Programmable and fast-switchable passively harmonic mode-locking fiber laser

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Abstract: Programmable harmonic mode-locking are achieved in graphene-based mode-locking fiber laser enabled by mode-locking discrimination algorithm and fast polarization tuning. Fundamental, second-order and third-order harmonic mode-locking states can be switched in microsecond level.
OCIS codes: (140.3600) Lasers, tunable; (140.4050) Mode-locked lasers

1. Introduction

Mode-locked lasers (MLLs) have been attracting many scientific concerns for extensively utilizing in various applications since they are capable of generating super-short pulses with extremely high peak powers and incredibly wide spectrums [1–2]. As a branch of mode-locking, harmonic mode-locking (HML) has drawn more attention for producing high repetition rate pulse train. Several approaches have been reported to realize HML. Actively HMLs [3,4] require external microwave driving signal and fine adjustment on the modulation frequency, while for HML using nonlinear polarization rotation (NPR) in passively MLLs [5-7], manual polarization control is essential in HML process, which is very time-consuming and sometimes it is very difficult to find the appropriate state of polarization (SOP) for a certain mode-locking state. So a programmable HML which can automatically switch to different harmonic mode-locking states is highly desired. Evolutionary algorithm based feedback polarization tuning and frequency-domain mode-locking discrimination has been proposed to achieve automatically mode-locking in noise-like pulse regime [2], which uses two electrical polarization controllers (EPCs) for polarization tuning and a high speed photodetector (PD) followed with high speed real-time oscilloscope for mode-locking discrimination.

In this paper, for the first time to the best of our knowledge, we proposed and demonstrated a programmable passively HML by automatic mode-locking discrimination algorithm and fast polarization control. An electrical polarization controller (EPC) with microsecond response time is used for fast polarization tuning and mode-locking state switching. A single EPC is sufficient for mode-locking attributed to a golden-coated graphene with polarization-dependent saturable absorption as mode-locker [1]. By using combined time-domain and frequency-domain mode-locking discrimination criteria, fundamental, second-order and third-order harmonic mode-locking states can be automatically achieved using only low-speed PD and analog-to-digital converter (ADC) for time-domain waveform sampling, which is easy for practical implementation. By finding the appropriate mode-locking discrimination criteria, abundant mode-locking states can be automatically achieved and switched in the same structure. The proposed programmable passively HML is supposed to be a powerful and convenient tool for versatile scientific researches.

2. Principle of automatic mode-locking

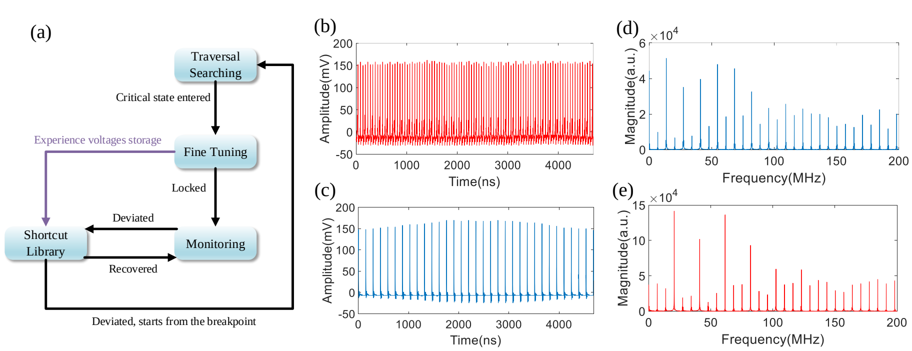

Fig. 1. (a) Simplified traversal algorithm for automatic mode-locking. (b) Harmonic mode-locking state. (c) Critical fundamental mode-locking state with large power variation. (d) FFT result of second-harmonic mode-locking state. (e) FFT result of third-harmonic mode-locking state

Traversal algorithm is adopted in automatic mode-locking process. In general, traversal algorithm can be divided into four parts as Fig. 1(a) indicates. The first part is traversal searching, simply tuning the 4 controlling voltages of

EPC from 0 V to 5 V channel by channel through digital-to-analog converter (DAC), then detect time-domain waveform sampled by ADC thus we can tell whether the fiber laser has entered the critical mode-locking state (correct pulse counting but fluctuant pulses' amplitude, see Fig. 1(c)) or not. In second part, fine tuning until the pulse train's amplitude is even, searching step decreases because the critical state is close to the stable mode-locking state. For convenience, we store every group of experienced voltages under mode-locking state into shortcut library. Mode-locking state is reached after fine tuning, hence the third part is monitoring. Monitoring confirms the deviation from mode-locking state will be detected once it happens. Last part is shortcut library, once deviation detected, we try every group of experienced voltages in this library to recover mode-locking state. If all the experienced voltages fail due to large deviation, the algorithm will go back to traversal searching starting from the breakpoint (last group of voltages leaving in traversal searching process). This method turns out to be very effective, most deviations caused by environmental disturbance or small-amplitude mechanical vibration can be recovered.

