Mode-locked 1.93 μm thulium fiber laser with a carbon nanotube absorber

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We report a ring-cavity thulium fiber laser mode locked with a single-wall carbon nanotube absorber used in transmission. A carboxymethyl cellulose polymer film with incorporated carbon nanotubes synthesized by the arc discharge method has an absorption coinciding with in the amplification bandwidth of a Tm-doped fiber. This laser is pumped by an erbium fiber laser at 1.57 μm wavelength and produces a 37 MHz train of mode-locked 1.32 ps pulses at 1.93 μm wavelength with an average output power of 3.4 mW. © 2008 Optical Society of America

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Recently, a saturable absorption observed in carbon nanotubes has been used for the passive mode locking of near-infrared lasers. This regime has been implemented in a number of mode-locked erbium fiber lasers operating at a wavelength about 1.55 μm. Different types of cavities and nanotube-based mode-locker constructions have been used [1–5]. In solid-state lasers with bulk elements, the carbon nanotube aqueous suspensions were used for mode locking at 1.06–1.56 μm [6,7]. The filmlike elements incorporating nanotubes were used at 1.34 μm [8]. However, to the best of our knowledge there has been no demonstration of the mode-locked laser with the carbon nanotube absorber operating in the mid-infrared spectral range and, particularly, around 1.9 μm range of the amplification band, a characteristic of a Tm-doped silica fiber.

Pulsed-laser sources in the mid-infrared range are useful for applications in a variety of fields, including medicine, spectroscopy, multiphoton microscopy, remote sensing, and pumping of optical parametric oscillators. The short-pulse fiber sources with well-known advantages, such as their compactness, excellent beam quality, and environmental reliability, start to challenge the bulk solid-state lasers. A thulium-doped silica fiber has a broad amplification bandwidth (1.7–2.1 μm) that makes it suitable for a short-pulse generation in the 2 μm range. Up to now, very few short-pulse Tm-doped fiber sources have been reported, to our knowledge. Authors of [9] used additive pulse mode locking to generate sub-500 fs pulses with an average output power of few hundreds of microwatts. A thulium fiber laser passively mode locked by an InGaAs-saturable absorber has been demonstrated [10]. The system has delivered 190 fs pulses with an output power of 1 mW. Recently, soliton pulses with a tunable wavelength (1.97 to 2.15 μm) and an average power up to 230 mW have been reported [11] and have been generated with a fiber power amplifier/Raman shifter being seeded with a subpicosecond tunable Tm–Ho-doped fiber oscillator mode locked with a Sb-based semiconductor saturable absorber mirror. The authors of [12] achieved pulses with 108 fs duration and 230 kW peak power at 1.98 μm and wavelength tuning over the range of 140 nm via amplification of a Raman-shifted femtosecond erbium fiber oscillator in a large-mode-area Tm-doped fiber.

In this Letter, we demonstrate a thulium fiber laser mode locked with a single-wall carbon nanotube absorber and report the results of our experiment. A polymer film incorporating carbon nanotubes synthesized by the arc-discharge technique forced a ring thulium fiber laser to produce 1.32 ps mode-locked pulses with a wavelength around 1.93 μm and an average output power of 3.4 mW.

We used carboxymetyl cellulose (CMC) as a host polymer for carbon nanotubes. The advantage of CMC is that it represents simultaneously a surfactant with a high nanotube dispersion activity and a medium forming a film after the suspension drying. Carbon nanotubes synthesized by the arc-discharge method have an optical-absorption band shifted to longer wavelengths (in IR range) than the absorption bands of nanotubes synthesized by other methods, such as a laser ablation and a high-pressure decomposition of CO gas. Usually the synthesis method defines a nanotube diameter distribution. On the basis of Raman spectral analysis we have found that the prepared CMC film contains nanotubes with diameters of 1.2–1.7 nm. Figure 1 presents the transmission spectra of the CMC polymer films. The upper curve corresponds to a pure polymer film without carbon nanotubes in it. The oscillation on the spectrum is caused by an interference in the thin film. At any rate, it is clear that a transparence of the CMC film in the 1.8-2 μm range is about 90%. The lower spectrum demonstrates a transmission of the CMC film incorporating the arc single-wall carbon nanotubes. The spectrum exhibits an absorption band extending from 1.5 to 2 μm, with its center at 1.75 μm. The absorption band width is determined by the width of

