Manipulating the harmonic mode-locked regimes inside a fiber cavity by a reinforcement learning algorithm

Alexey Kokhanovskiy, Evgeny Kuprikov, Kirill Serebrennikov, Aram Mkrtchyan, Ayvaz Davletkhanov, et al.

Alexey Kokhanovskiy, Evgeny Kuprikov, Kirill Serebrennikov, Aram Mkrtchyan, Ayvaz Davletkhanov, Yuriy Gladush, "Manipulating the harmonic mode-locked regimes inside a fiber cavity by a reinforcement learning algorithm," Proc. SPIE 12775, Quantum and Nonlinear Optics X, 127750N (26 November 2023); doi: 10.1117/12.2687649

SPIE.

Event: SPIE/COS Photonics Asia, 2023, Beijing, China

Manipulating the harmonic mode-locked regimes inside a fiber cavity by a reinforcement learning algorithm

Alexey Kokhanovskiy*[a], Evgeny Kuprikov[b], Kirill Serebrennikov [a], Aram Mkrtchyan[c], Ayvaz Davletkhanov[c], Yuriy Gladush[c]

[a]School of Physics and Engineering, ITMO University, Lomonosova 9, Saint-Petersburg, Russia, 191002; [b]Novosibirsk State University, Pirogova 2, Novosibirsk, Russia, 630090; [c]Skolkovo Institute of Science and Technology, Bolshoy boulevard 30, Moscow, 143026, Russia

ABSTRACT

Harmonic mode-locked fiber lasers provide generation of the ultrashort pulse train with high repetition rates up to gigahertz scale. However, setting appropriate parameters for the laser cavity to reach a harmonic mode-locked regime is often a non-trivial task. Depending on the dynamic of adjustment of the cavity elements one may reach unstable, multipulsing or harmonic mode-locked regimes at the same end-point parameters. Here, we demonstrate the state-of-the-art fiber mode-locked laser assisted with reinforcement Soft Actor-Critic algorithm that is capable of learning a dynamic strategy of adjusting cavity parameters to maximize the order of harmonic mode-locked regime. Control of the pumping power and nonlinear transmission function of the state-of-the-art single walled carbon nanotube saturable absorber allows reaching a stable harmonic mode-locked regime.

Keywords: mode-locked fiber lasers, harmonic mode-locked regime, machine learning, reinforcement learning

1. INTRODUCTION

Harmonic mode-locked (HML) fiber lasers have been proven to generate ultrashort pulse trains with up to GHz repetition rates[1]. Despite HML generation inside fiber lasers being known for decades, there are still many competing theories concerning mechanisms that drive the multi-pulse interaction. Experimentally, majority of the sources were based on manipulation with the states of polarization controllers skipping the precise route of adjustment. It was demonstrated that in one laser depending on the state of polarization controller various HML regime variations can be achieved with different HML order at the same pump power. However, fiber mode-locked lasers build with non-polarization-maintaining fiber suffer from inherent sensitivity to environmental influence and are not appropriate for commercial use. Adjusting of harmonic mode-locking in a polarization maintaining scheme requires control over other parameters, such as gain saturation, saturable absorption, which is also challenging to achieve at experimental realization. Here, we are treating the laser as a black box, considering only the possibility of the laser operating at a HML regime and controlling a discrete number of parameters of the laser cavity. We have implemented a Soft Actor – Critic algorithm that is capable of identifying a dynamic strategy for regulating pumping power and saturable absorption of a single walled carbon nanotube film, with the ultimate goal of achieving HML generation of the highest order.

2. EXPERIMENTAL SETUP

The experimental setup is demonstrated at Fig .1. We utilized 0.6 m of highly doped large mode area erbium doped fiber (EDF) LIEKKI Er80-8/125-PM as a gain medium. The EDF was excited by a 976 nm laser diode (LD) through a wavelength-division multiplexer combined with a fast axis blocked isolator (ISO) to keep polarized unidirectional lasing. The output of the laser cavity was released through 50:50 output optical coupler. The single wall carbon nanotube (SWCNT) film was used as a nonlinear absorber on a side-polished fiber (SPF). To change the nonlinear absorption of the SWCNT film, we used electrochemical methods[2]. In assembled fiber laser a continuous wave generation starts at 25 mW of the pump diode power. Laser operates at fundamental mode lock (ML) regime with 36.7 MHz repetition rate with time duration 700 fs at FWHM.