Throughout the entire algorithm, the core part is mode-locking state discrimination. To achieve accurate discrimination on various mode-locking states, we set a series of discrimination criteria. For fundamental mode-locking state, there are two discrimination criteria. First, we do a pulse count on time-domain waveform (after ADC sampling) and then compare the counting result with the ideal number calculated by the cavity length. Pulse train's amplitude under mode-locking state is relatively stable as is well-known. Harmonic mode-locking state shown in Fig. 1(b) apparently will be filtered by the first criterion. The second criterion is to set a variation threshold on pulse train's amplitude. This criterion supports the algorithm in discriminating the critical state, indicated in Fig. 1(c), from the stable mode-locking state where the amplitude variation is less than the threshold.

Discrimination criteria for second- and third-order harmonic mode-locking states are slightly more complicated. By fast Fourier transfer (FFT) on time-domain waveforms of harmonic mode-locking states, we found that for second (third)-order harmonic mode-locking states, the amplitude of the second (third) spectral component is the highest among all the spectral lines as shown in Fig. 1(d) and Fig. 1(e). Therefore, except for the pulse counting and amplitude variation judgement in time domain as in the fundamental mode-locking case, the extra discrimination criterion for second (third)-order harmonic mode-locking state is to verify whether the second (third) spectral line is the largest among all the spectral lines in frequency domain.

3. Experiment Setup and Results

The configuration of the proposed programmable passively HML is shown in Fig. 2. A laser operating at 980nm serves as a forward pump for Erbium-doped fiber (EDF) using as a gain medium. The core component of automatic mode-locking is an EPC that is driven by 4 channels of 0~5 V DC voltage with microsecond response time. Arbitrary SOP can be obtained via adjusting those 4 channels of DC voltage. Graphene acts as a both polarizer and saturable absorber to facilitate the achievement of mode-locking [1]. After optical-to-electrical conversion by a PD with 1-GHz bandwidth, part of signal is sent into an electronic spectrum analyzer (ESA) for frequency spectrum measurement, and the rest is utilized as input of the feedback control scheme. In this feedback scheme, an ADC is used to sample the time-domain waveform, then the sampled waveform is sent into a calculation center (a personal computer in this experiment and FPGA for real-time implementation) for mode-locking discrimination. After that, the calculation center adjusts 4 channels of DC voltage through a DAC. Repeating these steps once by once until the desired mode-locking state is achieved.

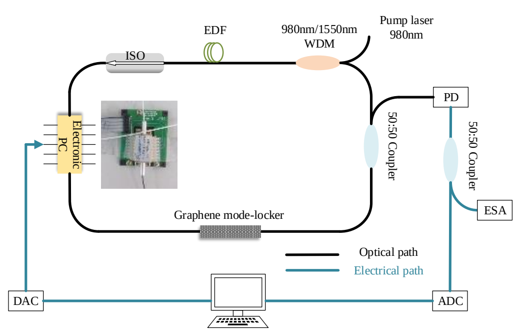

Fig. 2. Programmable passively mode-locking fiber laser

In this experiment, pump power is set as 450mW, sampling rate and resolution of ADC is 1.25 GS/s and ~1.96 mV respectively. For DAC, sampling rate is 1 MS/s and resolution is ~0.01 V. Cavity length of the fiber laser is ~30 m, thus fundamental frequency is ~6.85 MHz.

