# Development of Ultrafast Laser Oscillators Based on Thulium-Doped ZBLAN Fibers

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***Abstract*—Fluoride glass known as ZBLAN is well known for high transparency in the infrared region and is a promising candidate for the host material for infrared lasers. Furthermore, low material dispersion of ZBLAN glasses around 2-$\mu$m wavelength region suggests the usefulness of ZBLAN fibers for developing ultrafast fiber lasers. Based on these considerations, we have conducted a detailed study of ultrashort fiber laser oscillators based on thulium-doped ZBLAN fibers. Two types of diode-pumped, mode-locked oscillators are demonstrated using single-mode ZBLAN fibers and double-clad ZBLAN fibers. The oscillator with single-mode ZBLAN fibers generate stable output pulses at 67.5-MHz repetition rate with the average output power of 19 mW. The broad spectra spreading over 300 nm enabled the generation of pulses as short as 45 fs in 2-$\mu$m region. The oscillator with double-clad ZBLAN fibers was built with a multimode laser diode as the pump source and was successfully mode-locked at the pump power of 1.04 W. The output pulses with the spectrum extending over 150 nm are compressed to 90 fs.**

***Index Terms*—Fiber lasers, ultrafast oscillators, thulium-doped fibers, fluoride glasses.**

## I. Introduction

ULTRAFAST fiber lasers operating around 2 $\mu$m has been attracting increasing attention in the past years for their potential application in the fields of medical applications [1], remote sensing [2], micro-machining [3], high harmonic generation [4], [5], and mid-infrared generation [6]–[8]. Thulium-doped fiber lasers are considered to be the most promising candidate for the sources of ultrashort pulses at this wavelength region because of their broad emission spectrum extending over several hundred nanometers [9]–[11]. Mode-locked thulium-doped fiber lasers have been extensively studied over the past decades. The first femtosecond thulium-doped fiber laser [12] was demonstrated by mode-locking through a nonlinear polarization evolution (NPE) mechanism [13] and 360 fs pulses are generated. However, obtaining shorter pulses is difficult owing to large dispersion introduced by long fibers in the laser cavity. Several methods have been employed to compensate for the fiber dispersion such as inserting a stretcher setup in the laser cavity [14], [15] or using normal-dispersion fibers that compensate the dispersion of ordinary fibers [16], [17].

Another promising approach is to use fibers made of materials with less dispersion. Fluoride glass known as ZBLAN ($ZrF_4$-$BaF_2$-$LaF_3$-$AlF_3$-NaF) is an excellent candidate for this purpose. ZBLAN is well-known for its high transmittance in the mid-infrared region [18], and many kinds of ZBLAN fibers are commercially available. Another important property of ZBLAN is its low dispersion around 2 $\mu$m region, which can be inferred from its low absorption in the mid-infrared region and confirmed by differentiating the Sellmeier equation [19]. Thulium-doped fiber lasers based on ZBLAN fibers have been already demonstrated in cw regime, where performances superior to silica-based fiber lasers such as higher slope efficiency and lower lasing threshold are reported [20], [21]. High transparency of ZBLAN in mid-infrared region was extensively exploited in supercontinuum generation [22]–[26]. However, the property of low dispersion has been overlooked in the previous research on ZBLAN fibers. Recently, the authors demonstrated a thulium-doped fiber laser oscillator based on ZBLAN fibers pumped by a Ti:sapphire laser, and pulses as short as 45 fs are generated [27].

In this paper, we present diode-pumped femtosecond 2 $\mu$m fiber laser oscillators based on thulium-doped ZBLAN fibers in detail. Two types of oscillators are demonstrated using two different types of fibers. One is made with a single-mode ZBLAN fiber, which is a system similar to that presented in [27] but the Ti:sapphire laser used as the pump is replaced with laser diodes. The other is a completely new system built with double-clad ZBLAN fibers. Output pulses from either of the oscillators are compressed down to less than 100 fs, which confirms the effectiveness of ZBLAN fibers for ultrashort pulse generation.

