Higher-Order Soliton Generation in Hybrid Mode-Locked Thulium-Doped Fiber Ring Laser

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***Abstract*—A thulium-doped all-fiber laser passively mode-locked by the co-action of nonlinear polarization evolution and single-walled carbon nanotubes operating at 1860–1980 nm wavelength band is demonstrated. Pumped with the single-mode laser diode at 1.55 μm laser generates near 500-fs soliton pulses at repetition rate ranging from 6.3 to 72.5 MHz in single-pulse operation regime. Having 3-m long cavity average output power reached 300 mW, giving the peak power of 4.88 kW and the pulse energy of 2.93 nJ with slope efficiency higher than 30%. At a 21.6-m long ring cavity average output power of 117 mW is obtained, corresponding to the pulse energy up to 10.87 nJ and a pulse peak power of 21.7 kW, leading to the higher-order soliton generation.**

***Index Terms*—Carbon nanotubes, fiber lasers, laser mode locking, optical pulse shaping.**

I. Introduction

AFTER the first demonstration in 1990 [1], fiber based ultrafast pulse lasers have been intensively studied in various configurations and for different fiber base. Numerous mode-locking techniques have been developed and the ultrafast pulse generation has been achieved in a wide range of wavelength bands. Recently fiber lasers generating near 2 μm have attracted a great deal of attention due to a range of possible applications. The broad gain spectral band, extending from 1850 to 2100 nm provides more than 200 nm of available bandwidth, which is typical for thulium-doped fibers. Furthermore, thulium-doped fiber lasers exhibit excellent power scalability and high efficiency. Thulium gain spectrum covers several atmospheric transmission windows, offering numerous applications in remote sensing, laser radar [2] and free-space or hollow-core fiber telecommunications [3]. Obviously for these open-space applications eye-safe radiation is desirable. This can be achieved with the thulium-doped fiber lasers due to the fact that the laser radiation at the wavelength band near 2 μm is entirely absorbed before it can reach and damage the eye retina. This wavelength region also includes the water absorption peaks, making such lasers a unique instrument for non-invasive surgery [4] or ophthalmology. On the other hand, there are lots of absorption lines of green-house gasses (CO_2 and N_2O) around 2 μm wavelength, that allows to use thulium-doped lasers for gas detection and analysis [5]. High power 2 μm laser sources are well suited for nonlinear frequency conversion to obtain mid-IR and THz generation. Red-shifting of the generation band provides an increase of the fiber mode field size without sacrificing beam quality [6]. This helps to relax limitations for high-power applications imposed by optical nonlinearities.

A higher threshold of nonlinear effects in thulium-doped fiber lasers is an advantage for high-power operation and telecommunication applications, however, this also complicates self-starting mode-locking through fast nonlinear polarization evolution (NPE) mechanism based on the nonlinear optical Kerr-effect in fibers. For example, to obtain appropriate nonlinear phase shift for mode-locking initiation, every work presented earlier has demonstrated thulium-doped fiber lasers with the cavity length of more than 30 m [7], [8]. However, longer laser cavity may be responsible for pulse instabilities (see e.g. [9]–[11] and discussions therein). Most of current works on thulium-doped ultrafast fiber lasers have concentrated on mode-locking regime initiated by semiconductor saturable absorber mirrors [12], single-walled carbon nanotubes (SWCNTs) [13] and graphene [14] based saturable absorbers. Application of two saturable absorbers, slow and fast, in laser cavity simultaneously helps to generate ultrashort pulses with high average power, temporal purity, and high frequency stability [15]. Comparatively slow saturable absorber is used for mode-locking initiation as it has lower saturation threshold. Whereas the light modulator with fast response time ensures efficient pulse formation and stabilization at substantially higher powers [15], [16]. It is well known that saturable absorbers based on nonlinear optical Kerr-effect have the shortest response time around ~5 fs based

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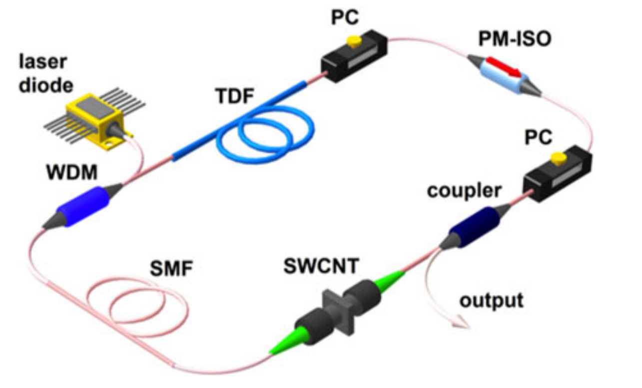

