Self-Starting Harmonic Mode-Locked Thulium-Doped Fiber Laser with Carbon Nanotubes Saturable Absorber

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Self-Starting Harmonic Mode-Locked Thulium-Doped Fiber Laser with Carbon Nanotubes Saturable Absorber *

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We report a ring cavity passively harmonic mode-locked thulium-doped fiber laser (TDFL) using a newly developed single-wall carbon nanotube-based saturable absorber. The TDFL generates the 25th harmonic mode-locked stretched pulse train with a high repetition rate of 213 MHz and a pulse duration of 710 fs. The laser operates at 1901.6 nm with an average power of 1.89 mW, which corresponds to the pulse energy of 0.008 nJ, at 1552 nm pump power of 719 mW. The peak-to-background ratio is measured to be 60 dB, which indicates the stability of the laser.

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Carbon nanotubes (CNTs) have gained tremendous attention due to their excellent electrical and optical properties, which enable them to be used for various high performance electronic and photonic devices.[1,2] In particular, their unique nonlinear optical properties make them ideally implemented in a wide range of photonic devices, such as saturable absorbers,[1−3] ultra-fast optical switches,[4] and wavelength converters.[5] In terms of nonlinear saturable absorption, CNTs are known to provide distinctive advantages in their ultra-fast recovery time and wide absorption bandwidth compared to their semiconductor-based counterparts.[1] Recently, pulsed fiber lasers have gained tremendous interest for various applications.[6,7] Many works have also been reported on the use of CNT-based saturable absorbers for the implementation of Q-switched or mode-locked lasers.[1−3] Most of these works focus on 1550 nm and 1060 nm applications, which can be implemented using an erbium- or ytterbium-doped fiber gain media, respectively.

Lasers based on thulium-doped fibers (TDF) can extend the accessible wavelengths towards the eye-safe 2-μm-region. It is well known that 2-micron pulsed lasers are useful in various applications such as medicine, LIDAR, and remote sensing.[2,8−10] However, only a few thulium-doped femtosecond fiber lasers have been demonstrated so far, based on different mode-locking mechanisms. Nelson *et al.* used a spectral filter and nonlinear polarization evolution as mode-locking mechanism.[11] Sharp *et al.* achieved mode-locking by using a semiconductor saturable absorber.[12] In this Letter, a mode-locked TDF laser (TDFL) is demonstrated using a simple and low cost CNT-based saturable absorber (SA). The SA is constructed by sandwiching a single walled CNT-polyethylene oxide (CNT-PEO) film, which is obtained using an evaporation technique, between two fiber connectors.

First, 250 mg single-walled CNTs were added to 400 ml sodium dodecyl sulphate (SDS) solution in deionized water at 1% concentration before being sonicated for 30 min at 50 W. The dispersion of single-walled CNTs in the solution was achieved ultrasonically with the aid of SDS. The solution was centrifuged at 1000 rpm to remove large particles of undispersed CNT to obtain dispersed suspension that is stable for weeks. CNT-PEO composite was prepared by adding 1.8 ml of dispersed CNT suspension containing 1.125 mg solid CNT into a solution of 1 g PEO (average molecular weight of 1 × 106 g/mol) in deionized water and mixing them thoroughly. The CNT-PEO composite was casted onto a glass petri dish and kept inside a vacuum oven at 60℃ for 48 h to form a thin film with a thickness of around 50 μm. The SA is fabricated by cutting a small part of the prepared film ($2 \times 2\,\mathrm{mm}^2$) and sandwiching it between two FC/PC fiber connectors, after depositing index-matching gel onto the fiber ends. The insertion loss of the SA is measured to be around 6 dB at 1550 nm.

