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Harmonic mode-locking in a fiber laser through continuous external optical injection

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ABSTRACT

The effect of an external continuous wave (cw) on the operating regime of a passively mode-locked double-clad fiber laser, operating in the anomalous dispersion regime, is experimentally investigated. Starting from different soliton distributions, we demonstrate that, under specific conditions, the cw signal forces the principal laser to operate in harmonic mode-locking regime. This effect is fully reversible and does not exhibit any hysteresis phenomena.

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1. Introduction

Soliton interaction has now a long history since the initial papers in the middle 80s which concerned conservative solitons [1,2]. With the emergence of fiber lasers, and in particular double-clad fiber lasers, there was a revival on soliton interaction in the framework of dissipative solitons [3–8]. Indeed, in passively mode-locked high power fiber laser, a large number of solitons can coexist in the cavity when operating in the anomalous dispersion regime. As a general rule, the number of solitons in passively mode-locked fiber lasers increases when the pumping power grows [9–11]. Many different soliton patterns have been reported independently of the exact mode-locking mechanism revealing some universal properties [12–17]. The resulting solitons distribution in fiber laser is a direct consequence of their interactions which can be repulsive or attractive or both at different scales. Attractive interaction is responsible of bound states [5,18,19] or soliton crystals [20,21]. Repulsive interaction is responsible of the well-known harmonic mode-locking (HML) [22]. In many HML fiber lasers, a continuous wave (cw) component is present in the optical spectrum suggesting that this component could play an important role in the HML mechanism [23–26]. Finally, one can note that although it is possible to easily generate different soliton patterns in a fiber laser by adjusting some external control parameter (in general it is a waveplate, a fibered polarization controller or merely the pumping power), a total control of the final distribution is not possible. Indeed the latter is reached after some evolution started from noise, and generally depends on it, which is random. This differs from the evolution of pulses in an amplifier, and of several theoretical approaches in which suitable initial data are chosen to obtain a desired soliton distribution. It has been recently shown theoretically that a small cw component allows controlling the nature and the strength of the soliton interaction [27]. Based on this prediction and on the role of the cw component in the HML, we have decided to conduct several series of experiments on a passively mode-locked fiber laser injected with an external cw component. To be complete it is worth to mention that a first attempt to investigate the role of an external cw component on a passively mode-locked fiber laser has been done in [28]. The authors demonstrated that the external laser allows forcing the principal laser to generate a rain of solitons. However, this control has low interest for practical applications.

In this paper we demonstrate experimentally for the first time that a passively mode-locked fiber laser can be forced to operate in HML regime by means of an external cw component. Starting from different initial soliton distributions, we show that (i) the external cw component can force the laser to change its operating regime, (ii) under specific injection conditions the laser operates in the harmonic mode-locking regime and (iii) the effect of the injected cw signal is reversible and reproducible. In Section 2 we describe the experimental setup. The experimental results are presented in Section 3.

2. Experimental setup

The experimental setup is schematically represented in Fig. 1 [26]. It is an all-fiber unidirectional ring cavity. Mode locking is

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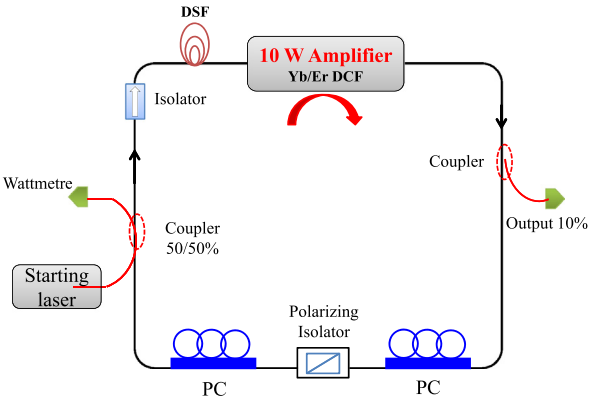


Fig. 1. Experimental setup.