Fig. 1. Schematic setup of the hybrid mode-locked thulium-doped fiber laser.

on the electric field interaction with the electrons of an active medium. Combination of NPE or nonlinear fiber loop mirrors with another saturable absorbers has been demonstrated earlier in [17], [18] giving the shortest pulse duration of 230 fs [18]. Previously presented mode-locked thulium doped ultrafast fiber laser output power was limited by the damage threshold of optical components. Using ferrule-type SWCNT saturable absorber, the demonstrated average output power was below ∼20 mW due to the polymer composites destruction [13]. So far, the highest pulse energy has been presented in a figure-eight laser based on the double-clad thulium-doped fiber generating 685-fs pulses with the energy of as much as 8.75 nJ by Rudy *et al.* [19].

Here we demonstrate high-power and high-energy thulium-doped all-fiber ring laser hybrid mode-locked by the co-action of SWCNT and NPE. The laser operates in single-pulse regime at all-anomalous cavity dispersion generating near 500 fs pulses in the wavelength band of 1.86–1.98 μm. At the minimum cavity length of 3 m, average output power reached 300-mW giving the pulse energy of 4 nJ with the slope efficiency higher than 30%. The laser with 21.6-m long cavity demonstrates ∼117 mW average output power at the 9.26 MHz-repetition rate corresponding to the pulse energy of 10.87 nJ and peak power of 21.7 kW. To the best of our knowledge, we have obtained the highest pulse energy and peak power directly from the mode-locked thulium-doped fiber laser with single-mode pumping without any further amplification.

II. Experimental Setup

Fig. 1 presents the schematic of the experimental setup of the thulium-doped fiber ring laser. Pump radiation from a CW single-mode laser diode at 1.55 μm amplified with a commercial EDFA up to 1.2 W maximum output power is launched through a 1.56/1.9 μm wavelength division multiplexer to a 1-m long thulium-doped active fiber. A commercial in-fiber polarization dependent isolator and a pair of polarization controllers (PC) are positioned after the active fiber to form the NPE based fast light amplitude modulator. A polymer film with dispersed SWCNTs is used as a relatively slow saturable absorber (typical SWCNTs response time is 300–500 fs [20]) to ensure mode locking self-starting. It is fixed between two angle-polished ferrules of optical FC/APC-connectors. An output coupler is positioned before SWCNT saturable absorber to decrease incident radiation power and therefore to prevent the damage or degradation of the SWCNT polymer film. Coupling ratio was optimized during the experiment to obtain the highest lasing efficiency. The step-index ($\Delta n = 0.012$) active thulium-doped aluminum-silica glass fiber has a 10 μm core containing 0.8 wt% of thulium and 3.6 wt% of aluminum and a cutoff wavelength of λ_c 2.2 μm. The active fiber absorption at the pump wavelength of 1.55 μm was measured as 60 dB/m providing almost entire pump absorption in one meter of the active fiber. The second order dispersion was estimated to be $\beta_2 = 76$ ps^2/km at the wavelength of laser operation ∼1.9 μm.

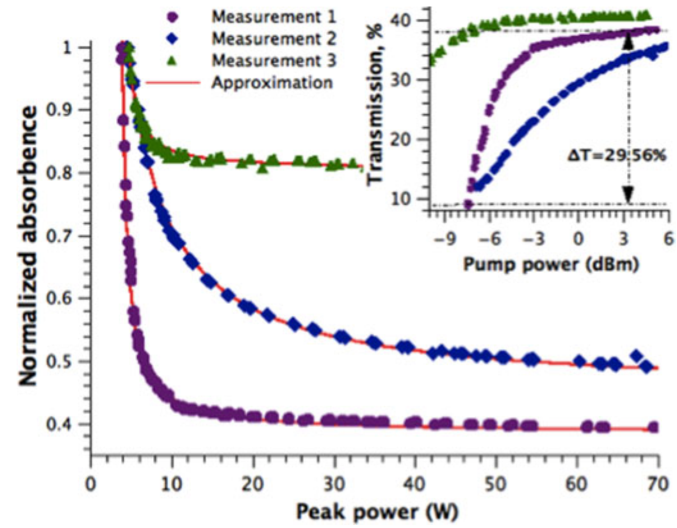

Fig. 2. Absorption saturation measurements of the PVA-based polymer film with dispersed SWCNTs using passively mode-locked fiber source operating at 1880 nm. Inset: Transmission saturation.

