Pulse width shaping of passively mode-locked soliton fiber laser via polarization control in carbon nanotube saturable absorber

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Abstract: We report the continuous control of the pulse width of a passively mode-locked fiber laser via polarization state adjustment in a single-walled carbon nanotube saturable absorber (SWCNT-SA). The SWCNT, coated on the side-polished fiber, was fabricated with optimized conditions and used for stable mode-locking of the fiber laser without Q-switching instabilities for any polarization state of the laser intra-cavity. The 3-dB spectral bandwidth of the mode-locked pulses can be continuously tuned from 1.8 nm to 8.5 nm with the polarization control for a given laser cavity length and applied pump power. A pulse duration varying from 470 fs to 1.6 ps was also observed with a change in the spectral bandwidth. The linear and the nonlinear transmission properties of the SA were analyzed, and found to exhibit different modulation depths depending on the input polarization state in the SA. The largest modulation depth of the SA was observed at the polarization state of the transverse electric mode that delivers shortest pulses at the laser output.

OCIS codes: (060.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (160.4330) Nonlinear optical materials.

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1. Introduction

Passively mode-locked fiber lasers generating ultra-short optical pulses have received considerable attention because of their advantages such as excellent spatial beam profile, cost-effectiveness, alignment-free structure and compact design over bulk solid-state pulse lasers. These lasers are now finding application in diverse fields including precise optical measurement, bio-medical study, and optical communications [1, 2]. In a passively mode-locked laser, saturable absorbers (SAs) exhibiting ultrafast nonlinear optical responses to the intensity of incident pulse are popularly employed to create favorable conditions for pulse operation rather than continuous-wave (cw) lasing [3]. Although passive mode-locking can be realized through artificial means such as nonlinear polarization evolution (NPE) [4], a saturable absorption element such as a semiconductor saturable absorber mirror (SESAM) [5] is preferably used in self-starting and environmentally robust operations in commercial fiber lasers.

In recent years, novel SAs based on low-dimensional carbon materials including a single-walled carbon nanotube (SWCNT) and graphene have been extensively studied as an alternative to the widespread SESAM [6–9]. Considering their fast recovery time (around 1 ps), broadband operation range covering near IR to mid-IR, ease of integration into optical systems, and a relatively simple fabrication process compared to the SESAM, which requires a complicated epitaxial process, these SAs have been successfully applied both in ultrafast bulk solid-state and fiber laser systems in various spectral ranges [6–11].

A majority of the proposed SWCNT or graphene SAs in fiber lasers adopted a carbon nano-material coated with a fiber connector. In spite of its simplicity, such direct interaction scheme potentially possesses several drawbacks. For example, the fiber-connector-type SA can cause mechanical damage during the process of fiber connection through physical touch. This scheme can also be vulnerable to optically induced thermal damage to the SA when the fiber laser operates at a high power. In addition, parasitic reflection between the optical connectors in the laser cavity might disturb the mode-locked operation. In order to overcome these issues, lateral interaction using an evanescent wave of the guided mode has been suggested on the basis of several platforms including side-polished fibers [12–14], tapered fibers [15], and ring-core fibers [16,17]. The SA based on a side-polished fiber, which is compatible with a standard fiber, has been successfully integrated into the all-fiber ultrafast laser system to scale up the pulse energy of ultrafast fiber lasers [13,18], even though it has a

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moderate nonlinear interaction length and polarization sensitivity compared to other approaches.

In the present work, we demonstrate the pulse duration control of an all-fiber Er-doped soliton laser via polarization adjustment in an SWCNT-SA using the side-polished fiber. The SWCNT-SA, which exhibits polarization dependent transmission in a moderate range, is fabricated through the optimized spin coating process of the SWCNT/polymer composite. Here, we intentionally use the polarization dependent behavior of the fabricated SA to tune the laser output properties. The pulsed fiber laser was built including the fabricated SA, which maintains a cw mode-locking state for any polarization state of the intra-cavity without Q-switching instability. The 3-dB optical bandwidth of the soliton mode-locked pulses can be controlled from 1.8 nm to 8.5 nm by adjusting the polarization state at a fixed pump power of 112 mW. The corresponding variation of the pulse width was measured to be from 1.6 ps to 470 fs for a given laser cavity at a fixed repetition rate of 48.96 MHz. The nonlinear transmission characteristics of the side-polished fiber type SWCNT-SA, which exhibits different modulation depths with various input polarization states, have also been investigated for the first time.