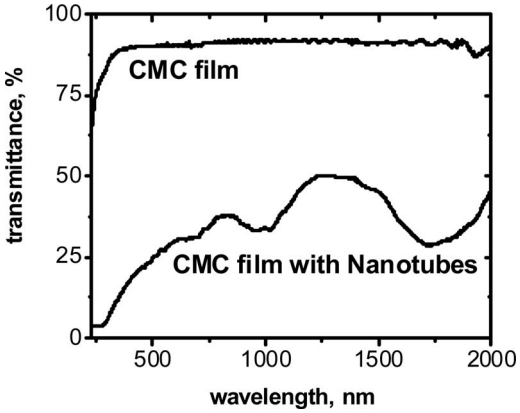

Fig. 1. Transmittance optical spectra of the pure CMC film (upper curve) and the CMC film with carbon nanotubes (lower curve).

the nanotube diameter distribution. This absorption band of these nanotubes overlaps with an amplification bandwidth of a thulium-doped silica fiber. A signal transmittance of the film at the operating wavelength 1.93 μm is about 37%.

The laser scheme is shown in Fig. 2. The ring cavity with a total length 5.6 m is comprised of 4 m Tm-doped fiber, wavelength-division-multiplexed 1.57/1.9 μm fused fiber coupler for pumping, the output fused fiber coupler, the polarization controller, and the carboxymethyl cellulose polymer film with incorporated carbon nanotubes inserted in the fixed connection/physical contact between two ferrules. The Tm-doped fiber has 0.16 NA, 9.5 μm mode-field diameter at 1930 nm, $\sim$1 W^{-1} km^{-1} estimated nonlinearity coefficient, and $\sim$–55 ps^2/km estimated dispersion. It is pumped with a cw erbium fiber laser at 1.57 μm to the core. Both pump and output fused couplers are made from SM28-like fiber that provides the polarization-sensitive loss at a working wavelength of 1.93 μm. The polarization controller was used to minimize polarization-sensitive loss in fiber couplers. It has to be noted that the control of the polarization does not directly influence the regime of generation but causes a small changing of the threshold and the output power. All fiber ends are angle cleaved. Unused fiber ends are immersed. There is no optical isolator in the cavity. Instead, 4 m of highly Tm-doped fiber (~6000 wt. parts per million) is applied to provide unidirectional start of laser operation. With pumping into the core, the power of the luminescence from the pump-input side is significantly higher than the luminescence from the other side of the active fiber. We assumed that, owing to this effect and the use of a nonlinear absorber in the cavity, the threshold of the generation in the counterdirection to pump propagation should be lower than in the codirection. Our experiment has proved the assumption that the laser prefers to start operating in the counterdirection to pump propagation.

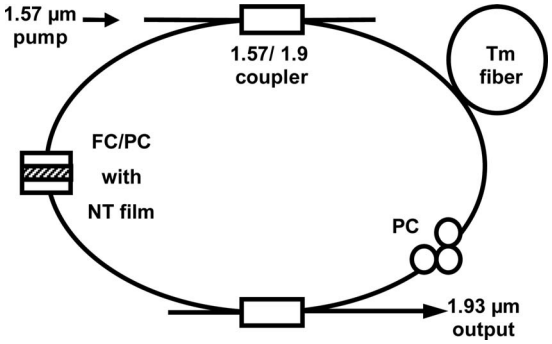

Fig. 2. Scheme of the ring-cavity Tm-doped fiber laser mode locked with a carbon nanotube absorber. PC, polarization controller; NT film, CMC polymer film with incorporated carbon nanotubes; FC/PC, fiber connector.

In case of absence of the carbon nanotube absorber in the cavity, the laser always works in a cw regime, being insensitive to the polarization state. Once the CMC film with nanotubes is inserted into the cavity, the laser starts to operate in a passive mode-locking regime with 280 mW pump threshold in the counterdirection to pump propagation. Exceeding the pump power over 330 mW leads to generation in both directions owing to a lack of a fiber-pigtailed optical isolator in the cavity. That makes laser operation unstable with Q-switch pulse occurrence and, in turn, results in damage of the polymer CMC film with carbon nanotubes. In this case the film with carbon nanotubes has to be replaced. With 300 mW pump power the laser produces a 37 MHz mode-locked pulse train with 3.4 mW average power at the output. Figure 3 shows the output pulse train measured by a fast photodetector with a 1.3–2.4 μm working spectral range and an oscilloscope with 500 MHz bandwidth.

