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Normal-dispersion fiber optical parametric chirped-pulse amplification

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Abstract

We demonstrate a fiber optical parametric chirped-pulse amplifier pumped in the normally dispersive regime. This approach is readily scalable, offering a route to microjoule-level, femtosecond pulses at new wavelengths. As a first demonstration, we pump with chirped pulses at 1.03 μm and seed with a continuous-wave beam at 0.85 μm , and are able to generate idlers at 1.3 μm with durations as short as 210 fs or energies as high as 180 nJ.

Ultrafast fiber lasers are becoming increasingly attractive sources for academia and industry alike. Compared to the solid-state lasers that are now commonplace in research laboratories, fiber lasers can be much more robust, compact, and cost-effective. These advantages do not come without trade-offs: light in a fiber experiences tight confinement and long interaction lengths, requiring a greater attentiveness to nonlinear effects than is necessary in solid-state lasers. Despite these challenges, fiber sources can now regularly generate the microjoule-level, femtosecond-scale pulses that are needed by many applications.

That said, high-performing fiber lasers remain conspicuously lacking in wavelength tunability. Available gain media restrict the vast majority of fiber lasers to spectral regions near 1, 1.55, and 1.9 μm . These restrictions can be limiting for popular applications such as nonlinear microscopy, where the laser's wavelength can be just as important as its power. For instance, in deep-tissue bioimaging, microjoule-level pulses with wavelengths near 1.3 or 1.7 μm can penetrate further into a sample [1], and bioimaging as a whole already benefits from significant investments into fluorophores active at specific wavelengths [2]. While work is ongoing to fill the spectral gaps using new fiber dopants [3–5], these efforts have yet to produce results on par with established ultrafast sources.

Nonlinear wavelength conversion offers a way to leverage existing technology to generate pulses at new wavelengths. Techniques such as the soliton self-frequency shift [6–8], soliton self-mode conversion [9], and self-phase-modulation-enabled spectral shifting [10,11] have performed impressively in this regard, but their reliance on dechirped pulses limits their scalability due to intensity-related damage thresholds. State-of-the-art solid-state optical parametric systems offer unparalleled performance [12], but suffer from their complexity, cost, and alignment sensitivity. Fiber optical parametric amplification offers another alternative. Through degenerate four-wave-mixing, two pump photons can be converted to a

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blueshifted signal photon and a redshifted idler photon, with the magnitude of the shift determined by energy conservation and phase-matching. The latter depends on the dispersive properties of the fiber. Pumping in the anomalous-dispersion regime results in broadband phase-matching, but only over a frequency range localized near the pump wavelength; by contrast, pumping in the weakly normal regime can make use of higher order dispersion to phase-match widely separated spectral bands, making this regime more directly applicable to the generation of brand new frequencies. Fiber optical parametric oscillators (FOPOs) and amplifiers (FOPAs) based on four-wave-mixing have been demonstrated over a variety of formats and wavelengths, but tend to produce pulses that are either energetic but long [13–16], or short but with lower energy [17–21]. Thus, the performance of fiber optical parametric systems remains below what is needed by emerging applications.

Fiber optical parametric chirped-pulse amplification (FOPCPA) has been proposed as a means of overcoming this trade-off [22]. The technique combines the spectral flexibility of fiber optical parametric amplification with the energy and peak power of chirped-pulse amplification (CPA). Temporally stretching the pulses prior to parametric amplification and subsequently recompressing them helps reduce unwanted nonlinear distortions, while the use of larger stretching factors offers tremendous scalability. Furthermore, chirping the pump gives rise to a chirped parametric gain profile where different processes are phase-matched at each point in time, permitting the overall gain spectrum to be very broad [23–25]. Since FOPCPA was proposed, several groups have experimentally demonstrated FOPCPA systems [23–29]. However, only recently have such systems produced femtosecond pulses with microjoule-level energies [30]. Furthermore, all experimental FOPCPA systems to-date have used anomalous-dispersion pumping, and as such, none has generated new wavelengths beyond what is already obtainable using standard doped fibers.

Here, we demonstrate an FOPCPA system pumped, for the first time, in the normally dispersive regime. This approach allows us to partially transfer both the energy and the bandwidth of femtosecond pulses to new wavelengths, which, due to the normal dispersion, may be widely separated from the pump. The FOPCPA is seeded with a continuous-wave signal beam, eliminating the need for complex seed pulse generation or precise pump-seed synchronization. As a proof of the method, we present results of femtosecond pulse generation near the important bioimaging window at 1.3 μm . Finally, we experimentally and numerically investigate prospects for scaling up the energy and peak power of the generated pulses.

