All-fiber high-power 1700 nm femtosecond laser based on optical parametric chirped-pulse amplification

YUKUN QIN,∗ ORKHONGUA BATJARGAL, BENJAMIN CROMEY, and KHANH KIEU

College of Optical Sciences, University of Arizona, 1630 E. University Blvd, Tucson, Arizona 85721, USA
∗yukunqin@email.arizona.edu

Abstract: We present the design and construction of an all-fiber high-power optical parametric chirped-pulse amplifier working at 1700 nm, an important wavelength for bio-photonics and medical treatments. The laser delivers 1.42 W of output average power at 1700 nm, which corresponds to ∼40 nJ pulse energy. The pulse can be de-chirped with a conventional grating pair compressor to ∼450 fs. Furthermore, the laser has a stable performance with relative intensity noise typically below the -130 dBc/Hz level for the idler pulses at 1700 nm from 10 kHz to 16.95 MHz, half of the laser repetition rate f/2.

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1. Introduction

Laser sources in the 1700 nm wavelength range are very attractive because of their potential applications in a variety of fields. For example, due to the high absorption of hydrocarbon bond near 1700 nm, these lasers can be used both for welding some polymers or plastics [1,2], and for lipid-targeted skin care treatments [3]. In addition, a high-power ultrashort laser source at 1700 nm is an essential tool for applications in the biomedical sciences because tissues have relatively low water absorption and long scattering length at this wavelength. 1700 nm pulsed lasers have demonstrated a large penetration depth for multi-photon microscopy [4], high-resolution optical coherence tomography [5], and precision eye surgery [6]. Because of the lack of traditional high-gain media for 1700 nm, generating high power laser output at this wavelength is still difficult. A high power 1700 nm femtosecond laser would have the flexibility to be used in high loss beam paths, or to generate strong nonlinear signal at even greater depths than previously reported, or to be more efficient in the processing of materials.

Crystal-based optical parametric oscillators and amplifiers are conventional methods for producing laser pulses near 1700 nm [7,8]. However, the critical alignment of the nonlinear crystal makes the system bulky and sensitive to the environment. An all-fiber design would remove this alignment concern, making the system more robust. Raman soliton fiber lasers are commonly used for providing ultrashort laser pulses near 1700 nm [9–11]. While this technique can preserve the all-fiber design, the power scaling is limited by the effective mode area of the fiber. To get around this, large-mode-area fibers are usually used for high-power soliton lasers [9,10], but they sacrifice the robustness of the fiber format due to the free-space optics needed for fiber-coupling or pre-compression of pump pulses. Recently, an all-fiber Raman soliton working at 1680 nm with 1.6 W average output power has been demonstrated [11], which utilized a specially designed Er-doped very-large-mode-area (VLMA) fiber by OFS [12]. Because this Er-doped VLMA can tolerate much higher peak power during the high-power amplification process, the output can be directly spliced to another VLMA to generate Raman soliton without the use of free-space optics for fiber-coupling. However, the VLMA is not commercially available yet, and the generated soliton’s energy is limited to ∼20 nJ by the effective mode area of the VLMA. Super-continuum generation (SC) is another common technique to generate laser pulses.
at 1700 nm based on nonlinear fiber optics [13,14]. Compared to the Raman soliton technique, this method has the advantage of using standard single mode fibers and depending less on the effective mode area. Nevertheless, in [14], because of the high energy pump pulse needed to be de-chirped close to transform-limited before launching into the fiber for spectral broadening, the pre-compression and free-space to fiber coupling decreased the compactness and increased complexity of the system. In order to directly produce signal at 1700 nm, Bismuth-doped fiber (BDF) and Thulium/Holmium co-doped fiber (THDF) have been investigated [15–17]. However, the low maturity level of BDF and the strong reabsorption of 1700 nm from the THDF make reaching high performance goals difficult.

