Real-Time Multi-Regime Programmable Mode-Locked Fiber Laser Enabled by Human-Like Algorithm

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Abstract: The first real-time programmable mode-locked fiber laser, automatically locking on multiple regimes enabled by the proposed human-like algorithm is demonstrated, achieving the fastest cold boost and recovery time of 0.22 s and 14.8 ms respectively.

OCIS codes: (140.3600) Lasers, tunable; (140.4050) Mode-locked lasers

1. Introduction

Nonlinear polarization evolution (NPE), as the main method to realize passive mode-locked fiber lasers (MLFLs), is particularly favored by researchers due to its rich dynamics[1-3]. NPE plays the role of the artificial saturable absorber in the mode-locking process via polarization control[1]. However, polarization control is really difficult especially in locating on some rare regimes like harmonic mode-locking (HML)[2]. Under the disturbance of thermal instability and mechanical vibration, polarization control in NPE mode-locking process become even harder[4]. Thus, fast and programmable polarization control based automatic mode-locking is in urgent need. Automatic mode-locking through traversally sweeping polarization space has been reported with the help of electronic polarization control[2,3]. This method is straightforward but low-efficiency. Recently, genetic and evolutionary algorithms are successfully utilized for automatic mode-locking[4,5]. Automatic mode-locking applying deep learning are demonstrated as well[6]. Nevertheless, due to the complexity of genetic algorithm, evolutionary algorithm, and machine learning methods, the automatic mode-locking procedure is very time-consuming and the algorithms are difficult to realize in a real-time manner. In the above off-line demonstration[4,5], about 30 minutes are required to achieve the mode-locking regime, which limits the real applications.

In this paper, we experimentally demonstrate the first real-time programmable passive MLFL that can automatically lock on fundamental mode-locking (FML), HML, Q-switching (QS) and Q-switched mode-locking (QML) regimes through fast and precise polarization control. Using an electrical polarization controller (EPC) with ~10 us response time, extremely fast polarization tuning and switching among different regimes can be realized. Notably, all these regimes can be achieved with an identical experiment setup. All automatic operations proceed under the guidance of our proposed human-like algorithm (HLA), consisting of advanced Rosenbrock searching (ARS) algorithm, random collision recovery (RCR) algorithm and monitoring phase. Therein, ARS algorithm guides the passive MLFL from free running to the desired regime. RCR is our proposed algorithm to recover the passive MLFL back to the desired regime from detachment induced by environmental disturbances. The shortest automatic searching utilizing our proposed HLA from the free running towards FML regime costs only 0.22 s. To the best of our knowledge, it is the fastest among all automatic mode-locking realizations. Additionally, the fastest recovery from detachment via HLA costs only 14.8 ms which also sets a new record. We believe this programmable MLFL will be a powerful tool to observe and study the transient dynamics between different mode-locking regimes by the dispersive Fourier transform technique[7].

2. Principle

Fig. 1(a) indicates that HLA consists of ARS algorithm, monitoring phase and RCR algorithm. HLA starts from ARS, enter into the monitoring phase after mode locked. Then HLA focuses on monitoring unless detachment is detected. RCR tries to pull the laser back on track afterward. HLA goes back to monitoring phase if recover successfully. Otherwise, restarting ARS is necessary to anchor a new mode-locking point. As the core part of HLA, the ARS is based on the traditional Rosenbrock optimization, an unconstrained direct search method[8]. Different from the traditional Rosenbrock method, we introduce a brand-new exiting scheme which is named as patience, the maximum of successive exploration failure that algorithm can tolerate. Once patience is running out, current optimization is terminated immediately. Owing to this brand-new exiting mechanism, the ARS algorithm outweighs the traditional Rosenbrock optimization in exploiting the potential towards various regimes of each initial point. When the environment changes slowly, the state of polarization (SOP) variation of light in fiber proves to be slow drift[9]. Therefore, after detached from the desired regime, current SOP is in the vicinity of the original SOP corresponding to the desired regime. The RCR algorithm changes the current SOP via adding a tiny SOP variation. Then RCR directly discriminates the waveforms under the new SOP till mode-locking regime is detected. RCR is judged as failed after quite a few trials have been conducted, then the algorithm will switch to ARS.

