Single-Walled Carbon Nanotubes for High-Energy Optical Pulse Formation

Yong-Won Song
Center for Energy Materials Research, Korea Institute of Science and Technology, Seoul 136-791, Korea
E-mail: *ysong@kist.re.kr*
Shinji Yamashita
Department of Electronic Engineering, University of Tokyo, Tokyo 113-8656, Japan
Shigeo Maruyama
Department of Mechanical Engineering, University of Tokyo, Tokyo 113-8656, Japan

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Abstract: We passively generate picosecond 6.5-nJ optical pulses directly from a single-stage oscillator using carbon nanotube mode locker. The mode locker immunized to the high optical power induced damage employs the evanescent field interaction of propagating light with the nanotubes. The mode locker endures the intracavity power of up to 27.7 dBm. For the enhanced interaction, vertically aligned nanotubes are synthesized and applied. The output pulses are monitored for 200 hours to find that there is no significant degradation of average power and spectral width.

Key words : Carbon nanotube, saturable absorption, mode-locked laser, high-energy pulse, aligned nanotube, evanescent field interaction, fiber ring laser

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Authors: Yong-Won Song, Shinji Yamashita, Shigeo Maruyama
Affiliations: Korea Institute of Science and Technology, University of Tokyo

Fiber mode-locked lasers have replaced bulk solid state lasers in many research/industrial fields that need high quality optical pulses with their remarkable advantages including simple structure, outstanding pulse quality, and efficient operation [1]. Especially, the high power fiber lasers have attracted wide attention with their extensive applications [2,3]. In most cases, the high power pulse generation employs master-oscillator-power-amplifier (MOPA) structure in which the weak-powered output from the master laser is stretched, amplified and compressed to avoid the fiber nonlinearities during the amplification [3]. So far, the MOPA scheme has boosted up the power level of the femtosecond pulse output up to 400 mW at 1550 nm [4]. However, the multistage pulse formation scheme introduces additional complexity and noise to the system in addition to the low power efficiency. The drawbacks can be avoided provided that a passive mode locker that can keep the mode locking operation under the significant intracavity power is employed directly in the master oscillator. Unfortunately, most commonly used passive mode locker, SESAM cannot endure such a high intracavity power for the high-energy pulse formation [5]. Although other all-fiber mode locking schemes support the high power operation, they cannot guarantee the stability of the pulse formation [6]. Quite recently, the mode lockers incorporating single-walled carbon nanotubes (SWNTs) have motivated the researches on the efficient pulse formation [1,7]. However, the SWNT mode lockers also suffer from the optical power-induced thermal damage such that the SWNTs are burned out with the optical power of less than 30 mW. Therefore, in order to keep the SWNT mode lockers operating for more efficient and robust pulse formation in the high-energy regime, a developed scheme of saturable absorption by the SWNTs should be introduced. So far, using the conventional SWNT mode locker without any post amplifier, the maximum pulse energy demonstrated is 2.5 nJ [8].

In this work, we realize a single stage of high-energy pulse generation without any additional amplification using SWNT mode-locker that has the dramatically improved optical damage threshold. The operation is based on the evanescent field interaction of the propagating light with SWNTs [9]. In the scheme, since only a part of the optical power of the propagating mode interacts with SWNTs for the mode locking, higher intracavity power can be introduced for higher energy pulse formation. For both improved operation efficiency and the preparation process, the nanotubes are prepared to form a vertically aligned SWNT (VA-SWNT) film [10]. Resultant pulsed output has the pulse energy of 6.5 nJ, the repetition rate of 38.9 MHz, the pulse width of 1.02 ps, and the average power of 250 mW. The output pulses are also monitored for over 200 hours to find that there is no significant degradation of the average power as well as in the output optical spectra.

For conventional SWNT mode lockers, the SWNTs are sprayed on an intracavity component in order for the interaction with the propagating mode that penetrates the SWNT layer. Because the high intracavity optical power induces the thermal damage of the nanotubes in the scheme, high-energy pulse formation is restricted (see Fig. 1(a)). To manage higher intracavity power, as can be seen in Fig. 1(b), we introduce a new scheme in which only a part of the optical power of the mode interacts with the SWNTs along the relatively long interaction length to give the loss modulation into the laser cavity. For all-fiber, non-blocking operation of the mode locker, a D-shaped fiber is employed as a substrate for the nanotube deposition. In case a part of the cladding of the single mode fiber (SMF) is removed, the propagating mode can be broadened due to the reduced effective refractive index to interact with any material system surrounding the fiber. In our scheme, the evanescent field broadened by the D-shaping interacts with the SWNTs to give the passive mode locking [11]. Here, % power of the propagating mode that interacts with the SWNTs can be controlled by adjusting the distance to the flat surface from the fiber center of D-shaped fiber.

