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HIGH-REPETITION RATE PASSIVELY MODE-LOCKED FIBER LASER

[1]F. Sanchez, [1]F. Amrani, [1]M. Salhi, [1]H. Leblond, [2]A. Komarov

[1]Laboratoire de Photonique d'Angers E.A. 4644, Université d'Angers, 2 Bd Lavoisier, 49000 Angers, France
[2]Institute of Automation and Electrometry, Russian Academy of Sciences, Acad. Koptyug Pr. 1, 630090 Novosibirsk, Russie

francois.sanchez@univ-angers.fr, foued.amrani@etud.univ-angers.fr, mohamed.salhi@univ-angers.fr, herve.leblond@univ-angers.fr, komarov@iae.nsk.su

Abstract: We investigate different ways to considerably increase the repetition-rate of passively mode-locked fiber lasers. We first report the harmonic mode-locking of a double-clad fiber laser passively mode-locked through nonlinear polarization rotation. We then consider the theoretical possibility to generate a bound-state filling the optical cavity thus resulting in ultra-high repetition rate with a remarkable stability.

Key words: fiber laser, mode-locking, soliton, high-repetition.

I. INTRODUCTION

Fiber lasers have today numerous applications from the industry to research. The problem related to the relatively small power supported by optical fibers has been overcome thanks to double-clad structures and, more recently, to large area microstructured fibers. The scaling-up of the optical power delivered by fiber lasers has allowed the realization of passively mode-locked fiber lasers with still increasing pulse energy when operating in the normal dispersion regime. The anomalous dispersion regime strongly limits the energy per pulse because it favours multiple pulsing behaviour. In this case, several pulses coexist in the cavity. Although such regime can be detrimental for some applications, it is essential for the realization of high repetition-rate fiber laser for which the repetition-rate is much higher than the fundamental frequency of the cavity (typically about 10 MHz in fiber lasers). Actually the quantum dots semiconductor lasers allow reaching high frequency rates. However, the average power remains small. Passively mode-locked double-clad fiber lasers could be a promising alternative. In this paper, we present two ways to considerably increase the frequency rate of a cavity. The first case is the harmonic mode-locking [1]. This operating regime starts spontaneously but suffers from a large temporal jitter. The second case is based on bound-states resulting from soliton interaction. [2] A bound state is a group of identical and equidistant solitons which are phase locked resulting in a very high stability. When the pumping power increases, the number of pulses in the cavity also increases leading, under specific conditions, to the formation of a soliton crystal [3]. Numerical simulations demonstrate that if the pumping power is high enough, the soliton crystal can fill the entire cavity resulting in a very high repetition-rate [4]. The remarkable point is the very high stability of such state in comparison to the harmonic passive mode-locking.

II. Experimental Setup

The experimental setup is shown in Fig. 1. Mode locking is achieved through nonlinear polarization rotation technique [5]. The laser cavity is a unidirectional ring which series several fibers. We use a double-clad Er:Yb fiber amplifier manufactured by Keopsys. Two identical laser diodes operating at 980 nm and emitting about 3 W each are used in a counter-propagating geometry. The 8 m long double-clad fiber (DCF) has a second order dispersion $\beta_2 = -0.015\,\mathrm{ps}^2/\mathrm{m}$. Pieces of standard fiber (SMF 28) and dispersion shifted fiber (DSF) are used to control the total dispersion of the cavity that is $\beta_2^{TOT} L = -0.04\,\mathrm{ps}^2$. Nonlinear losses can be varied by a rotation of the intracavity phase plates. A 10% output coupler is used to extract the power from the cavity. The output beam is detected with a high-speed photodiode and analyzed with either a high-speed oscilloscope (Tektronix TDS 6124C 12 GHz, 40 GS/s) or an electronic spectrum analyzer. Pulse duration is measured with an optical autocorrelator with a scanning range of $\pm 100\,\mathrm{ps}$, and an optical spectrum analyzer (Anritsu MS 9710C) is also used.

