ISSN 1054-660X, Laser Physics, 2011, Vol. 21, No. 2, pp. 283–286.

Mode-Locked Yb-Fiber Laser with Saturable Absorber Based on Carbon Nanotubes

S. M. Kobtsev*, S. V. Kukarin, and Y. S. Fedotov

Novosibirsk State University, ul. Pirogova 2, Novosibirsk, 630090 Russia

*e-mail: kobtsev@lab.nsu.ru

Received June 24, 2010; in final form, September 18, 2010

Abstract—An ytterbium-fiber laser with the self-mode-locking using a saturable absorber based on carbon nanotubes is presented. Original films that contain carbon nanotubes make it possible to generate pulses with a duration of 16 ps and a mean power of up to 10 mW at a wavelength of 1058 nm and a repetition rate of 125 MHz.

DOI: 10.1134/S1054660X11040062

INTRODUCTION

Mode-locked fiber lasers that generate ultrashort pulses are interesting for scientific study and technological applications [1]. One of the most widely used methods for the initiation of mode locking employs intracavity elements that allow the self-starting of the mode-locked lasing. Semiconductor saturable absorbers are often employed as mode lockers [2]. However, the disadvantages are a relatively high price and the damage induced by the high-intensity radiation upon the development of mode locking. In the fiber lasers with the semiconductor saturable absorbers, the energy of the femtosecond pulses can reach 18 nJ at a mean output power of 1.2 W [3]. Note that the nonlinear polarization rotation can also be used for the mode locking in fiber lasers [4, 5]. Such a regime employs the nonlinear effects in the optical fiber and makes it possible to generate pulses with relatively high energies (greater than 1 μJ) in relatively simple laser systems [6, 7]. However, the nonlinear evolution of polarization upon mode locking leads to long-term instabilities. The nonlinear polarization rotation depends on both temperature and tuning of the polarization controllers. Normally, the long-term stability of the mode-locking regime is impossible when the operation of the fiber polarization controllers is based on the mechanical deformation of fiber. Optical fiber is an amorphous medium, and its initial mechanical deformation exhibits a tendency towards plastic variations with time. Therefore, the nonlinear polarization rotation does not provide the long-term stability of mode locking in a fiber laser.

In this regard, it is expedient to search for reliable devices that allow the mode locking in fiber lasers owing to the disadvantages of the existing semiconductor saturable absorbers and the absence of the long-term stability in the lasers with the nonlinear evolution of polarization. One of the promising approaches for the further improvement of mode locking in fiber lasers involves the analysis of new methods and devices based on carbon nanotubes [8].

Mode-locked fiber lasers using saturable absorbers based on carbon nanotubes were demonstrated in several works [9–15]. Note that the technologies that make it possible to create nanotubes and absorbing films consisting of nanotubes are substantially different, so that the resulting laser parameters are different and it is expedient to analyze each specific system.

In this work, we present a mode-locked Yb-fiber laser with an original saturable film absorber based on carbon nanotubes.

SATURABLE FILM ABSORBER WITH CARBON NANOTUBES

We developed and implemented a technology that allows the fabrication of the polyvinyl alcohol films containing carbon nanotubes. The volume concentration of nanotubes can be controlled in the highly homogeneous films. We use single-wall carbon nanotubes (SWCNs) with a diameter of 0.8 nm, a mean length of 1 μm, and the saturable absorption in the range 900–1100 nm to fabricate saturable absorbers that make it possible to initiate and to maintain the self-mode-locking in the Yb-fiber laser over a relatively long time interval.

The physicochemical and optical properties of SWCNs [16, 17] show that they can be used instead of semiconductor saturable absorbers in the mode-locked fiber lasers [18] and the corresponding Raman converters and amplifiers [19, 20]. SWCNs exhibit relatively high nonlinearities and saturation recovery times of less than 1 ps. Note also that the SWCNs are relatively inexpensive and are stable against high-intensity radiation (i.e., the damage threshold of carbon nanotubes is significantly higher than the level above which the nanotubes exhibit the nonlinear optical properties).

