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# Generation of watt-class, sub-50 fs pulses through nonlinear spectral broadening within a thulium-doped fiber amplifier

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**Abstract:** We demonstrate direct generation of sub-50 fs pulses from a thulium-doped fiber amplifier. Broad spectra are obtained by exploiting nonlinear effects within the amplifier fiber itself. High fractional inversion densities of thulium ions achieved by a core-pumping scheme helped to extend spectra into the shorter wavelength region around 1.7 µm. Pulses with a duration of 48 fs are obtained at an average power of 2.5 W directly after the amplifier fiber, i.e., without using a compressor.



**OCIS codes:** (140.3510) Lasers, fiber; (320.7090) Ultrafast lasers; (320.5520) Pulse compression.

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## 1. Introduction

Laser sources operating around the 2 μm wavelength region have been intensively studied over the past decades because of their wide fields of applications such as micromachining, medical applications, remote sensing, high-harmonic generation, and mid-infrared generation. Thulium (Tm)-doped fiber lasers have been very successful in this wavelength region, especially for generating ultrashort laser pulses at high output power, thanks to its broad emission spectrum extending over several hundred nanometers [1, 2] and its capability to achieve kilowatt level average power [3].

To develop high power, femtosecond light sources at the 2 μm region, the most straightforward method is the chirped-pulse amplification (CPA) technique. A number of groups have developed CPA systems with the output of Tm-fiber oscillators as the seed pulses [4–10], where the durations of the amplified pulses range between 150 fs to several hundred femtoseconds and the average output power reaches as high as 150 W after compression. Some groups used frequency-shifted output of erbium (Er)-doped fiber lasers as the seed pulses for their CPA systems [11–14]. The shortest pulses obtained with this method had a duration of 80 fs at the average power of 3 W [13].

Another approach to build an ultrafast fiber laser amplifier is to make use of the nonlinearity within the fiber to broaden the spectrum rather than suppressing the nonlinearity. This approach was successful especially for developing ultrafast ytterbium-doped fiber laser amplifiers, where the self-similar evolution of the pulses results in smooth broadband spectra that can be efficiently compressed [15–18]. However, the situation is quite different for Tm-doped fiber lasers because the fibers have anomalous dispersion around 2 μm region and thus the nonlinearity during amplification leads to wave breaking, which is usually considered detrimental. Although some groups have shown that wave breaking can be exploited to generate ultrashort pulses [19], there are few reports that utilize nonlinearities within Tm-fiber amplifiers. Imeshev and Fermann [20] reported amplification in a Tm-doped fiber with limited nonlinear effects. In their work, a Raman-shifted output of an Er-doped fiber with the duration of 150 fs is amplified in a Tm-doped fiber to generate 108-fs pulses at 3.1 W. It should be noted that compressed pulses are obtained directly at the output of the amplifier fiber by pre-chirping the pulses incident to the amplifier fiber. In other words, their system requires no compressor, which typically introduces quite a high loss.

In this paper, we demonstrate direct generation of sub-50 fs pulses from a Tm-based fiber amplifier by utilizing nonlinearities within the amplifier fiber itself. Pulses with a duration of 48 fs are obtained at an average power of 2.5 W. The core-pumping scheme helped to obtain broad spectra extending into relatively short wavelength region around 1.7 μm. The setup uses no stretcher or compressor, resulting in an extremely simple system.

## 2. Experimental setup

The experimental setup is shown in Fig. 1. The seed source is an oscillator based on a Tm-doped fiber made of ZBLAN ($ZrF_4$-$BaF_2$-$LaF_3$-$AlF_3$-NaF) glass [10]. The pulses generated from the oscillator has a broad spectrum extending from 1.7 μm to 2.1 μm, capable of generating 41 fs

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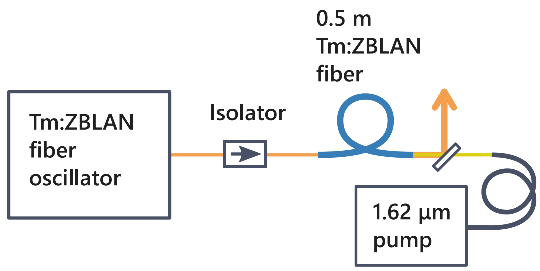


Fig. 1. Schematic of the experimental setup.

pulses. A pulse train with the average power of 36 mW is generated at 67.5 MHz repetition rate. The pulse right after the oscillator has a positive chirp and has a duration of ~600 fs when not compressed.

