Strong-Field Few-Cycle 2- μ m Pulses via Kagome-Fiber Compression of Picosecond Ho:YLF Laser Pulses

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Abstract: We present strong-field few-cycle 2- μ m pulses based on air-filled Kagome-fiber compression of 140- μ J, 3.3-ps pulses from Ho:YLF amplifier to 48 fs and 11 μ J energy. This is the first demonstration of 70-fold compression from Kagome fibers at 2 μ m.

OCIS codes: (140.3580) Laser amplifiers; (190.4370) Nonlinear optics, fibers; (190.7110) Ultrafast nonlinear optics

1. Introduction

Over the past decade, development of high-energy few- to single-cycle laser pulses from Ti:sapphire chirped-pulse amplification (CPA) systems have led to important breakthroughs in studying various attoscience phenomena in strong-field physics and in particular high-harmonic generation (HHG) [1]. With recent advancements of ultrashort pulses in the mid-IR (MIR) region, HHG can provide an effective way to extend the cutoff photon energy of HHG into the soft-X-ray region, as the cutoff energy scales with laser wavelength λ according to $\hbar\omega = I_p + 3.17U_p$, with ionization potential I_p , ponderomotive energy $U_p \propto I_L \lambda^2$, and laser pulse intensity I_L [2]. MIR pulses are typically generated by frequency conversion via optical parametric amplification (OPA), which due to the exclusive use of near-IR pumps at 800 nm and 1 μ m has prevented access to longer MIR wavelengths ($>5 \mu$ m). Longer MIR wavelengths are becoming accessible with OPAs based on non-oxide crystals like ZGP and OP-GaAs that require pumping at 2- μ m wavelength. Hence, mJ-level sub-ps pulses at 2- μ m are preferred for driving MIR-OPAs featuring self-CEP-stabilization of the idler [2]. Sub-ps durations can be reached using subsequent nonlinear spectral broadening via self-phase modulation (SPM) in fibers and recompression. In the past decade, major developments in hollow-core photonic crystal fibers (HC-PCF) have been achieved [3]. Especially, we have seen the emergence of a new light-guidance mechanism, namely inhibited coupling (IC). Kagome-lattice HC-PCF is part of the IC-guiding fiber family. This fiber can offer enlarged core diameter, low dispersion and broad transmission bandwidth [4]. By virtue of the IC, it exhibits ultralow optical power overlap with silica cladding (down to ppm level) leading to the demonstration of 1-mJ 600-fs Yb laser beam handling [5]. Self-compression in fibers via soliton effect occurs due to interplay between positive chirp induced by SPM and negative chirp induced by group-velocity dispersion (GVD). Self-compression of 80-fs pulses down to the single-cycle regime in these fibers has been demonstrated [6]. However, transferring such a compression technique and ratio starting from energetic ps-longer pulses is still a pressing challenge. This is particularly true in the case of 2- μ m laser systems for which fs-pulse generation is still under development. Due to the low GVD of these fibers (typically 1 ps/nm/km), ps-pulses experience several-km-long dispersion lengths and hence external compression is the way forward to compensate for the chirp introduced by SPM. Recently, we demonstrated compression of 1.8-ps and 225- μ J pulses from the Ho:YLF amplifier down to 285 fs using spectral broadening in Kagome fiber and subsequent pulse compression in a first compression stage [7]. Here, we demonstrate two-stage compression of 1.6-ps-long pulse and with an energy of 140 μ J from a Ho:YLF regenerative amplifier down to 48 fs with a compressed energy of 11 μ J. To our knowledge, this is the first demonstration of 7-cycle pulse generation at a 2- μ m wavelength without involving any parametric frequency conversion process.

2. Experiment

The experimental setup for the two-stage Kagome compressor is shown in Fig. 1. The laser system comprises a conventional CPA based on a home-built Ho-doped fiber seed oscillator and a prototype Ho:YLF regenerative

amplifier (RA) (Q-Peak Inc.). Chirped volume Bragg gratings (CVBGs) are used to stretch and compress the pulses. As a first step, we employ intracavity gain shaping method in the regen cavity and broaden the output spectrum by $\sim 50\%$. The pulses from the RA that was 3.3 ps are thus compressed down 1.6 ps in the same CVBG.

Fig. 1. (a) Experimental layout. Inset (top-left) shows the input beam profile of the Kagome stage 1, Inset (bottom-left) shows the scanning electron microscope image of the 7-cell fiber, inset (top-right) shows the calculated dispersion profile of the fiber used. (b) Input and output spectra of the two-stage Kagome fiber compressor in the presence of air. The inset shows the spectra on a logarithmic scale.

