Low-repetition-rate, all-polarization-maintaining Yb-doped fiber laser mode-locked by a semiconductor saturable absorber*

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A low-repetition-rate, all-polarization-maintaining (PM)-fiber sub-nanosecond oscillator is presented, which is simple and low-cost, composed of standard components. The ring cavity is elongated by 114-m-long standard PM fiber, and passively mode-locked by a fiber pigtailed semiconductor saturable absorber. Linearly polarized pulses with 1.66 MHz repetition rate and 22 dB polarization extinction ratio are generated at a wavelength of 1030 nm, which is determined by an intracavity filter. In addition, to demonstrate that the oscillator is a good seed for high energy pulse generation, an all-fiber master oscillator power amplifier is built and amplified pulses with energy about 2 μJ are obtained.

Keywords: mode-locked fiber laser, polarization maintaining, master oscillator power amplifier

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1. Introduction

Pulsed laser sources have great potential applications in many fields, e.g., optical measurement, optical fiber communication, medicine, and micromachining. Passively mode-locked fiber lasers, with the advantages of compact, stable, and low-cost, are alternative pulse sources to their solid-state counterparts.[1] However, the single-pulse energy of a soliton fiber laser is limited by the nonlinear effects of the fiber.[2] Recently, all-normal-dispersion (ANDi) mode-locked fiber lasers attracted lots of attention, which are promising compact pulse sources for their high-energy output and simplified laser cavity.[3–5] The pulse in the ANDi oscillator is a kind of dissipative soliton, which is formed by a balance of gain, loss, dispersion, and nonlinearity.[6,7] The architecture of ANDi lasers is especially convenient for the Yb-doped fiber laser working at the 1 μm regime, at which wavelength the dispersion of the standard fiber is normal. Thus the mode-locked Yb-doped fiber laser could be constructed in all-fiber form with standard components, avoiding additional dispersion-compensation devices. In the ANDi fiber laser, spectral filtering is required to counter the combined effects of normal dispersion and self-phase modulation (SPM), stabilizing the pulse output. Usually a filter is inserted in the cavity,[3,8] and in some cases the limited gain bandwidth serves as a virtual filter.[4] The intracavity spectral filter determines the output wavelength of the laser, and by using a tunable filter, wavelength-tunable ANDi mode-locked fiber lasers could be achieved.[9]

By extending the fiber length of the cavity, ANDi fiber lasers can still mode-lock and output low-repetition-rate pulses.[10] A long-cavity mode-locked fiber laser, as a seed of the master oscillator power amplifier (MOPA), is promising for generating high-energy pulses. Since the pulse energy can be calculated by dividing the average power by the repetition rate, decreasing the repetition rate will increase the pulse energy. Usually a pulse picker is used in the MOPA to decrease the repetition rate of the seed and increase the amplified pulse energy. Using the low-repetition-rate laser as the seed can refrain MOPA from the pulse picker.[10] There are lots of investigations on low-repetition-rate Yb-doped mode-locked fiber lasers, e.g., lasers mode-locked by nonlinear polarization rotation (NPR) with free-space components,[11] by NPR with all-fiber components,[12] by nanotubes absorber,[13] or by semiconductor saturable absorber mirror (SESAM).[14]

More recently, in order to obtain stable output pulses, low-repetition-rate Yb-doped fiber lasers composed of all-polarization-maintaining (PM) fiber were proposed and demonstrated. In the PM fiber, the linear polarization state of light could be forcedly maintained along the propagation, preventing the change of the polarization state due to environmental perturbation.[15] An all-PM fiber laser with a repetition rate of 1.7 MHz was obtained, which was mode-locked by a nonlinear amplified loop mirror (NALM).[16] In a cavity with similar structure, 2.47 MHz all-PM fiber laser with higher pulse energy was achieved.[17] By combining the angle-spliced PM fibers and a Faraday mirror, mode-locked all PM-fiber lasers were achieved by use of NPR, with repetition of 1 MHz[18] or 948 kHz.[19] A nanotube absorber was used to mode-lock a 641-kHz all-PM-fiber ANDi laser, where a segment of 300-m-long PM highly-nonlinear fiber was used in the cavity and the spectral filtering was provided by the limited

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gain bandwidth.[20] SESAM was used to mode-lock a linear cavity with a repetition rate of 0.7 MHz, where a narrow-band (< 0.1 nm) fiber Bragg grating (FBG) served as a filter and reflector.[21] However, the central wavelength of the narrow-band FBG is sensitive to the environment temperature, thus the output of the laser would be affected seriously by the temperature.