achieved through nonlinear polarization evolution technique. We use a double-clad Er:Yb 10 W fiber amplifier operating at $\lambda = 1.55$ μm manufactured by Keopsys. It consists in a 5 m long double-clad fiber (DCF) that has a group velocity dispersion coefficient $\beta_2^{DCF} = -0.021$ ps^2/m. The geometry of the inner clad has an octagonal shape which allows a high coupling efficiency of the multimode pump waves into the fiber. The diameter of the inner clad is 130 μm and the fiber core diameter is 12 μm. It is pumped at 980 nm with several laser diodes injected with the v-groove technique. The maximum available pumping power is up to 40 W which ensures a total output power of amplified spontaneous emission up to 10 W. This value coincides with the maximum achievable output power in continuous lasing operation. The two fiber ends of the double-clad fiber are spliced to pieces of standard single-mode fibers (SMF28). The fibers DCF and SMF28 operate in the anomalous dispersion regime. A piece of dispersion-shifted fiber ($\beta_2^{DSF} = 0.14$ ps^2/m) is added to control the total cavity dispersion. To favor multiple-pulse mode locking, the total dispersion is set in the anomalous regime with $\beta_2^{TOT} L = -0.16$ ps^2, with a total cavity length of $L = 32.5$ m corresponding to a round trip time of 162.4 ns and to a free spectral range of 6.16 MHz. Because of internal electronic security to avoid irreversible damages to the 10 W amplifier in the absence of input signal, an external signal must be used to start up the amplifier. The external light is provided by a home-made cw tunable fiber laser [29] and is launched with a 50/50 coupler to the principal cavity with a signal power which can be varied up to 800 mW (400 mW injected in the principal laser cavity). After the principal laser becomes operating, we switch-off the starting laser to avoid any coupling between both lasers. A polarizing isolator is set between two fibered polarization controllers. Mode locking is obtained through the adjustment of the latter. The output intensity is detected with a high-speed photodetector (TIA-1200) and visualized with a fast oscilloscope (Tektronix TDS 6124C, 12 GHz, 40 GSa). The spectral properties are analyzed with an optical spectrum analyzer (Anritsu MS 9710C) and the pulse duration is measured with an optical autocorrelator with a scanning range of ± 100 ps (Femtochrome FR-103 XL). An electronic spectrum analyzer (Rohde & Schwarz FSP Spectrum Analyzer 9 kHz to 13.6 GHz) is used to characterize the radio frequency spectrum of the laser. When the principal laser is mode-locked, the spectrum spans from 1540 nm to 1585 nm while the starting laser, which operates in cw regime, is tunable from 1530 nm to 1560 nm. The linewidth of the tunable laser is about 1 nm.

3. Experimental results and discussion

In the following the pumping power of the principal laser has been fixed to 10 W which corresponds to about 2 W of average circulating power at 1.55 μm and to 200 mW of average output power. As usual, the adjustment of the polarization controllers allows to obtain a large variety of soliton distributions [14,15].

For the experiments of injection described in this section, we processed as follows. First the principal laser is switched on by using the starting laser with an injected power level of about 17 dBm (50 mW), and with a wavelength out of the optical spectrum of the principal laser. Then the external laser is switched off and the polarization controllers of the principal laser are adjusted to obtain some soliton pattern. While this pattern is stable, we have switched on the external laser and then increased its wavelength starting from 1530 nm. Its influence on the operating regime of the principal laser is studied. Reversibility of the phenomena is checked in different ways. First the wavelength of the external laser is decreased to retrieve its initial value and secondly, without varying the wavelength we have reduced and then vanished the injected power. In all cases the initial soliton distribution is restored. Let us note that while the wavelength of the external laser is tuned with a fixed output power, the intracavity power of the principal laser does not vary significantly as confirmed by the nearly constant output power. Thus the nonlinear polarization evolution in the fibers, and then the nonlinear filtering, can be considered as slightly affected by the injected laser.

3.1. From bound states to harmonic mode-locking

With a suitable adjustment of the polarization controllers we obtain the soliton pattern represented in Fig. 2. It consists in a set of well separated soliton packets which do not move from one round-trip to the other. Each packet contains a different number of solitons and repeats from round-trip to round-trip. Additional insight is obtained from the optical spectrum shown in Fig. 3. The spectrum exhibits a modulation which is characteristic of a constant phase relation between the solitons, thus suggesting that the trains of solitons contain bound states [19], or soliton crystals [20] depending on the number of solitons involved in a given sequence. The spectral period is 0.2 nm which corresponds to a temporal separation of 41 ps (such small delay cannot be directly measured with our oscilloscope whose resolution is about 75 ps). This value is confirmed by the autocorrelation trace given in Fig. 4. The latter shows that solitons are equidistant and, because there is no pedestal, they are not in relative motion. In addition the nearly triangular envelop is characteristic of a bound state (or a crystal). The initial soliton state is therefore a superposition of soliton crystals similar to those reported in [14]. Of course this could be confirmed with a reconstruction [30]. However we are not