The complete details of the system can be found in Ref. [8]. The output of 1.6 ps is then launched into the first-stage 7-cell Kagome fiber designed to operate at 2- μm wavelength having a length of 3 m, whose hollow-core and outer diameters are 63 μm and 330 μm , respectively. The mode-field diameter of the fiber is 44 μm and the numerical aperture is 0.014. The inset of Fig. 1(a) shows the dispersion profile of the fiber having the ZDW at 1.6- μm wavelength. The experimental layout is shown in Fig. 1(a). Proper mode-matching of the input beam is obtained using a focusing lens of 50-mm focal length achieving a maximum transmission efficiency of $\sim 88\%$. The input energy in the fiber is 140 μJ , while the output energy is 123 μJ . Due to high peak intensity in the fiber, the pulses undergo SPM, and new frequencies are generated. The narrowband 10-nm spectrum from the regen is thus broadened to 88 nm (foot-to-foot) bandwidth in the fiber. The input (black) and the output (red) spectrum is shown in Fig. 1(b). Due to the low GVD of the fiber, self-compression of the long pulses is not feasible and therefore we employ a Si-prism compressor that introduces negative GVD of $\sim 162000 \text{ fs}^2/\text{mm}$ to compensate for the positive chirp arising from the SPM in the fiber. With an efficiency of 73 %, the remaining pulse energy is 90 μJ . We performed SHG-FROG on the compressed pulse to determine the spectral phase and the temporal pulse profile, whose results are shown in Fig. 2(a)-(d). The retrieved pulse duration shown in Fig. 2(d) (black) is 285 fs FWHM. More details of the experiment can be found in Ref. [7]. The compressed output from this first stage is then launched into a second-stage Kagome fiber of length 2 m with the same design characteristics. In the second stage, the pulses further undergo SPM, which leads to spectral broadening up to ~ 370 nm bandwidth (foot-to-foot). The output spectrum is shown in Fig. 1(b) (blue). The inset shows the spectra on a log-scale. Due to the ultrabroad spectrum, the positive chirp, that needs to be compensated, is quite small leading to pulse self-compression in the Kagome fiber. However the GVD of the fiber is not enough to fully compensate for the chirp. Therefore, we used a thin fused-silica window of 2 mm and a sapphire window of 5 mm. We optimized the required amount of dispersion from the windows by performing several scans of SHG-FROG on the output pulse by increasing the window's thickness in a step of 1 mm. The final results are discussed in the next section.

Fig. 2. SHG-FROG reconstruction results from the first-stage 7-cell Kagome fiber filled with air: (a) measured (red), simulated (green dashed), and retrieved (black) spectra with the spectral phase (blue); (b) retrieved temporal intensity profile (black) and temporal phase (blue) [7].

3. Second-stage Kagome-fiber compression results and discussion

Fig. 3. SHG-FROG results of the self-compressed pulses from the second-stage 7-cell Kagome fiber filled with air: (a) Measured FROG trace shown on the *full* time scale, (b) measured FROG trace after filtering out the compressed part using a super-Gaussian filter in time, (c) reconstructed FROG trace retrieved from the *filtered* trace shown in panel (b); (d) measured (black) and retrieved (red) spectra with the spectral phase (blue), (e) retrieved temporal intensity profile (black) and the temporal phase (blue).

Fig. 3(a)-(e) shows SHG-FROG results obtained after optimizing the extra-dispersion required to compensate for the chirp remaining after pulse self-compression. The measured FROG trace shown on the *full* time scale in Fig. 3(a) exhibits a spectrally broadband, ultrashort *compressed* feature riding on top of a several-ps-long component. For numerical reasons emerging from the high complexity of the FROG trace data, in a preliminary reconstruction we filtered out the compressed part using a super-Gaussian filter in time. The resulting filtered FROG trace shown in Fig. 3(b) comprises 28 % of the energy contained in the full pulse. From the reconstruction of this filtered FROG trace, as depicted in Fig. 3(c)-(e), we obtain a 48-fs FWHM duration of the compressed component, which contains 67 % (within -100 fs to 300 fs). Thus, overall the compressed part contains $28\% \times 67\% = 19\%$ of the total output pulse energy of 60 μJ , i.e., we generated 11- μJ 48-fs FWHM pulses centered at 2050 nm.

4. Conclusion

We experimentally demonstrate two-stage compression of 2- μm , 3.3-ps long pulses from Ho:YLF amplifier down to a 7-cycle 48-fs FWHM duration with 11 μJ energy. This strong-field 7-cycle MIR source will have intriguing applications in strong-field attoscience experiments.

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