The SWCNT were prepared with laser ablation method [21]. Compared with the other production methods, the laser ablation provides higher homogeneity in SWCNT parameters such as chirality and diameter. The raw SWCNTs (2 mg) were dispersed in (25 ml) DI water by (20 mg Sodium dodecylbenzenesulfonate) surfactant-assisted sonication and the large SWCNT bundles were removed by filtration through a 1 μm glass microfiber filter [22]. The resulting dispersion was used to produce the polyvinyl alcohol (PVA) composite incorporating SWCNTs with a diameter ranged between 1.25 and 1.5 μm [20]. Fig. 2 shows power-dependent transmission measurement of the SWCNT saturable absorber. Self-made thulium-doped passively mode-locked fiber laser generating 550 fs soliton pulses at 74 MHz repetition rate was used as a laser source for modulation depth measurements. As it is seen from the Fig. 2 the absorption decreases with the launched peak power increase according to the equation [22]

$$\alpha(P_{\mathrm{peak}}) = \frac{\alpha_0}{1 + \frac{P_{\mathrm{peak}}}{P_{\mathrm{peaksat}}}} + \alpha_{\mathrm{ns}}. \quad (1)$$

The PVA-based composite with dispersed SWCNTs shows non-saturable absorption $\alpha_{\mathrm{ns}} = 60\%$, absorption modulation depth $\alpha_0 = 40\%$ and saturation peak power $\mathrm{P}_{\mathrm{peaksat}} = 1.44$ W, which corresponds to the saturation intensity of 1.22 MW/cm^2. Such values are typical for polymer-based films with dispersed

SWCNTs [20]. The corresponding growth of the sample transmission is about 30% as it is shown in the inset of Fig. 2.

It should be noticed that with further series of measurements, PVA polymer film degrades during high-power laser operation. Non-saturable losses and saturation peak power increase up to 80.5% and 5.46 W (corresponding to the intensity of 4.63 MW/cm^2), whereas absorption modulation depth drops to 19.5% (see Fig. 2, measurement run 3), corresponding to the film transmission modulation depth of 8%. Though such a degradation of PVA-based composite occurs, modulation depth is still quite high, so that the polymer film with dispersed SWCNTs can effectively initiate self-starting mode locking.

It is worth mentioning that SWCNT film modulation depth measurements at $\sim$1.9 μm wavelength have not been performed and demonstrated in details earlier.

III. Experimental Results

The length of the laser cavity was varied from 2.7 to 22.5 m by inserting a section of passive SMF 2000 fiber.

A. Short Cavity Laser

The output coupling ratio was firstly chosen to be 50/50 so that radiation power inside the cavity was equal to the output one. The cavity length has been shortened to 2.7 m corresponding to the pulse repetition rate of 72.5 MHz [23].

To explore the key roles playing by the two types of saturable absorber in the hybrid mode-locking mechanism realization, we have compared the described laser with another thulium-doped fiber ring laser mode-locked just with the same SWCNT-based saturable absorber. Both laser setups were built by means of identical components. The only difference is that polarization sensitive isolator has been replaced by polarization independent one. In addition only one PC has been retained in the cavity.

Fig. 3 presents experimental autocorrelation traces and spectra of pulses generated in both hybrid and SWCNT-only mode-locked lasers at the pump power of 320 mW. Both lasers can achieve mode-locking easily, with generated pulse-width of 590 fs and comparable spectral bandwidths of 6.58 and 6.78 nm respectively. The lasers average output power is 27 mW. It is evident that output characteristics of both lasers were quite similar; the spectrum of SWCNT-only mode-locked laser is slightly red-shifted due to different PC setups. This fact indicates that the SWCNTs play dominant role in the mode-locking initiation and pulse formation at low pump powers below 400 mW, whereas the NPE threshold has not been achieved yet.

Through the pump power increase, nonlinearity in the laser cavity affects generation more crucially and the NPE mechanism contribution to the pulse formation becomes more pronounced. During the pump power increase, NPE smoothly maintains mode-locking operation. On the other hand, it tends to break into non-regular multi-pulse generation and, finally, into Q-switching operation. That results in the PVA-based polymer film degradation. Though it has been preserved undamaged in the hybrid mode-locked laser.

