1 μJ, sub-500 fs chirped pulse amplification in a Tm-doped fiber system

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We demonstrate a Tm-doped fiber laser system producing ~300 fs pulses with 1 μJ energy, corresponding to peak powers greater than 3 MW. Pulses of 150 fs with 30 nm spectral bandwidth and 3 nJ pulse energy are generated in a Raman-soliton self-frequency shift amplifier, then stretched to ~160 ps using a chirped Bragg grating. The 60 MHz oscillator repetition rate is reduced to 100 kHz using an electro-optic modulator. After a single-mode fiber preamplifier and a large-mode-area fiber power amplifier, pulses were compressed using a folded Treacy grating setup to below 500 fs with up to 1 μJ pulse energy. To the best of our knowledge, this is the highest energy yet demonstrated as well as the first demonstration of peak powers exceeding 1 MW from a Tm:fiber laser system.

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Femtosecond pulsed sources operating near 2 μm are promising for the generation of high peak power at long wavelengths, particularly as pump sources for mid-IR light generation via nonlinear processes. Thulium fiber oscillators have been demonstrated with output energies ranging from picojoules to a few nanojoules [1–3], primarily operating in the soliton regime. To date, pulse amplification has been achieved via Raman-soliton self-frequency shift (SSFS) [4,5] and/or chirped pulse amplification (CPA) [6–8].

In the two previous CPA demonstrations with the longest temporal stretching, lengths of passive fiber were used to stretch the pulses both in the normal and anomalous dispersion regimes. In one case, the oscillator operated at relatively low repetition rate and was directly amplified in two single-mode fiber stages to 650 nJ pulse energy after compression, reaching ~800 kW peak power [7]. In the second demonstration, pulses were stretched in a large-mode-area (LMA) fiber with anomalous dispersion, amplified to 151 nJ in LMA fiber, and compressed with a Martinez compressor, reaching ~600 kW peak power [6]. In both cases, the pulses were stretched to 10 s of picoseconds, therefore limiting high-energy amplification due to accumulation of nonlinear phase. In one other demonstration, pulses were stretched to a few picoseconds, then amplified and compressed in a highly anomalous dispersive amplifier to 31 nJ energy with ~100 fs duration, corresponding to 230 kW peak power [8].

We have recently developed a system using a chirped Bragg grating (CBG) to stretch the pulses from 150 fs to 160 ps and recompress them after amplification to 550 fs with 85 nJ [9]. The uncompressed output of this previously developed system provides the front end for the work presented here. In this Letter, we describe a laser system that produces pulses with up to 1 μJ energy and sub-500 fs FWHM pulse duration after compression, exceeding the MW peak power level.

The front end for this work contains an all-fiber oscillator, a Raman SSFS amplifier producing 150 fs pulses with 30 nm bandwidth at 60 MHz, a CBG (Optigrate Corp.) with a calculated dispersion of 12.6 ps^2 for stretching pulses to 160 ps, and a single-mode preamplifier (Fig. 1). The CBG has a 52 nm rectangular reflective bandwidth at a center wavelength of 2020.5 nm. Pulses at 5 nJ from the preamplifier propagate through a rubidium titanyl phosphate electro-optic modulator (EOM) capable of picking the pulse repetition rate down from 60 MHz to a maximum of 100 kHz (Quantum Technology, Inc). There is factor of ~1000× reduction in average power due the change in duty cycle and loss through the EOM. The EOM has a measured contrast ratio of 20 dB at 2000 nm.

As indicated in Fig. 1, we use a single-mode Tm:fiber preamplifier to increase the energy of the pulse from 5 to 50 nJ. This preamplifier is based on ~5 m of 10/130 polarization maintaining (PM) Tm:fiber (Nufern, Inc), pumped with 6.5 W via a $2 + 1:1$ pump combiner (ITF labs 3S Photonics S.A.S.). The output of this preamplifier is spliced to a polarization-sensitive fiber isolator (Shinkohsa Co Ltd.) with >20 dB polarization extinction ratio (PER). Our investigations, both experimental and simulation, indicate that ~100 nJ is the maximum energy that can be sustained in Tm:single-mode fiber at this stretched pulse duration; therefore we use an LMA fiber as the final amplifier.