For an efficient mode locking operation of the SWNTs, the nanotube alignment is managed. When polarized light interacts with SWNTs, only the parallel polarization component of the light with respect to the nanotubes can be absorbed by π-plasmon excitation [12]. Couple of years ago, this selective interaction of the nanotubes with the polarized light was well described with an evaluation methodology [13]. Motivated by the theoretical analysis, the VA-SWNT film that can be transferred to an arbitrary substrate using only a hot water thanks to the hydrophobic property of the film is prepared and employed. Unlike the sprayed SWNTs whose direction is 2-dimensionally randomized on the substrate, the almost all aligned nanotubes within the field can interact with the vertically polarized mode, thereby achieve the improved interaction efficiency. The preparation process of the VA-SWNT film is described in the reference [12]. Note that tapered fibers also provide the mode broadening, however, the tapered waist with the diameter around 6 μm cannot guarantee the durability against the high power operation accompanied by thermal shock onto the waist [7]. The prepared device is shown in Fig. 2. The cross section of the D-shaped fiber along with the attached carpet-like VA-SWNT film can be clearly seen in Fig. 2(a). The individual aligned nanotubes can be verified by the magnified SEM photo in Fig. 2(b). With the morphological investigation, we find that the transferring the film onto the D-shaped fiber does not introduce any significant distortion or defect in the film and on the nanotube/fiber interface.

The high-energy pulse formation attributes to both VA-SWNT film and the evanescent field-nanotube interaction scheme combined with the optimization of laser cavity condition. As depicted in Fig. 3, the laser cavity has a high power erbium-doped fiber amplifier (HP-EDFA) as the intracavity gain medium. The amplifier is dual pumped. In order to manage the anomalous dispersion that combines with the intracavity nonlinearity to form soliton pulses, 15 m of SMF is added. An isolator in the amplifier ensures the unidirectional operation. In order to maximize the output power, a 70/30 fiber coupler is employed. The isolator located at the output port filters out the deleterious reflection back from the end facet of the port. The length of the output port is 5 m. The polarization controller (PC) optimizes the round trip polarization state in the cavity. The mode locker is pig-tailed and packaged to keep away from any contamination or physical damage.

As a result, the stable and uniform picosecond pulses are realized from a sing-stage oscillator by the SWNTs. Fig. 4(a) shows the optical spectrum of the pulsed output illustrating that the center wavelength is 1563 nm, and the full width at half maximum (FWHM) is 2.6 nm. The pulse train of the laser output depicted in Fig. 4(b) verifies the pulse formation showing the repetition rate of 38.9 MHz. The autocorrelation trace in Fig. 4(c) illustrates the pulse width of

1.02 ps. Considering the average power of the output, 250 mW, the pulse energy and the pulse peak power can be calculated to 6.5 nJ and 5.6 kW, respectively. To our knowledge, the pulse energy achieved is the highest one realized by the SWNTs. We have tried to form higher energy pulses with longer cavity length, however, excessive pulse energy gives the pulse breaking that causes multiple irregular pulses with lower peak powers. Additionally, non-optimized condition of longer cavity induces increased temporal pulse width, thereby decreased pulse peak power.

So far, only a work has addressed the long-term stability of the SWNT mode locker prepared with a polymer matrix [14]. However, unfortunately, the degradation of nanotube functionality has been found after the 100 hour operation in this case. In order to make sure the long-term stability of our pulse formation scheme, we test the laser operation and monitor the output for 200 hours. As described in Fig. 5, there is the consistency in terms of the FWHM of output pulses and the average output power with the fluctuations of ±0.2 nm and ±0.03 dBm, respectively. Since the demonstrated fiber laser does not employ a polarization maintained (PM) cavity, the environmental fluctuation may cause the drift of the pulse properties. However, the principal mode locking operation as well as the morphology of the SWNTs is not degraded. Note that, in addition to the evanescent field interaction, there are more points in our scheme that give the immunization against the thermal damage. Unlike the conventionally sprayed SWNTs, the VA-SWNT film doesn’t include any combustible residue from solvent, therefore the heat damage threshold can be improved. Moreover, it is considered that good heat dissipation through the densified CNTs in the VA-SWNT film helps the high power operation without any significant thermal damage.

In this work, our scheme highlights that the SWNT mode locker can deal with the high intracavity power up to 590 mW with which the conventional SWNT devices are certainly damaged. We expect to introduce higher intracavity power by adjusting the distance between the VA-SWNT film and the fiber core, as well as by re-optimizing the ring laser cavity condition.

