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High energy and average power single-mode all-fiber ANDi laser

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ABSTRACT

We proposed and demonstrated a technique to increase the pulse energy output in a single-mode all normal dispersion (ANDi) passively mode-locked fiber laser, which is based on nonlinearity optimization within the cavity together with a high output coupling ratio. With an output ratio of 95%, an average power of 460 mW at a repetition rate of 1.3 MHz is achieved, corresponding to a single-pulse energy of 354 nJ. To the best of our knowledge, the result is the highest energy with high average power output for ANDi passively mode-locked fiber lasers based on single-mode fibers.

1. Introduction

Recently, passively mode-locked fiber lasers have attracted increasing interest because of their simplicity, stability, relatively low cost, and potential applications such as ultra-short pulse generation and frequency comb. However, their pulse energies lag behind solid-state lasers. Fiber lasers that deliver transform-limited pulses in anomalous-dispersion regime [1,2] or stretched pulses with managed dispersion [3] yield single pulse energies of only several nJ. The challenge for high energy output is attributed to the combined effect of the nonlinearity and group velocity dispersion (GVD) leading to pulse-breaking when the accumulated nonlinear phase exceeds a certain level. Overdriving the ultrafast saturable absorber effect, as in the nonlinear polarization evolution (NPE) mode-locking scheme, is also an issue [4,5].

These effects can be circumvented via the temporal stretching of the pulse within the cavity, which reduces the peak power and maintains nonlinearity under control. All-normal dispersion (ANDi) lasers [6–9] were proposed based on this strategy to generate large chirped pulses with higher energies. This method was first demonstrated in an Yb-doped fiber laser (YDFL) that involved free-space propagation and operated at 1 μm, where conventional SMFs and fiber components all exhibit normal dispersions. This YDFL produced 3 nJ pulses [10]. When considering the positive correlation between pulse energy and cavity length, a similar oscillator at a reduced repetition rate of 12.5 MHz was constructed that resulted in the generation of 20 nJ pulses [11]. An all-fiber-integrated ANDi laser with a compact structure also reportedly yielded a 3.6 nJ output pulse [12]. However, as the pump power increased, multiple-pulsing still happened to the chirped pulses that were once considered pulse-breaking free in the ANDi lasers. It had been experimentally observed in [13,14]. Measures are needed to weaken the nonlinearity so that the pulse energy can be further improved.

In this letter, we proposed and demonstrated a technique to increase the pulse energy output for a single-mode ANDi passively mode-locked fiber laser based on nonlinearity optimization within the cavity together with a high output coupling ratio. By increasing the output coupling ratio and shortening the length of the single-mode fiber (SMF) between the gain fiber and output coupler, we can manage the nonlinearity and increase the energy output. At a high output coupling ratio of 95%, the laser outputs large chirped pulses with an average power of 460 mW at a repetition rate of 1.3 MHz, which corresponds to a single pulse energy of 354 nJ.

2. Experimental setup

The experimental setup for our laser system is shown in Fig. 1. The laser is a ring-cavity configuration that is ~153 m in total length. Mode-locking is achieved via the NPE technique, and the laser operates in the clockwise direction, as shown. The system includes LD lasers (LDs), a pump combiner, a 980 /1060 nm wavelength division multiplex (WDM), an Yb-doped fiber (YDF) section, a SMF section, two polarization controllers (PC1 and PC2), a polarization dependent isolator (PD-ISO), and an optical coupler (OC). The LD lasers at 976 nm is used to pump the YDF (back pumping) through the pump combiner and WDM. The YDF (Coractive Yb164, Core Absorption of 470 dB/m at the wavelength of

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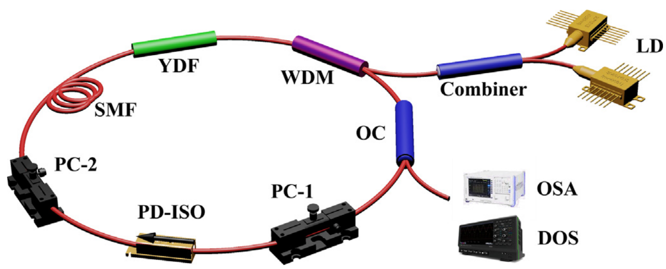

Fig. 1. Schematic diagram of the experimental setup. LD, laser diode; WDM, wavelength division multiplex; YDF, Ytterbium-doped fiber; OC, optical coupler; PD-ISO, polarization dependent isolator; PC, polarization controller; OSA, optical spectrum analyzer; DOS, digital oscilloscope.

976 nm) is 110 cm long, and a maximum pump power of 764 mW is coupled into it. The OC is used to output the amplified pulses with a high ratio. The PD-ISO and two PCs are used to implement the NPE unidirectional mode-locked operation. According to [15], the NPE effect performs as an equivalent spectral filter that cuts off the temporal wings and shapes the chirped pulses; thus, no additional filter was adopted. The section of SMF is approximately 150 m long. It is employed to reduce the mode-locking threshold and enlarge the normal dispersion. All of the components are SMF integrated, and the total calculated GVD is approximately 4.6 ps^2.