The operating principles of our system are illustrated by the spectrograms in Fig. 1. At the system's input [Fig. 1(a)], a broadband, stretched pump pulse is launched with a continuous-wave (CW) seed. As an example, a 400-nJ pump pulse centered at 1.03 μm with a chirped duration of 30 ps and a bandwidth of ≈ 7 nm is shown, alongside a 40-mW seed at 0.85 μm (marked with a dashed line to aid visibility). We numerically simulate the propagation of these two waves in a photonic crystal fiber (PCF) with a zero-dispersion wavelength near 1.04 μm (NKT SC-5.0-1040). The fiber length is chosen to be short enough to support the desired pulse evolution (see below), yet long enough to physically handle with ease; in the simulation shown, 6.7 cm is chosen to match experiments. In the PCF, the pump experiences weakly normal dispersion, leading to phase-matching at a signal band near 0.85 μm and an

idler band near 1.3 μm . As a result, the simulations show significant energy conversion into these two spectral bands, manifesting, respectively, as a narrowband, amplified signal component and a broadband, 70-nJ idler pulse [Fig. 1(b)]. The latter exhibits a clearly linear chirp, allowing it to be cleanly compressed to its 260-fs transform limit.

The nonlinear pulse evolution in the PCF can be easily understood if temporal effects such as group-velocity dispersion (GVD) and group-velocity mismatch (GVM) are neglected. This situation can be engineered by keeping the PCF length well below the dispersion and temporal walk-off lengths of the stretched pulses, which also helps curtail the fabrication-induced, longitudinal fiber fluctuations that might otherwise impede wavelength conversion [31,32]. Under these conditions, each point in time can be thought of independently as a separate, quasi-CW, four-wave-mixing process driven by a different temporal-spectral component of the chirped pump. Because each such process must independently conserve energy, the energy conservation relation between the pump at frequency ω_p , the signal at frequency ω_s , and the idler at frequency ω_i can be written explicitly as a function of time:

$$\omega_i(t) = 2\omega_p(t) - \omega_s, \quad (1)$$

where the constant ω_s reflects the seed's CW nature. Thus, seeding a CW signal results in a broadband idler that mimics the pump's phase up to a factor of two. This behavior has been previously observed and studied [23,24,33], and is furthermore evident in our simulations (Fig. 1), validating the assumption of negligible GVD and GVM. This transfer of the pump's phase to the idler is a crucial feature of CW-seeded FOPCPA: not only does the factor of two in Eq. (1) help buffer the idler against parametric gain narrowing, but the preservation of the pump's chirp allows the idler to be dechirped as easily as the pump, retaining the advantages of existing CPA technology. Note that while the idler is background-free, the signal retains a pedestal in the form of the unamplified, interpulse seed light (not visible on the spectrogram's linear scale). Our described system bears similarities to that presented in [13]; however, where that system deliberately targeted narrowband pulse generation, ours uses a broadband, highly chirped pump, resulting in qualitatively different pulse propagation dynamics and a femtosecond-scale output.

We experimentally validate our simulations by constructing a system along the lines of Fig. 2. A CPA system based on ytterbium-doped fiber generates linearly polarized pump pulses at 1.03 μm with ≈ 7 nm of bandwidth, stretched in fiber to 30 ps and amplified up to ≈ 500 nJ at a repetition rate of 1.2 MHz. A polarizing beam splitter and two half-wave plates permit precise control of the incident power and polarization. The CW seed wave is supplied by a linearly polarized, 0.85- μm diode with a 1-MHz linewidth, and is also equipped with a half-wave plate to align its polarization with that of the pump. Finally, the pump and signal beams are combined at a dichroic mirror and simultaneously coupled into a 6.7-cm piece of the PCF specified above. At the output of the PCF, the beams are collimated, and another dichroic mirror isolates the idler for characterization.

With 390 nJ of pump energy and 40 mW of seed power coupled into the PCF, we obtain the results shown in Fig. 3. The full-field spectrum [Fig. 3(a)] shows three distinct waves: the

broadband pump at 1.03 μm ; the narrowband, amplified signal at 0.85 μm ; and the newly generated, broadband idler at 1.3 μm . Note that due to chromatic aberrations in coupling to the optical spectrum analyzer, relative intensities are only accurate within each distinct spectral band, and should not be compared quantitatively between different regions. When we isolate the idler using a dichroic mirror, we measure its energy to be 47 nJ, corresponding to 12% power conversion. Accounting for the signal as well, the total pump depletion is therefore 30%. Compressing the idler using a standard grating pair (Lightsmyth T-1200-1310) yields the autocorrelation in Fig. 3(b). We infer from this a pulse duration of 210 fs, very near the 200-fs transform limit calculated from the spectrum. Coupling a fraction of the dechirped pulses into a length of passive fiber results in spectral broadening in good agreement with simulations, confirming the coherent and transform-limited nature of the generated pulses. The idler spectrum exhibits some structure [Fig. 3(a), inset], which we speculate may be a result of nonlinear dynamics in the locally depleted pump regime; this does not appear to significantly affect the dechirped pulse quality.