Maximum average output power of 170 mW in the SWCNT-only mode-locked laser was achieved at the maximum pump

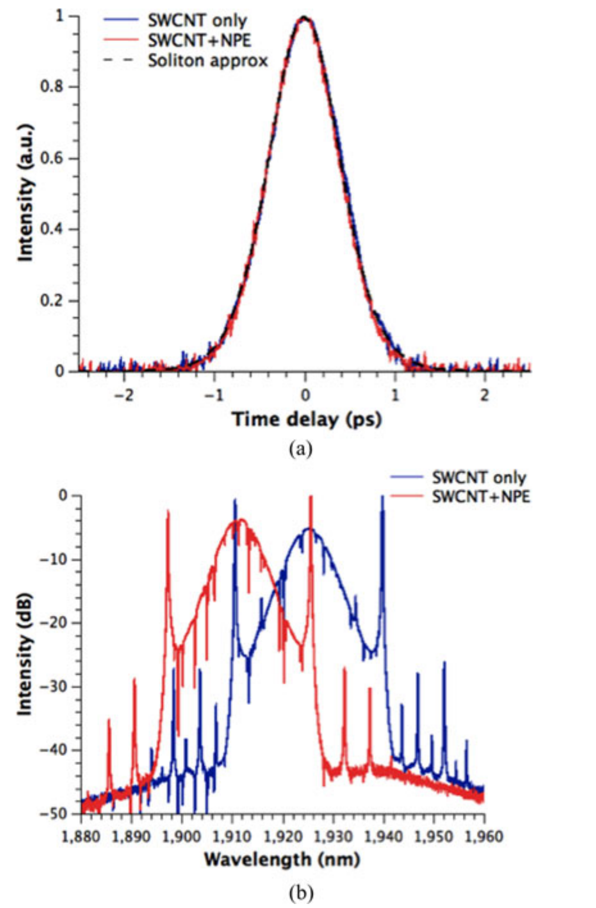

Fig. 3. Output autocorrelation traces (a) and spectra (b) at $P_{\rm pump} = 320$ mW.

power of 1.2 W (see Fig. 4). However, laser generated at such a high-power mode just for several seconds. After that PVA-film has degraded and the laser has turned to CW operation. In the case of a hybrid mode-locking, the laser can steadily operate in two different regimes according to the possible polarization state adjustments giving $\sim$300 mW output average power at the same slope efficiency of $\sim$32.6% (see Fig. 5). Output pulses have a duration of 600 fs (state 1) and 1.28 ps (state 2) with a spectral bandwidths of 8.7 and 3.1 nm, correspondingly (see Fig. 4). Time-bandwidth products for both states have been approximately calculated as 0.411 and 0.316 respectively.

In both cases output spectra possess typical for soliton pulses Kelly side-bands originating from periodic spectral interference between the soliton wave and a co-propagating dispersive wave [24]. Due to high-intensive Kelly side-bands in the output spectrum in the state 1, pulse contains 68% of all generated energy giving 2.93 nJ and the peak power of 4.88 kW, respectively. In the state 2, however, side-bands contain negligible part of the energy. The peak power in the pulse reached 3.19 kW corresponding to the pulse energy of 4.08 nJ.

The pulse characteristics of the SWCNT-only mode-locked laser were close to above-mentioned state 1. Laser generates 600-fs pulses with the spectrum bandwidth of 10.86 nm and time-bandwidth product of 0.54. It should be noted that sharp spike at 1905 nm was observed in the spectrum (see Fig. 4(b),

