Chirped pulse amplification in Tm doped fiber using a chirped Bragg grating

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ABSTRACT

Femtosecond pulses were generated and amplified via chirped pulse amplification in Tm:fiber. The mode-locked oscillator centered at 1975 nm produced 800 fs transform limited pulses with 40 pJ energy at 60 MHz repetition rate. Subsequently, a soliton self-frequency shift in a thulium-doped fiber pumped with a 793 nm diode was used to amplify pulses to 3 nJ, shift the center wavelength, and reduce the pulse duration to 150 fs. This pulse was tuned to 2020 nm to match the center wavelength of a chirped Bragg grating. The pulses were stretched to >160 ps pulses, amplified to 85 nJ in single-mode Tm:fiber and recompressed to 400 fs.

Keywords: Fiber Laser, Thulium, Chirped Pulse Amplification, Volume Bragg Grating

1. INTRODUCTION

Development of femtosecond pulsed laser sources operating at 2 μm make them compelling pumps for mid-IR optical parametric oscillators [1] and super continuum generation [2]. The rate of development of Tm-doped ultrashort pulsed fiber sources has increased rapidly with mode-locking through numerous techniques [3–6], pulse amplification via soliton self-frequency shift (SSFS) [1,7,8], and chirped pulse amplification (CPA) [9–14]. Using a SSFS sub-100 fs pulses operating at 75 MHz and with 1 W of average power have been demonstrated and used for broad band OPO [1].

Here we report a CPA system where pulses were generated and amplified in Tm:fiber. Two cases of CPA will be presented in low and high energy regimes, where pulses were stretched using a CBG and compressed with both a CBG or a grating pair respectively. The CBG offers the ability to use a single element for stretching and compressing of pulses using the temporal reciprocity of the chirped structure in the Bragg grating. This CBG was fabricated in photo-thermo-refractive glass by Optigrate Corp. CBGs have been utilized at both 1 and 1.5 μm, and have achieved compressed pulses with 650 fs duration and 100 W average power at 1 μm [12,13]; however we are the first group to utilize this technology for CPA in the 2 μm wavelength regime. [15,16].

2. PASSIVELY MODE-LOCKED OSCILLATOR

Femtosecond pulses were generated in an all-fiber ring cavity pumped by an Er:Yb fiber laser. The oscillator, shown in Figure 1, contains sections of SMF28E passive fiber and a ~1-m long section of non-PM 10/130 Tm fiber (Nufern, Inc) doped fiber. The oscillator was passively mode-locked using a single-walled carbon nanotube saturable absorber fiber taper (KPhotonics) and polarization controllers in the system [17]. Time-bandwidth limited pulses were emitted from the 90/10 tap output coupler with pulse durations of ~800 fs with ~5 nm (FWHM) spectral bandwidth centered at 1975 nm. Due to the anomalous dispersion of the fibers in the cavity, the oscillator operates in the soliton regime and the pulse energy is limited to ~40 pJ at 60 MHz. The mode-locked oscillator exhibits Kelly-side bands typically associated with soliton pulses; therefore a pumped Raman-soliton amplifier was used to broaden and smooth the spectrum for further amplification, shown in figure 2.

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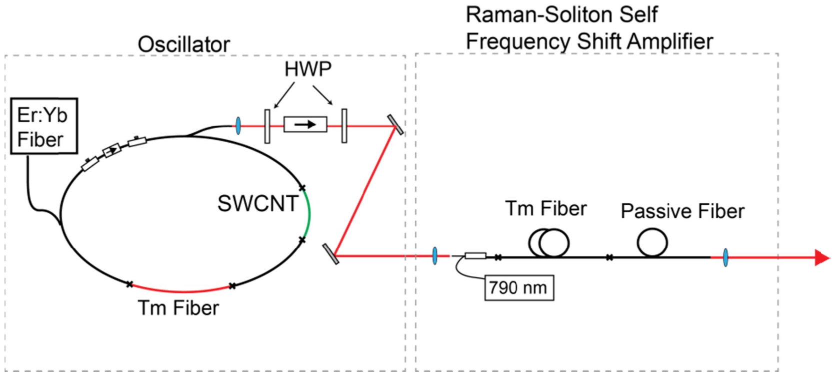

Figure 1: Schematic of oscillator and Raman-Soliton self-frequency shift amplifer.