## II. Oscillator With Single-Mode ZBLAN Fibers

In this section, we present a mode-locked thulium-doped fiber laser system based on single-mode ZBLAN fibers.

### A. ZBLAN Fibers

We used a 0.2 m-long single-mode, thulium-doped ZBLAN fiber (TDZF) as an active fiber. The fiber has a core diameter of 6 $\mu$m and a numerical aperture (NA) of 0.2. The concentration of thulium ion in the core is 4 mol%. To estimate the absorption of the TDZF at 793 nm, the pump beam is coupled into a short piece of TDZF and the transmitted power is measured after a dichroic mirror designed for the pump beam coupling, which is used as a filter to remove amplified spontaneous emission. The estimated value of absorption is ~100 dB/m.

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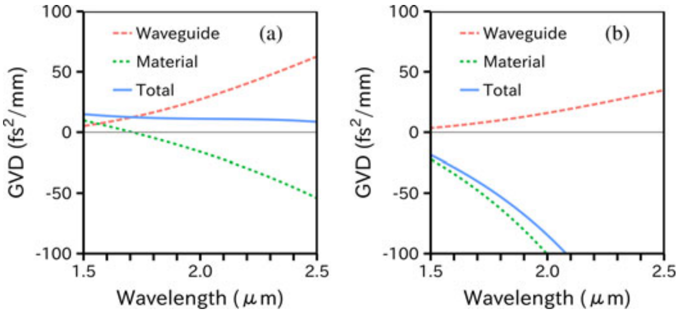

Fig. 1. Calculated material (green dotted curve), waveguide (red dashed curve), and total dispersion (blue solid curve) of (a) single-mode ZBLAN fibers used for the experiments and (b) standard silica fibers (SMF28e).

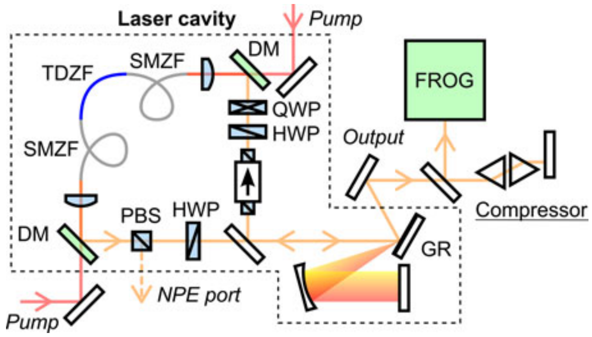

Fig. 2. Schematic of the experimental setup. TDZF: thulium-doped ZBLAN fiber; SMZF: single-mode ZBLAN fiber; DM: dichroic mirror; PBS: polarizing beam splitter; HWP: half-wave plate; QWP: quarter-wave plate; GR: grating.

On each end of the TDZF, 1m of passive single-mode ZBLAN fiber (SMZF) is attached so that there is sufficient nonlinearity to initiate mode-locking through an NPE mechanism. The core diameter and NA of the SMZF are the same as those of the TDZF. Although fusion splicing would be an ideal method to connect these fibers, it was not possible because the melting temperature of ZBLAN is much lower than that of silica, which made it extremely difficult to control the splicing process. Therefore, the TDZF and SMZFs are mechanically spliced and fixed so that the transmission loss is minimized. The transmission loss at each connection point is ~0.2 dB.

The material dispersion of ZBLAN glass around 1.8–2.0 $\mu$m ranges between $-5$ fs$^2$/mm to $-16$ fs$^2$/mm, which can be calculated from the Sellmeier equation [19]. The waveguide dispersion is calculated by substituting experimental parameters into the equations of [28]. The dispersion curves of the ZBLAN fibers used for the experiment are shown in Fig. 1(a). Although the material dispersion of ZBLAN is negative around 1.9 $\mu$m, 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 group-velocity dispersion (GVD) of ZBLAN fibers used for the experiment is estimated to range between $+11$ fs$^2$/mm to $+12$ fs$^2$/mm. The flatness of the total dispersion curve suggests that the ZBLAN fibers used for the experiment have almost no third-order dispersion (TOD), whose value is as low as ~$+6$ fs$^3$/mm.

