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Carrier-envelope phase stabilized 5.6 fs, 1.2 mJ pulses

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The authors report the generation of 1.2 mJ pulses with a duration of 5.6 fs from a neon filled hollow-core fiber seeded with carrier-envelope phase stabilized 2.2 mJ, 25 fs pulses. The carrier-envelope phase after the fiber was measured by a second, out-loop f-to-$2f$ interferometer. With seed pulse power locked, the carrier-envelope phase of the two-cycle pulses is controlled to a standard deviation of 370 mrad. The peak power of the carrier-envelope phase stabilized pulses, 0.2 TW, is twice that previously generated. The significance of seed pulse energy stability for carrier-envelope phase stabilization of few-cycle laser pulses is demonstrated. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2724919]

To obtain attosecond pulses from high harmonic generation (HHG), a driving laser with duration close to one laser cycle is desirable.[1,2] However, the width of the pulses generated directly from chirped pulse amplifier[3] (CPA) is limited by the gain narrowing of the amplifier. To reduce the pulses to few-cycle duration, additional spectral broadening is achieved via self-phase modulation (SPM) using a hollow waveguide filled with a noble gas,[4–8] bulk material,[9,10] or self-compression (filamentation).[11–15] The field strengths of few-cycle pulses depend strongly on the carrier-envelope (CE) phase. Therefore, the CE phase is a critical parameter for strong-field interactions with atoms and molecules, such as HHG, and therefore for attosecond pulse generation as well.[3,16–18] To increase attosecond pulse photon flux and reduce the attosecond pulse duration, the energy of the CE phase stabilized few-cycle pulse should be as high as possible.

Previously, the energy of CE phase stabilized few-cycle pulses was limited to ~0.5 mJ.[15,19] The major limitation is posed by the energy of the seeding pulses to the hollow-core fiber or filamentation. The CE phase stabilized seed pulses are produced from a CPA system that uses a glass block and prism pairs to stretch and compress pulses in a single stage multipass amplifier, which limits the output energy of the pulses to less than 1 mJ.[20] Grating-based CPA systems can provide CE phase locked pulses with much high energy.[21]

In this letter, we studied the scaling of the energy of phase stabilized few-cycle pulses by seeding the hollow-core fiber with much higher energy pulses. Furthermore, we investigated the effects of pulse energy stability on the CE phase stability of the pulses from the hollow-core fiber compressor.

The high energy seed pulses in our experiments were generated using the Kansas Light Source (KLS) laser system,[22] which utilizes a grating-based stretcher and compressor (Fig. 1). The laser system is a 14 pass, liquid nitrogen cooled Ti:sapphire amplifier. By combining preamplifiaction and power amplification in a single amplification stage, the system produces 25 fs pulses with output energy of 2.5 mJ at 1 kHz. The CE phase of the oscillator is stabilized using the self-referencing technique. Half of the oscillator beam was sent to a photonic crystal fiber for spectral broadening and then to a Mach-Zehnder f-to-$2f$ interferometer. The optical path length difference of the two arms in the interferometer was stabilized to avoid the effects of its drift on the phase locking of the oscillator.[23] The CE phase offset frequency of the oscillator was stabilized by feedback control of the Kerr-lens mode lock using an acousto-optic modulator. The other beam was sent to the CPA amplifier. To stabilize the CE phase of the amplified pulses, 10% of the 2.5 mJ was reduced to ~1 μJ by neutral density filters and iris when focused to a sapphire plate. The slow drift of the CE phase after the CPA measured by this in-loop interferometer was then corrected by feedback control of the grating separation in the stretcher.[24]

The remaining 2.2 mJ was focused into a hollow-core fiber with an interaction length of ~1 m. To accommodate the high energy seeding, large core diameter (0.4 mm) hollow-core fibers filled with Ne gas (pressure ~3 bars) were used for spectral broadening. The pulses from the fiber were then compressed by chirped mirrors. The pulse duration was then measured by frequency-resolved optical gating (FROG).[25] Figure 2(a) shows the fiber input and output spectra and Fig. 2(b) shows the pulse shape and temporal phase reconstructed by FROG. The Fourier transform limited pulse duration calculated from Fig. 2(a) was 5.0 fs. The measured pulse duration is 5.6 fs with energy of 1.2 mJ. We performed a z-scan using a focusing mirror with a radius of curvature of 1.5 m. The output beam had a beam quality factor M^2 of 1.08.