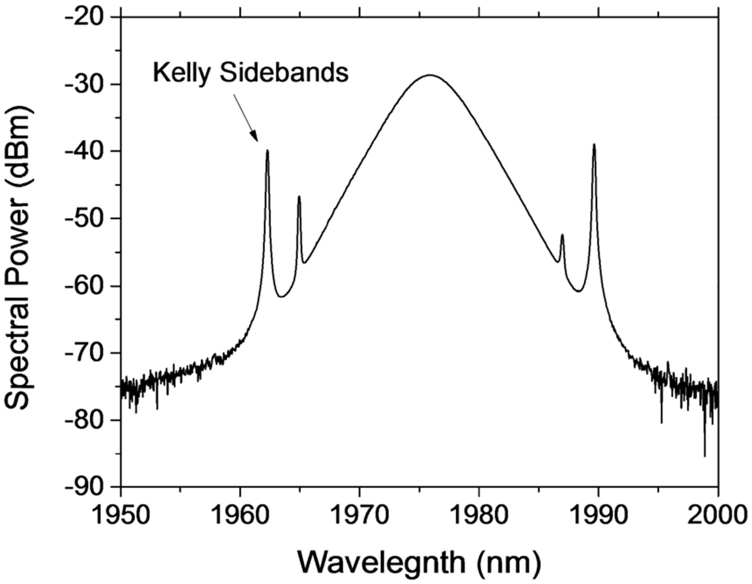

Figure 2: Optical spectrum of mode-locked oscillator.

3. RAMAN SOLITON SELF FREQUENCY SHIFT AMPLIFIER

Output from the mode-locked oscillator propagates through a free space isolator and half-wave plate before being coupled into the single-mode PM 10/130 fiber input port of a 2+1:1 taper fiber bundle (TFB) (ITF Labs/3S Photonics). The TFB is pumped with a 35 W diode (DILAS Diodenlaser GmbH) with 100 µm diameter delivery fiber coupled pump diode, and spliced to a ~5 m long section of PM 10/130 Tm doped fiber. This amplification process produces a Raman-soliton self-frequency shift, where the output signal was tunable from 1980 to 2100 nm depending on the input pump power. The output of this system produced an amplified, spectrally clean pulse, red-shifted in wavelength from the oscillator center wavelength of 1975 nm. The total output power was split between the residual input and the frequency shifted pulse, with ~60% of total power in the shifted pulse. Figure 3 shows both the spectral and temporal characteristics of this 3 nJ pulse. The pulse spectral width was ~30 nm (FHWM) with a pulse duration of ~150 fs.

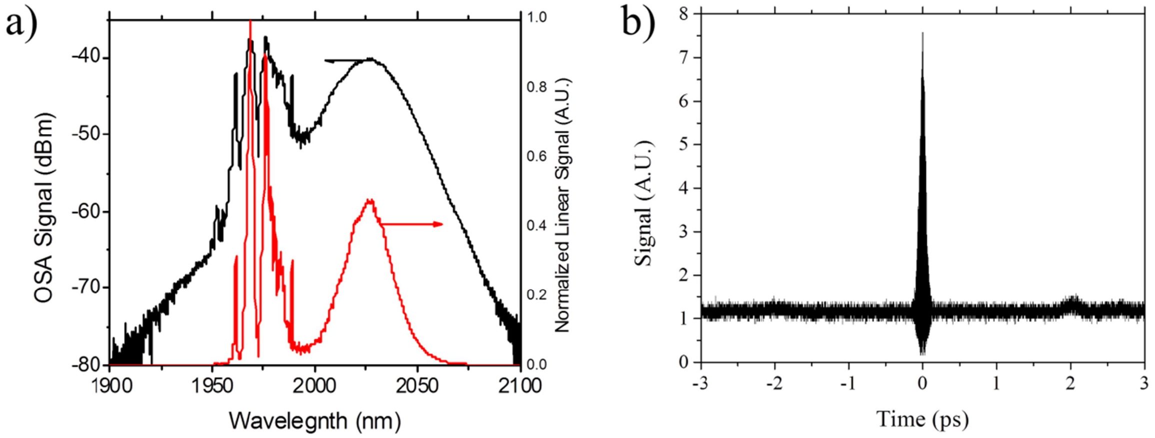

Figure 3: a) Spectrum from Raman SSFS amplifier. b) Autocorrelation trace from shifted soliton.