2. Fabrication of the SWCNT-SA and the fiber laser

We prepared the SWCNT/polymer composite using the commercial SWCNTs synthesized through the high-pressure CO conversion (HiPCO) method. The SWCNT powder was dispersed via ultrasonic agitation and mixed with poly(methyl methacrylate) (PMMA) solution [7]. The linear transmission of the SWCNT/polymer composite film measured using a spectrophotometer shows broadband absorption around 1550 nm, which corresponds to the E_{11} transition of semiconducting SWCNTs. The SWCNT/polymer composite was then coated onto the side-polished fiber, as shown in Fig. 1(a). The fabricated side-polished fiber using a standard single-mode fiber (SMF-28e®) initially has the polarization independent insertion loss of −0.1 dB without the SWCNT/polymer composite. We monitored the insertion loss and the polarization-dependent loss (PDL) of the sample as a function of the number of spin coating processes of the SWCNT/polymer composite to control the nonlinear interaction of the SWCNT with the propagating light [13]. The polarization- dependent transmission varies with an oscillatory behavior on increasing the number of spin coating processes, and we finally obtained a linear transmission of the sample ranging from −3.98 dB to −8.58 dB at 1550 nm. We experimentally verified that the transverse magnetic (TM)-mode, the polarization direction of which is normal to the lateral facet of side-polished fiber, has maximum transmission while the transverse electric (TE)-mode, orthogonal to the polarization direction of the TM mode, has minimum transmission.

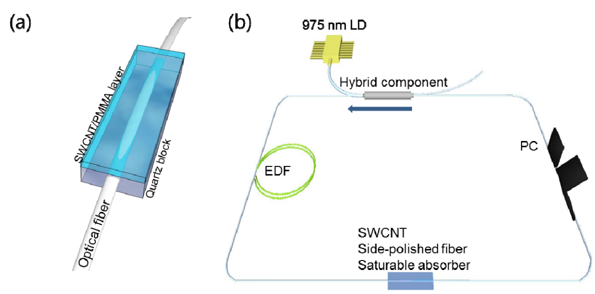

Fig. 1. (a) Schematic image of the SWCNT-SA using a side-polished fiber (b) Configuration of the constructed soliton fiber laser with the SWCNT-SA.

A passively mode-locked fiber laser was built by employing the fabricated SWCNT-SA, as depicted in Fig. 1(b). A highly Er-doped 1-m long fiber (EDF) was pumped using a 980 nm laser diode (LD) via the hybrid component comprised of a wavelength division multiplexing (WDM) coupler, an optical isolator and a directional coupler with 10% output coupling ratio. The polarization state of the intra-cavity is adjusted by a polarization controller (PC). Finally,

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we inserted the fabricated SA into the laser cavity. All optical components were connected by fusion splicing to prevent any parasitic reflection in the laser cavity. The total length of the laser cavity is estimated to be 4.23 m with a net cavity dispersion of −0.082 ps^2.

3. Laser experiment and discussions

The laser experiment was performed by simultaneously monitoring the optical spectrum, pulse duration, radio-frequency (RF) spectrum, and pulse train from the laser output. The self-started passive mode-locking of the fiber laser was observed from the applied pump power of 63 mW. Figure 2 shows the laser output characteristics at the applied pump power of 112 mW. A soliton pulse with a 3-dB spectral bandwidth of 5.75 nm was observed at a central wavelength of 1566 nm, as shown in Fig. 2(a). The inset of Fig. 2(a) shows a pulse duration of 520 fs measured using an intensity auto-correlator assuming $sech^2$-shaped pulse. The estimated time-bandwidth product (TBP) of 0.36 was slightly larger than that of the transform-limited one (0.315) because of the fiber extension of the laser output to the intensity auto-correlator. Figure 2(b) and its inset show the RF spectrum and the time trace of the oscilloscope, respectively. The repetition rate of the laser output was measured to be 48.96 MHz, which corresponds to a laser cavity length of 4.23 m. The background noise was suppressed by 79 dB from the fundamental repetition rate, as shown in Fig. 2(b), indicating a stable mode-locking state without Q-switching instability. In a fiber laser, a polarization sensitive SA can contribute to the mode-locking operation by the NPE, but we observed that mode-locking is well sustained against external perturbations, such as touching the fiber laser cavity, over a broad range of the applied pump power. Thus, we expect that saturable absorption of the SA plays a dominant role for self-starting and stabilizing the laser pulse.