The CE phase of the 5.6 fs pulses was monitored by a second collinear f-to-$2f$ interferometer, again utilizing spectral broadening in a sapphire plate. Since the first (in-loop) f-to-$2f$ interferometer is positioned before the fiber and is used for feedback control, a second (out-loop) measurement after the fiber is critical for understanding the CE phase stability. The power fluctuation in the sapphire plates of both f-to-$2f$ interferometers can affect the CE phase measurements.[20,26] To study the influence of the energy fluctuation, the power stability before the fiber was measured using the zeroth order diffraction beam from the grating compressor. In order to reduce energy fluctuation, an energy lock technique is applied to the CPA laser system.[27] Another power meter measured the energy stability after the fiber. The pulse energy fluctuation of our CPA system (before the fiber) is ~1.5%, expressed as the standard deviation. It can be reduced to 0.6% by using a power locking procedure.

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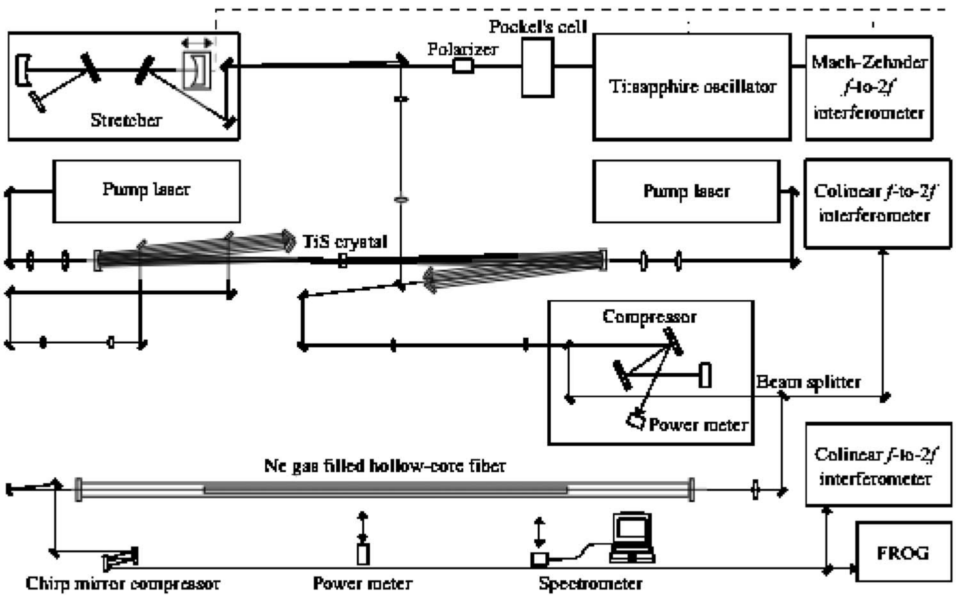

FIG. 1. Laser system for generating phase locked, high energy, few-cycle pulses.

Figures 3(a) and 3(b) show the CE phase fringes obtained by the f-to-$2f$ interferometers and the phase stability for the seed pulse and the 5.6 fs pulse when the amplifier power was locked. The power fluctuations before and after the fiber were 0.6% and 1.4%, respectively. The CE phase before and after the fiber shows 189 and 370 mrad, respectively; both expressed as the standard deviation over 50 s. The energy of the CE phase stabilized, <6 fs pulses are twice of that demonstrated previously. The larger CE phase fluctuation measured by out-loop measurement as compared to the seed pulse could likely be due to the larger power fluctuation in the sapphire plate of that interferometer.[27] The power fluctuation after the fiber is larger due to the variation of the coupling efficiency caused by beam pointing fluctuations. To reduce these power fluctuations, the pointing stability of the beam coupled to the fiber must be improved.