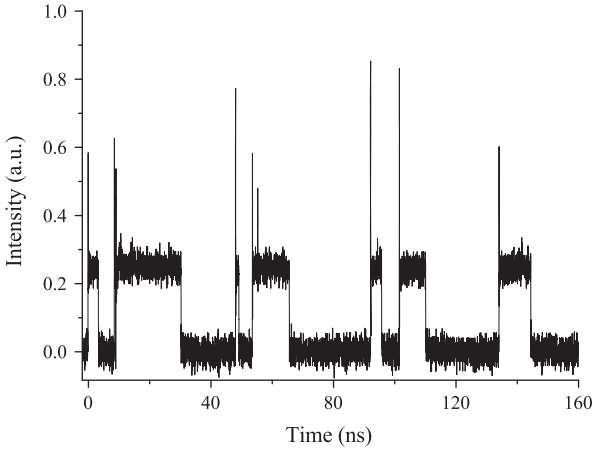


Fig. 2. Initial soliton distribution.

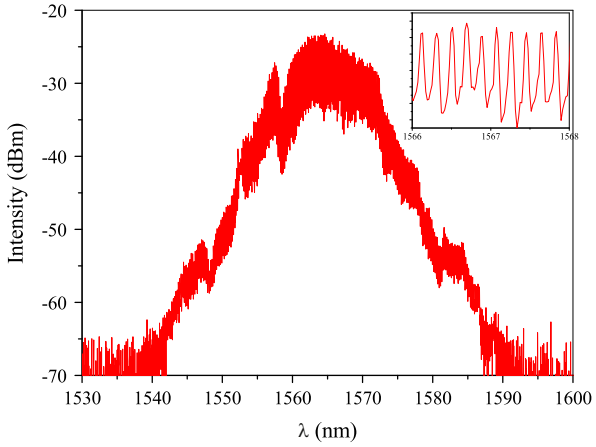


Fig. 3. Optical spectrum corresponding to data of Fig. 2 The inset shows a zoom.

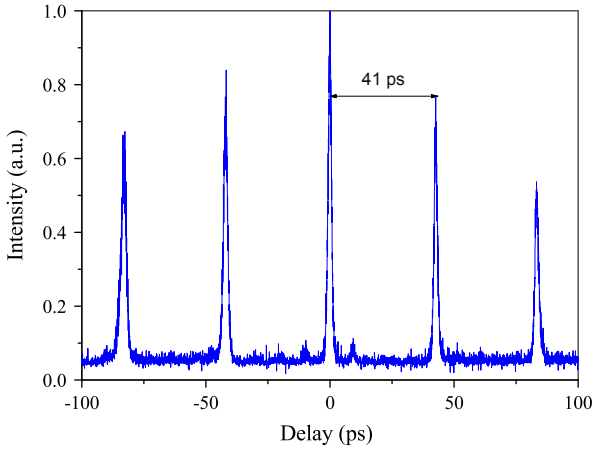


Fig. 4. Autocorrelation trace of the initial soliton distribution.

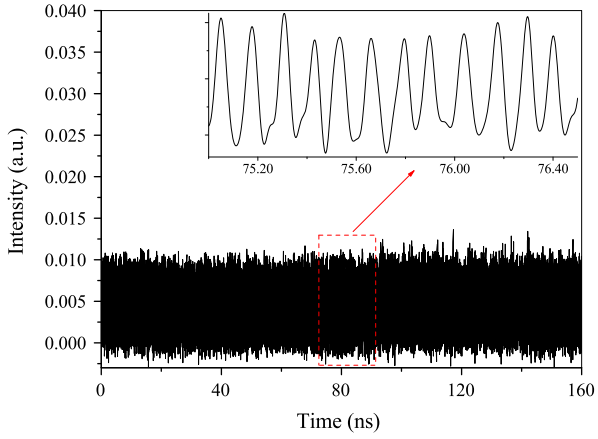


Fig. 5. Temporal trace of the harmonic mode-locking regime.

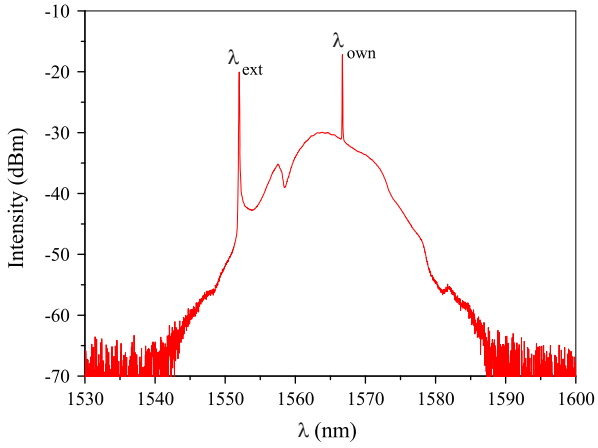


Fig. 6. Optical spectrum of the HML regime.