Fiber-based parametric generation, the technique of degenerate four-wave-mixing [18], offers an alternative approach to overcome the above issues. By using dispersion-shifted fiber as a gain medium, a fiber optical parametric oscillator (FOPO) has been demonstrated to work near 1700 nm [19]. However, because of the nonlinearity of the fiber, the power scaling of the FOPO approach can be very challenging, leaving the output power levels around the milli-Watt range. To further increase the output power, the use of fiber optical parametric chirped-pulse amplifier (FOPCPA) has been proposed [20–25], which combines chirped-pulse amplification and parametric interaction to achieve high power amplification inside the fiber. In [26], microjoule-level pulses have been produced with a FOPCPA, which shows great energy scalability of the approach. Additionally, by properly satisfying the phase-matching condition, this approach also gives wavelength tunability that has some more flexibility in the tuning range compared with the Raman soliton approach [27]. In this paper, we discuss the design and performance of a watt-level high pulse energy all-fiber femtosecond laser working at 1700 nm using the FOPCPA approach. In our design, we used a SC as the seed pulse in the FOPCPA. Because the SC pulses originated from the same oscillator as the pump pulses, it eliminated the need for electronic synchronization between the pump and the seed. Notably, by using this approach, a constant relative phase relation can be maintained between signal/idler and pump, which is important for many applications. This approach has been used to generate high power ultrashort pulses at other difficult wavelengths to generate in fiber such as 1300 nm [28]. Compared to the other approaches, our FOPCPA uses a standard single mode dispersion-shifted fiber (DSF), as the wavelength conversion tool and the energy scalability is better than the Raman soliton technique. In addition, our system uses highly chirped pump pulses, and it does not require pre-compression for the pump pulse as was needed in [14]. Another advantage of the FOPCPA approach is the capability of selecting the desired chirp of the amplified 1700 nm pulses, while the Raman soliton can only provide a transform-limited pulse. In practice, silica is often used in optical instrumentation and has anomalous dispersion at 1700 nm; thus, up-chirping the 1700 nm pulses can be used to counter the effects of material dispersion of silica [29].

2. Experimental setup

The schematic of the laser system is shown in Fig. 1, which includes six stages. In Fig. 1 (stage 1), the mode-locked laser oscillator was built with a fiber-taper carbon nanotube saturable absorber [30] and operated at 33.9 MHz with 1.7 mW average output power. The spectral full-width half-max (FWHM) bandwidth of the soliton mode-locked laser was ~8 nm centered at 1561 nm. The corresponding transform-limited pulse duration was ~315 fs assuming a sech squared pulse shape. In Fig. 1 (stage 2), the output of the oscillator was launched into a home-built erbium-doped fiber amplifier (EDFA) and amplified to 68 mW. The EDFA was built using a normal dispersion erbium-doped fiber (ER30-4/125, Liekki, D ~ -38 ps/nm/km at 1550 nm). Due to the normal dispersion of the gain fiber, the seed laser’s spectrum was broadened to ~40 nm and the output pulses were highly chirped. After the EDFA, a 90/10 fiber coupler was used to split the amplified pulses into two branches for creating the signal and pump pulses. We used a polarization maintaining (PM) DSF (DS15-PS-U40A, Fujikura) as the parametric gain
Fig. 1. Schematics of the FOPCPA setup: (1) fiber ring-oscillator of the Er-doped mode-locked oscillator, (2) first stage pre-amplifier, (3) super-continuum generation stage, (4) second-stage pre-amplifier, (5) high power amplifier, (6) fiber-based optical parametric amplifier and diagnostics, SA: Saturable absorber, EDF: Erbium doped fiber, OC: output coupler, PC: Polarization controller, HNLF: Highly nonlinear fiber, BPF: Band-pass filter, WDM: Wavelength-division multiplexer, DSF: PM Dispersion-shifted fiber, DM: Dichroic mirror.

Fig. 2. (a) Phase-matching calculation of the PM DSF, (b) Super-continuum spectrum in stage 3 (black: before the filter, purple: after the filter), (c) Spectrogram of the parametric gain induced by 1 kW chirped pump pulse at 1543 nm, (d) Pump spectrum in stage 4 (black: before the filter, purple: after the filter).

fiber. The zero-dispersion wavelength of this DSF was at $\sim 1547$ nm. The pump wavelength was calculated using a 1 kW peak power and plotted in Fig. 2(a); the red curve represents the idler, the blue curve represents the signal, and the black dashed line indicates the ideal pump wavelength 1543 nm and signal 1410 nm that should be chosen for the FOPCPA. In Fig. 1 (stage 3), the 90% output was spliced with $\sim 60$ cm of SMF-28 fiber for soliton compression. After the pulses were compressed, a $\sim 5$ cm piece of a highly nonlinear fiber (HNLF), made by OFS, was directly spliced to the output to generate the SC. The splice loss was $\sim 20\%$ between the single-mode fiber and HNLF. The black line in Fig. 2(b) shows the full spectrum of the SC. In our design, we decided to use the down-chirped signal at 1410 nm to seed the FOPCPA to create an up-chirped idler at 1700 nm. In Fig. 2(c), the calculated spectrogram of the induced parametric gain from the chirped pump [31] depicts that an up-chirped idler can be obtained by phase matching with
both a down-chirped pump and signal. After the HNLF, a film-based band-pass filter (BPF) with a cutoff at 1500 nm was used to select the signal pulse, after which the signal pulse was launched into ~250 m of SMF-28 to acquire the down chirp sign. In Fig. 1 (stage 4), the 10% output was launched into a tunable BPF before the second pre-amplifier. This BPF was used to select the center wavelength, 1543 nm, for the pump according to the calculation in Fig. 2(a). The FWHM bandwidth of this BPF is ~5 nm. The spectrum before and after the filter are shown in Fig. 2(d). The filtered pump pulses were launched into a ~1.6 km long SMF-28 to create the required down chirp pulses. After this, a fiber-pigtailed optical delay line was used to synchronize the pump and signal pulses. The delay line is a fiber-pigtailed component that consists of an input and an output fiber with no alignment needed from the user. At the output of the second pre-amplifier, the pump pulses were amplified to ~30 mW and launched into a 1400/1550 nm wavelength division multiplexer (WDM) (stage 5, Fig. 1) to combine with the signal pulses. Because the WDM was made with polarization maintaining (PM) fiber (blue color in Fig. 1), in-line polarization controllers and fiber isolators/polarizers with ~0.5 dB insertion loss were used before the WDM to set the linearly polarized pulses into the WDM. In stage 5, a high-power fiber amplifier was built with ~2 m PM double-clad Er/Yb co-doped fiber (DCF-EY-10/128-PM, CorActive) to further amplify the pump pulses up to 7 W. In stage 6, the output port of the Er/Yb co-doped fiber was directly spliced to ~3.5 m PM DSF for the parametric amplification. The splice loss between the PM DSF and the gain fiber was ~8%.