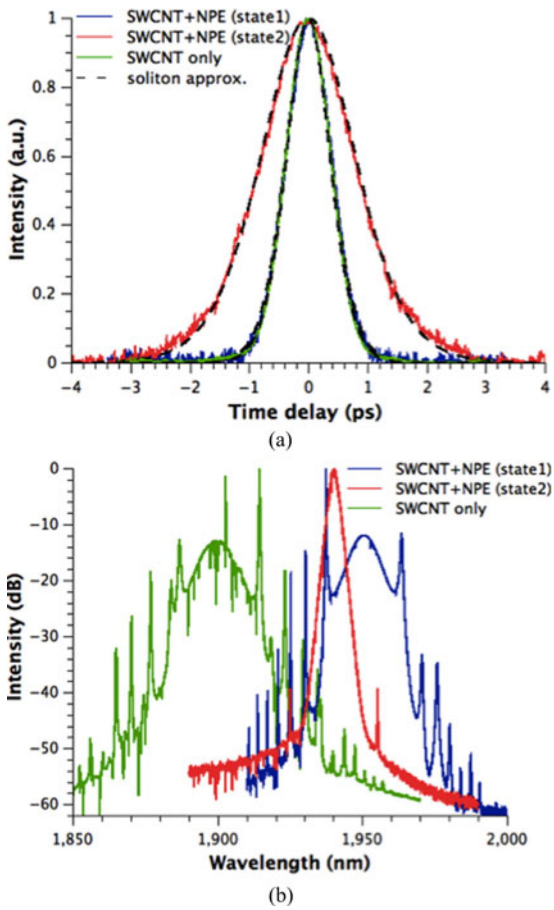

Fig. 4. Output autocorrelation traces (a) and spectra (b) at $P_{\rm pump} = 1.2$ W.

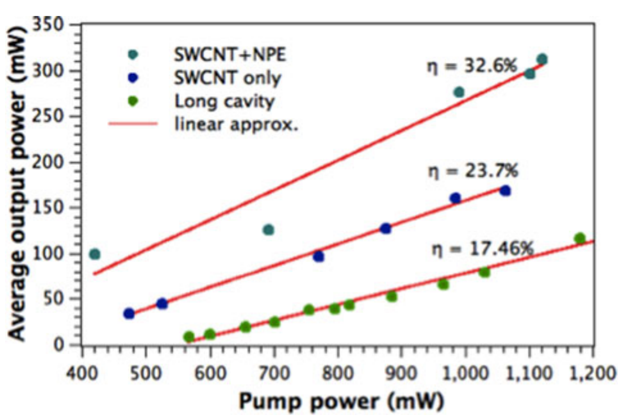

Fig. 5. Laser slope efficiency.

green plot) justifying that the mode-locking operation is not complete and high-power CW component is transmitted through the laser cavity. Pulse peak contains 65% of all generated energy according to spectrum integration, that corresponds to the value 1.34 nJ and the peak power of 2.24 kW.

The slope efficiency of SWCNT-only mode-locked laser is measured to be 23.7% (see Fig. 6). It is worth noting that the pump radiation was entirely absorbed by active fiber. This is proved by monitoring the average power at the wavelength of

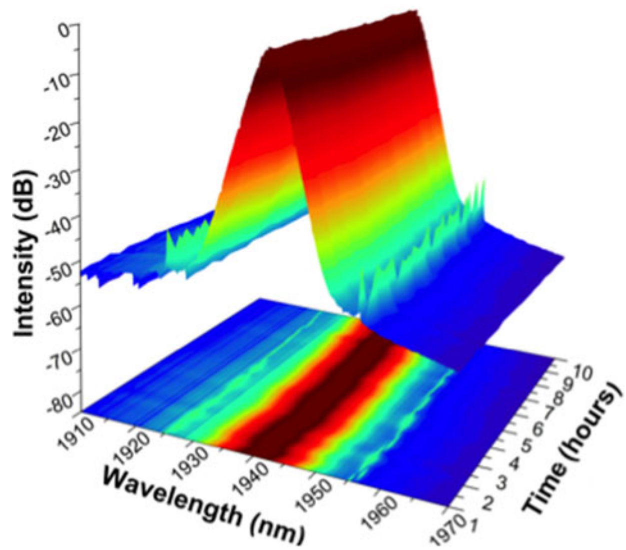

Fig. 6. Pulse stability during 10 h of continuous work at $P_{\rm pump} = 1.2$ W.

1.55 μm, which did not exceed several milli-watts at the laser output when the pump power was higher than 1 W.

We have also examined the long-term stability of the proposed laser. Laser generating 1.28 ps pulses at a 300 mW output power has exhibited stable output under the laboratory conditions for 10 h. We have recorded the optical spectra of the laser at a 10-min interval, as shown in Fig. 6. No obvious change has been observed for the soliton parameters, such as the central wavelength, 3-dB spectral bandwidth, Kelly sideband positions and the spectral peak powers. Also, no obvious damage or degradation of SWCNT polymer films was observed using the same sample for self- starting mode-locking in the next day after several times switch-on and off. Laser could effectively resist the mechanical effects and perturbation.