Figures 4(a) and 4(b) compare the CE phase fringes and the phase stability for the seed pulses and 5.6 fs pulses measured without the power lock of the seed pulses. The power fluctuations before and after the fiber were 1.5% and 2.5%, respectively. The CE phase fluctuations of the seed pulses as measured by the in-loop f-to-$2f$ interferometer were 195 mrad comparable to Fig. 3(a), but the CE phase fluctuation after the fiber increased to 567 mrad. This result shows that the power stabilization is important for the stabilization and evaluation of the CE phase after the fiber.

In order to estimate CE phase fluctuation given by SPM in the fiber, we measured the CE phase fringes and stability with the fiber pumped to vacuum with power lock, as shown Fig. 5. The power fluctuations before and after the fiber were 0.6% and 1.2%, respectively. The CE phase stability of the seed pulses was 195 mrad and that of the pulses from the fiber was 372 mrad. The CE phase stability and power fluc-

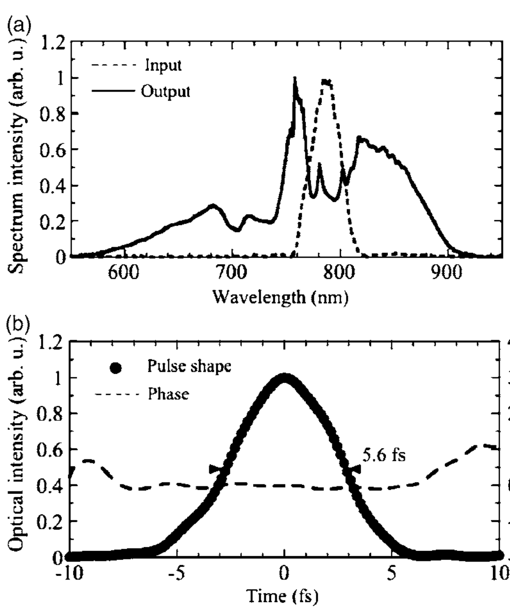

FIG. 2. (a) Spectra of the input (dashed line) and output (solid line) of the fiber. (b) The pulse shape (filled circle) and temporal phase (dashed line) as reconstructed by FROG.

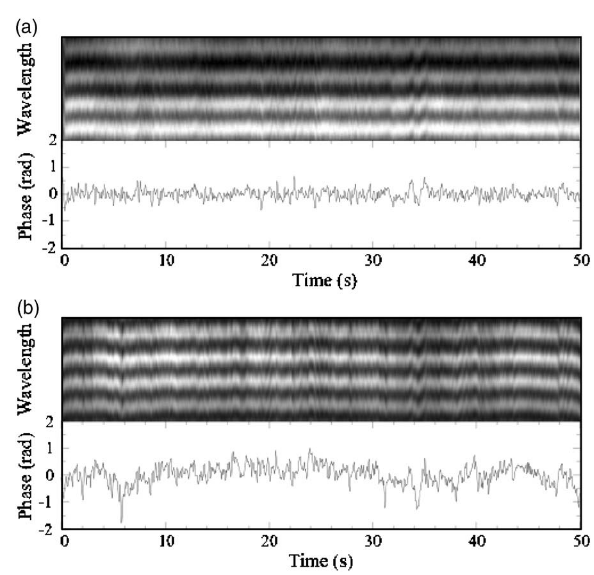

FIG. 3. (a) CE phase fringes and phase drift of the seeding pulses. (b) The CE phase fringes and phase drift of the 5.6 fs pulses at Ne gas pressure of 3 bars. The seed power was locked to 0.6%.

