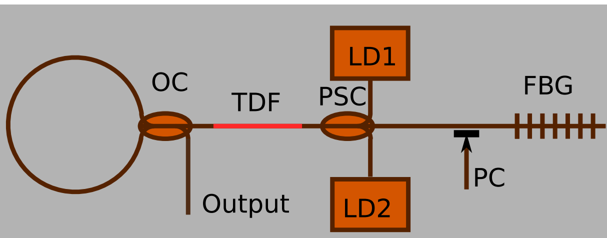
Abstract: We have demonstrated an all-fiber mode-locked thulium-doped fiber laser with extremely long pulses, a very narrow spectrum and a high average power. The mode-locker is formed by a nonlinear loop mirror. The laser generates sinus-squared waveform with a repetition period of 82 ns and an average power between 100-150 mW. The wavelength is defined by the fiber Bragg grating and it is 1956 nm.



Mode-locked thulium-doped fiber laser setup.

A mode-locked thulium-doped fiber laser based on a nonlinear loop mirror

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1. Introduction

Passively mode-locked fiber lasers are known to generate stable and high quality periodic pulse trains, especially when a single pulse exists in the laser resonator. All-fiber mode-locked lasers have been demonstrated with ytterbium [1], erbium [2] as well as thulium-doped fibers [3]. Alternatively, hybrid lasers made of active and passive fibers and bulk elements were demonstrated. Extremely large pulse energy of 780 nJ was achieved in hybrid laser based on an ytterbium-doped very large mode area fiber where a periodic train of pulses compressible down to 91 fs with an average power of 60 W was generated [4]. Ultrashort pulses with small energy were generated in hybrid lasers based on erbium [5] and thulium [6]. Mode-lockers based on semiconductor saturable absorption mirrors (SESAM) attracted interest of many researchers and were used in ytterbium [7], thulium [8] and thulium-holmium-doped [9] passively mode-locked fiber lasers. Alternatively, carbon nanotubes were used to achieve passive mode-locking in ytterbium [10], erbium [11], thulium [12], and holmium [13] doped fiber lasers.

As thulium has the broadest emission peak of all rare-earth ions, it makes thulium-doped pulse fiber lasers attractive for their wideband tunability in eye-safe spectral region that covers both wavelengths with strong absorption in water or plastics as well as spectral ranges free of absorption. Such lasers can find their applications in minimally invasive surgery, plastic welding, lidars etc.

Saturable absorption in semiconductor structures [8] and carbon nanotubes [12] were used as a mode-locking mechanism in thulium-doped fiber lasers. Alternatively, all-fiber mode-locked lasers based on nonlinear polarization evolution in optical fiber were demonstrated [3, 14].

In this paper we present a mode-locked thulium-doped fiber laser that generates very long pulses with a pulse width of tens of nanoseconds. The output power has a form of sinus-squared function and only a few modes are synchronized by a weak mode-locking mechanism in the output fiber loop mirror. The laser can be used whenever the harmonic modulation with low content of higher harmonics is required, e.g. for sensitive detection etc.

