Amplifier similariton generation from a Yb-doped all-normal-dispersion fiber laser employing a hybrid-mode-locking technique

Xinyang Liu*[a], Mikko Närhi[a], Dmitry Korobko[b], Regina Gumenyuk[a]
[a] Laboratory of Photonics, Tampere University, Korkeakoulunkatu 3, Tampere 33720, Finland;
[b]Ulyanovsk State University, 42 Leo Tolstoy Street, Ulyanovsk 432017, Russia

ABSTRACT

Apart from the classical nonlinear polarization rotation (NPR) mechanism, we incorporate an additional stabilization mechanism of frequency shifting in a Yb-doped all-normal-dispersion fiber laser oscillator. The similariton pulse with a pulse duration of 7.8 ps and a spectrum width of 20.5 nm is generated. By using a grating pair, the pulse duration can be compressed to be 140 fs. By employing time-stretch dispersion Fourier transform (TS-DFT) technique, the mode-locking pulse buildup process is investigated. The use of frequency shifting as a stabilization technique opens a new route towards reliable laser oscillator fabrication for the industrial-grade system.

Keywords: similariton laser, frequency shifting, all-normal-dispersion fiber laser, laser operation stabilization

1. INTRODUCTION

Governed and predicted by the generalized nonlinear Schrödinger equation (GNLSE), different types of optical wave packets have been extensively studied by researchers in recent decades. Following a route of gradually enhanced maximum pulse energy and peak power, conventional soliton [1], dispersion-managed (DM) soliton [2], dissipative soliton in all-normal dispersion (ANDi) cavity [3] and similariton [4, 5] are observed and investigated sequentially. In the shaping of these pulses, the dominance of different mechanisms has been identified. Balance of nonlinearity and dispersion results in the formation of conventional solitons. By engineering the dispersion map and energy dissipation of the cavity, the last three types of solitons can be obtained [6, 7]. The pulse energy or peak power is essentially limited by nonlinearity induced pulse distortion or wave-breaking [7], being especially pronounced in laser cavities with anomalous-dispersion components. The latest discovered amplifier similariton, an asymptotic solution of GNLSE with gain and normal dispersion, features distinctively parabolic pulse profile and linear frequency chirp through pulse, which grant amplifier similariton ability to tolerate high nonlinearity and consequent property of wave-breaking free [7]. Because linear chirp through pulse can be compensated by dispersive components like grating pairs, this makes amplifier similariton pulses highly attractive for fiber laser systems which are based on chirped pulse amplification (CPA) technique, possibly enabling delivery of high-peak-power Fourier transform-limited pulses without sidelobes at the output. Even though the gain fiber as a nonlinear attractor plays the main role in similariton pulse formation, saturable absorption (SA) is still important in stabilizing pulses, which occurs through suppression of low-intensity instabilities. NPR as an effective SA mechanism has been applied in many mode-locking lasers. The shortest pulses to date from fiber laser were obtained from the cavity with self-consistent similariton evolution employing NPR mode-locking [8]. However, NPR is subject to environmental perturbation and requires adjustment from time to time to maintain laser operation.

To further support stable self-similar evolution in the cavity, we propose to use a hybrid approach incorporating NPR and frequency shifting. NPR results in the establishment of pulse operation whereas a small frequency shift of 69.46 MHz leads to efficient filtering of low-intensity CW signal and vanishing undesirable perturbations in the cavity. We demonstrate a mode-locked Yb-doped fiber laser generating 7.8 ps similariton pulses with 20.5 nm spectrum bandwidth. The pulses are further compressed down to 140 fs using a grating pair. Furthermore, the starting dynamics of the hybrid laser is studied by using a time-stretch dispersion Fourier transform (TS-DFT) technique.

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*xinyang.liu@tuni.fi

2. PRINCIPLE OF FREQUENCY SHIFTING FOR MODE-LOCKING

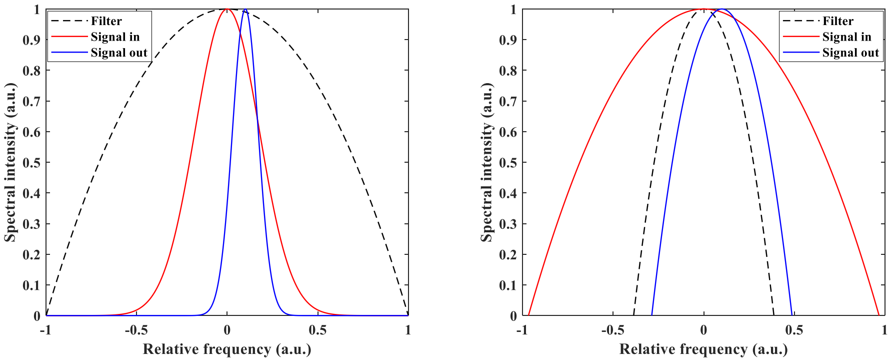

Fig.1. The principle of frequency shifting operation in a mode-locked fiber laser incorporating an intracavity filter. (a) FSF mode-locking scheme for the pulsed regime characteristic to conservative, DM and dissipative solitons formed in ANDi laser; (b) the FSF-mode-locking scheme with a similariton amplifier laser specific. The red line indicates a broadband pulse's spectrum arriving to the frequency shifter, the blue line –a narrow band spectrum, the dashed line is a filter's spectral profile.

