Sub-50-fs pulse generation from thulium-doped ZBLAN fiber laser oscillator

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Abstract: An ultrafast, passively mode-locked fiber laser oscillator has been realized using thulium-doped ZBLAN fibers. Very low dispersion of ZBLAN glass fibers enabled generation of pulses with broad spectra extending from 1730 nm to 2050 nm. Pulses are obtained with the average power of 13 mW at the repetition rate of 67.5 MHz when the pump power is 140 mW. The output pulses are compressed with a pair of SF10 prisms and their durations are measured with SHG FROG, from which we obtained the pulse duration as short as 45 fs.

OCIS codes: (060.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (320.7090) Ultrafast lasers.

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1. Introduction

Passively mode-locked fiber lasers operating around 1 µm and 1.5 µm have been extensively studied over the past decades. In recent years, thulium-doped fiber lasers have attracted significant attention because they extend the operating wavelength toward 2 µm region, which will be useful for various fields such as medical applications [1], remote sensing [2], micro-machining [3], high harmonic generation [4,5], and mid-infrared generation [6–8]. In particular, broad emission spectra of thulium-doped fibers make them ideal candidates for ultrashort pulse sources in this wavelength region. However, it is not trivial to obtain ultrashort pulses from fiber lasers where the effect of the dispersion from long fibers is quite significant. The first femtosecond thulium-doped fiber laser was realized without dispersion compensation within the laser cavity [9] and was mode-locked by nonlinear polarization evolution (NPE) mechanism using waveplates and a spectral filter. Dispersion compensation was attempted with several methods such as inserting a stretcher in the cavity [10,11] or using normal-dispersion fibers that compensate the dispersion of ordinary fibers [12,13]. The shortest pulses reported from thulium-doped fiber laser oscillator so far was 58 fs [14].

Another approach would be using fibers made of materials with less dispersion. Fluoride glass known as ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) has high transmittance in the mid-infrared region. The property of low absorption suggests that it also has low dispersion in the mid-infrared region, which can be confirmed by differentiating the Sellmeier equation of ZBLAN [15]. Thulium-doped ZBLAN fiber lasers have been thoroughly studied in cw regime and are known to exhibit performances superior to thulium-doped silica fiber lasers such as higher slope efficiency and lower lasing threshold [16, 17]. High transparency of ZBLAN in mid-infrared region was extensively exploited in supercontinuum generation [18–21]. However, the property of low dispersion has been overlooked and no previous work has utilized

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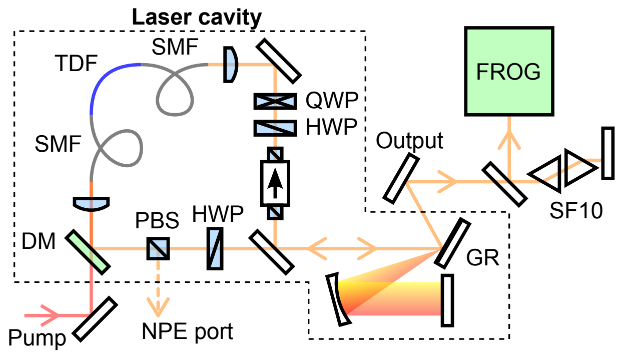

Fig. 1. Schematic of the experimental setup. TDF: thulium-doped fiber; SMF: single-mode fiber; DM: dichroic mirror; PBS: polarizing beam splitter; HWP: half-wave plate; QWP: quarter-wave plate; GR: grating.

ZBLAN fibers for developing ultrafast laser oscillators.

In this work, we present a passively mode-locked laser oscillator based on thulium-doped ZBLAN fibers with a broad output spectra extending over 300 nm. The output pulses are compressed down to 45 fs, which are the shortest pulses generated directly from laser oscillators around this wavelength region to our knowledge.