interested to fully characterize the initial state but rather to study its modification under external injection of a cw signal. Before proceeding, one can note that there is an intense peak at the beginning of each soliton packet. The physical origin of these peaks is not yet understood. It is relevant to estimate the total number of solitons along the cavity. For that we first measure from the time series of Fig. 2 the total extent of the condensate phases ΔT_{cp} which is about 61 ns. At this stage it is necessary to emit some hypothesis concerning the delays between neighboring solitons. For simplicity we assume that the average delay is $\Delta\tau_{sol} \cong 41$ ps which corresponds to data of Fig. 4. Now the total number N of solitons is obtained by dividing the total extent of the condensate phases by the estimated delay between two solitons, $N = \Delta T_{cp}/\Delta\tau_{sol} \cong 1500$. Assuming a secant hyperbolic pulse shape, the width of the central peak of Fig. 4 leads to pulse duration of about 1 ps.

We then switched on the external laser with a starting wavelength $\lambda_{ext} = 1530$ nm and with an injected power of 110 mW into the principal laser. The wavelength is then tuned towards longer values. While λ_{ext} approaches the spectrum of the principal laser, the spectral modulation decreases revealing that the cw component significantly modifies the nature of the soliton interaction and breaks the strong coupling of the solitons in a bound-state [31]. In the temporal domain, the soliton packets become unstable and move and collide to form larger condensate phases without evident internal order. While λ_{ext} falls in the spectrum of the principal laser, pulses get loose from the condensate phases and span over the whole cavity. Solitons move like a soliton gas and when λ_{ext} goes toward the center of the optical spectrum of the principal laser, the relative motion of the solitons decreases. When $\lambda_{ext} = 1552$ nm, solitons are at rest and nearly identical and equidistant as shown in Fig. 5 which gives the final temporal distribution of the pulses. The optical spectrum is represented in Fig. 6. There is no spectral modulation and, in addition to the cw component due to the injected laser (λ_{ext}), there is an additional cw component generated by the principal laser (λ_{own}) and characteristic of many passively HML fiber lasers [23–25]. The pulse duration is deduced from the autocorrelation trace of Fig. 7. Assuming a deconvolution factor of about 1.5 for a secant hyperbolic pulse shape we obtain pulse duration of about 1 ps.

We are convinced that the self-generated cw component takes a key role in the self-organization of the pulses. Indeed, its emergence, which is expected to be induced by the external field, coincides with the fact that the pulses get loose from condensate phases, suggesting that the effect induced by this component counter-balances the initial short-distance attractive interaction allowing the condensate phase to exist. Therefore, the process can be interpreted in terms of soliton interaction as follows. The initial state is formed thanks to the equilibrium between short distance attraction and repulsion. While the cw external field is tuned within the optical spectrum of the laser, this equilibrium is broken through the emergence of a self-generated cw component which lowers the initial short-distance attraction part. When the condensate phases are destroyed, the pulses move under the effect of a long-range repulsion (attributed to the external injected wave) leading to the final soliton distribution (HML regime).

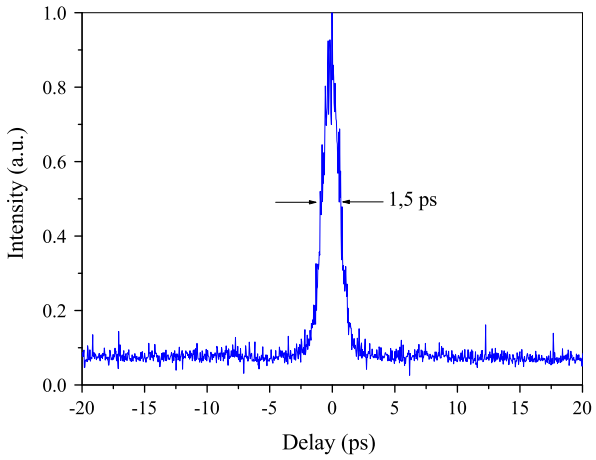


Fig. 7. Autocorrelation trace of the HML regime.