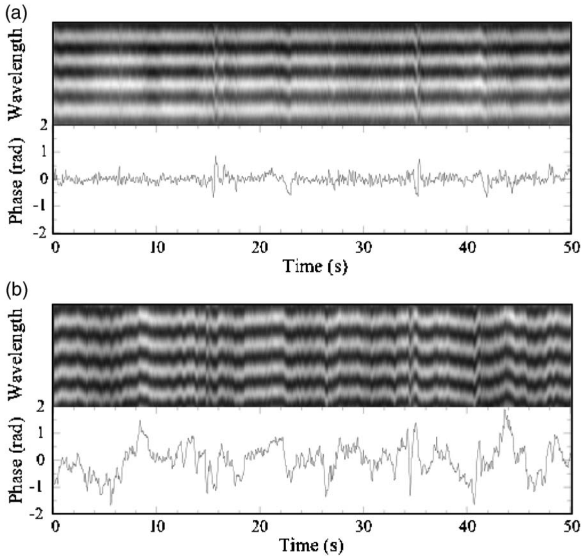

FIG. 4. CE phase fringes and phase drift of the seeding pulses. (b) The CE phase fringes and phase drift of the 5.6 fs pulses at Ne gas pressure of 3 bars. The seed power fluctuation is 1.5%.

tuation after the fiber were comparable to the results with Ne gas pressure of 3 bars shown in Fig. 3. Thus, the contribution from SPM to the measured CE phase noise is much smaller than that from the energy fluctuation in the f-to-$2f$ interferometers. This result also shows the importance for power and beam pointing lock.

The CE phase error introduced by the hollow-core fiber obtained by our measurers is higher than that reported in Ref. 20 In that work, the phase shift in a narrow spectral range (~30 nm, i.e., the width of the pulse before the fiber) around 800 nm was measured using a linear, Mach-Zehnder interferometer instead of using two f-to-$2f$ interferometers like we did. The results can be considered as a low limit of the true CE phase shift of the pulses from the fiber, which has a much broader bandwidth (>150 nm).

In conclusion, we have generated CE phase stabilized pulses with a duration of 5.6 fs and energy of 1.2 mJ by seeding large core hollow fiber with CE phase locked pulses from a grating-based CPA system. The CE phase stability of the 5.6 fs pulses was 370 mrad, measured by an out-loop f-to-$2f$ interferometer when the CPA system was power locked. As compared to CPA systems based on the glass block and prisms, the grating-based CPA system should be able to produce CE phase locked pulses with much higher energy than demonstrated here (2.2 mJ); thus it is anticipated that the energy of the CE phase stabilized few-cycle pulses is scaled to even higher values. Such pulses are important not only for generating intense attosecond pulses but also for studying other strong field processes such as above-threshold ionization and relativistic plasma physics.

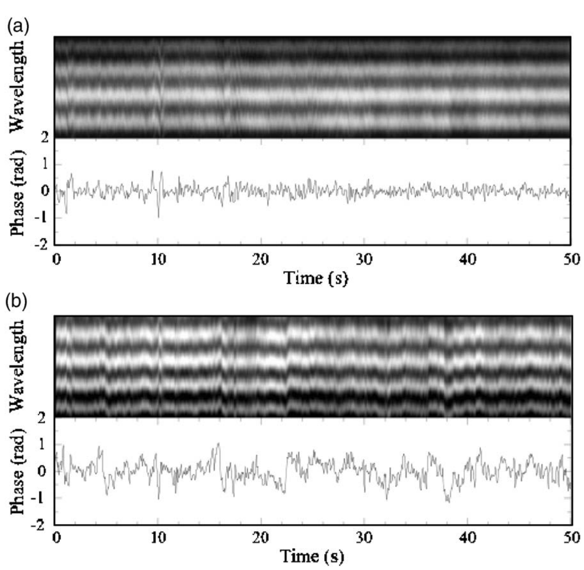

FIG. 5. (a) CE phase fringes and phase drift of the seeding pulses. (b) The CE phase fringes and phase drift of the 5.6 fs pulses at Ne gas pressure of 0 bars. The seed power was locked to 0.6%.

