Ultrafast 2 µm Laser Oscillators Based on Thulium-Doped ZBLAN Fibers

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Abstract: Mode-locked fiber laser oscillators are demonstrated by using thulium-doped ZBLAN fibers. Thanks to very low dispersion of ZBLAN glass fibers, pulses as short as 45 fs are generated at 1900 nm.

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In recent years, passively mode-locked fiber lasers operating around 1 µm and 1.5 µm have been studied extensively. Thulium-doped fiber lasers extend the operation wavelength to 2 µm region, which will be useful in many fields such as medical applications, eye-safe LIDAR, remote sensing, and mid-IR generation. Furthermore, broad emission spectra of thulium-doped fiber lasers make them promising light sources for ultrashort pulse generation in this wavelength region, which can be used for nonlinear processes such as micro-machining of transparent materials or efficient mid-infrared generation.

To obtain short pulses, the dispersion within the laser cavity must be compensated, which is not a trivial task for fiber lasers. The first mode-locked thulium-doped fiber laser is realized without any dispersion compensation and the duration of the generated pulses was $\sim$ 500 fs [1]. Dispersion compensation was attempted with various methods such as inserting a stretcher in the cavity [2] or using normal-dispersion fibers that compensate the dispersion of ordinary fibers [3] and pulses as short as 119 fs are reported.

Here we demonstrate another approach, where we can significantly reduce the dispersion from the fiber itself. We used a thulium-doped fiber made of fluoride glass known as ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF). ZBLAN is known to have excellent optical properties in the mid-infrared region such as high transparency and low dispersion, which makes it a promising laser material. Using thulium-doped ZBLAN fibers, we have built a laser oscillator with a broad output spectra extending over 300 nm. The output pulses could be compressed down to 45 fs, which are the shortest pulses generated directly from laser oscillators around this wavelength region to our knowledge.

The laser setup is shown in Fig. 1. The cavity consisted of 0.2 m of single-mode, thulium-doped ZBLAN fiber (TDF) with the core diameter of 6 µm and NA of 0.2. The concentration of thulium ion is as high as 4 mol %. The absorption

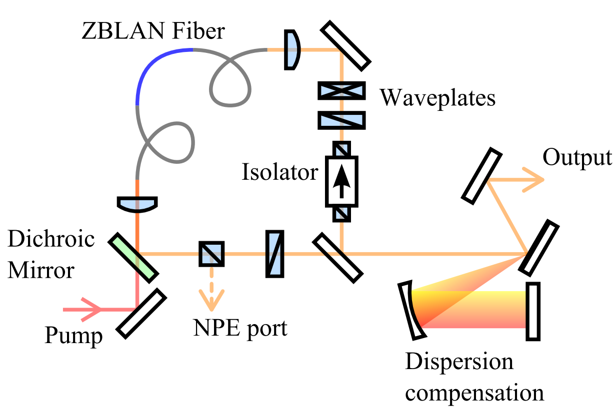

Fig. 1. Schematic of the experimental setup.

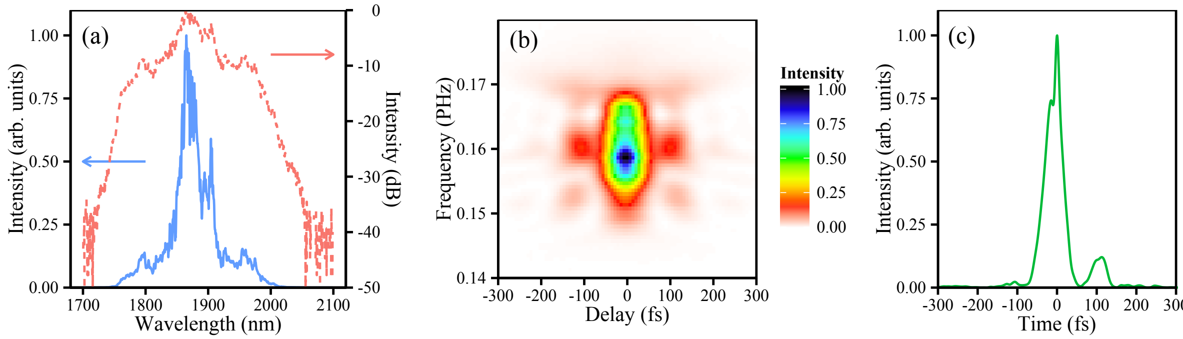

Fig. 2. Output from the oscillator. (a) Spectrum plotted in linear (blue solid curve) and log (red dashed curve) scale. (b) Measured FROG trace of compressed pulses. (c) Temporal profile retrieved from the FROG trace shown in (b).

at 793 nm is estimated to be $\sim 100\,\mathrm{dB\,m^{-1}}$. On each end of the TDF, a passive single-mode ZBLAN fiber (SMF) with the same core diameter and NA as the TDF with the length of 1 m is attached to increase the cavity length and help mode-locking by nonlinear polarization evolution (NPE).

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 dichroic mirror and coupled into a fiber with an aspherical lens ($f = 6\,\mathrm{mm}$). The coupling efficiency is estimated to be $\gtrsim 70\,\%$.

Unidirectional operation is enforced by an isolator placed in the free space section of the ring cavity. A half-wave plate (HWP) and a quarter-wave plate (QWP) are used to adjust the polarization 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-pass Martinez-type stretcher is placed in the cavity. Although the beam transmitted through this stretcher setup has spatial dispersion, the effect is rather small and did not deteriorate the laser operation. The zeroth-order reflection from the grating is used as the main output beam instead of the beam from the NPE rejection port. The HWP in front of the grating is used to optimize the output coupling ratio.

Figure 2(a) shows the output spectrum measured with a monochromator. The spectrum extends from 1730 nm to 2050 nm at 30 dB below the peak. Stable pulses with the output power of $\sim 13\,\mathrm{mW}$ are obtained from the main output at the pump power of 140 mW while pulses with $\sim 10\,\mathrm{mW}$ power are obtained from the NPE rejection port. The pulse-to-pulse stability is $\sim 1\,\%$ rms. When the pump power was increased to a higher level, the laser started to operate either in a multi-pulse regime or with a CW peak.

The pulse duration was measured with a home-built second-harmonic generation (SHG) frequency-resolved optical gating (FROG) device using a 30 µm-thick BBO crystal as the nonlinear medium. Figure 2(b) shows a typical FROG trace measured with the device. The pulse shape retrieved from this trace is shown on Fig. 2(c). The pulse duration of 45 fs is obtained with a FROG error of 0.4 %, which is the shortest pulse generated from laser oscillators operating around the 2 µm region to the best of our knowledge.

Although our system uses a Ti:sapphire laser as the pump source, it would be beneficial if we could replace it with an inexpensive laser diode. At the conference, we would like to discuss the results of a mode-locked laser with LD-pumped operation.

References

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