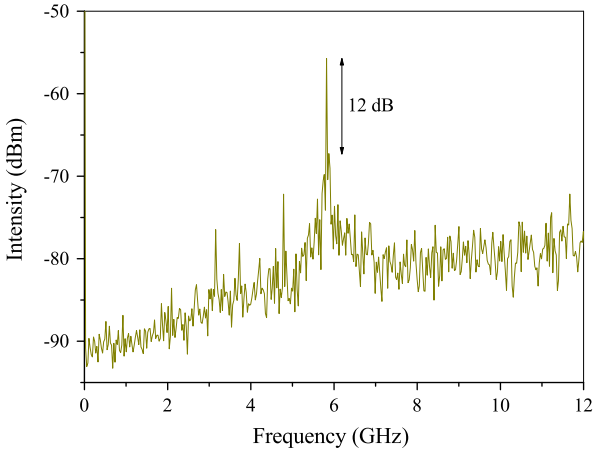


Fig. 8. Low frequency spectrum of the output intensity in the HML regime.

HML is also pointed out through the low-frequency spectrum of the intensity given in Fig. 8. The repetition rate of the laser is actually 5.82 GHz which corresponds to the 945th harmonics. The supermode suppression ratio is 12 dB. The time jitter and the amplitude fluctuations are important and clearly visible in the zoom of Fig. 5. From the data series, the amplitude fluctuations are estimated to be about 18%. Statistical analysis of the data series obtained with the delays between consecutive solitons gives a variance of about 58 ps. The variance provides an upper limit for the time jitter and is probably overestimated because it corresponds approximately to the temporal resolution of the oscilloscope. It is interesting to compare the actual number of soliton, about 1000, to the number of solitons in absence of injected signal, 1500. Thus, while the reorganization of the solitons along the cavity takes place, the number of pulses is reduced by a factor of about 33%. The pulse duration remains practically constant of the order of 1 ps and one can expect that the energy per pulse remains constant as a consequence of the soliton energy quantization. We have measured that the average output power of the principal laser decreases by an amount of 10% (about 20 mW) under injected signal. This reduction of the output power is related to the modification of the nonlinear losses by the external resonant cw component. In itself this reduction does not explain the significant decrease of the number of pulses per cavity round-trip. There is still an amount of missing energy which is necessarily contained in both the self-generated cw component and the amplified cw injected laser. To be more quantitative, the 200 mW of initial average output power is equally distributed between 1500 solitons. When the laser operates in the HML regime under external injection, the total output power is about 180 mW which is distributed by an amount of about 135 mW between the solitons and an amount of 45 mW between the two cw components.

If λ_{ext} is further increased, the same HML regime persists until $\lambda_{ext} = 1553$ nm. For longer values of λ_{ext}, the HML regime is lost and we obtain a regime where all solitons are in perpetual movement and fill the whole cavity: it is a soliton gas. If λ_{ext} is now decreased, we observe the reverse scenario without any hysteresis phenomena: first the regime becomes HML and finally the initial soliton crystals and bound states are restored (same temporal trace, same optical spectrum and same autocorrelation trace). Hence, the effect of the external cw component is fully reversible. We have also verified that for $\lambda_{ext} = 1552$ nm, if the injected power is reduced, the HML regime persists in a wide range of injected powers. Indeed, HML occurs until the injected power reaches the lower value 50 mW. Below this power, the initial soliton distribution is retrieved. If the injected power is increased again, the HML regime is restored. Let us note that the fact that no hysteresis occurs in our experiments is not in contradiction with theoretical results reported in [10,11]. Indeed in [10,11], hysteresis is demonstrated versus the pumping power and also versus the orientation of the phase plates while our control parameters in our experiments are the external wavelength and the external injected power. We have kept constant the pumping power of the principal laser and the orientation of the polarization controllers.

3.2. From a soliton gas to harmonic mode-locking

We consider in this section a different initial soliton distribution. By adjusting the polarization controllers without injected signal, we obtain a state in which solitons fill the whole cavity and are in perpetual motion, analogous to a soliton gas [14]. The temporal trace is shown in Fig. 9 and reveals some reduced trains of solitons which move from one round trip to the other. The experiment shows that solitons move inside the packets. The optical spectrum is similar to the one represented in Fig. 3 except that there is no modulation. The autocorrelation trace is very noisy as usual with a soliton gas but exhibits some very large peaks for distances of about 50 ps revealing some short-range order as shown in Fig. 10.

