

Operation-Switchable Bidirectional Pulsed Fiber Laser Incorporating Carbon-Nanotube-based Saturable Absorber

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Abstract— We present an operation-switchable bidirectional ring-cavity pulsed fiber laser incorporating a carbon-nanotube-based saturable absorber and a polarization-dependent four-port circulator. By manipulating the intra-cavity polarization state of light, two sets of mode-locked pulses in terms of fundamental repetition rate and pulse width can be achieved separately from the same laser cavity. In clockwise direction, the laser generates mode-locked output pulse train with a pulse width of 600 fs and a fundamental repetition rate of 12.68 MHz. While in counter-clockwise direction, the laser generates mode-locked pulses with a pulse width of 480 fs and a fundamental repetition rate of 16.46 MHz. Furthermore, the same laser cavity can produce bidirectional Q-switched output pulse trains with synchronized repetition rate. Such synchronized repetition rate is linearly proportional to pump power. The results show a multi-functional pulsed fiber laser with selectable output pulse trains.

Index Terms—optical fiber lasers, optical materials, optical pulse generation

I. INTRODUCTION

Fiber lasers generating optical pulses with short duration and high energy have emerged as one of best light sources in a broad range of applications including frequency metrology, microscopy, micromachining, ranging finding, and sensing [1, 2]. In general, two mechanisms are involved for fiber lasers to generate pulses: mode-locking and Q-switching. Mode-locked fiber lasers generally produce soliton-like pulses in anomalous net cavity dispersion through the interplay between fiber dispersion and nonlinearity [3]. Such pulses have typical duration down to sub-picoseconds [4]. On the other hand, Q-switched fiber lasers produce pulses only when the population inversion of gain medium at its highest level is larger than the cavity loss [2]. Q-switched fiber lasers are capable of generating pulses with pulse energy much higher than that generated from mode-locked fiber lasers [5]. As the

two types of lasers can produce pulses with extinguished features, the design of one multi-functional fiber laser to generate versatile types of pulse trains is much attractive. By inserting an isolator into the laser cavity, the pulsed lasers can operate in unidirectional cavity configuration. In 2009, K. H. Lin *et al.* demonstrated the generation of Q-switched pulse train as well as mode-locked pulse train from a unidirectional fiber laser incorporating hybrid saturable absorbers (SAs) [6]. Distinct from the unidirectional cavity configuration, the bidirectional cavity configuration enables pulsed lasers to operate without isolators. Such bidirectional mode-locked lasers emitting ultrashort pulses in the opposite directions are very useful for gyroscopic sensors applications [7, 8]. Also, bidirectional Q-switched lasers emitting pulse trains with difference wavelength and synchronized repetition rate in the opposite directions have potential applications in various fields including sum-frequency mixing [9] and synthesis of optical waveform [10, 11]. In 2011, Ouyang *et al.* demonstrated that the bidirectional fiber laser incorporating two semiconductor saturable absorber mirrors (SESAMs) can simultaneously emit two soliton-like pulse trains with distinct fundamental repetition rates in the opposite directions [12]. Recently, Y. Cui *et al.* demonstrated that the bidirectional fiber laser mode-locked by graphene and carbon nanotubes (CNTs) based SAs can separately generate dissipative and conventional solitons [13].

In recent years, CNT-based SAs have been extensively explored in pulsed fiber laser due to its advantages including fast recovery time, wide operation bandwidth with tube diameter control, compatible to fiber, and capacity to work in bidirectional modes [14, 15]. In this work, we demonstrate an operation-switchable bidirectional pulsed fiber laser incorporating a CNT-based SA and a polarization-dependent four-port circulator. By controlling the intra-cavity polarization state of light, two counter-circulating mode-locked pulse trains with different features are enabled from the same laser cavity. In the clockwise (CW) direction, the laser generates mode-locked output pulse train with a pulse width of 600 fs and a fundamental repetition rate of 12.68 MHz. While in the counter-clockwise (CCW) direction, the laser generates mode-locked pulse train with a pulse width of 480 fs and a fundamental repetition rate of 16.46 MHz. Furthermore, the

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laser can operate in Q-switching state in both CW and CCW directions. An output pulse train with pulse energy of 18.7 nJ in the CW direction and that with pulse energy of 23.3 nJ in the CCW direction are found to be synchronized at the same repetition rate of 8 kHz. Such synchronized repetition rate is found to be linearly proportional to pump power.