In this paper, a simple and low-cost low-repetition-rate, all-PM Yb-doped fiber laser is reported, which consists of standard components. The ring cavity, elongated by 114-m-long standard PM ANDi fiber, is passively mode-locked by a fiber pigtailed semiconductor saturable absorber (SSA) in transmission mode. Linearly polarized sub-nanosecond pulses with 1.66 MHz repetition rate and 22 dB polarization extinction ratio (PER) are generated at a wavelength of 1030 nm, which is determined by a band-pass filter. Based on the oscillator, a MOPA is built to demonstrate the amplification of the oscillator, and high energy pulses (about 2 μJ) are generated.

2. Experimental setup and results

Figure 1 shows the experimental setup of the low-repetition-rate, mode-lokced all-PM Yb-doped fiber laser. A ring cavity is built, where a PM-fiber pigtailed SSA in transmission mode (SA-1064-40-500fs, BATOP GmbH) is used to mode-lock the fiber laser. The absorptance of the SSA is 40%, the relaxation time is $\sim$ 500 fs, and the saturation fluence is 300 μJ/cm^2. A 70-cm-long PM Yb-doped fiber (Nufern PM-YSF-HI with 250 dB/m peak core absorption at 975 nm), core pumped by a 976 nm laser diode, serves as the gain fiber. A PM isolator with fast axis blocking is used to ensure unidirectional and linear-polarization operation, and a commercial integrated band-pass filter with PM-fiber pigtail (centered at 1029.9 nm with 0.5 dB-bandwidth of 2.86 nm) is inserted in the cavity to help form and stabilize the optical pulse. A PM coupler provides a 20% output, and a segment of standard PM single-mode fiber (Nufern PM980-XP) is used to elongate the cavity.

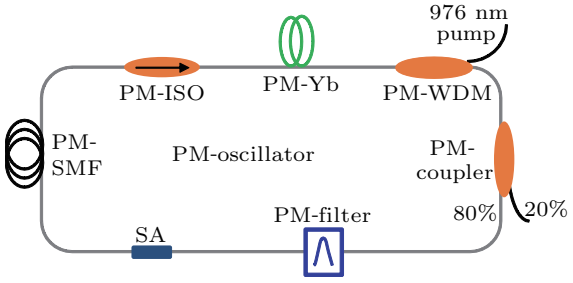


Fig. 1. (color online) Experimental setup of the low-repetition-rate, semiconductor SA mode locked, all-PM fiber laser. PM: polarization-maintaining, WDM: wavelength division multiplexer, Yb: Yb-doped fiber, ISO: isolator, SMF: single-mode fiber, SA: saturable absorber.

In order to obtain a mode-locked laser with sufficient low-repetition-rate, intracavity standard PM fibers with different lengths are tried to extend the cavity as long as possible. Once the cavity is built, only one parameter, i.e., the pump power, can be tuned to reach the mode-locking state. For a cavity with appropriate length, self-starting mode-locking can be achieved in a range of pump powers. The pump power ranges corresponding to mode-locked lasers with different repetition rates are illustrated in Fig. 2, where the zero power range means that the laser cannot be mode locked at any pump power. It is found that, for the cavity with very long PM fiber (repetition rate less than 1 MHz), stable output cannot be achieved. It can be explained from the following two aspects. For the cavity with very long fiber, the nonlinear effect (e.g. SPM) will accumulate, thus the pulse circulating in the cavity becomes unstable and will break in the time domain.[22] In addition, very long fiber will induce large dispersion and stretch the pulse significantly, which cannot be balanced by other components in the cavity. Thus in the time domain it is difficult to get self-consistent for the pulse circulating in the cavity. With the cavity length decreasing, the pump power range for mode-locking increases. According to these results, the cavity with 114-m-long standard PM fiber (corresponding to 1.66 MHz repetition rate) is adopted in the following experiments.

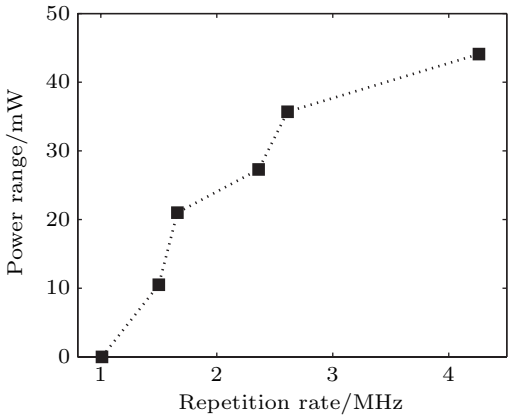


Fig. 2. Pump power range for mode-locking the oscillator with different repetition rates.

