SESAM Mode-Locked, Environmentally Stable, and Compact Dissipative Soliton Fiber Laser

Lei Zhang, Jiaqi Zhou, Zhaokun Wang, Xijia Gu, and Yan Feng

***Abstract*— We report an environmentally stable and ultracompact dissipative soliton mode-locked fiber laser with a semiconductor-saturable absorber mirror (SESAM). A polarization-maintaining fiber loop mirror is used as the linear cavity end mirror, which also serves other purposes, such as a laser output coupler, a polarizer, and a pulse-shaping bandpass filter. Self-starting stable mode-locking operation with 2-nJ pulse energy and 24-ps pulsewidth is achieved. The laser emission shows high polarization extinction ratio of over 22 dB, with excellent stability.**

***Index Terms*— Ultrafast optics.**

I. Introduction

MODE-LOCKED fiber lasers have become a subject of intensive research because of their tremendous potential in laser material processing, optical frequency combs, optical sensing, and supercontinuum generation. Numerous methods and components have been developed to achieve stable mode locking, such as, nonlinear polarization rotation (NPR) [1], [2], figure-of-eight mode-locking [3], [4], semiconductor-saturable absorber mirror (SESAM) [5], [6], and carbon nanotube (CNT) saturable absorber [7], [8]. However, many reported mode-locking methods have inherent environmental instabilities. For example, the NPR method suffers from environmental fluctuations and requires the adjustment of the polarization controllers for self-starting operation. The figure-of-eight mode-locked technique may not be able to sustain the mode locking if subjected to significant temperature changes. These instabilities can be largely reduced by using all-polarization maintaining (PM) components in a mode-locked fiber laser.

All-PM mode-locked configurations with SESAM and CNT have been demonstrated as more reliable sources of ultrafast pulses. Hartl et al. reported ultra-compact dispersion-compensated femtosecond fiber oscillators with saturable absorber in an all-fiber PM cavity configuration [9]. A self-starting, self-similar, all-PM, Yb-doped fiber laser has been demonstrated in [10]. However, the use of the waveplate and a pair of bulk gratings for dispersion management in the laser cavity complicate the laser configuration. Chong et al. reported an all-normal-dispersion SESAM mode-locked fiber laser with 2.2 nJ pulse energy [6]. However the free-space optical elements used in the laser cavity lessen the advantages of the fiber laser. Recently, with an all-fiber PM ring cavity all-normal dispersion (ANDi) mode-locked laser has been achieved, in which the pulse-shaping mechanism is attributed to SESAM and to the filtering effect of the titled chirped fiber grating. The laser output could be dechirped to 457 fs [11]. With CNT as the saturable absorber, an all-PM, Er-doped ultra-short pulse fiber laser having kW peak power has been achieved [12]. With a nonlinear amplifying fiber loop mirror, Aguergaray et al. reported an all-normal dispersion, linearly polarized mode-locked laser with linear chirp, which could be compressed to 120 fs [13].

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L. Zhang, Z. Wang, and Y. Feng are with the Shanghai Key Laboratory of Solid-State Lasers and Applications, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China (e-mail: feng@siom.ac.cn).

J. Zhou and X. Gu are with the Department of Electrical and Computer Engineering, Ryerson University, Toronto, ON M5B 2K3, Canada (e-mail: xgu@ee.ryerson.ca).

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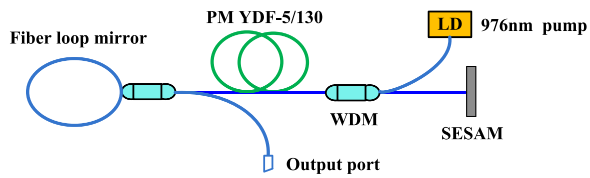

Fig. 1. Schematic diagram of the experimental configuration.

In this letter, an environmentally stable and ultra-compact ANDi mode-locked fiber laser constructed using only five components is demonstrated. The laser cavity with all-PM fiber components generates an environmentally stable, linearly polarized laser pulses. The fused PM fiber loop mirror serves multiple roles, such as being a cavity end mirror, a laser output coupler, a polarizer, and a pulse-shaping bandpass filter. Self-starting and stable dissipative soliton mode-locked operation is achieved with 2 nJ pulse energy and 24 ps pulse width. The output power test over 2 h shows the excellent mode-locking stability of this design.