II. BIDIRECTIONAL PULSED FIBER LASER INCORPORATING CNT-BASED SA

Fig. 1(a) shows the experimental setup of the all-fiber bidirectional laser incorporating a CNT-based SA. A 0.63-m-long piece of erbium-doped fiber (EDF: LIEKKI Er80) with a group velocity dispersion (GVD) parameter β_2 of $-0.022 \text{ ps}^2/\text{m}$ is pumped by a 976-nm laser diode via a 980/1550 nm wavelength-division multiplexing (WDM) coupler. The WDM coupler comes with 0.62-m-long HI1060 fiber pigtailed with β_2 of $+0.02 \text{ ps}^2/\text{m}$. A fiber based polarization controller (PC-1) after the EDF is used to adjust and optimize the polarization condition of the common laser cavity. A polarization-dependent four-port circulator with polarization maintaining (PM) fiber pigtailed is adopted. In the cavity, light passes through the circulator following the configuration $1 \rightarrow 2$, $2 \rightarrow 3$, $3 \rightarrow 4$, and $4 \rightarrow 1$. Ports 1 and 3 are directly spliced to the common laser cavity, where port 2 is spliced to a fiber based polarization controller (PC-2) and then connected to a highly reflected mirror, which forms the arm-1 for CW directional operation. Port 4 with 1.77-m-long polarization maintaining fiber pigtail is connected to another highly reflected mirror, which serves as arm-2 for CCW directional operation. A 10/90 fiber coupler is used to extract 10% of power from the common laser cavity as the laser output for each direction. The total lengths of the cavity in CW direction and CCW direction are around 16.2 m and 12.5 m, respectively. Note that the net cavity GVD in each direction is anomalous which enables soliton shaping in the laser.

The CNT-based SA is constructed by optically-driven deposition of CNTs to form a thin film on a FC/APC connector [16]. The SA is finished by connecting another FC/APC connector by a conventional adaptor. In our experiment, the CNTs are synthesized by high-pressure CO conversion (HiPCO) and dispersed in dimethylformamide (DMF) solvent. The CNTs show a desirable absorption peak near C-band [17]. The nonlinear absorption of the prepared CNT-based SA is first characterized by a conventional pulsed fiber laser with a center wavelength of 1562 nm. Such laser delivers pulse trains with pulse width of 260 fs, repetition rate of 68.27 MHz and maximum average power of 20 mW. Fig. 1(b) shows the measurement result of the nonlinear transmission of the prepared CNT-based SA. The modulation depth and nonsaturable losses are calculated to be 12% and 47.5%, respectively. The saturation intensity is estimated to be $\sim 53 \text{ MW}/\text{cm}^2$.

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III. BIDIRECTIONAL MODE-LOCKING OPERATION

The laser operation can be optimized by adjusting PC-1 and PC-2 as there is polarizer effect in the four-port circulator. By controlling the polarization state of PC-1, the intra-cavity power in the common laser can be optimized where the total output power in both CW direction and CCW direction are maximized. While changing the polarization state of PC-2, the operation state of laser can be tuned. In the experiment, we always fix the PC-1 after the optimization of the intra-cavity power and only adjust the polarization state of PC-2. The pump threshold for mode-locking in the CW direction is found to be $\sim 26.7 \text{ mW}$ together with adjusting polarization state of PC-2. The output power is measured around $126.5 \text{ }\mu\text{W}$ in the CW direction while it is only $\sim 2 \text{ }\mu\text{W}$ in CCW direction under the pump power of 26.7 mW. Fig. 2(a) shows the spectral profile of the laser output from the CW direction. The center wavelength of optical spectrum is 1562.58 nm with a 3-dB bandwidth of 4.3 nm. The sharp sidebands periodically superimposed on the pulse spectrum clearly indicate that soliton-like pulses are