*alexey.kokhanovskiy@gmail.com

Quantum and Nonlinear Optics X, edited by Qiongyi He, Dai-Sik Kim, Chuan-Feng Li, Proc. of SPIE Vol. 12775, 127750N · © 2023 SPIE
0277-786X · doi: 10.1117/12.2687649

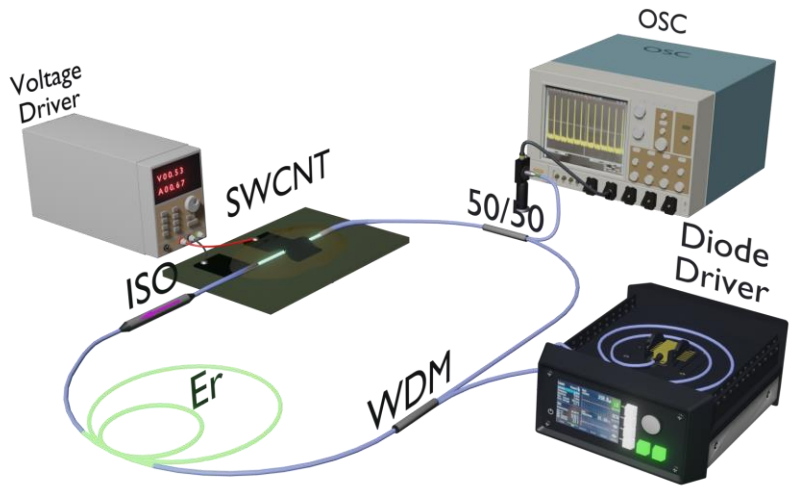

Fig.1. Experimental setup including fiber mode-locked laser and measurement setup.

3. REINFORCEMENT ALGORITHM: SOFT ACTOR-CRITIC

Soft Actor Critic (SAC) is a model-free off-policy reinforcement learning algorithm that optimizes a stochastic policy[3]. In addition to maximizing the reward, it also seeks to maximize the expected entropy of the policy over policy:

$$J_{soft} = \sum_{t=0}^{T} \mathbb{E}_{(s_t,a_t)\sim\pi}\left[r(s_t,a_t) + \alpha\mathcal{H}(\pi(\cdot|s_t))\right],$$

where $r(s_t,a_t)$ – is the reward that was obtained by performing an action a_t in state s_t at time step, T – is the number of steps in the session, $(s_t,a_t) \sim \pi$ – means that actions are chosen according to policy π. $H(\pi(\cdot|s_t))$ is the entropy of the policy π at state s_t and is calculated as $H(\pi(\cdot|s_t)) = -\log(\pi(a_t|s_t)$$. α – is a hyperparameter called temperature. This parameter determines the relative importance of the entropy term against the reward. The entropy part encourages exploration and improves convergence. As a reward we have chosen the ration between fundamental frequency of the cavity to repetition rate of the mode-locked laser.

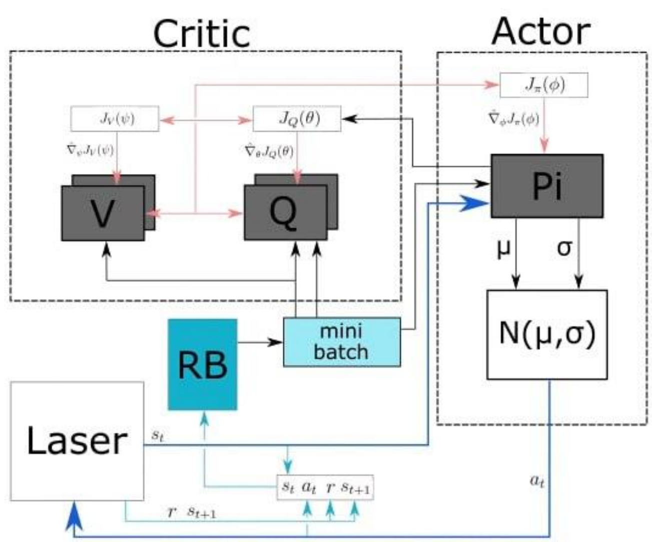

Fig.2. Principle scheme of the Soft – Actor Critic Algorithm optimizing the order of harmonic md

4. RESULTS

Figure 3 demonstrates the map of output regimes generated inside fiber laser. The map was made in this order: we started with 0 Volts on the SWCNTs film and gradually increased the current of the diode from 160 to 400 mA. We measured the oscilloscope trace for each step. Then the current of the diode was reduced back to 160 mA, while the voltage was increased by 0.1 V. The procedure was repeated until the voltage became equal to 1 Volt. Colors of the map correspond to the number of solitons at multi-pulsing regimes. The white regions correspond to the HML regimes. Increasing the current and voltage resulted in the maximum order of the obtained HMLregimes not exceeding 9.
The white and black lines corresponds to trajectories leading to 6th order HML and Q-switch regimes correspondingly.
The red line corresponds to trajectory leading to 11th HML and was found by SAC algorithm.

