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Noise-like rectangular pulses in a mode-locked double-clad Er:Yb laser with a record pulse energy*

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Generation of noise-like rectangular pulse was investigated systematically in an Er–Yb co-doped fiber laser based on an intra-cavity coupler with different coupling ratios. When the coupling ratio was 5/95, stable mode-locked pulses could be obtained with the pulse packet duration tunable from 4.86 ns to 80 ns. The repetition frequency was 1.186 MHz with the output spectrum centered at 1.6 μm. The average output power and single pulse energy reached a record 1.43 W and 1.21 μJ, respectively. Pulse characteristics under different coupling ratios (5/95, 10/90, 20/80, 30/70, 40/60) were also presented and discussed.

Keywords: rectangular noise-like pulse, mode-locked laser, Er–Yb co-doped fiber laser

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1. Introduction

Fiber lasers with pulse duration on nanoseconds scale have been applied in widespread fields including laser material processing, generation of supercontinuum, retinal treatment, and micro-machining.[1–4] Rapid developments in these application fields asked for higher pulse energy and tunable pulse duration. However, in the process of increasing the single pulse energy, pulse breaking could occur due to the excessive nonlinear phase accumulation in a resonator.[5] Rectangular pulses have drawn much attention since their pulse energy can be power-scaled along the pump power without pulse splitting. As a result, rectangular pulses are expected to be applied in many special fields, all-optical square-wave clocks, laser micromachining, optical sensing,[6–8] and so on.

In general, high-energy rectangular pulses were generated in the passively mode-locked fiber laser from two main regimes, called dissipative soliton resonance (DSR) pulse and rectangular noise-like pulse (NLP). The DSR pulse was defined and verified by Chang *et al.* in both normal and anomalous dispersion regimes.[9,10] One of the most remarkable features is that the single pulse duration and energy of generated solitons would keep increasing while the pulse peak power and amplitude are clamped approximately as a constant. Such rectangular pulse with the energy of 421.22 nJ was achieved by Yang *et al.* in a novel sigma-shape cavity at the wavelength of 1.5 μm.[11]

Another regime is the rectangular NLP. Both NLPs and DSR pulses obtain similar feature on the evolution of pulse duration and energy against pump power. The mutual transformation between these two kinds of rectangular pulses in the same cavity was explored and reported in Refs. [12,13]. In fact, difference exists in that the rectangular NLP is a wave packet consisting of many ultrafast, sub-pulses,[14] which makes it more suitable to be applied in supercontinuum generation[14,15] and optical coherence tomography.[16] Till now, rectangular NLPs have been obtained in different types of mode-locked mechanisms like nonlinear polarization rotation (NPR), nonlinear optical loop mirror (NOLM), nonlinear amplifying loop mirror (NALM), carbon nanotube (CNT), and topological insulator as saturable absorbers.[12,17–22] However, the reported pulse energy of rectangular NLP in Er-doped or Er:Yb co-doped fiber lasers was limited to the level of nJ. Zheng *et al.* obtained rectangular NLP with pulse energy of 135 nJ in an Er-doped fiber laser with a figure-of-8 configuration.[18] The single pulse energy of rectangular NLPs was increased up to 200 nJ in an NPR mode-locked Er-doped fiber laser.[12] Rectangular NLP with the highest reported energy 840 nJ was achieved by Li *et al.* in an NPR mode-locked Er-doped fiber laser.[22] However, no experimental work has been reported to explore the influence of parameters in a cavity towards the properties of rectangular NLPs. The coupling ratio of the intra-cavity coupler, for example, may deserve further exploration.

In this paper, systematic investigation on the influence of coupling ratios in a dumbbell-shaped NLP cavity is presented. Through the change of couplers with five different coupling ra-

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tios (5/95, 10/90, 20/80, 30/70, and 40/60), the properties and the evolution of rectangular NLPs were recorded and analyzed at the stable operation of mode-locking state. All measured data of the generated pulses were in quite consistent with the typical feature of the rectangular NLPs. In particular, an average output power 1.43 W corresponding to the single pulse energy of 1.21 μJ was obtained. Up to now, this is the highest average power and single pulse energy in rectangular NLP regime operated at the wavelength around 1.6 μm.