References

[1] S. Y. Set, H. Yaguchi, Y. Tanaka, M. Joblonski, J. on Select. Top. in Quantum Electron., **10**, 137 (2004).

[2] Y. Jeong, J. Nilsson, J. K. Sahu, P. Dupriez, C. A. Codemard, D. B. S. Soh, C. Farrell, J. Kim, D. J. Richardson, D. N. Payne, CLEO/Pacific Rim, Paper CWI4-1 (2005).

[3] P. Dupriez, A. Piper, A. Malinowski, J. K. Sahu, M. Ibsen, B. C. Thomsen, Y. Jeong, L. M. B. Hickey, M. N. Zervas, J. Nilsson, D. J. Richardson, IEEE Photon. Technol. Lett., **18**, 1013 (2006).

[4] J. W. Nicholson, A. D. Yablon, P. S. Westbrook, K. S. Feder, M. F. Yan, Optics Express, **12**, 3025 (2004).

[5] D. J. Farrell, M. J. Damzen, Optics Express, **15**, 4781 (2007).

[6] J. Limpert, F. Roser, T. Schreiber, A. Tunnermann, IEEE J. Select. Top. Quantum Electron., **12**, 233 (2006)

[7] Y. W. Song, K. Morimune, S. Y. Set, S. Yamashita, Appl. Phys. Lett., **90**, 021101 (2007).

[8] K. H. Fong, S. Y. Kim, K. Kikuchi, H. Yaguchi, S. Y. Set, Optical Amplifiers and Their Applications (OAA), paper OMD4, Whistler, BC, Canada (2006).

[9] Y. W. Song, S. Yamashita, C. S. Goh, S. Y. Set, Opt. Lett., **32**, 148 (2007).

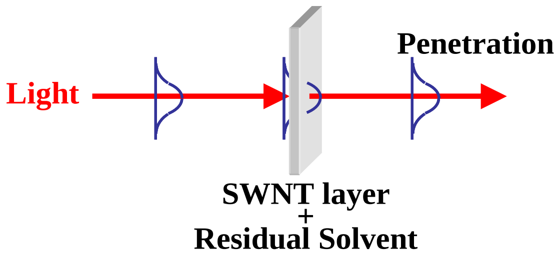
[10] Y. W. Song, S. Yamashita, E. Einarsson, S. Maruyama, Optics Lett., **32**, 1399 (2007).

[11] S. T. Huntington, K. A. Nugent, A. Roberts, P. Mulvaney, K. M. Lo, J. Appl. Phys., **82**, 510 (1997).

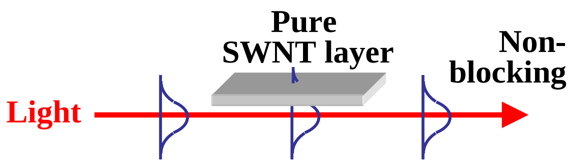
[12] Y. Murakami, E. Einarsson, T. Edamura, S. Maruyama, Phys. Rev. Lett., **94**, 087402 (2005).

[13] Y. Murakami, E. Einarsson, T. Edamura, S. Maruyama, Carbon, **43**, 2664 (2005).

[14] T. R. Schibli, K. Minoshima, H. Kataura, E. Itoga, N. Minami, S. Kazaoui, K. Miyashita, M. Tokumoto, Y. Sakakibara, Opt. Exp., **13**, 8025 (2005).

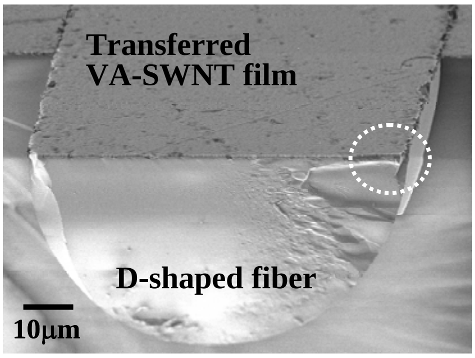


(a)



(b)

Fig. 1. Interaction schemes of the propagating light and nanotubes layers. (a) direct interaction, and (b) evanescent field interaction.



