Wideband All-Polarization-Maintaining Yb-Doped Mode-Locked Fiber Laser Using a Nonlinear Optical Loop Mirror

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We report on a wide-band and stable mode-locked all-polarization-maintaining fiber laser configuration using a nonlinear optical loop mirror. The central wavelength of the laser is 1080.14 nm and the 3 dB bandwidth is 20.29 nm. The repetition rate of the pulse is 3.28 MHz and the pulse width is 848 ps. By tuning the pump power, which is centered at 980 nm, from 300 mW to 380 mW, we obtain a linearly changed output power from 6 mW to 7.12 mW. The all-polarization-maintaining fiber configuration is fundamental to the stability of the output power.

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During the past few years, the development of the mode-locked fiber lasers with the operating wavelength of 1 μm has achieved significant progress.[1,2] Fiber lasers with polarization-maintaining fibers are highly desirable in both the scientific and commercial field. In 2005, Nielsen *et al.* experimentally obtained self-similar pulses from a self-starting saturable absorber mirror based on polarization maintaining fiber.[3] In 2008, Nishizawa *et al.* used a polarization-maintaining anomalous dispersive fiber and carbon nanotube saturable absorber to achieve a self-starting and stable mode-locking operation with pulse width of 314 fs.[4] As we know, the nonlinear optical loop mirror (NOLM) can operate as a nonlinear switching device due to the nonlinear phase difference between the clockwise and anticlockwise signals.[5] Demonstrated by Aguergaray *et al.* in 2010, an NOLM fiber laser based on all-polarization-maintaining fiber can work well without the drawbacks of long-term reliability and limitation in power-handling capabilities.[6]

In this Letter, the wide-band all-polarization-maintaining Yb-doped mode-locked fiber laser is proposed and demonstrated. The Yb-doped double-clad fiber is used to provide high gain and large dispersion which can help to broaden the bandwidth of the mode-locked pulses. The remarkable feature of this laser system is that the 3 dB spectral bandwidth is about 20.29 nm, which is, to the best of our knowledge, the widest output bandwidth of the mode-locked pulses at 1 μm and the laser can directly output the maximum average output power of 7.12 mW, with a repetition rate of 3.28 MHz.

The experimental setup of the 1 μm all-polarization-maintaining fiber laser is illustrated in Fig. 1. It is based on the figure-8 passively mode-locked Yb fiber laser. The laser system consists of two loops, the left loop and the right loop, which is connected by a 3 dB coupler (PM-OC 5:5). The left loop consists of a laser diode (LD), a PM-FWDM, a section of PM-Yb-doped double-clad fiber (YDF-PM, with the length of 1.0 m), a polarization-maintaining isolator (PM-ISO), while the right loop consists of a 9:1 output coupler (PM-OC 9:1) and a section of long PM-980 fiber of about 50 m. It can be seen from Fig. 1 that the right loop is a well-known nonlinear optical loop mirror (NOLM), which can operate as a nonlinear switching device due to the nonlinear phase difference between the clockwise and anticlockwise signals in the right loop.[5] The LD centered at 976 nm is used to pump the Yb-DCF through the PM-FWDM. The YDF-PM (LIEKKI Yb1200-6/125DC-PM, 1.0 m length with the absorption coefficient of 2.6 dB/m at 976 nm) which can provide high gain and large dispersion so as to broaden the bandwidth of the mode-locked pulses. The 9:1 OC is placed in the right loop with 10% of the pulse energy output through the output port. The PM-ISO ensures the unidirectional operation of the left loop. The output mode-locked pulse signal is monitored by an optical spectrum analyzer and an oscilloscope simultaneously.

In our fiber laser system, when the pump power was increased to about 300 mW, the stable mode-locked pulse train could be observed by properly squeezing the fiber, and it could be very stable. Then the mode-locking process in the time domain was investigated. The temporal behavior of the pulse train and the temporal profile of the single pulse are shown in Figs. 2(a) and 2(b), respectively, with the LD pumping at about 330 mW. The signal was measured with a 10 GHz photodetector and a 4 GHz digital oscilloscope (LeCroy Wave Runner 640Zi). The mode-locked pulse with a duration of 848 ps was measured, as shown in

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Fig. 2(b).

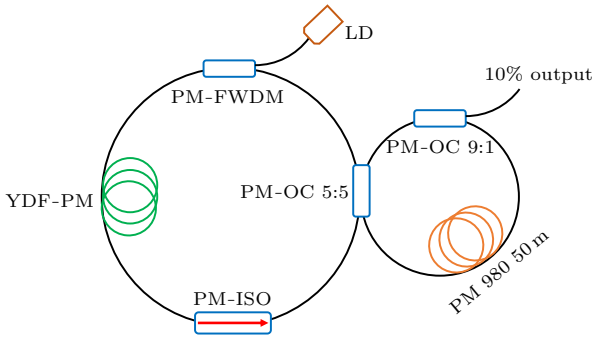

Fig. 1. The experimental setup of the all-polarization-maintaining fiber laser. YDF-PM, polarization maintaining ytterbium-doped-fiber; PM-OC, polarization-maintaining optical coupler; PM 980, polarization-maintaining optical fiber; PM-ISO, polarization-maintaining isolator; LD, laser diode; and PM-FWDM, polarization-maintaining filter WDM.

