Generation of 5 fs, 0.5 TW pulses focusable to relativistic intensities at 1 kHz

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Abstract: We have demonstrated the generation of 5 fs, 0.5 TW pulses at 1 kHz repetition rate using a pulse compression technique in a hollow fiber with a pressure gradient. Owing to the excellent beam quality by passing through the hollow fiber, the beam after pulse compression could be focused to a nearly diffraction-limited spot size. We obtained for the first time a peak intensity as high as $5\text{x}10^{18}$ W/cm^2 in the 2-cycle regime.

OCIS codes: (140.7090) Ultrafast lasers; (190.7110) Ultrafast nonlinear optics; (320.5520) Pulse compression; (320.7160) Ultrafast technology.

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1. Introduction

Ultrashort laser pulses offer a unique opportunity to investigate ultrafast laser-matter interactions. This includes high-harmonic conversion toward the generation of isolated single attosecond pulses [1-4]. Until recently, pulse compression with a gas filled hollow fiber has been the most widely used technique to generate intense sub-10 fs laser pulses [5]. The advantage of hollow fiber pulse compression, compared to other techniques [6-9], is the ease with which it can be used to generate pulses in the few-cycle regime and the excellent spatial quality of the beam after pulse compression. The intensity at the focal point can be as high as 10^{15} to 10^{17} W/cm^2, which is suitable for ultrafast high-field physics studies.

However, a drawback of hollow fiber pulse compression is its energy scaling. Although the generation of 5 fs pulses has been reported, the pulse energy was limited to less than 1 mJ. The problem is the occurrence of self-focusing and ionization of the gas medium near or around the entrance of the fiber, which degrades the coupling between the beam and the hollow fiber and subsequent spectral broadening due to Kerr-based self-phase modulation (SPM) inside the fiber. We therefore proposed and demonstrated the use of a hollow fiber with a pressure gradient [10]. The idea of applying this technique is to prevent the beam from unfavorable nonlinear processes such as self-focusing and plasma defocusing at the entrance of the fiber [11]. After the beam is coupled to the fundamental mode of the fiber under the ideal condition, for spectral broadening to occur, the beam undergoes an SPM-based nonlinear process. Such a situation can be realized by a pressure gradient method, in which the gas pressure is distributed from zero at the entrance to the maximum at the exit of the fiber. With this technique, we have already generated 9.8 fs, 5 mJ pulses compressed from 40 fs, 8.5 mJ input pulses at a repetition rate of 10 Hz [10] and 10 fs, 2.5 mJ pulses from 23 fs, 5 mJ input pulses at a repetition rate of 1 kHz [12]. Sung et al. have demonstrated further shortening of pulse duration to 5.5 fs from 4.5 mJ, 25 fs input pulses, however, the pulse energy in this case was limited to 1.1 mJ [13]. In our recent theoretical study [14], we found that there is a trade-off between energy throughput and spectral broadening when the medium is strongly ionized by multiphoton ionization (MPI), which starts to occur at an intensity of approximately 2×10^{14} W/cm^2 for neon. Therefore, for efficient temporal compression of an intense laser pulse to the few-cycle regime, the peak intensity of the pulse inside a fiber must be below or comparable to the threshold value of MPI, in addition to the careful adjustment of coupling between the input beam and the fiber.

In this paper, we demonstrate the generation of 5 fs, 0.5 TW pulses at 1 kHz repetition rate using a pressure gradient in a hollow fiber pulse compressor. Developing this technique, we obtained nearly ideal spectral broadening based on SPM nonlinearity. We also characterized the temporal profile and the focusability after pulse compression and obtained, for the first time, a peak intensity as high as 5×10^{18} W/cm^2 in the 2-optical cycle regime, which is sufficiently high to explore high-harmonic conversion in the relativistic regime [15].

2. Experimental setup

The experimental setup for pulse compression in a hollow fiber with a pressure gradient is shown in Fig. 1. Since the detail has been presented elsewhere [12], we briefly describe several improvements we have made so far. A Ti:sapphire chirped pulse amplification (CPA) system was used to provide an output energy of 5 mJ with a pulse width of 25 fs at a repetition rate of 1 kHz. Special care was taken to suppress thermal lensing occurring at the grating-pair compressor, where the wavefront is modified and degraded due to the high average power of the beam. We replaced the first blazed grating with a high-throughput holographic one with a Zerodure substrate. To stabilize the output power, we adopted a power

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lock system, by which the power fluctuation was monitored through zeroth-order diffraction from the second grating and feedback signals were sent to a Pockels cell driver to control the intensity of the seed pulses to the amplifiers. With this power lock system, the output power fluctuation from the CPA system was well stabilized within 0.25% rms.