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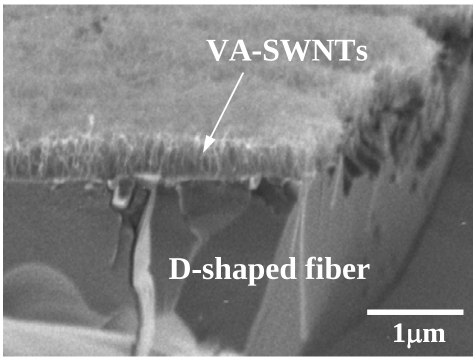


(b)

Fig. 2. SEM photos of the SWNT-based all-fiber mode locking device. (a) Cross section of the mode locker. The VA-SWNT film is transferred onto the flat surface of the D-shaped fiber. (b) Magnified photo of the circled area in (a). Individual VA-SWNTs without any significant distortion or defect after the transfer are verified.

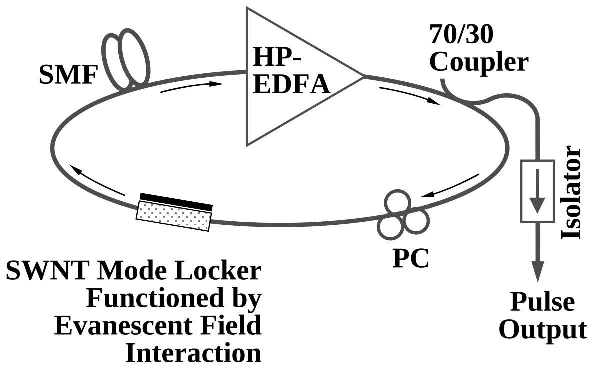
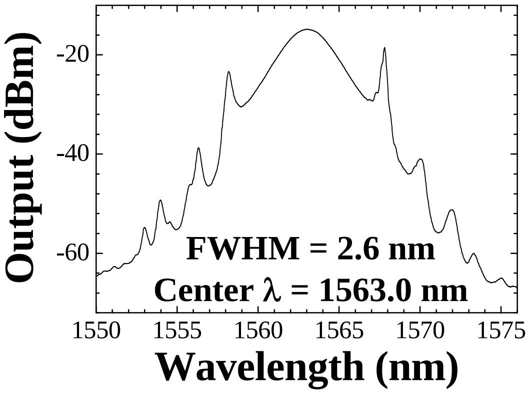
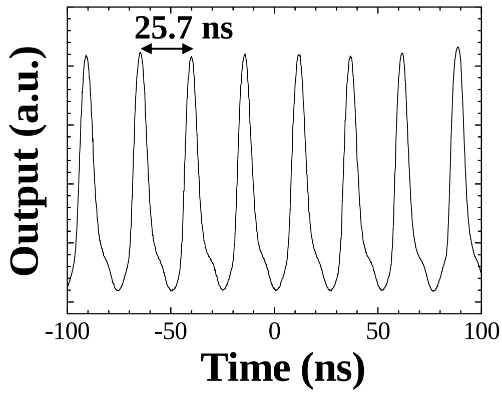


Fig. 3. Structure of our mode-locked laser.



(a)



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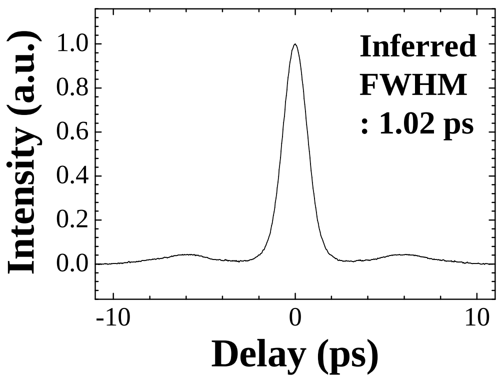

(c)

Fig. 4. (a) Optical spectrum of the laser output, and (b) output pulse train. The spectral FWHM is 2.6 nm, and the repetition rate is 38.9 MHz. (c) Autocorrelation trace of the pulse. The inferred temporal pulse width is 1.02 ps.

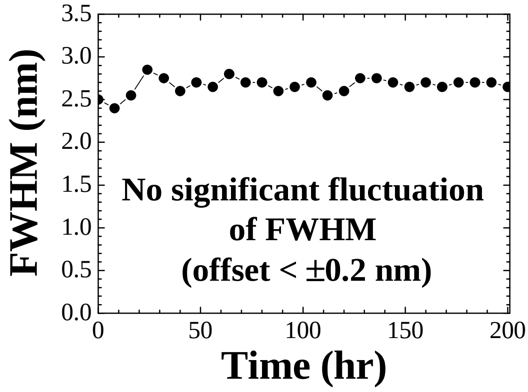

Fig. 5. Long-term operation of the pulsed laser. The fluctuation of the FWHM is negligible. Average power is also not degraded showing the negligible fluctuation of ±0.03 dBm.