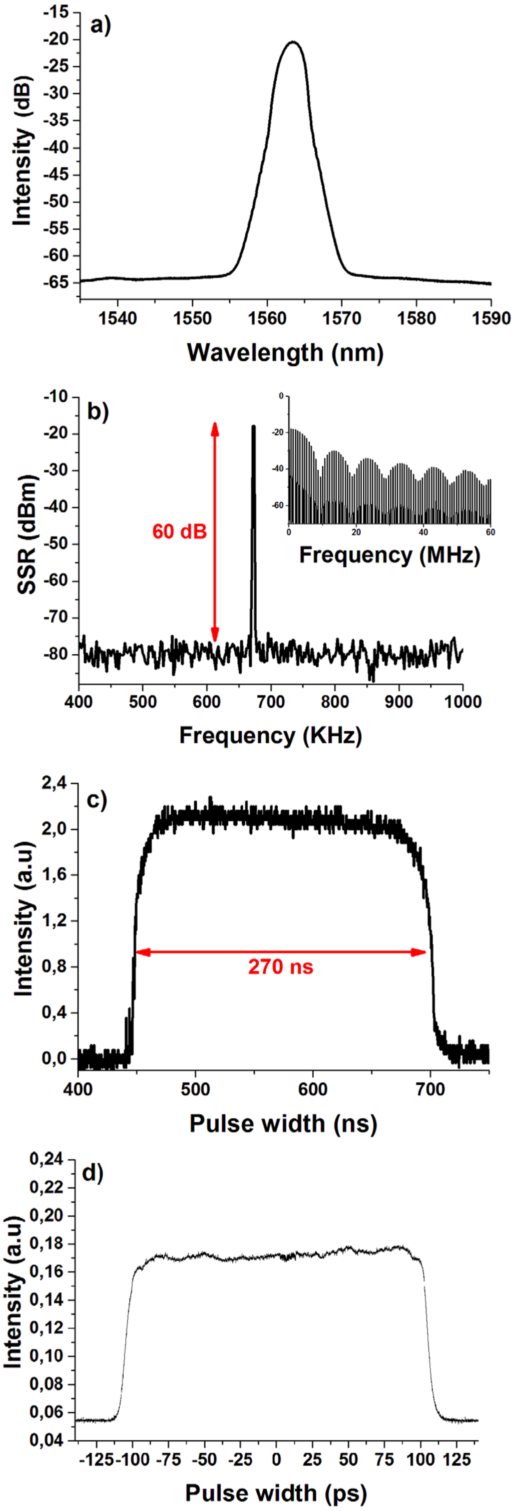

Figure 2. Mode-locked emission at 3 W of pump power: (a) optical spectrum trace, (b) RF spectrum trace with 1 Hz bandwidth, the inset shows the RF spectrum trace with 500 MHz span, (c) temporal trace and (d) autocorrelation trace.

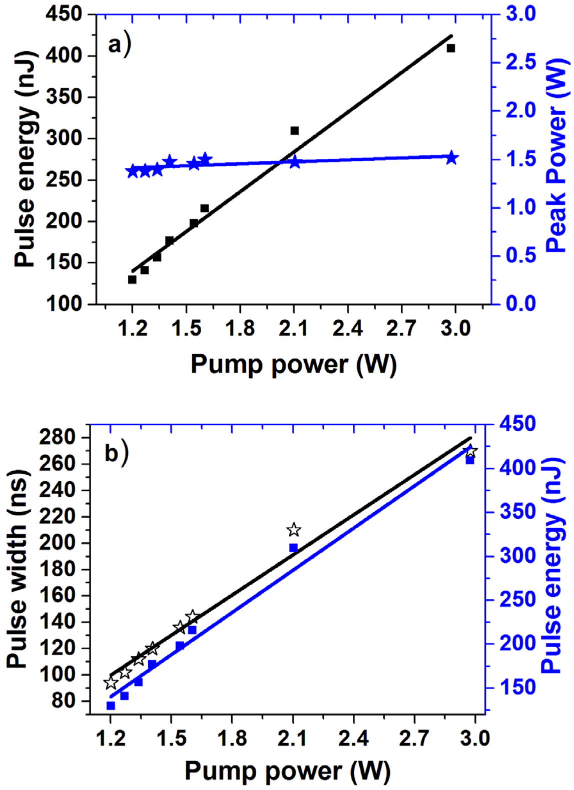

Figure 3. Evolution of the pulse characteristics: (a) pulse width and peak power versus pump power (squares for the pulse energy, stars for the peak power). (b) Pulse width and pulse energy versus the pump power (square for pulse energy, stars for the pulse width).