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2. Experimental setup

The fiber laser involves only fibers and pigtailed optical components, which greatly simplifies adjustment and improves reliability. The laser topology is shown in Fig. 1. The resonator consists of an active fiber, a fiber Bragg grating (FBG) and a partly reflecting output loop mirror. We used a 3.5 m long polarization maintaining thulium-doped double-clad fiber (PM-TDF-10P/130-HE, Nufern) as an active fiber. The fiber has a core diameter of 10um and an inner-cladding diameter of 130um. It is covered by a low index polymer coating with a diameter of 215um. The numerical apertures of the core and the inner cladding are 0.15 and 0.46, respectively. The stress elements of the Panda-like fiber randomize the ray paths of pump radiation in the inner cladding so that neither the inner cladding shaping nor the special fiber winding is necessary to make the skew rays to cross the core. The active fiber was surrounded by short lengths of matched passive fibers (GDF-10P/130, Nufern). The GDF fiber was tapered and spliced with the pump-signal combiner which was (2+1PM)/1PM type from ITF. A pair of multimode laser diodes at a wavelength of 793 nm were used for pumping the active fiber. Each of the pump diodes gives power up to 3 W coupled into a 105/125 μm multimode fiber with a NA of 0.22. The wavelength was defined to be 1956 nm by a highly reflective FBG with a reflectivity of 0.99 and a bandwidth of 0.3 nm. The FBG is written into a SMF28 fiber and it is the only non-polarization maintaining element in the resonator. The polarization controller is used at the FBG pigtail to adjust the polarization states. We used a fiber loop mirror made of the polarization maintaining fiber coupler with a coupling coefficient 0.07/0.93 at a wavelength of 2000 nm as an output coupler. The fiber loop mirror has a reflectivity coefficient of 0.26. The loop length was approximately 2m.

The signal was observed with a highly sensitive detector with a response time of 30 ns of our own design. The detector is based on an InGaAs photodiode intended for 2000 nm spectral band. Complementary, the signal was detected with a fast photodetector (DET01CFC, Thorlabs) designed for 1550 nm band. The detector was operated in a two-photon absorption (TPA) regime. The response time of TPA detector was estimated to be 430 ps in a separate experiment with short-pulse mode-locked thulium-doped fiber laser. During the measurements almost the whole output power was sent towards the TPA detector, while only 0.2% were tapped and measured with the highly sensitive detector.

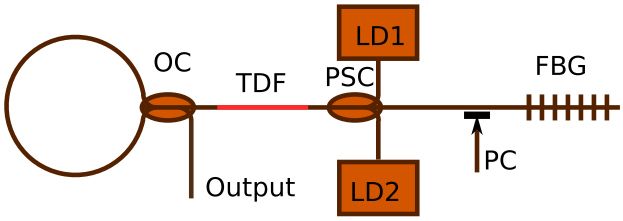

Figure 1 Scheme of the thulium-doped fiber laser. TDF–thulium-doped fiber, OC–output coupler, PC–polarization controller, LD–laser diode, PSC–pump-signal controller

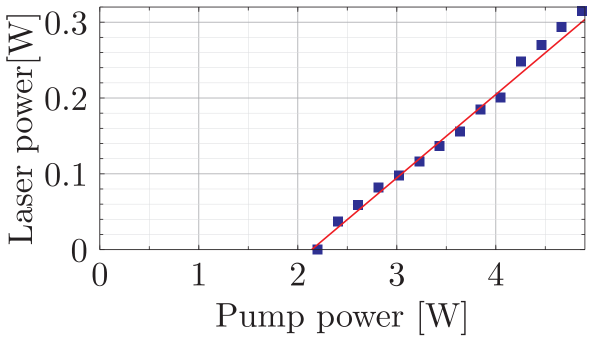

Figure 2 Pump power dependence of the laser power.

3. Experimental results and discussion

The laser has a threshold of 2.14 W and a slope efficiency of 0.11. The relatively low slope efficiency is given by the large reflection coefficient of the fiber loop mirror. The dependence of the output power on the pump power is shown in Fig. 2. It is known that the thulium-doped fiber laser have tendency to self-pulsing [15]. We observed chaotic pulsations on a characteristic microsecond time-scale close to the threshold as can be seen in Fig. 3a. This regime changes to mode-locked regime at a pump power of 3 W. Both the sensitive detector and the TPA detector displayed the same waveforms. The signal at the output of the sensitive detector is less noisy and it is reproduced in Fig. 3b). The details are shown in Fig. 3c). We can see that the waveform can be very precisely fitted with a sinus-squared function with a small background. We can conclude that the full-width at half maximum of the pulses is 41 ns, which is one half of the pulse period. It means that only a few modes take part in forming the pulses. The pulse period of 82 ns corresponds to the round trip time of the resonator. The overall length of the laser including a length of the fiber in the fiber loop mirror is estimated to be 8.2 m. The signal is destabilized above 3.6 W, as can be seen in Fig. 3d).