Considering the output coupling ratio of 50%, the radiation energy transmitting along the laser cavity to the SWCNT module is equal to the output one, and mounts to 4.08 nJ in the case shown in Fig. 6. Thus the PVA based SWCNT-polymer composite film could endure an optical fluence of at least 3.46 mJ/cm^2 without any significant damage that verifies its strong thermal stability.

With the pump power increase, no gain saturation was observed for pump powers near 1.2 W. Thus it is expected that through the further laser cavity optimization on the saturable absorption parameters and with careful polarization adjustment, mode-locked pulses of significantly higher pulse average powers and shorter duration could be generated, giving rise to higher pulse energy.

B. Long Cavity Laser

To achieve higher output energy and reduce the energy fluence transmitting through the PVA-based polymer film with incorporated SWCNTs, 50/50 output coupler was replaced by a 30/70 coupler providing 70% output for generated energy.

By careful initial PCs adjustment self-starting mode-locking has been achieved at the pulse repetition rate between 6.37 and

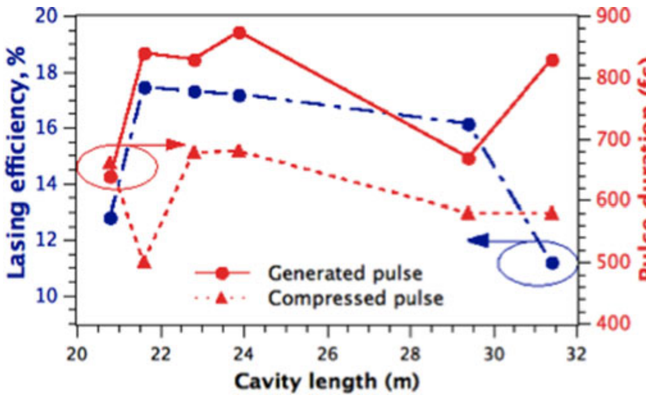

Fig. 7. Output pulse parameters evolution by varying the cavity length.

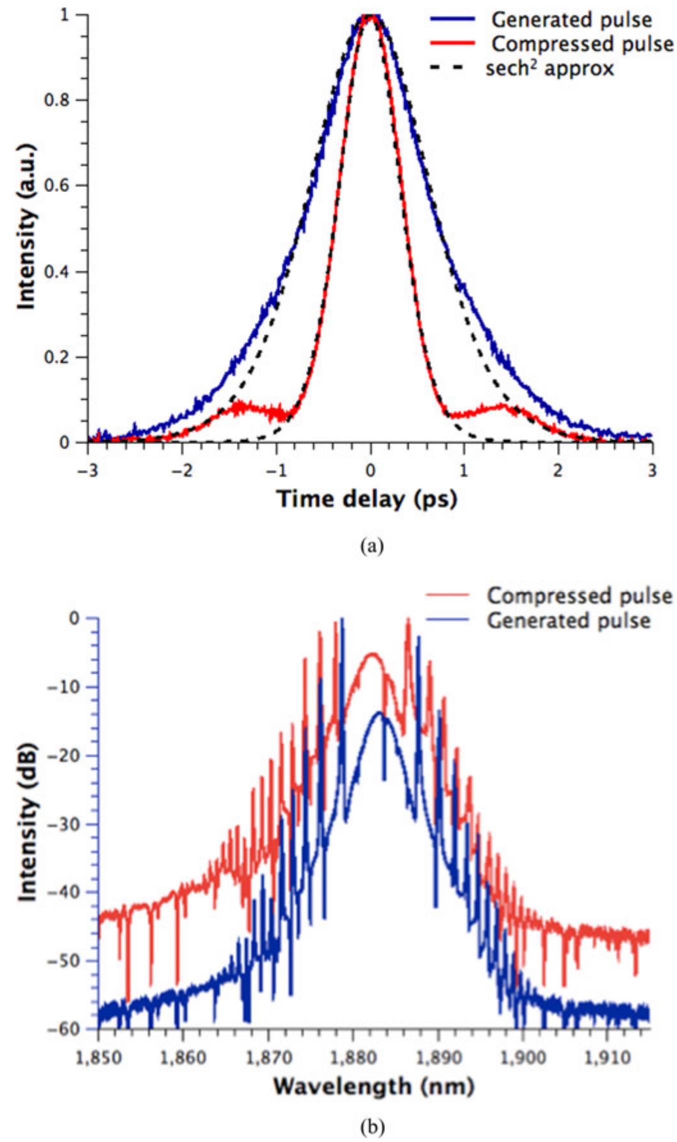

Fig. 8. Output autocorrelation trace (a) and spectra (b) of the laser pulse at pump power $P_{\rm pump} = 1.2$ W and cavity length $L = 21.6$ m.

