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Efficient chirped-pulse amplification based on thulium-doped ZBLAN fibers

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We demonstrate a chirped-pulse amplifier system operating around 1900 nm using thulium-doped ZrF_4–BaF_2–LaF_3–AlF_3–NaF (ZBLAN) fibers. The pulses from a thulium-doped ZBLAN fiber laser oscillator are stretched by a passive ZBLAN fiber and subsequently amplified in a double-clad thulium-doped ZBLAN fiber to an average power of 6.9 W at a pump power of 17 W. We found that ZBLAN fibers require a much lower pump and/or seed power than silica fibers for efficient amplification. The amplified pulses are compressed to a duration of 150 fs with an average power of 3.9 W. © 2017 The Japan Society of Applied Physics

High-power ultrafast lasers operating around the 2 µm wavelength region have been attracting increasing attention in recent decades owing to a number of potential applications in fields such as medical applications, micromachining, remote sensing, and mid-infrared generation. Thulium-doped fiber lasers are one of the most promising candidates for developing high-power ultrafast light sources in this wavelength region because of their broad emission bandwidths, which support femtosecond pulse generation,[1)] and the ability to achieve a kilowatt-level average output power.[2)] In fact, watt-level, 2 µm laser pulses with femtosecond pulse durations were obtained by amplifying the output from Tm-fiber oscillators using the chirped-pulse amplification technique.[3–8)] Even shorter pulses were obtained by utilizing nonlinear effects within the fibers.[9–11)] All these studies were conducted using fibers made of silica glass.

To develop a watt-level ultrafast fiber laser system, fibers made of a fluoride glass called ZBLAN (ZrF_4–BaF_2–LaF_3–AlF_3–NaF) show great potential. Many distinctive properties of fluoride glasses, including ZBLAN, arise from the fact that their phonon energies are much lower than those of oxide glasses such as silica.[12)] For example, the multiphonon absorption edge of ZBLAN is shifted towards the lower-frequency region, thus opening up a broad transmission window extending into the mid-infrared region.[13)] For Tm-doped fiber lasers, the lower phonon energy theoretically means that there is less nonradiative decay, and the lifetimes of the excited states are significantly longer,[14,15)] which results in a higher cross-relaxation efficiency, a higher lasing efficiency, and less heat generation.[15)] In fact, experimental studies in the continuous-wave regime show that Tm-doped ZBLAN fiber lasers exhibit characteristics superior to those of silica-based systems, such as a higher slope efficiency and lower lasing threshold.[14–16)] Another important property of ZBLAN glass is its low material dispersion in the near- to mid-infrared region compared to silica. This property is useful for developing ultrafast laser systems. In fact, we have demonstrated generation of pulses as short as 45 fs from oscillators based on Tm-doped ZBLAN fibers.[17,18)] Because of these properties, ZBLAN fibers show great promise for the development of efficient, high-power ultrafast laser systems operating around 2 µm.

In this work, we demonstrate a chirped-pulse amplifier system based on ZBLAN fibers. The pulses are amplified to an average output power of 6.9 W and subsequently compressed to a duration of 150 fs. By comparing the performance with that of silica-based amplifiers, we found that ZBLAN fibers are much more efficient even when the pump or seed power is not very high.

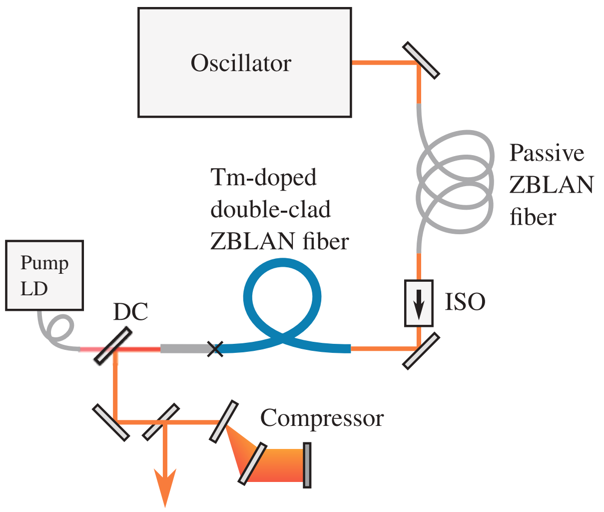

Fig. 1. Schematic of the experimental setup. ISO: isolator; DC: dichroic mirror.