We now switch on the external laser with an initial wavelength $\lambda_{ext} = 1530$ nm and with an injected power of 200 mW into the principal laser. While λ_{ext} is increased, several soliton packets are created and move along the cavity. When $\lambda_{ext} = 1545.4$ nm, the

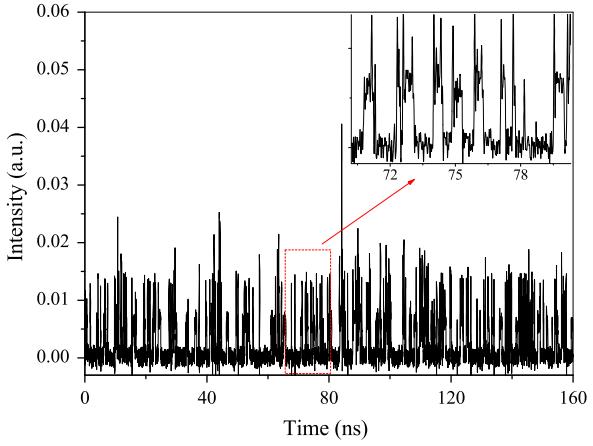


Fig. 9. Soliton distribution of a soliton gas.

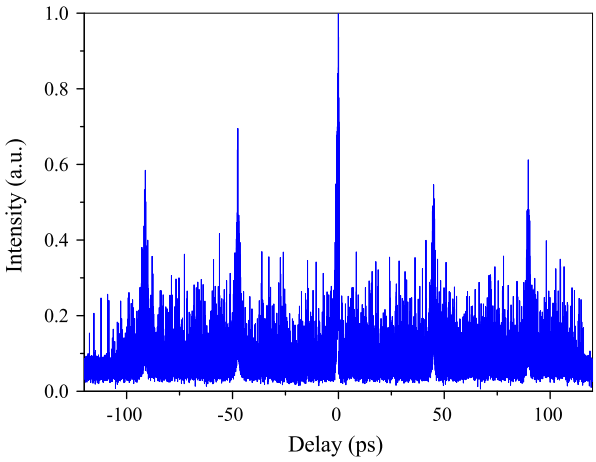


Fig. 10. Autocorrelation trace of the initial soliton distribution.

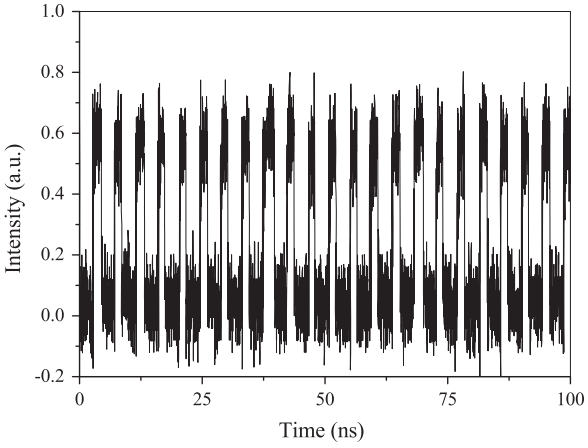


Fig. 11. Final soliton distribution with injected cw signal.

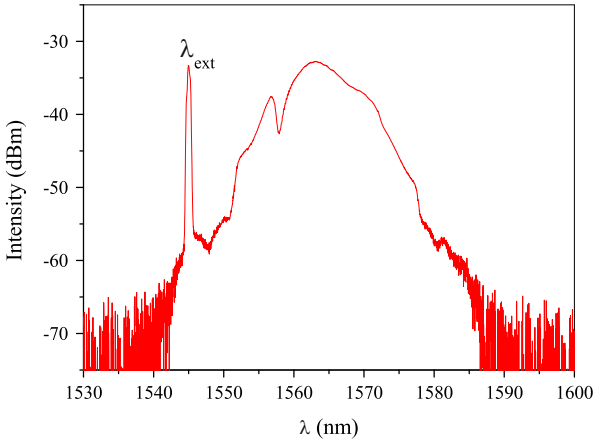


Fig. 12. Optical spectrum of the final state.

packets of solitons stop their relative motion while solitons move inside the packets. The final soliton distribution is shown in Fig. 11. It consists in a nearly equidistant soliton packets characteristic of harmonic mode-locking. Solitons are in motion inside the packets.

The optical spectrum is given in Fig. 12. It exhibits only the injected cw component, there is no additional cw component related to the HML regime as it was the case in the previous subsection. If we assume that the external cw wave provides a long distance repulsion between solitons, the absence of a self-generated cw peak could explain why soliton drops are not destroyed. Therefore, in this case the external field is not

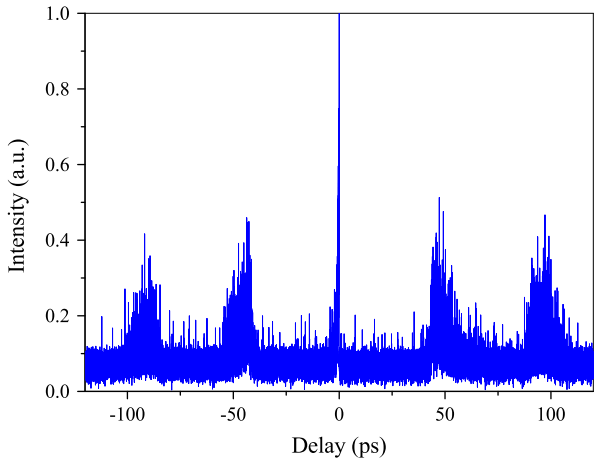


Fig. 13. Autocorrelation trace of the final state.