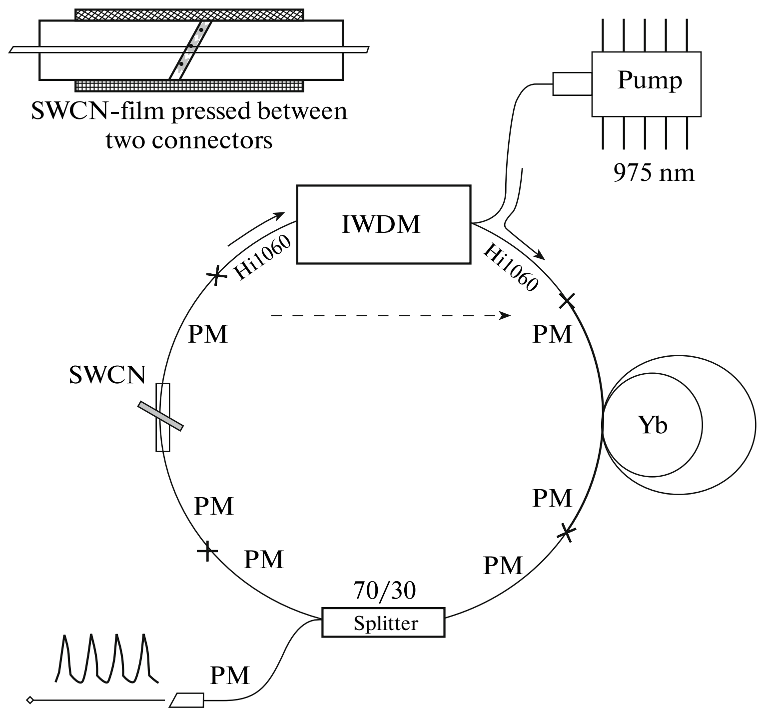

Fig. 1. Scheme of the ring Yb-fiber laser with the SWCN-based saturable absorber.

The SWCN-based saturable absorbers can be created using several methods: for example, sputtering or direct synthesis on the substrate, deposition on the end surfaces of optical fibers, and dissolution and mixing with polymers (e.g., polyvinyl alcohol, polymethylmethacrylate, polycarbonate, etc.). Such methods for the fabrication of saturable absorbers are appropriate for the lasers that work in wide wavelength ranges (1–2 μm) with various SWCNs.

The main problem in the creation of the SWCN-based saturable absorber is related to the linking of nanotubes in solution. The linked nanotubes give rise to the optical inhomogeneity and induce scattering in the films made of such liquids. Therefore, the maxi-

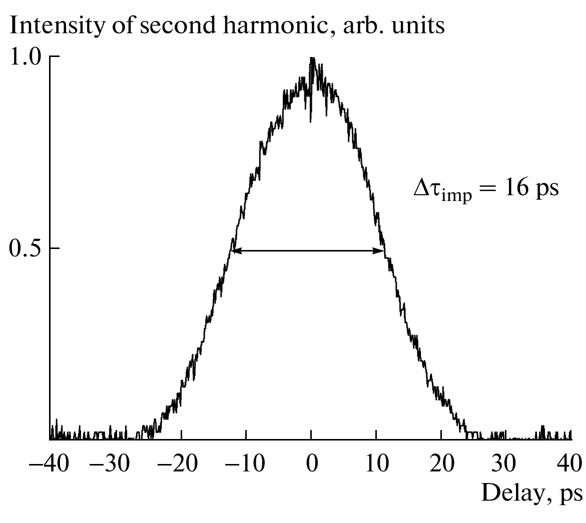

Fig. 2. Autocorrelation function of the laser pulse radiation intensity.