4. LOW ENERGY AMPLIFICATION

In order to amplify to high peak powers, the pulses were temporally stretched in a CBG. The CBG reflectivity is centered at 2020.5 nm with 52 nm bandwidth, and both surfaces are anti-reflection coated from 1900-2200 nm. The reflectivity averages ~82% across the full reflection bandwidth, and the chirp of the CBG results in a calculated group velocity dispersion of 12.3 ps^2 [18]. At this time, we are not able to directly measure the stretched pulse directly but we estimate it to be ~160 ps.

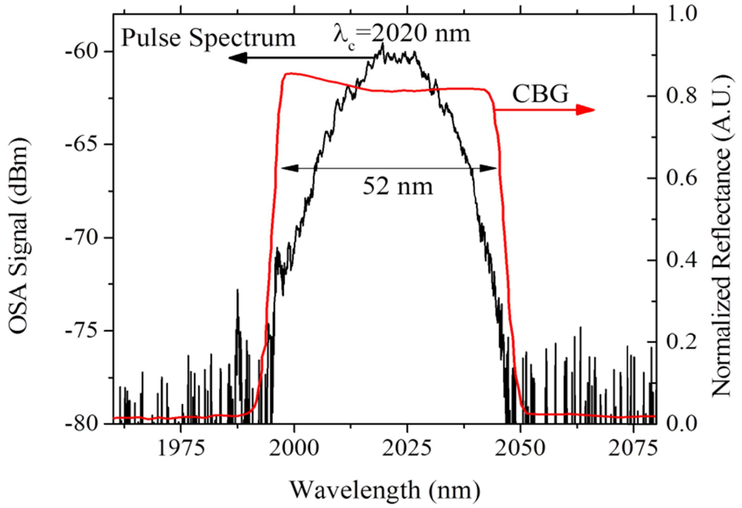

Figure 4: Reflective spectrum of the CBG (red) and spectrum of the stretched pulse (black).

The schematic for the CPA stage of this laser system is shown in figure 5. The Raman-soliton was free space coupled to the amplifier stage after pulse stretching in the CBG. The polarization is controlled by a quarter-wave plate (QWP) and upon reflection from the CBG is rotated 90º from the incident orientation, so that CBG output is coupled through the side facet of a polarizing beam splitter (PBS). The residual signal from the oscillator pulse centered at 1975 nm was not reflected by the CBG and was therefore not amplified.