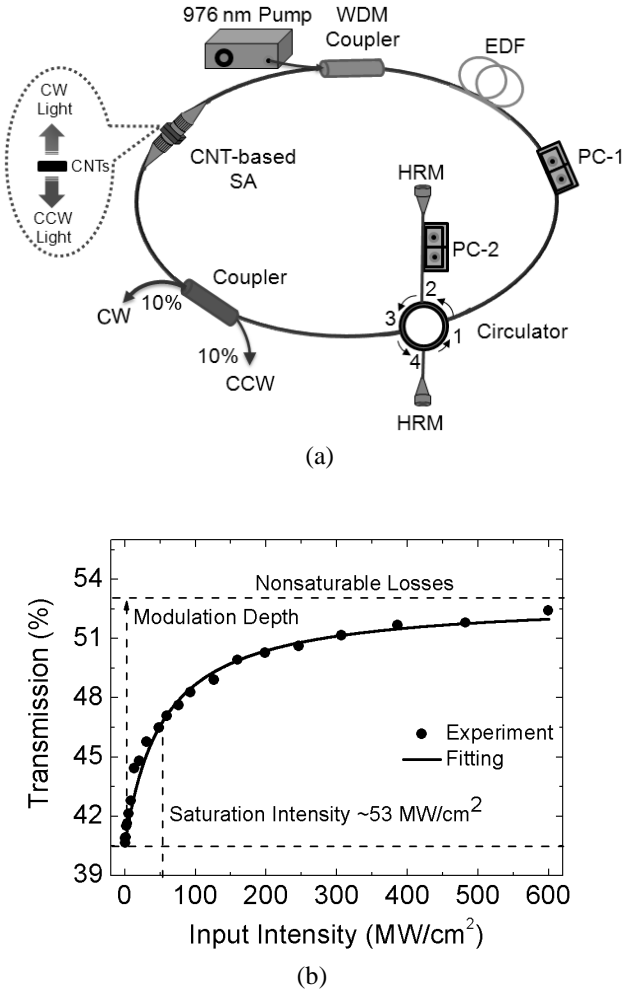


Fig. 1. (a) Schematic diagram of all-fiber bidirectional laser incorporating carbon-nanotube- (CNT) based saturable absorber (SA) and (b) transmission characteristics of the CNT-based SA. WDM: wavelength-division multiplexing; EDF: erbium-doped fiber; PC: polarization controller; HRM: highly reflected mirror; CW: clockwise; CCW: counter-clockwise.

generated in the laser cavity [3]. Fig. 2(a) also depicts the autocorrelation trace of the output pulse with a resolution of 25 fs. The pulse width is estimated to be 600 fs with a sech^2 fitting and the time-bandwidth product is calculated to be 0.317, which is nearly transform-limited. The RF spectrum of the output pulse is also given in Fig. 2(b). The output pulse train exhibits an extinction ratio of 80 dB at the fundamental repetition rate of 12.68 MHz. Moreover, no sidebands within a wide frequency range are observed as shown in the inset of Fig. 2(b), which further confirms that stable mode-locking is obtained. When the pump power is further increased to 32 mW or above, multiple pulses are observed due to the soliton energy quantization [18]. In the operation state of CW directional mode-locking, the characterization of optical properties of the CCW directional laser is impossible due to its extremely low output power.

