Mode locked Er-doped fiber laser with single-wall carbon nanotube saturable absorber

ZhenhuaYu (于振华)[1], Yanrong Song (宋晏蓉)[1*], Xinzheng Dong (董信征)[1], Jinrong Tian (田金荣)[1], and Yonggang Wang (王勇刚)[2]

[1]*Institute of Information Photonics Technology and College of Applied Sciences, Beijing University of Technology, Beijing 100124, China*

[2]*State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, China*

[*]*Corresponding author: yrsong@bjut.edu.cn*

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A mode locked Er-doped fiber laser based on a single-wall carbon nanotube saturable absorber is demonstrated. A high quality single-wall carbon nanotubes (SWCNTs) absorber film is fabricated by a polymer composite. The pulse duration is 488 fs with 9.6-nm spectral width at the center of 1564 nm. The repetition rate is 30.4 MHz. The maximum output power is 3 mW. And the single pulse energy is 0.1 nJ.

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The optical absorption of the single-wall carbon nanotubes (SWCNTs) decreases with intensity or energy of the incident light. This nonlinear optical behavior makes them promisie for applications in ultrafast photonics[1−3]. For passively mode locked lasers, the SWCNTs are indeed good saturable absorbers because of their broad absorption bandwidth, ultrafast recovery time (∼1 ps), high optical damage threshold and easy fabrication[4−7]. Till now, SWCNTs have been used as the saturable absorber in a variety of lasers, such as solid-state lasers[8−10], and fiber lasers[6,11−17]. There are various strategies to prepare SWCNTs saturable absorbers[18], such as spray coating, direct growth, optically driven deposition, and polymer composite. Among them, the polymer composite is the most attractive and efficient way because the SWCNTs can be uniformly distributed in the polymer film. Thus, a high quality saturable absorber film can be used in fiber lasers effectively[6,17,19−21].

In this letter, a SWCNTs saturable absorber film was fabricated by a polymer composite. A mode locked Er-doped fiber (EDF) laser was demonstrated by using the SWCNTs film as the saturable absorber. By managing the amount of the dispersion and the nonlinearity of the ring cavity, pulses were obtained. The pulse duration was 488 fs with 9.6-nm spectral width at the center of 1564 nm. The repetition rate was 30.4 MHz. The maximum output power was 3 mW, and the single pulse energy was 0.1 nJ.

The SWCNTs used in this experiment were grown by the electric arc discharge technique. Firstly, several milligrams of SWCNTs powder were poured into 10 ml 0.1% sodium dodecyl sulfate (SDS) aqueous solution. Here SDS was used as a surfactant. In order to obtain SWCNTs aqueous dispersion with high absorption, SWCNTs aqueous solution was ultrasonically agitated for 10 h. After the ultrasonic process, the dispersed solution of SWCNTs was centrifuged to induce sedimentation of large SWCNTs bundles. After decanting the upper portion of the centrifuged solution, some polyvinyl alcohol (PVA) powder was poured into the solution and dissolved at 90 °C with ultrasonic agitation for 6 h. Then, the SWCNTs/PVA dispersion was poured into a Petri dish to spin-cast. Finally, the SWCNTs/PVA film was obtained. Figure 1 shows the Raman spectral of the SWCNTs/PVA film with a pump laser of 532 nm. The frequency of the radial breathing mode root mean square (RBM) depends sensitively on the diameter of the nanotubes[1]. In the Raman spectral, the RBM is 168 cm^{-1}, which proves a mean nanotube diameter of

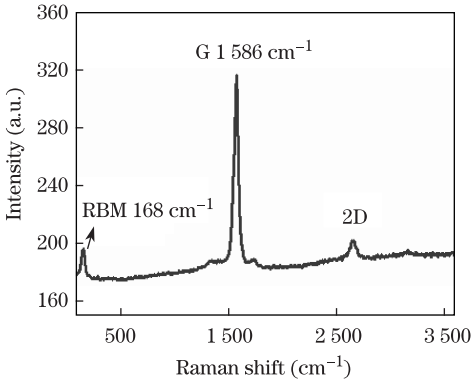

Fig. 1. Raman spectral of the SWCNTs/PVA film.

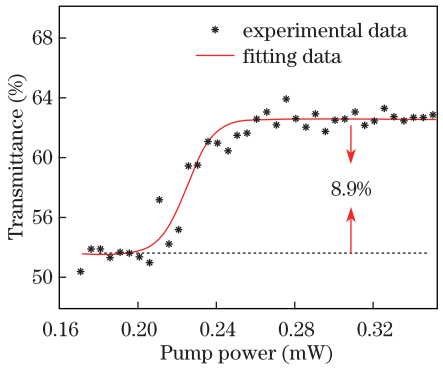

Fig. 2. Transmittance as a function of pump power.

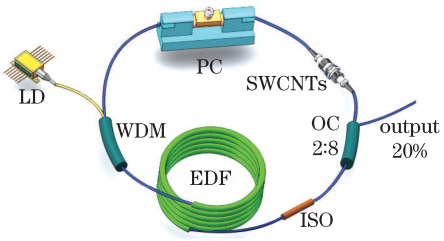

Fig. 3. Schematic diagram of the Er-doped mode locked fiber laser.

1.33 nm[22]. Both the RBM 168 cm^{-1} and the G mode 1586 cm^{-1} show that the carbon nanotubes are single walled. Moreover, the D mode almost cannot be observed, which indicates a low density of defects in the SWCNTs/PVA film. The nonlinear transmittance of the SWCNTs/PVA film increased from 53.6% to 62.5%, which corresponded to modulation depth of 8.9%. The saturable incident power was about 0.25 mW corresponding to saturation intensity of ~77 MW/cm^2(Fig. 2).