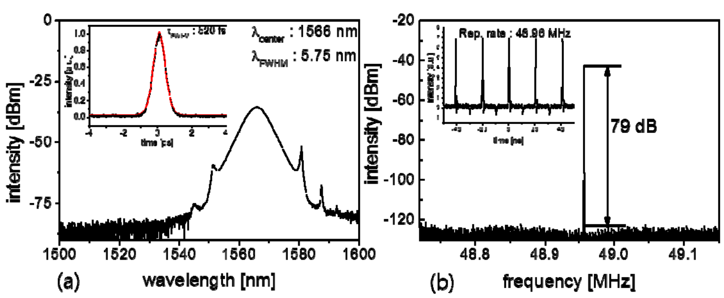

Fig. 2. Mode-locked soliton pulse laser using the SWCNT-SA (a) optical spectrum (inset: autocorrelation trace) (b) RF spectrum characteristics (inset: pulse train).

We subsequently investigated the output characteristics of the mode-locked laser as a function of the polarization state of the intra-cavity. Figure 3(a) shows the optical spectra of several mode-locked states obtained by adjusting the polarization state incident to the SA at the fixed pump power of 112 mW. We observed that the 3-dB spectral bandwidth of the laser output was continuously tunable from 1.8 nm to 8.5 nm while maintaining a fundamental repetition rate of 48.96 MHz. Figure 3(b) shows the corresponding pulse duration, which varies from 470 fs to 1.6 ps according to the polarization change. All the mode-locking states are maintained stably without Q-switching instability. The spectral bandwidth control in the mode-locked fiber using the SWCNT-SA has been reported through the concentration rate control of the SWCNT or the net cavity dispersion change of the fiber laser [19, 20]. In these previous works, several bandwidths of the optical spectrum could be obtained by using SAs fabricated under different conditions or by controlling the laser cavity length, whereas in the present work, we actively controlled the pulse duration only by adjusting the polarization for a given pump power and laser cavity length. Another set of experiments was performed with a pump power of 153 mW. We observed results similar to those of the experiment at 112 mW, though the tuning range of the spectral bandwidth was slightly smaller. The mode-locked fiber laser started to deliver multiple pulses at pump powers higher than 153 mW.

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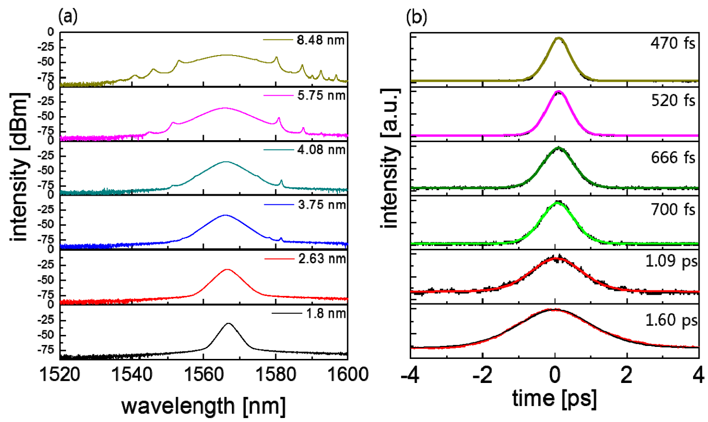

Fig. 3. Pulse width control of the passively mode-locked soliton laser by adjusting the polarization state of the laser intra-cavity at the applied pump power of 112 mW (a) optical spectra (b) pulse durations.

The optical power of the laser was measured at various pulse durations, and Fig. 4 summarizes the results as a function of the 3-dB spectral bandwidth. We observe that the average output power gently decreases as the spectral bandwidth increases at applied pump powers of both 112 mW and 153 mW. From the linear transmission measurement of the fabricated SA mentioned in the previous section, we expect that the laser generates the shortest pulse for the polarization direction of the TE mode and the longest pulse for that of the TM mode at the SA.

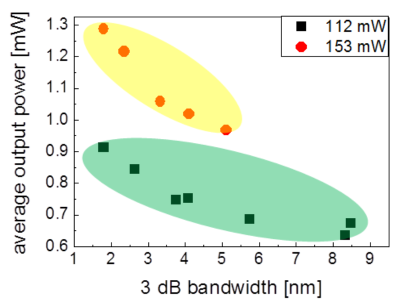

Fig. 4. Average output power of the mode-locked laser vs. 3-dB spectral bandwidth for applied pump powers of 112 mW (black square) and 153 mW (red circle).