2. Experimental setup

Schematic diagram of the mode-locked fiber laser is illustrated in Fig. 1. The configuration was designed to be a dumbbell shape with two fiber loop mirrors (FLMs). The FLM 2 was fusion spliced with two fiber ends of a 3-dB coupler. Amplification was achieved in a 4.2-meter-long Er/Yb co-doped double-clad active fiber. The core/cladding diameter of the active fiber is 10 μm/125 μm respectively and the cladding absorption coefficient at 976 nm is 9.2 dB/m. The fiber was pumped by a 976 nm multimode laser diode through a combiner. The FLM 1 was composed of three components. The coupling ratio (denoted as a parameter k in Fig. 1) of the coupler was varied ($k = 0.05$, 0.1, 0.2, 0.3, 0.4) to have a systematic investigation on the influence towards pulse properties. Two polarization controllers were set on the two sides of the 150-meter-long SMF-28 to adjust the reflection curve of the FLM 1 that stable mode-locking state could be obtained. No isolator was designed in both loops to reduce the transmission loss. And the output pulses were spatial coupled and monitored by an oscilloscope, a RF spectrum analyzer, an optical spectrum analyzer, and a power meter.

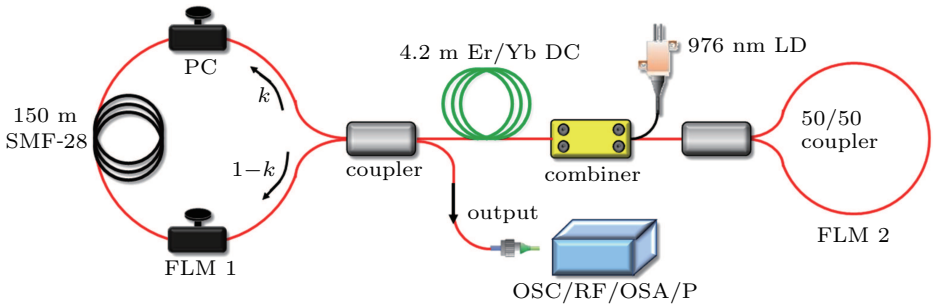


Fig. 1. Experimental setup of the dumbbell-shape fiber laser. LD – laser diode, Er/Yb DC – erbium/ytterbium co-doped double-clad fiber, FLM – fiber loop mirror, PC – polarization controller, OSC – oscilloscope, RF – radio frequency spectrum analyzer, OSA – optical spectrum analyzer, P – power meter.

3. Experimental results and discussion

3.1. Pulse properties at the coupling ratio of 0.05

The coupler with the coupling ratio $k = 0.05$ was firstly fusion spliced in the FLM 1. In our setup, a mode-locking state arouse due to the function of the two FLMs: one worked as a saturable absorber to ensure the self-starting mechanism and to shape the pulses. The other operated as a resonance mirror to provide feedback for the oscillator. Once a stable mode-locking state was achieved, paddles of the polarization controller would be locked tightly. This guaranteed that the laser experienced self-starting each time the pump power was cycled on-off in a particular state. Continuous-wave mode-locked, rectangular pulse self-started at the threshold pump power of 3.82 W. Then the stable mode-locked state was maintained in the pump power scale from 0.976 W to 8.7 W. All properties and evolutions of the mode-locked pulses are shown in Fig. 2.

As illustrated in Figs. 2(a) and 2(b), the output average power, single pulse energy, and pulse duration are all approximately fitted as a linear function of the pump power, while the pulse peak power remains stably as a constant $\sim$ 15 W. The whole evolution of pulse duration is depicted in Fig. 2(c). Maintaining the stable mode-locked state without wave-breaking, the pulse duration could be tuned from 4.86 ns to around 80 ns with the pump power increased from 0.976 W to 8.7 W. To check the type of the obtained pulses, the autocorrelation trace at the pump power of 8.7 W was measured, which is shown in Fig. 2(d). A narrow coherent peak was recorded in the time scale of 50 ps. All these pulse characteristics above were well consistent with the typical feature of rectangular NLPs.[12–14,18] The output pulse spectrum demonstrated in Fig. 2(e) had the 3-dB bandwidth from 1607.4 nm to 1614.5 nm. The output RF spectra were measured and recorded in Fig. 2(f). The fundamental frequency was centered at 1.186 MHz and the RF signal-to-noise ratio was as high as 66 dB, which indicated a fine stability of the mode-locking operation. In the inset, a broad RF spectrum was given in a wide range of 100 MHz. The modulation width $\sim$ 12.5 MHz matched well with the pulse duration $\sim$ 80 ns at the pump power of 8.7 W. The maximum average output power reached 1.43 W in the rectangular NLP regime generated from the Er-doped or Er/Yb co-doped fiber laser. The corresponding single pulse energy was 1.21 μJ.