Our mode-locked TDFL is schematically shown in Fig. 1. The inset shows the images of the film pasted onto a fiber ferrule and the constructed SA. The fiber laser was constructed using a simple ring cavity, in which a TDF with an absorption of 5 dB/m at 1550 nm was used for the active medium and the fabricated CNT-based SA was used as a mode-locker. The TDF used has a numerical aperture of 0.15 and core and

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cladding diameters of 9 µm and 124 µm, respectively. It was pumped by a 1552 nm erbium-ytterbium co-doped fiber laser via a 1550/1590 nm wavelength division multiplexer (WDM). The operating wavelength of the proposed TDFL was determined by the FBG, which was connected to port 2 of the circulator so that the reflection from the FBG could be routed back into the laser cavity via port 3. The circulator was used to allow the reflected light from the FBG to oscillate in the ring cavity as well as to ensure a unidirectional operation of the laser. The FBG used has a central wavelength of 1901.6 nm with a 3 dB bandwidth of 1.5 nm and a reflectivity of 99.6%. The ring cavity length was estimated to be around 24.3 m corresponding to a fundamental repetition rate of 8.4 MHz, and the net dispersion was estimated to be positive since most of the fibers that formed the cavity had positive dispersion. The temporal characteristics of the laser output were monitored using a combination of a photo-detector and a real time oscilloscope. The optical spectrum was measured using an optical spectrum analyzer (OSA).

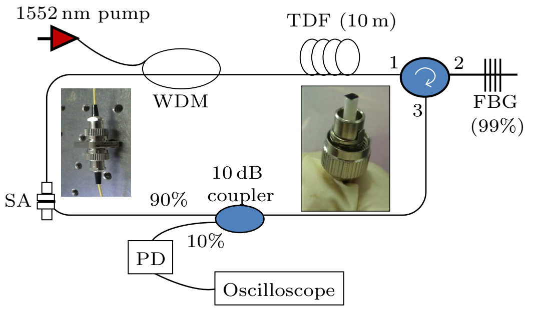

Fig. 1. Schematic configuration of the proposed mode-locked TDFL. Inset: the attachment of the film on the fiber ferrule and the constructed SA.

The TDFL starts to lase at the threshold pump power of 440 mW for the cw operation. It is observed that the laser always works in the cw operation with efficiency of around 9.1% in the absence of the SA in the cavity, and the operation was insensitive to the polarization state. As the CNT-based SA is incorporated in the laser cavity, the mode-locked laser self started at 1552 nm pump power of 656 mW without the requirement of introducing any disturbance to the intracavity fiber. However, the generated mode-locking pulse is unstable due to the absence of a polarization controller to control the interaction between the acoustic waves induced by the pulse propagation in the fiber. Further increase in pump power has resulted in a stable pulse splitting, hence generating the self-arrangement of stable harmonic mode locking. Figure 2 shows the optical spectrum of the passively mode-locked TDF at its 25th harmonic analyzed by an OSA limited by a resolution of 0.05 nm. It operates at the central wavelength of 1902.0 nm, which coincides with the FBG wavelength without any observation of Kelly sidebands. A spectral broadening is observed with full width at half maximum of 0.24 nm, which is most probably due to self-phase modulation effect (SPM), where the optical Kerr effect induces a phase shift in the pulse that leads to a change in the frequency spectrum. This is consistent with the estimated positive net dispersion at 2000 nm region, which results in the fiber laser operating in stretched pulse mode. This indicates that the interaction between nonlinearity and dispersive wave propagating in the cavity is not in a phase matching condition, wherein the large positive and negative dispersion causes the propagating pulse to be alternately stretched and compressed as they oscillate in the ring cavity.

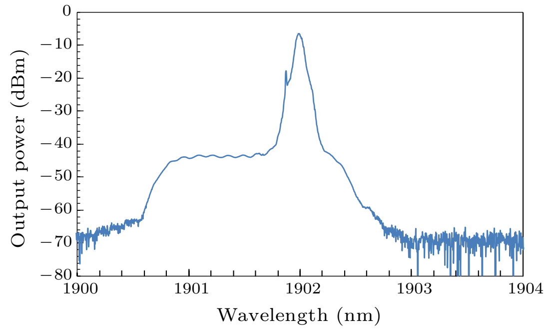

Fig. 2. Output spectrum of the proposed mode-locked TDFL at 1552 nm pump power of 723.3 mW.