In order to eliminate free-space coupling into the LMA fiber amplifier, the isolator output is spliced to a mode field adaptor (MFA) (ITF Labs 3S Photonics S.A.S.) that couples light from 10/130 PM fiber to 25/400 PM fiber. The undoped MFA fiber is spliced directly to a 3.5 m section of Tm-doped PM 25/400 fiber (Nufern, Inc). This splice is coated with a high-index epoxy ($n = 1.56$) to strip signal light coupling into the cladding by the splice and to prevent residual counterpropagating pump light from possibly damaging the isolator during amplification.

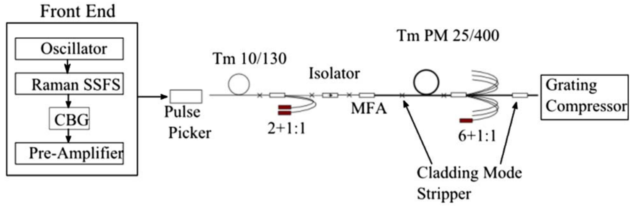

Fig. 1. (Color online) Schematic of the CPA system.

The 3 m Tm-doped fiber is wrapped around a water-cooled mandrel and spliced to the 25/400 PM pass-through fiber of a 6 + 1∶1 pump combiner (ITF Labs, 3S Photonics S.A.S.) with a 70 W, 790 nm diode (QPC Lasers) spliced to one of the combiner-pump inputs. A portion of the passive output fiber is window-stripped and coated with high-index epoxy to remove any signal light propagating in the cladding. The pulses are then compressed using a folded Treacy grating compressor consisting of two 50 mm × 50 mm, 600 line/mm, gold-coated reflection gratings.

A Treacy compressor is used to give more flexibility in compression than CBG compression as shown in [9] because the distance between gratings can be changed. It would be possible to compress using the CBG by incorporating more normal-dispersion fiber to compensate additional anomalous dispersion introduced by the amplifiers after the pulse picker; however, the accumulated nonlinear phase prior to amplification would be much larger due to the relatively high nonlinearity of the compensation fiber. In this case the Treacy compressor is used to compensate only group velocity dispersion, ignoring higher-order dispersion.

The maximum average power output directly from the LMA amplifier was 1.9 W. Of this average power, 20% is amplified spontaneous emission (ASE), as determined by spectrally filtering ASE in the Fourier plane of the compressor; therefore, average power is reduced to 1.52 W. The peak of the ASE in LMA fiber is centered at 1960 nm, while the center wavelength of the laser emission is 2020 nm, extending from 1994 to 2046 nm. We believe that any ASE that extends into the spectral region of the pulse is minimal but do not have a way to measure this power at this time. The Treacy compressor is ~50% efficient, so the maximum average power after the compressor is 0.76 W. Due to the ~20 dB contrast ratio of the EOM, the maximum energy in the main pulse after compression is ~1.4 μJ. The maximum energy in the LMA fiber prior to compression was ~2.6 μJ, corresponding to 16 kW peak power. The energy in the main pulse after compression is shown as a function of pump power in Fig. 2. The PER of the compressed output is 18 dB.