We also calculated the dispersion of standard single-mode silica fibers (SMF28e). The results are shown in Fig. 1(b). It can be clearly seen that the waveguide dispersion of the standard silica fibers is not large enough to compensate for their material dispersion. The total GVD of the standard silica fibers is negative, and their absolute values are a factor of 5 to 8 larger than those of our ZBLAN fibers around 1.9 $\mu$m. Relatively large slope of the dispersion curve suggests that they have comparatively large TOD, whose value is $+300$ fs$^3$/mm.

### B. Setup

The laser is built in a ring cavity configuration as shown in Fig. 2. The active fiber is pumped by two laser diodes (LU0793M200, Lumics) operating at 793 nm with single-mode fiber pigtails. The maximum output power of the laser diodes is 200 mW each. The pump beams are sent into the cavity through specially coated dichroic mirrors ($T > 97\%$@790 nm, $R > 98\%$@1600–2200 nm, Sigma-Koki) and coupled into the fiber with aspherical lenses ($f = 6$ mm). The coupling efficiency is estimated to be ~73% by coupling the pump beam into a piece of SMZF 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 state in the cavity. A polarizing beam splitter (PBS) is used as a rejection port for the NPE process.

To compensate for the dispersion from the fibers and optimize the cavity dispersion, we used a single-transit Martinez-type "stretcher" [29]. 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 makes it suitable for our setup where the fibers have small positive dispersion. It should also be noted that it is more common to use this type of stretcher in double-transit scheme to avoid spatial dispersion. However, that will significantly reduce the transmission efficiency of the stretcher. We made it a single transit to reduce loss in the stretcher at the cost of imposing a spatial dispersion on the beam. This spatial dispersion is not necessarily detrimental to the laser operation. Coupling spatially dispersed beams into fibers means that the beam experiences spectral filtering [30], which helps mode-locked operation of certain kind of fiber lasers such as fiber lasers using normal-dispersion fibers [31], [32].

Although it is common to use the beam coupled out from the NPE rejection port as the laser output, we chose to use the zeroth-order reflection from the grating as the main output beam to obtain pulses with better quality [32], [33]. Since the grating used for the experiment is polarization dependent, the output coupling ratio can be controlled by the HWP placed in front of the grating.

### C. Mode-Locked Operation

Mode-locked operation was obtained through an NPE mechanism by adjusting the angles of the waveplates and moving the grating in the stretcher. The position of the grating is optimized

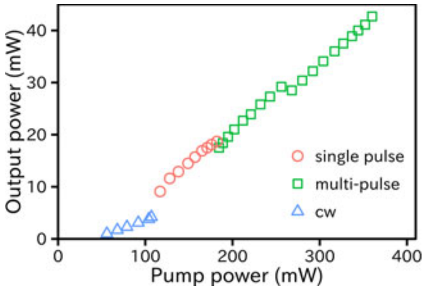

Fig. 3. Output power of single-mode ZBLAN fiber laser plotted against the pump power. Red circles indicate single-pulse operation, whereas green squares and blue triangles indicate multi-pulse operation and cw operation, respectively.

so that the output spectrum becomes broad and stable. Typical dispersion of the stretcher is estimated as $\sim -2 \times 10^4$ fs$^2$. We expect the net cavity dispersion to be close to zero and slightly negative, where the oscillator is expected to operate in dispersion-managed soliton regime [32].