The pulse train is directly sent into a 0.5-m-long, large-mode-area thulium-doped ZBLAN fiber used for the amplification. Using a ZBLAN fiber helps to achieve efficient amplification when the seed power is relatively low [10] as in our current system. The core of the fiber has a diameter of 20 µm with a numerical aperture of 0.08 and is doped with Tm ions at 2 mol%. As the pump source, a Raman fiber laser operating at 1.62 µm with a single-mode beam output (RLR-30-1620, IPG Photonics) is used. The pump beam is coupled into the core of the fiber rather than the clad. This helps to obtain gain in the short wavelength region by maximizing the fractional inversion densities of Tm ions [21]. The amplified beam is separated from the pump beam using a dichroic mirror.

## 3. Spectral Broadening and Pulse Compression During Amplification

Figure 2 shows the evolution of spectra measured after the amplifier fiber as the launched pump power is increased. It can be seen that the spectrum extends toward the shorter wavelength region at the beginning, and starts to rapidly broaden into both directions once the power reaches a certain level. The broadening in the first phase can be attributed to the increase in the gain bandwidth caused by the increase in the fractional inversion level of Tm ions. As the pump power is increased, the gain starts to overcome reabsorption of Tm ions in the short wavelength region, which is why the spectrum extends mainly into the shorter wavelength region. The broadening in

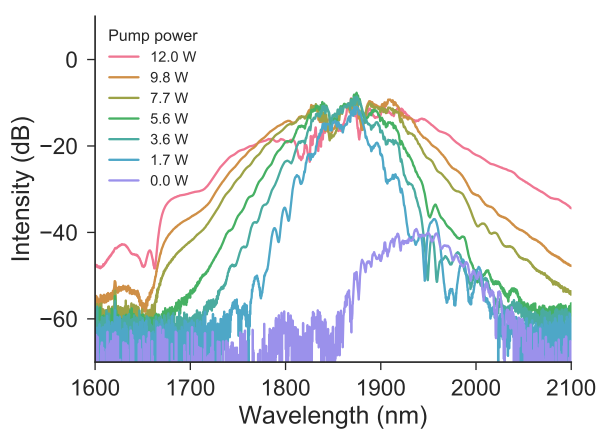


Fig. 2. Evolution of the amplified spectra measured as the launched pump power is increased.

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the second phase is attributed to self-phase modulation (SPM), which becomes significant once the peak intensity reaches a certain level. A small dip observed around 1650 nm is due to the coating of the dichroic mirror used to separate the amplified beam from the pump beam.

Figure 3 shows the average output power as the function of the launched pump power. The power scales up linearly until it reaches ~ 2.5 W at the pump power of ~ 10 W. The peak-to-peak fluctuation measured over one hour at this power level is ~ 2 %. Although the pump power could be further increased, the amplified power did not change significantly. At first glance, this saturation seems to have occurred because the length of the Tm-doped fiber is not enough. However, we do not believe this is the case because a higher output power of more than 5 W is obtained with the same fiber and pump laser when the input pulse is stretched to ~ 25 ps. It seems that the power saturates once the SPM becomes too strong. One possible explanation is that the larger SPM makes amplified power to dissipate to shorter or longer wavelength region where loss from the fiber and/or optics used for the experiments are much higher, which somewhat cancels out the higher gain. Further investigation is needed to identify the reason for this saturation.

The inset of Fig. 3 shows a near-field beam profile measured after the amplifier fiber at the pump power of 10 W. No significant distortion is observed at this power level.