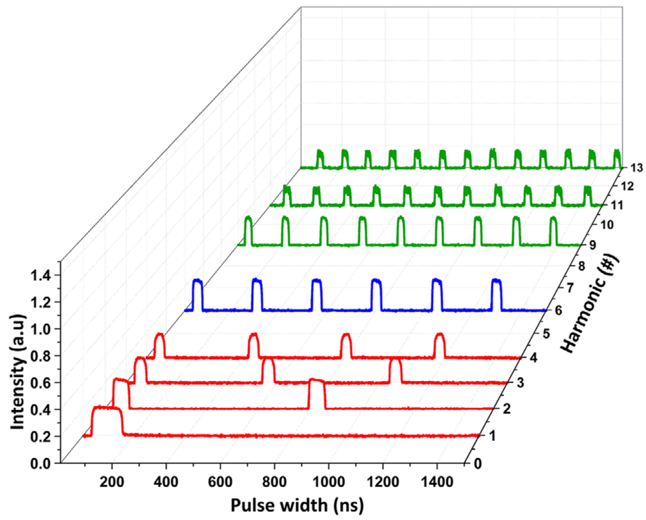

Figure 4. Harmonic mode-locked DSR square pulses train of different orders achieved by adjusting the PC. Each color is assigned to different pump power (red for 1.18 W, blue for 1.6 W and green for 2.2 W).

triangular shape [28] as it would be the case with a scanning range 1000 times larger.

By fixing the polarization controllers and increasing the pump power, the pulse broadens while the peak power remains nearly constant which demonstrates the dissipative soliton resonance operational mode [29]. The evolution of the pulse width and pulse energy for fixed PCs and variable pump power is presented in figure 3.

We notice that the pulse duration and the pulse energy can be quasi-linearly increased with the pump power without significantly affecting the peak power. At a maximum pump power, the highest achieved pulse energy is 409 nJ, whereas

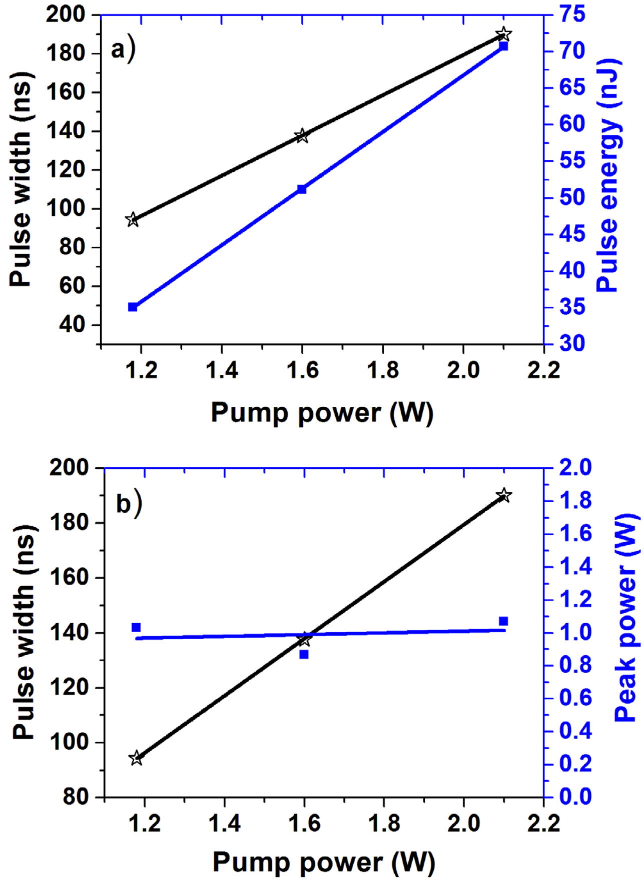

Figure 5. Evolution of the 4th order harmonic mode-locked square pulse's characteristics: (a) pulse width and energy versus pump power (stars for pulse width, squares for pulse energy). (b) Pulse width and peak power versus pump power (stars for pulse width, squares for peak power).

the generated square pulse's width can be tuned in a range from 95 ns to 270 ns as shown in figure 3(b).

