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Generation of stable nanosecond dual-pulse in an erbium-doped fiber laser with normal dispersion

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ABSTRACT

Because of the special needs for nanosecond double pulse applications in micromachining and material processing, we demonstrated a stable nanosecond dual-pulse erbium-doped fiber laser based on nonlinear polarization rotation technology. The fiber laser operates in a normal dispersion regime with a length of 256 m OFS-980 fiber. With the pump power of 1120 mW, the laser generates a highly stable dual-pulse train with the pulse widths of 6.2 ns and 1.2 ns respectively. By simply changing the pump power, the pulse width of one of dual-pulse can be tuned from 2.1 to 6.2 ns while the other pulse keeping almost the same duration of 1.2 ns. The maximum dual-pulse energy is about 72.5 nJ with a repetition rate of 783.3 kHz. The formation of such nanosecond dual-pulse is attributed to the pulse splitting and depends on the parameters of the laser cavity, such as the cavity-length and the state of polarization controller. The experiment of a single square pulse splitting into different shapes of nanosecond dual-pulse was demonstrated.

1. Introduction

In the past two decades, double-pulse lasers have been investigated in the field of micromachining and material processing [1,2], such as drilling micro holes [3,4] and laser ablation [5,6]. Usually, the efficiency is low when drilling processing is fulfilled by a single pulse laser without gas-assist. Increasing the laser power does not work well because of the resolidification of the molten pool. Two main mechanisms responsible for material removal in pulse laser drilling are melt ejection and material vaporization. In order to improve the processing efficiency and quality of laser drilling, double-pulse technique was proposed and attracted great interest [7]. The second pulse can interact with melt or heated surface, which should assist with an ablation mass removal while minimizing redeposition and heat-affected zones [6]. Nanosecond pulses can provide a high processing efficiency and high quality because of their middle pulse width and enough high energy. A combination of these two advantages of nanosecond pulse and double-pulse for precision machining was realized [3,4]. To drill high-aspect ratio holes, a nanosecond double-pulse laser with 3 ns pulse duration and several tens of nanoseconds inter-pulse separation was utilized [4]. A nanosecond double-pulse with 21 ns pulse duration and 52 ns inter-pulse separation for laser drilling of stainless steel are demonstrated [3]. By controlling the second laser pulse duration, a promising way to improve plasma emission was proposed [6]. There are usually two ways to obtain the nanosecond double pulse. One is providing a delayed divided pulse scheme by some mirrors [3] or modulators [6] with a single laser. The other one is beam combining from two pulse lasers [2,7]. However these double pulse systems are complex, expensive and difficult to adjust. High energy nanosecond pulsed fiber lasers have their inherent technical advantages such as simple, compact, adjust-free, easily amplified by master-oscillator power amplifier (MOPA) [8]. Self-Q-switched [9,10], passively Q-switched [11,12] or mode-locked [13–16] fiber lasers in nanosecond domain have been realized. Till now, these nanosecond fiber lasers almost emit single pulse train, while dual-pulse fiber lasers are almost picosecond scale [17,18]. Nanosecond dual-pulse mode-locked fiber laser is less reported till now.

Here, we demonstrated a stable nanosecond dual-pulse mode-locked fiber laser based on nonlinear polarization evolution technique. The laser is an erbium-doped all-fiber laser and operates in a large normal dispersion regime. The fiber laser emits a self-started mode-locked dual-pulse with pulse widths of 2.1 and 1.2 ns respectively at a pump power of 130 mW. By simply changing the pump power, the pulse width of higher amplitude pulse can be tuned from 2.1 to 6.2 ns while the other pulse with duration of 1.2 ns has no significant change. The inter-pulse separation of 32 ns nearly does not change. With the maximum pump power

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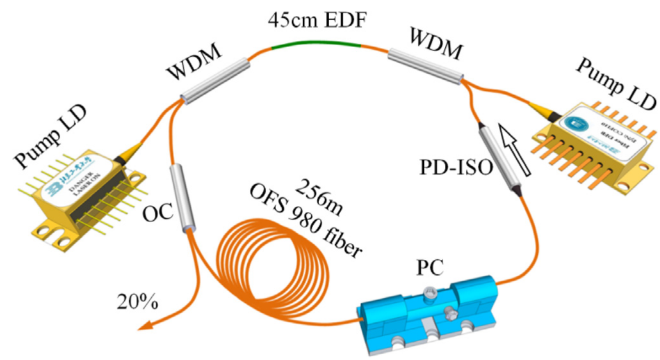

Fig. 1. Schematic diagram of the experimental setup. LD: laser diode; WDM: wavelength-division-multiplexer; EDF: erbium-doped fiber; PD-ISO: polarization-dependent isolator; PC: polarization controller; OC: output coupler.

of 1120 mW, the laser generates a highly stable dual-pulse with duration of 6.2 ns and 1.2 ns respectively and the dual-pulse energy is as high as 72.5 nJ with a repetition rate of 783.3 kHz. This kind of nanosecond dual-pulses with controlled tunable pulse width and energy has potential applications in micromachining and material processing.