We further investigated the SA properties by a nonlinear transmission measurement. A home-built mode-locked laser exhibiting 1 ps pulse duration was used for the measurement along with a variable attenuator and a photo detector as shown in the Fig. 5(a). The polarization state of the incident light to the SA was carefully aligned from the TM mode to the TE mode during the measurement. Figure 5(b)-5(c) shows the results of the nonlinear transmission of the SA for several input polarization states. The TE mode polarization exhibited an initial linear loss of approximately 14% and the transmission increased up to 24% with an increase of the input power, as shown in Fig. 5(b). However, it could not be fully saturated because of the limited incident power. When we changed the input polarization state, the initial loss of the SA increased to 24% and it reached 30% at the maximum power, as shown in the Fig. 5(c). Figure 5(d) shows the nonlinear transmission results when we moved the input polarization state to the TM mode, indicating a modulation depth of 4% with an initial loss of approximately 30.5%. The transmission curve at the TM mode polarization could not be obtained at present because of the limitation in the resolution of the current measurement system. A more precise measurement over the full range of the nonlinear

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transmission curve is in progress with a higher power laser source. The results in Fig. 5 show that the nonlinear change of the transmission in the SA has the largest value at the TE mode with a higher initial loss while the modulation depth reduce as the polarization state is closer to the TM mode. Thus we expect that the pulse duration change shown in Fig. 3, originates from the different pulsating ability of the SA for the different input polarization states. It is also instructive to compare the range of the polarization dependent transmission (–3.98 dB ~-8.58 dB) of the current SA with the range (–4.6 dB ~-19.9 dB) reported in [13]. Considering the insertion loss and the PDL, we expect that the modulation depth of the current SA will be smaller than that of the previous SA. Therefore, from the Q-switching instability conditions [21], we expect that the smaller modulation depth of our SA might enable stable cw mode-locking without instability over all polarization states of the intra-cavity, in contrast to previous works [13, 22].

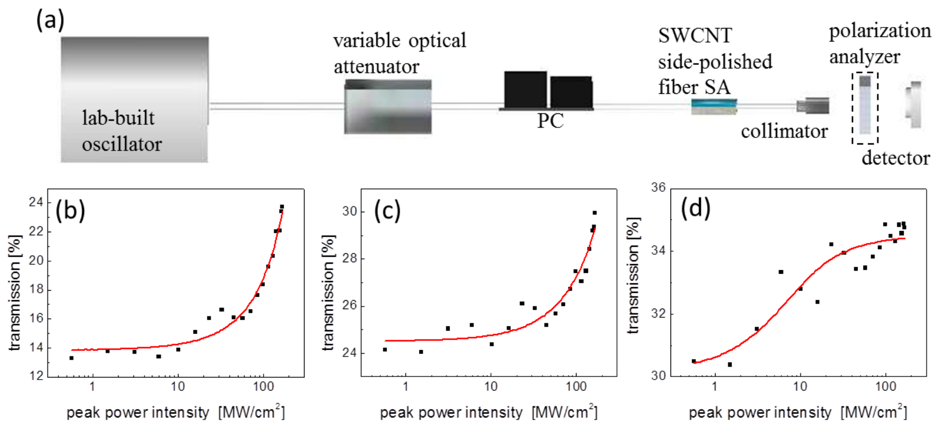

Fig. 5. (a) Experimental set-up for nonlinear transmission measurement of the SA and the results for several input polarization states from (b) the TE-mode (c) intermediate state and (d) close to the TM mode

4. Conclusion

We demonstrated the active control of the pulse duration in a mode-locked fiber laser including the side-polished fiber-based SWCNT-SA by adjusting the polarization of the laser intra-cavity. The SWCNT-SA, which possesses a polarization dependent transmission, was fabricated with optimized conditions to realize the stable mode-locking of the fiber laser without Q-switching instability for all polarization states of the intra-cavity. The spectral bandwidth of the fiber laser can be continuously tuned from 1.8 nm to 8.5 nm depending on the different polarization states of the laser cavity. The corresponding pulse duration varies from 1.6 ps to 470 fs at a fixed repetition rate of 48.96 MHz while maintaining the stable mode-locked operation. The nonlinear transmission measurement of the SA reveals that the polarization-dependent modulation depth of the SA enables the pulse width control in the mode-locked fiber laser. We believe that our pulse laser with controllable pulse duration can be versatile source for the applications both in fs and ps regime providing flexibility of the optical system.

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