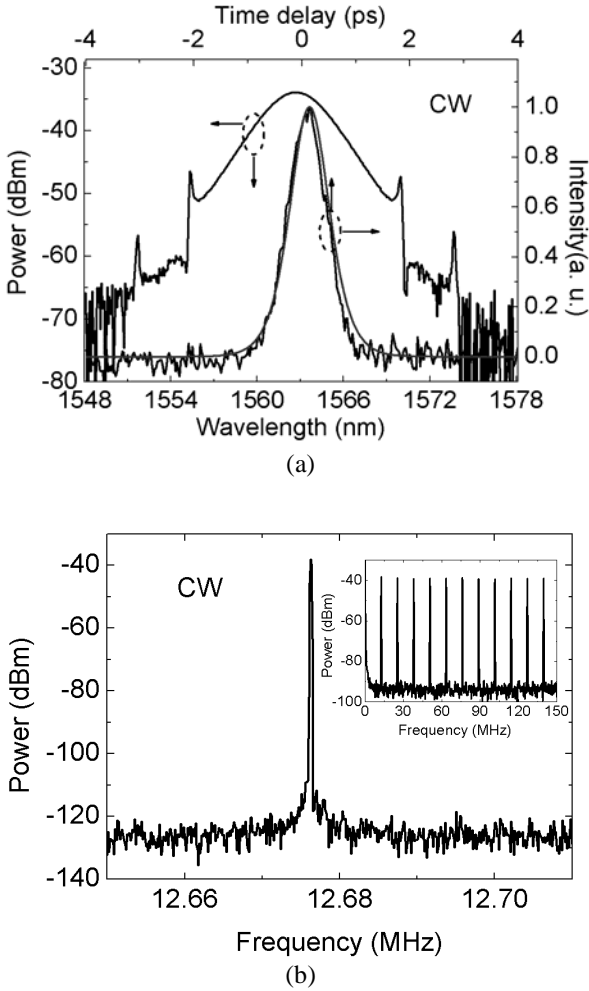


Fig. 2. (a) Output optical spectrum and autocorrelation trace of the CNT-based bidirectional pulsed laser in CW direction, and (b) the corresponding RF spectrum with the inset showing the RF spectrum in a wider frequency range.

By further changing the polarization state of PC-2 and tuning the pump power to 30.9 mW, the single-soliton generation in the CCW direction can be obtained. The corresponding output

power is measured to be 246 μW from the CCW direction with that of 0.4 μW from the CW direction. Fig. 3(a) shows the output optical spectrum from the CCW direction showing a center wavelength of 1562.08 nm and a 3-dB bandwidth of 5.4 nm. Kelly-sidebands are superimposed on the soliton spectrum. The pulse width is estimated to be 480 fs with a sech^2 fitting and the time-bandwidth product is calculated to be 0.319. Fig. 3(b) gives the corresponding RF spectrum of the laser output. An extinction ratio of 90 dB at the frequency of 16.46 MHz shows that the laser operates in fundamental cavity frequency. The RF spectrum in a wider frequency range is also given in the inset of Fig. 3(b). Once the laser is mode-locked, it shows considerable stable operations for hours. By further increasing pump power to 34 mW, multiple pulses are produced from the laser cavity.

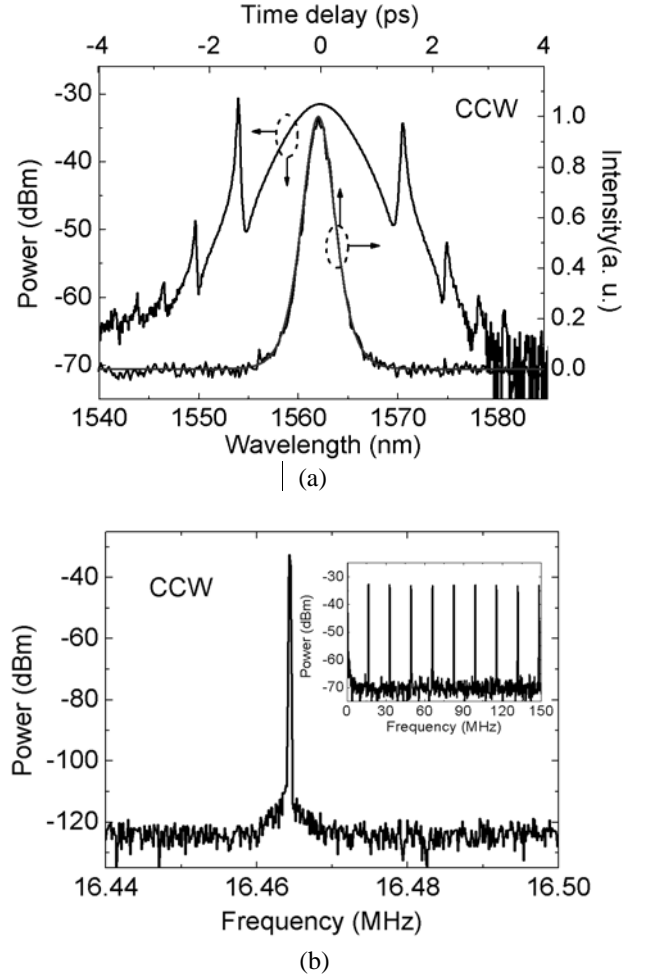


Fig. 3. (a) Output optical spectrum and autocorrelation trace of the CNT-based bidirectional pulsed laser in CCW direction, and (b) the corresponding RF spectrum with the inset showing the RF spectrum in a wider frequency range.