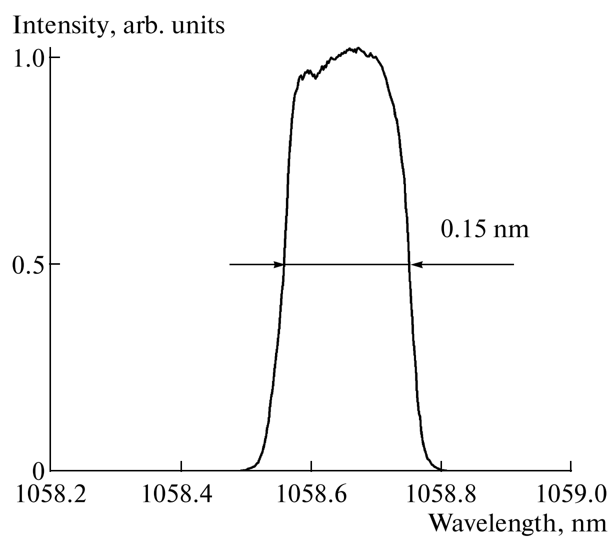

Fig. 3. Radiation spectrum of laser pulses.

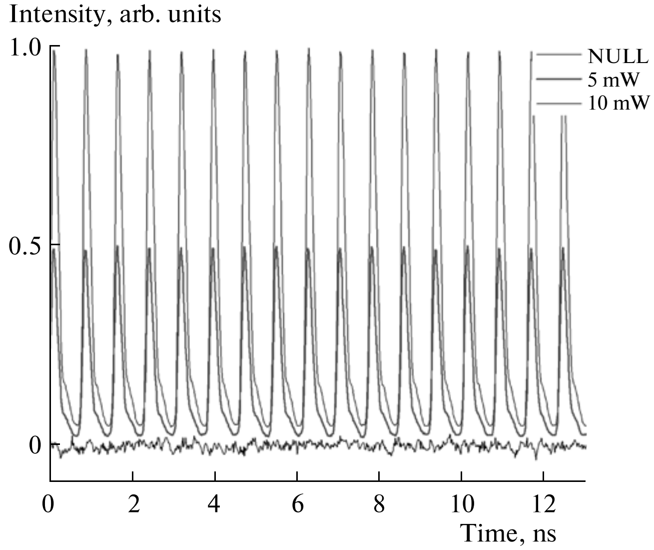

Fig. 4. Trains of laser pulses at output powers of 5 and 10 mW.

mum homogeneity of solution must be reached when the nanotubes are dissolved in liquid.

In this work, we dissolve SWCNs in the polyvinyl alcohol. An ultrasonic bath is used for the homogenizing, and the residual linked nanotubes are removed owing to the additional filtering. Then, the polymer is added to the suspension and the liquid is dried in a mold until solidification occurs. We use a Shimadzu UV-3600 spectrometer to measure the absorption and film thickness. The absorbance of the samples ranges from 50 to 90% in the wavelength interval 1000–1100 nm, and the film thickness ranges from 6 to 20 μm.

EXPERIMENT

Figure 1 demonstrates the block diagram of the Yb-fiber laser. The ring cavity predominantly contains polarization-maintaining components, so that the nonlinear evolution of polarization is minimized. An Yb1200-6/125DC-PM polarization maintaining fiber serves as the active medium. The radiation is outcoupled from the cavity using a 30% beam splitter. The active medium is pumped by a laser diode at a wavelength of 975 nm via a fiber combiner. The maximum pumping power at the exit of the single-mode fiber is 150 mW.

The film with the carbon nanotubes is placed between two FC/APC fiber connectors. The mode locking is self-started at a mean output power of 2 mW and is maintained when the power increases to 13 mW. At intermediate output powers (2–13 mW), the laser generates almost bandwidth-limited pulses with a duration of 16 ps (Fig. 2) and a spectral width of 0.15 nm (Fig. 3) at a repetition rate of 130 MHz (Fig. 4). For a spectral width of 0.15 nm (Fig. 3), the duration of the bandwidth-limited pulse with the sech^2 shape is 8 ps. This circumstance indicates the phase modulation of the laser pulses.

At a relatively long working time (greater than 30 min) and a mean output power of greater than 10 mW, the instability of lasing emerges due to the heating of the film. At a mean output power of greater than 13 mW, the *Q* switching is observed. When the mean output power ranges from 2 to 10 mW, the laser exhibits stable mode locking over several hours or days and even the reliable self-starting of the regime upon the on-off switching in the absence of additional tuning.