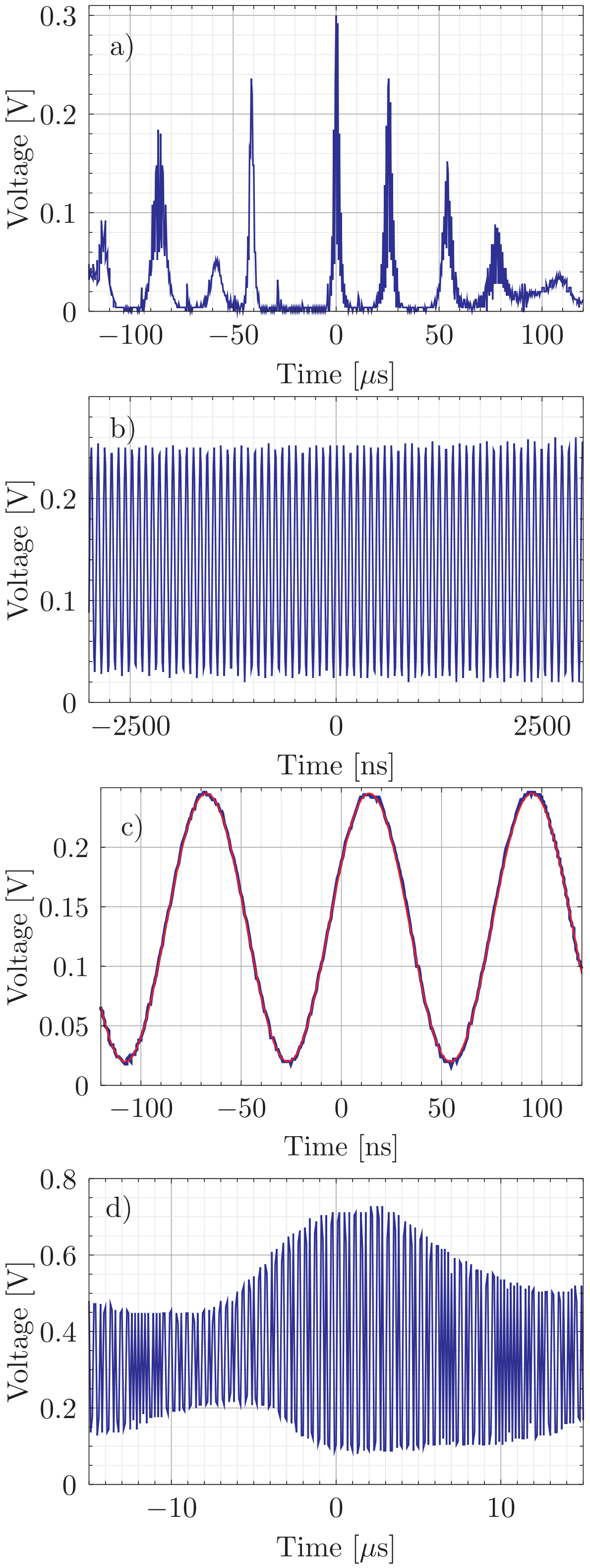

Figure 3 Three regimes of the fiber laser. a) Self pulsations close to the threshold. (b,c) Sinus-squared regime. (d) Destabilized regime at high pump power.

4. Conclusions

We investigated dynamics of a thulium-doped fiber laser with a resonator consisting of a highly-reflective narrow-band fiber Bragg grating and a partially reflecting fiber loop mirror. Almost perfect sinus-squared waveform was observed at the laser output with a period equal to the round-trip of the laser resonator. The form of the laser signal means that only a few modes take part in the waveform formation. Due to a small number of modes, a weak nonlinearity of the nonlinear loop mirror is sufficient to achieve the mode synchronization. Destabilization of this regime was observed for high pump powers.

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