3. Numerical simulation

To study the parametric amplification process, we performed numerical simulations using realistic experimental parameters that were based on solving the nonlinear Schrödinger equation via the split-step method [18]. Because the chirp-rate match influences the output of FOPCPA [31], this was considered in our simulations by matching the chirp-rate for five different pulse durations. In the simulation, the bandwidth of the pump pulse was fixed at 6 nm, and the average power was 7 W at 33.9 MHz, which was based on our actual data from the Er/Yb fiber amplifier shown in Fig. 1. The bandwidth of the signal pulse seeding the FOPCPA was 30 nm.

The numerical results are shown in Fig. 3. For the 160 ps pump pulse, the graph shown in Fig. 3(a) confirms the dependence of the output power on the pulse duration (chirp-rate) of the signal pulses. At the optimal pulse duration (chirp-rate matched, inset(ii)) of the signal pulse, the calculation predicted that conversion efficiency could be higher than ~30%. In addition, the insets of Fig. 3(a) show the energy scaling of the idler pulse by seeding signal pulses at (i) 50 ps, (ii) 92 ps, and (iii) 130 ps, respectively; the maximum output pulse energy increases as the signal pulse duration increases. The inset (i) shows a power saturation occurs at ~1.7 m inside the DSF for 50 ps signal pulse, then the back-conversion process takes place and attenuates the signal/idler [18,32]. In inset (ii), by stretching the signal pulse more, the maximum output pulse energy was increased because of the low peak power and high saturation level, and it reached the best efficiency as well. In inset (iii), the signal pulse only partially overlapped with the pump pulse because it was stretched much longer than the pump pulse. Thus, the maximum output pulse energy become slightly lower than that in inset (ii). However, the maximum output pulse energy here was still more than that in inset (i) because of the lower peak power. According to the simulation, it is clear that the output pulse energy can be scaled up by stretching the signal pulse (at a fixed pump pulse duration), but the conversion-efficiency is limited by the back-conversion effect and the temporal overlapping between the pump and signal pulses.

Furthermore, in order to investigate the signal pulse duration for the optimal conversion-efficiency and the amplified idler bandwidth, we fixed the input pump power and performed simulations for different durations of the pump pulses. The results were plotted in Fig. 3(b). The signal pulse duration for achieving the optimal conversion-efficiency increases when the pump pulse duration increases, but the bandwidth of the amplified idler was almost constant at around
Fig. 3. Numerical simulation results: (a) For an 160 ps pump, the maximum output pulse energy of the idler (1700 nm) at different pulse widths of the signal (1410 nm) is shown; the insets show the energy evolution of the idler pulse in the PM DSF fiber. (b) For varied pulse widths of the pump, the optimal pulse widths of the signal pulse (black) are shown along with the bandwidth of the amplified 1700 nm idler (red). (c) Output spectra by using the optimal pulse widths in (b).
Figure 3(c) shows the optical spectra of the simulated results of the FOPCPA. Overall, the numerical simulation confirmed good parametric amplification in the DSF fiber and gave us the insight needed for choosing the final design of our system.