2. Experimental setup

Fig. 1 shows the diagram of the experimental setup. The fiber oscillator is in a ring cavity. To increase the pump power, two 980-nm laser diodes (LDs) with a total pump power of 1120 mW are utilized to provide bidirectional pump via two 980/1550 nm wavelength-division multiplexers (WDMs) respectively. The gain medium is a 45-cm-long erbium-doped fiber (EDF, Liekki Er 80-4/125), which has an absorption of 80 dB/m at 980 nm. A fused 20/80 optical couple after the gain fiber is used as output coupler (OC) and the 20% port extracts the pulses from the cavity. An inline polarization controller (PC) is capable of fine-tuning the polarization state of the lasing light. A polarization-dependent optical isolator (PD-ISO) ensures unidirectional propagation of the light in the cavity and it can provide polarization selectivity. It makes the light linearly polarized after leaving the isolator, which is necessary to achieve nonlinear polarization rotation (NPR) mode-locking.

In addition to the gain fiber, the laser cavity contains standard single-mode fiber (SMF-28) with a length of 3.55 m and OFS-980 fiber with a length of 256 m. OFS-980 fiber has a normal dispersion of the group velocity in 1.5 μm [19]. The total length of cavity is about 260 m, which is about 26 times beat length of standard single-mode fiber. The advantage of fiber laser working in the multi-beat length regime is easily producing a nanosecond square pulse by exploiting nonlinear polarization switching [20]. The group-velocity dispersions for the EDF, SMF and OFS-980 fiber are about 0.0319 ps^2/m, −0.0228 ps^2/m and 0.0045 ps^2/m respectively [19]. The net cavity dispersion of the laser system is estimated to be +1.08 ps^2, which is benefit for producing a nanosecond square pulse [21]. A nanosecond square pulse formed in the net negative cavity dispersion fiber lasers may quickly evolve to a state of soliton bunching due to the soliton forming effect, while in the case of net positive dispersion cavity lasers, the state can exist in a large pump strength range.

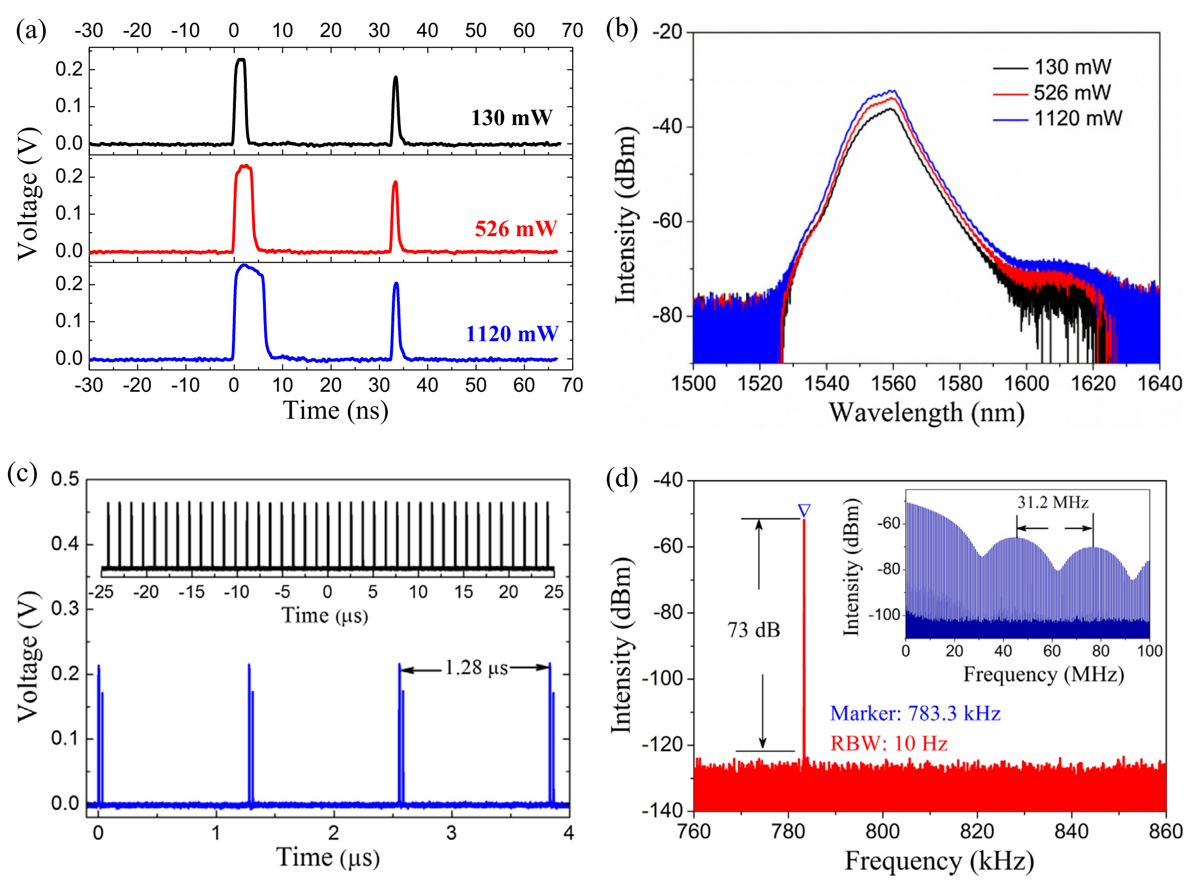

Fig. 2. The characteristics of the nanosecond dual-pulse fiber laser. (a) oscilloscope traces of dual-pulse under different pump powers; (b) optical spectra of the dual-pulse under different pump powers; (c) oscilloscope trace of dual-pulse train, the upper insert: corresponding pulses train in a 50 μs scale; (d) RF spectra around the fundamental repetition rate, inset: RF spectrum in a large span of 100 MHz.