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Experimental Observations of Multiple Solitons Generation in a Carbon-Nanotube based Passively Mode-locked Fiber Laser

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Abstract

We report the experimental observations of multiple solitons generation from a carbon nanotube (CNT) – based passively mode-locked fiber lasers. After a fiber-connector-type saturable absorber in which CNT is coated on the fiber connector end is successfully fabricated, stable mode-locked pulses with a 18.8MHz fundamental repetition rate at 1568nm central wavelength is self-started with only 12mW pumping power. The dynamic evolution of solitons as a function of the pump power is presented. Our laser produces multiple solitons of up to ten for the pump power of only 60mW.

1. Introduction

Generation of ultrashort optical pulses is a rapidly evolving field including many scientific fundamental researches and various applications [1-3]. When operated in the anomalous net cavity dispersion regime, due to the balanced interaction between the group velocity dispersion (GVD) and nonlinear Kerr effect, soliton operation is obtained [4]. By implementing the soliton pulse shaping techniques in the lasers, it was demonstrated that optical pulses in the sub-picoseconds range could be routinely generated. Various passive mode-locking techniques, such as nonlinear loop mirror (NOLM) [5], nonlinear polarization rotation (NPR) [6], and semiconductor saturable absorber mirrors (SESAM) [7], have been used to mode-lock the lasers. However, these techniques have some drawbacks. NPR requires additional elements in the cavity, including a polarizer and polarization controllers (PCs). Furthermore, fiber lasers mode-locked with NPR and NOLM will generally not be environmentally stable. SESAMs have recently become readily available, but tend to damage in fiber lasers, perhaps owing to the large modulation depth that is needed. Recently, carbon nanotube (CNT) based saturable absorber (SA) exhibits unique

properties, in particular intrinsically fast saturable absorption [8], which makes them an interesting alternative to SESAMs. While SESAMs have to be fabricated using sophisticated epitaxial technology [9], CNT-SAs can be manufactured with relatively simple technology and at low cost.

In this paper, we report a fiber-connector-type CNT saturable absorber, which enables us to generate a passively mode-locked fiber laser (PMFL) at a repetition rate of 18.71MHz when only 12mW pump power is introduced. Later, immediately after the self-started mode-locking, multiple solitons are formed in the cavity. To the best of our knowledge, we firstly report the experimental observations of multiple solitons generation from the CNT-based passively mode-locked fiber lasers. Our laser produces the multiple solitons of up to ten for the pump power of about 60 mW.

2. Experimental setup

Fig. 1 Schematic diagram of CNT-based PMFL
The CNT-based PMFL is schematically shown in Fig.1. It consists of a self-made fiber-connector-type

CNT saturable absorber, a polarization controller (PC), a 980/1550nm wavelength-division-multiplexed (WDM), an Er-doped fiber (EDF), and a fused coupler (10% output). The highly-concentrated EDF has a length of 1.8 m with anomalous dispersion. The other fibers in cavity are dispersion shifter fiber with a length of 1m and standard single-mode fiber (SMF) with a length of 7.5 m, respectively. The total length of cavity is 10.3 m and the net cavity dispersion is anomalous for the purpose of soliton generation. The polarization insensitive isolator provides unidirectional operation. The polarization state of laser in the cavity can be controlled by adjusting the PC. A 980-nm laser diode (LD) is used to provide the pump power of up to 100 mW. An optical spectrum analyzer (OSA) with a resolution of 0.01nm, and a 50-GHz oscilloscope and a 40 GHz electrical spectrum analyzer (ESA) together with a 40-GHz photodetector are used to monitor the laser output. The CNT in our experiment is kindly donated by our research partner. Typically, CNTs have been embedded into polymer or liquid. In our case, the CNTs, together with the polymer-based material, is plated on the surface of a fiber-connector and operated in transmission-mode to mode-lock a ring-cavity laser, as shown in Fig. 1. It is noted that polymer is undesirable as an intracavity laser material due to its relatively low damage threshold and high optical absorption. It should be avoided, especially for high power applications [10].

3. Experimental results and discussions

With appropriate settings of the PC, self-started mode locking can be achieved when the pump power P is only 12mW. In such case, the measured output average power is about 45 μ W. Fig.2 (a) to (c) show the optical spectrum of the pulses, the oscilloscope traces and the electrical spectrum of the pulses, respectively. We can observe that the optical spectrum has the typical characteristic of anomalous-dispersion pulses (i.e., symmetrical spectral). The 3-dB spectral width $\Delta\lambda$ is about 5 nm and the center wavelength of spectra is about 1568 nm. Due to the low average power, we can't measure the full width at half maximum (FWHM) of generated pulse by our existing autocorrelator. Meanwhile, we can conclude, from Fig. 2 (b) and (c), the fundamental frequency of cavity is 18.8 MHz, corresponding to the pulse separation of about 53.2 ns. From the zoom-in electrical spectrum, as shown in Fig. 2 (d), it clearly shows that the laser is mode-locked at 18.71 MHz with an extinction ratio 25dB.

Fig. 2 Characterization of the generated pulse trains. (a) Optical spectrum, (b) Oscilloscope trace, (c) Electrical spectrum, (d) Zoom-in fundamental frequency. It is found experimentally that the PMFL always started mode-locking at the same pump power level, and immediately after the mode-locking multiple solitons

are formed in the cavity. Experimentally it is observed that if there are already solitons in the cavity, carefully increasing the pump power, new solitons can be generated one by one in the cavity. As in this case the laser is already mode-locked, the generation of a new soliton only requires a small increase of the pump power. As shown in Fig. 3 (a), two solitons are successfully generated when the pump power is growing from 12 mW to 15 mW. The number of solitons is sharply increased to 10 when the pump power is growing to 57 mW, as shown in Fig. 3 (b). Compared with the optical spectrum of single soliton, the optical spectrum of multiple solitons is observed some changes, as shown in Fig. 4.

Fig. 3 A typical experimentally measured oscilloscope trace of the multiple soliton operation of PMFL

Fig. 4 A typical optical spectrum of 10 solitons operation of the PMFL

The detailed evolution process of multiple solitons generation is shown in Fig. 5, where the black lines show the ascending procedure of the stable N -soliton state ($N=1, 2 \dots 10$). We can also infer from Fig. 5 that the formation and annihilation of each pulse show the correctness of pump power hysteresis [11].

Furthermore, the threshold power of multistability for our PMFL is low. Next, we measure the 3-dB spectral width $\Delta\lambda$ almost keep the same value as the case of single soliton generation. Finally, the average output power is measured with the growing of pump power, as shown in Fig. 6. The conversion efficiency is almost kept as a constant.

Fig. 5 Relationship between the soliton number N and the input pump power

Fig. 6 Output average power of mode-locked pulse with respect to the input pump power

4. Conclusion

We proposed and demonstrated an all-fiber, anomalous cavity dispersion; Er-doped PMFL by using CNT as mode-locker. We have successfully achieved a self-started stable fundamental mode- locking with a 18.71 MHz repetition rate, when the input pump power is only 12 mW. The dynamics of the number of solitons is demonstrated by increasing pump power. Our PMFL

can generate multiple solitons from 1 to 10 when the pump power is increased from 12mW to 60mW.

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5. References

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