Fine repetition rate tuning of harmonically mode-locked fiber laser using continuous wave injection

V.A. Ribenek[1], D.A. Stoliarov[1,2], D.A. Korobko[1]and A.A. Fotiadi[1, 3, 4]
[1]Ulyanovsk State University, 42 Leo Tolstoy Street, Ulyanovsk, 432970, Russia
[2]Aston Institute of Photonic Technologies, Aston University, Birmingham B4 7ET, UK
[3]University of Mons, Electromagnetism and Telecommunication Department, B-7000 Mons, Belgium
[4]Ioffe Physical-Technical Institute, RAS, 26 Polytekhnicheskaya Street, St. Petersburg 194021
Andrei.Fotiadi@umons.ac.be

Abstract: We report on an optical injection as a new technique enabling fine one-by-one tuning of the pulse repetition rate (PRR) of a soliton harmonically mode-locked (HML) fiber laser built on the nonlinear polarization evolution (NPE).

Laser sources delivering high repetition rate pulses are of great interest for many applications in spectroscopy, microwave photonics, ranging sensing, telecommunications, etc. Passively mode-locked fiber lasers have become a valuable alternative to semiconductor and solid-state lasers ensuring reliability, compactness, convenient output and single-mode beam quality inherent to the laser configurations spliced in all-fiber format [1]. In HML regime the laser emits regular pulses with much higher PRR equal to an integer multiple of the fundamental PRR. Harmonic mode-locking could be implemented in the fiber laser configuration with NPE provided that uniform distribution of pulses along the cavity is established through their mutual repulsion governed by different processes, e.g. gain depletion and recovery [2]. The role of background radiation as a mediator providing the equalizing interaction between pulses has been intensively discussed in this context [3]. Besides, the idea to handle HML through the CW light injection has been raised and investigated including the cases the CW light forces the laser to operate HML [4]. Recent studies of the transit processes in the HML laser have confirmed an importance of the pulse interaction with the background radiation in the build-up or annihilation of soliton pulses. In this work, we study the effect of the CW light injected into the HML laser cavity from an external CW narrow-band laser source on the HML laser operation demonstrating its ability to control one-by-one the birth and death of solitons inside the HML laser cavity.

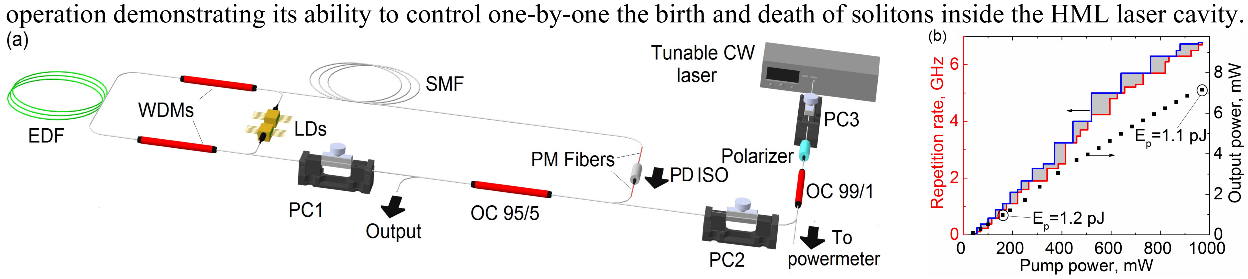

Fig. 1. (a) Experimental HML laser setup. (b) PRR as functions of the increasing (red line) and decreasing (blue line) pump power. The output power is shown by black squares. E_p is the energy of single soliton pulse.

The experimental configuration of an Er-doped soliton NPE mode-locked fiber ring laser is shown in Fig. 1 (a). The total length of the laser cavity of 20.5 m corresponds to the fundamental PRR $f_0 = 13.46\ MHz$. Fig. 1 (b) highlights details of the laser operation without optical injection. The laser wavelength is set to $\lambda \sim 1562\ nm$. Once the lasing threshold (30 mW) is achieved, the mode-locking operation is established. At a low pump power level (~50 mW) the laser operates regular pulses with the fundamental PRR f_0. With an increase of the pump power the laser switches to multi-pulse regime. At this stage, an extra delicate adjustment of PC1 regularizes the generated pulses enabling HML laser operation. Fig. 1 (b) shows evolution of the laser average output power and the PRR with the total pump power. Hereinafter, PC1 setting is kept fixed making the presented data completely reproducible. The total pump power is increased up to 1W and then decreased down to ~60 mW. With the maximal pump power of ~1W, the PRR gets 6.75 GHz. Red and blue lines highlight the soliton hysteresis effect [16] reflecting instantaneous PRR changes in cases of increasing and decreasing pump power. The positive or negative PRR jumps $\Delta f_{rep} = \Delta m f_0$ are associated with simultaneous birth or annihilation of Δm solitons.