The output of the oscillator (with repetition rate of 1.66 MHz) is measured and shown in Fig. 3. The spectrum is measured by an optical spectrum analyzer (OSA) with 0.06 nm bandwidth resolution, and the temporal pulses are measured by a fast photo-detector with a rise time of 100 ps and an oscilloscope with a bandwidth of 2 GHz (Agilent Infiniium DSO80204B). The center wavelength of the output is around 1030 nm, which is coincided with that of the intracavity spectral filter, and the 3-dB bandwidth is measured as 2.0 nm. The measured pulse duration, as shown in Fig. 3(c) with a full width at half maximum of $\sim$ 400 ps, is limited by the bandwidths of the detector and oscilloscope. On the other hand, the pulse duration is beyond the scan range (about 160 ps) of our autocorrelator (FR-103XL, Femtochrome Re-

search Inc.). These results indicate that the pulse duration is sub-nanosecond.

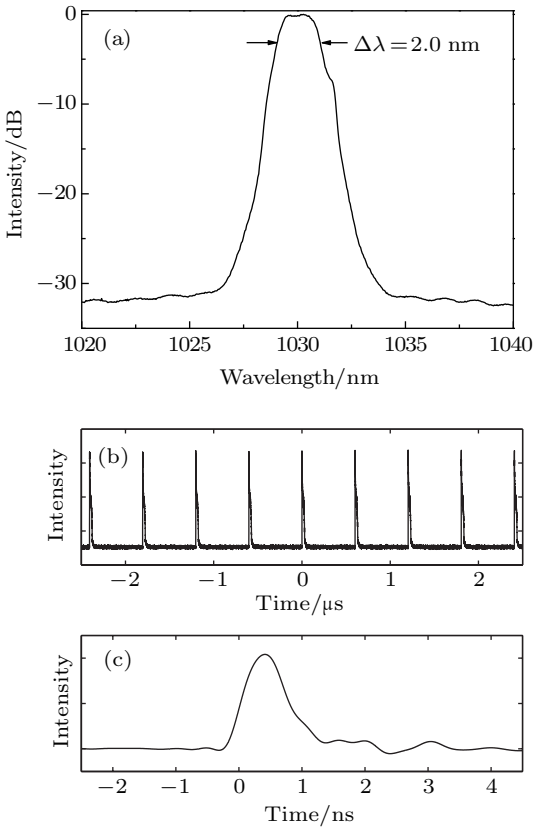


Fig. 3. Output of the oscillator with 1.66 MHz repetition rate. (a) Spectrum measured by OSA with 0.06 nm bandwidth resolution, (b) pulse train, and (c) one pulse measured by a fast photo-detector with rise time of 100 ps and an oscilloscope with 2 GHz bandwidth.

The stability of the output average power is measured by keeping the laser running for 8 hours. The measured output powers at different times are shown in Fig. 4, which reveals that the oscillator has good stability. The fluctuation of the output power is less than 0.5% in 8 hours.

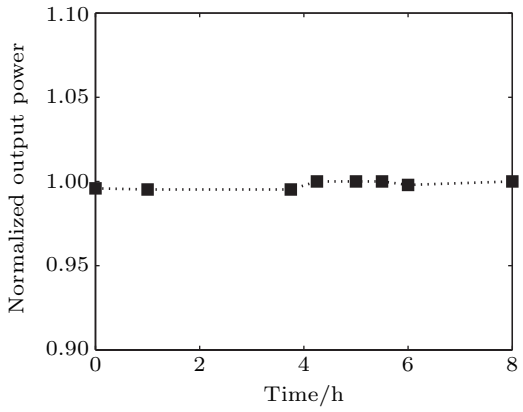


Fig. 4. The normalized output power of the oscillator measured in 8 hours.

In order to confirm the polarization of the output, a setup for PER measurement is built, as shown in Fig. 5(a), where the output is collimated, then transmits through a half waveplate, a polarization beam splitter (PBS, serves as a polarizer), and is detected by an optical power meter. By rotating the waveplate, the transmission power of PBS alters, and the measured power versus the rotation angle of the waveplate is shown in Fig. 5(b). The maximum and minimum measured powers are 888 μW and 6.3 μW, respectively, and the calculated PER is 22.2 dB, which indicates that the output is linearly polarized.