Figure 1 illustrates the experimental setup for chirped-pulse amplification. The seed pulses are generated from an oscillator slightly upgraded from previously reported oscillators.[17,18)] The oscillator is based on a dispersion-managed ring cavity and is mode-locked through a nonlinear polarization evolution process. By optimizing the waveplate configuration and output coupling ratio, we obtained pulses with broad output spectra and an average power of 36 mW at a 67.5 MHz repetition rate. These pulses can be compressed to a duration of 41 fs using an external compressor.

The output pulses of the oscillator are stretched by a passive ZBLAN fiber with normal dispersion. Although ZBLAN glass has anomalous dispersion around a wavelength of 2 µm, its absolute value is relatively small compared to that of silica glass. This anomalous material dispersion can be readily overcompensated by the waveguide dispersion of the fiber by setting the core diameter and numerical aperture (NA) to appropriate values. In the experiments, we used a 15-m-long, single-mode ZBLAN fiber with a core diameter

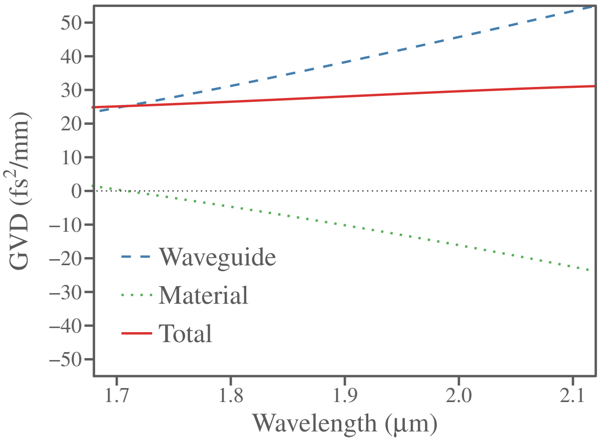

Fig. 2. Dispersion curves of the passive ZBLAN fiber used as the stretcher.

of 5 μm and an NA of 0.20, whose group velocity dispersion around 2 μm is ~+30 fs^2/mm, as shown in Fig. 2. Thanks to this normal-dispersion fiber, both the stretcher and the compressor are free from complicated optical systems that provide normal dispersion, such as a Martinez-type setup[19] or an Öffner-type setup.[20] After the stretcher fiber, pulses with a duration of ~25 ps are obtained with ~50% transmission efficiency. The average power after an isolator placed between the stretcher and the amplifier is ~12 mW.

The stretched pulses are coupled into the core of a 3.5-m-long, Tm-doped, large-mode-area double-clad ZBLAN fiber. The core of the fiber has a diameter of 32 μm and an NA of 0.08, and is Tm-doped with a concentration of 2 mol %. The first cladding of the fiber has a diameter of 200 μm and an NA of 0.5. The fiber is pumped in the counterpropagating direction by a fiber-coupled laser diode operating around 793 nm. A 0.5-m-long, passive double-clad ZBLAN fiber with the same parameters as the active fiber is fusion-spliced to the rear end of the Tm-doped fiber to avoid thermally induced problems such as pointing instability. This end of the fiber is mounted on a water-cooled V-groove. Both ends of the fiber are angle-polished to avoid parasitic lasing within the fiber. The amplified pulses are separated from the pump beam using a dichroic mirror. These pulses are compressed by a grating compressor composed of a pair of transmission gratings with grooves of 560 mm^{-1}.

Figure 3(a) shows the average output power of the amplifier as a function of the launched pump power. The coupling efficiency of the pump beam is assumed to be 90%. Because the power of the transmitted pump beam is slightly less than 1% of that of the coupled pump beam, we expect 99% of the pump beam to be absorbed by the fiber. The maximum output power of 6.9 W is obtained when a pump power of 17 W is launched. This corresponds to a slope efficiency of 47%, which is comparable to the values reported in previous studies of Tm-fiber master oscillator and power amplifier (MOPA) systems based on silica fibers.[3,6,7] The output power stability at the maximum pump power is ~0.2% rms over 1 h.

To compare the efficiency of the ZBLAN fiber amplifier with that of silica fibers, we replaced the amplifier fiber with a 3.5-m-long, Tm-doped, large-mode-area double-clad silica fiber that has a core diameter of 25 μm and a cladding