9.6 MHz that corresponds to the laser cavity length ranging between 31.4 and 20.8 m. Once the mode-locking has been realized, polarization tuning is no longer needed during the pump power increase. The laser runs steadily for hours without any perturbation under laboratory conditions. In the whole available pump power range, the laser operates in the single-pulse regime; no pulse breaking, Q-switching or multiple pulse operation was observed.

By changing the length of SMF-2000 inside the laser cavity lasing efficiency varies in the range from 11.2 to 17.46% whereas output pulse duration at the maximum pump power of 1.2 W alters in the range between 640 and 875 fs respectively as it is shown in Fig. 7. The maximum efficiency of 17.46% has been obtained with the cavity length of 21.6 m. In this case laser generates 840-fs pulses with the maximum average output power of 126.4 mW. The lasing slope efficiency in this case is depicted in Fig. 5 (green plot). It is worth noting that power saturation has not been observed even at the highest pump powers, meaning that it could be further increased.

The measured autocorrelation trace and spectrum of generated pulses in this case are presented in Fig. 8 (blue solid line). Laser output spectrum possesses well-resolved Kelly sidebands, proving soliton pulse generation. It can be obviously seen in Fig. 8(a) that autocorrelation trace contains non-compressed pedestal part. Nonlinear pulse chirp causes deviations from the ideal soliton pulse (see sech^2 approximation in Fig. 8). By examining the output characteristics it was found out that pulse peak contains just 80% of generated energy. Assuming the pulse repetition rate of 9.26 MHz, the pulse energy is estimated to be 10.92 nJ corresponding to the peak power of 13 kW.

To compress the pulse, the SMF-28 fiber section of variable length in the range from 2.5 to 5 m has been inserted at the laser output [25]. It is worth noting that the laser output parameters were strictly fixed during these experiments. The evolution of the shortest output pulse duration by varying cavity length is presented in Fig. 7 (dashed plot).

As it is seen, the shortest pulse duration of 500 fs has been achieved in the case of 21.6-m cavity length using 4.9-m long external fiber line giving the compression factor of 1.5X. It is worth to say that this cavity length corresponds to the highest lasing efficiency as it is shown in Fig. 7. However due to losses caused by external section of SMF-28 fiber, average output power decreased down to 117 mW. The autocorrelation trace and spectrum of compressed pulse are presented in Fig. 8 (red traces). Though the pulse peak can be accurately approximated with sech^2 function, pulse contains low intensive pulse pedestal [see Fig. 8(a)]. By autocorrelation traces and pulse spectra integration along with corresponding soliton function integration it has been calculated that pulse peak contains 86% of entire generated energy reaching 10.87 nJ at 9.26 MHz repetition rate which corresponds to the pulse peak power of as high as 21.7 kW.

Assuming that 70% of entire generated energy has been coupled from the laser cavity, the pulse energy of 3.28 nJ is launched to the PVA-based polymer film with incorporated SWCNT. According to the previous experiments on the long-term stability,

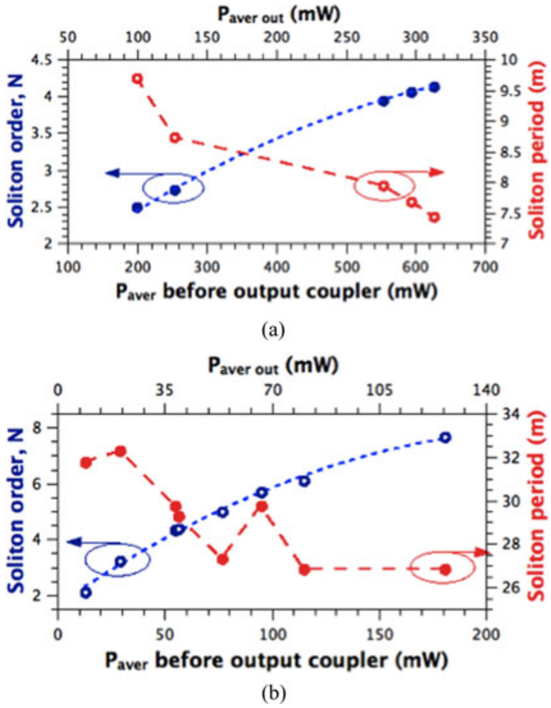

Fig. 9. High-order soliton evolution through the power increase in short cavity (a) long cavity (b) laser.

the polymer film possesses enough thermal reliability to ensure stable mode-locking at such high energies.

