Fiber Laser Mode Locked by Carbon Nanotubes-N-methyl-2-Pryrrolidone Solution in Fiber Microchannel

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Abstract: We demonstrated an Erbium-doped picosecond fiber laser mode locked by carbon nanotube in N-methyl-2-pyrrolidone solvent in an in-fiber micro-channel.

OCIS codes: (060.3510) Lasers, fiber; (140.4050) Mode-locked lasers;

1. Introduction

Passively mode locked fiber lasers have a vast range of applications in telecom, medical science, metrology and other fields of science and technology. Various methods have been successfully implemented to achieve mode locking with two most popular and efficient being nonlinear polarization evolution and semiconductor saturable absorber mirror (SESAM) [1]. Recently, carbon nanotubes (CNTs) exhibiting nonlinear optical properties have attracted a great deal of attention in application of CNTs as a saturable absorber element for laser mode locking. CNTs can be used as a saturable absorber in passively mode locked fiber laser directly [2,3] or as a CNTs polymer composites [4,5]. Compared to other methods of using CNTs in mode locking, liquid solutions have been less studied. So far, only Dimenthylformanmide (DMF) solution [6] and poly-methyl-methacrylate (PMMA) variant [7] have been studied in the context of fiber laser mode locking. In [7] a special component such as hollow core fiber was employed which potentially might create some problems with robustness and packaging. The method proposed in [6] provides a more robust design using in-fiber microfludic device, however, CNT in DMF solution tends to show unwanted properties resulting in agglomeration of CNTs which may lead to unstable mode locking of fiber lasers in long terms. Here we propose and demonstrate fiber laser mode locking using CNT in N-methyl-2-pyrrolidone (NMP). This new type of saturable absorber shows stable generation while maintaining good heat dissipation capability, hence offering in perspective stable and high energy mode locking of Erbium-doped fiber laser. By applying the in-fiber microfludic device the proposed fiber laser keeps the advantages of the compactness, robustness of fiber format and also low cost through using all standard telecom compatible components.

2. Fabrication of in-fiber microchannel and carbon nanotube solution

The fabrication of the in-fiber microchannel was carried out through femtosecond laser micromachining followed by selective chemical etching of the machined area. A femtosecond laser emitting at 800 nm with 1 kHz repetition rate, 150 fs pulse duration and ~150 nJ pulse energy was employed for the micromachining. The femtosecond laser was tightly focused onto the fiber. The fiber with the laser modified area was then chemically etched in 5% HF acid to facilitate forming of the microchannel.

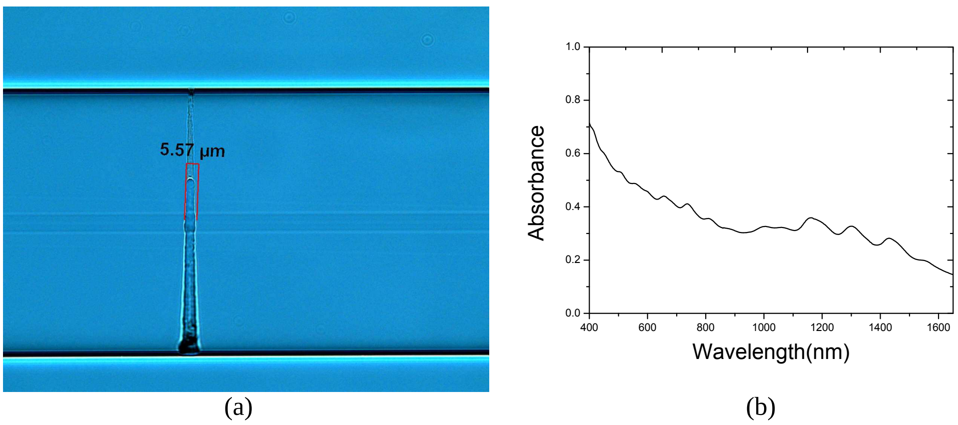

Fig.1 (a) Microscopic image of the microchannel examined by a 100× oil immersion microscope; (b) absorption spectrum of CNTs in NMP solution.

Figure 1(a) depicts a typical microscopic image of the femtosecond laser machined micro-channel in a standard telecom fiber. It shows a diameter of 5.57 μm across the fiber core area.

For the CNT saturable absorber preparation, we used the purified single wall carbon nanotubes (SWNT) purchased from Unidym. The SWNTs were ultara-sonicated by Nanoruptor Processor (Diagenode SA) during one hour at 170 W in N-Methyl-2-pyrrolidone (NMP) with the presence of Triton X-100 non-ionic surfactant. To remove residual bundles, the dispersion was placed in to MLS 50 rotor and centrifuged at 30kRPM during 2 hour with Beckman Optima Max-XP ultracentrifuge. The resulting solution shows excellent homogeneity with no visible SWNT's aggregates. The absorption spectrum of CNT solution subtracted on absorption of pure NMP is shown in Fig.1(b). It shows the typical multi peak structure between 1000 and 1600 nm, which corresponds to the absorption of semiconducting single wall CNTs with diameter distribution between 0.8 and 1.3 nm. No obvious agglomeration of CNTs has been observed even when the solution has been kept in the lab for months.