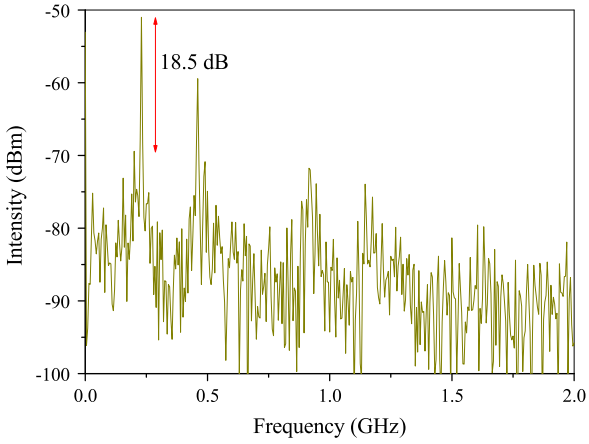


Fig. 14. RF spectrum of the HML regime of soliton drops.

sufficiently efficient to break the short-range ordering, which would allow traditional HML to take place. This point of view is supported by the autocorrelation trace of Fig. 13 which points out some order at short distance.

In the continuity of the physical interpretation we proposed in the case investigated in the previous sub-section, we give here the following scenario. While the external cw component is tuned from shorter to longer wavelengths, a long distance repulsion is induced between solitons. This effect is too weak to break the soliton drops but strong enough to induce a relative motion between the drops. We expect that the self-generated cw component, at a wavelength greater than the center frequency, is responsible for the emergence of short distance repulsion strong enough to break any condensate phase of solitons such as bound states or soliton drops. Its absence in our case could explain why soliton drops do not split into individual solitons. This assumption is partially supported by previous publications, related to HML Er-doped fiber lasers operating in the anomalous dispersion regime, in which a self-generated cw component is always present at a frequency above the center of the spectrum [20–22].

Fig. 14 gives the radio-frequency spectrum of the output intensity. It gives a repetition rate of about 229 MHz which corresponds to the 37th harmonic with a supermode suppression of 18.5 dB. The amplitude fluctuations are estimated to be about $\pm$ 13%.

If λ_{ext} is further increased up to its maximum value, the HML becomes unstable. If λ_{ext} is decreased to its initial value, the HML is

first retrieved, then lost and finally the initial state (soliton gas) is obtained when $\lambda_{ext} = 1530$ nm. No hysteresis phenomenon is observed. Here again, we have checked that when $\lambda_{ext} = 1545.4$ nm, if the injected power is reduced, the HML occurs in a wide range of powers and the initial state is achieved for no injection. The HML is restored if the injected power is increased above a threshold of about 50 mW. Hence, the effect of the external cw component is fully reversible.

4. Conclusions

In this paper, we have experimentally investigated the effect of an external cw signal on the soliton distribution in a passively mode-locked fiber laser operating in the soliton regime. The main result is that harmonic mode-locking operation can be forced by the external injected wave. In a first series of experiments, a superposition of soliton bound states has transformed into a harmonic mode-locking regime. Bound states exist because there is equilibrium between short range attraction and repulsion. The coupling between solitons is high and is revealed by a highly contrasted modulated optical spectrum. While the external cw wave is tuned within the optical spectrum of the principal laser, the modulation decreases and a self-generated cw component appears. At the same time solitons get loose from the condensate complexes. In addition to the external cw field, it arises a self-generated component which, in turns, is expected to be responsible of the destruction of bound states. While the later is destroyed, long distance repulsion leads finally to the HML regime. This point of view is supported by the results of the second series of experiments in which a soliton gas becomes a HML regime of soliton drops. In this case no self-generated cw component is observed suggesting that no short distance repulsion takes place. As a consequence, the solitons evolves under the action of the long distance repulsive interaction induced by the injected cw signal. The drops cannot be split into individual solitons because there is no strong enough short distance repulsion.