It is worth emphasizing that, although we refer to our system as an amplifier, the wavelength we aim to generate is not actually the one we seed. While the seeded wave is indeed amplified, it is of more limited use due to its small bandwidth and its long pedestal of unamplified, interstitial, CW light. Rather, the desired, broadband pulse is generated from scratch as a byproduct of amplifying the ultimately discarded seed. Not only does the seed's presence galvanize this process [34], but it also ensures (provided that its coherence time is much longer than the pump duration) that the newly generated wave is coherent despite it not itself being seeded: every idler photon created is associated with a conjugate signal photon, leading to a shared coherence between the two waves. This stands in contrast with wholly unseeded systems, in which noisy and incoherent pulses form from amplified vacuum fluctuations. While we have chosen here to seed the 0.85- μm signal and reap the 1.3- μm idler, that choice might be easily reversed without significantly altering the system. In that case, a narrowband wave at 1.3 μm would be obtained alongside a train of broadband, dechirpable, 0.85- μm pulses. Simulations and theoretical considerations alike suggest that such a system would perform comparably to ours.

Although FOPCPA is but one means of generating pulses at new wavelengths, it possesses a key advantage in its potential for scalability. Because the pump's various temporal components evolve largely independently of one another in the PCF, stretching the pump further while maintaining a constant peak power preserves the nonlinear optical dynamics while scaling them in time. The result is an increase in the generated pulse's energy independently of its bandwidth or phase, limited only by the compressor's subsequent ability to compensate the additional stretching. One estimate of the ultimate performance of FOPCPA can be reached by considering a super-Gaussian pump stretched to 1 ns, corresponding roughly to the practical limit of high-performance CPA systems [35]. Numerical simulations of such a pulse reveal that, given adequate management of third-order dispersion from the stretcher and compressor, 1.3- μJ , 140-fs pulses at 1.3 μm might be within reach (see below).

As a step towards realizing this scalability, we construct a different 1.03- μm pump source, this one generating up to 4- μJ pulses with a 7-nm bandwidth, which we stretch to 150 ps

using a grating stretcher (Lightsmyth T-1000-1040). Coupling 1.9 μJ into the PCF, we generate idlers with energies up to 180 nJ (Fig. 4). The quality of the compressed pulses is noticeably diminished, as evidenced by the 600-fs inferred pulse duration, the low-intensity pedestal, and the appearance of secondary temporal structures; however, the generated idler remains broadband enough to support 220-fs pulses, indicating that it has still inherited a significant fraction of the pump's bandwidth. Furthermore, the loss of pulse quality appears to be a direct consequence of this bandwidth inheritance: when we dechirp and characterize the pump pulses themselves without idler generation, we observe a comparable duration (680 fs) and similar temporal features [inset of Fig. 4(b)]. We therefore believe that the idler's poor compressibility stems from irregularities of unknown provenance in the pump phase. We expect that using a pump source with a more linear chirp will eliminate this problem, yielding high-energy idlers that can be compressed to their femtosecond-scale transform limit.

In addition to the two experimental results presented here, we have performed four more experiments spanning a range of pump durations. Figure 5 summarizes the idler energies obtained using each pump duration, evincing the expected, linear relationship (red line). Furthermore, extrapolating this trend to a 1-ns pump duration shows reasonable agreement with the numerical simulations previously discussed (blue circle and inset). This is a significant extrapolation, and one that should be interpreted with caution. While the observed agreement between experiments and simulations lends credence to it, realizing it may require additional experimental practicalities to be overcome, such as control of third-order dispersion in the stretcher/compressor. Although we expect the peak pump power to remain below the threshold for fiber end-facet damage [36], coreless endcaps may be useful for extending the margin of error. Successfully achieving the predicted limit would bring all-fiber sources into a new performance class, allowing them to fulfill a wide array of new application demands as cheaper, more robust alternatives to existing solid-state systems.

In summary, we have demonstrated FOPCPA pumped in the normally dispersive regime. Using highly chirped pump pulses and a CW seed, our system generates femtosecond-scale pulses at wavelengths far from the pump, and can be scaled up to microjoule-level energies by stretching in the time domain. In experiments, we use a 1.03- μm pump and a 0.85- μm seed to generate 1.3- μm pulses with energies as high as 180 nJ that can be dechirped to a few hundred fs. Our results support the theoretically-predicted scalability of our approach, indicating a route for wavelength-flexible fiber lasers to reach unprecedented performance levels.

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Fig. 1.

Spectrograms depicting the simulated pulses at the (a) input and (b) output of the photonic crystal fiber. The dashed white line in panel (a) marks the CW seed, which is otherwise not visible on this scale. Panels are separately scaled to the maximum intensity.

Fig. 2. Operation of the FOPCPA system. PBS, polarizing beam splitter; HWP, half-wave plate; PCF, photonic crystal fiber.

Fig. 3. Measured FOPCPA output using a 30-ps stretched pump. (a) Full-field spectrum (inset: idler, linear scale). (b) Interferometric autocorrelation of the dechirped idler pulses (black), and the intensity autocorrelation numerically calculated from it (orange).

Fig. 4.

Measured FOPCPA output using a 150-ps stretched pump. (a) Full-field spectrum (inset: idler, linear scale). (b) Intensity autocorrelation of the dechirped idler pulses (inset: dechirped pump pulses without idler generation).

Fig. 5.

Observed scaling of the idler energy versus the stretched pump duration. Red line: linear fit and extrapolation. Lower inset: close-up of the short-pump region. Upper inset: simulated 1.3-μJ, 140-fs, dechirped idler corresponding to the blue circle (pump duration = 1 ns).