The output power and the behavior of laser operation was studied by changing the total pump power from the two LDs. Fig. 3 shows a typical behavior of the laser output power as a function of the total pump power launched into the fiber. To initiate mode-locking, the total pump power had to be at least ∼250 mW. At that power level or higher, however, the laser operated either in a multi-pulse regime or with a cw emission. When the total pump power is decreased gradually, we observed abrupt changes in the spectral profiles at certain power levels and also small increases in the output power. We believe this happens when the number of the pulses circulating in the cavity decreases. By reducing the total pump power to ∼180 mW, we achieved single-pulse operation with the output power of 19 mW. The pump power can be further reduced to ∼120 mW while maintaining the single-pulse operation. The mode-locked operation ceases below that power level. The behavior described above did not change significantly even when the ratio of the pump power from the two LDs were changed. All the following measurements for this oscillator are carried out at single-pulse operation regime with the pump power of 180 mW.

Single pulse operation was verified by measuring autocorrelation over the delay of ∼130 ps. Long time scale measurement was made by observing the pulse train and its radio-frequency (RF) spectrum with a 7 GHz InGaAs photodiode combined with a 16 GHz oscilloscope and an 1.5 GHz RF spectrum analyzer. No sign of double-pulsing was observed in either of the measurements. Typical pulse train and the RF spectrum are shown in Fig. 4, showing that stable pulses are obtained with a repetition rate of 67.5 MHz, which corresponds to the pulse energy of 280 pJ. The shot-to-shot stability of the pulses is ∼1% over a couple of hours.

### D. Pulses and Spectra

Output spectra are measured using a monochromator (SP-2300, Princeton Instruments) with an InGaAs photodiode used as the detector. A typical output spectrum measured at the resolution of 0.4 nm is plotted in Fig. 5. The spectrum extends from 1730–2030 nm at 30 dB below the peak.

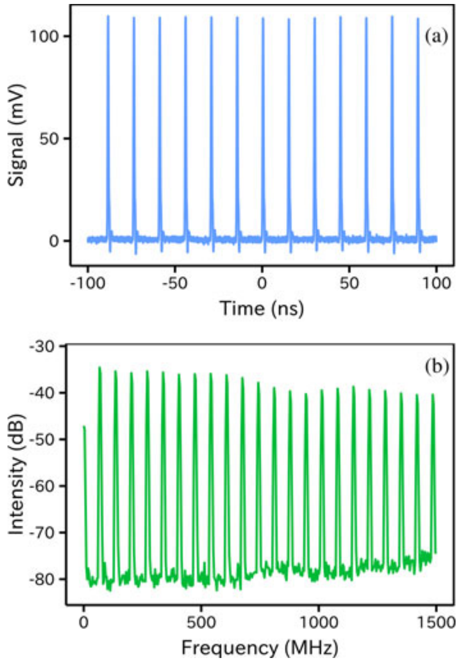

Fig. 4. Pulse train observed with an InGaAs photodiode. (a) Output pulse train measured with an oscilloscope. (b) RF spectrum measured with an RF-spectrum analyzer.

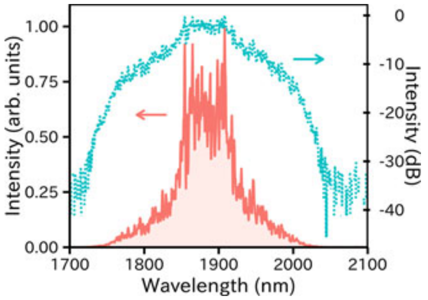

Fig. 5. Optical spectrum measured with a monochromator, plotted in linear scale (red filled curve) and log scale (green dotted curve).

The duration of the output pulses are determined by second-harmonic generation (SHG) frequency-resolved optical gating (FROG) [34], [35]. For this purpose, we built an SHG FROG apparatus with a 30 $\mu$m-thick BBO crystal used as the nonlinear medium. The duration of the pulses without any dispersion compensation was ∼120 fs. These pulses are compressed with a pair of SF10 prisms, which have negative dispersion around this wavelength region. A typical FROG trace of the compressed pulses measured with the device is shown in Fig. 6(a). The optimal compression was obtained when 26 cm of SF10 was inserted into the output beam. This means that the output pulses have positive chirp, which is reasonable because pulses are output after accumulating positive dispersion from the fibers and before acquiring negative dispersion from the stretcher.