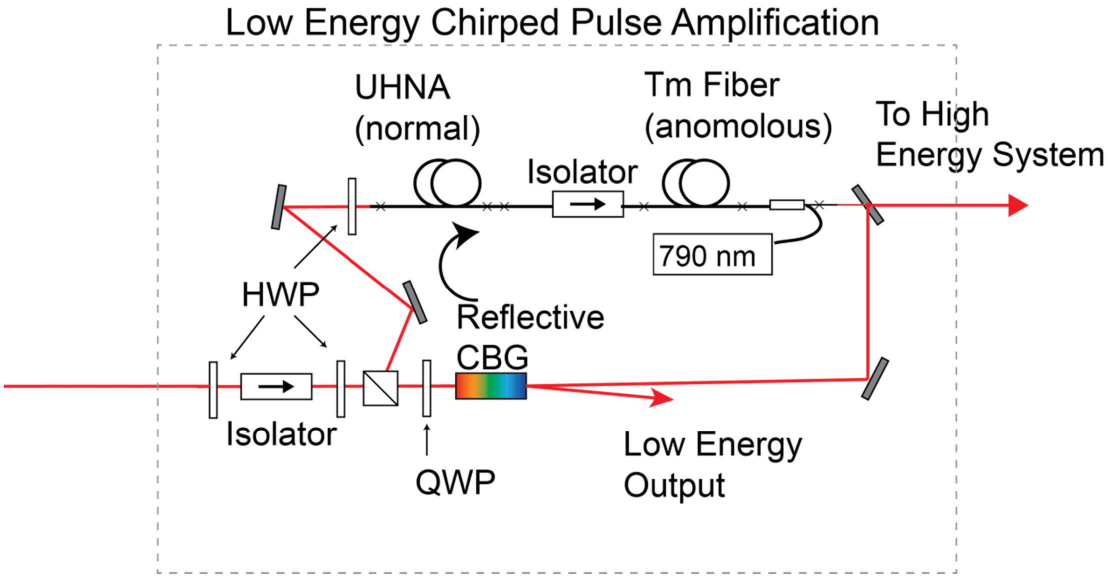

Figure 5: Schematic for Low energy CPA. UHNA-ultra high numerical aperture, QWP- quarter wave plate, HWP- half wave plate.

A section of ultra-high numerical aperture (UHNA) fiber was inserted to provide normal dispersion to compensate the anomalous dispersion of the Tm:fiber amplifier; without the UHNA pulses were compressed to 4 ps. Due to the small mode-field diameter of the UHNA, a mode field adaptor (MFA) was fabricated between SM2000 (ThorLabs) and the DCF to increase efficiency into the amplifier. A ~9 m section of DCF, bookended by MFAs was inserted prior to the amplifier, introducing ~1 dB insertion loss. The SM2000 fiber was spliced to the undoped fiber pigtail (PM 10/130) of a polarization sensitive fiber-coupled optical isolator (Shinkoshsa) to remove any backward propagating amplified spontaneous emission (ASE) and ensure linear polarization of light prior to amplification. The isolator was spliced to 4 m section of Tm-doped PM 10/130 fiber that was wrapped around a water-cooled mandrel for thermal management during amplification. Counter-propagating pump light was coupled into the amplifier using a 2+1:1 TFB. A final section of PM 10/130 was spliced to the TFB and cutback to balance the dispersion of the DCF and anomalous fiber in the cavity. For low energy experiments, the pulse was compressed in the CBG using the opposite facet from that for pulse stretching and the beam and polarization dependent transmission (input) and reflection (output) from a PBS.

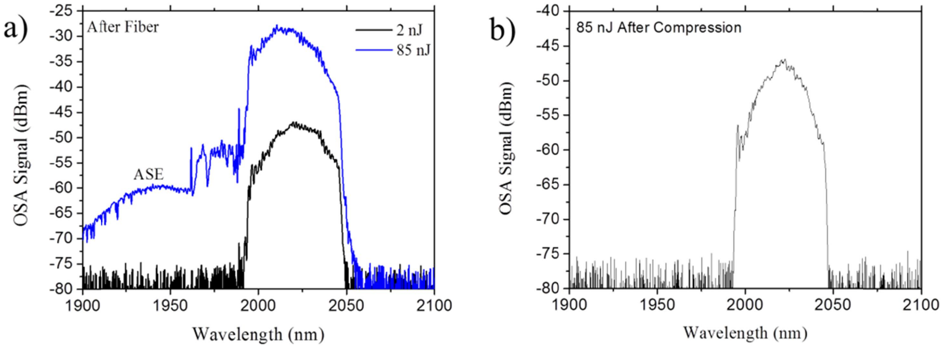

Figure 6: a) Output spectrum from single-mode amplifier directly after fiber. b) Output spectrum after CBG compression.