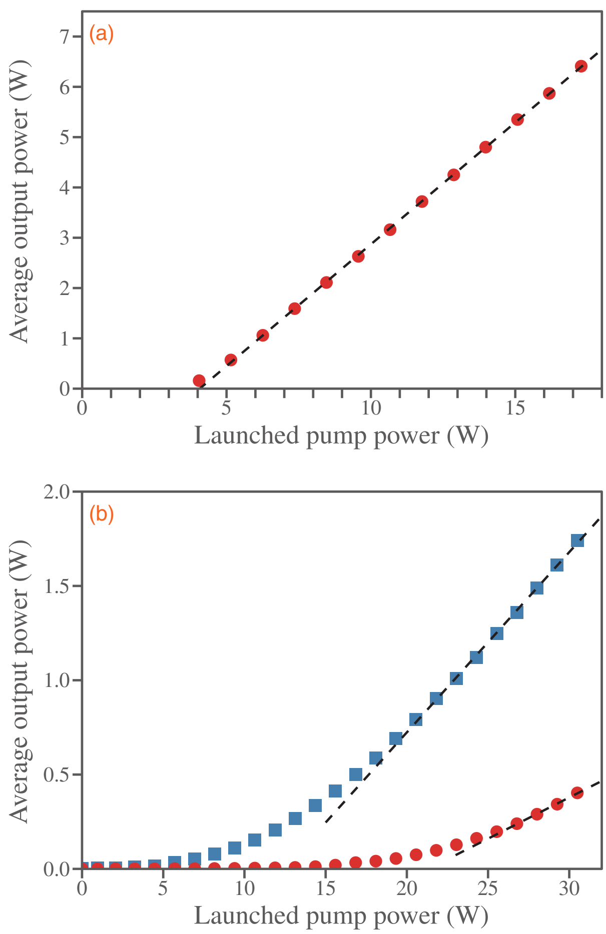

Fig. 3. Average output power after the amplifier. (a) Output power obtained using a ZBLAN fiber. The dotted line shows a linear fit corresponding to a slope efficiency of 47%. (b) Output power obtained using a silica fiber. The red circles indicate the output power obtained using the same seed pulses as those used in (a), whereas the blue squares indicate the output power obtained using seed pulses with higher power. The dotted lines are fitted at the maximum slopes of these measurements.

diameter of 250 μm (Nufern LMA-TDF-25P/250-LC). The power of the transmitted pump beam is ~1%, which is comparable to that of the ZBLAN fiber. The output power as a function of the launched pump power is shown as red circles in Fig. 3(b). Amplification is clearly much more difficult with the silica fiber. Although the amplified output power of ~400 mW at a pump power of 30 W is comparable to the power obtained in one of the previous reports,[8] it is much lower than the power in another report.[3] We attribute this difference to the difference in the seed power, where the former report used a seed power of 2–8 mW, whereas the latter used a seed power of 124 mW. In other words, we assumed that not only a high pump power but also a high seed power is required to achieve efficient amplification using silica fibers. To verify this hypothesis, we replaced the oscillator used to produce the seed beam with another one that has much higher output power. This oscillator is basically an upgraded version of the cladding-pumped oscillator using a double-clad ZBLAN fiber described in Ref. 18 and generates 90 fs pulses with an average output power of 165 mW at a repetition rate of 52 MHz. After passing through the same stretcher fiber and the isolator, the beam, which has an average power of 65 mW, is sent into the

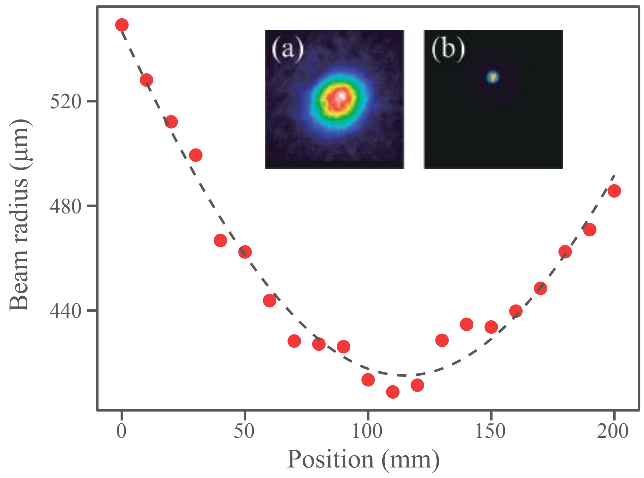

Fig. 4. Result of M^2 measurement. The insets show (a) near-field and (b) far-field beam profiles after the amplifier.