The optical spectrum of the output pulses measured with 0.33 nm resolution is demonstrated in Fig. 4. The central wavelength is 1932 nm, and the spectral width at a half-maximum level is 5 nm. An output spectrum exhibits typical sidelobes that corresponds to a solitonlike pulse shape. An autocorrelation trace of the output pulses is presented in Fig. 5. The FWHM level of the autocorrelation trace is 2 ps. According to a soliton pulse shape, the calculated pulse duration is 1.32 ps. Thus the time-bandwidth product is 0.528, exceeding a typical value of a transform-limited pulse waveform (0.315). This means that the output pulse is chirped and can be shortened down to 800 fs after complete compensation of the chirp. On the other hand, the laser cavity was not specially designed to obtain the shortest pos-

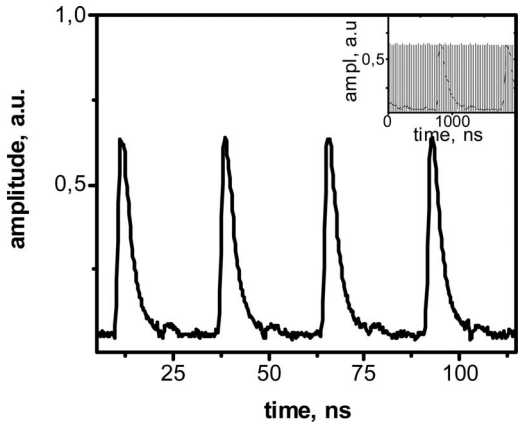

Fig. 3. Output pulse train with a repetition rate of 37 MHz. Inset, a pulse train in a 2 μs time segment.

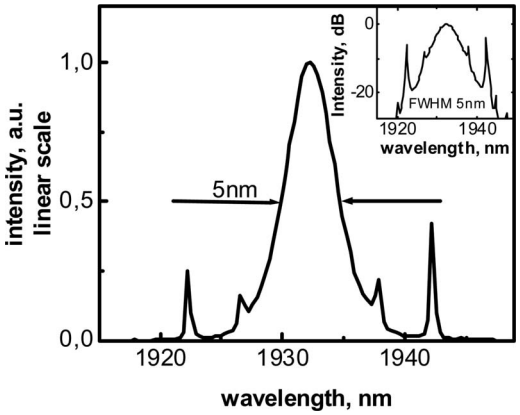

Fig. 4. A typical output spectrum on a linear scale. Inset, spectrum on a logarithmic scale.

sible pulse duration; the aim was to find out the suitability of a carbon nanotube absorber for mode locking around 1.9 μm and to create an all-fiber mode-locked thulium laser. The cavity dispersion was sacrificed for the simplicity of the laser scheme. The mode-locking operation is stable while the pump power is in the 280–330 mW range. No sensitivity from vibration or small temperature drift was noticed. Mode locking self-starts and does not require tuning of the polarization controller to start and to operate. Long-term stability measurement was not made; nevertheless, for several tens of minutes during experiments laser operation is stable.

To summarize, we have demonstrated for the first time (to the best of our knowledge) a mode locking of a ring-cavity thulium fiber laser with the help of carbon nanotubes synthesized by the arc discharge method. This all-fiber simple and compact thulium laser delivers pulses at a 1.93 μm spectral range with a 2 ps autocorrelation trace and produces a 37 MHz mode-locked pulse train with a 70 W peak and 3.4 mW average output optical power. Our results indicate that the CMC film with incorporated carbon nanotubes synthesized by the arc discharge method is a promising optical material for the mode-locking laser in the 1.9 μm spectral range. The results presented here can be extended to higher power and the shorter pulse durations through a minimization of the losses, a compensation of dispersion, and an increase in the damage threshold of the polymer film incorporating single-wall carbon nanotubes.

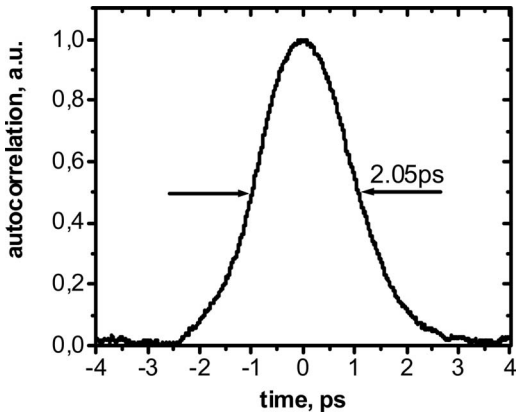

Fig. 5. Autocorrelation trace of the output pulses.

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