After stretching in the CBG, the power was ~120 mW. Due to coupling losses as well as insertion losses from the DCF and fiber isolator, we estimate the average power injected into the Tm:fiber was ~50 mW. This was amplified to a maximum average powers of 5.8 W with ~10% power in ASE, and were re-compressed to ~400 fs minimum pulse duration. Amplification to 85 nJ lead to slight increase of the pulse duration to 550 fs, shown Figure 7. The OSA traces in Figure 6a) shows spectra after amplification. There is no evidence of spectral modulation due to self-phase modulation and only a slight blue-shift of the center wavelength towards the ASE peak near 1950 nm. Figure 6b) shows the final spectrum of the compressed beam at 85 nJ. The output appears narrower than the corresponding case in figure 6a) because the beam is slightly spatially chirped.

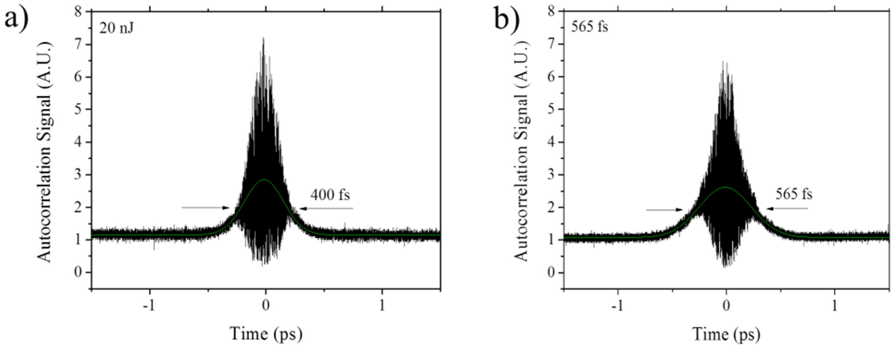

Figure 7: a) Interferometric autocorrelation trace for 20 nJ amplication. b) Interferometric autocorrelation trace for 85 nJ amplification.

5. HIGH ENERGY AMPLIFICATION

Pulses from the preamplifier propagated through a rubidium titanyl phosphate (RTP) 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 was factor of ~1000x loss 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. The high energy system schematic is shown in figure 8.

We used a single-mode Tm preamplifier to increase the energy of the pulse to 50 nJ. This preamplifier was based upon ~5 m of 10/130 PM Tm:fiber (Nufern, Inc), pumped by two 35 W, 790 nm diode lasers (DILAS Diodenlaser GmbH) via a 2+1:1 pump combiner (ITF labs 3S Photonics S.A.S.). The output of this preamplifier was spliced to a polarization sensitive fiber isolator (Shinkohsa Co Ltd.). This single-mode amplifier was limited due to the nonlinear phase accumulation that would build up in the single-mode; therefore we use a LMA fiber as the final amplifier.

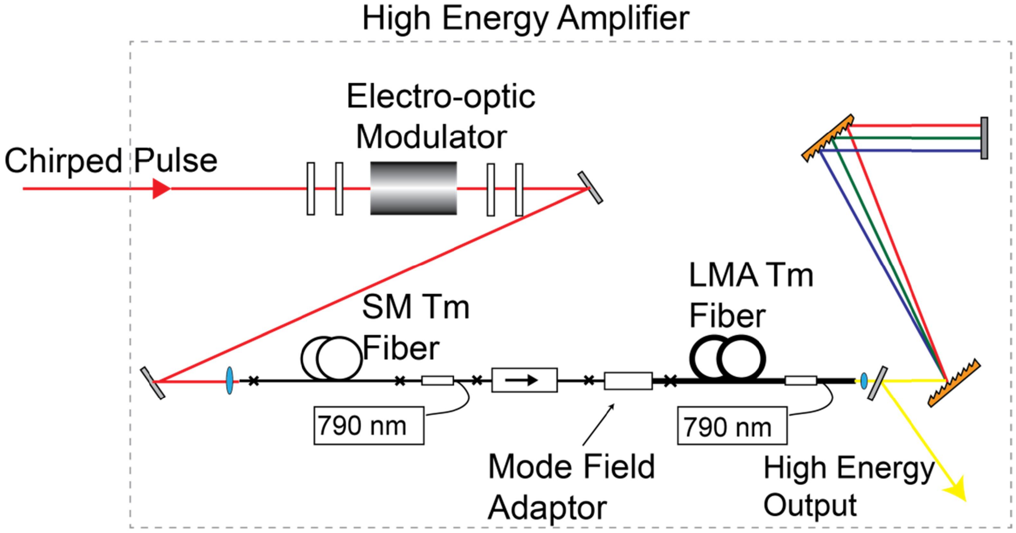

Figure 8: Schematic for high energy amplification.

