EPJ Web of Conferences **287**, 06004 (2023) https://doi.org/10.1051/epjconf/202328706004
EOSAM 2023

An overview of dissipative soliton resonance in fiber lasers

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Abstract. Because of the pulse energy quantization in fiber lasers, it is of great importance to find effective ways to increase the pulse energy directly from a fiber laser. An efficient technique is based on the dissipative soliton resonance (DSR) effect. The DSR manifest as a square pulse with constant peak power and a linear increase of both the pulse energy and duration for increasing pumping power. In practice, DSR is favoured with the use of long cavities. In this communication we propose an overview of DSR in fiber lasers including general theoretical approaches together with the most recent relevant experimental results.

1 Introduction

A common feature to PMLFL is that, while the pump power is increased, additional pulses are created one by one at the expense of increasing the pulse energy [1,2]. This is due to energy quantization of the dissipative solitons occurring for any dispersion regime [2,3]. However, wave-breaking can be avoided, and pulse energy can be increased through various strategies. They can be classified into two categories: the management of the nonlinear effects, and pulse shaping. The first strategy includes the use of stretched-pulse cavities, direct management of the nonlinearity, all-normal dispersion cavity, or intra-cavity power management in the normal dispersion regime. In the latter case, record pulse energy above 12 µJ has been demonstrated in the ytterbium doped PMLFL [4]. Pulse shaping, on the other hand, includes the use of self-similar parabolic pulses [5], and square-wave pulses. The possibility of increasing the width of a generated pulse with the pump power while maintaining a constant peak power was first theoretically reported by A. Komarov in 2005 [1]. The model was not based on a master equation but on laser equations including the effects of the phase plates. Few years later, the concept of 'dissipative soliton resonance' (DSR) was introduced by W. Chang *et al* [6]. DSR appears as a particular soliton solution of the cubic-quintic Ginzburg-Landau equation (CGLE) with an energy which increases indefinitely.
The aim of this presentation is to give a review of the dissipative soliton resonance in fiber lasers. Theoretical approaches and experimental demonstrations will be presented.

2 Theoretical approaches

The existence of a soliton solution with peak power clamping and an increase of the pulse width was first reported in [1]. The model was based on two equations, one for the evolution of the electric field in a nonlinear dispersive medium and the second accounting for the nonlinear losses resulting from the combined effects of optical Kerr effect, the polarizer, and the phase plates. An example of the evolution of the pulse intensity for increasing pumping power is shown in Figure 1.

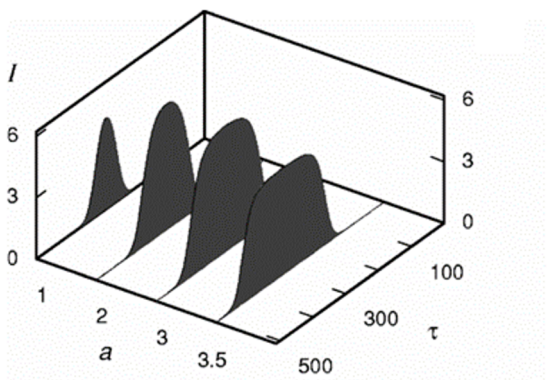

Fig. 1. Temporal distribution of the intensity versus the pumping parameter a [1].

The concept of Dissipative Soliton Resonance has been defined in [6] in the case of normal dispersion. The model was based on a nonlinear propagation equation of CGLE type. It has been demonstrated that for some specific values of the parameters, the energy of some stationary pulses can increase indefinitely.

The case of an erbium-doped fiber laser has been considered by X. Liu [7]. The model was based on laser equations including two nonlinear coupled equations for the electric field polarization components, and an equation for the nonlinear transmission resulting from nonlinear polarization evolution.

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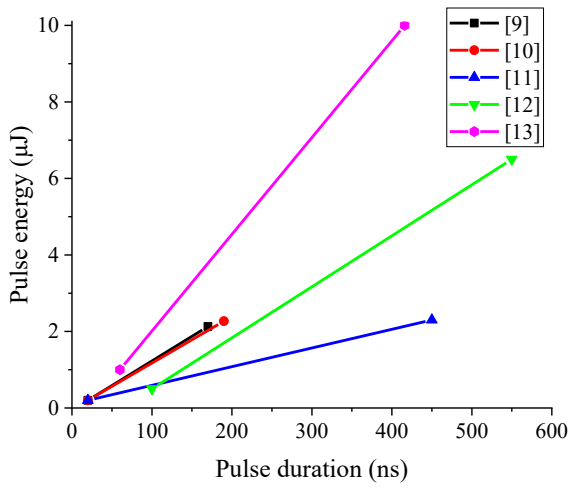

Fig. 2. Range of variation of the pulse duration and energy in double clad passively mode-locked fiber lasers [14].

3 Experimental demonstrations

In fiber lasers, DSR operation is favored with the use of long cavities. Indeed, long cavities allow to benefit from large dispersion and nonlinearity together with high energy stored by cavity round-trip. DSRs are characterized by their square-wave emission, linear increase in pulse duration and energy with respect to pumping power, and a bell-shaped optical spectrum with nearly constant linewidth. Additionally, the pulse peak power remains almost independent of the pump power. These features of DSRs have been observed in different rare-earth doped fiber lasers and using various mode-locking mechanisms. We focus here on the erbium-doped fiber laser.

Historically, DSR has been first reported in EDFL [7,8]. Typically, the energy was limited to some tens to few hundreds of nJ and the pulse duration to some tens of nanoseconds. DSR has then been observed using different optical configurations and different mode-locking mechanisms including real saturable absorber. However, the pulse energy was limited by the available pumping power. To overcome this limitation, an important step was taken by using double-clad fibers. The first experimental demonstration of microjoule DSR pulses was realized by K. Krzempek, using a new design of a F8L in a NALM configuration [9]. The laser delivered DSR square-wave pulses with an energy up to 2.13 µJ and a pulse duration ranging from 20 ns to 170 ns. Few months later, Semaan *et al* established a new record of 2.27 µJ using a ring cavity passively mode-locked through NPR [10]. Subsequently, several new records were demonstrated with figure-9 laser [11] or F8L in NOLM configuration [12], leading to the symbolic value of 10 µJ [13]. Figure 2 summarizes the results concerning the evolution of the pulse energy and duration. The 10 µJ was obtained in a modified F8L including two erbium-doped amplifiers as initially proposed by Mei [14] for the ytterbium-doped fiber laser. The basic idea was to tune independently the pulse duration and the peak power of the square-wave pulses. It was demonstrated in [13] that although it is possible to modify both the pulse duration and peak power by adjusting the pumping power of the two amplifiers, their effects were not independent. Further studies on DSR using DCF were dedicated to the optimization through the investigation of the influence of the total cavity length and other cavity parameters [16,17].

4 Conclusion

DSR has been demonstrated in many optical configurations and using different rare-earth ions. And appears as a universal regime occurring independently of both the mode-locking mechanism and the exact doping ion and even independently of the glass host fiber. Record pulse energy above 10 µJ and pulse duration above the µs have been reported directly from the fiber laser oscillator. In the future, higher energies could be achieved by an optimization of the optical cavity together with more flexibility for the pulse duration and peak power. In addition, DSR regime should be explored in ZBLAN fiber laser since there is very little results on this subject.

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