The result of CW light interaction with the HML laser radiation inside the cavity depends on the wavelength, power and polarization state of the injected light, all adjusted independently. To get the effect with the HML laser operating at 1562 *nm* the wavelength of the injected CW laser should be selected within one of two narrow bands (typically <0.2 nm) centered at $\lambda_{1cw} \approx 1557.5\ nm$ and at $\lambda_{2cw} \approx 1572.5\ nm$. These spectral bands become broader (up to ~ 1 nm) with an increase of the CW power. We have concluded that the wavelengths λ_{1cw}, λ_{2cw} are close to the transmittance peaks of the fiber birefringence filter surrounding the HML laser operation wavelength. Beyond these bands, no effect of the injected CW light on the HML laser behavior has been observed. The effect of the injected external CW light on the HML laser PRR is demonstrated in Fig. 2. Keeping the pump power fixed, we can accurately tune PC3 to increase gradually the CW light power injected into the HML laser cavity. Figs. 2 (a, b) show the fine tuning from 97th to 112th (a) and from 112th down to 96th (b) harmonics. With an increase of the injected power, the number of pulses inside the HML laser cavity (and PRR, correspondingly) increases or decreases one-by-one, until the next stable level of PRR shown in Figs. 1(b) is achieved.). Importantly, this process could be stopped at any moment by reducing the injected power down to zero. In this case, the HML laser continues to generate pulses with the PRR corresponding to the last transition. Note, it distinguishes the observed effects from the (reversible and hysteresis-free) optical injection effects reported in the experiment [10] earlier. PRR tuning could be monitored with the radio-frequency (RF) spectrum analyzer. A typical RF spectrum of the HML laser consists of the main peaks and small peaks surrounding the main peaks. The main peaks are spaced by the PRR, whereas the surrounding small peaks are spaced by the fundamental PRR. When the CW power injected into the HML laser cavity is gradually increased, the monitored RF spectrum is perturbated and then switches to a new position corresponding to the new PRR. Precise control of the injected light power enables PRR switching with the elementary step equal to f_0. Figs. 2 (c, d) demonstrate switching obtained with different initial PRRs. The RF spectra recorded before and after the switching are directly compared. One can see that in all cases the optical injection with a proper power triggers a transition process in the HML laser resulting in the birth of one soliton. Importantly, the the supermode noise level (SSL) remains the same after the switching. In general, it decreases with an increase of the PRR varying from ~ 57 dB at 330 MHz down to ~ 46 dB at 6500 MHz.

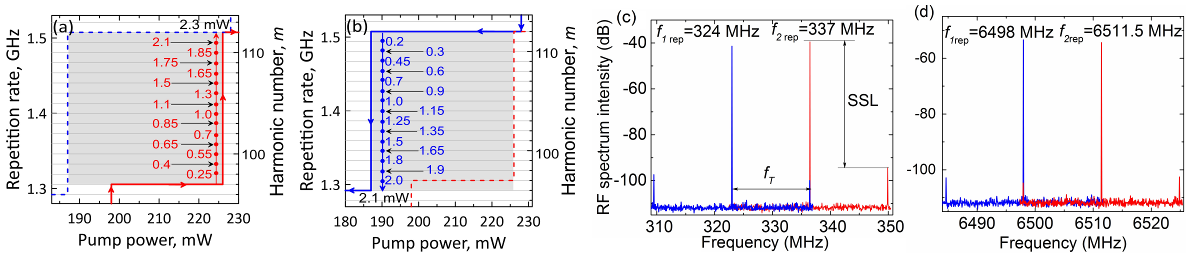

Fig.2. (a, b) Fine one-by-one tuning from 97th to 112th (a) and from 112th down to 96th (b) harmonics provided by the gradual increase of the injected CW power from 0 to 2.3 mW (a) and from 0 to 2.1 mW (b). Numbers correspond to the CW powers injected into the cavity. (c, d) Laser RF spectra before (blue lines) and after (red lines) PRR tuning with the step of f_0 at different pump power levels: 120 mW (c), 960 mW (d).

In summary, we have offered the method for precise PRR tuning in a soliton HML fiber laser built on NPE [5]. The method employs a direct injection of narrow-band CW light from an external laser source into the HML laser cavity. Whereas perfect adjustment of the HML laser pump power provides only approximate PRR setting, the control of the injected CW power enables precise PRR tuning with the elementary step equal to the fundamental PRR. The effect exhibits strong resonant dependence on the CW laser wavelength and is available within two narrow-band spectral windows surrounding the HML laser wavelength. PRR switching induced by the injected CW light does not affect the laser performance characteristics. With a gradual increase of the injected CW light power the PRR changes with the elementary step one-by-one. This process could be stopped at any moment by reducing the injected power down to zero. In this case, the HML laser continues to operate pulses with the PRR corresponding to the last transition. We believe that our findings offer important insights into the transient HML laser dynamics associated with the birth and annihilation of solitons, which are crucial for the HML laser design and optimization. The work is supported by the Russian Science Foundation (19-72-10037) and the Ministry of Science and Higher Education of the Russian Federation (075-15-2021-581).

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