Experiment results are as follows. From the time-domain waveforms we can tell that three different mode-locking states are achieved. The average spacing among pulses are 183 sampling points, 91.5 sampling points and

61 points for fundamental, second-order and third-order harmonic mode-locking states respectively. Hence, repetition frequency can be calculated according to Eq. (1). Corresponding repetition frequencies of fundamental, second-order and third-order harmonic mode-locking states are ~6.83MHz, ~13.66MHz and ~20.49MHz.

$$f_{repeat} = \frac{1}{Average\_spacing \times 0.8 \times 10^{-9}} \tag{1}$$

The measured time-domain waveform, frequency-domain spectrum and optical spectra for fundamental, second-order and third-order harmonic mode-locking states are shown in Fig. 3, Fig. 4 and Fig. 5, respectively. In frequency domain, fundamental mode-locking state operates at fundamental repetition rate consequently the first spectral component is the strongest. For second-order harmonic mode-locking state, it is clear that the second spectral line is the strongest, the fourth and sixth spectral lines are stronger than the third and fifth spectral lines respectively. While in third-order harmonic mode-locking state, it is obvious that the triple order of fundamental spectral components is stronger than the rest spectral components. Overall, the measured characters of frequency spectra are consistent with the proposed discrimination criteria. Besides, there is no significant difference in optical spectra of those three mode-locking states. Hence, it is almost impossible to distinguish different mode-locking states via optical spectra.

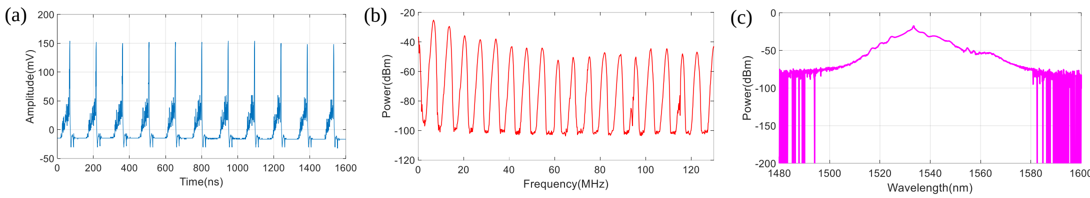

Fig. 3. Fundamental mode-locking state. (a) Time-domain waveform. (b) Frequency-domain spectrum. (c) Optical spectrum

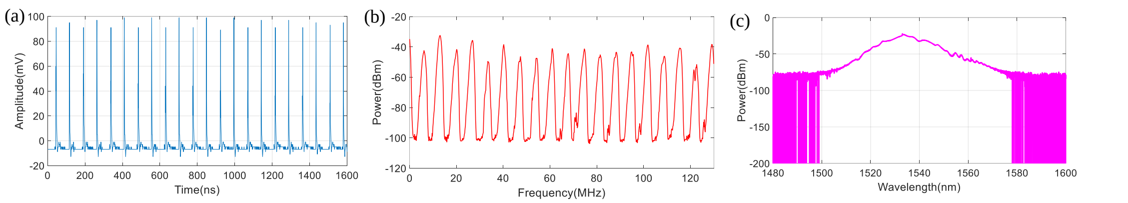

Fig. 4. Second-order harmonic mode-locking state. (a) Time-domain waveform. (b) Frequency-domain spectrum. (c) Optical spectrum

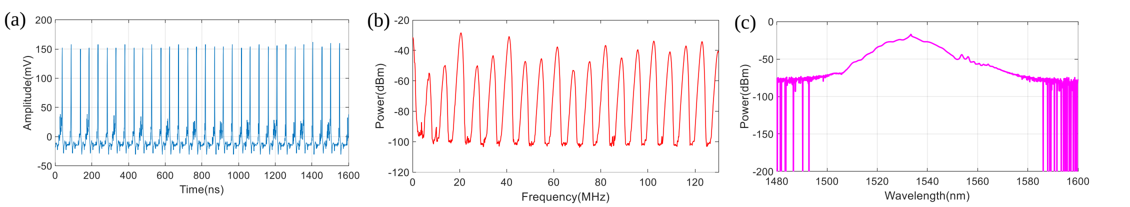

Fig. 5. Third-order harmonic mode-locking state. (a) Time-domain waveform. (b) Frequency-domain spectrum. (c) Optical spectrum

4. Conclusion

We have experimentally demonstrated a programmable passively harmonic mode-locking fiber laser using golden-coated graphene as both polarizer and saturable absorber for mode-locking. With an effective and fast control on SOP through an EPC and mode-locking state discrimination criteria in both time domain and frequency domain, fundamental, second-order and third-order harmonic mode-locking states have been automatically realized and can be fast-switched in microsecond level. Compared to manually-controlled MLL, the proposed scheme has improved flexibility in applications and great potential in those occasions demanding different mode-locking states.

5. References

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