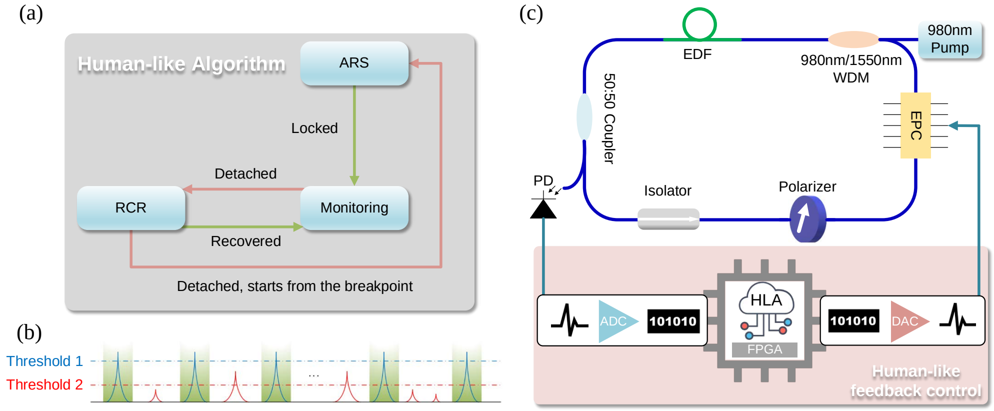


Fig. 1. (a) Schematic of human-like algorithm. (b) Mode-locking discrimination by dual-pulse count (DPC) scheme. (c) Experimental setup

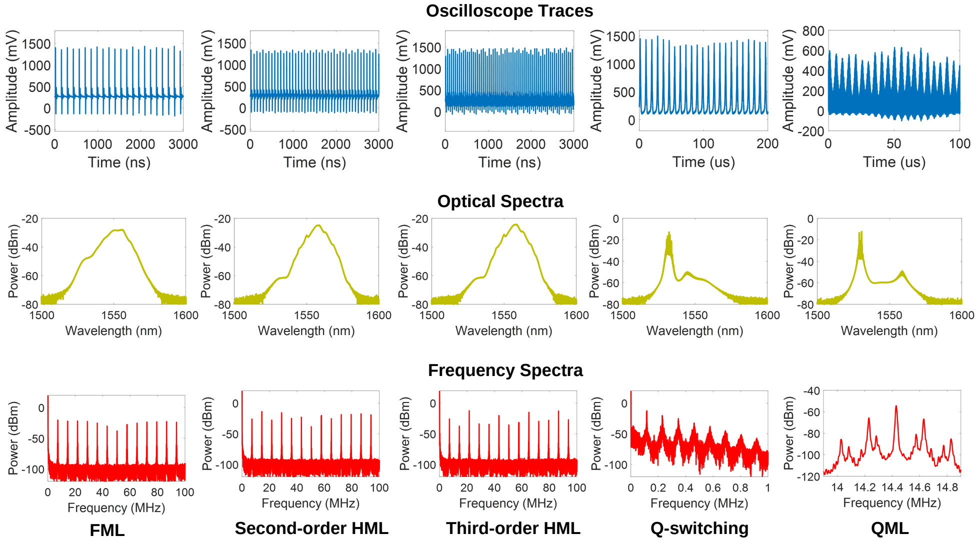
We term the entire algorithm strategy as HLA because it has many features in common with human's behaviors in manually mode-locking process. ARS process somehow is an analogy of human's behaviors in polarization tuning. For instance, in FML process, when we notice the pulse peaks' voltages increasing by a scope, we continue tuning on current direction just like the ARS pace reward mechanism. Otherwise, we tune toward the opposite direction corresponding to the pace punishment mechanism in ARS. On the other hand, since the majority of detachments are considered as the results of environmental perturbance, human usually conduct randomly fine tuning on the original SOP. Thus, human's interference after detachment is exactly similar to the RCR algorithm.

Pulse count proves to be an effective method in mode-locking discrimination[2,3]. In order to differentiate HML regimes, dual-pulse count (DPC) scheme is proposed and illustrated in Fig. 1(b), blue pulses in green areas are desired while red pulses out of green areas are considered as noise. For ideal situation, count out of green areas should be zero. The waveform is evaluated as FML regime when DPC is satisfied. The n-th HML regime discrimination is slightly more complicated. Through observation on massive fast Fourier transfer (FFT) results of HML regimes, we find that, for the n-th HML, the amplitude of the n-th spectral component is largest among all the spectral lines. The waveform is only judged as the n-th HML regime when both time-domain DPC and FFT condition are satisfied simultaneously. Analogously, QS and QML regime discrimination can be achieved in virtue of FFT result. Due to the low repetition rate of QS and the envelope of QML, the majority of FFT spectral components of these two regimes concentrate on low frequencies. The difference of QML is that there are mode-locked pulses under the envelope, indicating the existence of higher-frequency spectral components. Therefore, the discrimination criteria of QML is strong low-frequency spectral components and obvious existence of higher-frequency spectral components. When FFT result only exhibits very strong low-frequency spectral components, the current waveform is judged as QS regime.