The laser beam after the CPA system was loosely focused onto a hollow fiber with an inner diameter of 500 μm and a length of 220 cm using an f=4.5 m focusing lens. The hollow fiber was placed on a metal block with a straight V-groove inside a stainless-steel cell. The beam diameter was set to be 65% with respect to the hollow fiber diameter to maximize the coupling efficiency [16]. Then, the intensity inside the fiber was estimated to be 2.4×10^{14} W/cm^2. In order to employ the pressure gradient scheme, the input side of the hollow fiber was placed in vacuum, while the output side was pressurized with neon. Accordingly, the gas flowing inside the fiber has a pressure gradient along the optical axis. In addition, we used a beam lock system to stabilize the beam position at the fiber entrance [17]. With the beam lock system, the power fluctuation after spectral broadening was successfully decreased from 5.3% rms to 1.1% rms.

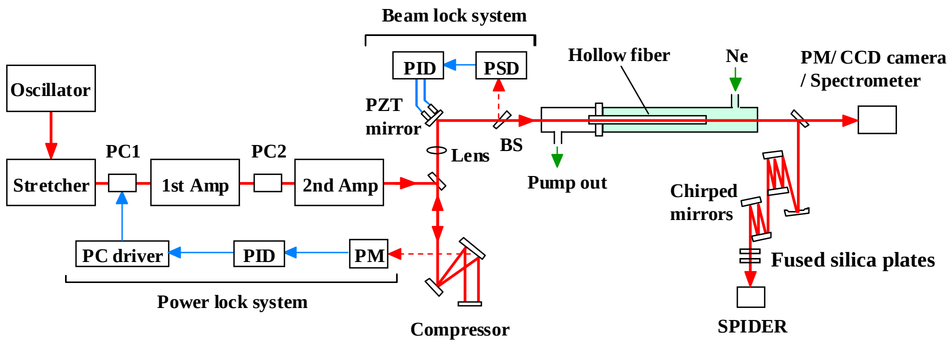

Fig. 1. kHz Ti:sapphire laser chirped pulse amplification system with a pressure-gradient hollow fiber pulse compressor. PC: Pockels cell, PID: proportional-integral-derivative controller, BS: beam splitter, PSD: position-sensitive detector, PM: power meter, CCD: charge coupled device. The spectrum broadened by the self-phase modulation in the fiber was monitored with a spectrometer. The compressed pulse duration was measured with SPIDER after dispersion compensation with chirped mirrors.

3. Results and discussion

Figure 2(a) shows transmittances as functions of distance between the focusing lens and the fiber entrance for input energies of 0.5 mJ and 5 mJ in vacuum and 5 mJ at a neon pressure of 1.5 atm. Since the Kerr-lens effect induced at the lens and window materials at high intensities shortened the focal length by approximately 10 cm, the position of the focusing lens had to be carefully adjusted to compensate for the distance to the fiber entrance. After the optimization, the energy throughputs were 75% in vacuum and 63% when pressurized at 1.5 atm on the exit side. Figure 2(b) shows plots of transmittance and $1/e^2$ beam diameter measured at 2.3 m away from the fiber exit as functions of neon gas pressure. The transmittance did not change so much with increasing neon gas pressure. On the other hand, the beam diameter rapidly decreased with increasing neon pressure. At a pressure of 1.6 atm, the input power to the fiber was about 2.4 times as high as the critical power for self-focusing, $P_{cr}=\pi(0.61\lambda)^2/8n_0n_2$, where λ is the center wavelength, n_0 and n_2 are the refractive index and nonlinear index coefficient of the gas medium [18]. Taking into account the fiber throughput of approximately 65% and slight pulse stretching due to dispersion, we find that the power at the exit of the fiber is almost the same as the critical power.

Figure 3 shows the spectral broadening for various neon pressures on the exit side. In order to understand the mechanism driving the spectral broadening, we also performed

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simulations with the same parameters as those used in the experiments and compare them with the experimental data. The simulation is based on a method described elsewhere [11, 14].