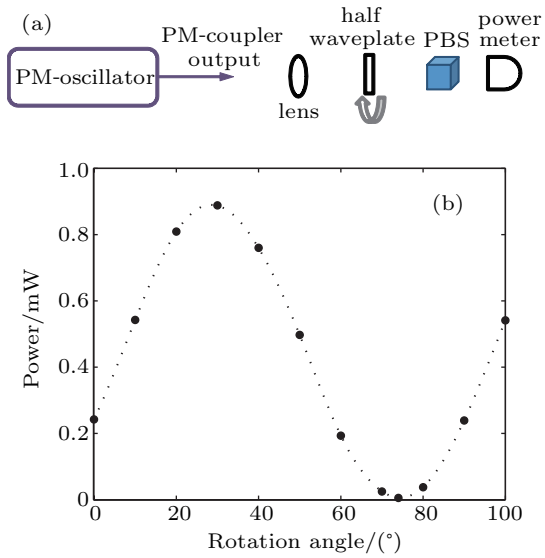


Fig. 5. (color online) (a) Experimental setup for measuring the polarization extinction ratio of the output from the oscillator. (b) The measured power versus the rotation angle of the half waveplate. PM: polarization-maintaining, PBS: polarization beam splitter.

In order to demonstrate the performance of the oscillator serving as a seed for MOPA, an all-fiber three-stage Yb-doped fiber amplifier is built, as shown in Fig. 6. The 1st- and 2nd-stage amplifiers consist of single-mode Yb-doped fibers, and the active fiber of the 3rd-stage amplifier is a segment of 3-m-long double cladding Yb-doped fiber with a 25 μm core diameter (Nufern LMA-YDF-25/250-M). The 2nd- and 3rd-stage amplifiers are connected by a mode field adapter (MFA). Before the angle-cleaved output fiber, a cladding power stripper (CPS) is used to eliminate the residual pump. For a pump power of 132.3 mW in the oscillator, the output power of the seed is 1.47 mW. Then the seed with a pigtail of PM fiber is connected to the 1st-stage amplifier with a pigtail of Hi-1060 fiber. With a pump power of 311.3 mW in the 1st-stage amplifier, 10.7 mW output is obtained. Then the output is amplified to 113.3 mW by the 2nd-stage amplifier with a pump power of 460 mW. Finally, high energy pulses are output by the 3rd-stage amplifier due to the low repetition rate of the seed. Figure 7(a) shows the output power with the increase of the pump power of the main amplifier. Figure 7(b) compares the spectra of the seed and the amplified outputs with average powers of 2.18 W and 3.36 W, respectively. As seen

from Fig. 7(b), the 3-dB spectral bandwidth increases from 2.0 nm (seed) to 3.8 nm and 5.7 nm for 1.25 μJ and 2.02 μJ output pulse energies, respectively. With the increase of the pump power, the amplified spectrum broadens mainly due to the SPM. The amplification experiments demonstrate that the proposed low-repetition-rate, all-PM fiber laser is a good seed for MOPA to become an all-fiber, high-energy pulse source without the requirement of a pulse picker.

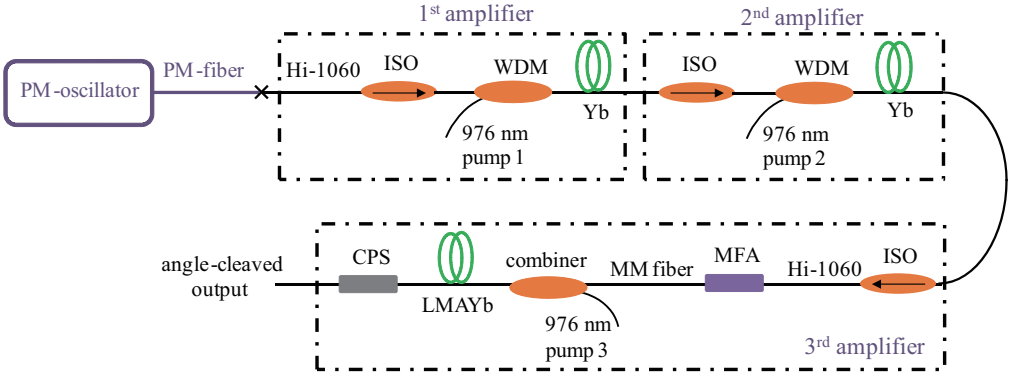


Fig. 6. (color online) Experimental setup of an all-fiber master oscillator power amplifier with the low-repetition-rate all-PM fiber seed and a three-stage amplifier. PM: polarization-maintaining, ISO: isolator, WDM: wavelength division multiplexer, Yb: Yb-doped fiber, MFA: mode field adapter, MM fiber: multimode fiber, LMA fiber: fiber with large mode area, CPS: cladding power stripper.