Our experimental results are only the first step towards a knowledge of the link between an external cw signal and the interaction between dissipative solitons. We are currently investigating different theories of passively mode-locked fiber laser subjected to optical injection. The first approach is based on a master equation which has a universal character and applies to many physical systems. The second approach is based on the laser equations proposed in [10]. Preliminary numerical simulations, obtained with the latter model, show that a bound state of several solitons lead to harmonic mode-locking when an external cw component is present thus theoretically confirming our experimental results. The approach is then very promising. From the experimental point of view, it will be necessary to explore the effect of the injected wave when the wavelength is tuned over the whole spectral range of the principal laser because we are currently limited by the tuning range of the external laser.

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References

[1] J.P. Gordon, Optics Letters 8 (1983) 596.
[2] F.M. Mitschke, L.F. Mollenauer, Optics Letters 12 (1987) 355.
[3] B.A. Malomed, Physical Review A 44 (1991) 6954.
[4] V.V. Afanasjev, B.A. Malomed, P.L. Chu, Physical Review E 56 (1997) 6020.
[5] N.N. Akhmediev, A. Ankiewicz, J.M. Soto-Crespo, Physical Review Letters 79 (1997) 4047.
[6] N.N. Akhmediev, A. Ankiewicz, J.M. Soto-Crespo, Journal of the Optical Society of America B 15 (1998) 515.
[7] H. Leblond, A. Komarov, M. Salhi, A. Haboucha, F. Sanchez, Journal of Optics A: Pure and Applied Optics 8 (2006) 319.
[8] A. Komarov, A. Haboucha, K. Komarov, H. Leblond, M. Salhi, F. Sanchez, in: S. G. Pandalai (Ed.), Recent Research Developments in Optics, **7**, 63.
[9] D.Y. Tang, L.M. Zhao, B. Zhao, A.Q. Liu, Physical Review A 72 (2005) 043816.
[10] A. Komarov, H. Leblond, F. Sanchez, Physical Review A 71 (2005) 053809.
[11] X. Liu, Physical Review A 81 (2010) 023811.
[12] A. Haboucha, H. Leblond, M. Salhi, A. Komarov, F. Sanchez, Optics Letters 33 (2008) 524.
[13] D.Y. Tang, B. Zhao, L.M. Zhao, H.Y. Tam, Physical Review E 72 (2005) 016616.
[14] F. Amrani, A. Haboucha, M. Salhi, H. Leblond, A. Komarov, F. Sanchez, Applied Physics B 99 (2010) 107.
[15] F. Amrani, M. Salhi, H. Leblond, Ph. Grelu, F. Sanchez, Optics Letters 36 (2011) 1545.
[16] A. Zaviyalov, R. Iliew, O. Egorov, F. Lederer, Applied Physics B 104 (2011) 513.
[17] Ph. Grelu, J.M. Soto-Crespo, Journal of Optics B: Quantum and Semiclassical Optics 6 (2004) S271.
[18] Y.D. Gong, P. Shum, T. Hiang, Q. Cheng, Wen, D.Y. Tang, Optics Communications 200 (2001) 389.
[19] Ph. Grelu, F. Belhache, F. Gutty, J.M. Soto-Crespo, Optics Letters 27 (2002) 966.
[20] A. Haboucha, H. Leblond, M. Salhi, A. Komarov, F. Sanchez, Physical Review A 78 (2008) 043806.
[21] A. Komarov, A. Haboucha, F. Sanchez, Optics Letters 33 (2008) 2254.
[22] A.B. Grudinin, S. Gray, Journal of the Optical Society of America B 14 (1997) 144.
[23] F. Amrani, A. Haboucha, M. Salhi, H. Leblond, A. Komarov, Ph. Grelu, F. Sanchez, Optics Letters 34 (2009) 2120.
[24] G. Sobon, K. Krzempek, P. Kaczmarek, K.M. Abramski, M. Nikodem, Optics Communications 284 (2011) 4203.
[25] Z.X. Zhang, L. Zhan, X.X. Yang, S.Y. Luo, Y.X. Xia, Laser Physics Letters 4 (2007) 592.
[26] F. Amrani, A. Niang, M. Salhi, H. Leblond, F. Sanchez, Optics Letters 36 (2011) 4239.
[27] A. Komarov, K. Komarov, H. Leblond, F. Sanchez, Journal of Optics A: Pure and Applied Optics (2007)1149.
[28] S. Chouli, Ph. Grelu, Optics Express 17 (2009) 11776.
[29] M. Salhi, H. Leblond, F Sanchez, Optics Communications 247 (2005) 181.
[30] F. Amrani, M. Salhi, H. Leblond, F. Sanchez, Optics Communications 283 (2010) 5224.
[31] A. Komarov, K. Komarov, F. Sanchez, Physical Review A 79 (2009) 033807.