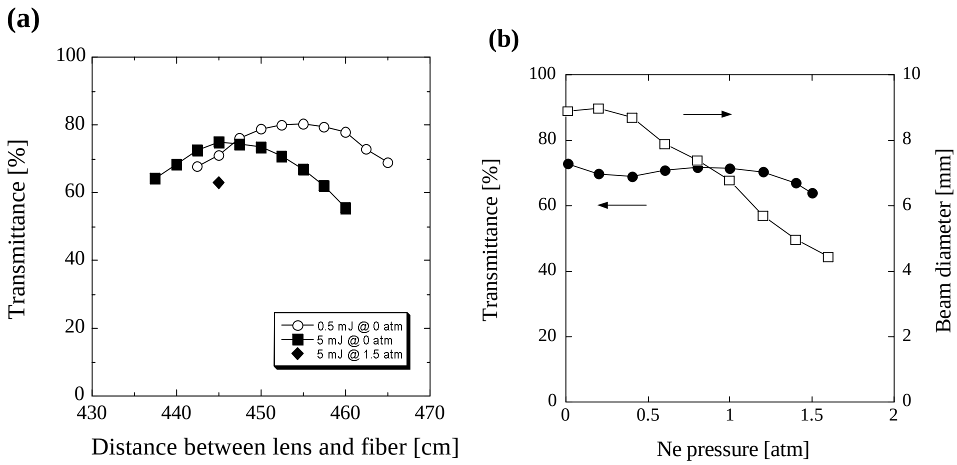

Fig. 2. (a). Transmittances as functions of distance between focusing lens and fiber entrance for input energies of 0.5 mJ and 5 mJ in vacuum and 5 mJ at a neon pressure of 1.5 atm and (b) transmittance and beam diameter as functions of neon pressure on the exit side.

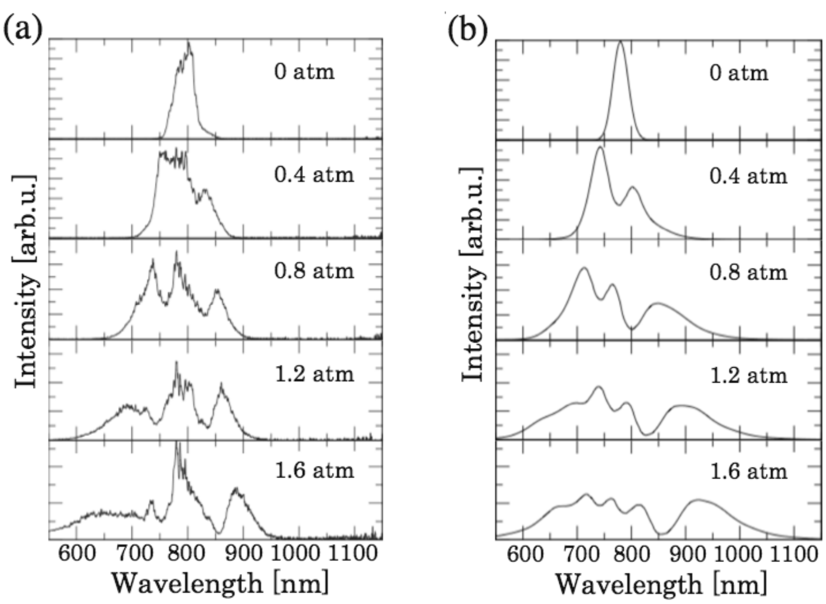

Fig. 3. Comparison of spectral broadening at various neon gas pressures on the exit side. (a) Experimental data and (b) simulated results.

We can see qualitatively good agreement between them. A lack of long-wavelength components (>950 nm) in the experimental data is due to the low sensitivity of the Si-based detector array used in the spectrometer. By investigating the simulation data in details we found that the spectral broadening is predominantly driven by SPM. This indicates that the pressure gradient method prevents the beam from collapsing due to self-focusing as well as

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from plasma defocusing, while allowing the pulse to undergo SPM during its passage through the hollow fiber. At a pressure of 1.6 atm, spectral broadening in excess of 300 nm was obtained, which corresponds to a pulse width of less than 5 fs. Although further spectral broadening would be possible by increasing the neon gas pressure, self-focusing occurring after exiting from the fiber limits the maximum pressure on the exit side of the gas cell, as shown in Fig. 2(b). From the standpoint above, we decided to set the gas pressure to 1.4 atm in the following experiment.

After the hollow fiber, the dispersion of the pulse was compensated with chirped mirrors. We employed a combination of two sets of chirped mirrors, i.e. those from Femtolasers Produktions GmbH and Layertec GmbH. The former can compensate for a group delay dispersion (GDD) of -306 fs^2 and a third-order dispersion (TOD) of -182 fs^3 after 5 reflections, whereas the latter provides a GDD of -180 fs^2 and a TOD of +60 fs^3 after 4 reflections. We also inserted several pieces of fused-silica plates (a total of 5 mm in thickness) with a broadband anti-reflection coating to compensate a small amount of dispersion in a daily basis. Accordingly, the net dispersion for the compensator including the chirped mirrors and the fused-silica plates was a GDD of -306 fs^2 and a TOD of +15 fs^3 at 800 nm. Figure 4(a) shows the spectral intensity and phase measured with spectral phase interferometry for direct electric-field reconstruction (SPIDER) after compensating for dispersion. The dispersion was well compensated for with a combined set of chirped mirrors and fused-silica plates over a wide range of the spectrum spanning from 600 nm to 1000 nm. It should be noted that the spectral profile was well stabilized from pulse to pulse and for a long term owing to the beam-lock system installed before the hollow fiber [17]. The temporal profile was reconstructed from the spectral intensity and phase, and is shown in Fig. 4(b). The compressed pulse width is 5.4 fs corresponding to 2.1 optical cycles at the center wavelength of 760 nm. The energy after compensation for dispersion was 2.7 mJ.