II. Experimental Setup

The laser setup is illustrated in Fig. 1. The gain medium is a 30 cm-long, high-concentration, Yb-doped PM single-mode fiber, with peak absorption of 750 dB/m at 976 nm. The pump source used is a 400 mW single-mode pigtailed laser diode emitting at 976 nm, and the pump laser is launched through a 976/1030 PM fiber pigtailed multiplexer (both axes passing). A SESAM with 15 ps relaxation time and 37% modulation depth is used at the end of the laser cavity to permit reliable self-starting mode-locked operation. All PM fiber components

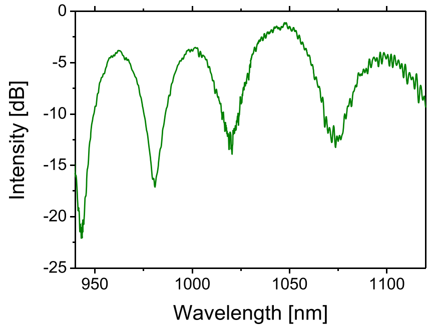

Fig. 2. Reflectivity spectrum of the PM loop mirror.

with estimated polarization extinction ratios (PER) of more than 35 dB are carefully spliced together. The round trip cavity length is 8.1 m, with an overall round trip cavity dispersion of about −0.3 ps/nm at 1035 nm.

The fiber loop mirror is made by splicing together two output ports of a fused PM fiber biconic coupler [14]. The total length of the fiber loop is less than 0.5 m, and the reflectivity of a fiber loop mirror is given by [15]

$$R = 2\rho(1-\rho)\{1+\cos[1-2\rho)\gamma P_0 L]\}T^2 \quad (1)$$

where T refers to the single pass total transmission through the fiber coupler and ρ stands for the coupling ratio to one of the two ports. The peak power of the input laser and the Kerr nonlinearity coefficient used in Eq. 1 are $P_0 = 100$ W and $\gamma = 0.005$ $\mathrm{m}^{-1}\mathrm{W}^{-1}$, respectively. The fiber coupler is fabricated for WDM, operating on its slow axis. The reflectivity of the fiber loop mirror from 1030 nm to 1040 nm is measured before the experiments. The total transmissions for the fast and slow axes of the fiber coupler are 80% and 95%, respectively. The coupling ratios ρ are 90% and 80%, respectively. Such differences in transmissions and coupling ratios between the two axes are typical of PM fiber multiplexers.

From Eq. 1, the overall reflectivity on the slow and fast axes at the wavelengths from 1030 nm to 1040 nm are calculated to be 56% and 25%, respectively, which provides polarization discrimination between the light propagating along the two axes. At the same time, the free port of the PM loop mirror could be used as an output coupler with a 44% output ratio.

Fig. 2 shows the slow axis reflectivity spectrum of the fiber loop mirror measured with an ASE source and a circulator from 940 nm to 1120 nm; it shows periodical reflectivity. The peak reflection of about 75% is located at 1048 nm, with a 30 nm 3 dB bandwidth between 1030 nm to 1060 nm, which could provide strong spectral filtering for the highly chirped pulse to stabilize the mode locking operation.

As it is well-known, all-normal dispersion mode locking strongly depends on dissipative processes as the result of the interaction among gain, loss, nonlinear saturable absorption, and self-phase modulations. Spectral filtering is essential in shaping the pulse [16]. Self-amplitude modulation occurs through the spectral filtering of a chirped pulse, which cuts off the temporal wings of the pulse to stabilize mode locking [17]. The fiber loop mirror incorporated in the laser cavity has a pivotal function in forming the dissipative soliton. First, it acts

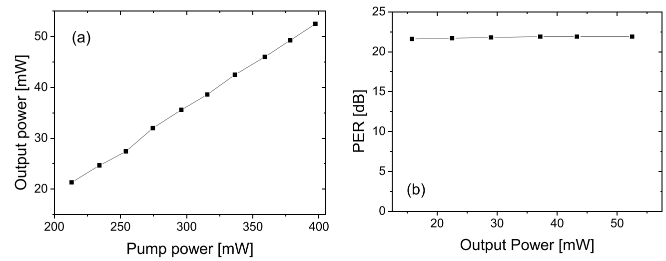

Fig. 3. (a) Output power and (b) PER of the mode-locked laser as a function of pump power.

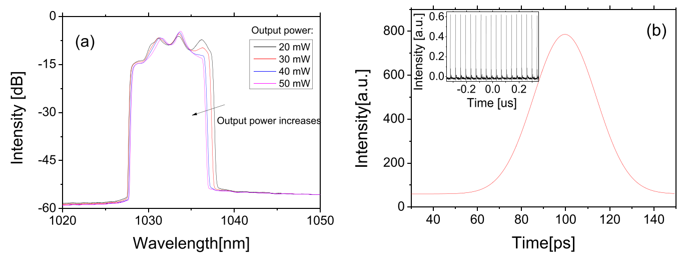

Fig. 4. (a) Output spectra of the mode-locked laser as a function of the output power. (b) Autocorrelation trace of the mode-locked laser; inset, Output pulse trains of the same laser.

as an output coupler with a variable output ratio (depending on the output wavelength), which could automatically select the proper loss of the laser cavity to form the dissipative soliton. Second, it acts as a bandpass filter with a 30 nm bandwidth, which provides the necessary spectral filtering of a chirped pulse and stabilizes mode locking. Third, it provides polarization discrimination between the light propagating along the two axes, which leads to linearly polarized laser oscillation.