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[1]I. P. Christov, M. M. Murnane, and H. C. Kapteyn, Phys. Rev. Lett. **78**, 1251 (1997).
[2]Z. Chang, Phys. Rev. A **70**, 043802 (2004).
[3]D. Strickland and G. Mourou, Opt. Commun. **56**, 219 (1985).
[4]M. Nisoli, S. D. Silvestri, and O. Svelto, Appl. Phys. Lett. **68**, 2793 (1996).
[5]G. Tempea and T. Brabec, Opt. Lett. **23**, 1286 (1998).
[6]S. Ghimire, B. Shan, C. Wang, and Z. Chang, Laser Phys. **15**, 838 (2005).
[7]A. Suda, M. Hatayama, K. Nagasawa, and K. Midorikawa, Appl. Phys. Lett. **86**, 111116 (2005).
[8]A. J. Verhoef, J. Seres, K. Schmid, Y. Nomura, G. Tempea, L. Veisz, and F. Krausz, Appl. Phys. B: Lasers Opt. **82**, 513 (2006).
[9]E. Mével, O. Tcherbakoff, F. Salin, and E. Constant, J. Opt. Soc. Am. B **20**, 105 (2003).
[10]C. Hauri, W. Kornelis, F. Helbing, A. Heinrich, A. Couairon, A. Mysyrowicz, J. Biegert, and U. Keller, Appl. Phys. B: Lasers Opt. **78**, 673 (2004).
[11]A. Braun, G. Korn, X. Liu, D. Du, J. Squier, and G. Mourou, Opt. Lett. **20**, 73 (1995).
[12]I. G. Koprinkov, A. Suda, P. Wang, and K. Midorikawa, Phys. Rev. Lett. **84**, 003847 (2000).
[13]D. Mikalauskas, A. Dubietis, and R. Danielius, Appl. Phys. B: Lasers Opt. **75**, 899 (2002).
[14]O. Shorokhov, A. Pukhov, and I. Kostyukov, Phys. Rev. Lett. **91**, 265002 (2003).
[15]A. Guandalini, P. Eckle, M. Anscombe, P. Schlup, J. Biegert, and U. Keller, J. Phys. B **39**, S257 (2006).
[16]M. Nisoli, G. Sansone, S. Stagira, S. De Silvestri, C. Vozzi, M. Pascolini, L. Poletto, P. Villoresi, and G. Tondello, Phys. Rev. Lett. **91**, 213905 (2003).
[17]R. Kienberger, E. Goulielmakis, M. Uiberacker, A. Baltuska, V. Yakovlev, F. Bammer, A. Scrinzi, Th. Westerwalbesloh, U. Kleineberg, U. Heinzmann, M. Drescher, and F. Krausz, Nature (London) **427**, 817 (2004).
[18]I. J. Sola, E. Mével, L. Elouga, E. Constant, V. Strelkov, L. Poletto, P. Villoresi, E. Benedetti, J.-P. Caumes, S. Stagira, C. Vozzi, G. Sansone, and M. Nisoli, Nat. Phys. **2**, 319 (2006).
[19]A. Ishizawa and H. Nakano, Jpn. J. Appl. Phys., Part 1 **44**, 6039 (2005).
[20]A. Bultuška, M. Uiberacker, E. Goulielmakis, R. Kienberger, V. S. Yakovlev, T. Udem, T. W. Hänsch, and F. Krausz, IEEE J. Quantum Electron. **9**, 972 (2003).
[21]K.-H. Hong, J. Lee, B. Hou, J. A. Nees, E. Power, and G. A. Mourou, Appl. Phys. Lett. **89**, 031113 (2006).
[22]B. Shan, C. Wang, and Z. Chang, U.S. Patent No. 7,050,474 (23 May 2006).
[23]E. Moon, C. Li, Z. Duan, J. Tackett, K. L. Corwin, B. R. Washburn, and Z. Chang, Opt. Express **14**, 9758 (2006).
[24]C. Li, E. Moon, and Z. Chang, Opt. Lett. **31**, 3113 (2006).
[25]R. Trebino and D. J. Kane, J. Opt. Soc. Am. A **10**, 1101 (1993).
[26]C. Li, E. Moon, H. Wang, H. Mashiko, C. M. Nakamura, J. Tackett, and Z. Chang, Opt. Lett. **32**, 796 (2007).
[27]H. Wang, C. Li, J. Tackett, H. Mashiko, C. M. Nakamura, E. Moon, and Z. Chang, Appl. Phys. B: Lasers Opt. (submitted).