CONCLUSIONS

A picosecond ring Yb-fiber laser with the SWCN-based saturable absorber is demonstrated. A method for the fabrication of the SWCN films under laboratory conditions is presented. The results prove the advantages of the SWCN-based saturable absorbers that can be used as reliable mode lockers in fiber lasers.

REFERENCES

1. A. Tünnermann, J. Limpert, and S. Nolte, "Ultrashort Pulse Fiber Lasers and Amplifiers, in *Femtosecond Technology for Technical and Medical Applications* (Springer, Berlin, Heidelberg, 2004), vol. 96, pp. 35–54.
2. U. Keller, "Semiconductor Nonlinearities for Solid-State Laser Modelocking and Q-Switching," in *Semiconductors and Semimetals* (Academic, Boston, 1999), 59A.
3. Y.-J. Song, M.-L. Hu, C.-L. Gu, L. Chai, C.-Y. Wang, and A. M. Zheltikov, Laser Phys. Lett. **7**, 230 (2010).
4. V. J. Matsas, T. P. Newson, D. J. Richardson, and D. N. Payne, Electron. Lett. **28**, 1391 (1991).
5. S. Kobtsev, S. Kukarin, S. Smirnov, S. Turitsyn, and A. Latkin, Opt. Express **17**, 20707 (2009).
6. S. M. Kobtsev, S. V. Kukarin, S. V. Smirnov, and Y. S. Fedotov, Laser Phys. **20**, 351 (2010).
7. B. N. Nyushkov, V. I. Denisov, S. M. Kobtsev, V. S. Pivtsov, N. A. Kolyada, A. V. Ivanenko, and S. K. Turitsyn, Laser Phys. Lett. **7**, 661 (2010).
8. T. Hertel, Nature Photon. **4**, 77 (2010).
9. S. Y. Set, H. Yaguchi, Y. Tanaka, and M. Jablonski, IEEE J. Sel. Top. Quantum Electron. **10**, 137 (2004).
10. S. Yamashita, Y. Inoue, S. Maruyama, Y. Murakami, H. Yaguchi, M. Jablonski, and S. Y. Set, Opt. Lett. **29**, 1581 (2004).
11. S. Yamashita, Y. Inoue, K. Hsu, T. Kotake, H. Yaguchi, D. Tanaka, M. Jablonski, and S. Y. Set, Photon. Technol. Lett. **17**, 750 (2005).

12. A. V. Tausenev, E. D. Obraztsova, A. S. Lobach, V. I. Konov, A. V. Konyashchenko, P. G. Kryukov, and E. M. Dianov, Quantum Electron. **37**, 847 (2007).
13. S. Kivistö, T. Hakulinen, A. Kaskela, B. Aitchison, D. P. Brown, A. G. Nasibulin, E. I. Kauppinen, A. Härkönen, and O. G. Okhotnikov, Opt. Express **17**, 2358 (2009).
14. E. J. R. Kelleher, J. C. Travers, Z. Sun, A. G. Rozhin, A. C. Ferrari, S. V. Popov, and J. R. Taylor, Appl. Phys. Lett. **95**, 111108 (2009).
15. A. Schmidt, Opt. Express **17**, 20109 (2009).
16. Y. C. Chen, N. R. Raravikar, L. S. Schadler, P. M. Ajayan, Y. P. Zhao, T. M. Lu, G. C. Wang, and X. C. Zhang, Appl. Phys. Lett. **81**, 975 (2002).
17. P. L. McEuen, Physics World **13**, 31 (2000).
18. F. Wang, A. G. Rozhin, V. Scardaci, Z. Sun, F. Hennrich, I. H. White, W. I. Milne, and A. C. Ferrari, Nature Nanotechnol. **3**, 738 (2008).
19. S. M. Kobtsev and A. A. Pustovskikh, Laser Phys. **14**, 1488 (2004).
20. S. Kobtsev, S. Kukarin, S. Smirnov, and Y. Fedotov, Proc. SPIE **7580**, 758023 (2010).