The realization of any mode-locking technique is possible only in the cavity with positive feedback, i.e., the greater intensities must undergo lower losses. In the case of NPR mode-locking, appropriate selection of orientation of polarization controllers and polarizers leads to an increase of cavity transmission with an increase of peak power of pulses or pulse narrowing as well as effective discrimination of broadband and narrowband spectra [9]. Positive feedback in the case of frequency-shifted feedback (FSF) mode-locking is formed when the generated pulse passes through frequency shifter and subsequent bandpass filter (Fig. 1a) [10]. Under the influence of the frequency shifter, the pulse spectrum is displaced from the center of the filter, however, the filter induces a reverse shift of the spectrum center due to attenuation of spectral components' edge, and the amount of this shift is proportional to filter slope and to the square of pulse spectrum width [11]. As a consequence, a situation arises that corresponds to positive feedback - a pulse with a wide spectrum experiences less loss because its carrier frequency is shifted closer to the center of the filter than a narrowband pulse (Fig. 1). Apart from that, pulses with wider spectrum/higher intensity can induce more spectrum broadening through self-phase modulation (SPM) to compensate for a frequency shift effect than CW signal and narrowband/low-intensity pulses. Eventually, the CW signal and narrowband pulses are filtered, and their energy is transferred to the broadband pulse.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental setup is shown in Fig.2 (a). About 1 m Yb-doped fiber (YDF) is employed to provide gain. The ring cavity is composed of ~6 m single-mode passive fiber and 32 cm free space incorporating an acousto-optic tunable filter (AOTF). 22% coupler is used to extracted power from the cavity. A polarization-independent isolator ensures counterclockwise operation. The AOTF is driven by a signal generator at 69.5 MHz and has a transmission bandwidth of ~4 nm with a central wavelength of 1030 nm. It works as a versatile device to provide both spectral filtering and frequency shifting effects. One pair of lenses are used to optimize the free space light coupling in/out the AOTF. After the AOTF, first-order diffracted light, which is linearly polarized and frequency-shifted, is coupled into the following fiber. A polarization controller (PC) applied on YDF maintains the polarization state. Setting the total pump power at 869 mW and carefully adjusting the PC, the laser can run into a stable mode-locking regime with an average output power of 7.4 mW.

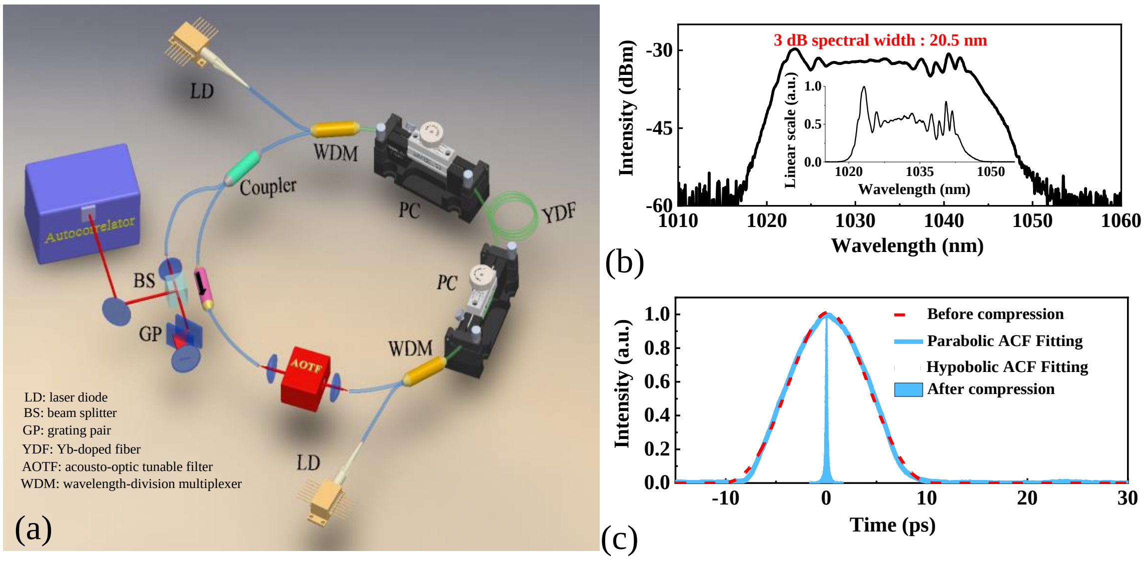

Fig. 2(a) The laser setup. (b) Output spectrum. (c) Autocorrelation traces before and after compression with the corresponding approximation.