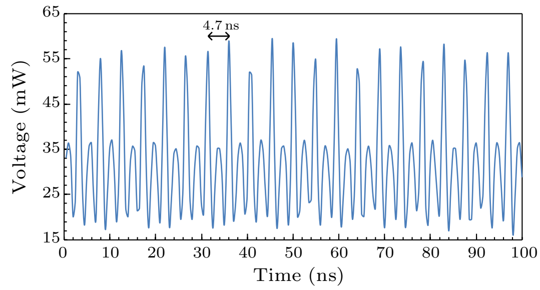

Fig. 3. Oscilloscope trace of the laser output at pump power of 719 mW showing a pulse train with a repetition rate of 213 MHz.

Figure 3 shows a pulse train from the mode-locked TDFL recorded by an oscilloscope at 1552 nm pump power of 719 mW. As is seen, the time interval is measured to be around 4.7 ns, which corresponds to a repetition rate of 213 MHz. The repetition rate represents 25th harmonic mode since the fundamental repetition rate is estimated to be around 8.4 MHz based on the actual ring cavity length. Multiple pulses are generated as identified in the pulse train, which is due to the energy quantization. The high repetition rate obtained is due to the multiple pulses circulating inside the cavity that generate harmonic mode-locked fiber laser. The major factors that create this phenomenon are inter-related with the peak-power limiting effect of the laser cavity besides the gain competition between the multiple pulses. It is observed that the repetition rate is unchanged and the pulse width decreases as the pump power increases. The average pump power increases from 0.60 mW to 1.89 mW as the pump power increases from 656 mW to 719 mW. The generated mode-locked laser is operating in the 25th harmonic mode from the fundamental mode. This proves that the proposed CNT-based SA is able to operate efficiently in the ring TDFL.

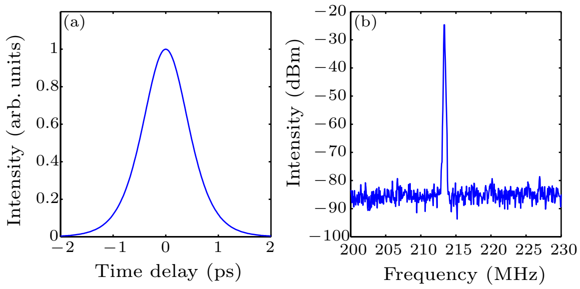

Fig. 4. (a) Autocorrelation trace of output pulses with FWHM of 0.71 ps. (b) The rf signal of the mode-locked TDFL.

Figure 4(a) shows a plot of a typical output second harmonics generation autocorrelation trace for the proposed mode-locked TDFL. The pulse duration at its full width half maximum (FWHM) is estimated to be about 710 fs. At the pump power of 719 mW, the measured average output power is 1.89 mW, which corresponds to the pulse energy of 0.008 nJ. The calculated time bandwidth product is 88, which shows that the generated pulse is highly chirped. It is also observed that the average output power increases with the rise in 1552 nm pump power as well as the pulse energy. Figure 4(b) shows the mode-locked laser output in frequency domain, which was obtained by using an rf spectrum analyzer. The measured rf spectrum indicates that the mode-locked laser output works in its 25th harmonic mode with the repetition rate of 213 MHz. The peak-to-background ratio, which is obtained from the intensity ratio of the fundamental peak to the pedestal extinction, is obtained at 60 dB, which indicates the stability of the laser.

In conclusion, a 25th harmonic mode-locked TDFL is demonstrated using a newly developed single-walled CNT-based SA in all-fiber configuration. The TDF is pumped by a 1552 nm fiber laser to operate at 1902.0 nm with the help of an FBG. The SA is obtained by sandwiching an earlier prepared CNT-PEO film between two fiber connectors for passive mode-locking. It generates a stretched pulse train with a repetition rate of 213 MHz and pulse duration of 710 fs. The laser has an average power of 1.89 mW, which corresponds to the pulse energy of 0.008 nJ at 1552 nm pump power of 719 mW. The peak-to-background ratio of the rf signal is obtained at 60 dB, which indicates the stability of the laser.

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