Current Optics and Photonics
Vol. 1, No. 3, June 2017, pp. 203-206
ISSN: 2508-7266(Print) / ISSN: 2508-7274(Online)
DOI: https://doi.org/10.3807/COPP.2017.1.3.203

Passively Q-switched Erbium Doped All-fiber Laser with High Pulse Energy Based on Evanescent Field Interaction with Single-walled Carbon Nanotube Saturable Absorber

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(Received May 19, 2017 : revised June 2, 2017 : accepted June 2, 2017)

We report a passive Q-switching of an all-fiber erbium-doped fiber laser delivering high pulse energy by using a high quality single-walled carbon nanotube saturable absorber (SWCNT-SA). A side-polished fiber coated with the SWCNT is employed as an in-line SA for evanescent wave interaction between the incident light and the SWCNT. This lateral interaction scheme enables a stable Q-switched fiber laser that generates high pulse energy. The central wavelength of the Q-switched pulse laser was measured as 1560 nm. A repetition rate frequency of the Q-switched laser is controlled from 78 kHz to 190 kHz by adjusting the applied pump power from 124 mW to 790 mW. The variation of pulse energy from 51 nJ to 270 nJ is also observed as increasing the pump power. The pulse energy of 270 nJ achieved at maximum pump power is 3 times larger than those reported in Q-switched all-fiber lasers using a SWCNT-SA. The tunable behaviors in pulse duration, pulse repetition rate, and pulse energy as a function of pump power are reported, and are well matched with theoretical expectation.

Keywords : Fiber laser, Passive Q-switching, Nonlinear optic switch, Carbon nanotubes
OCIS codes : (060.3510) Lasers, fiber; (140.3540) Lasers, Q-switched; (160.4330) Nonlinear optical materials

I. INTRODUCTION

Q-switching operation of a laser is a powerful and simple technique to generate short pulses with high pulse energy. The Q-switched lasers are normally accomplished by periodic modulation of the cavity Q-factor via active or passive optical elements in the lasers [1-4]. When the laser cavity experiences high optical loss, the laser action is not allowed while accumulating the energy in the gain medium by a pump. If the cavity Q-factor rapidly increases, the laser action occurs delivering giant optical pulses with pulse duration ranging from microseconds (μs) to nanoseconds (ns). Q-switched lasers possessing pulses with high energy have been widely used in diverse fields including range finding at eye-safe wavelength, material processing, medical applications, and nonlinear optics studies [5-7].

Compared to the actively Q-switched lasers that need electronic components to modulate the cavity Q-factor, the passively Q-switched laser has a simpler configuration where the cavity Q-factor is automatically modulated by a saturable absorber (SA) [2, 3]. Recently low-dimensional carbon nanomaterials such as single walled-carbon nanotubes (SWCNTs) or graphene have drawn much attention as SAs for passive mode-locking or passive Q-switching [8-14] due to their distinguishing features such as fast nonlinear response time of ~ picosecond (ps), broadband operation range covering near IR to mid-IR, easy integration with optical systems, and relatively simple fabrication process compared to the wide-spread semiconductor saturable mirrors (SESAMs). To date, the SWCNT or graphene SAs are mostly realized by covering the fiber connector ferrule with these materials. Although such fiber connector-type SAs are relatively simple and easy to fabricate, they have shown mechanical or optical damage during laser operation due to direct interaction between the light and the carbon nanomaterials with limited nonlinear interaction length [15]. Thus the connector-type SAs are unsuitable for passively Q-switched lasers that deliver high energy pulses. In order to avoid

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damage issues, an indirect interaction scheme based on evanescent field interaction has been suggested [16-22]. Among them, an SA based on a side-polished fiber (SPF) platform is one of the common approaches for efficient evanescent field interaction with carbon nanomaterials, yielding several advantages such as long nonlinear interaction length, compatibility with a standard optical fiber, and structural robustness [18, 21, 22].

In the present work, we demonstrate stable passive Q-switching of the erbium-doped fiber laser by employing a SWCNT-SA on the SPF. High quality SWCNT/polymer composite is prepared and spin-coated on the SPF to realize an in-line SWCNT-SA operating at high power. We optimized the coating thickness by controlling the number of spin-coating processes while monitoring the optical properties of our in-line SA. We observed self-starting operation of Q-switching in an all-fiber laser where pulse repetition rate, pulse energy, and pulse duration could be controlled by changing the applied pump power. The maximum pulse energy of 270 nJ was obtained at the applied pump power of 790 mW, which is the highest value, to our knowledge, among Q-switched all-fiber laser oscillators based on SWCNT-SA.

