Carbon Nanotube Mode Lockers for High-Energy Pulsed Lasers

Yong-Won Song [1,2], Sze Y. Set [3], Shinji Yamashita [1], and Shigeo Maruyama [4]

[1] Department of Electronic Engineering, University of Tokyo, Tokyo 113-8656, Japan
[2] Korea Institute of Science and Technology (KIST), Seoul 136-791, Korea
[3] Alnair Labs Corporation, Tokyo 154-0005, Japan
[4] Department of Mechanical Engineering, University of Tokyo, Tokyo 113-8656, Japan
E-mail: ywsong@sagnac.t.u-tokyo.ac.jp

Normally, 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 (1). However, the multi-stage pulse formation scheme introduces additional complexity and noise to the system. The complexity can be reduced 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. Quite recently, the mode lockers incorporating single-walled carbon nanotubes (SWNTs) have motivated the researches on the efficient pulse formation. However, the SWNT mode lockers 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 with efficient and robust pulse formation in the high-energy regime, a developed scheme of the 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 (2). 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 (3). Unlike the conventional scheme (see Fig. 1(a)) in which the light penetrates the SWNT layer to induce the damage, only a part of the optical power of the propagating mode interacts with SWNTs for the mode locking in the new scheme (see Fig. 1(b)), thereby higher intracavity power can be introduced for high-energy pulse formation. Furthermore, for both improved operation efficiency and the preparation process, the nanotubes are prepared to form a vertically aligned SWNT (VA-SWNT) film (4), and the film is transferred onto a D-shaped fiber as shown in Fig. 1(c). 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.

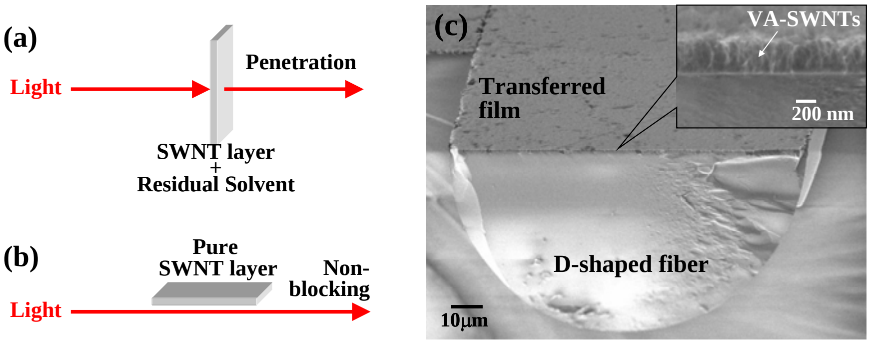


Fig. 1. Mode locking schemes realized by SWNTs. (a) In conventional scheme, the light interacts with SWNT layer directly, on the other hand, (b) in the proposed scheme, the evanescent field of the light interacts with the nanotube film. (c) Cross section of the all-fiber mode locker. The VA-SWNT film is transferred onto the flat surface of the D-shaped fiber. Inset: individual VA-SWNTs.

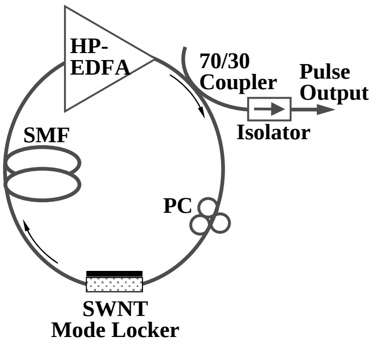
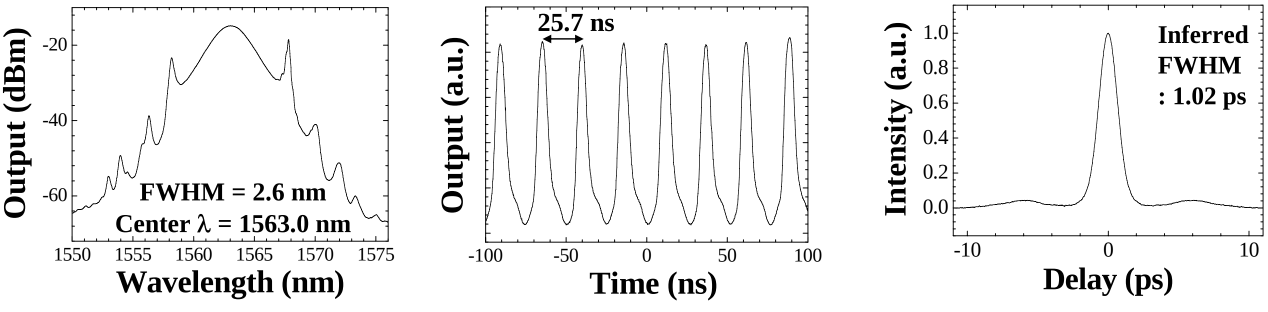


Fig. 2. Ring structure of our high power pulsed laser functioned by carbon nanotubes.

For conventional SWNT mode lockers, the SWNTs are sprayed on an intracavity component in order for the interaction of the SWNT layer with the light that passes through the layer. However, the high optical power induces the thermal damage of the nanotubes in the scheme. To improve the damage threshold of the layer, 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 configuration, a D-shaped fiber is employed as a substrate for the nanotube deposition. Thus, the evanescent field broadened by the D-shaping a single mode fiber (SMF) interacts with the SWNTs. Moreover, the efficiency of the mode locking operation is improved by managing the nanotube alignment. Understanding that only the parallel polarization component of the light with respect to the nanotubes can be absorbed by π-plasmon excitation (5,6), we control the growth direction of the nanotubes so that almost all aligned nanotubes within the field can interact with the vertically polarized mode to maximize the interaction efficiency. As depicted in Fig. 2, 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 coupler is employed. 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.



(a) **(b)** **(c)**

Fig. 3. (a) Optical spectrum and (b) pulse train of the laser output. The spectral FWHM is 2.6 nm, and the repetition rate is 38.9 MHz. (c) Autocorrelation trace of the pulse showing the pulse width of 1.02 ps.

As a result, the stable and uniform picosecond pulses are realized from a sing-stage oscillator by the SWNTs. Fig. 3(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. 3(b) verifies the pulse formation showing the repetition rate of 38.9 MHz. The autocorrelation trace in Fig. 3(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 the multiple irregular pulses with lower peak powers. So far, only a work has addressed the long-term stability of the SWNT mode locker prepared with a polymer matrix (7). 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. 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.

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. It is also possible to introduce higher intracavity power by adjusting the distance between the VA-SWNT film and the fiber core. We expect to improve the pulse energy and quality by re-optimizing the ring laser cavity condition.

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