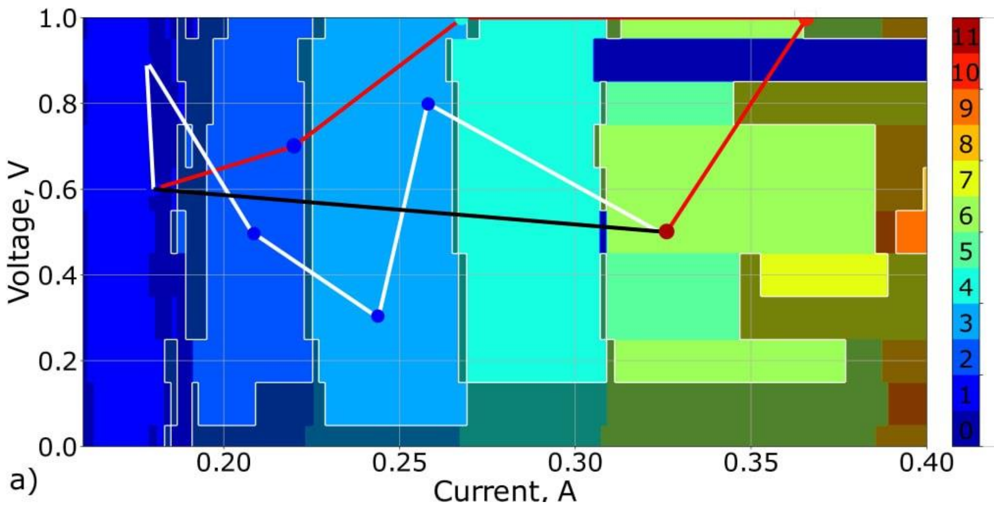

Fig.3. The map of output regimes was obtained by scanning the area of parameter space. The color indicates the quantity of pulses in the mode-locked regime. The light color indicates HML regimes.

Figure 4 demonstrates optical radio-frequency spectrum at different frequency spans for mode-locked and 11th order HML regimes.

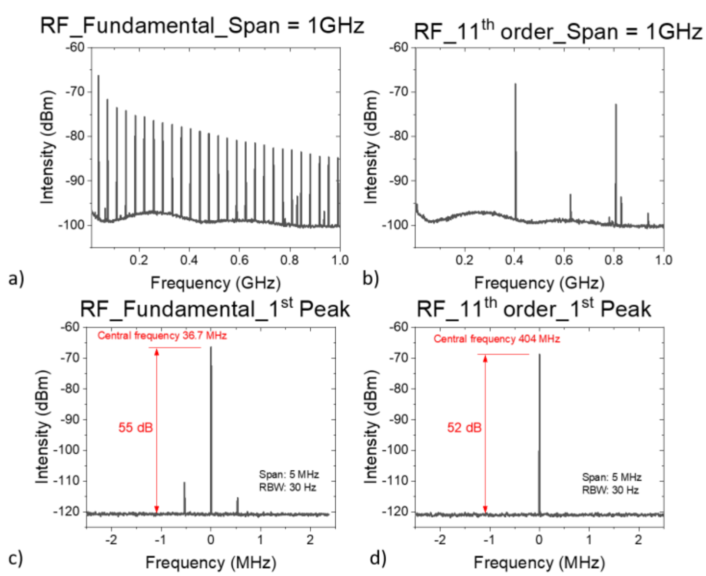

Fig.4. a, b - Optical spectrums of the mode-locked regime and 11th order harmonic mode-locked regime; c, d – Autocorrelation functions of the mode-locked regime and 11th order harmonic mode-locked regime

5. CONCLUSION

Here we demonstrate the feasibility of implementing the reinforcement learning algorithm, particularly Soft Actor-Critic algorithm, for guaranteed automatic adjustment a harmonic mode-locked regimes inside fiber mode-locked fiber laser. It was shown that the algorithm after appropriate setting reward function is capable to find a route of adjusting cavity parameters to achieve harmonic mode-locked regimes with a highest order achievable at fixed fiber cavity.

6. ACKNOWLEDGEMENTS

The work of EK and KS (automatization the experimental process, development of reinforcement learning algorithms) was financially by Russian Science Foundation (Grant No. 17-72-30006-P)

The work of AM, AD, YG (design of nanotube saturable absorber, design of a fiber mode-locked laser) was financially supported by Russian Science Foundation (Grant No. 20-73-10256)

The work of AK (analytical analysis, development of the algorithms) was financially supported by ITMO Fellowship Program.

REFERENCES

[1] Korobko, D. A., Ribenek, V. A., Itrin, P. A. and Fotiadi, A. A., "Birth and annihilation of solitons in harmonically mode-locked fiber laser cavity through continuous wave injection," Optical Fiber Technology 75 (2023).

[2] Gladush, Y., Mkrtchyan, A. A., Kopylova, D. S., Ivanenko, A., Nyushkov, B., Kobtsev, S., Kokhanovskiy, A., Khegai, A., Melkumov, M., Burdanova, M., Staniforth, M., Lloyd-Hughes, J. and Nasibulin, A. G., "Ionic Liquid Gated Carbon Nanotube Saturable Absorber for Switchable Pulse Generation," Nano Lett 19(9), 5836–5843 (2019).

[3] Haarnoja, T., Zhou, A., Abbeel, P., & Levine, S., "Soft actor-critic: Off-policy maximum entropy deep reinforcement learning with a stochastic actor". In *International conference on machine learning* PMLR, 1861-1870 (2018)