Of the total pulse energy, up to 1 μJ energy is confined within a 500 fs window, as shown in the interferometric autocorrelation in Fig. 3. The autocorrelation shows evidence of energy outside the 500 fs window that is

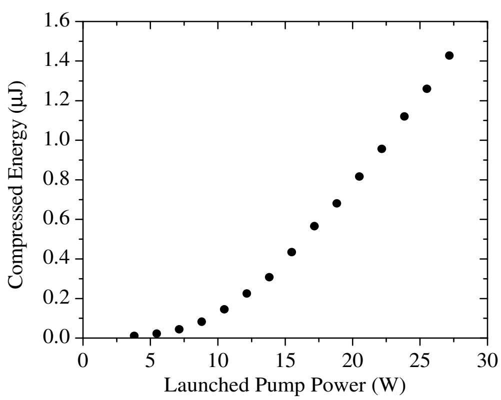

Fig. 2. Compressed pulse energy as a function of launched pump power.

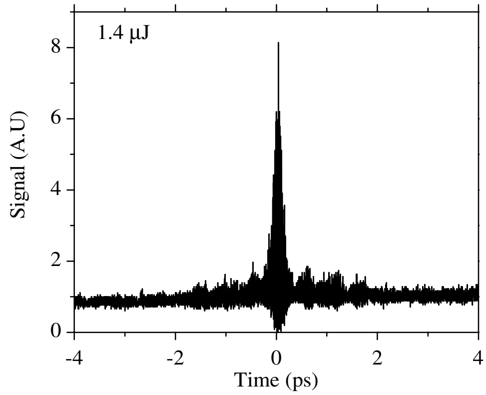

Fig. 3. Interferometric autocorrelation of pulses at 1.4 μJ compressed pulse energy. The 1.4 μJ takes into account the energy of the pulse extending outside the 300 fs peak.

related to spectral distortions occurring in the LMA fiber amplifier, as well as the positive third-order dispersion added by the amplifier fibers and the compressor. As energy increased, the ratio of the peak signal relative to the satellite pulses remained constant, indicating that the amplification is linear. By integrating the autocorrelation to compare the energy in the central pulse (~300 fs) relative to the small satellite pulses, we estimate at least 75% of the energy is within a 500 fs bucket.

Figure 4(a) shows the output from the LMA amplifier without a spectral filter in a logarithmic scale. ASE is centered at 1960 nm, spanning from 1925 to 1996 nm,

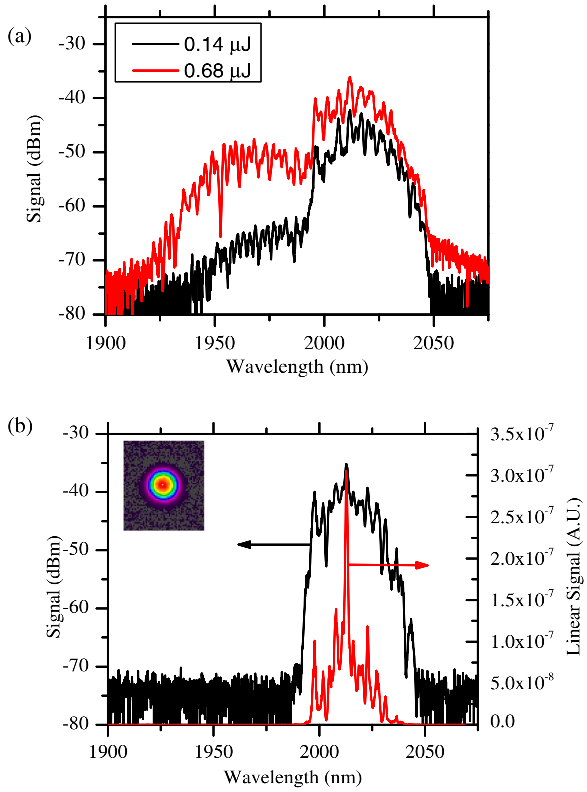

Fig. 4. (Color online) (a) OSA traces before spectral filtering of ASE at 0.14 and 0.68 μJ energies. (b) OSA traces of both the logarithmic (black curve) and linear (red curve) scale for spectrally filtered pulses after the compressor operating at 1.4 μJ. The inset is the beam image from the LMA amplifier.

and is spectrally modulated with the same frequency as the signal light centered at 2020 nm. Comparing the 0.14 and 0.68 μJ energy levels shows that the spectral modulation was not dependent on pulse energy. Figure 4(b) shows the spectrum of the compressed pulses after ASE filtering at full energy in linear and logarithmic scales.