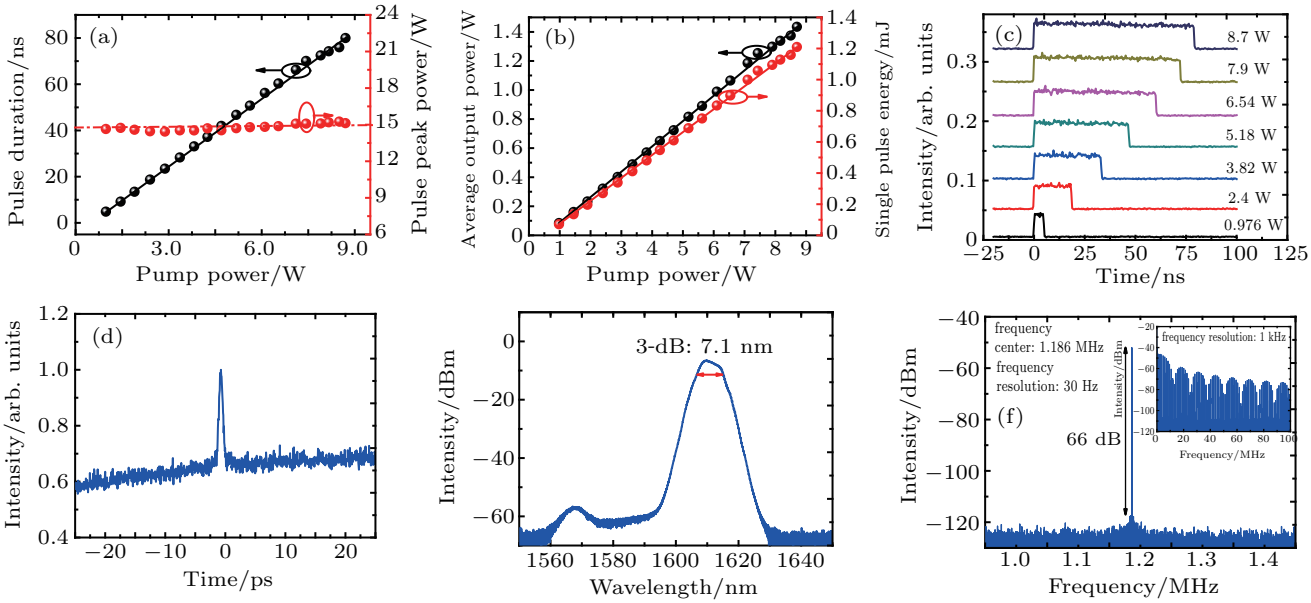


Fig. 2. Properties of obtained mode-locking pulses at a 1.186 MHz repetition rate in our configuration. (a) Pulse duration and peak power against the pump power. (b) Average output power and single pulse energy against the pump power. (c) Pulse shape evolution for the pump power of 0.976 W, 2.4 W, 3.82 W, 5.18 W, 6.54 W, 7.9 W, and 8.7 W. (d) Autocorrelation trace of the pulses in the scale of 50 ps. (e) Spectrum at the pump power of 8.7 W. (f) RF spectrum at the fundamental frequency with the resolution of 30 Hz. Inset: Broadband RF spectrum (100 MHz span).

3.2. Comparison on pulse properties at 5 different coupling ratios

Then we changed the coupling ratio of the coupler in the FLM 1 to further explore the evolution towards the properties of the rectangular NLPs. Five different types of couplers with the coupling ratios $k = 0.05$, 0.1, 0.2, 0.3, 0.4 were selected in the cavity. For different coupling ratio, we calculated the output R of the FLM 1 as a function of the input peak power P by the following formula:[23]

$$R = 1 - 2k(1-k)\{1 + \cos[(1-2k)\cdot\gamma PL]\}, \qquad (1)$$

where γ and L stand for the fiber nonlinear coefficient and the length of FLM 1, respectively.