IV. BIDIRECTIONAL Q-SWITCHING OPERATION

When the output power from both CW and CCW directions are adjusted to have similar levels, the laser switches to operate

in bidirectional Q-switching state. Fig. 4(a) shows the output pulse trains of the laser with a pump power of 30.3 mW. It is found that the pulse trains from the two directions are synchronized and exhibit a common repetition rate of ~ 8 kHz. There is little amplitude modulation shown on the pulse envelopes in Fig. 4(a), illustrating that the effect of self-mode-locking on the Q-switching operation is suppressed [19]. The duration of the Q-switched pulses in both directions is estimated to be 10 μ s. The corresponding output powers are measured to be 149.6 μ W and 186.6 μ W in CW direction and CCW direction, respectively. Thus, the pulse energies are calculated to be 18.7 nJ and 23.3 nJ, respectively. It is worth mentioning that the obtained pulse energy is higher than current reports on the passively Q-switched fiber lasers which incorporate CNT-based thin-film SAs [19, 20]. For conventional ring-cavity fiber lasers that operate in Q-switching and prohibit from broadband mode-locking, the cavity configurations need SAs as well as narrowband filters such as fiber Bragg grating which might sacrifice pulse energy. In our experiment, a relatively high energy bidirectional Q-switched ring-cavity fiber laser is achieved with a

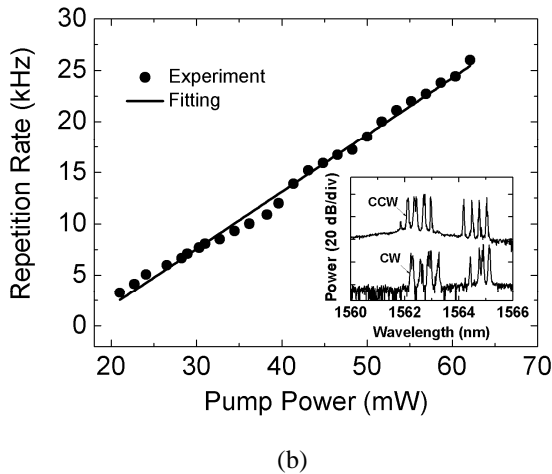
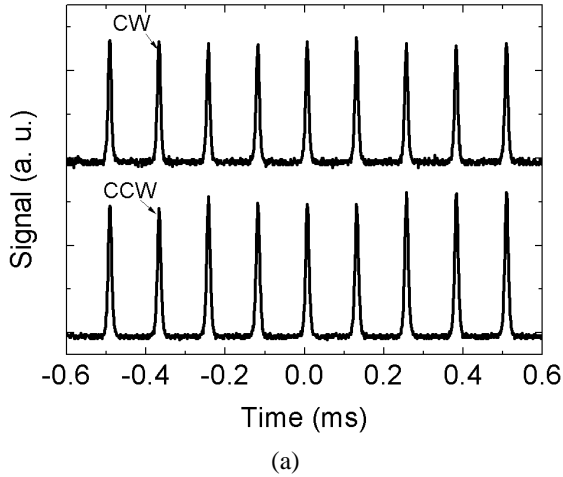


Fig. 4. (a) Output of CW direction (upper) and CCW direction (lower) of the bidirectional Q-switched pulse trains with synchronized repetition rate, and (b) plot of the synchronized repetition rate against pump power; the inset shows the offset optical spectra of Q-switched pulse trains in CW direction and CCW direction.

CNT-based SA with no lasing mode selector. The optical spectra of Q-switched pulse trains in CW direction and CCW direction under pump power of 30.3 mW are measured simultaneously as in the inset of Fig. 4(b). Different from the unidirectional mode-locked laser with large spectral bandwidth, multi-wavelength emission with narrow spectral bandwidth is observed for bi-directional Q-switched lasers. It is found that the emitted wavelengths in CW direction are mostly suppressed in CCW direction and vice versa, which reveals that the gain competition (or mode competition) could take place in the opposite directions. The synchronized repetition rate is linearly proportional to pump power as shown in Fig. 4(b). When the pump power is ~ 60 mW, the repetition rate is raised to ~ 25.8 KHz.