IV. Discussions

Obviously, the pulse energy of both short and long cavity lasers is higher than that expected from the traditional conservative soliton fiber lasers. We will discuss here this interesting point only briefly and the comprehensive theoretical and numerical analysis will be presented elsewhere.

A fundamental soliton duration τ_p is limited by the total cavity dispersion value [26] whereas the fundamental soliton energy E_s is inherently limited by the soliton area theorem [27]

$$E_s \propto \frac{|\beta_2|}{\gamma \cdot \tau_p}. \tag{2}$$

Here γ is the fiber nonlinear coefficient, $\gamma = 0.78\ \mathrm{W}^{-1}\mathrm{km}^{-1}$. If the pump power is strongly increased laser pulses tend to break into multi-soliton operation, giving rise to the soliton quantization effect [27], which is responsible for the pulse energy limitation of common soliton fiber lasers.

The soliton order, scaled by the peak power value of fundamental soliton, could be found as [28]

$$N^2 = \frac{P_{\text{peak}} \cdot \gamma \cdot \tau_p^2}{3.11 \cdot \beta_2}. \tag{3}$$

Assuming pulse parameters achieved in both short and long cavities, soliton order would vary from 2 to 9.5 before transmitting through the output coupler, as it is shown in Fig. 9. Previously higher-order soliton generation was reported in mode-locked dye [29] and Ti:Sapphire lasers [30]. It is well known that higher-order solitons undergo periodical evolution while propagating in an optical fiber, but restore their shape with the so-called soliton period determined as [27]

$$Z_0 = \frac{\pi}{2} \cdot 0.322 \cdot \frac{\tau_p^2}{\beta_2}. \tag{4}$$

The estimated change of the soliton period through the pulse average power increase is shown in Fig. 9 (red plots).

It is important to stress, however, that pulse propagation in the laser cavity in general cannot be explained with a standard theory of higher-order soliton periodical evolution. A laser presents a complex nonlinear dissipative system and pulse experiences at high powers strong intracavity variations [31], [32]. Due to the distribution of gain and losses along the cavity, pulse energy significantly varies during propagation, resulting in pulse energy and, consequently, soliton order decrease before it is restored again in the gain medium. Thus, periodical multi-soliton evolution is overimposed on the strong intra-cavity dynamics and, actually, occurs only in the fiber segment of the 65-cm length on the distance between the thulium-doped fiber and the output coupler [33], [34]. At the highest pulse peak powers soliton period corresponds to 14.7 and 48.15 propagation lengths for short and long cavity laser setups respectively. This means that pulse at the laser output is not changed dramatically and its shape is close to one of the fundamental soliton.

V. Conclusion

In conclusion we have demonstrated the hybrid passive mode-locked thulium-doped all-fiber soliton laser. Application of SWCNTs-based saturable absorber (as comparatively slow one) facilitates mode-locking startup whereas the fast NPE mechanism based on the nonlinear optical Kerr effect allowed to achieve high average output power and pulse energy with the high long- and short-term stability. The laser benefits from the simple ring cavity design and single-mode pumping by available high-power laser diode at 1.55 μm. Two different cavity schemes have been studied, possessing different cavity lengths. Thus, laser with the short cavity generates 600-fs or 1.28-ps pulses at 72.5 MHz repetition rate with the average output power of 300 mW, that is more than one order of magnitude higher than earlier reported results for SWCNT mode-locked fiber lasers. The peak power has reached 4.88 kW and the pulse energy is 2.93 nJ. The lasing efficiency is 32.6%. At a 21.6-m long ring cavity (at 9.25 MHz repetition rate) laser generates 500-fs pulses with corresponding energy up to 10.87 nJ and a pulse peak power of 21.7 kW. The average output power reached 120 mW at the slope efficiency of 17.46%.

Such a high pulse energy and peak power with the excellent long and short-term stability could find numerous applications, including supercontinuum generation in Mid-IR range. Typical sources in this case are pumped by a master oscillator power amplifier consisting of seed mode-locked fiber laser and one or several amplification stages. Such a complicated scheme makes it technically challenging for applications whereas obtaining high power directly from a seed laser without the chirped pulse amplification technique is very attractive.

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