II. FABRICATION OF SWCNT-SA

We prepared the SWCNT/polymer composite where the SWCNTs synthesized through the high-pressure CO conversion (HiPCO) method were dispersed via ultrasonic agitation and mixed with poly (methyl methacrylate) (PMMA) solution [9]. We observed that the fabricated composite showed broad absorption around 1550 nm, which corresponds to the E_{11} transition in semiconducting SWCNTs [17]. We also fabricated an SPF where the insertion loss of the device was -0.1 dB with negligible polarization-dependent loss (PDL) before SWCNT/polymer composite coating. Dispersed SWCNT/polymer composite was then spin-coated on the fabricated SPF. Figure 1(a) shows a structure of the fabricated SWCNT-SA on the SPF. The concentration of SWCNT and the number of spin-coating conditions were optimized to achieve stable Q-switched pulse laser operation. An optical microscopic image of the SA at the interaction region is shown in Fig. 1(b), indicating that the SWCNT composite was uniformly coated on the SPF without significant defects near the core. The fabricated device has polarization dependent transmission ranging from -1.71 dB to -4.26 dB. Thus the PDL of the device was estimated to be 2.55 dB with insertion loss of -1.71 dB.

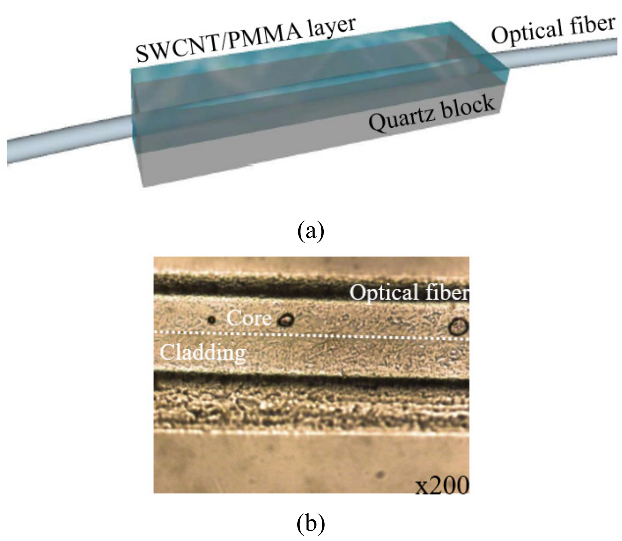


FIG. 1. (a) Schematic structure and (b) optical microscopic image of interaction region of the SWCNT-SA on the SPF.

III. LASER EXPERIMENT AND DICUSSION

A passively Q-switched pulse all-fiber laser was built by employing our in-line SWCNT-SA, whose schematic diagram is shown in Fig. 2. Highly erbium doped fiber (peak absorption 150 dB/m at 1530 m, dispersion -48 ps/nm/km) with a length of 0.7 m was used as a gain medium and pumped by a 980-nm laser diode (LD) via a wavelength division multiplexing (WDM) coupler. The cavity includes a directional coupler with 50% output coupling ratio and an optical isolator. A polarization controller (PC) was also included to control the polarization states of intracavity. The fabricated SWCNT-SA was inserted between the PC and the isolator. We observed continuous wave operation at low pump power level, but when the pump power increases to 124 mW, the laser operation transits to Q-switched mode.

Figure 3 shows the output properties of our Q-switched laser. The laser operates at a central wavelength of 1560 nm as shown in Fig. 3(a). The repetition rate of the Q-switched laser measured at the applied pump power of 559 mW is 163 kHz, which is shown in the inset of Fig. 3(a). The side-mode suppression ratio (SMSR) in radio frequency spectrum was -47 dB, which indicates stable operation of the Q-switched laser. A repetition rate of the