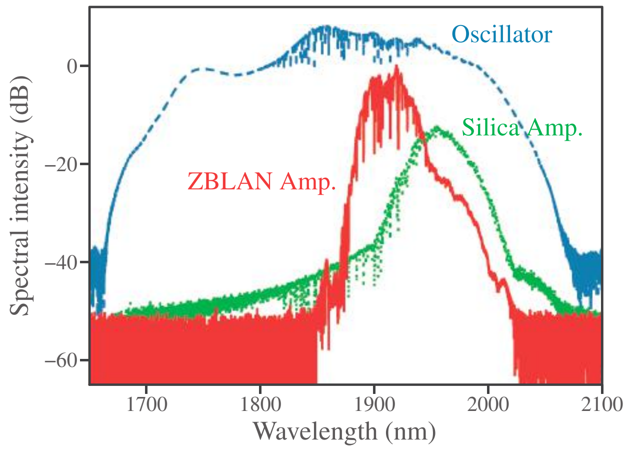

Fig. 5. Spectra of the oscillator (blue dashed curve), the ZBLAN fiber amplifier (red solid curve), and the silica fiber amplifier (green dotted curve).

silica-based amplifier fiber. The result of the amplification is shown as blue squares in Fig. 3(b). It is obvious that the efficiency has significantly improved, thus corroborating the validity of our hypothesis and measurements. We should note that it is difficult to compare the slope efficiency of ZBLAN and silica fibers from these measurements because some of the parameters of silica fibers, such as the Tm ion concentration, are unknown.

Another finding we would like to point out is that a much higher pump power is required for silica fibers to reach the maximum slope efficiency. For the silica-based amplifiers, a pump power as high as $\gtrsim$20 W is needed to reach the maximum slope efficiency, whereas only ~5 W is required for the ZBLAN-based amplifier. This difference can be explained by the higher phonon energy of silica compared to ZBLAN.[15,16] As Eichhorn and Jackson pointed out,[16] the much higher phonon energy makes multiphonon relaxation quite efficient, and hence a much higher pump power is required to make the stimulated emission dominant over the multiphonon relaxation, i.e., nonradiative decay. In other words, a higher pump power is required to achieve sufficient population inversion in silica. This leads to a higher lasing threshold in the case of oscillators. Similarly, a higher pump power is necessary to saturate amplifiers. Therefore, we conclude that ZBLAN fibers are much more efficient than silica fibers, especially when the seed and/or pump power are low to moderate.

To further study the suitability of ZBLAN fibers for use as amplifiers, we characterized other properties of the output beams. The beam profiles at the maximum output power were measured using a pyroelectric camera (Ophir Pyrocam IIIHR). A series of beam profiles was obtained by focusing the output beam using a lens with a focal length of $f = 500$ mm and moving the position of the camera in the focal direction. Figure 4 shows the variation of the beam radius around the focus. The radius at each point is determined by calculating the 4σ value from each image. Fitting onto these values yields an M^2 value of 1.4. The inset images show (a) a near-field profile and (a) a far-field profile. These results indicate that the output has a reasonable beam quality.

The output spectrum at the maximum output power measured with an optical spectrum analyzer (Yokogawa AQ6375) is shown in Fig. 5 as a red curve, which extends over more than 100 nm. This is significantly narrower than the oscillator spectrum, which has a width of 350 nm, as shown in the same figure as the blue dashed curve. This narrowing can be explained by a gain narrowing effect and reabsorption of Tm ions. Gain narrowing occurs most probably because the bandwidth of the oscillator is too broad for the amplification factor of 26 dB. Reabsorption is caused by insufficient inversion of thulium ions,[21] which results in higher radiation losses at shorter wavelengths around 1700 to 1850 nm, thus shifting the spectrum to the longer-wavelength side. We also measured the spectrum after the silica fiber amplifier. The result is shown as a green dotted curve in Fig. 5. Because the broad feature extending from 1700 to 1900 nm and above 2020 nm is due to amplified spontaneous emission (ASE), the spectral width of the amplified pulse is comparable to that obtained from the ZBLAN amplifier. The appearance of the ASE signal suggests that the seed beam in our experiments is not strong enough for the silica fiber. We can also see that the entire spectrum is shifted slightly toward longer wavelengths, which is the result of the stronger absorption in silica fibers.

The output pulses from the ZBLAN amplifier are compressed by the grating compressor, after which the average power is 3.9 W. The compressed pulses are characterized using a home-built second-harmonic generation (SHG) frequency-resolved optical gating (FROG)[22] device, where a 100-μm-thick BaB_2O_4 crystal is used as the nonlinear medium. Figure 6(a) shows a typical FROG trace measured with the device. The pulse shape retrieved from the trace is shown in Fig. 6(b), which shows a pulse with a duration of 150 fs. The retrieved spectral intensity and phase profiles are shown in Fig. 6(c). The structure within the pulse could be due to a higher-order phase that remained after the compressor and/or absorption by water vapor,[23] which could be seen in the spectra shown in Fig. 5.