The similariton laser generates an output spectrum of 20.5 nm full-width-at-half-maximum (FWHM) as shown in Fig. 2(b). The spectrum has a typical profile of similariton pulses with smooth edges and a curved central part (inset of Fig.2(b)). The spectrum also exhibits a complex structure on the top of both edges caused by accumulated nonlinearity. The autocorrelation traces are shown in Fig. 2(c). The retrieved pulse duration from parabolic autocorrelation function (ACF) fitting is 7.8 ps. A pair of 1250 line/mm diffraction gratings are subsequently used to compress the pulse externally. Assuming compressed pulse has a hyperbolic shape, the retrieved pulse has a duration of 140 fs (Fig. 2(c)), leading to a time-bandwidth product of 0.808. The residual chirp is considered to stem from a high order dispersion contributed by both a fiber and a grating pair. The autocorrelation trace of the compressed pulse is clean and without oscillating pulse wings, providing further evidence of the near parabolic nature of the pulse from the oscillator.

The TS-DFT technique, taking advantage of chromatic dispersion of a dispersive medium with group-velocity dispersion (GVD), has been adopted by researchers to investigate ultrafast transient processes in various fields to overcome the speed limitation of traditional measurement instruments [12]. In ultrafast optics, transient dynamics such as soliton buildup [13,14], soliton evolution [15] and rouge wave generation [16] have been extensively studied in recent years. For NPR mode-locking laser, pulse buildup process follows different paths in all-normal-dispersion and dispersion-managed laser cavities [17,18]. In our hybrid laser, to study the influence introduced by frequency shifting and reveal corresponding pulse buildup process we performed TS-DFT investigation.

To perform the study, 5 km SMF28 fiber and 1 km SMF980 fiber are subsequently connected with the laser output port. Newport 1414 photodetector with 25 GHz bandwidth and Tektronix DSA 72004 oscilloscope with 20 GHz bandwidth and 50 GS/s sampling rate are used for data acquisition. Pulse duration is stretched to be ~2.3 ns, which can be well resolved by the combination of the photodetector and oscilloscope, whose pulse duration resolution ability is measured to be ~40 ps. As a time reference, a small portion of the pump signal leaked from the free port of WDM is monitored by one channel of oscilloscope through Thorlab DET01CFC photodetector. Two typical sets of laser buildup dynamics are shown in Fig. 3(a) and (b), as the process can vary from time to time. Pump rising time is around 25 ms, relaxation oscillation starts quickly in the cavity after the pump is on. The buildup time of the mode-locking pulse from the pump on is measured to vary from ~3 s to ~5 s, evidencing mode-locking operation in this cavity is a try-until-success process and it is stochastic. Fig. 3(c) and (e) shows the close-up measurement of cavity output after 1s delay of pump-on timepoint. Fig. 3(c) depicts the waveform acquired from the oscilloscope and Fig. 3(e) shows laser radiation evolution from a round trip to a round trip by segmenting sequential waveform data according to round trip time of 38 ns. At this stage, weak noisy pulses are circulating in the cavity with a pulse-to-pulse interval varying from ~1 ns to ~ 5 ns. The transition from a weak noisy pulse to a mode-locking pulse is illustrated in Fig. 3(d) and corresponding round trip to round trip plotting is shown in Fig. 3(f). In the relaxation oscillation stage, weak noisy pulses are continuously evolving. At ~5364 round trip, pulse peak intensity grows to 2-9 times high than previous weak pulses. After this point, the spectrum broadens quickly and mode-locked pulse forms relying on a nonlinear polarization rotation caused SA effect.

The transition from the relaxation oscillation stage to the mode-locking stage can be explained as follows. In the relaxation oscillation stage, the polarization state of weak noisy pulses evolves continuously. Until ~5364 round trip, polarization evolution caused by fiber intrinsic birefringence and nonlinearity caused birefringence can induce effective SA effect, then the pulse is shortened and spectrum is broadened. After the balance of dispersion, nonlinearity and dissipation effects is reached, the self-consistent mode-locking operation is initiated and maintained.