2. Experimental setup

The laser is built in a ring cavity configuration as shown in Fig. 1. The cavity has 0.2 m of single-mode, thulium-doped ZBLAN fiber (TDF) with the core diameter of 6 µm and the numerical aperture (NA) of 0.2. The concentration of thulium ion is as high as 4 mol %. The absorption at 793 nm is estimated to be $\sim$ 100 dB/m by sending the pump beam through a short piece of TDF and measuring the power of the transmitted pump beam. On each end of the TDF, 1 m of passive single-mode ZBLAN fiber (SMF) is attached to increase the cavity length and help mode-locking by NPE. The core diameter and NA of the SMF are the same as those of the TDF. Since it is difficult to splice ZBLAN fibers, each end of the ZBLAN fibers to be connected was finely polished and butt-coupled so that the transmission loss was minimized. The transmission loss at each connection point is $\sim$ 0.2 dB.

The material dispersion of ZBLAN glass around 1.8 µm to 2.0 µm ranges between $-5\,\mathrm{fs}^2$/mm to $-16\,\mathrm{fs}^2$/mm, which can be calculated from the Sellmeier equation [15]. These values are much smaller compared to those of fused silica, where the dispersion values range between $-45\,\mathrm{fs}^2$/mm to $-100\,\mathrm{fs}^2$/mm. Although the material dispersion of ZBLAN is negative around this wavelength region, relatively large NA and small core diameter of the fibers used for the experiment generate positive waveguide dispersion that overcompensates the material dispersion of the fiber, which makes the total dispersion of the fibers to be slightly positive. The total dispersion of ZBLAN fibers used for the experiment is estimated to range between $+11\,\mathrm{fs}^2$/mm to $+12\,\mathrm{fs}^2$/mm.

The active fiber is pumped by a Ti:sapphire laser (MaiTai, Spectra-Physics) operating at 793 nm. The pump beam is sent into the cavity through a specially coated dichroic mirror ($T > 97\,\%$@790 nm, $R > 98\,\%$@1600–2200 nm, Sigma-Koki) and coupled into a fiber with an aspherical lens ($f = 6$ mm). The coupling efficiency is estimated to be $\sim$ 75 % by coupling the pump beam into a piece of SMF and measuring the transmission.

Unidirectional operation is enforced by an isolator placed in a free space section of the cavity. A half-wave plate (HWP) and a quarter-wave plate (QWP) are used to adjust the polarization

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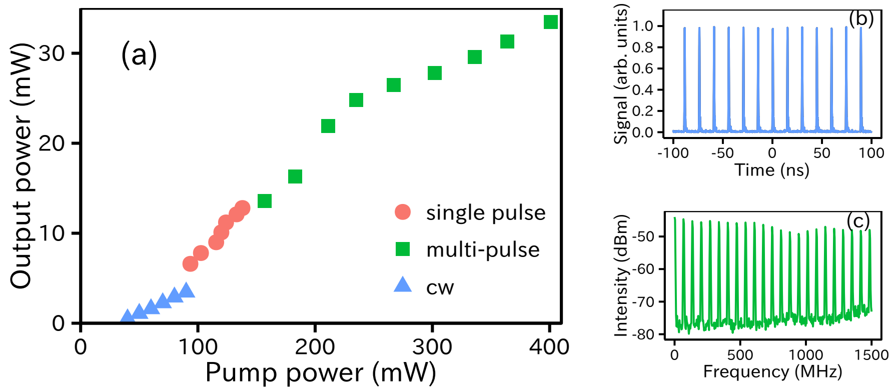

Fig. 2. Behavior of the output pulses. (a) Output power versus pump power. Red circles indicate single-pulse operation, while green squares and blue triangles indicate multi-pulse operation and cw operation, respectively. (b) Pulse train. (c) RF spectrum.

state in the cavity to mode-lock the laser by NPE. A polarizing beam splitter (PBS) is used as a rejection port for the NPE. To adjust the dispersion within the cavity, a single-transit Martinez-type "stretcher" [22] is placed in the cavity. Although this type of stretcher is usually used for adding positive dispersion, it can also be used for adding a small amount of negative dispersion, which is useful for our setup where the fibers have small positive dispersion. The position of the grating is adjusted so that the output spectra become broad and stable. Typical dispersion of the stretcher system is estimated to be $\sim -2 \times 10^4\,\mathrm{fs}^2$, with which the oscillator is expected to operate in dispersion-managed soliton regime [23]. It should be noted that the beam transmitted through this stretcher setup has spatial dispersion. However, the effect is rather small and did not deteriorate the laser operation. It is even possible that coupling the spatially dispersed beam into the fiber acts as a spectral filter that helps the mode-locked operation of the laser [24]. The zeroth-order reflection from the grating is used as the output beam instead of the beam from the NPE rejection port to obtain pulses with better quality [23,25]. The HWP in front of the grating is used to optimize the output coupling ratio.