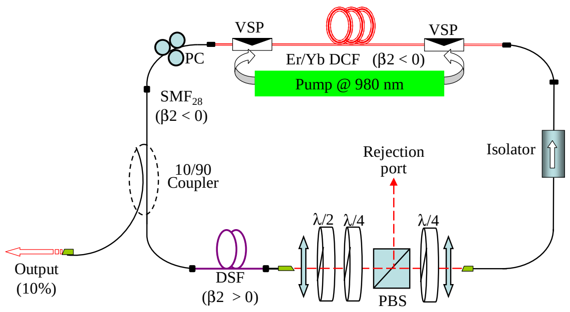

Fig.1. Experimental setup.

III. Passive Harmonic Mode-Locking

With a pumping power above 2W, mode locking with several hundred pulses is readily achieved, but most of the corresponding regimes do not consist in regularly spaced pulses. Instead, grouping of pulses is frequently observed [6]. However, we have found particular sets of orientations for the intracavity wave plates that allow a transition from a large bunched state of pulses to high-order harmonic mode locking (HML). The transition is particularly long and we have recorded it as illustrated in Fig. 2 that presents the temporal distribution of the output intensity at different times. The results have been obtained for a total pumping power of 2.2 W. At the beginning, the signal consists in an unresolved bunched state of several hundred pulses that fill about 10 % of the cavity length (see Fig. 2a). Gradually, the bunch spreads over a large part of the cavity as shown in Figs. 2b, c, d. This takes place in about 40 seconds. After that, the evolution is slower and it takes about 160 seconds for the pulses to fill the whole cavity as displayed on Fig. 2e. The horizontal magnification of Fig. 2e (Fig. 2f) reveals that the pulse distribution is uniform. Thus the laser operates in a high-order HML regime. The final repetition rate is 3.079 GHz which has to be compared to the fundamental cavity frequency 9.562 MHz, resulting in the generation of the 322nd harmonic, a record for this type of laser configuration to the best of our knowledge. The HML is self-starting in the sense that if the pump power is switched off and then switched on, the HML regime is restored and is stable over several hours when the external temperature does not vary. In the experiment, we have obtained even higher frequencies (about 5 GHz) but with a lower stability. Therefore, we focus in the characterization on the 322nd harmonic order.

HML quality is determined through different parameters. The first one is the rate of suppression of supermodes [7] that is deduced from the analysis of the radio-frequency spectrum of the output intensity, around the harmonic-repetition-rate frequency. Figure 3 clearly shows the repetition frequency of the laser and its harmonics and also additional peaks separated by the fundamental cavity frequency. The inset shows a magnification from which we can deduce the rate of supermode suppression, better than 25 dB.

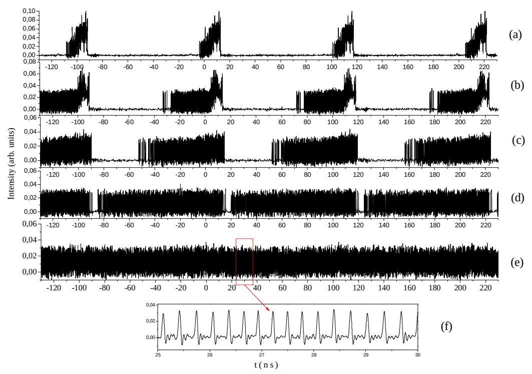

Fig.2. Temporal distribution of the output intensity at different recording times. (a) t = 0, (d) t = 40 s and (e) t = 200 s. (f) is a zoom of Fig. 2(e).

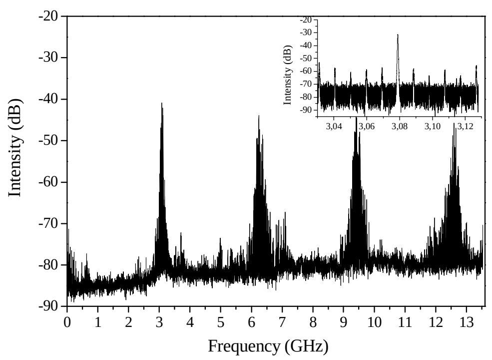

Fig.3. Radio-frequency spectrum of the output intensity in the range 0 – 13 GHz. The inset shows a zoom around the repetition frequency of the cavity.