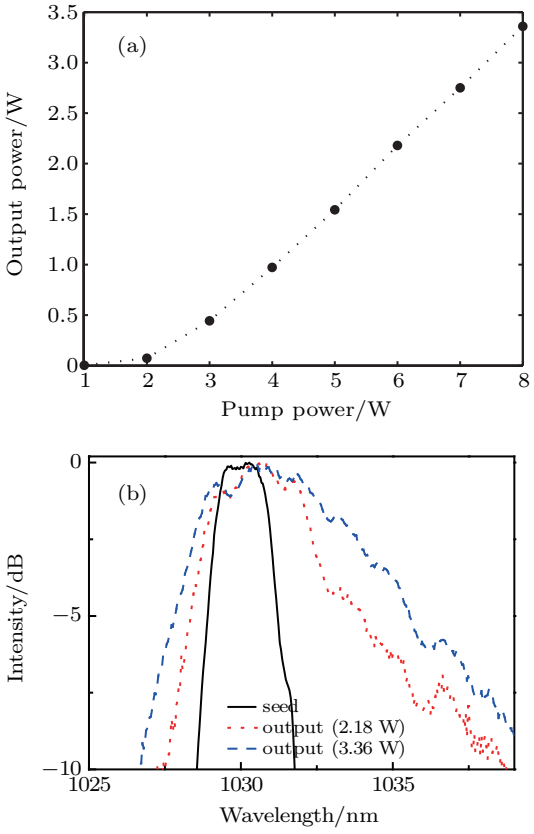


Fig. 7. (color online) (a) Output power of the MOPA with increasing pump power of the 3rd-stage amplifier. (b) Spectra of the seed and the amplified outputs with average powers of 2.18 W and 3.36 W, respectively.

3. Discussion

Firstly, the architecture and components of the proposed laser cavity are discussed. Since the pulse duration is sub-nanosecond, which is much longer than the relaxation time of general SA, there is no specific requirement for the SA's relaxation time. For the WDM, it has a limited bandwidth for the pulse, however, the bandwidth is much broader than that of the following PM-filter, and thus the filtering effect of the WDM can be neglected. In order to further validate it, simulations of the proposed oscillator are conducted, with a numerical model similar to that in Ref. [8] and simulation parameters the same as those in our experiments. By neglecting the bandwidth of the WDM, simulations show that the laser can be mode-locked, indicating that the filtering effect of the WDM could be neglected. Moreover, we also numerically and experimentally investigate the pulse dynamics by changing the placement of different components in the cavity. It is found that, it is not necessary to place these components in the cavity strictly in the order shown in Fig. 1.

Then the process of MOPA is discussed. As shown in Fig. 7(b), the spectral bandwidth of the output pulse (with energy of 2.02 μJ) broadens about 3 times compared to that of the seed. For applications based on optical pulses, pulses with a broader spectrum may correspond to a worse performance, e.g., pulses with broader bandwidth, served as the pump light, will cause lower spectral resolution in the application of coherent Raman scattering microspectroscopy.[23] In addition, the spectral broadening of the amplified pulse reflects the accumulated nonlinear phase of the pulse induced by nonlinear effects (e.g. SPM), which will distort (and even break) the pulse in the time domain. However, the 2 GHz oscilloscope cannot resolve the sub-nanosecond internal pulse structure. The degree of spectrum broadening depends on the accumulated nonlinear phase.[22] For high-energy output pulses from fiber MOPA, the spectrum usually broadens several times.[24,25] The accumulated nonlinear phase of the amplified pulse can be reduced by increasing the pulse duration and core diameter of the fiber, and decreasing the amplified pulse energy (i.e., peak power).

4. Conclusion

An all-PM Yb-doped fiber laser, with low-repetition-rate (1.66 MHz), sub-nanosecond duration, and linearly-polarized (PER of 22 dB) output pulses, is reported. The length of the ring cavity is extended by a segment of standard PM fiber, and a PM-fiber pigtailed SSA and a PM band-pass filter are used to initiate the pulse output. Moreover, based on the oscillator, an all-fiber MOPA is demonstrated to obtain high-energy (2 μJ) pulses. Compared to other low-repetition-rate all-PM fiber oscillators, the proposed laser is simple and low-cost, which is constructed by standard fiber components. Therefore, the proposed oscillator is a good seed for high-energy pulse generation.

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