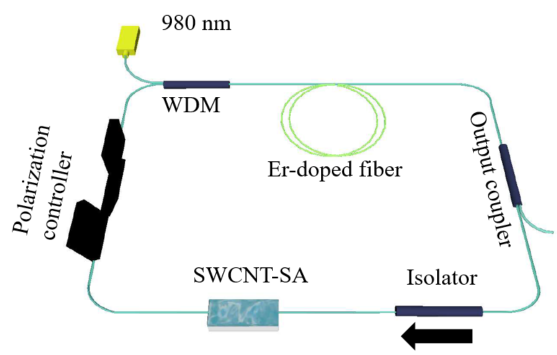
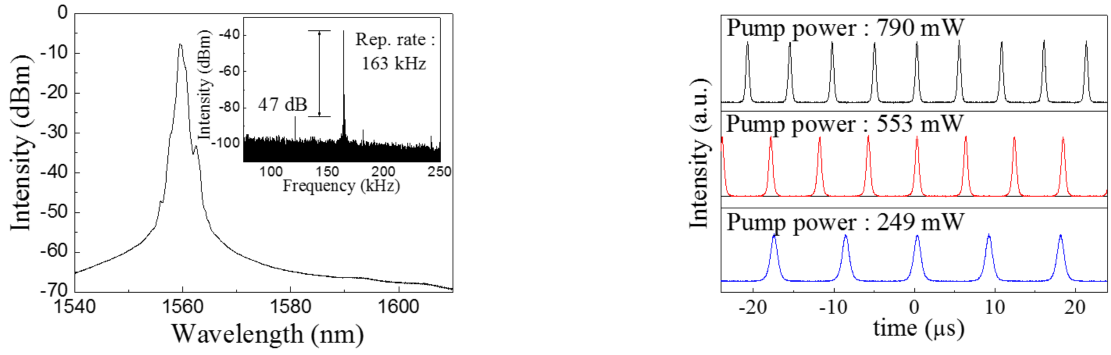
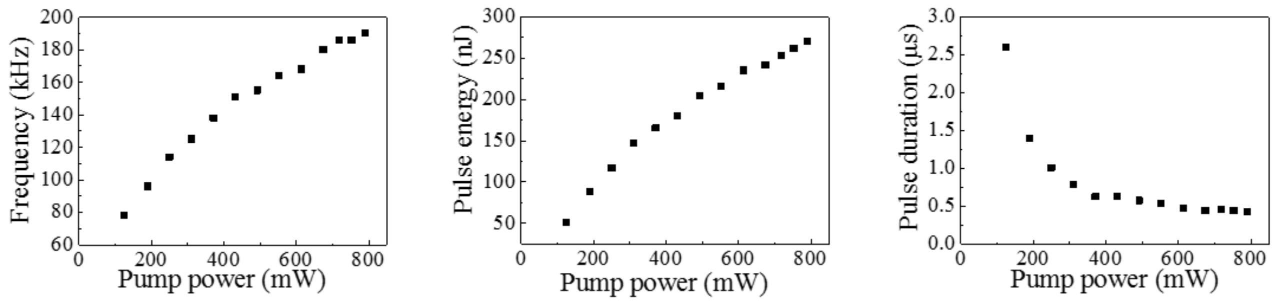


FIG. 2. The configuration of Q-switched all-fiber pulse laser with the SWCNT-SA



(a) (b)

FIG. 3. Output properties of the fabricated Q-switched laser (a) optical spectrum (inset: radio frequency spectrum of pulse train), and (b) pulse trains for three different pump powers.



(a) (b) (c)

FIG. 4. Output properties of the fabricated Q-switched laser (a) optical spectrum (inset: radio frequency spectrum of pulse train), and (b) pulse trains for three different pump powers.

Q-switched laser can be tuned by adjusting the applied pump power. Figure 3(b) exemplifies the tunable behavior of the repetition rate in the laser output for several applied pump powers. An increase of the period of the pulse train was clearly observed as the pump power was decreased from 790 mW to 249 mW.

Figure 4 summarizes the laser output properties that depend on the pump power level. The repetition rate of the Q-switching pulse varies from 78 kHz to 190 kHz as we increase the pump power from 124 mW to 790 mW as shown in Fig 4(a). The pulse energy also increases from 51 nJ to 270 nJ for the same pump power range. The tunable behavior both in repetition rate frequency and pulse energy agrees well with that of theoretical expectation [2, 3]. Figure 4(c) shows the relationship between the pulse duration and the pump power. The pulse duration related to the cavity lifetime is inversely proportional to the pump power. It decreases from 2.57 μs to 0.42 μs as predicted by theory [23]. It should be noted that the pulse energy of 270 nJ we achieved in this work is 3 times larger than those reported among similar lasers using SWCNT-SA [12-14]. We believe that such improved laser properties originate from our high quality SA exhibiting low scattering loss, high optical damage threshold and large modulation depth.

IV. SUMMARY

In conclusion, we report a Q-switched erbium-doped all-fiber laser based on SWCNT-SA on the SPF. Self-starting and stable Q-switching operation are observed above the threshold pump power of 124 mW. The repetition rate is changed from 78 kHz to 190 kHz as the pump power increases from 124 mW to 790 mW, meanwhile the pulse duration decreases from 2.57 μs to 0.42 μs. The maximum pulse energy we achieved is 270 nJ, which is 3 times greater than the previous record of Q-switched Er-doped all-fiber laser using a SWCNT-SA. We believed that the pulse energy can be increased up to tens of μJ level in an all-fiber laser configuration by using a double clad gain fiber combined with high power multimode LDs and by further optimizing the SWCNT-SA. We expect that our laser can be applied as a potential source to various fields including medical applications, range finding and detection, and soft-material laser machining.

ACKNOWLEDGMENT

This work was supported by "Human Resources Program in Energy Technology" of the Korea Institute of Energy

Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 20164030201380), and by the GRRC program of Gyeonggi province. (GRRC-Ajou 2016B01, Photonics-Medical Convergence Technology Research Center)

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