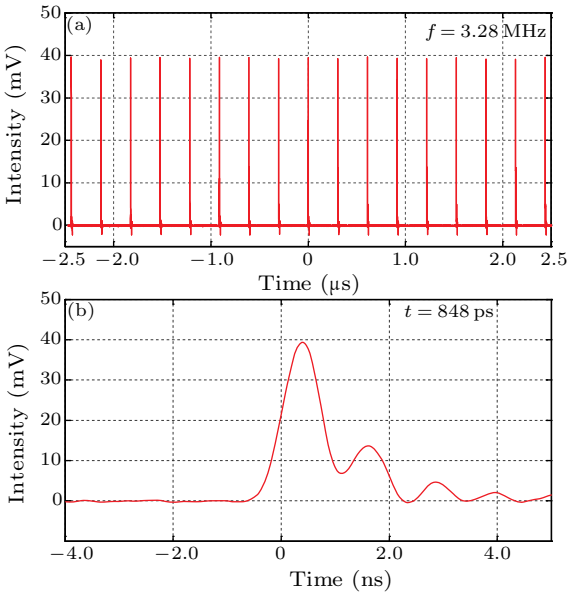

Fig. 2. Oscilloscope trace of the mode-locked pulse train (a) and a temporal profile of the single pulse (b).

The corresponding spectrum was measured by an optical spectrum analyzer (ANDO AQ6317B) with the resolution of 0.01 nm, as shown in Fig. 3. The central wavelength and the 3 dB bandwidth are measured of 1080.14 nm and 20.29 nm, respectively. The spectral bandwidth is much broader than that of the published reports.[7,8] The rf spectrum of the mode-locked pulse train is measured with an rf spectrum analyzer. The rf spectrum presented in Fig. 4 reveals a fundamental cavity repetition rate of 3.28 MHz, corresponding to the cavity length of ~61 m. The signal-to-noise ratio (SNR) exceeding 50 dB and narrow rf linewidth confirms that the mode-locked pulse is stable.

We find that the output power of the mode-locked pulse is tunable just by simply changing the pump power while the output power is very stable. Figure 5 shows the dependence of the output power versus the pump power. When the pump power of LD is tuned to 300, 310, 320, 330, 340, 350, 360, 370 and 380 mW, respectively, the corresponding output power of 6.00, 6.22, 6.36, 6.58, 6.75, 6.85, 6.94, 7.02 and 7.12 mW are observed. It can be seen from Fig. 5 that the output power increases linearly with the pump power with the slope efficiency of 0.013.

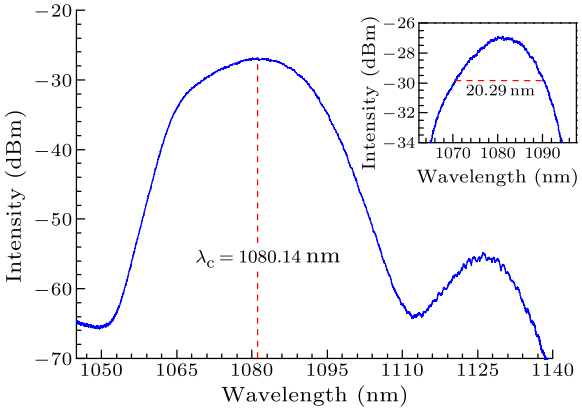

Fig. 3. The output spectrum of the mode-locked fiber laser, centered at 1080.14 nm, with the 3 dB bandwidth of 20.29 nm, as shown in the top inset.

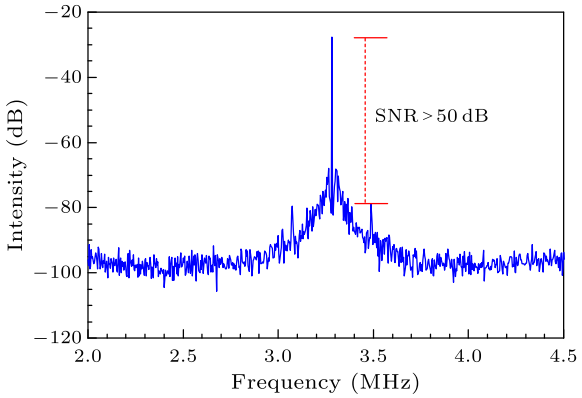

Fig. 4. The rf spectrum of the output mode-locked pulse train.

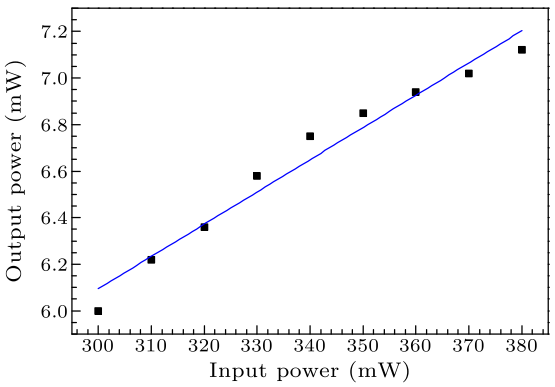

Fig. 5. Curve of the output power versus the pump power.

The all-PM fiber configuration is fundamental to

the stability of the laser operation. As we know, the NOLM is based on interference between pulses with different phases propagating clockwise and anticlockwise. Without special care from environmental changes, the all-PM fiber keeps the light in the same polarization state. Szczepanek *et al.* proved that an NOLM mode-locked laser constructed entirely of PM fibers is very stable to thermal and mechanical perturbations.[9]

In conclusion, we have proposed and demonstrated a wide-band all-polarization-maintaining pulse generation in a Yb-doped figure-8 passively mode-locked fiber laser. The YDF-PM is used to provide high gain and large dispersion, which broadens the bandwidth of the mode-locked pulses. The laser can emit a pulse with the maximum output power of 7.12 mW, and pulse duration of 848 ps. The fiber laser operates at 1080.14 nm, and the 3 dB spectral bandwidth 20.29 nm is obtained, which is, to the best of our knowledge, the widest output spectrum band of the all-polarization-maintaining mode-locked pulse at 1 μm band. Experimental results also show the great potential of obtaining a much higher and stable average output power.

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