V. DISCUSSION

The investigation on the tunable operation states of the developed bidirectional fiber laser is further performed by adjusting polarization state of PC-2. Fig. 5 plots the power-splitting ratio of the CCW direction against the total output power of both directions. It is found that the power-splitting ratio keeps nearly constant as the total power increases by increasing the pump power. When the power-splitting ratio is greater than 80%, the laser falls in CCW directional mode-locking. When the power-splitting ratio is less than 20% the laser operates in CW directional mode-locking. Once mode-locking is achieved in one direction, light circulating in the opposite direction is strongly suppressed although there is no obvious isolator embedded in the laser cavity. Such unidirectional mode-locking with high suppression of the power-splitting ratio in the opposite direction could be explained by gain competition when the emitted light dominates in one direction. By tuning the power-splitting ratio in the range of 20%-80%, the laser only

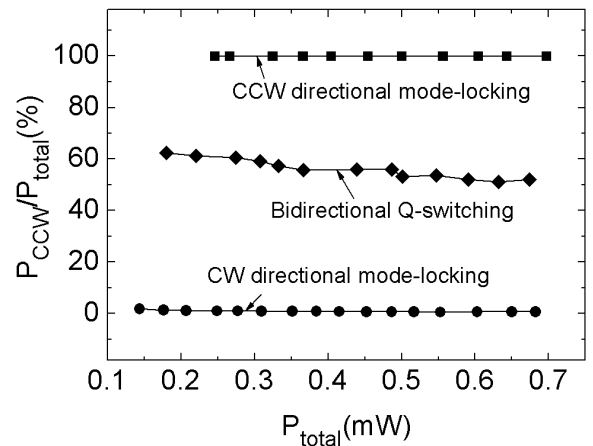


Fig. 5. Plot of power-splitting ratio against total output power of the fiber laser with different operation states.

produces bidirectional Q-switched pulse trains with synchronized repetition rate even though under high pump power. The laser operating in Q-switching rather than mode-locking is believed to be a result of the mutual saturation of the thin-film CNT-based SA by incident light beam in the opposite directions. Since the SA has low absorption at high incident power, the loss experienced by two pulses passing through the SA simultaneously is less than that of passing through the SA separately. As a Q-switched pulse has typical pulse duration of $\sim\mu\text{s}$ which is much shorter than the cavity round-trip time of $\sim\text{ns}$, the SA is occupied before it is hit by the pulse from the opposite direction. Such bidirectional pulses saturate SA simultaneously could result in high transmission of SAs. The laser tends to operate in state of bidirectional Q-switching due to the less intra-cavity loss. In order to achieve simultaneously mode-locking from both output ports, either a CNT-deposited tapered fiber with a long CNT-light interaction length or two active modulators have been previously reported for deferring the mutual saturation of SA in the bidirectional fiber lasers [7, 8]. In our experiment, the simultaneously mode-locking from both output ports can be obtained when CNTs are deposited on the two highly reflected mirrors for functioning as two individually reflective CNT-based SAs. When we remove the CNT-based SAs from the bidirectional fiber laser cavity, no matter how the polarization states of PCs is adjusted, only continuous wave is emitted from the two output ports within the pump power of 100 mW. Although the effective polarization together with two PCs could act as an artificial SA via the effect of nonlinear polarization evolution, the self-started mode-locking of the laser through fiber nonlinearity is hardly achieved under the relatively low pump power [21, 22]. Since the concrete SAs play important roles in influencing the operation regime of bidirectional pulsed lasers, future work on the investigation of the fiber laser incorporating a common CNT-based SA with various CNT-light interaction lengths is suggested.

VI. CONCLUSION

In summary, we demonstrate an operation-switchable bidirectional ring-cavity fiber laser incorporating a carbon-nanotube-based saturable absorber and a polarization-dependent four-port circulator. By adjusting the intra-cavity polarization state, pulse trains from the opposite directions with different features are enabled from the common laser cavity. The laser can operate among states of both passive mode-locking and Q-switching. Mode-locking in the CW direction is achieved under pump power of 26.7 mW and the laser outputs pulses with a pulse width of 600 fs and a repetition rate of 12.68 MHz. While the mode-locked laser in the CCW direction generates pulses with a pulse width of 480 fs and a repetition rate of 16.46 MHz under pump power of 30.9 mW. Although no isolator is inserted into the laser cavity, the unidirectional mode-locking can be obtained with high suppression of the power-splitting ratio on the light circulating in the opposite direction. By carefully adjusting the

power-splitting ratio in the two circulating directions, the laser can operate in the state of bidirectional Q-switching. Output pulses with energy of 18.7 nJ in the CW direction and that of 23.3 nJ in the CCW direction are found synchronized at a repetition rate of 8 kHz. Such synchronized repetition rate is linearly proportional to pump power. The results show a multi-functional pulsed fiber laser with selectable output pulse train.

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