The other performances of the HML laser are as follows. The average output power is 54 mW leading to an output energy of 18 pJ per pulse. Higher pulse energy can be expected in our experiment by simply increasing the output coupling. The autocorrelation trace allows to deduce a pulse duration of $\Delta\tau \approx 1\,\text{ps}$ assuming a sech-pulse shape. The optical spectrum is given in Fig. 4. The spectral bandwidth at half maximum is $\Delta\lambda \approx 10\,\text{nm}$. Thus the time – bandwidth product is $\Delta\tau \cdot \Delta\nu \approx 1.2$, about 4 times higher than the Fourier-transform limit. Such frequency chirping arises from the location of the output port after the SMF in the dispersion-managed cavity. Inspection of the optical spectrum reveals additional physical insights on the mechanism of formation of the harmonic mode-locked regime. Indeed, every HML regime is correlated in our setup to the existence of a cw component observable in the optical spectrum.

Although several hypothesis have been put forward to explain the formation of HML, it seems that the interaction of pulses through a cw component is responsible for high-order HML [8].

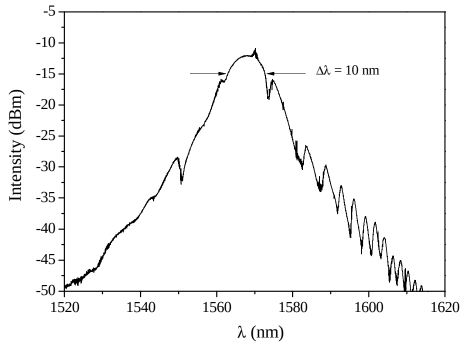

Fig.4. Optical spectrum.

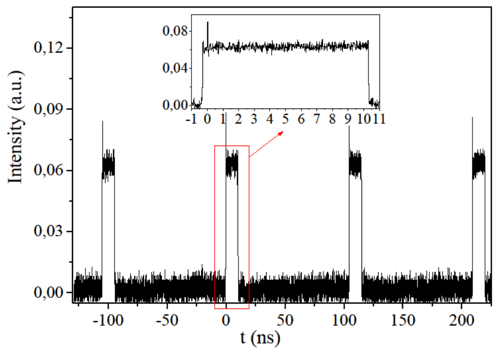

Fig.5. Temporal evolution of a soliton crystal.

IV. Harmonic Mode-Locked Soliton Crystal Fiber Laser

We consider in this section the possibility of realization of a high repetition-rate fiber laser based on bound-state. A bound state is a group of identical and equidistant solitons which are phase locked resulting in a very high stability [2]. When the pumping power increases, the number of pulses in the cavity also increases leading, under specific conditions, to the formation of a soliton crystal [3]. Fig. 5 shows an example of a soliton crystal of 480 pulses [9] obtained with the experimental setup of Fig. 1. The fast oscilloscope gives only the envelope of the signal because pulses cannot be separated. Inspection of the optical spectrum and the autocorrelation trace, shown in Fig. 6 and Fig. 7, respectively, reveals that the signal is composed of hundreds of identical pulses, which are mutually coherent and regularly spaced. This is proved by the strong modulation of the optical spectrum. The autocorrelation trace demonstrates that the pulse separation is 23 ps. The total extent of the soliton crystal is 11 ns, leading to a total number of solitons of about 480 [9].

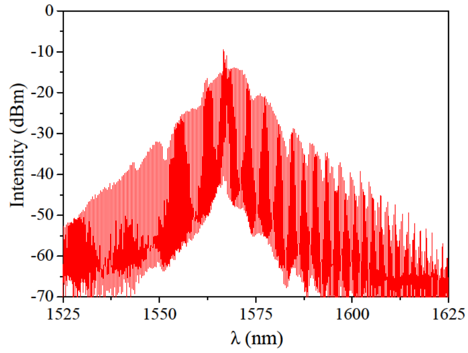

Fig.6. Optical sepctrum of a soliton crystal.