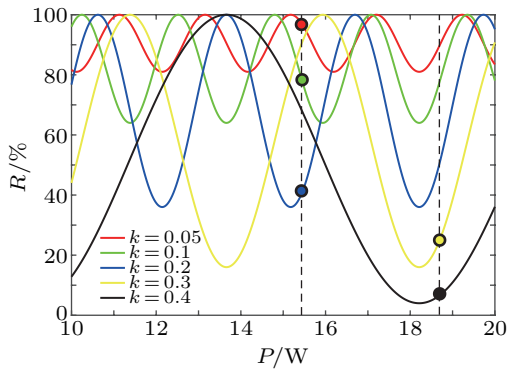


Fig. 3. Calculated output R of the FLM 1 as a function of the input peak power P (in the range of 10–20 W) with $\gamma = 1.3\ \mathrm{W^{-1}\cdot km^{-1}}$, $L = 153$ m, $k = 0.05$, 0.1, 0.2, 0.3, 0.4.

As shown in Fig. 3, the FLM 1 with different coupling ratios possess equivalent periodic saturable absorption effect. When the coupling ratio $k = 0.05$, the FLM 1 had the smallest modulation depth ($\sim 20\%$). When the coupling ratio was changed as $k = 0.1$, 0.2, 0.3, and 0.4, the corresponding modulation depth of the FLM 1 was $\sim 35\%$, $\sim 65\%$, $\sim 85\%$, and $\sim 95\%$, respectively. All the recorded experimental data were summarized and compared in Fig. 4.

Through fine adjustment on the polarization controller, stable mode-locking operation of NLPs was always achieved in our dumbbell-shape cavity with 5 different coupling ratios ($k = 0.05$, 0.1, 0.2, 0.3, 0.4). No sign of pulse breaking or harmonic pulses was observed in the process of tuning the pump power from 0.976 W to 8.7 W. Figure 4(a) demonstrates the average output power against the pump power. In the cavities with 5 different coupling ratios, higher slope efficiency was obtained when lower coupling ratio k was applied. Both the highest slope efficiency (17.5%) and the highest output power 1.43 W were achieved at the coupling ratio $k = 0.05$. In Fig. 4(b), the tuning range of pulse duration against different coupling ratios is demonstrated. When the coupling ratio was $k = 0.05$, the widest tuning range (from 4.86 ns to 80 ns) of the rectangle NLPs was obtained. Under five different coupling ratios, the corresponding pulse shape at the maximum pump power of 8.7 W is shown in the inset. All the generated pulses were in similar rectangular shape, consistent with the feature of rectangular NLP. Figure 4(c) depicts the pulse peak power and single pulse energy against different coupling ratios of the intra-cavity coupler. The change of the couplers did not change the length of the cavity that the fundamental frequency was remained at around 1.186 MHz. Therefore, when coupling ratio k was lower, the output pulses would obtain higher average power as well as higher single pulse energy. To maintain the stable mode-locking state under different coupling ratios, the polarization controllers were adjusted and locked at

different positions. However, the randomity on the position of the polarization controller cannot guarantee a clear evolution of the pulse peak power. As shown in Fig. 4(c), when the pump power was 8.7 W, the peak power of pulse remained $\sim$ 15 W for the coupling ratio $k = 0.05$, 0.1, and 0.2 while reached around 19 W for the coupling ratio $k = 0.3$ and 0.4. Then we draw two dashed lines at the input peak powers of $\sim$ 15 W and $\sim$ 19 W in Fig. 3, five points were obtained at the intersection of the dashed lines and periodic saturable absorption curves. The output R of the FLM 1 was $\sim$ 95%, $\sim$ 80%, $\sim$ 40%, $\sim$ 30%, and $\sim$ 10% when $k = 0.05$, 0.1, 0.2, 0.3, 0.4, respectively, which was in agreement with the tendency of the output average power and pulse energy shown in Figs. 4(a) and 4(c). Consequently, the FLM 1 with lower coupling ratio would output higher average power and pulse energy at the maximum pump power, consistent with the consideration discussed in Ref. [24]. The generated pulses under coupling ratios $k = 0.05$, 0.1, 0.2, 0.3, 0.4 all had a spectrum centered at around 1610 nm, similar to the spectrum shown in Fig. 2(e). The corresponding spectral 3-dB bandwidth at the maximum pump power of 8.7 W is depicted in Fig. 4(d). A slightly gradual broadening on the 3-dB spectral width (from 7.11 nm to 9.9 nm) was observed as the coupling ratio k increased from 0.05 to 0.4. The reason could be that a cavity with higher coupling ratio would obtain pulses with higher peak power, as shown in Fig. 4(c). Stronger self-phase modulation effect induced by higher peak-power pulses would broaden the output spectrum. Similar phenomenon has been reported in Ref. [25].