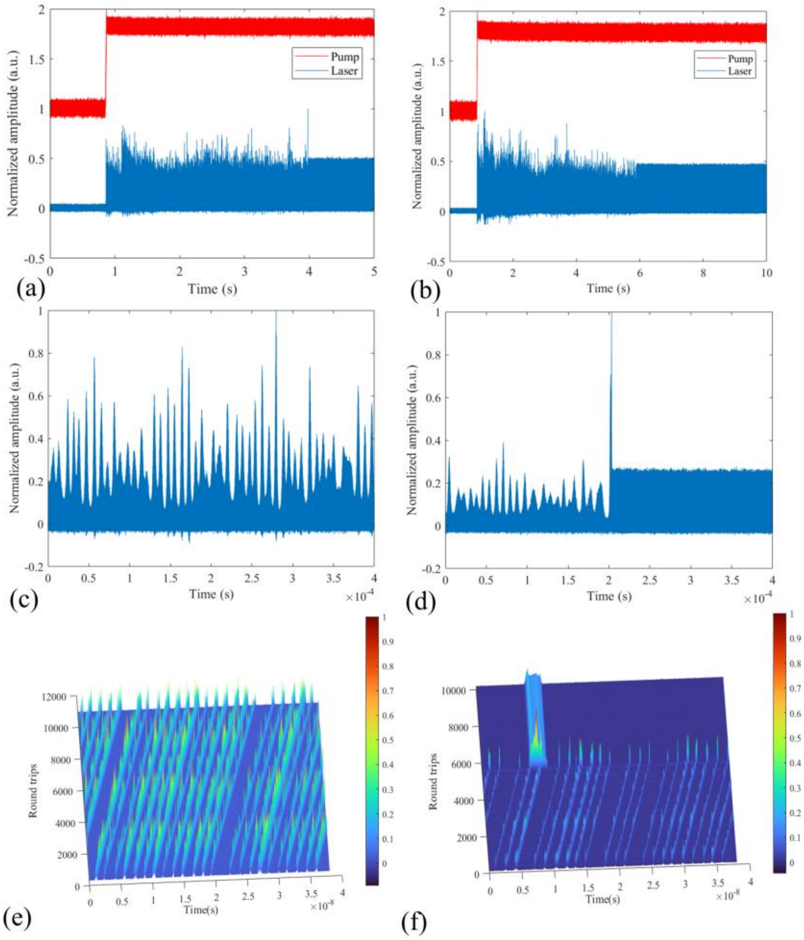

Fig. 3 Illustration of different stages of mode-locking buildup process. (a), (b) Laser output evolution dynamics from pump on to mode-locking. Red: pump signal, blue: laser signal; (c) Laser output after 1 s delay from the pump on; (d) Laser output dynamics around mode-locking transition point; Illustration of the round trip to round trip evolution of laser output (e) after 1 s delay from the pump on and (f) around mode-locking transition point.

As shown in Fig. 3(d) and (f), before the mode-locking transition point weak noisy pulses vary from a round-trip to a round-trip, meaning at this stage a noisy pulse generation is dominated by relaxation oscillation. When a mode-locked pulse is generated, e.g. NPR mechanism is working properly to introduce SA effect, pulse generation is dominated by NPR caused pulse forming effect and pulse evolution becomes self-consistent between round-trips. It is noteworthy that in the relaxation oscillation stage pulse relative position in the cavity is shifted from a round-trip to a round-trip. However, the pulse locates in a relatively stationary position of the cavity in the mode-locking stage. We attribute this phenomenon to the frequency shifting effect introduced by AOTF. In the relaxation oscillation stage, the spectrum of laser radiation is narrow and shifted up 69.5 MHz after passing through AOTF. The spectral filtering effect is not significant. After another round trip, laser radiation is shifted further and corresponding phase velocity decreases due to the normal dispersion of fiber. After every round trip, the same noisy pulse needs more time to complete one round trip. In the mode-locking stage, incident laser pulse on AOTF has a spectrum bandwidth much wider than the bandwidth of AOTF, which is ~4 nm. When the mode-locked pulse passes AOTF, both frequency shifting effect and spectral filtering effect are significant, leading to the result that spectra after AOTF are the same from round trip to round trip. Thus, the pulse can evolve self-consistently.

4. CONCLUSION

We demonstrate a similariton operation in a Yb-doped fiber laser with a hybrid mode-locking technique incorporating nonlinear polarization rotation and frequency shifting techniques. The laser oscillator delivers 7.8 ps pulse with 20.5 nm spectrum and can be further compressed down to 140 fs. By using the TS-DFT method, laser buildup dynamics is studied in detail. The frequency shifting caused pulse velocity change is clearly observed when the laser operates in the relaxation oscillation stage.

ACKNOWLEDGEMENTS

This work is supported by the Academy of Finland (320165), European Commission (824996), Russian Science Foundation (19-72-10037) and Russian Ministry of Science and High Education (075-15-2021-581).

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