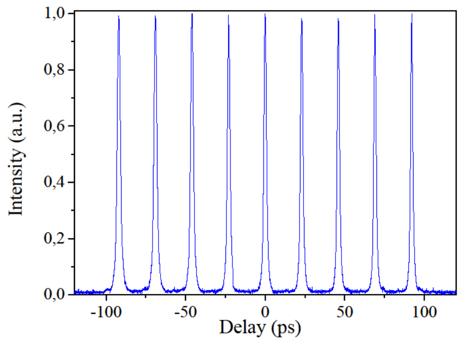

Fig.7. Autocorrelation trace of a soliton crystal.

When the total laser cavity is filled by such train, the harmonic passive mode-locking is realized. The rate of repetition of ultrashort pulses in output of this laser is determined by distance between neighbouring solitons. That is, it can be as high as the inverse ultrashort pulse duration. That means that the pulse-repetition-rate of such laser can lay in the tera-hertz frequency range for sub-picosecond pulses. To investigate theoretically such behaviour we use the model developed in [10] which consists in two nonlinear equations. The numerical simulations are done with parameters characteristic of the Er-doped fiber laser operating in the anomalous dispersion regime. For specific orientations of the phase plates we obtain a soliton crystal of 154 pulses as shown in Fig. 8.

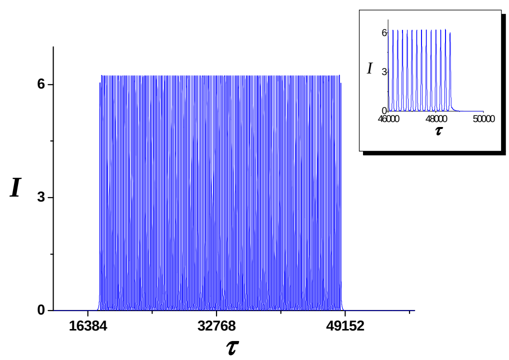

Fig.8. Temporal evolution of a soliton crystal obtained from numerical simulations.

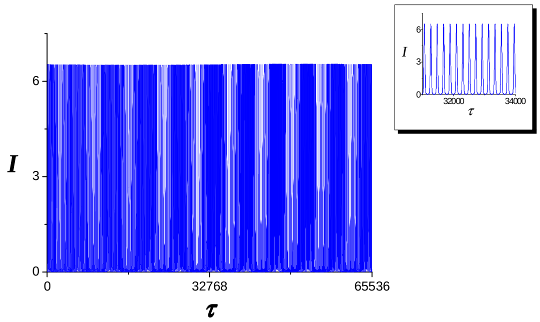

Fig.9. Modelling of the regime of harmonic passive mode-locking due to the bound soliton mechanism.

With increasing pump power the number of pulses in the train increases and the train length also increases. When the duration of the train becomes equal to the cavity roundtrip time, the harmonic passive mode-locking is realized. Fig. 9 shows modelling of the regime of harmonic passive mode-locking due to the bound soliton mechanism. Transition into the harmonic passive mode-locking regime and reverting into the original operation with changing pump are described by hysteresis dependence. Up to now, it has been obtained experimentally by our team a long train of bound solitons which fills approximately one tenth of the total resonator length [3], [9]. We have demonstrated that the realization of a train having a length matching the total resonator length is an important task having a technical solution through an increase of the pumping together with an optimization of the laser parameters. We are actually realizing a soliton fiber laser with an optical fiber amplifier of 10 W which is about one order of magnitude greater than the previous one.

V. Conclusion

In summary we have presented two methods to considerably increase the repetition-rate of a passively mode-locked fiber laser. The first one is the passive harmonic mode-locking. We have experimentally demonstrated that the erbium-doped double-clad fiber laser operates at the 322nd harmonic of the fundamental cavity frequency. Repetition rates up to 3 GHz have been obtained with pulses of 1 ps duration and 18 pJ energy. The supermode suppression at the 322nd harmonic is better than 25 dB. We have then consider the formation of bound-state containing a large number of solitons. In this case, we have obtained experimentally a soliton crystal of 480 pulses. Theoretical modelling shows that the soliton crystal can fill the entire cavity with higher pumping powers. This is actually under investigation in our laboratory.

VI. Acknowledgment

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