The optical spectrum analyzer (OSA) traces presented in Fig. 4 show large spectral modulations induced within the LMA amplifier. The modulation on these pulses is similar to that found in [6], where the LP_{11} or LP_{02} mode in the fiber is excited, causing multimode interference (MMI). Reference [10] measures the higher-order mode content, using an S^2 method, for a similar passive fiber and determined the fiber supports both the LP_{01} and LP_{02} modes.

In Fig. 4(b), the primary spectral peak is centered at 2012 nm with a FWHM of 2 nm and contains ~18% of the total spectral power. The FWHM of the spectrum excluding the central peak was 17 nm. The Fourier transform of the spectrum in Fig. 4(b) corresponds to a pulse FWHM of 226 fs. Despite the spectral interference, the spatial output of the beam appears to be LP_{01}, as shown in Fig. 4 (inset), taken after compression with a 4 mm beam diameter.

Figure 5 shows the spectrum taken at three different points relative to the system schematic. MMI is first seen after propagation through the MFA but is primarily the result of higher-order modes originating from the splice between the passive LMA fiber and the Tm-doped LMA fiber.

Despite amplification to ~16 kW peak power in the LMA amplifier, self-phase modulation does not appear to degrade the quality of the pulse even in the presence of significant spectral degradation as the result of MMI. This system has been modeled using FiberDesk, and we have calculated the B-integral to be 4.1 rad; however, the current model has provided limited information on the quality of the pulse compared to the experimental results. We are continuing to work to characterize the amount and effects of nonlinearity in our system and to determine the nonlinear limits in Tm:fiber lasers and compare this to ultrashort-pulse Yb:fiber lasers.

These experimental results indicate a pathway to GW peak power generation using a large stretching ratio and amplification in Tm-doped LMA fiber. In this Letter, we show for the first time, to our knowledge, a Tm:fiber laser system operating at 2 μm with up to 1 μJ energy in 300 fs pulses, with peak powers greater than 3 MW. To our knowledge, these results represent the highest peak power generated to date by a Tm-doped fiber laser system. To verify this result, we have accounted for the energy in the pulse compared to ASE and background signal, as well as carefully investigating the spectral evolution of the pulses through amplification. There is clearly room for improvement in pulse quality, but there is also significant room to further scale pulse energy and peak power in Tm:fiber CPA systems.

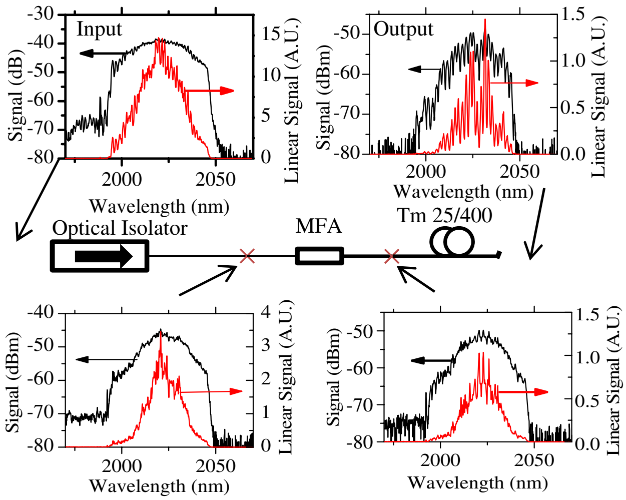

Fig. 5. (Color online) Schematic of the system following the single-mode preamplifier and comparing the OSA traces after each splice. MMI occurs after the MFA, which increases after the 25/400 fiber.

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