The experimentally measured FROG trace is analyzed with a FROG retrieval algorithm. The results are shown in Fig. 6(b)–(d). Fig. 6(b) shows the FROG trace retrieved from the ex-

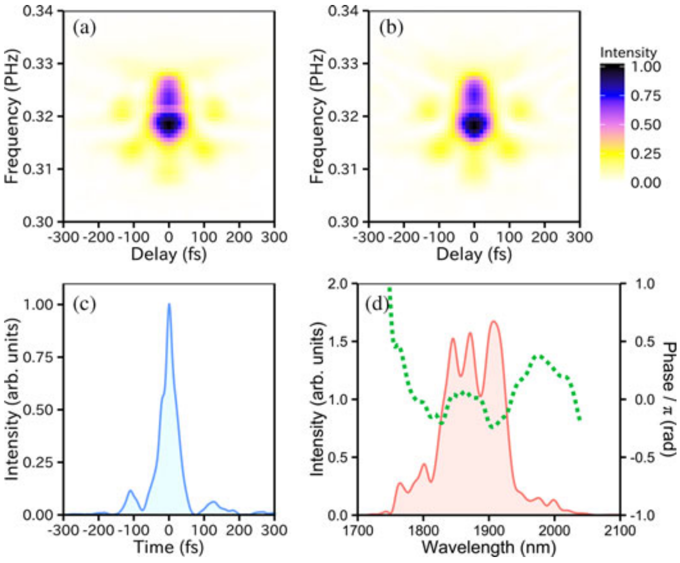

Fig. 6. Results of FROG measurement. (a) Measured FROG trace. (b) FROG trace retrieved from the experimental FROG trace shown in (a). (c) Retrieved pulse shape. (d) Retrieved spectral profile (filled red curve) and phase (green dotted curve).

perimental trace with the FROG error of 0.4% ensuring the reliability of the measured and analyzed results. Fig. 6(c) and (d) show the corresponding shapes of the retrieved pulse and spectrum. The duration of the compressed pulse was as short as 45 fs. Small side pulses observed in Fig. 6(c) are due to residual higher-order chirp, which can also be seen in Fig. 6(d). The energy contained in the main pulse is estimated to be $\sim$84%. Apart from the resolution, the retrieved spectrum looks reasonably similar to the spectrum measured with the monochromator, which also confirms the validity of the FROG measurement.

## III. Oscillator With a Double-Clad ZBLAN Fiber

The difficulty in building oscillators using single-mode fibers is finding appropriate pump lasers. The pump lasers need to have good beam profiles such as single-mode fiber output. For thulium-doped fiber lasers it is common to use either 790 nm or 1.6 $\mu$m laser as the pump sources. However, output power from laser diodes with single-mode fiber output are limited, and other sources such as Ti:sapphire lasers or Er-doped fiber lasers are rather expensive.

One way to solve this problem is to build oscillators using double-clad fibers. This way, pump beams from laser diodes with much higher output power can be efficiently coupled into the clad of the fibers and thus can effectively pump the active fiber. Several reports have been made using this method [14], [15], [36]. Pump beams with the power as high as 5 W are coupled into the active fibers and pulses as short as 173 fs has been demonstrated.

Here we demonstrate an oscillator based on a double-clad, thulium-doped ZBLAN fiber pumped with a $\sim$1 W laser diode with a multi-mode fiber output.

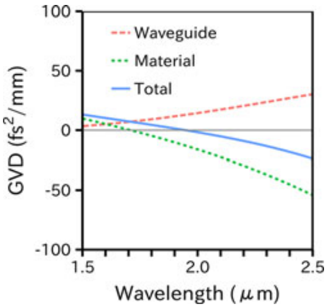

Fig. 7. Calculated dispersion of double-clad ZBLAN fibers used for the experiment.