4. Experimental results

In the experiment, we chose the pump to be a ~160 ps down-chirped pulse and the signal to be ~90 ps down-chirped pulse according to the numerical simulation results. The amplified spectra were measured directly after the PM DSF fiber and are shown in Fig. 4(a). In order to characterize the power of the signal and idler separately, we used two dichroic mirrors, one with a cut-off at 1500 nm, and the other at 1650 nm. Figure 4(b) shows the measured average power of idler and signal at increasing pump power. The 1.42 W idler and 1.26W signal were obtained by using a 6.5 W pump. The conversion efficiency was 22% for the idler, and 20% for the signal. This unusual power asymmetry between the amplified signal and generated idler is due to the Raman assisted parametric process [33]. The measured FWHM spectral bandwidth of the amplified idler was ~32 nm. The amplified spectrum shows good agreement with the numerical simulation result shown in Fig. 4(c). The autocorrelation measurement of the compressed pulse is shown in Fig. 4(d). The compressed pulse has duration of ~450 fs at FWHM. As a comparison, we plotted the autocorrelation trace deduced from the measured spectrum (using zero-phase Fourier transform), which has ~200 fs transform-limited pulse duration. The measured pulse duration was close but not quite transformed-limited. The imperfect compression might be due to uncompensated high-order dispersion from the system. The total loss of the compressor was 40%, which indicates the peak power of the compressed pulse was about ~55 kW. We used a suboptimal transmission grating pair designed for operation near 1550 nm (due to availability). For that reason, the grating compressor has a high loss for 1700 nm.

![Figure 4](image-url)  
**Fig. 4.** (a) The output spectrum of the FOPCPA is synchronized (blue), not synchronized (red), and the spectrum of seed signal (black), (b) the output power of the FOPCPA, (c) the numerical simulation result of the FOPCPA, (d) the measured autocorrelation trace of compressed idler pulse (blue), the deduced autocorrelation trace from the measured spectrum.

A stable laser source is essential for many applications. Thus, we measured the relative intensity noise (RIN) of the laser outputs. All the measurements were made with a Thorlabs 70 MHz DET410 photodetector in combination with a RF spectrum analyzer (Tektronix, RSA6114A) and plotted in Fig. 5. The red curve in Fig. 5 is the RIN spectrum of the mode-locked pulses after the first EDFA (stage 2, Fig. 1) that had low RIN of -152 dBc/Hz (at >2 MHz) and converged to
the instrument noise floor at higher frequencies. The black curve is the RIN spectrum of the filtered SC [Fig. 2(d), purple]. The green curve is the RIN spectrum of the pump pulse after the power amplifier. Below 1 MHz, the pump and the SC pulse have a similar RIN to the EDFA’s RIN. However, both of the pump and SC pulse show a strong high-frequency noise from 1 MHz to 16.9 MHz, which does not appear on the red curve. The idler at 1700 nm (the purple curve in Fig. 5) also inherited features of the high-frequency noise from the SC seed and the filtered pump but still at a level below -130 dBc/Hz. We performed RIN measurements at the output of the tunable BPF that is located after the EDFA in order to understand this high-frequency noise feature better. We experimentally measured the RIN spectra for four different settings of the bandpass filter shown in Fig. 6(a). The corresponding RIN for each filter setting is plotted with the same color in Fig. 6(b). From the measurement, it is clear that the high-frequency noise features depend on the wavelength and bandwidth of the filtered pump after the EDFA. Notably, as the wavelength gets far from the center wavelength of the initial mode-locked laser oscillator, the high-frequency noise becomes more enhanced. In addition, the noise peak around ~5 MHz was more enhanced as the filter was adjusted to overlap with one of the Kelly sidebands [black arrow in Fig. 6(a)]. Based on this observation, we think that this high-frequency noise resulted from the nonlinear broadening in the EDFA and fiber laser oscillator design. This also suggests that this is the origin of the high-frequency noise features in the SC seed signal pulses.

Fig. 5. The measured RIN of pump pulses after first the EDFA (red), pump pulses after the power amplifier (green), seed pulses after the filtered super-continuum (black), and idler pulses after the grating compressor (purple).

Fig. 6. (a) The measured spectra of the mode-locked laser oscillator (black dash-dot line), the first EDFA (black dot line), setting 1 of the tunable filter (blue solid line), setting 2 of the filter (red solid line), setting 3 of the filter (black solid line), and setting 4 of the filter (purple solid line), (b) the measured spectra of RIN for the setting 1 (blue), the setting 2 (red), the setting 3 (black), and the setting 4 (purple).
Optimizing the center wavelength of the initial mode-locked laser oscillator may improve the noise performance of the FOPCPA significantly. Similar noise peaks in the RIN measurement after nonlinear wavelength conversion are also reported in a publication from another group [34].

5. Conclusion

We have built and characterized an all-fiber high-power femtosecond FOPCPA operating at 1700 nm. The laser source provides up-chirped pulses with more than ~40 nJ energy per pulse, which corresponds ~1.42 W average power. By using a conventional grating pair compressor, the idler pulses were compressed down to ~450 fs. We believe this all-fiber high-power laser source will be well-suited for many applications in bio-photonics and biomedical treatment.

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