The NPE-based passive MLFL is indicated in Fig. 1(c). A 980 nm laser pumps an 8 m erbium-doped fibre (EDF) as the gain medium. A 50:50 optical coupler keeps half of the power inside the cavity for oscillation while the other half is sent for detection. The isolator guarantees unidirectional running of cavity and a polarizer is the key component in NPE-based mode-locking. The EPC is driven by 4 channels of DC voltage and can respond in ~10 microseconds. A 10 GHz photodetector is used to realize optical-to-electrical conversion. Cavity length of the fibre laser is ~28.7 m, corresponding to fundamental repetition rate of ~7.2 MHz. Additionally, a 400 MSa/s ADC, an FPGA and a 100 MSa/s DAC are used to realize the human-like algorithm in real time.

3. Experiment Results

Under the guidance of HLA, the laser can automatically lock on multiple regimes without any physical structure or parameter alteration on the setup. The measured oscilloscope traces, optical spectra and frequency spectra for FML, second-order and third-order HML, QS and QML under 600 mW pump power are illustrated in Fig. 2. From the frequency spectrum of the second-order HML regime, the power of the second spectral line is the largest and the even-order line is stronger than the odd-order line. While in the third-order HML regime, it is obvious that the triple-order of fundamental spectral lines is larger than the rest spectral lines. Overall, the characteristics of frequency spectra validate the effectiveness of the proposed HML discrimination criteria. Through the frequency spectrum of QS regime, the repetition rate of QS pulse is about 115 kHz that is far lower than mode-locking regimes. As expected, the optical spectral bandwidth is much narrower than the mode-locking cases. The envelope frequency of QML is 200 kHz and the basis in the carrier is the second-order of fundamental repetition as illustrated in Fig. 2. Additionally, through recording each set of voltages leading to these regimes, i.e., the experienced values, the laser can achieve microsecond-level switching among different regimes.



FML　Second-order HML　Third-order HML　Q-switching　QML

Fig. 2. Multiple regimes including FML, second-order HML, third-order HML, QS and QML

To demonstrate the initial locking and recovery time consumption of our system, 10 continuous experiments of FML on cold boosting and recovery are carried out, the results as Fig. 3 shows. Certainly, the initial DC voltages of EPC for each time ARS is completely random. Benefited from high-efficient ARS algorithm, it only takes a few seconds from free running to FML regime. The mean of 10 cold boosting times is just 3.1 s and the shortest cold boost only takes 0.22 s. To the best of our knowledge, it is the fastest record in the field of automatic mode-locking. In terms of recovery time, 10 continuous recoveries all finish within 100 ms. The mean of 10 recover times is 58.9 ms. The shortest recover only costs 14.8 ms. Still, it is the fastest recovery ever. Notably, except for the three recoveries that marked in gray, the rest seven recoveries are successfully recovered through the proposed RCR algorithm. Obviously, the time consumption of the seven recoveries is distinctly less compared with the three relocking via ARS. This demonstrates the speediness and efficiency of the RCR algorithm.

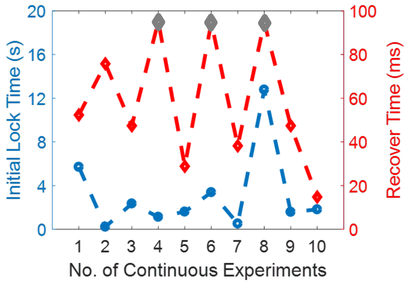


Fig. 3. Initial locking and recovery time consumption

4. Conclusion

In conclusion, we experimentally demonstrate the first real-time programmable MLFL. Under the guidance of proposed HLA, the laser can be configured as different regimes including FML, HML, QS and QML regimes. The laser can switch among regimes in microsecond-level through feeding the EPC experienced values. It sets new records on both automatic mode-locking and recovery time consumption with 0.22 s and 14.8 ms respectively.

5. References

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