In our laser system design, the key is to let high-energy pulses experience the short fiber to avoid pulse-breaking caused by nonlinear phase accumulation and to let low-energy pulses experience the long fiber to accumulate sufficient nonlinear phase to maintain the NPE mode-locking operation. We put the OC close to the YDF to export the high power pulses shortly after they are amplified in the YDF, and the SMF length between the YDF and OC is controlled to less than 30 cm. The high-energy pulses experience a short SMF, so the nonlinearity accumulation is greatly reduced, and the pulse-breaking effect can be avoided. When a high output ratio OC is used in our laser system, most of the pulse energy is output through the OC, and the remain low-energy pulses return back to the laser cavity after the OC; therefore, we add an SMF section before the Yb-doped fiber in order to maintain a sufficient nonlinear phase accumulation for the NPE mode-locking operation.

3. Experimental results

This nonlinearity optimization technique allows us to output high-energy pulses. Different OCs are spliced into the cavity, and Fig. 2(a) shows the relationship between the pulse average power P_{out} and the output coupling ratio for a constant pump power (maximum power of 764 mW) under mode-locking operation. It can be seen that as increase the output coupling ratio, the average output power P_{out} increases almost linearly. Due to the known coupling ratio for each OC, we estimate values of P_{sum} and P_{in}, where P_{sum} refers to the average power before the OC within the laser cavity, and P_{in} stands for the average power returning back to the laser cavity after the OC. Fig. 2(b) shows the variations of P_{sum} and P_{in} versus the output coupling ratio. Clearly, with the rising output coupling ratio, P_{in} decreases, whereas P_{sum} only varies within a small range. It comes to a conclusion that high output coupling ratio leads to high output energy and low cavity nonlinearity.

Based on the experimental results shown in Fig. 2, we choose a coupler with an output coupling ratio of 95% for high pulse energy output. We don't adopt a higher output ratio, because no mode-locking can be achieved when it exceeds 95% for the fixed condition in our cavity. If higher pump power is available, potential optimal output ratio could be higher. By adjusting the two PCs, stable mode-locked pulses can be achieved when the pump power is tuned beyond the threshold. An optical spectrum analyzer (OSA, ANDO AQ6317B) and a digital oscilloscope (DOS, LeCroy Wave Runner 640Zi digital oscilloscope,4 GHz bandwidth) combined with a photoelectric detector (10 GHz bandwidth) are employed to simultaneously monitor the spectrum and pulse train, respectively.

The mode-locking threshold is about 340 mW. At the maximum pump power of 764 mW, the laser generates stable pulses with the average power of 460 mW. The output results are displayed in Fig. 3. Excellent beam quality can be expected for only single mode fibers are involved in the all-fiber laser cavity.

The output pulse train is shown in Fig. 3(a) with a repetition rate of 1.3 MHz, corresponding to single pulse energy of 354 nJ. Fig. 3(b) shows the output single-pulse profile with a full width at half maximum (FWHM) of 550 ps. This graph reveals a relatively long pulse resulting from the large normal dispersion cavity. The autocorrelation trace of the pulse is also measured with an autocorrelator (Pulse Check-250 from APE Cor.), and within the scanning range of 250 ps, no multi-pulsing is observed. The optical output spectrum of the signal pulses is measured with a 0.01 nm resolution, and as shown in Fig. 3(c), the optical spectrum is quite smooth with a 3 dB bandwidth of 18.5 nm at the central wavelength of 1034 nm. The calculated time-bandwidth product is about 2850. This value is larger than that of Fourier-transform-limited pulse, which indicates that the pulse is highly chirped. Fig. 3(d) shows the measured RF spectrum for the pulse train output. The repetition rate is 1.308 MHz, which corresponds to the fundamental mode-locking, and the signal-to-noise ratio (SNR) is greater than 80 dB. The inset in Fig. 3(d) exhibits the broadband RF

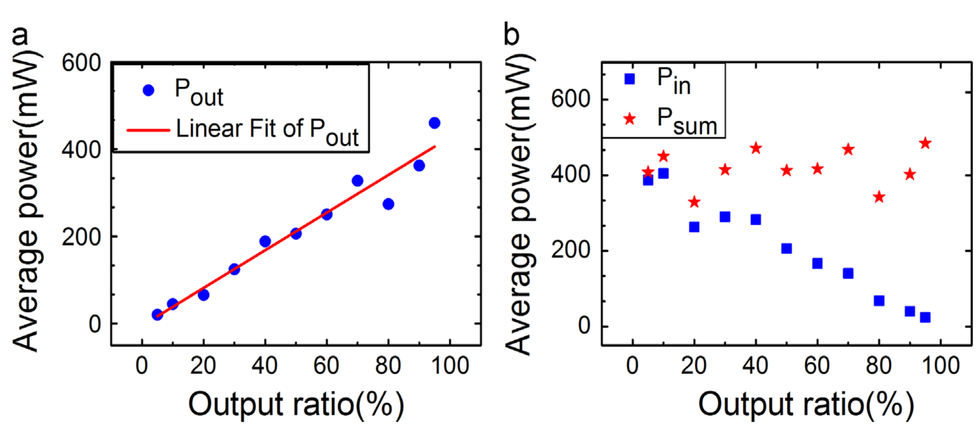

Fig. 2. (a) P_{out} (blue dot for experimental data, red line for linearly fitted curve), (b) P_{sum} (red star) and P_{in} (blue square) vary with output ratio. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)