III. Results and Discussions

Self-starting mode-locked operation is obtained by increasing the pump power above the threshold without any polarization control. As shown in Fig. 3(a), the laser output power almost linearly increases with the pump power above the mode-locking threshold of 200 mW pump power. The output power of 53 mW is reached at the maximum pump power of 400 mW. As the pump power increases, the operation state of the laser changes from cw oscillation to Q-switching, and then to Q-switched mode locking, and finally to stable, single-pulse mode locking at above 200 mW pump power. The corresponding maximum pulse energy is 2.1 nJ at a pulse repetition rate of 25.8 MHz. The PER of the laser output is measured at different laser output power levels. As shown in Fig. 3(b), PER larger than 22 dB is achieved at all power levels because of the PM loop mirror, which provides the necessary polarization discrimination between the slow and fast axes.

The spectra of the mode-locked fiber laser at different output powers are shown in Fig. 4(a), which exhibits the typical characteristics of the dissipative soliton obtained through the spectral filtering of the highly chirped pulse in the all-normal dispersion regime. Steep sides could be observed at the edges of the spectra. The central wavelength is at 1034 nm, with a 10 nm bandwidth at −10 dB. Some ripples on the top of the

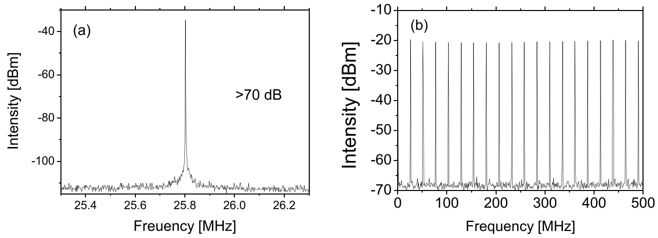

Fig. 5. The radiofrequency (RF) spectrum (a) around the fundamental and (b) harmonic repetition rates of the mode-locked laser.

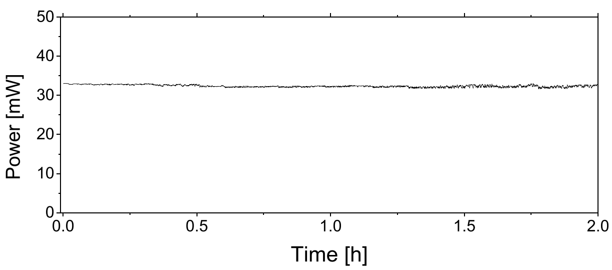

Fig. 6. Output power stability test with a duration of 2 h.

spectrum can be observed in Fig. 4(a), which can be ascribed to the Lyot filtering induced by the imperfect PM splicing and the polarization dependent components in the laser cavity. As the pump power is increased, the spectral width decreases monotonically until the maximum pump power is reached. The autocorrelation traces of the chirped pulses are measured with a long-range autocorrelator (APE SM 1200). A pulse width of 24 ps is obtained, as illustrated in Fig. 4(b). The pulse train measured with a photodiode (1.2 GHz bandwidth) is shown in the inset of Fig. 4(b). It exhibits a pulse spacing of 38.8 ns, corresponding to the pulse repetition rate of 25.8 MHz, which matches well with the cavity length.

The radio frequency (RF) spectrum around the fundamental repetition rate is shown in Fig. 5(a). It is measured with a high-resolution RF spectrum analyzer (Agilent E4405B) at full output power. No residual sidebands caused by the Q-switched mode locking could be observed. A 70 dB peak-to-background ratio and a narrow spectral width indicate excellent pulse energy stability and low pulse timing jitter. The RF spectrum measured over the 500 MHz range consists of a comb of the harmonics corresponding to the repetition frequency of 25.8 MHz, as shown in Fig. 5(b). The resolutions used for the measurement of the RF spectra around the fundamental and harmonics repetition are 10 Hz and 1 kHz, respectively.

Fig. 6 shows the result of the output power measurement of the mode-locked laser for over 2 h. A mean output power of $\sim$32.5 mW with $\sim$1.3 mW rms instabilities over 2 h represents a 1.6 % relative rms noise with respect to the average signal power, indicating the good power and mode-locking stability of the laser. For long-term stability, we lower the output power to 32.5 mW to prevent any damage to the SESAM. For higher power operations, we could increase the beam spot size on the SESAM to improve the damage threshold. Benefiting from the all-PM configuration, the mode locking operation could be maintained by softly knocking the fiber and by changing the environmental temperature.

IV. Summary and Perspective

In conclusion, we have successfully demonstrated an environmentally stable, all-fiber mode-locked laser. The linear cavity is constructed with a SESAM for self-starting mode-locking, and a PM fiber loop mirror, which remarkably serves four purposes: as a laser cavity end mirror, an output coupler, a polarizer, and a pulse shaping bandpass filter. The ultra-compact all fiber laser cavity with all the PM components can generate mode-locked pulses of 2 nJ pulse energy and 24 ps pulse width. The output power measured over 2 h shows the excellent environmental stability of this design.

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