3. Results

The output power and the behavior of laser operation was studied by changing the pump power. Figure 2 shows the laser output power as a function of the pump power measured in front of the dichroic mirror. The laser can be mode-locked at the pump power of $\sim 300\,\mathrm{mW}$. At that power level, however, the laser operated either in a multi-pulse regime or with a cw emission. When the pump power is reduced to $\sim 140\,\mathrm{mW}$, the oscillator started operating in a single-pulse regime with the output power of 13 mW. The pulses are output with a repetition rate of 67.5 MHz, which corresponds to the pulse energy of 190 pJ. The shot-to-shot stability of the pulses is $\sim 1\,\%$ over a couple of hours. The pump power could be further reduced to $\sim 90\,\mathrm{mW}$ while maintaining the single-pulse operation. The mode-locked operation ceases below that power level. Single-pulse operation is confirmed by observing the pulse train with a 7 GHz photo diode in combination with a 16 GHz oscilloscope and a 1.5 GHz radio-frequency (RF) spectrum analyzer. The results are shown in Fig. 2(b) and (c).

A typical output spectrum measured with a monochromator at the resolution of 0.4 nm is plotted in Fig. 3. The spectrum is centered around 1880 nm and extends from 1730 nm to

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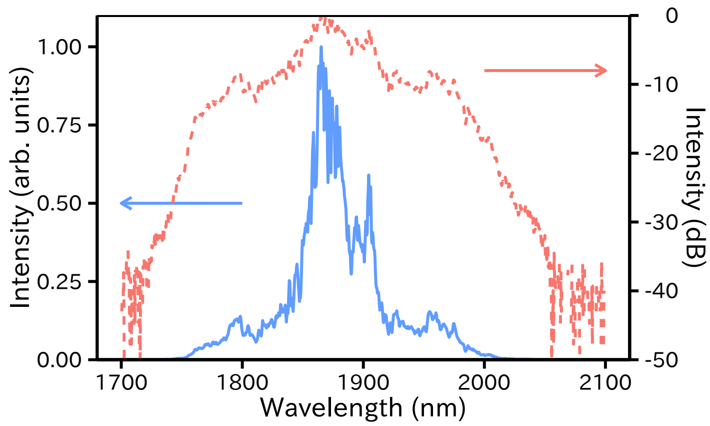

Fig. 3. Optical spectrum measured with a monochromator, plotted in linear scale (blue solid curve) and log scale (red dashed curve).

2050 nm at 30 dB below the peak. Previous work using Tm-doped silica fibers reports observation of sharp dips in the output spectra [13], which they attributed to absorption in the optical fibers. Contrastingly, we observed only a small structure around 1870 nm, which is much less pronounced compared to the structures observed in [13]. This could be caused by the difference between ZBLAN fibers and silica fibers. However, a spectrometer with better resolution and higher sensitivity is required to confirm this hypothesis.

To determine the duration of the output pulses, we used a home-built second-harmonic generation (SHG) frequency-resolved optical gating (FROG) device [26] with a 30 μm-thick BBO crystal installed as the nonlinear medium. Figure 4(a) shows a typical FROG trace of compressed pulses measured with the device. The output pulses are compressed by using a pair of SF10 prisms, which have negative dispersion in this wavelength region. The optimal compression was obtained when 36 cm of SF10 was inserted, which corresponds to the dispersion of -1.3×10^4 fs^2. This means that the output pulse has positive dispersion, which is reasonable because the pulses are output after accumulating positive dispersion from the fiber and before acquiring negative dispersion at the stretcher.