The schematic diagram of the Er-doped mode locked fiber laser is shown in Fig. 3. The ring cavity consisted of gain fiber, wavelength division multiplexer (WDM), polarization-independent isolator (PI-ISO), 20:80 optical coupler (OC), polarization controller (PC), and SWCNTs saturable absorber. A 1-m EDF with absorption of 61 dB/m at 980 nm was employed as the gain medium. The EDF was pumped by a 980-nm laser diode (LD). A PI-ISO was used to force the laser to propagate unidirectionally. The 20% port of the OC provided the laser output. A PC was mounted on the fiber to achieve different polarization orientation states. A piece of SWCNTs/PVA film was placed between two fiber connectors as the saturable absorber. The total of the fiber laser cavity was about 6.6 m. The dispersion of EDF was 9.3 ps^2/km at 1560 nm. The net dispersion of the whole cavity was about –0.11 ps^2.

When the pump power increased to 85 mW, the self-started mode locking was obtained. Figure 4 shows a typical pulse train with the fundamental cavity repetition time of 32.9 ns corresponding to the total cavity length of 6.6 m. The repetition rate was 30.4 MHz. The insert of the figure is the pulse train of continuous wave (CW) mode-locking in millisecond time scale, which is very stable. The optical spectrum of the mode locked fiber laser is shown in Fig. 5. The 3-dB bandwidth of the optical spectrum is about 9.6 nm at the center of 1564 nm, and the Fourier transformed limited pulse width should be ~267 fs. Figure 6 shows the autocorrelation trace, which is fitted by $sech^2$ profile very well. The full-width at half-maximum (FWHM) was 754 fs corresponding to the real pulse width of 488 fs. The time-bandwidth product (TBP) of the pulses was ~0.574, about 1.8 times than the Fourier transform limit. It indicates that the mode locked pulses were slightly chirped. The maximum output power was 3 mW at the pump power of 110 mW.

When the pump power was further increased, the pulse splitting was observed in oscilloscope (Fig. 7). In the experiment, the increase of the splitting pulses was not linear with the pump power, because the pulse splitting was not only connected with the single pulse energy but also with the external disturbance.

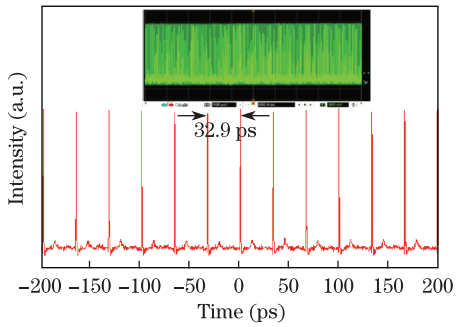

Fig. 4. Pulse train of the mode locked laser, the insert is the pulse train of the long time scale.

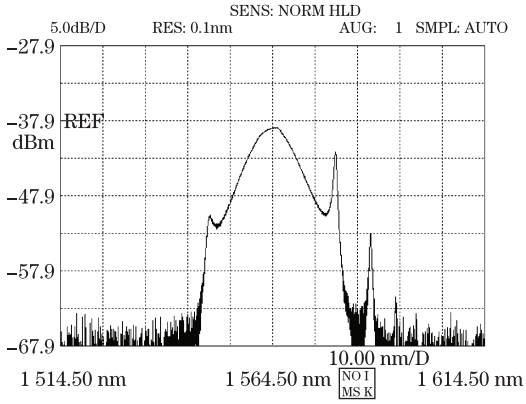

Fig. 5. Optical spectrum of the mode locked fiber laser.

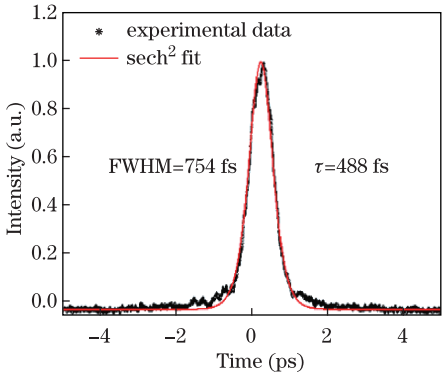

Fig. 6. Autocorrelation trace with $sech^2$ fitting.

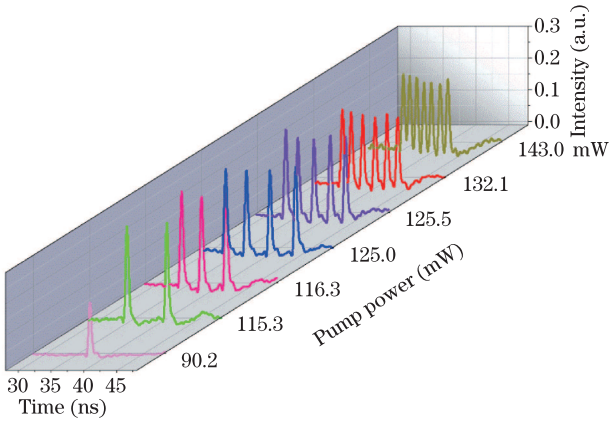

Fig. 7. Pulse splitting evolution of the mode locked fiber laser.

In conclusion, mode locked EDF laser based on single-wall carbon nanotubes (SWCNTs) is investigated experimentally. The pulse duration of 488 fs with 9.6-nm spectral width at the center of 1564 nm is obtained. The time-bandwidth product (TBP) of the pulses is ∼0.574. The repetition rate is 30.4 MHz. The maximum output power is 3 mW, and the single pulse energy is 0.1 nJ.

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