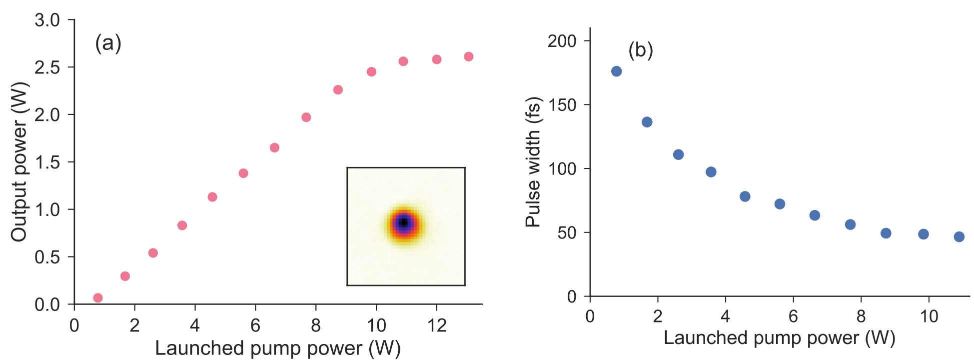


Fig. 3. (a) Average output power measured after the amplifier. The power increases linearly up to the pump power of 10 W, above which power the amplification saturates. The inset shows the near-field beam profile measured after the amplifier fiber at the pump power of 10 W. (b) Pulse duration obtained from FROG measurements plotted as a function of launched pump power.

The output pulses right after the amplifier fiber are characterized with a home-built second-harmonic generation frequency-resolved optical gating (FROG) device [10]. Figure 3(b) shows the pulse duration obtained at each pump power. It can be clearly seen that the pulse duration decreases as the pump power is increased. Figure 4 summarizes the results of FROG measurements at the pump power of 10 W. A typical FROG trace measured experimentally is shown in Fig. 4(a). The pulse shape retrieved from this trace is shown in Fig. 4(b). The duration of the pulse is as short as 48 fs, which is only 7% above the transform limit duration of 45 fs. Although the pulses with slightly shorter duration were obtained by increasing the pump power, the distortion of the spectrum became larger and the side pulses became stronger. The spectral intensity and phase profiles retrieved from the same FROG trace are shown in Fig. 4(c). It can be seen that the phase is more or less flat for the main parts of the spectrum, whereas distorted in the region where the spectral intensity is relatively low. Increasing the pump power causes the two peaks in the spectrum to move apart from each other and results in a shorter main pulse and larger side peaks in the temporal profile.

We have also numerically simulated the amplification within the fiber by using the nonlinear Schrödinger equation similar to that shown in Ref. [15]. Other than the 2nd- and 3rd-order

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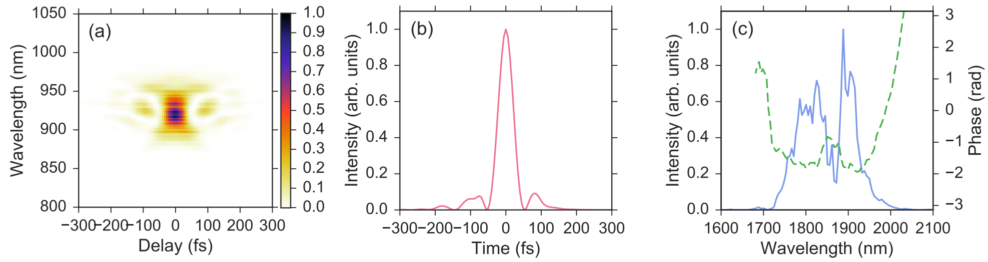


Fig. 4. Results of FROG measurements at the pump power of 10 W. (a) Experimentally measured FROG trace. (b) Pulse shape retrieved from the trace shown in (a). (c) Spectral intensity (blue solid curve) and phase (green dashed curve) profiles retrieved from the trace shown in (a).

dispersion, nonlinear effects, and gain curve, we have included loss effects to take account of re-absorption from Tm ions. The gain and loss curves are each modeled with a simple gaussian curve with a bandwidth of 20 THz so that the curves resemble those shown in Ref. [22]. The fractional inversion level can be changed between 0 to 1 so that the effect of core-pumping can be taken into account. Although this simple model overestimates the loss in the short wavelength region around 1600 nm, this does not affect the simulation results so much because this region is outside the region where the gain exists.

Using this model, we have made a series of simulation to reproduce experimental results. The equation is solved with the split-step Fourier method using a step size of 1 mm. The fiber parameters at the center wavelength of 1.85 µm are the group velocity dispersion of $\beta_2 = -7\,\mathrm{fs}^2/\mathrm{mm}$, the third-order dispersion of $\beta_3 = +100\,\mathrm{fs}^3/\mathrm{mm}$, and the nonlinear parameter of $\gamma = 1.3 \times 10^{-4}\,\mathrm{W}^{-1}\,\mathrm{m}^{-1}$. The initial pulse is assumed to have a gaussian spectrum with a bandwidth supporting 41 fs pulses with a second-order phase of $7.6 \times 10^3\,\mathrm{fs}^2$ and a third-order phase of $1.0 \times 10^4\,\mathrm{fs}^3$ at a wavelength of 1850 nm. These values are obtained from a FROG measurement with oscillator output pulses. The increase of the pump power is simulated by the increase in the fractional inversion level. The maximum fractional inversion level was set to 40 % so that the peak wavelength of the gain curve matches the peak of the experimentally obtained spectrum at the maximum pump power. Figure 5(a) shows the spectra obtained by the simulations, which qualitatively reproduce the experimental spectra shown in Fig. 2, where the spectrum extends into the shorter wavelength region at low pump power and starts to broaden significantly once the pump power reaches a certain level.