Figure 4(b) shows the FROG trace retrieved from the experimental trace shown in Fig. 4(a) with a FROG error of 0.4 %. Figure 4(c) and (d) show the corresponding shapes of retrieved pulse and spectrum. The pulse duration was obtained to be 45 fs. A small side pulse observed in Fig. 4(c) is due to residual higher-order dispersion observable in Fig. 4(d). The retrieved spectrum looks reasonably similar to the spectrum measured with the monochromator, which also confirms the validity of the FROG measurement.

From the NPE rejection port, pulses with average power of 10 mW was obtained at the pump power of 140 mW. However, these pulses could not be fully compressed in contrast to the pulses from the main output port. The shortest pulse obtained from the NPE rejection port was ~ 90 fs, and it had a significant pedestal that couldn't be compressed.

It should be noted that the pump power required for the system is at most a few hundred milliwatts, which can be obtained from commercial laser diodes (LD) with single-mode output. This means that the Ti:sapphire laser used as the pump laser for the current experiment can be replaced with much less expensive LDs.

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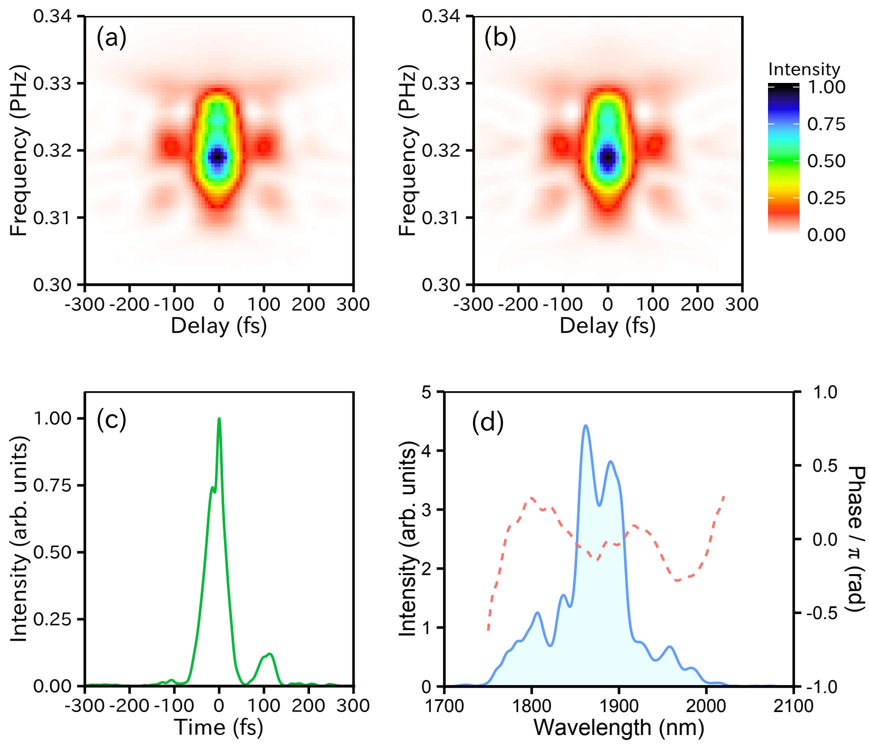

Fig. 4. Results of FROG measurement. (a) Measured FROG trace. (b) FROG trace retrieved from the experimental FROG trace shown in (a). (c) Retrieved pulse shape. (d) Retrieved spectral profile (filled blue curve) and phase (dashed red curve).

4. Conclusion

We have demonstrated a passively mode-locked thulium-doped ZBLAN fiber laser oscillator. Output pulses with the average power of 13 mW are obtained at the repetition rate of 67.5 MHz. Thanks to low dispersion of ZBLAN, the spectra of the output beam was as broad as 300 nm at 30 dB below the peak. The generated pulses could be compressed to 45 fs, which is the shortest pulses generated from laser oscillators operating around 2 µm wavelength region to the best of our knowledge.

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