The average output power obtained from our ZBLAN-based system is much lower than that in previous reports of ultrafast Tm-fiber MOPA systems based on silica fibers.[5–7] The main limitation comes from heat-induced damage to the end of the amplifier fiber, which made it difficult to apply a higher pump power. However, the duration of 150 fs is the shortest for pulses generated directly by watt-class Tm-fiber

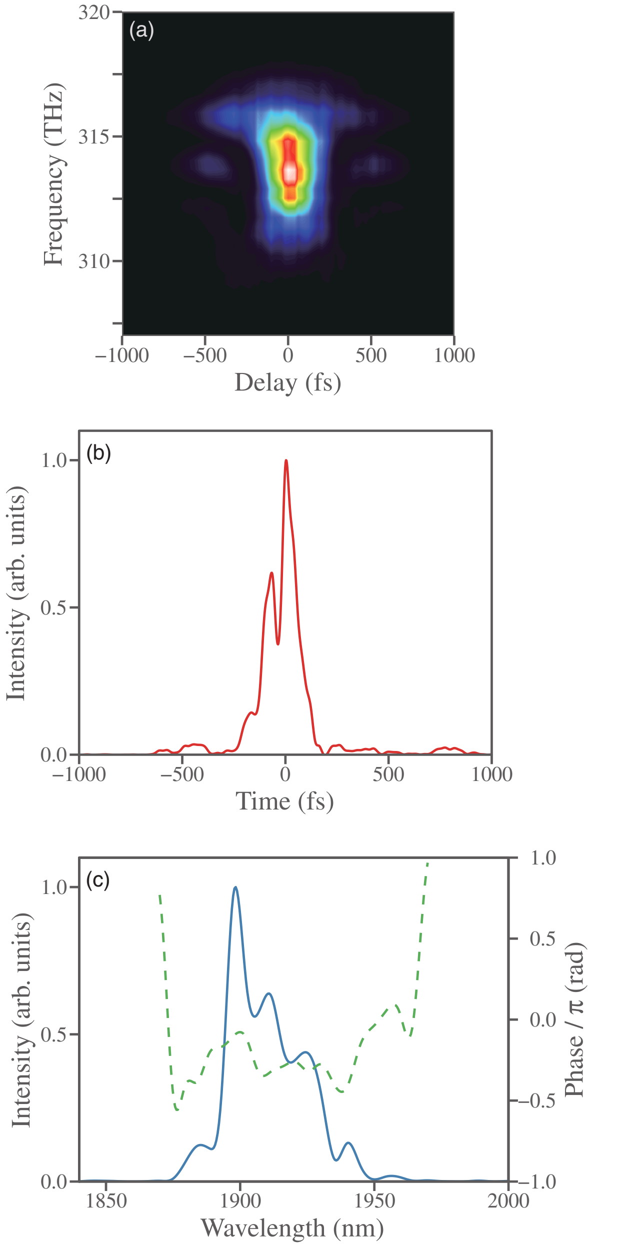

Fig. 6. Results of SHG FROG measurements. (a) Experimentally obtained FROG trace. (b) Retrieved FROG trace. (c) Retrieved pulse shape. (d) Retrieved spectral intensity (blue solid curve) and phase (green dashed curve).

MOPA systems. Furthermore, the pump and/or seed power required for ZBLAN-based amplifiers to reach the maximum slope efficiency are much lower, thanks to the longer lifetime of the $^3Fe_4$ level of thulium ions, which is the result of the lower phonon energy of ZBLAN fibers.[16] These results suggest that ZBLAN fibers would be suitable for use in the development of laser systems at a low-to-moderate power and would be useful for applications that require only moderate power or for developing preamplifiers before high-power silica-based amplifiers.

To summarize, we developed a chirped-pulse amplifier system for a Tm-doped fiber laser based on ZBLAN fibers. A ZBLAN fiber with normal dispersion is used as a stretcher, which significantly simplifies the setups for both the stretcher and the compressor. The pulses are amplified to an average power of 6.9 W at a pump power of 17 W with a slope efficiency of 47%. Unlike silica-based amplifiers, ZBLAN fiber amplifiers are quite efficient even when the pump and/or seed power is limited, which makes ZBLAN fibers ideal for building preamplifiers. The amplified pulses can be compressed to a duration of 150 fs with an average power of 3.9 W at a 67.5 MHz repetition rate. We believe that Tm-doped ZBLAN fibers are most useful for developing efficient, ultrafast light sources for applications that require moderate power such as nonlinear microscopy.

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