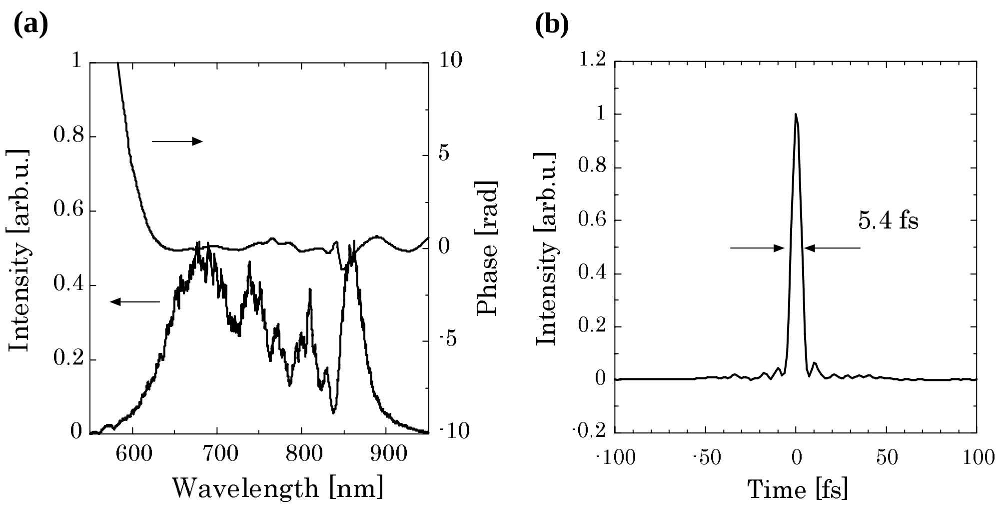

Fig. 4. (a). Spectral profile and phase after compensation for dispersion and (b) reconstructed temporal profile.

Finally, we investigated the focusability of the beam after hollow fiber compression. We focused the beam using an off-axis parabolic mirror with a focal length of 6 cm and monitored the focal spot images transferred onto a CCD camera by image relay optics with a magnification of 30. Figure 5 shows plots of the spot size as a function of the distance from the parabolic mirror. The beam size on the mirror was about 13 mm in diameter, which corresponds to a diffraction-limited spot size of 2.4 μm at the beam waist. The solid lines

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represent theoretical curves assuming a diffraction limit. Fairly good agreement was obtained between the experimental data and the theoretical curves, indicating that the beam of compressed pulses has excellent focusability. It is also noted that the energy content within the $1/e^2$ area was 78 %. From this value and the $1/e^2$ spot size of ω=2.5 μm at the waist position, the intensity averaged over the area $\pi\omega^2$ was 2.3×10^{18} W/cm^2, and thus, the intensity at the center of the focused spot was evaluated to be 4.6×10^{18} W/cm^2.

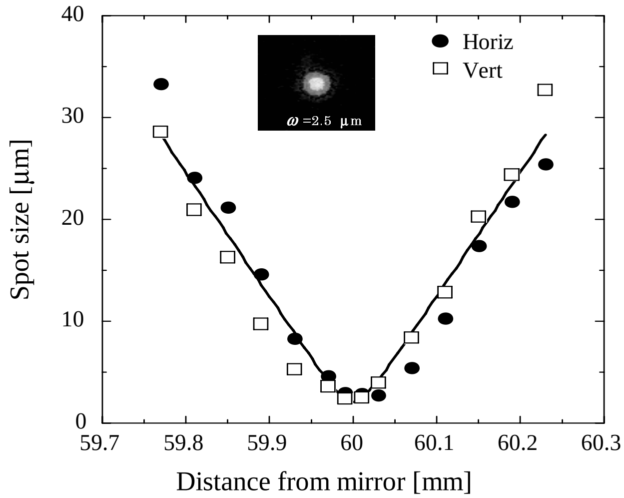

Fig. 5. Focusability of the beam after hollow fiber compression. The insert shows the focal spot image.

4. Conclusion

In conclusion, we have demonstrated the generation of 5 fs, 0.5 TW laser pulses at 1 kHz repetition rate using a hollow fiber pulse compressor with a pressure gradient. We have characterized the spectral profile and spectral phase, and compared the spectral data with simulation result. We found that the spectral broadening is predominately driven by SPM. The focusability of the output beam after pulse compression is excellent, which can be focused to a spot of just a few times the center wavelength without a need of wavefront correction. The estimated peak intensity after focusing was 5×10^{18} W/cm^2, which enables one to study laser-matter interactions in the relativistic regime. Further upscaling in the energy would be possible by decreasing the gas pressure, changing the gaseous medium from neon to helium, or combination of these two.

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