### A. *Setup*

The cavity design is basically the same as that for single-mode ZBLAN fibers shown in Fig. 2 except for the fibers and the pump laser. For this experiment, we used only one LD as the pump laser, which was sent into the cavity from the bottom left corner in the figure.

We used a single piece of 4.4-m-long, thulium-doped double-clad ZBLAN fiber. The fiber has the core diameter of 8.6 $\mu$m, the first-cladding diameter of 123 $\mu$m, and the second-cladding diameter of 200 $\mu$m. The NA of the core and the first clad are 0.13 and 0.50, respectively. The concentration of thulium ion in the core is 4 mol%. The absorption around 790 nm is $\sim$ 2 dB/m, which is much lower compared to single-mode fibers because the pump beam propagating in the clad has much smaller overlap with the core. Fig. 7 shows the dispersion curves of the double-clad fibers calculated similarly to those of the single-mode fibers. The zero-dispersion wavelength of the double-clad fiber used for the experiment is found to be at 1.95 $\mu$m, which is favorable for development of ultrafast oscillators operating around this wavelength. However, the slope of the curve corresponding to the TOD is larger than that of single-mode fiber, which might cause difficulties in generating ultrashort pulses. The GVD and TOD of the double-clad ZBLAN fiber at 1.9 $\mu$m are +1.5 fs$^2$/mm and +59 fs$^3$/mm, respectively.

As the pump source, we used a 1.5 W LD operating around 790 nm (B1-785-1500-15A, Axcel Photonics) that has a multi-mode fiber pigtail with the core diameter of 100 $\mu$m. The output beam is imaged to one end of the ZBLAN fiber to maximize the coupling efficiency. After all the optics between the LD and the ZBLAN fiber, the maximum power of the pump beam was reduced to 1.04 W.

### B. *Results*

The oscillator is mode-locked through NPE by using the same methods as those described in Section II. Fig. 8 shows the behavior of the output pulses as we changed the incident pump power. Stable single-mode operation is achieved when 1.04 W of pump power is launched into the fiber. The average output power of 20 mW is obtained at the repetition rate of 41 MHz. The minimum pump power required to keep mode-locked operation was 0.87 W.

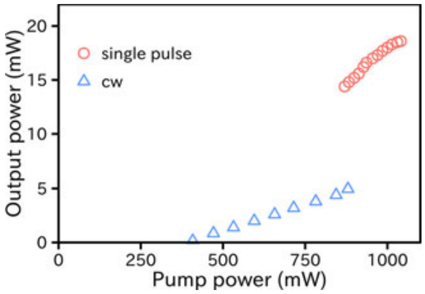

Fig. 8. Output power of double-clad ZBLAN fiber laser plotted against the pump power. Red circles indicate single-pulse operation, whereas blue triangles indicate cw operation.

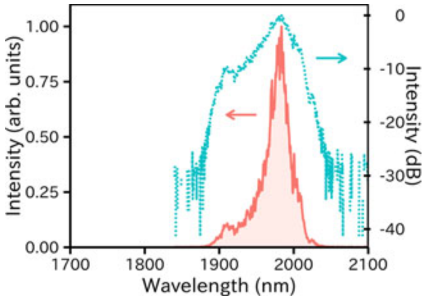

Fig. 9. Optical spectrum measured with a monochromator, plotted in linear scale (red filled curve) and log scale (green dotted curve).

Fig. 9 shows a typical spectrum measured with the monochromator at the resolution of 0.4 nm. The spectrum spread from 1880–2030 nm at 25 dB from the peak. The center wavelength is shifted toward a longer wavelength compared to the oscillator with single-mode fibers. This shift can be explained by absorption of thulium-doped fibers. Since thulium-doped ZBLAN glass has a broad absorption peak centered around 1.7 $\mu$m [10], a longer section of thulium-doped fiber causes higher absorption for shorter wavelength radiation and thus shifting the spectrum to longer wavelength. This effect could also explain the relatively low efficiency of this system compared to the system described in Section II.