3. Fiber laser configuration and experimental results

The schematic configuration of the mode locked fiber laser is shown in Fig.2a. In this laser, ~1m of highly doped Erbium fiber serves as the gain medium with nominal absorption of 80 dB/m at 1530 nm, a 976 nm laser diode giving out up to ~370mW is used to pump the laser via a 980/1550 wavelength division multiplexing (WDM), two isolators (OIS) are employed to ensure single direction oscillation, an in-line polarization controller (PC) is used to optimize the intracavity polarization of the pulses and a 50:50 coupler to couple out 50% of the intracavity power. An extra ~78m SMF was added to create the required cavity dispersion therefore forming a total cavity length of ~91m.

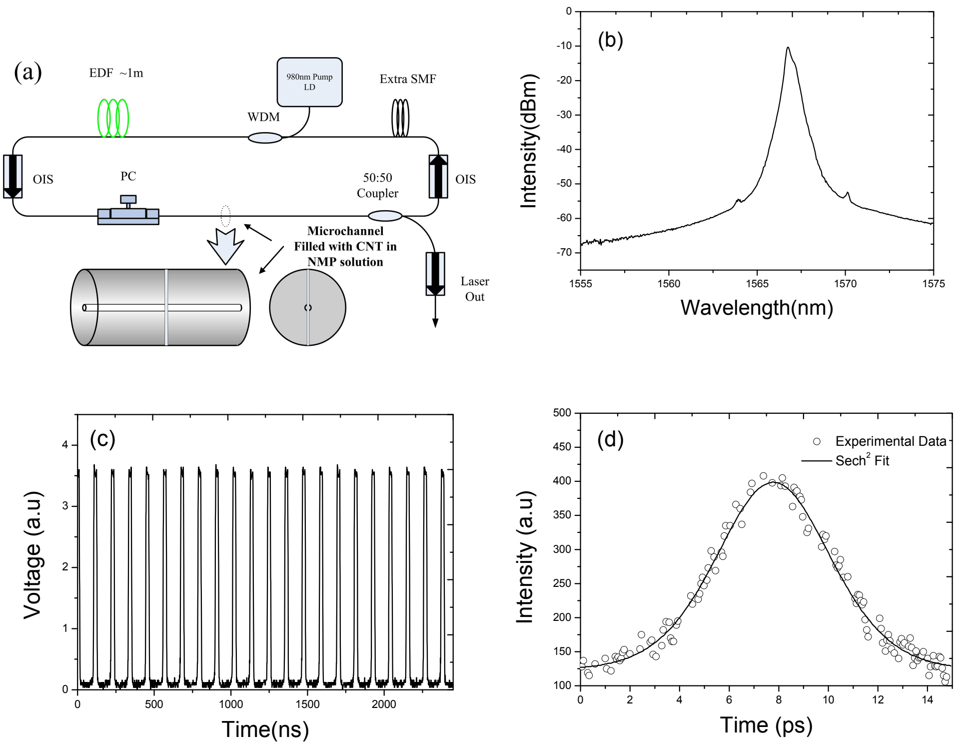

Fig.2 (a) schematic configuration of the proposed fiber laser; (b) typical optical spectrum of the pulse; (c) a typical output pulse train of the mode-locked fiber laser giving a repetition rate of ~2.27MHz; (d) typical pulse shape and corresponding sech fit.

The laser resonator is constructed with fibers having anomalous dispersion to employ soliton laser regime. A standard laboratory grade syringe was used to inject the CNT NMP solution into the micro-channel. Followed by another isolator, the output mode locked pulses were then examined by an autocorrelator (Pulsecheck) and an oscilloscope (Tektronix). An optical spectrum analyzer (ANDO AQ6317B) with 0.2 nm resolution was employed to record the optical spectrum of the laser pulses. A standard power meter was adopted to measure the average output pulse power.

Initially, the micro-channel was exposed to air and no mode locking was observed for any pump power. When the CNT NMP solution was filled in the micro-channel, stable mode locking was observed at ~370 mW pump power with an average output power of 24 mW at 1566 nm.

Figures (b) shows a typical output spectrum of mode locked laser pulse. The well known side bands indicate the typical soliton laser operational regime. The output spectrum has a spectral bandwidth at full width half maximum (FWHM) of ~0.34 nm. A typical mode-locked pulse train is shown in Fig. 2(c) with a 440 ns interval between two adjacent pulses corresponding to a repetition rate of ~2.27MHz. As it is seen from Fig. 2(d) the sech function provides a rather good fit (sech square for the intensity) to the temporal shape of the generated pulses. The estimated output energy is ~11 nJ which is much higher than the mode locked lasers using the solid format of CNTs [8]. This further confirms that the CNT solution can be applied for high energy mode locked fiber lasers [6]. It is also found that CNTs dispersed in NMP solution are not apt to agglomerate. Samples which were prepared 3 months ago are still able to mode lock the fiber laser. However, one major drawback of the liquid phase saturable absorber is the evaporation of NMP and moister adsorption by solvent. Thus, in the case the solution would be exposed in air for long time, the evaporation of NMP and moister adsorption by solvent will disturb the thermodynamic equilibrium in the solution leading to the CNT aggregation. This will be a source of significant scattering losses (non saturable losses) in the laser cavity. We believe, though, that by proper packaging, a highly stable high energy mode locked fiber laser by CNT in NMP solution can be fabricated.

4. Conclusion

In this paper, we proposed and demonstrated for the first time an Erbium-doped fiber laser mode locked by CNT in NMP solution. The sample solution without any optimization and control shows high stability over long time which demonstrates great potential of the liquid phase saturable absorber. The application of the CNTs in NMP solution based mode locker using an in-fiber micro-channel maintains the all-fiber format of the laser configuration. The laser generates stable pulses with ~0.34 nm spectral width and ~11nJ pulse energy.

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