The corresponding spectral phases and pulse shapes are plotted in Fig. 5(b) and (c), respectively. It can be seen that the curvature of the spectral phase becomes smaller and the pulse shape starts to shorten as the pump power is increased. It should be noted that all these curves are obtained with the same fiber length. In other words, the fiber dispersion experienced by the pulse takes a constant value of $-3.5 \times 10^3\,\mathrm{fs}^2$ at 1850 nm for all the curves. This suggests that the SPM helps to compensate for the initial phase and the dispersion of the fiber, and the pulse shortening could be attributed to interplay among spectral broadening, fiber dispersion, and SPM.

In the simulation, we also observed a kind of saturation effects in the output power. Although it was rather difficult to quantitatively match the simulation results with the experimental results, a qualitatively similar behavior was observed, i.e., the output power stops growing where the spectral broadening due to the SPM becomes significant. This result suggests that higher output power could be achieved if the effect of SPM is reduced by, for example, increasing the initial chirp of the input pulses.

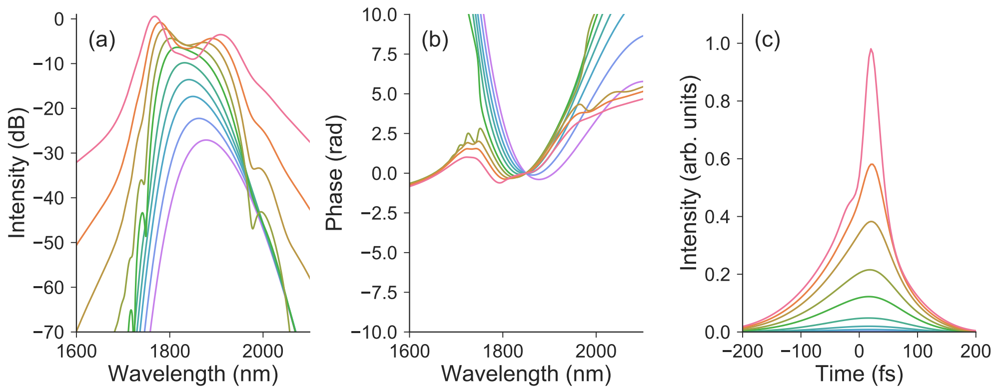


Fig. 5. The results of numerical calculations to simulate the effects of pump power increase. Plots with the same color correspond to the same data set. (a) Evolution of spectral profile plotted in a log scale. (b) Evolution of spectral phase. (c) Evolution of pulse shape plotted in a linear scale.

## 4. Conclusion

To summarize, we have demonstrated a simple amplifier system that generates watt-class, sub-50-fs pulses around 2 μm. Nonlinearity within the amplifier fiber is utilized to broaden the spectrum. Core-pumping helped to broaden the spectrum into the shorter wavelength region by increasing the fractional inversion levels of Tm ions. Pulses with a duration of 48 fs are obtained at an average power of 2.5 W without a stretcher or a compressor. Qualitative behaviors of the experimental results are reproduced with numerical simulations.

The output pulses has a peak power sufficient for high-harmonic generation in solid targets, as Lee *et al.* recently demonstrated using a 2 μm fiber laser system with a similar output [23]. Although it might be possible to increase the output power by carefully adjusting the initial chirp of the input pulses, it would become exceedingly difficult as the pulse energy increases because the SPM within a solid-core fiber would become too large and cannot be controlled any more. To achieve a high peak power necessary for extreme nonlinear optics, using a gas-filled hollow-core fiber to spectrally broaden and temporally compress the high energy pulses generated from a CPA system [24] would be more appropriate. The simple setup of our system would be useful for certain applicational uses, especially for those that require pulses with moderate energies at high-repetition rates such as ultrafast spectroscopy and nonlinear microscopy.

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