The output pulses are compressed with a pair of SF10 prisms and characterized with the home-built SHG FROG device (see Fig. 10). The pulse duration of 90 fs is obtained with a FROG error of 0.6% which is the shortest pulse generated from thulium-doped fiber laser oscillators built with double-clad fibers.

The significance of this oscillator is its low requirements, especially for the pump source. In fact, the laser diode used for the system is not single-mode either transversely or longitudinally. The threshold pump power is as low as ∼350 mW, which is more than one order of magnitude lower than that from silica-based double-clad fiber laser oscillators [14], [15], [36] and the pump power required for mode-locked operation is also a factor of 6 lower than that for silica-based oscillators. This could be explained by lower loss from the stretcher setup and/or more efficient cross relaxation process in ZBLAN fibers [20].

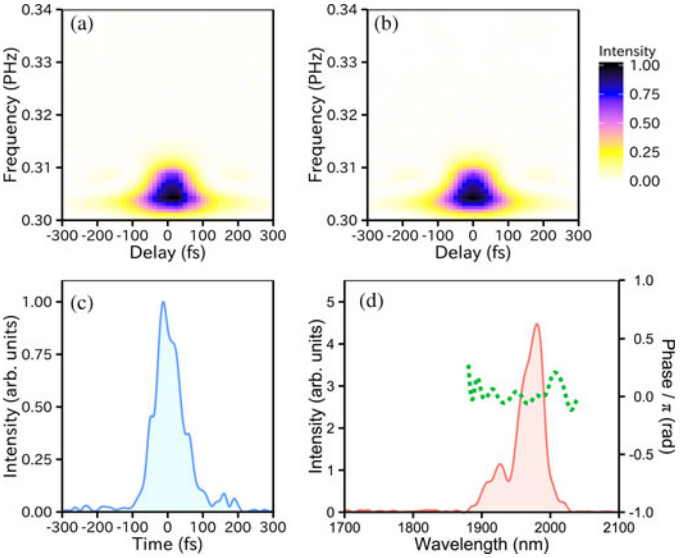

Fig. 10. FROG results for the oscillator built with a double-clad fiber. (a) Measured FROG trace. (b) FROG trace retrieved from the experimental FROG trace shown in (a). (c) Retrieved pulse shape. (d) Retrieved spectral profile (filled red curve) and phase (green dotted curve).

## IV. CONCLUSION

We developed diode-pumped, passively mode-locked fiber laser oscillators based on two types of thulium-doped ZBLAN fibers.

The oscillator with single-mode ZBLAN fibers generates stable output pulses at 67.5 MHz repetition rate with the average output power of 19 mW. The calculated dispersion curves of the ZBLAN fibers clearly show their advantage for ultrashort pulse generation. The broad spectra spreading over 300 nm enabled the generation of pulses as short as 45 fs in 2 $\mu$m region.

Another oscillator is realized using a double-clad ZBLAN fiber with a laser diode with multi-mode beam as the pump source. The oscillator operates with the pump power of 1.04 W with the spectrum extending over 150 nm. A longer section of thulium-doped fibers compared to that from the SMZF-based oscillator resulted in a red-shift in the output spectrum. The pulse as short as 90 fs is generated with a low-end LD used as the pump source.

It would be important to mention the possibility to develop an all-fiber system, which would be more robust and easier to handle. The main challenges would be the lack of fiber-based components made with ZBLAN fibers. Although silica-based components are commercially available, those components would add larger dispersion and thus would compromise the performance of the system. One possible solution is to develop dispersion-managed ZBLAN fibers by controlling the core diameter and NA of the fibers. This could be used not only for compensating the dispersion of the silica-based fiber components, but also for removing the stretcher system used in the current setup. It would be even better if the fiber components could be manufactured using ZBLAN, but that would be more challenging.

Overall, we have exploited the low dispersion of ZBLAN fibers to develop ultrafast 2 $\mu$m fiber laser oscillators generating sub-100-fs pulses. We believe ZBLAN fibers will add a useful tool for ultrashort fiber laser development in this wavelength region.

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