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 the 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 LMA fiber (Nufern, Inc). This splice is coated with a high index epoxy (n=1.56) to strip signal light propagating forward in the cladding due to scattering at the splice and to prevent residual counter-propagating pump light from possibly damaging the isolator during amplification. 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 compressed using a folded Treacy grating compressor consisting of two 50 x 50 mm, 600 line/mm, gold-coated, reflection gratings.

A Treacy compressor is used to give more flexibility in compression than CBG compression Ref [12] 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 in the amplifiers; however the third-order dispersion would not be compensated and the accumulated nonlinear phase prior to amplification would be much larger due to the relatively high nonlinearity of the compensation fiber.

The average power was measured after the grating compressor, in which a knife-edge in Fourier plane was used to spectrally filter out amplified spontaneous emission (ASE) corresponding to ~20% of the average power in the system. The peak of the ASE in LMA fiber is centered at 1960 nm, while the center wavelength of the pulses is 2020 nm extending from 1994 to 2046 nm. The Treacy compressor is ~50% efficient, including the spectral filtering of ASE. Due to the ~20 dB contrast ratio of the EOM, the maximum output energy in the LMA amplifier is ~2.6 μJ before compression, corresponding to 16 kW of peak power in the fiber.

The pulses are compressed, as shown in the interferometric autocorrelations in Fig. 9, with up to 1 μJ pulse energy inside the sub-500 fs. The autocorrelation shows evidence of small satellite pulses that are related to spectral distortions occurring in the LMA fiber amplifier, as well as the positive third order dispersion added by the 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 peak of the pulse (~300 fs) with the small satellite pulses, we estimate at least 75% of the energy is within a 500 fs bucket.

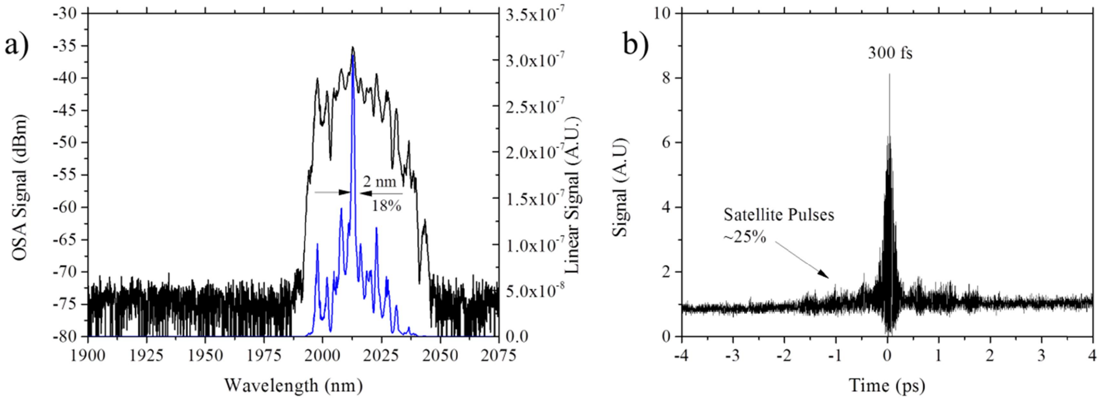

Figure 9: a) Linear and logarithmic output for pulses amplified to 1 μJ. b) Interferometric autocorrelation trace for 1 μJ with satellite pulses containing 25% of the total energy.

6. CONCLUSION

In this work we developed both low and high energy systems for fiber chirped pulse amplification at 2 μm. In the high energy case pulses operating at 100 kHz were able to reach 1 μJ with a compressed pulse duration of 300 fs. This work is an advancement of CPA at 2 μm and highlights methods for stretching and compressing that can amplify pulses to GW peak powers.

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