In contrast to what has been demonstrated recently where there is a possibility to compress dissipative soliton resonance square pulses in the range of hundreds of picoseconds [22], it is impossible to achieve a successful compression when the pulses are in the order of hundreds of nanoseconds since it requires extremely large values of dispersion.

As mentioned before, by continuously increasing the pump power, the square pulse operating in dissipative soliton resonance regime widens and does not suffer from wave-breaking at a maximum 3 W pump power. When the pump power is fixed and by adjusting properly the PCs, the square pulse packet can split into two or more pulses similar to the original square pulse and the laser evolves into a higher harmonic DSR square pulse mode-locking as shown in figure 4.

At a pump power of 1.18 W while modifying the polarization controllers, we achieved up to the 4th harmonic order. This was the maximum harmonic that was being generated by a set of specific parameters. By increasing the pump to 1.6 W, we managed to obtain up to the 6th harmonic order while carefully adjusting the PC. Further increase of the pump power to 2.2 W while conserving the exact same optical spectrum, leads to the generation of several harmonic orders up to the 13th harmonic order. Above this pump power, no increase in the harmonic order is detected since the harmonic regime is lost and we return to a single square pulse in the cavity. The square pulse width varies from 102 ns at the fundamental frequency to 18 ns at the 13th harmonic order. The autocorrelation trace of the harmonic mode-locked pulses showed no fine structures, indicating that the harmonic mode-locked square pulses were not the envelops of noise-like pulses.

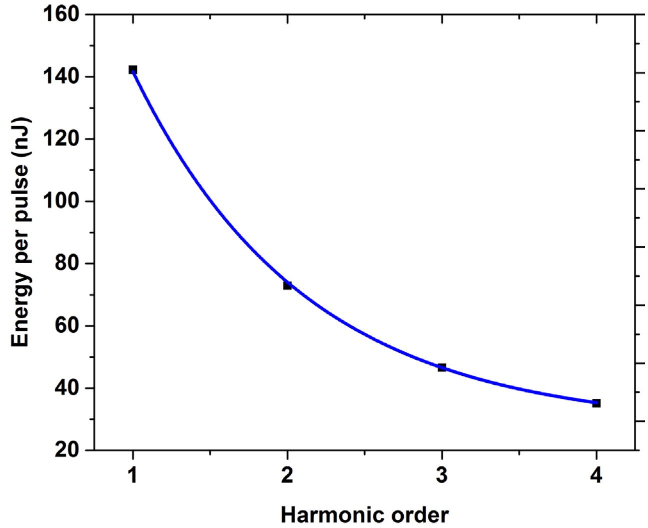

Figure 6. Pulse energy versus harmonic order at a fixed pump power. The solid line is a $1/n$ fit.

To verify that the achieved HML distribution operates under the dissipative soliton resonance regime, we compared the 4th harmonic order obtained under different pump powers. As shown in figure 5(a), under the 4th harmonic order distribution, when we increase the pump power, the square pulses widen and become more energetic continuously without wave-breaking. The pulse duration increases from around 95 ns to 190 ns whereas the energy from 37 nJ to 70 nJ. Also, we measure the peak power during this process as presented in figure 5(b), and it remains nearly constant when the pulse width is modified.

We notice that the average output energy per pulse at a fixed pump power of 1.18 W, follows a scaling law of $1/n$ where the pulse energy is inversely proportional to the harmonic order as described in figure 6. This is due to the fact that the average output power remains nearly unchanged.

Summary

In conclusion, we have experimentally demonstrated the generation of harmonic mode-locked dissipative soliton resonance square pulses from a fiber laser operating in the anomalous dispersion regime. Stable DSR square pulses were achieved at a fundamental repetition frequency of 672 kHz, with pulse width tunable from 95 ns to 270 ns by increasing the pump power and the maximum single pulse energy reached up to 409 nJ. The fundamental square pulse can evolve into a stable higher-order harmonic mode-locking of DSR square pulses by slightly adjusting the polarization controllers. Increasing the pump power allowed higher harmonic orders to be obtained. At 2.2 W of pump power while carefully adjusting the PCs, we demonstrated the generation of the 13th harmonic mode-locked DSR square pulses. Finally, let us note that the HML regime was obtained by carefully adjusting the polarization controllers without wave-breaking for any of the harmonic orders when the pump power was increased.

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