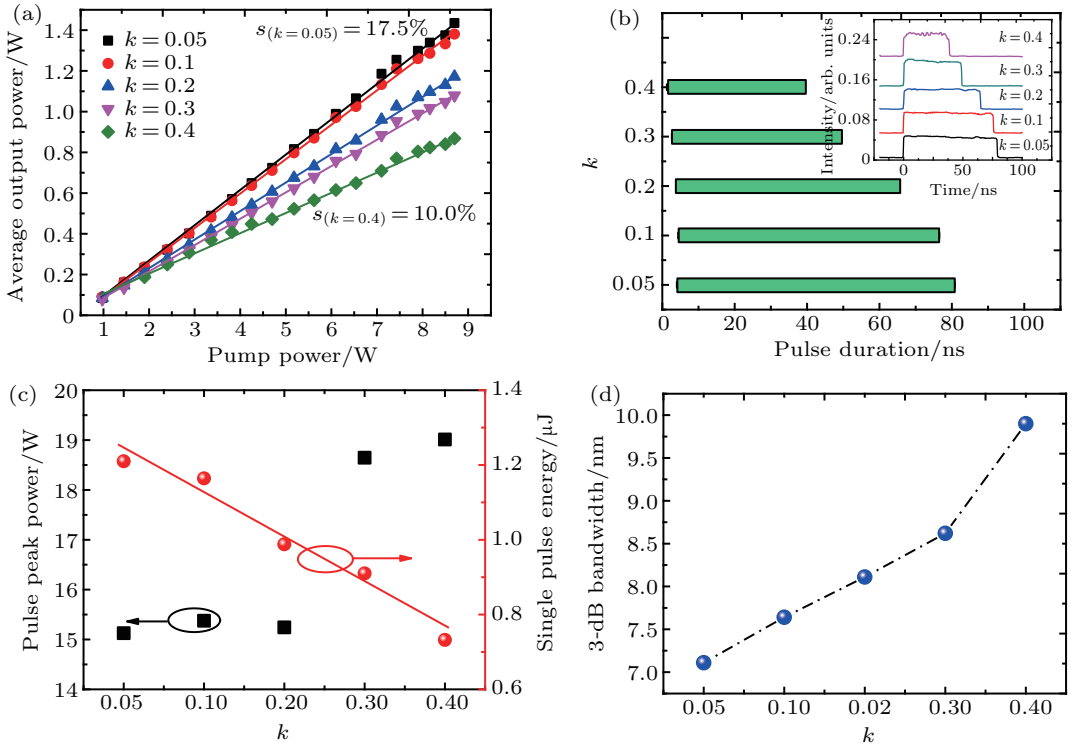


Fig. 4. (a) Average output power for different coupling ratios against the pump power. (b) Tuning ranges of pulse duration under different coupling ratios. Inset: Pulses shape at the pump power of 8.7 W under corresponding coupling ratios. (c) Pulse peak power (black squares) and single pulse energy (red spheres) against 5 different coupling ratios at the pump power of 8.7 W. (d) Spectral 3-dB bandwidth of the NLP pulses for different coupling ratios.

4. Conclusion and perspectives

A systematic experimental investigation on the influence of different coupling ratios towards pulse properties of a 1.6 μm double-clad Er:Yb co-doped, rectangular, noise-like mode-locked laser was presented in our paper. Through precise set towards the parameters of the cavity, mode-locked pulses whose properties were in consistent with the typical features of rectangular NLPs were obtained under 5 different coupling ratios ($k = 0.05$, 0.1, 0.2, 0.3, 0.4). The output pulse with an average power 1.43 W corresponding to the pulse energy 1.21 μJ was obtained in the NLP regime at the wavelength of 1.6 μm when the coupling ratio was $k = 0.05$. Under lower coupling ratio, more energy would be extracted as analyzed in the FLM 1, wider pulse duration and spectrum would be obtained in the emitted pulses as well.

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